School of Design and the Built Environment

Conceptual Foundations for the Governance of Shared Solar Energy Resources

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This thesis is presented for the Degree of
Doctor of Philosophy
of
Curtin University

August 2020

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Human Ethics

The research presented and reported in this thesis was conducted in accordance with the National Health and Medical Research Council National Statement on Ethical Conduct in Human Research (2007) – updated March 2014. The proposed research study received human research ethics approval from the Curtin University Human Research Ethics Committee, Approval Number **HRE2018-0107.**

[redacted]

Paula Hansen

Date: 18/08/2020

Statement of contribution of others

I conceptualised and coordinated as well as undertook the analysis and writing for the following publications:

- Hansen, P., Liu, X., & Morrison, G. M. (2019). Agent-based modelling and socio-technical energy transitions: A systematic literature review.
- Hansen, P., Morrison, G. M., Zaman, A., & Liu, X. (2020). Smart technology needs smarter management: Disentangling the dynamics of digitalism in the governance of shared solar energy in Australia.
- Hansen, P.: Optimising shared renewable energy systems: An institutional approach.
- Hansen, P. & Morrison, G.M.: Beyond the local scale: Action and impact of sustainability initiatives from a polycentric perspective

I coordinated the collaboration on

- Monroe, J.G., Hansen, P., Sorell, M., Zechman Berglund, E.: Agent-based model of a blockchain enabled peer-to-peer energy trading trial in Perth, Australia.

I conceptualised the publication together with my co-author Jacob G. Monroe. I also assisted with the analysis (data acquistion and aggregation, interpeting results) did the literature review and wrote some of the paper's sections.

I contributed to the conceptualisation and writing of

- Syed, M., Hansen, P. & Morrison, G.M.: Performance of a shared solar and battery storage system in an Australian apartment building.

Signed statements from all co-authors confirming my contributions are provided in Appendix A [redacted]

Paula Hansen

Date: 18/08/2020

Abstract

Shared renewable energy systems (SRES) are a prominent feature of the energy transition. As the energy system progresses towards decarbonisation through renewable energy penetration, shared resources are as much a result as a possible solution. The situation is further affected by increasing decentralisation and digitalisation. However, the potential of shared resources to enhance the effectiveness and efficiency of the low carbon transition is restricted by a limited understanding of how these novel configurations function. This research builds on the notion of a sociotechnical energy system with a view to develop the conceptual foundations needed to design and govern small-scale shared energy systems effectively. Drawing on the complementarities of systems theory and common resource governance approaches, the notion of sociotechnical interactions was operationalised as rules that guide the behaviour of social and technical agents. Empirical data from two case study SRES in Perth, Western Australia, was collected and analysed, with the aim of identifying the elements and interactions that shape the structure and governance of SRES. A multi-pronged approach to the analysis of stakeholder interviews and complementary quantitative data was used in conjunction with the theoretical literature to generate empirical and conceptual insight. The findings from the case studies direct attention to the role and effects of digital technologies in the operation of SRES. While they open up new possibilities for the equitable and efficient sharing of renewable energy, they also require additional technical expertise, and social and technical monitoring and communication. Improving operational performance through digital technologies requires that actors recognise and mitigate the effects of added complexity in institutional design. The findings further suggest that the performance of SRES mainly depends on the alignment of the incentive structures of actors with system purpose. The thesis contributes to interdisciplinary energy studies by proposing a conceptual map based on the shared ontological roots of systems theory and common resource governance. It enables the integrated examination of SRES by specifying structural social and technical system elements and properties; and provides a set of propositions as conceptual foundations for the study and governance of SRES.

Acknowledgements

What a trip.

Greg. I know I didn't always make things easy for you but I honestly could not have wished for a better supervisor! Thank you for all the hours you spent helping me navigate my way through complexity, and for your patience. Thank you for having seemingly unwavering trust in my abilities, and for listening to my ideas. And for encouraging me to apply for jobs I never would have otherwise applied for!

Thank you, Xin, for being so enthusiastic about my work, for all your feedback and for staying involved all the way from China. And Atiq, thank you for coming on board and offering your time and feedback. I would also like to thank my (not-so-) new (-anymore) PI Sarah for being so supportive! I am truly grateful to have a boss who encourages vacations!

Nachito, there are more things I thank you for than I could possibly list here so I will just say: thank you, for everything. I cannot express how grateful I am to have had your support throughout this journey. Gracias por todo, y gracias Universo!

Roberto. Thank you for endless conversations about life and love, and academia, and philosophy and feelings and pretty much everything else in this universe. Thank you for breathing, laughing and crying with me. For your honesty; for challenging me; for being my intellectual sparring partner; for inspiring me. Thank you for your friendship.

Moiz, thank you for your friendship, too. I don't know what I would have done without you on this project! Thanks for making me feel like we were in it together, and for listening to my rants and for sharing your wisdom.

Geeta, I don't know how to put into words how glad I am that the universe brought us together when it did! Thank you for giving me a home. And of course, thank you for bringing Bob into my life. And Billi. And Roeli! Thank you both for countless beach walks and for being the beautiful souls that your are.

I am also incredibly grateful for the other home I had - Jaccy, Nick, Olive, thank you, thank you, thank you! You are amazing. Thank you for taking care of me, for caring, for your friendship. Thank you for Mala, my little yoga heaven and safe place.

And my newest home – Lizzy, thank you for being the kindest and most understanding flatmate and lockdown companion.

And last but not least, to my parents – thank you for letting me go. For always supporting me even if you don’t always agree with my decisions. For providing the safest of safety nets. And for teaching me the value and importance of family.

Dedication

To my ten-year-old self,

who had big plans of writing a novel;

and to everyone else who is yet to discover

that sometimes reality inspires fiction,

and sometimes fiction inspires reality.

List of publications included as part of the thesis

I. Hansen, P., Liu, X., & Morrison, G. M. (2019). Agent-based modelling and socio-technical energy transitions: A systematic literature review.
Published in Energy Research & Social Science, 49, 41-52.

II. Hansen, P., Morrison, G. M., Zaman, A., & Liu, X. (2020). Smart technology needs smarter management: Disentangling the dynamics of digitalism in the governance of shared solar energy in Australia.
Published in Energy Research & Social Science, 60, 101322.

III. Syed, M. M., Hansen, P., & Morrison, G. M. (2020). Performance of a shared solar and battery storage system in an Australian apartment building.
Published in Energy and Buildings, 225, 110321.

IV. Monroe, J.G., Hansen, P., Sorell, M., Zechman Berglund, E.: Agent-based model of a blockchain enabled peer-to-peer energy market: Application for a neighbourhood trial in Perth, Australia.
Published in Smart Cities, 3, 1072–1099.

V. Hansen, P.: Optimising shared renewable energy systems: An institutional approach.
Under review in Energy Research & Social Science

VI. Hansen, P. & Morrison, G.M.: Beyond local scale: Action and impact of sustainability initiatives from a polycentric perspective.
Under review in Heliyon

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Glossary

ABM	Agent-based model(ling)
ARENA	Australian Renewable Energy Agency
BESS	Battery energy storage system
CPR	Common-pool resource
DER	Distributed energy resource
ICT	Information and communication technologies
IAD	Institutional Analysis and Development
MI	Methodological individualism
SES	Social-ecological system(s)
SRES	Shared renewable energy system(s)
STS	Sociotechnical system(s)
WGV	White Gum Valley

ONE |
Introduction

This thesis is an investigation into energy systems that are organised for the shared use of a renewable resource. Drawing on two case studies in Perth, Western Australia, it examines the sociotechnical structure of shared renewable energy systems (SRES) with the specific intention to improve our ability to design and govern them effectively. This thesis contributes to the social scientific discussion on the governance of small-scale shared energy systems by developing the conceptual basis needed to productively continue the conversation. This first chapter provides the background to the thesis and specifies the research problem (1.1); sets out the research questions, aims and objectives (1.2); and offers a short guide through the thesis content (1.3).

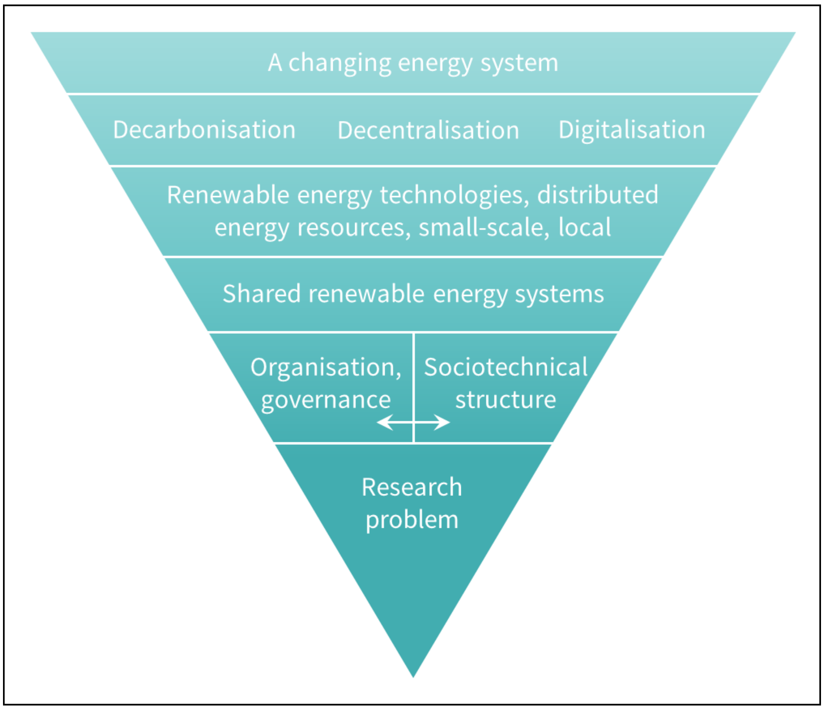


Figure 1.1: Contextualising and pinpointing the research problem.

1.1 Setting the scene: A changing energy system

The following two sections provide the background to the research. I first outline key trends in the energy transition (1.1.1). I then consider the emergence of collective forms of energy generation and ownership (1.1.2), and finally focus on the research problem (1.1.3). Figure 1.1 illustrates the key themes for defining the research problem and the structure of section 1.1.

1.1.1 Towards a low-carbon future

There are three interrelated trends that offer a useful leverage point to penetrate the complexity of contemporary energy system changes; decarbonisation, decentralisation and digitalisation. Climate change mitigation, and achieving the transition from a carbon intensive to a sustainable energy system – without compromising social development or equity – represents a pivotal challenge for the 21st century (Bauwens & Eyre, 2017; Byrne & Taminiau, 2016; Davidson & Gross, 2018). A vision of a low carbon future has thus become a guiding principle for the global effort to affect and manage energy system change (*e.g.* Eyre, Darby, Grünewald, McKenna, & Ford, 2018). The urgent need to reduce the amounts of carbon dioxide emitted into the atmosphere has accelerated global interest in renewable sources of energy (Adil & Ko, 2016; Koirala, van Oost, & van der Windt, 2018; REN21, 2020). Their uptake and development has further been driven by the dependence of much of the industrial world on finite sources of energy and a steady increase in global energy needs (*cf.* Adil & Ko, 2016; Davidson & Gross, 2018; Zafar et al., 2018).

Globally, total renewable power generating capacity reached over 2500 GW at the end of 2019 (REN21, 2020), with solar PV being the leading technology for new electricity generating capacity (ibid). The continued, effective integration of further renewables into the existing system is a requirement if we are to reach decarbonisation goals but effective integration is also a key challenge (Eyre et al., 2018; Mengelkamp, Notheisen, Beer, Dauer, & Weinhardt, 2018; REN21, 2020). Problems relate particularly to the variable, intermittent nature of renewable sources of electricity (Eyre et al., 2018; Koirala et al., 2018; Kraan, Kramer, Nikolic, Chappin, & Koning, 2019; REN21, 2020). The term energy trilemma is sometimes used to refer to the resulting challenge of decarbonising the energy system whilst ensuring its reliability, security and affordability (Johnson & Hall, 2014; Kraan et al., 2019; Morstyn, Farrell, Darby, & McCulloch, 2018).

Distributed energy resources (DER) have been framed as one solution to the trilemma (Morstyn et al., 2018). The term is frequently used to refer collectively to technologies and mechanisms that contribute to balancing the distribution system, importantly, generation, storage and flexibility mechanisms (Morstyn et al., 2018). Distributed generation, specifically, refers to small-scale generators such as rooftop solar PV systems installed on private homes that connect directly to the distribution network (Ackermann, Andersson, & Söder, 2001; Adil & Ko, 2016; Eyre et al., 2018; Heldeweg & Lammers, 2019; McKenna, 2018; Mehigan, Deane, Gallachóir, & Bertsch, 2018). DER are becoming increasingly common and important in the global energy landscape (Adil & Ko, 2016; Koirala, Koliou, Friege, Hakvoort, & Herder, 2016; Koirala et al., 2018; Mehigan et al., 2018; REN21, 2020).

Given the increasing numbers of small power plants and other DER, a trend towards decentralisation has become another prominent feature of the energy transition (Gui & MacGill, 2018; Koirala et al., 2016; McKenna, 2018). In addition to greater geographic dispersion of energy generation, decentralisation also implies and leads to emerging patterns of distributed ownership and decision-making (Judson et al., 2020; REN21, 2020). The process of fostering participatory governance and civic ownership of energy generation and transmission is often termed democratisation (Szulecki, 2018). While its goal – energy democracy – is a normative concept (Szulecki, 2018), the emergence of smaller-scale renewable sources of energy has enabled the recent and increasing involvement of a greater variety of actors and roles in the energy system (Adil & Ko, 2016; Koirala et al., 2018; McKenna, 2018; Szulecki, 2018).

One example is the energy prosumer. With the advent of rooftop solar PV on private homes, energy users, previously regarded exclusively as consumers of energy, have become the owners and beneficiaries of novel sources of energy (Koirala et al., 2016). The term prosumer describes the ability that rooftop solar PV provides to the home owner to both produce and consume energy (Koirala et al., 2018; Mengelkamp et al., 2018; Zafar et al., 2018). Given these interwoven trends of decentralised energy production and decentralised (energy-related) decision-making and ownership, it has been argued that the energy system may be better described as increasingly polycentric (Moroni & Tricarico, 2018; Skjølsvold, Ryghaug, & Berker, 2015; Wolsink, 2020), *i.e.* a system in which decisions regarding the use of a resource system are made by many semi-autonomous decision-making units (Ostrom, 2010b).

With the growing prominence of DER, there is also a need to adapt the operation and management of electricity markets and the wider energy system (Andoni et al., 2019; Eyre et al., 2018; Heldeweg & Lammers, 2019). For example, decentralised energy systems require much larger amounts of data for operation than centralised ones. This has led to a growing need for, and reliance on, Information and Communication Technologies (ICT) (McKenna, 2018).

Digitalisation has played an important role in both enabling a continued transition and increasing the complexity of the energy system. Digital technologies such as smart meters, for example, have been essential for the continued integration of renewable energy technologies into the existing system (Mengelkamp et al., 2018; Zafar et al., 2018). Smart grids have supported the more active involvement of energy users in the energy system by enabling the real-time, transactive, and bi-directional flow and exchange of energy and information between end-users and utilities through the use of ICT (Adil & Ko, 2016; Zafar et al., 2018). The combination of the possibilities of digitalisation, more participatory, decentralised governance and decision-making, and the need for decarbonisation, have led to the emergence of a variety of novel, small-scale system configurations.

1.1.2 Sharing renewable energy resources

The umbrella term community energy is often used to discuss a plethora of possible setups based on the notion of shared, or communal, access to renewable sources of energy (Brummer, 2018; Hoffman & High-Pippert, 2010; Klein & Coffey, 2016; Walker & Devine-Wright, 2008). There is a general understanding that the concept of community energy entails improved technological sustainability, better opportunities for (citizen) participation, and more democratic control of the system (Brummer, 2018). Other frequently cited characteristics include citizen involvement, solutions that are based on collaboration, an interest in supporting the uptake of sustainable energy technologies and/or practices, and local production of renewable energy (Bauwens & Eyre, 2017; Bauwens, Gotchev, & Holstenkamp, 2016; Van der Schoor & Scholtens, 2019). However, it has also been argued, for example, that local energy is distinct from community energy in that the former views individuals merely as consumers, whereas the latter emphasizes the collective actions of citizens (Devine-Wright, 2019).

As alluded to in the previous section, digitalisation has played an important role in facilitating shared set-ups. In the context of distributed systems, online platforms are important as they enable the exchange of distributed resources (Kloppenburg & Boekelo, 2019). A prominent example is the concept of peer-to-peer (P2P) trading, that is, the exchange of surplus renewable energy between prosumers and consumers (Zhang, Wu, Zhou, Cheng, & Long, 2018). P2P energy trading is commonly facilitated by an online platform (ibid.). These local energy markets, in which energy is virtually traded within a community, may increase consumer choice while also contributing to balancing local demand and supply (Mengelkamp et al., 2018). P2P trading has received significant recent interest for its potential to effectively manage system interactions, within microgrids as well as across distribution networks (Zhang et al., 2018).

Shared systems have played a central role in shaping current energy system changes, and are widely regarded as an essential part of a fair, effective and secure energy transition and low-carbon future (Gui & MacGill, 2018; Van der Schoor & Scholtens, 2019). While they facilitate carbon reductions and power security (Augustine & McGavisk, 2016; Brummer, 2018), economic benefits such as reduced electricity or investment costs are also frequently associated with shared access to renewable energy (Berka & Creamer, 2018; Panagiotou, Klumpner, & Sumner, 2017; Walker, 2008). Solutions such as P2P trading may even enable private households to receive extra income through the sale of excess solar electricity (Brummer, 2018; Park & Yong, 2017; Wilkinson, Hojckova, Eon, Morrison, & Sandén, 2020). Local energy systems may also stimulate local economies through job creation (Koirala et al., 2016; McKenna, 2018) or by keeping income, such as from the trading of locally generated electricity, within the community (Mengelkamp et al., 2018).

The social benefits of energy sharing may also include increased awareness and acceptance of, and participation and engagement in, renewable energy and the energy transition (Brummer, 2018; Hoffman & High-Pippert, 2010; Koirala et al., 2016; Van der Schoor & Scholtens, 2019). In the context of global climate change mitigation efforts, community-based energy systems can serve as a vehicle for collective action by fostering change at the level of the individual (Bauwens & Eyre, 2017). Promoting sustainable, energy-related practices and behaviour by involving citizens in the development of energy system solutions may be a fruitful alternative to top-down policy-making to address the global collective action problem of climate change mitigation (Bauwens & Eyre, 2017). In addition, collectively organised energy systems may also foster community cohesion, empower citizens and improve social wellbeing (Bird & Barnes, 2014). In short, shared renewable energy resources have the potential to optimise the availability, accessibility, and affordability of energy for households, whilst contributing to the continued reliability, security, and efficiency of the existing grid (Davidson & Gross, 2018; Grunewald, Hamilton, Mayne, & Kock, 2014; Klein & Coffey, 2016).

1.1.3 Structure and governance of sociotechnical shared renewable energy systems

If we are to unlock the full potential of shared renewable energy systems (SRES) then an in-depth understanding of how they function and interact with other elements of the wider energy system is required. In turn, this understanding is essential to our ability to optimise the energy transition process. Although significant progress has been made, the novelty of the issue, the pace of change and technological innovation, and the complexity of the energy system pose continuing challenges (Koirala et al., 2016). Practically, issues pertaining to organisational or legal form; insufficient institutional and political support; and insufficient financial, knowledge and time resources are frequently cited as impeding the development of community energy initiatives (Brummer, 2018). Importantly, organising energy (sub-) systems around shared resources requires new modes of governance, that is, new institutional arrangements that allow for the effective design and operation of local or community-based energy systems (Adil & Ko, 2016; Gui, Diesendorf, & MacGill, 2017; Heldeweg & Lammers, 2019).

Given the changing types and roles of actors and technologies involved in the emerging energy system, the way shared systems are socially constructed will differ decisively from conventional configurations (Wolsink, 2012). SRES may vary with regards to the goals and values of the users, the type of renewable source, the way energy is distributed, paid for and supplied, its geographic reach and other factors (Gui & MacGill, 2018). The question of institutional design, energy governance structures and mechanisms is thus far not well-understood (Gui et al., 2017; Koirala et al., 2016; Wolsink, 2012).

This thesis proposes that these questions of governance arrangements go hand in hand with discussions of energy systems as complex, dynamic constructs comprised of social and technical elements. There is widespread agreement in the academic community that energy systems are sociotechnical in nature (Cherp, Vinichenko, Jewell, Brutschin, & Sovacool, 2018); they consist of interacting social and technical elements that together produce the observable system outcomes, and are thus equally important to understanding the system as a whole (Eyre et al., 2018; Geels, Sovacool, Schwanen, & Sorrell, 2017; Koirala et al., 2016; Love & Cooper, 2015). In thinking about how a SRES is or may be governed, social and technical elements – and their interactions – should thus be taken into account. It follows that to advance our understanding of SRES governance, we need information concerning what these social and technical elements are, how they interact, and how these characteristics relate to outcomes. Figure 1.2 schematically illustrates the two themes – sociotechnical energy systems, and shared energy systems – and their relationship.

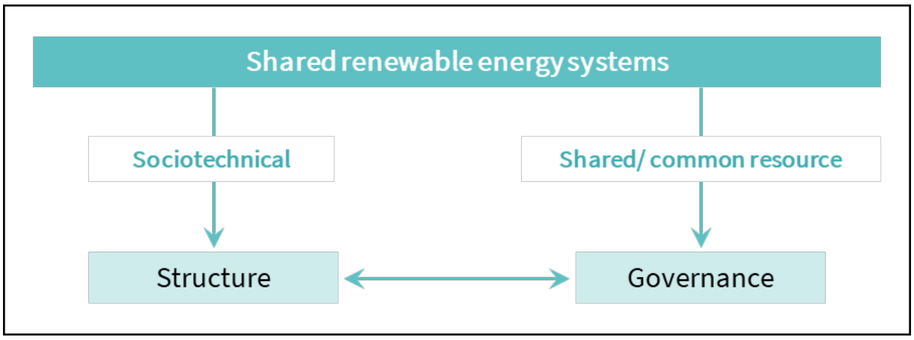


Figure 1.2: Schematic illustration of the problem space.

Despite the use of the sociotechnical concept as a descriptor in a substantial number of studies, there is thus far little agreement or consistency as to the specificities of sociotechnical structure. Furthermore, sociotechnical interactions tend to be considered only at a macro level (Love & Cooper, 2015) and sociotechnical structures cannot be adequately described with existing approaches (Fuenfschilling & Truffer, 2014). Specifically, an understanding of what the term sociotechnical means for empirical research is also missing (Love & Cooper, 2015). For the concept to add value to empirical research, critical thinking, and – in the context of this thesis – to provide the basis for an improved appreciation of SRES governance, it needs to be clearly defined, and be used consistently and rigorously (Wolsink, 2019). A consistent conceptual basis is important to enable a structured dialogue between practitioners (Sovacool & Hess, 2017) and ultimately advance the field.

Against the backdrop of these observations, I argue that in order to gain a better understanding of how SRES function, we first need to establish a well-defined understanding of their structure. This structure may be derived from the existing notion of a sociotechnical system. In addition, existing knowledge regarding the governance of other types of shared resources may aid in developing a better grasp of this structure, and its relation to how SRES are organised and governed. This body of literature concerned with common resource governance is introduced in the following chapter. In this thesis, the term shared renewable energy system will be used. This avoids the normative framing of many community energy definitions and instead, shifts the focus to the sharing of energy (i.e. of allocating and distributing resource outputs). This issue has been extensively studied in the context of other common (natural) resources. It thus offers a leverage point to explore questions pertaining to the governance of energy systems that are based on a shared source of generation. For the purpose of this thesis, SRES are defined as systems in which access to a distributed renewable source of generation (behind the meter generation) is shared by a group of users.

1.2 Research questions, aims and objectives

In order to optimise the design and performance of SRES – and thereby contribute to the success of the energy transition – we need to understand how these systems work. To address this missing understanding, we need a conceptual basis that guides study and analysis. In addressing this research problem, the thesis is guided by the following principal research question and sub-questions.

Principal research question

How do small-scale shared renewable energy systems work from a sociotechnical perspective?

Conceptual sub-question

How may the notion of sociotechnical dynamics be operationalised to inform the governance of shared renewable energy systems?

Empirical sub-question

What are the sociotechnical elements and interactions that shape SRES? And how may they affect outcomes?

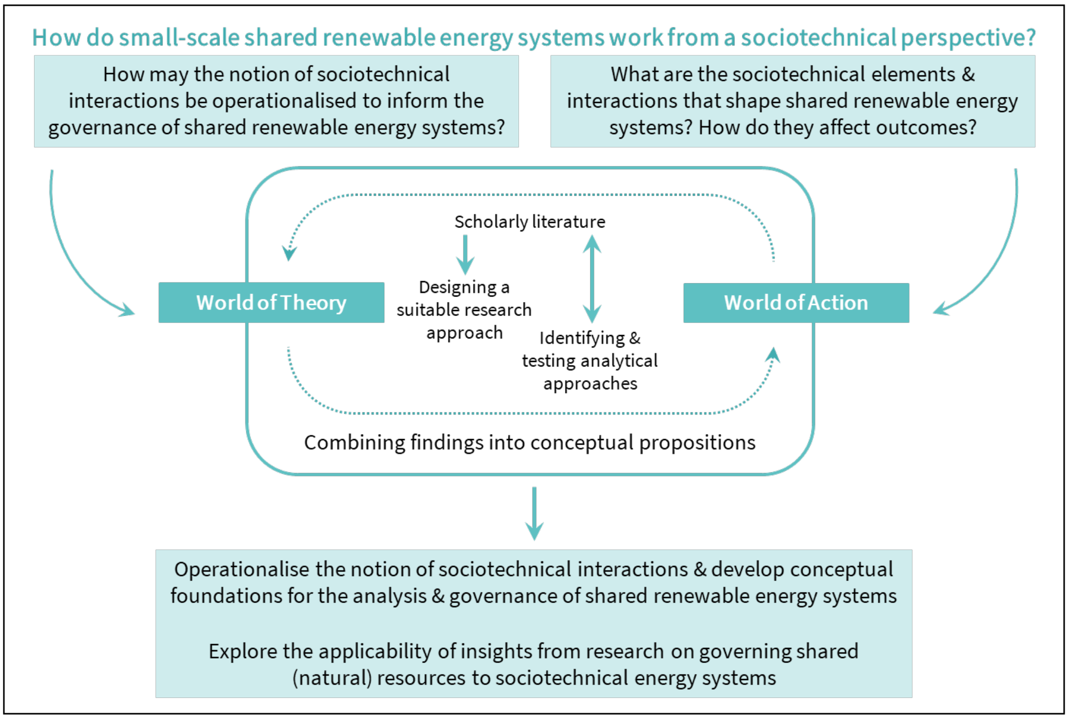


Figure 1.3: The principal research question of how SRES work from a sociotechnical perspective is divided into two sub-questions to explore the worlds of theory and action. This is facilitated by the research objectives shown in the centre. The research aims are addressed through the combination of findings into conceptual propositions, and by drawing on both, the world of theory and the world of action.

Aims

The aims of the research were to:

1. Operationalise the notion of sociotechnical interactions in the context of shared renewable energy systems to develop the conceptual foundations required to analyse and govern them effectively.

2. Explore the applicability of insights from research on governing shared (natural) resources to sociotechnical energy systems.

Objective

To facilitate the achievement of these aims, the objective guiding the research was to combine empirical and theoretical findings into a set of conceptual propositions by engaging in an iterative process of;

- reviewing the literature at the interface of common resource governance and sociotechnical systems
- designing a suitable research approach
- identifying and testing analytical approaches.

Figure 1.3 illustrates how the research questions relate to the objectives and aims. The phrases world of action and world of theory are sourced from Ostrom (1990) and used to refer to the strategy of moving back and forth between the field and the theoretical body of knowledge to gain an understanding of how the problem of resource sharing is solved (ibid). In the context of this thesis it means moving back and forth between the case studies and empirical evidence, and the literature on common resource governance and sociotechnical systems. Chapters 2-4 expand on the two worlds, that is, the theoretical foundations and the research design. Table 1.1 links each of the publications of this thesis to the research questions, aims and objective by summarising the topic and main contributions.

1.3 Thesis organisation

The thesis is comprised of the six published and submitted journal articles which follow this exegesis. The exegesis serves to situate the publications within the overarching research project by providing the background to the study, and presenting and evaluating its aggregate findings.

Chapter 1 outlines the context of the research and specifies the research questions, aims and objectives.

Chapter 2 reviews the literature at the interface of sociotechnical systems, common resource governance and energy research and thus provides the theoretical foundations for the study.

Chapter 3 links the theoretical background to the research design by outlining the analytical tools offered by the literature and applied in this study.

Chapter 4 explains the methodology and methods.

Chapter 5 summarises findings from the publications in the context of the overarching research questions.

Chapter 6 discusses the aggregate findings and their implications in view of operationalising the sociotechnical notion for the study and governance of SRES.

Table 1.1: Topics discussed in the publications and how they contributed to answering the research questions and addressed the aims and objectives.

Publication	Topic & contributions to answering research questions
I. Hansen, P., Liu, X., & Morrison, G. M. (2019). Agent-based modelling and socio-technical energy transitions: A systematic literature review.	**Topic:** How agent-based modelling (ABM) has contributed to understanding energy transitions as sociotechnical processes – Gaining an understanding of the applicability of ABM to the research problem – Developing a suitable research approach
II. Hansen, P., Morrison, G. M., Zaman, A., & Liu, X. (2020). Smart technology needs smarter management: Disentangling the dynamics of digitalism in the governance of shared solar energy in Australia.	**Topic:** How the use of digital technology affects the governance of a SRES & the system's sustainability – Applying the Social-ecological system framework – Elements, interactions, outcomes: focus on smart technology & resulting interactions & outcomes
III. Syed, M., Hansen, P. & Morrison, G.M. Performance of a shared solar and battery storage system in an Australian apartment building.	**Topic:** Technical (energy) performance of a case study renewable energy generation & storage system Elements, interactions, outcomes: zooming in on the technical sub-system; understanding technical (types of) elements & interactions
IV. Monroe, J.G., Hansen, P., Sorell, M., Zechman Berglund, E. Agent-based model of a blockchain enabled peer-to-peer energy trading trial in Perth, Australia.	**Topic:** Simulation of case study P2P trading trial & alternative scenarios – Applying ABM – Elements, interactions, outcomes: interactions as algorithmic rules; effect of additional technology (battery storage) & forecasting on system outcomes; understanding technical elements – Outcomes as average electricity prices & untraded excess solar energy
V. Hansen, P.: Optimising shared renewable energy systems: An institutional approach	**Topic:** Identifying rules that govern energy sharing & the institutional factors affecting system performance – Elements, interactions, outcomes: interactions as rules; understanding factors supporting & inhibiting optimality; understanding social elements – Evaluating sociotechnical system performance by evaluating performance of interactions (rules) – Applying the Institutional Analysis & Development framework (IAD)
VI. Hansen, P. & Morrison, G.M.: Beyond the local scale: Action and impact of sustainability initiatives from a polycentric perspective	**Topic:** Exploring how SRES may contribute to positive change at a higher level within a polycentric system – Elements, interactions, outcomes: zooming out to explore links to wider system & impact; understanding social elements – Applying a polycentric governance perspective – Conceptualising scaling as interactions between diverse actors

TWO |

Sociotechnical shared renewable energy systems: Theoretical foundations

This chapter lays the theoretical foundations for the research reported in this thesis. It begins with a brief introduction to systems thinking (2.1.1), before describing the origins of the sociotechnical systems (STS) concept (2.1.2), and its use in energy studies (2.1.3). I then briefly revisit the research problem of structure and governance of SRES in the context of the theoretical foundations (2.1.4). Section 2.2 continues by introducing the work of Elinor Ostrom (Ostrom, 1990, 2005, 2009c). A growing number of energy scholars are recognising the usefulness and applicability of Ostrom and her colleagues' work which has been concerned with the governance of shared natural resources. This includes social-ecological systems (SES) which has advanced our understanding of sociotechnical energy systems. An overview of these existing applications is provided in section 2.3. The chapter closes by outlining how the reviewed literature informs the remainder of the thesis (2.4). Table 2.1 offers an overview of the four main sections of this chapter and their relevance in the context of the thesis.

Table 2.1: Guide for this chapter.

Chapter		Relevance in the context of this thesis
2.1	**Sociotechnical systems and energy studies**	Introduction to the high level theoretical foundations shared by all theoretical elements of this work; origins of the STS concept and applications to energy systems
2.2	**Governing shared resources**	Introduction to the literature that may help address the knowledge gap; overview of its key concepts
2.3	**Energy commons: From social-ecological to sociotechnical systems**	Review of how 2.2 has been applied to energy systems
2.4	**Towards an understanding of sociotechnical energy systems**	Summary of the chapter and (preliminary) definitions for the research

Three interdisciplinary applications of general principles are discussed in the course of this chapter; sociotechnical systems, sociotechnical systems change, and social-ecological systems. A fourth one, agent-based modelling, is discussed in Chapter 3.

2.1 Sociotechnical systems and energy studies

2.1.1 A note on dynamic systems

This research and the concepts it draws on are based on the paradigm of systems thinking. As such, before turning our attention to the special case of sociotechnical systems, a brief introduction to systems in general is in order. It is no coincidence that thinking in terms of systems has become a hallmark of interdisciplinary sustainability studies (which includes the study of renewable energy systems). In 1950, von Bertalanffy (1950) observed that scientific disciplines, from physics and biology, to social sciences and philosophy, all seemed to share similar fundamental conceptions. Despite the substantial differences in subject matters and philosophical underpinnings, systems across disciplines appeared guided by “principles of dynamic wholeness” (von Bertalanffy, 1950) – the perhaps best known expression of this concept being the notion of a whole being greater than the sum of its parts. A General Systems Theory was thus proposed as a means towards the unification of science, towards the identification of “a general superstructure of science” (ibid, p.139). This theory was to define the general principles of the problem of dynamic interactions which was at the core of “all fields of reality” in modern science (von Bertalanffy, 1950, p. 165).

Today there are numerous variants of the kind of general theory envisioned by Von Bertalanffy (Adams, Hester, Bradley, Meyers, & Keating, 2014) (for a brief history see for example Bausch (2002); an in-depth account is offered, for example, in Bausch (2001)). As any attempt at delineating the subtleties of system theory’s various framings would inevitably result in (for our purposes) unnecessary complexity (not least, historic), an introduction to some overarching concepts will suffice here. The terms systems thinking and systems theory will be used interchangeably in this thesis to refer to these overarching principles. While the heart of systems thinking is the notion that a system is more than the sum of its parts (Meadows, 2008; Ropohl, 1999; Savaget, Geissdoerfer, Kharrazi, & Evans, 2019), the primary concern is understanding the three building blocks of any system: elements, functions and interconnections (Meadows, 2008; Savaget et al., 2019). An element can be anything, tangible or intangible, and can be divided into ever-smaller sub-elements. Elements are held together by interconnections or relationships. Interconnections may be thought of as flows. While flows may be physical, such as electrons moving from a point of generation, many interconnections are flows of information (Meadows, 2008). A few further concepts should be mentioned:

- **Feedback loops** are mechanisms that cause changes in an element to also cause changes in the flows affecting the element. They are "closed chains of causal connections" that may be balancing, leading to stability or resistance to change, or reinforcing, leading to positive or negative self-enhancement (Meadows, 2008).
- **Self-organisation** describes the power of a system to change its own structure (and/ or make it more complex), the ability to learn, and the capacity to create entirely new ones (Meadows, 2008).
- **Hierarchy** may be generated in the process of self-organisation (Meadows, 2008). An implication of the hierarchical feature of systems is the need to deal with the issue of boundaries. The principle of excluded reductionism holds that a single level of hierarchy is never sufficient to describe a system completely (Ropohl, 1999). However, boundaries may be superimposed for clarity and sanity in line with the purpose of the discussion (Meadows, 2008). Although taking systems apart and studying different hierarchical levels separately can be a valuable exercise, Meadows (2008) warned that it is important to remember that they are artificially created, and to not lose sight of the interconnections between systems and different levels of the hierarchy.
- **Well-functioning systems** usually exhibit the characteristics of resilience, self-organisation or hierarchy (Meadows, 2008). When the goal or purpose of a given subsystem is prioritised over the goals of the overall system, sub optimisation ensues (Meadows, 2008). Because different sub-systems may have different functions, keeping these sub-functions aligned with the functions of the overarching system is essential to successful system

performance (Meadows, 2008). Self-organisation has been described as the strongest form of resilience (ibid).

- **Non-linearity** describes disproportional cause-effect relationships (Meadows, 2008). A related concept is that of unpredictability.

Systems thinking is about going back and forth between structure and behaviour (Meadows, 2008). Structure is the result of interlocking between elements and interconnections, and, over time, gives rise to system behaviour (Meadows, 2008). Generally speaking, elements are easiest to identify; information-based relationships can be hard to identify; and a system's function is often implied in how it operates and therefore tends to be the most difficult to grasp of the three building blocks (Meadows, 2008). As such, understanding a given system will often start with the identification of its elements, before turning to its interconnections. This is intuitive and Bausch (2001) pointed out that in language, we start with nouns, and verbs follow; and likewise, in thought processes, things come before relationships.

This study thus begins with the broad assumption that the structure and behaviour of SRES is based on social and technical elements. What these are, and what their interconnections are, is the subject of the investigation. As such, the following sections outline what the sociotechnical notion has meant in the past, how it has been applied to energy systems (in social energy studies), where we currently lack understanding (and why we need it), and how this may be addressed. A first observation that should be made in reviewing the notion of a STS is the breadth of its ambit. While acknowledging the disparity of interpretations and uses (Baxter & Sommerville, 2011; Elatlassi & Narwankar, 2016; Klein, 2014), I focus here on the origins of the concept and its relevance in energy system studies.

2.1.2 Sociotechnical systems: origins

The STS concept was born out of research undertaken at the Tavistock Institute of Human Relations in the 1950s and 60s that investigated practices of work organisation in the British coal mining industry (Fox, 1995; Pasmore, Winby, Albers Mohrman, & Vanasse, 2019; Ropohl, 1999; Trist, 1981; *cf.* also Baxter & Sommerville, 2011). Researchers initially observed an innovative change in work practices: workers at the Haighmoor seam had organised in a way that afforded them more autonomy and group cohesion, in addition to more decision-making powers with regards to their work arrangements (Trist, 1981). This was in contrast to the dominant organisational design of previous decades, which had responded to increases in scale and mechanisation with increased bureaucratisation (Trist, 1981). In this alternative to the technological imperative, social and technical systems could no longer be considered in isolation (ibid). Based on these observations, work organisations were reframed as socio-technical systems (ibid). Outcomes such as economic performance and job satisfaction were determined by “the goodness of fit” between the social and technical systems (Trist, 1981, p. 10). This notion later became known as the principle of joint optimisation (Mumford, 2000; Trist, 1981). Reflecting on the conceptual developments of the past decades, Trist (1981) offered the following description of STS:

> “The technical and social systems are independent of each other in the sense that the former follows the laws of the natural sciences while the latter follows the laws of the human sciences and is a purposeful system. Yet they are *correlative* in that one requires the other for the *transformation* of an input into an output, which comprises the functional task of a work system. Their relationship represents a *coupling* of dissimilars which can only be jointly optimized. Attempts to optimize for either the technical or social system alone will result in the suboptimization of the socio-technical whole. […] The distinctive characteristics of each must be respected else their *contradictions* will intrude and their *complementarities* will remain unrealized.”

The concept of STS has continued to evolve over the past 40 years. Importantly, and particularly so in the context of this thesis, its meaning and applications are no longer limited to organisational psychology and work organisation. The extent of the concept’s popularity led Walker (2015) to describe it as “something of a buzzword in some circles”, while Klein (2014) pointed out that the term was “inevitably imprecise, almost as imprecise as the term system”. The one concept that the otherwise disparate interpretations of the term had in common, Klein (2014) further argued, was that of interdependence. Seeking a more refined definition, Walker (2015) thus referred to “sociotechnical theory proper”, which he defined as based on two principles: system performance is determined by the interactions of social and technical elements; and optimisation of only one of the two inhibits performance because what works for one, may not work for the other (Fox, 1995; Walker, 2015). These have also been referred to as the requirements of dual focus and joint optimization (Fox, 1995). Today the concept of a STS constitutes an interdisciplinary knowledge domain (Di Maio, 2014). It continues to be used in complex organisational work design but is also, for example, prominent in engineering, where it has given rise to the practice of sociotechnical systems engineering (Di Maio, 2014); and applied in computer sciences with a focus on the joint optimisation of whole systems (ibid).

Although the theoretical study by researchers at the Tavistock Institute played an important part in driving the development of the field of STS, it has been argued that even more important was the fact that implementation of its main principles led to drastically more resilient, better performing systems (Walker, 2015). Walker (2015) thus proposed a return to STS theory as a means of improving the resilience of engineering systems, of harnessing what he referred to as "the edge-of-chaos phenomena" that result from human-engineering interactions (ibid). A similar sentiment has been expressed by Pasmore et al. (2019), who argued that current technological advancements are leading to the same conditions that led to the original formulation of the STS concept. Technological development, in particular in view of digitalisation, is outpacing the adaptation of organisational capabilities, necessitating a conscious re-evaluation of, and subsequent adaptation to the way STS are managed (ibid). This is in line with the argument that the changes occurring in energy systems require a closer consideration of how they operate.

2.1.3 Sociotechnical energy systems

Interestingly, it is the question of how such changes occur over time that (social) energy studies have made use of the sociotechnical notion. Although it is used in a wide range of studies, it is conceptually most developed in the context of large-scale systems and long-term transition processes (Ahlborg & Sjöstedt, 2015). The central premise of the sociotechnical change concept is that social and technical systems co-evolve (Ahlborg & Sjöstedt, 2015; Savaget et al., 2019; Smith & Stirling, 2007; Ulsrud, Winther, Palit, & Rohracher, 2015). In facilitating a more sustainable future, the key challenge is to change current STS configurations (Savaget et al., 2019). This is difficult because dominant, established technologies, policies and practices are deeply entrenched in the existing STS (ibid). New technologies do not diffuse easily (or, break through) when technologies (or a particular technology) are deeply embedded within their surrounding system and socio-institutional structures, (Geels, 2002; Goldthau, 2014). These lock-ins make the system resistant to change (Goldthau, 2014).

In studying how transitions to new sociotechnical systems come about, three nested levels are commonly differentiated as a basis for analysis (Geels, 2005). In keeping with the theme of interdisciplinarity, the development of this Multi-level perspective (MLP) of transitions was informed by Science and Technology Studies, evolutionary economics, as well as sociology and the history of technology studies (Cherp et al., 2018; Fuenfschilling & Truffer, 2014). It conceptualises transitions as the (re-) alignment of various processes interacting within and across three levels (Geels et al., 2017). At the highest level, a sociotechnical landscape serves as the external structure; sociotechnical regimes guide and coordinate actions and provide stability; and niches within the regime serve as protected spaces in which experimentation and innovation occurs (ibid). In this realm of research, the use of the term sociotechnical to describe systems has helped stress the embeddedness of technologies or infrastructures within their wider environment (Goldthau, 2014).

Related fields of research have also used similar interpretations with a broader interest in the relationships between society and technology. In the field of Science and Technology Studies for example, the STS concept has been used in inquiries into the social construction of technology, large technical systems, and technological practices (Hess & Sovacool, 2020). Analyses of sociotechnical transitions have made important contributions to our understanding of change processes in the context of renewable sources of energy and the facilitation towards a low-carbon future. But since transitions involve complex interactions between changes at micro and macro levels, achieving a low-carbon future also requires an understanding of the specific changes occurring at the micro level.

Table 2.2: Illustrative examples of applications and conceptualisations of the STS concept in energy studies.

Application of the STS concept	Definitions/ conceptualisation	Reference
Integrated community energy systems are dynamic sociotechnical systems	Humans and technology interact within a sociotechnical setting comprised of economic, political, social & other factors	(Acosta, Ortega, Bunsen, Koirala, & Ghorbani, 2018)
Experiments have a sociotechnical configuration	Sociotechnical learning; experiments are initiatives in which "new networks of actors with knowledge, capabilities and resources" cooperate in learning processes	(Berkhout et al., 2010, p.262)
Socio-technical community energy systems	Compilation of actors, resource flows, technical artefacts, infrastructure Control mechanisms and design principles coordinate interactions and system operation	(Cayford & Scholten, 2014)
Socio-technical configurations; Context: deployment of micro-generation technologies	"Assemblies of technological components, and non-technological components such as human factors […] built up to meet the particular requirements of organization"	(Juntunen & Hyysalo, 2015, p.858)
Integrated community energy systems	Defined as multi-source, multi-product, complex sociotechnical systems Include combination of technical elements, institutions & active links	(Koirala et al., 2016)
Community energy storage as a complex sociotechnical system	Interaction between physical system & actor network: Physical system includes DERs, storage technologies, energy management systems, platforms, network infrastructure, communication networks and buildings; Actor network encompasses households, communities, housing corporations, energy suppliers, aggregators, system operators, balancing service providers, local market operators, technology providers & municipalities; Exact system configuration is further influenced by market & regulatory conditions and other external factors, *e.g.* dominant technologies	(Koirala et al., 2018)
Local sociotechnical configurations; Context: Solar energy at village level	Socio-technical systems as configurations of heterogeneous technical & social elements Social: organisational aspects, actors, social practices & competences related to implementing & using technology, power relations, discourse & meaning related to technology Technical: includes technical devices, technical artefacts	(Ulsrud et al., 2015)
Complex sociotechnical systems e.g. power grid	Scientific and technological components Socio-economic, cultural, organisational components	(Wolsink, 2020)

As outlined in the introduction (chapter 1), an important change is the small-scale generation of renewable energy shared by groups or communities of people. Although the term sociotechnical is frequently used in the context of such novel, small-scale SRES, its usefulness is currently limited by a lack of conceptual clarity. Table 2.2 illustrates the variety of interpretations and definitions in the literature through a number of examples. In addition to the diversity of definitions, the examples also demonstrate that, thus far, inadequate consideration has been given to the effect of scale on the sociotechnical notion. While concepts such as institutions or infrastructure may suffice to conceptualise the structure of a slow-changing, large-scale system, they do not serve to adequately conceptualise the structure of small-scale systems. The same holds for the treatment of interactions within such systems.

This thesis aims to contribute to the development of a differentiated understanding of what the term sociotechnical can and should mean in the context of small-scale SRES. Such conceptual advancement is essential to understanding and improving the way these novel systems are governed.

2.1.4 Governing shared renewable energy systems

Establishing the relationships between structure and behaviour is a prerequisite for understanding how a given system works and how to achieve desirable or optimal results (Meadows, 2008). And while new behaviour in the form of novel types of organisation are being observed in the energy system, there is not a simple understanding of their sociotechnical configurations (Moss, Becker, & Naumann, 2015). What is lacking is an explanation of the interactions between social and technical system elements; of the effects of these dynamics on the performance and viability of a given system (Ulsrud et al., 2015). In parallel, it has been argued that there is a lack of insight into how emerging governance structures work in practice, and how new and emerging types of small-scale SRES may be governed effectively (S. Becker, Kunze, & Vancea, 2017; Koirala et al., 2016; Parag, Hamilton, White, & Hogan, 2013).

This thesis takes the position that the questions of how small-scale SRES function and how they may be governed are intrinsically linked. The conceptualisation is shown in figure 2.1 and indeed, to govern SRES is to coordinate sociotechnical dynamics. To address the knowledge gaps outlined in the preceding sections (lacking understanding of the sociotechnical structure of SRES, and lacking understanding of their governance) I will draw on the literature on social-ecological systems and their governance. Sociotechnical and social-ecological systems analyses have been described as two parallel traditions concerned with interactions between social practices and technological artefacts in the case of the former, and social processes and biological aspects of ecosystems in the case of the latter (Hodbod & Adger, 2014). Both are concerned with multi-scale, complex, dynamic systems, and include notions of adaptability, transformation, and learning (ibid). The following section offers an overview of this literature in the context of the thesis.

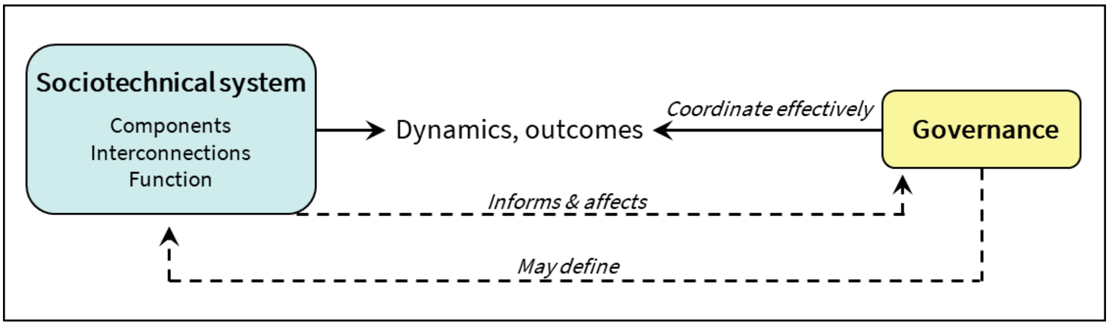


Figure 2.1 Conceptualisation of the connections between sociotechnical systems and governance used in this thesis.

2.2 Governing shared resources

The sociotechnical systems discussed in this thesis centre around the shared use of a renewable energy resource. The question of how to govern the use of shared resources – the commons – has received considerable interest over the past 50 years in the context of natural resources (*i.e.* social-ecological systems). The work of Elinor Ostrom and her colleagues at the Workshop in Political Theory and Policy Analysis at the University of Indiana (hereafter: Ostrom Workshop) in particular has been highly influential in shaping the way in which the commons may be studied, conceptualised and governed (Forsyth & Johnson, 2014; McGinnis & Walker, 2010). For the purpose and scope of this thesis, I limit the review of Ostrom's contributions to three areas of focus: types and characteristics of resources; the nature of human behaviour; and the concept of institutions. These three themes are underpinned by the phenomenon of collective action and the conditions that promote and inhibit it.

2.2.1 Types of resources

Problems of collective action (also called social dilemmas) occur when individuals take actions in interdependent situations (Ostrom, 2009b). If individuals take actions based on narrow self-interest (to maximise benefit to self), outcomes will be less favourable than what could be achieved if they acted instead as a group based on collective interests (Cox, Ostrom, Sadiraj, & Walker, 2012). In other words, if individuals in interdependent situations act as rational egoists pursuing their own maximum short-term benefits, the overall outcome will be socially sub-optimal.

Perhaps the most widely discussed problem of collective action relates to the use of (natural) resources. Resources, or goods, may be differentiated based on two criteria: difficulty or cost of excluding potential beneficiaries, and subtractability of use, *i.e.* whether the use of a resource unit by one individual will subtract from the amount available for use by someone else (Ostrom, 2005). Resources that are characterised by both, ease of access, and substractable supply are called common-pool resources (CPRs). These characteristics of CPRs give rise to the problems of overuse and free-riding (Dietz, Dolsak, Ostrom, & Stern, 2002). The result is a high risk of resource depletion.

In a 1968 publication Hardin (Hardin, 1968) famously referred to this risk of resource destruction, in a situation in which there is unrestricted access to a scarce resource, as the Tragedy of the Commons. The fate of destruction is inevitable, he argued, because individuals are rational actors; they will always seek to maximise their own benefits, and will thus disregard other individuals and the common interest. Hardin believed that individuals involved in situations of this kind were unable to solve social dilemma themselves. Thus, unless government intervened, or the resource was privatised, it would ultimately and tragically be depleted (ibid).

2.2.2 The nature of human behaviour

Ostrom (1990) began her book-length discussion of commons governance with a reflection on the Tragedy of the Commons. She argued that while the problem itself was interesting and permeated human-resource interactions across the world, the assumptions and implications of Hardin’s model were flawed. Specifically, she argued that rather than presuming that commons dilemmas were inescapable, the degree to which individuals are able to solve dilemma situations varied between situations (Ostrom, 1990).

She thus called for a revised theory of collective action that allowed for the possibility of individuals self-organising to achieve collective benefits. Based on empirical evidence gathered from diverse case studies over many years of research, Ostrom was subsequently able to demonstrate that contrary to Hardin's fatalistic prediction, groups of individuals can cooperate, *i.e.* are able to self-organise and govern resources sustainably (Ostrom, 1990). This supported the development of an empirically-based theory of collective action. Ostrom thus suggested that a theory of boundedly-rational and norm-based human behaviour may be a more suitable approach to explaining collective action (Ostrom, 2009a, 2009b). Human rationality is constrained – bounded – by incomplete information and limited cognitive and information-processing capabilities (McGinnis, 2016).

2.2.3 Institutions and robust systems

In addition, the choices humans make are also influenced by human devised constraints *viz* institutions (North, 1990). The analogy to "the rules of the game in a competitive team sport" (North, 1990, p. 4) is often used to explain the concept. In other words, institutions are the written and unwritten, formal and informal rules and codes of conduct that structure and guide human interaction and thereby reduce uncertainty (North, 1990). In Ostrom's words, they are the understanding that participants in a given situation share regarding the prescriptions they use to make decisions about their actions (Ostrom, 1990, 2005). Institutions are much easier to grasp than human behaviour and are therefore a useful heuristic for studying complex systems (Ghorbani, 2013; Meadows, 2008).

Ostrom was interested in how institutions are created, evolve, and affect the structures and outcomes of human interactions (Ostrom, 2010a). Her applications of institutionalism to problems of resource governance resulted in a number of seminal (empirical, methodological and theoretical) contributions to the field of environmental policy and governance (Forsyth & Johnson, 2014). One example is a set of design principles that emerged from the study of diverse, local institutions for the use of natural resources. Eight principles were identified that characterise robust resource systems, *i.e.* systems in which institutional arrangements have enabled and maintained the sustainable use of a CPR over long periods of time (Becker & Ostrom, 1995; Ostrom, 1990, 2005). Institutions that successfully manage human-resource interactions in the long term tend to exhibit the following features:

1. Clearly define the boundaries of the resource and the actors allowed to use it (clearly defined boundaries)
2. Benefits are allocated in proportion to the inputs required to produce them (proportional equivalence between benefits and costs)
3. A majority of actors affected by the rules of using and protecting the resource are also able to participate in changing these rules (collective-choice arrangements)
4. Monitoring of the resource's condition and of user behaviour is undertaken by either the users themselves or by actors that are at least partially accountable to them (monitoring)
5. When rules are broken, graduated sanctions are imposed by other users or other accountable actors (graduated sanctions)
6. Mechanisms are in place that enable fast, low-cost, local conflict resolution (conflict-resolution mechanisms)
7. Users hold long-term rights to (access) the resource, and their rights to create their own institutions, *i.e.* to self-organise, are not contested by external authorities (minimal recognition of rights to organise)
8. If the resource is part of a larger system, multiple levels of nested enterprises are used to organise activities regarding use, provision, monitoring, conflict resolution, and governance of the resource (nested enterprises) (C. D. Becker & Ostrom, 1995; Ostrom, 1990, 2005).

In the context of the present study, the eighth design principle demands additional elaboration. The notion of nested enterprises is closely related to that of polycentric (governance) systems. A system that is polycentric, features many independently organised centres of decision-making at multiple scales, each with the authority to create at least some of the rules within a specified domain (*e.g.,* a local CPR), and all jointly affecting the collective benefits and costs for the system (Ostrom, 2005, 2009d, 2012; V. Ostrom, Tiebout, & Warren, 1961). The concept of polycentricity developed in the context of studies of collective action problems related to the provision of public goods and services in the 1960s and 70s, where polycentric approaches were frequently found to lead to better outcomes than monocentric ones (Ostrom, 2010b; Ostrom et al., 1961; Sovacool, 2011).

Polycentric systems effectively offer a larger scale view of the dynamics surrounding local resource systems that Ostrom initially studied. In 2009, she proposed a polycentric approach to address the question of climate change mitigation (Ostrom, 2009d). In contrast to a common belief at the time that problems of global scale were best addressed through actions at a global level, Ostrom (2009d, 2010b, 2012) argued that polycentric systems for coping with climate change were already emerging and likely to expand. Instead of relying exclusively on transnational agreements for climate change mitigation, it was important to realise that actions being taken at various levels (including individuals, households, and local governments) could cumulatively contribute to reducing carbon emissions (ibid).

Polycentric systems can deal more effectively with problems of collective action because they enable the use of local knowledge (Ostrom, 2009d, 2010b). This enables solutions that are more fit for purpose, increases levels of trust and reciprocity, facilitates innovation and experimentation, and (in parallel with the notion of diversifying investments to reduce risk) reduces the probability of failure for a large region or population (Bauwens, 2017; Morrison et al., 2019; Ostrom, 1999, 2005). The result is more efficiency locally, and a more robust and flexible system overall (ibid).

Shared renewable energy systems hold the potential to support an efficient transition to a low-carbon, sustainable energy system. To fully exploit this potential, we need to understand and optimise the behaviour of SRES. However, since system behaviour is a function of system structure (Meadows, 2008), we must gain an understanding of structure before we can start to optimise behaviour. The field of common resource governance offers insights that complement our existing understanding of sociotechnical energy systems. To highlight the parallels between the different streams of literature discussed in this chapter, it is worth noting that they have employed the same examples to describe their respective conceptualisations of structure. In parallel to the explanation by North (1990) of institutions, Meadows (2008) used the analogy of sports to illustrate the importance of a system's interconnections. Referring to the rules of a football game as the system's interconnections (players being its elements), she stated:

> “If the interconnections change, the system may be greatly altered. It may even become unrecognizable, even though the same players are on the team. Change the rules from those of football to those of basketball, and you’ve got, as they say, a whole new ball game” (Meadows, 2008, p. 16).

2.3 Energy commons: From social-ecological to sociotechnical systems

Insights into the governance of natural resources are increasingly being recognised as relevant and useful for understanding energy systems (Melville, Christie, Burningham, Way, & Hampshire, 2017; Moss et al., 2015; Šahović & Pereira da Silva, 2016; Wolsink, 2020). This section reviews these applications. It is organised along four main themes; co-evolving systems, new institutions for energy governance, energy systems as commons, and framework applications. Although these overlap (and many scholars are referenced in multiple sub-sections), they serve to provide a stylised picture of the main avenues into common resource governance taken by scholars interested in sociotechnical energy systems. They also offer a useful means to structure in the context and scope of this thesis.

2.3.1 Co-evolving systems

The concept of institutions is frequently acknowledged in energy transition studies but rarely elaborated or discussed in more detail (Andrews-Speed, 2016; Moss et al., 2015; Nilsson, Nilsson, Hildingsson, Stripple, & Eikeland, 2011). However, a number of studies have highlighted the relevance of commons scholarship to the study of energy transitions (Goldthau & Sovacool, 2012; Koster & Anderies, 2013; Moss et al., 2015; Nilsson et al., 2011). As social-ecological systems, sociotechnical energy systems are commonly described as complex and dynamic (*cf. e.g.* Acosta et al., 2018; Cherp et al., 2018). In addition, the notion of co-evolving sub-systems is central to research on both types of systems (Cherp et al., 2018). As such, it has been suggested that energy transitions may be viewed as processes of institutional change (Moss et al., 2015).

Moreover, the performance of the wider energy system ultimately depends on the fit between institutional and technical coordination (Acosta et al., 2018). Ensuring the continued alignment between the two is an important implication of the large-scale integration of new technologies into the existing system (ibid). Acosta et al. (2018)

argued that this was in accord with the need for alignment between ecological and social systems. In addition to these interdependencies, it has also been argued that institutions themselves interact and interlock in complex ways, often leading to path-dependencies (Andrews-Speed, 2016). As a consequence, institutional change in one place often requires concomitant change in connected institutions (ibid).

Comparing the challenge of achieving an energy transition within a social dilemma, Koster and Anderies (2013) argued that the path-dependency of coordination and collective action problems are in fact a main barrier to transitions. Building on Ostrom's design principles, the same authors identified a number of institutional drivers relevant to energy transitions, including (among others) polycentricity, pilot programs and technology innovation, stakeholder participation and community building. Practically, achieving a transition to a low-carbon energy system requires collective action and the formation of new (and/ or more effective) institutions at various levels and with participation from stakeholder communities (Koster & Anderies, 2013). Other studies have similarly suggested that the acceptance, support, and participation of citizens is essential to a successful transition and to the operation of new institutional arrangements for SRES (Acosta et al., 2018; Wolsink, 2013).

2.3.2 New institutions for energy governance

In a similar vein, others have also stressed the importance of accounting for the interplay between institutional conditions and local energy initiatives (Hasanov & Zuidema, 2018; Heldeweg & Lammers, 2019; Wolsink, 2012). It has been suggested that during the development of new energy systems, institutional differences may be more important than technical ones (Wolsink, 2012). As such, it is essential to gain an understanding of the social construction and embeddedness of new energy systems (ibid). Similarly, Heldeweg and Lammers (2019) pointed to the importance of collective action at and throughout various stages and processes of microgrid development and operation. They explained that the need for collective action in the context of microgrid development relates, on the one hand, to the collective production (or co-production) required for the establishment of infrastructure and energy generation (Heldeweg & Lammers, 2019; Wolsink, 2018); and on the other hand, to the collective consumption of this energy (Heldeweg & Lammers, 2019). In addition, because of this need for collective action, there is also a need for institutional arrangements to facilitate it at higher levels (ibid).

The need for collective action in establishing and sustainably managing renewable energy microgrids has received particular attention in the literature. For example, Lammers and Hoppe (2019) examined the institutional conditions that enable or disable the implementation of smart energy systems. While the above findings suggested the importance of stakeholder participation, this study found that end users were generally insufficiently involved in the development process, which was often initiated and driven by an individual project leader as the sole, active participant (Lammers & Hoppe, 2019). Furthermore, Bauwens et al. (2016) investigated the contextual factors that drive the development of wind energy cooperatives, identifying power issues as a critical determinant. Wirth (2014) found that community spirit was an important driver for the emergence of biogas cooperatives.

2.3.3 Energy systems as commons

In addition to these framings, the conceptualisation of renewable energy as a common resource or, common good, has gained traction in the scholarly literature (Wolsink, 2020). A number of authors have argued that infrastructures (in general, and in the context of the energy system) may be viewed as CPRs (*e.g.* Blomkvist & Larsson, 2013; Goldthau, 2014; Künneke & Finger, 2009; Wolsink, 2012). Künneke and Finger (2009) pointed out that, as with CPRs, the use of electricity infrastructure would not be sustainable without an institution providing, for example, capacity management and voltage control to counter the effects of multiple users on the system. Building on this CPR conceptualisation, it has been suggested that the governance of energy infrastructure calls for a polycentric approach (Goldthau, 2014). As for other CPRs, energy infrastructure expands across multiple scales, geographically as well as in terms of jurisdiction (ibid). A polycentric governance regime has also been suggested as a suitable mode of governance for energy systems more generally (Bauwens et al., 2016; Koster & Anderies, 2013; Wolsink, 2020).

The presence of multiple decision-making centres across scales characteristic of polycentric systems is becoming increasingly evident with the growth in DER and small-scale energy systems (*cf.* Wolsink, 2020). The CPR perspective as well as governance implications have also been discussed in the context of these smaller scale, decentralised systems. Sociotechnical renewable energy microgrids share the objective of optimal resource use with traditional (social-ecological) CPRs (Wolsink, 2012). To this end, notions of collective production, collective ownership and collective resource management have been considered (Bauwens et al., 2016; S. Becker, Naumann, & Moss, 2017; Moss et al., 2015; Šahović & Pereira da Silva, 2016). For example, Melville et al. (2017) described "consumption and production activities being carried out by the same groups of individuals" as a feature of commons that also applies to community-based smart grids; and defined commons as resources that are communally owned and managed, with a set of rules governing production and consumption activities (ibid). Through an interest in property rights in the context of smart grids, Hall, Jonas, Shepherd, and Wadud (2019) used a commons approach because its focus on collective provision and participation offers an alternative to a public-private binary of governance options.

Jenny, Hechavarria Fuentes, and Mosler (2007) considered a shared solar storage system as a CPR because the capacity of the PV panels and storage technology delimit the amount of energy available to the community. Rules for energy management are therefore required to avoid the unfair overconsumption by individuals, and system failures resulting from collective overuse and strain on the system (ibid). Systems that are not connected to a main power network, and therefore depend solely on a renewable source, are more susceptible to these types of CPR problems (Heldeweg & Lammers, 2019; Wolsink, 2012). Given the risk of such collective action problems, and the increased social and technical complexity of the energy system, there is a need for new institutional arrangements and governance approaches – which commons research may help address (Heldeweg & Lammers, 2019; Koirala et al., 2016; Lammers & Hoppe, 2019; Melville et al., 2017).

2.4 Towards an understanding of sociotechnical shared energy systems

This chapter has set out the theoretical background for the investigation of sociotechnical SRES and their structure and governance and provided a review of how the concepts and theories from common resource governance have been used in the context of energy studies. Building on the fields of research discussed here, the following chapter takes a closer look at the analytical approaches they offer that may support the aims of the present study. Unless otherwise specified, the terms element and component will be used interchangeably throughout the thesis. To reiterate, governance is understood here as the purposeful coordination, or orchestration, of the dynamics of a system.

THREE |

Systems thinking in action: Introduction to analytical approaches

This chapter relates the theoretical foundations discussed in the previous chapter to the methodology and methods (chapter 4) by outlining the analytical approaches used in the research. Specifically, this chapter offers an introduction to the Institutional Analysis and Development framework (IAD), the Social-ecological system framework, and agent-based modelling. Reference is also made to polycentrism, which was introduced in the previous chapter (section 2.2.3). I briefly describe the common principles that underlie these approaches and then introduce each in turn.

3.1 Simplifying complexity for analysis

All approaches discussed in this chapter have in common that they rely, broadly speaking, on the same set of variables; agents or participants, the role they fulfil, what actions they (may) take, how actions are linked to outcomes, the set of possible outcomes, and conditions or incentives for certain paths of actions (Ostrom, 2005, 2011; Poteete, Janssen, & Ostrom, 2010). The logic underlying these approaches is thus; agents in an interdependent situation make decisions (in relation to a given problem) and take actions, actions lead to or involve interactions between various agents, interactions eventually generate outcomes (*e.g.* Macal, 2016). Lastly, evaluations of outcomes may feed back into, and affect, a next round of decision-making. Decision-making agents may be conceptualised at any level of aggregation, that is, may refer for instance, to an individual, a household or a firm. The realm of possible decisions, actions and outcomes – and the associated uncertainty – is limited by (formal and informal) structures known as rules, or institutions.

3.1.1 The Institutional Analysis and Development framework

The Institutional Analysis and Development (IAD) framework (shown in figure 3.1) was developed as a conceptual map to facilitate the analysis of situations in which the actions and decisions human actors take are interdependent (Ostrom, 2005, 2011). The framework helps understand the institutional structure of a given problem space by identifying the elements and principal logical relationships that the analyst needs to consider (McGinnis, 2011; Ostrom, 2005, 2011). In other words, it identifies the structural variables that are present in some form or other in any institutional arrangement (Ostrom, 2011). It may therefore also serve as a common language that supports the systematic and comparative study of diverse institutional settings (Ostrom, 2005, 2011).

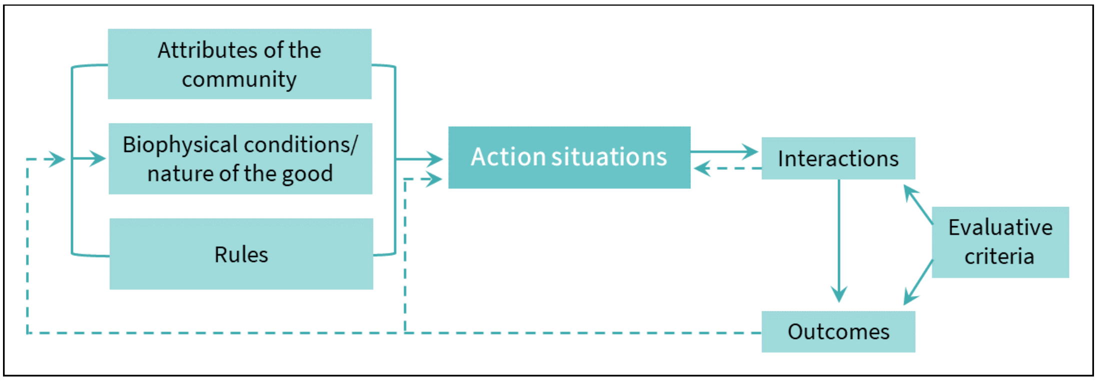


Figure 3.1: The Institutional Analysis and Development framework, adapted from Ostrom (2005, 2011). The original formulation differentiated between the action situation and the participants involved in it; the action situation and participants were therefore contained in an additional conceptual unit called an action arena. This was later simplified (Ostrom, 2011).

At the core of the framework is the action situation, a conceptual unit in which interactions take place in relation to a given problem (*see* figure 3.1, 3.2). In the context of CPRs, for example, an important action situation is concerned with the appropriation of a resource (*e.g.* Ostrom, 2005). In the action situation actors take positions, *e.g.* of resource user, that come with a set of actions they may take. How actors interact further depends on the information available to them regarding the link between a given action and potential outcomes and on the level of choice they have over which action to select. Valuations are assigned to different possible outcomes (ibid). This internal structure of an action situation is illustrated in figure 3.2. The seven elements shown in bold are referred to as the working parts or components of the action situation (ibid).

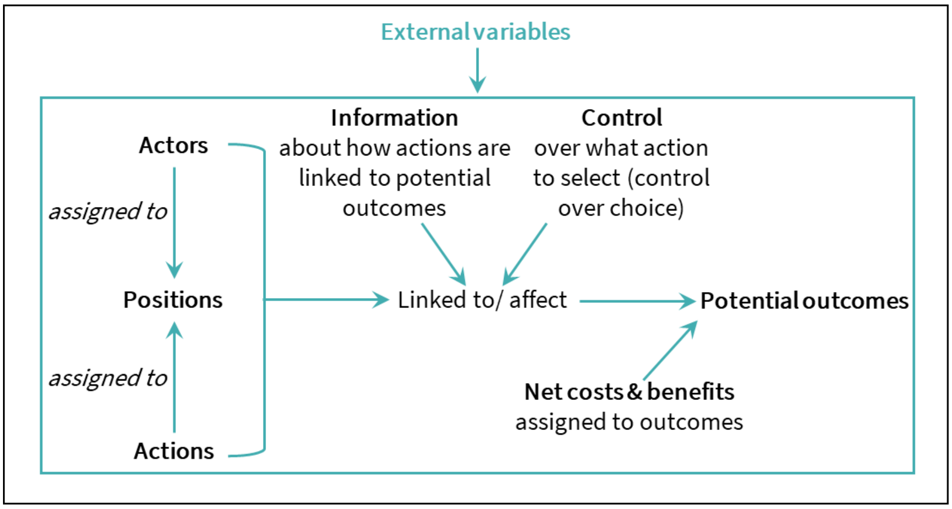


Figure 3.2: Internal structure of an action situation, adapted from Ostrom (2005, 2011).

The action situation is shaped by three types of external factors; the community, the biophysical environment, and rules used by participants to order their relationships (Ostrom, 2005, 2011) (see figure 3.1). Attributes of the community that affect the structure of an action situation may include factors such the size of the group, reciprocity, common understanding, social capital, or cultural repertoire (McGinnis, 2011, 2016; Ostrom, 2005). Biophysical conditions refer primarily to the nature of the good and specify, for example, whether the resource is a CPR (ibid). Rules affect the structure of the action situation by specifying the actions and outcomes that participants are required, permitted, or prohibited to take (Ostrom, 2005).

Rules are classified according to the effect they have on the working parts of the action situation (Ostrom, 2005, 2011). Seven types of rules thus exist. Starting with actions in figure 3.2, in clockwise direction, they are; choice, position, boundary, information, aggregation, scope and payoff rules (Ostrom 2005, 2011). To give an example, boundary rules specify eligibility criteria for joining the action situation; choice rules specify the set of allowable actions (ibid). As actors interact in the action situation, outcomes are generated and evaluated, while evaluation may affect the action situation or the external factors by for example provoking a change in rules.

A last aspect of the IAD framework that needs to be mentioned is the existence of multiple levels of analysis. The IAD framework uses a nested hierarchy of three levels of analysis. At the operational levels actors take concrete actions and generate direct outcomes (McGinnis, 2011; Ostrom, 2005, 2011) – for example, harvesting crops from a CPR directly affects the amount of crops still available to harvest. The rules that determine the structure of this operational level are the outcome of decision-making at the collective-choice level. In turn, at the highest level, constitutional choice processes set out the rules guiding interactions at the collective choice level (McGinnis, 2011; Ostrom, 2005, 2011). As such, outcomes of interactions at one level are explicitly, directly linked to those at other levels (McGinnis & Ostrom, 2014).

Note that the same logic was described earlier (section 2.2.3) in the context of polycentric systems. Using the language of the IAD framework, the constitutional choice rules in a polycentric system allow a comparatively high degree of freedom regarding who can participate in collective choice level decision-making processes. The operational rules pertaining, for example, to how a resource may be shared by a group of individuals may therefore be made in a more differentiated fashion, perhaps even by the group itself. This may lead to the pattern of distributed decision-making by multiple, independent, or semi-independent, but interacting governing authorities characteristic of polycentric systems (McGinnis, 2016).

Polycentricity has been gaining recent popularity, including in the context of energy systems. It has, for instance, been suggested that energy infrastructure should be governed polycentrically to create better opportunities for innovation, experimentation, and, ultimately, sustainability (Goldthau, 2014). Understanding and optimising the interactions between different levels of governance is a prerequisite to understanding and influencing the decision-making processes that support (or inhibit) the development of renewable energy (Newell, Sandström, & Söderholm, 2017). While polycentrism is not a framework as such, it has been described as a useful analytical approach to analyse interdependent situations and interactions, and the benefits they may produce at varying system levels (Ostrom, 2010b; Thiel, Garrick, & Blomquist, 2019). It complements the approaches described in this chapter by offering a higher level, larger scale perspective on these types of complex interactions.

3.1.2 Social-ecological systems framework

The SES framework was developed out of the IAD framework to improve analytical capacities to capture the dynamics of social-ecological systems (SES) (McGinnis & Ostrom, 2014; Ostrom, 2007). The SES framework is illustrated in figure 3.3. It is based on a set of first-tier categories (shown in figure 3.3) – the actors, the governance system, the resource system and the resource units – that feed into an action situation in which interactions produce outcomes (Ostrom, 2007, 2011).

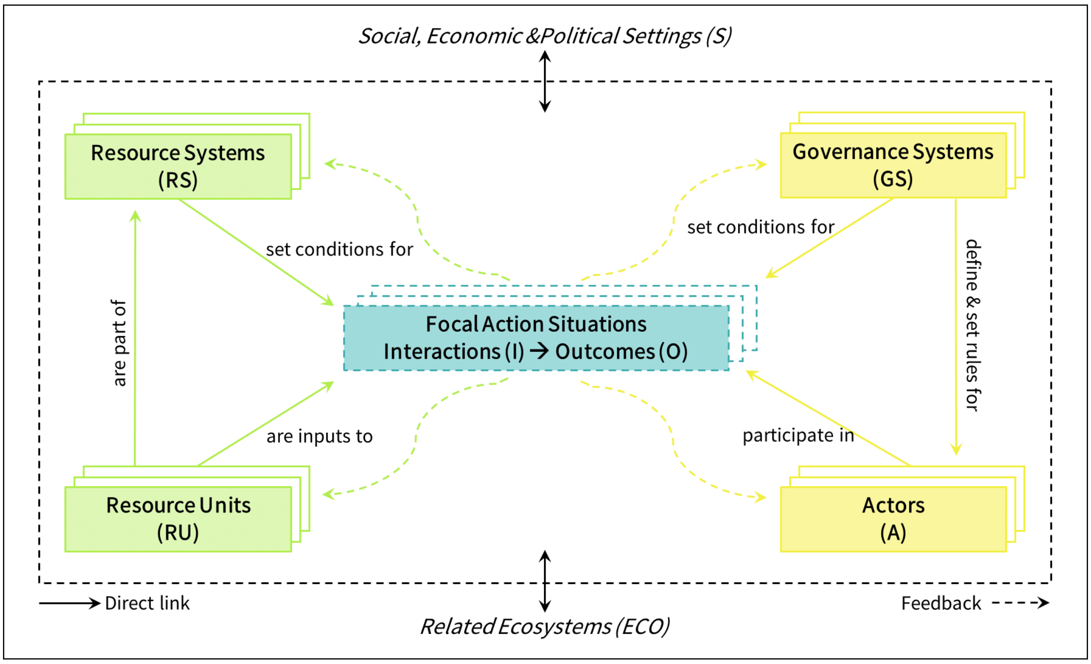


Figure 3.3: The social-ecological systems framework, adapted from Ostrom (2011), McGinnis and Ostrom (2014).

Sets of second-tier variables exist for each of these categories, as well as for the other broad components, namely, interactions and outcomes, social, economic and political settings, and related ecosystems (Ostrom, 2007) (*see* figure 3.3). These variables are potential explanatory factors in making sense of the interactions and outcomes observed in action situations (McGinnis & Ostrom, 2014; Ostrom, 2007, 2011). The framework represents complex, nested, multi-tiered, decomposable social-ecological systems, and serves as a diagnostic tool to analyse their sustainability (McGinnis & Ostrom, 2014; Ostrom, 2007, 2011).

Both the IAD and SES framework have more recently started to be applied to the analysis of energy systems. Publication II of this thesis applies the SES framework to explore the effects of digital technologies on system dynamics, while Publication V uses the IAD framework to identify institutional factors supporting and inhibiting the performance of SRES. Table 3.1 provides examples of other studies applying the two frameworks in the context of energy systems.

Table 3.1 Examples of applications of analytical tools from the commons literature to energy systems.

Framework	Application	Reference
IAD framework	Decision-making related to the establishment of smart local microgrids, institutional conditions that affect the implementation of smart energy systems; IAD framework combined with Institutional Legal Theory	(Heldeweg & Lammers, 2019; Lammers & Hoppe, 2019)
	Formulating a structured approach to the design and simulation (ABM) of policies, specifically in the context of Renewable Energy Sources for Electricity	(Iychettira, Hakvoort, & Linares, 2017)
	Identifying and leveraging institutional factors that affect the energy transition, i.e. how policies, biophysical conditions and community attributes affect energy transitions	Koster and Anderies (2013)
	Effect of values on institutional change in the energy transition; IAD combined with concept of social learning	(Milchram, Märker, Schlör, Künneke, & van de Kaa, 2019)
	Actor networks involved in and affecting local development processes for renewable energy investment	(Newell et al., 2017)
SES framework	Applicability of SES framework to integrated community energy system; framework to support planning, implementation, and analysis of governance	(Acosta et al., 2018)
	Factors influencing community participation in wind power cooperatives	Bauwens et al. (2016)
	SES framework as basis for approach to analyse the viability of self-governance in community energy systems	(Cayford & Scholten, 2014)
	Refined SES framework to be used as diagnostic tool in context of rural electrification and cooperative ownership	(Holstenkamp, 2019)

3.1.3 Agent-based modelling

Frameworks guide analysis by identifying the elements and general relationships that need to be considered to examine a particular type of problem (Ostrom, 2011). They are metatheoretical in that these elements and relationships should be contained in any of the relevant theories (ibid). In contrast, models are a more specific form of analysis, concerned with generating predictions based on clearly defined variables and theory (ibid). Models allow the systematic investigation of how a set of precise assumptions and variables affects a limited set of outcomes (ibid). For a model to be useful, its assumptions and the situation it examines need to be closely aligned (ibid).

Agent-based modelling (ABM) is a computer simulation approach that, although not developed by the Ostrom Workshop, was frequently used by its scholars. Agents are discrete, autonomous units that may represent any element of a system and that are endowed with a set of properties and actions (Macal & North, 2006; Wilensky & Rand, 2015). An agent's behaviour and decision-making are based on its properties and a set of simple rules (Macal & North, 2006; Macy & Willer, 2002; Wilensky & Rand, 2015). Agents in a simulation are interdependent. The behaviour of the system as a whole emerges from the interactions between (heterogenous) agents over time (Macal & North, 2010). As such, ABM provides a means of simulating how a system's behaviour evolves over time (Ghorbani, Dijkema, Bots, Alderwereld, & Dignum, 2014). ABM has also been combined with the IAD framework (*e.g.* Ghorbani, Bots, Dignum, & Dijkema, 2013; Iychettira et al., 2017; Ligtvoet, Ghorbani, & Chappin, 2011).

ABM is widely regarded as a useful tool for modelling systems that are marked by complex interdependencies and interactions between agents (Macal & North, 2006; Wilensky & Rand, 2015). Its ability to deal with complexity has made it an increasingly popular tool in the context of energy systems research (Hansen, Liu, & Morrison, 2019). Because it facilitates the simulation of interactions between system components, it is a promising tool for the study of sociotechnical systems (ibid). A recent review of the literature at the interface of ABM and sociotechnical energy systems (Publication I) found that electricity markets and consumer behaviour were two particularly popular areas of application (Hansen et al., 2019).

As alluded to in section 3.1, the thinking underlying ABM is closely related to the approaches of the Ostrom Workshop. The similarities are such that Ostrom in fact likened her conceptualisation of nested rule systems to the logic of computer language (Ostrom, 1990, 2005):

> “The nesting of rules within rules at several levels is similar to the nesting of computer languages at several levels. What can be done at a higher level will depend on the capabilities and limits of the rules at that level and at a deeper level” (Ostrom, 2005, p. 58).

FOUR |
Research design

This chapter describes how the research was designed to answer the research questions. Figure 4.1 provides an overview of the core components of the design. A review of the literature on sociotechnical energy systems as well as common resource governance informed the development of a bottom-up research approach. Continuous engagement with the literature throughout the research process helped refine theoretical understanding and the selection and application of tools. This is in line with the practice of case study research (Yin, 2009), as well as the idea of Ostrom (1990) of moving back and forth between the worlds of theory and action (*cf.* figure 1.3). The following section (4.1) explains the methodology in more detail. Section 4.2 explains the literature review methods. Section 4.3 introduces the two case studies; White Gum Valley and RENeW Nexus. Against the backdrop of the cases, section 4.4 describes the data collection methods, and section 4.5 explains the means of analysis.

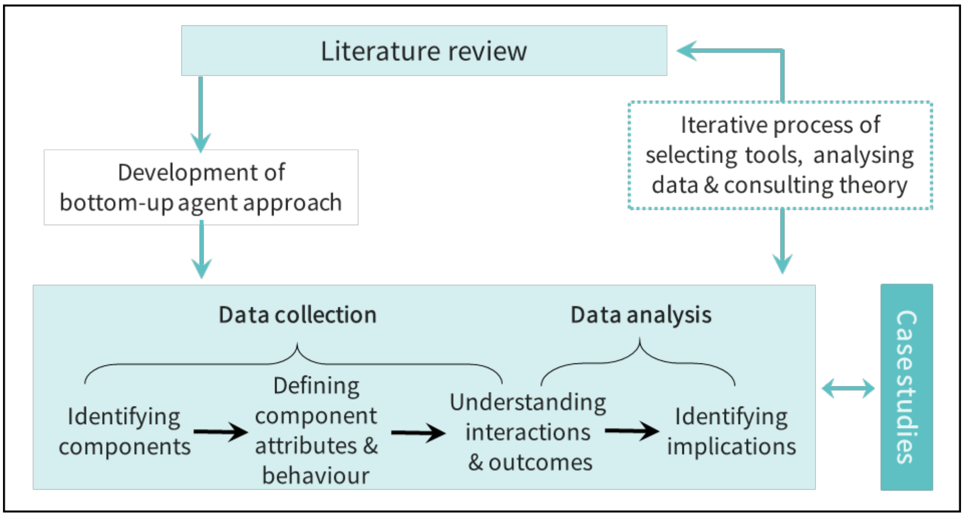


Figure 4.1: Overview of the research design.

4.1 Methodology

In drawing on the literature concerning common resource governance and institutions, this thesis generally follows the tradition of methodological individualism (MI) employed by the Ostrom workshop (*cf.* Arturo, 2015; Boettke & Coyne, 2005; Forsyth & Johnson, 2014). MI focuses on the actions and decisions of individuals to analyse and understand the behaviour of groups or collective phenomena (Forsyth & Johnson, 2014; McCay, 2002). Given the focus of the research on sociotechnical – rather than purely social – systems, the heuristic of the individual is conceptualised as encompassing social and technical individual agents. In this regard, and in having taken (sociotechnical) systems thinking as a starting point, the approach could also be described as systemist (Bunge, 2000). For the purposes of this thesis, the two are understood as effectively the same (Di Iorio & Chen, 2019).

The translation of this approach into a practical research strategy is shown schematically in figure 4.1. A bottom-up approach, centred on characterising the social and technical agents (*i.e.* components) in the case study systems, was developed following the initial literature review. The term agent(s) will be used throughout this chapter to refer to system elements that have agency – that is, elements that are presumed to perform actions. This agent approach enabled the identification of the agents involved in the shared case study system; the identification of their attributes and behaviour and thirdly; an understanding of how they interact with each other and what the outcomes are; and a consideration of the implications of these for the system and the aims of the thesis (*cf.* figure 4.1). By treating social and technical system elements as conceptually the same, the research design sought to generate an integrated understanding of sociotechnical energy systems (Love & Cooper, 2015). An inductive and exploratory mixed-methods approach guided the collection and analysis of data based on the two case studies (Sovacool, Axsen, & Sorrell, 2018).

4.2 Literature review

Two types of literature review were used to support the research; narrative and systematic (Sovacool et al., 2018). The purpose of the narrative reviews was twofold. Firstly, they supported the ongoing research process by guiding the problem framing and direction for the publications. Secondly, they supported the analysis and writing processes by providing, on the one hand, the background and framing for each of the publications, and on the other hand, the theory required for analysis. In addition, a systematic review was conducted at the beginning of the research process. Systematic literature reviews are structured with a stringency generally not found in narrative reviews. They aim to reduce bias in the set of reviewed literature and promote replicability by employing a more rigorous (and systematic) research design (Sovacool et al., 2018). A systematic review was conducted as part of this thesis (Publication I) to evaluate how agent-based modelling (ABM), a computer simulation technique, has been applied to the study of sociotechnical energy systems. The findings of this review (Hansen et al., 2019) informed the research design by evaluating the applicability and potential usefulness of ABM for answering the research questions. It also contributed to the identification of a suitable ontology (*cf.* previous section). The process of article selection and analysis is explained in detail in Publication I (Hansen et al., 2019).

4.3 Introduction to the case studies

The usefulness and appropriateness of using case studies to address the research questions was encapsulated by Poteete et al. (2010, p. 33) when they asserted that case studies were

> "opportunities to develop concepts and theory, identify the limits of general relationships […], and disentangle causal processes",

and that they were

> "especially appealing in the effort to make sense of complex processes".

As such, the phenomenon of energy sharing was examined in two different real life settings (Yin, 2010). The research was based on two case studies of energy sharing projects in Fremantle, Western Australia: White Gum Valley (WGV) and RENeW Nexus. Sections 4.3.1. and 4.3.2 introduce the case studies.

The primary criterion for the selection of cases was access. Both cases were accessible in terms of their location, as well as in terms of hospitality of stakeholders. As both cases were linked to established research projects, there was a willingness and readiness of stakeholders to cooperate. This meant that access to data – i.e. willingness to be interviewed and availability of quantitative data – was much better than would have been the case elsewhere. In addition, both cases feature the use of innovative technological solutions. As discussed in the introductory chapter, the use of new – and often digital – technologies is a common feature of novel shared energy system configurations. It was thus considered important that the cases accounted for this. WGV further made for a good case because it allowed for the investigation of three variants of the same basic sharing configuration. This improved the potential robustness of the case by offering a means of in-case comparison and validation. The RENeW Nexus study was added as a second case because it allowed an additional perspective on the employed technology. In addition, the RENeW Nexus and WGV projects were linked in terms of many of the involved stakeholders (the former having evolved as from the latter) and therefore allowed for an examination of the notion of scaling from a polycentric perspective (Publication VI).

4.3.1 White Gum Valley (WGV)

The WGV case study is concerned with a governance model for solar energy sharing amongst occupants of multi-unit dwellings. The model was implemented in three apartment buildings in a sustainable residential precinct in the Fremantle suburb of the White Gum Valley. distriThis also motivated the inclusion of apartment buildings in the development which is located in an otherwise low density area. Research on the energy sharing model in the WGV apartment buildings was undertaken as part of a research project funded by the Australian Renewable Energy Agency (ARENA).

Table 4.1: Relevant characteristics of the three apartment buildings of the WGV case study.

	Gen Y	**SHAC**	**Evermore**
Number & type of units	3 1-bedroom units	12 units of varying size (1 to 3 bedrooms), plus 2 shared artists' studios	24 units of varying size (1 to 3 bedrooms)
Solar PV & battery storage system	9kW Solar PV, 10kWh Li-Ion battery	19.6kW Solar PV, 40kWh Li-Ion battery	54kW Solar PV, 150kWh Li-Ion battery
Date the building was occupied	July 2017 - Dec 2017	Aug – Sept 2017	Sept – Oct 2018
Other information	Developed by the state land development agency as a demonstration site of sustainable 21st century (targeted at Generation Y); the building occupies a standard 250 m^2 lot but hosts 3 apartments and 3 separate outdoor spaces to show that space-efficient living can be an attractive and sustainable option	Developed by an affordable housing provider (in collaboration with the SHAC cooperative) to offer affordable housing for Fremantle artists; occupants are tenants renting from the affordable housing provider	Developed by a commercial developer; occupants are owner-occupiers or rent from private investors

This project investigated the sharing model in view of increasing the uptake of solar PV and battery storage systems in apartment buildings across Australia. The basic premise was to use solar PV in combination with battery storage and a blockchain-enabled peer-to-peer (P2P) platform to provide the equitable distribution of renewable energy and costs amongst residents.

Existing models for using solar PV in apartment buildings tend to either connect panels directly to individual apartments or use the renewable energy solely for common spaces (Roberts, Bruce, & MacGill, 2018). In contrast, at WGV, the battery technology, sub-metering architecture, and P2P platform are used to decouple flows of electricity and finances, thus enabling a more differentiated and efficient set-up. Residents pay for their solar energy based on allocations. This is meant, firstly, to provide a sinking fund to cover costs related to, *e.g.* system maintenance. Secondly, it may serve as a potential incentive for residents to be conscious of their electricity consumption by pricing units of solar electricity below the retailer's rate for grid-sourced electricity. The three apartment buildings are named Gen Y, SHAC (Sustainable Housing for Artists and Creatives) and Evermore. Table 4.1 provides an overview of the buildings' key features.

4.3.2 RENeW Nexus

The RENeW Nexus trial that served as the second case study for this research was part of a wider transdisciplinary project focused on the integration of renewable energy and water (RENeW) systems in an urban setting. The trial tested the trading of surplus solar energy amongst Fremantle residents and across the regulated network. Insofar as many of the same actors involved in WGV also participated in the RENeW Nexus project, WGV is often viewed as the precursor to the project. Moreover, the same platform which was previously used to provide the P2P functionality of sharing within an embedded network was employed to enable trading across the regulated distribution network. A small cohort of Fremantle residents with and without rooftop solar PV was recruited and their homes fitted with smart meters. A pricing system was developed by the project consortium consisting of the rates shown in table 4.2. In addition, participants were able to set the prices they were willing to buy and sell solar electricity *via* the online platform.

Trades were executed at 30 minute intervals. The trial ran from August 2018 to June 2019 (with trading starting at the end of November 2018).

Table 4.2: Tariff structure used for electricity pricing in the RENeW Nexus trial.

Type of rate	Price (in Australian Dollars, including GST)
Rate for grid-sourced energy	\$0.0572 per kWh (off-peak) \$0.0990 per kWh (peak: 3pm-9pm)
Retailer rate for purchase of any unsold excess	\$0.04 per kWh
Retailer daily capacity charge	\$1.10
Daily network operator charge	\$2.20
Platform transaction fee	\$0.005 per kWh purchased through trading

4.4 Data collection

The most important type of data used in this research consisted of semi-structured interviews with stakeholders of the two case studies. Seventeen interviews with representatives of the involved organisations, and 21 interviews with WGV residents were conducted between April 2018 and December 2019. The interviewed organisations were:

- The government agency that provided funding for the WGV energy study
- The developers of the three apartment buildings
- The state electricity retailer and network operator
- The engineering firm that designed and implemented the solar PV and battery storage systems at WGV
- The technology/ software start-up that developed the P2P platform
- The software firm acting as an intermediary in the RENeW Nexus Trial
- A building manager for Gen Y (SHAC is managed by the developer although the Evermore manager declined to be interviewed)
- The City of Fremantle as a supporting actor
- The project manager of the RENeW Nexus project

Table 4.3 shows the actors, their case study association, the time period in which they were interviewed, as well as the format of the generated data. Interviews generally lasted between 30 to 60 minutes. All interviews were initially audio-recorded and transcribed (with the exception of written responses and a phone interview). Interviews with WGV residents at the end of 2019 were not audio-recorded because of the paucity of information residents were able to share with regards to the questions. The structure of the interviews is shown in figure 4.2. Interview questions were guided by the agent approach outlined in section 4.1. Questions sought to identify the components (agents) of the system, define their attributes and behaviour in relation to the shared solar energy systems, and understand interactions and outcomes. Figure 4.2 lists the key themes of interest.

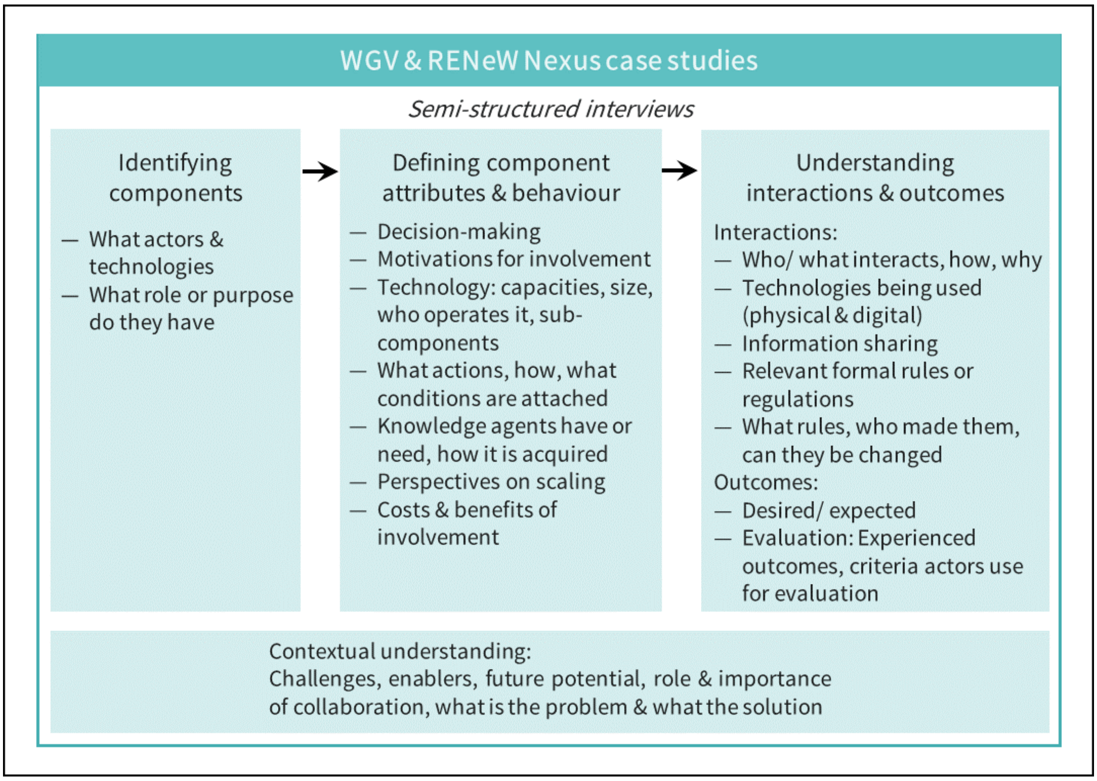


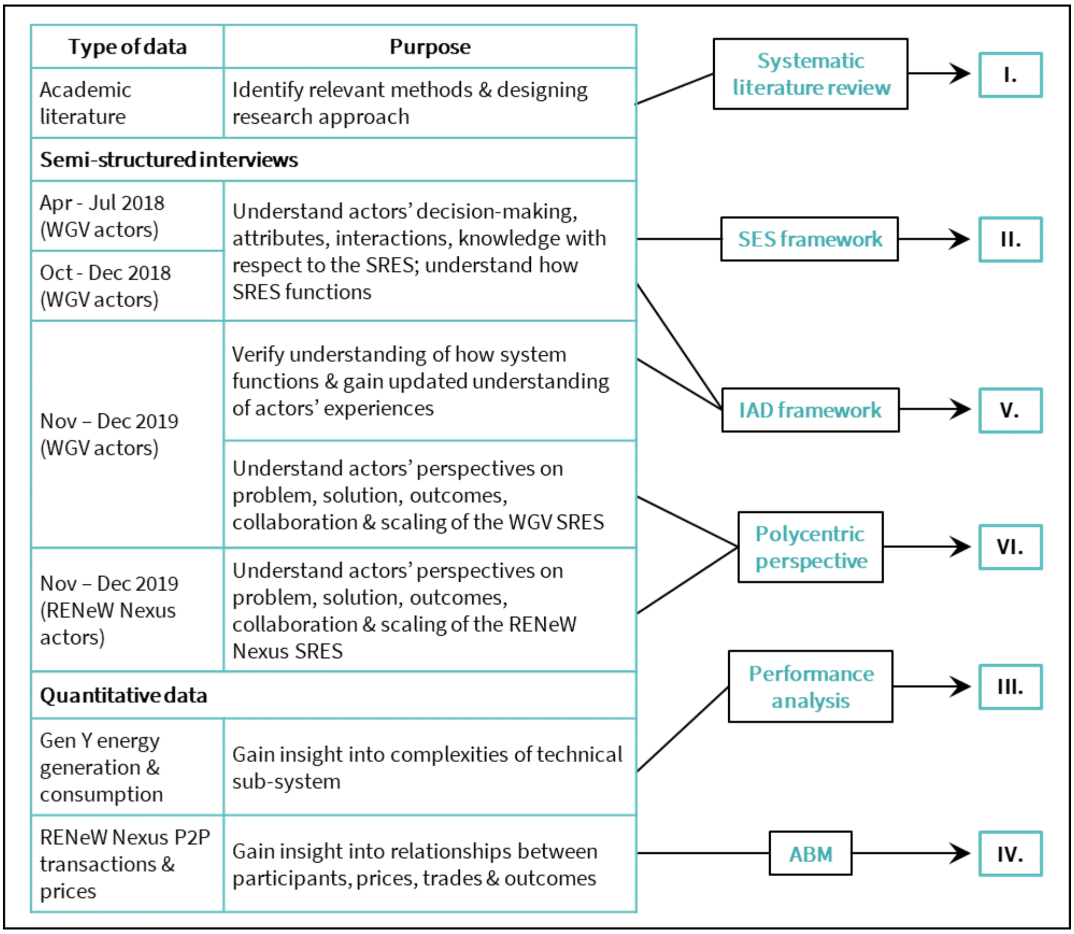
Figure 4.2: Semi-structured interviews served to understand the components, their attributes and behaviour, and the interactions and outcomes in the case study systems, as well as provide contextual understanding.

The overarching logic was to understand the decision-making processes and criteria of different actors that motivated and guided their behaviour in the past, present and future. Interviews with representatives of the organisations involved in the technical system design were additionally asked to specify the properties and behaviour of the technologies used. In some cases interviews also served to identify other relevant actors.

Table 4.3: Overview of interviews conducted as part of the research.

Data collection	Case study	Actor	Interview data
April-July 2018	WGV	Government funding agency	Interview answers provided by email
		Building manager Gen Y	Audio-recorded and transcribed
		SHAC developer	Audio-recorded and transcribed
		Electrical engineering firm	Audio-recorded and transcribed
		Technology start-up	Audio-recorded and transcribed
		Retailer	Audio-recorded and transcribed
		Network operator	Audio-recorded and transcribed
		State land developer	Audio-recorded and transcribed
		City of Fremantle	Audio-recorded and transcribed
		Residents Gen Y	3 people (3 households) Audio-recorded and transcribed
October-December 2018		Developer Evermore	Audio-recorded and transcribed
		Residents SHAC	4 people (4 households) Audio-recorded, notes taken by interviewer
		Residents Evermore	7 people (6 households) Audio-recorded, notes taken by interviewer
November – December 2019		Residents Evermore	5 people (4 households) Notes taken by interviewer
		Residents SHAC	1 person (3 residents were present and made a few comments) Notes taken by interviewer
		Residents Gen Y	1 person (1 household) Notes taken by interviewer
		Electrical engineering firm	Audio-recorded and transcribed
		SHAC developer	Interview conducted over the phone, notes taken by interviewer
	WGV RENeW Nexus	Technology start-up	Interview answers provided by email in February 2020
	RENeW Nexus	Retailer	Audio-recorded and transcribed
		Network operator	Audio-recorded and transcribed
		Software firm	Audio-recorded and transcribed
		Project manager	Audio-recorded and transcribed

Figure 4.3 further specifies the purpose of each round of interviews in the context of the research overall and the publications. While initial interviews focused on gaining an understanding of how the WGV systems were set up and worked, the focus of later interviews was on higher level interactions (in addition to serving to verify earlier findings). It should be noted that the RENeW Nexus project developed within the same core actor network after this research was already underway. I was able to follow the development of the system design as it unfolded and therefore did not have to cover the detailed system operation to the same extent as in earlier WGV interviews.



Type of data	Purpose
Academic literature	Identify relevant methods & designing research approach
Semi-structured interviews	
Apr - Jul 2018 (WGV actors)	Understand actors' decision-making, attributes, interactions, knowledge with respect to the SRES; understand how SRES functions
Oct - Dec 2018 (WGV actors)	
Nov – Dec 2019 (WGV actors)	Verify understanding of how system functions & gain updated understanding of actors' experiences
	Understand actors' perspectives on problem, solution, outcomes, collaboration & scaling of the WGV SRES
Nov – Dec 2019 (RENeW Nexus actors)	Understand actors' perspectives on problem, solution, outcomes, collaboration & scaling of the RENeW Nexus SRES
Quantitative data	
Gen Y energy generation & consumption	Gain insight into complexities of technical sub-system
RENeW Nexus P2P transactions & prices	Gain insight into relationships between participants, prices, trades & outcomes

Figure 4.3: Relationships between types of data, general purpose of the data, analytical approach and publications.

In addition to the interviews, quantitative data from WGV (the Gen Y building) and the RENeW Nexus Trial was used to supplement the qualitative data and gain greater insight into the technical aspect of the sociotechnical systems under investigation. Quantitative types of data are specified in table 4.4.

Table 4.4: Types of data from each case study used in the thesis.

Case study	Type of data
WGV: Gen Y building	Energy consumption (from renewables and grid) of the 3 apartments and common property; battery performance data 1 year of data: Dec 2017-2018
RENeW Nexus Trial	For all participants (12 prosumers, 6 consumers): Transactions recorded over the course of the trial; Buying and selling rates set by participants; Electricity consumption and solar PV generation (prosumers only)

4.5 Data analysis

4.5.1 Interview analysis

The analysis of the qualitative (interview) data generally followed the five phases proposed by Yin (2010):

1. **Compiling:** Written (*i.e.* from transcripts and notes) interview data was organised in a database (Excel).
2. **Disassembling:** Data was broken up into smaller fragments based on interview questions and themes (*cf.* figure 4.2).
3. **Reassembling:** Identifying emergent themes, reorganising in line with the applied frameworks.
4. **Interpreting:** Interpretation of reassembled data in line with the applied frameworks.
5. **Concluding:** Based on 1-4.

Phases 3-5 were carried out separately for each of the publications based on qualitative data (Publications II, V, VI). The SES and IAD frameworks, and the polycentric perspective outlined in chapter 3 were used to analyse the interview data for Publications II, V and VI, respectively. The evaluation of the aggregate evidence presented in chapter 6 was also based on these steps, with the reassembling phase being guided by the research sub-questions.

4.5.2 Quantitative analysis: Gen Y

The Gen Y energy data was analysed in terms of seasonal load profiles, self-sufficiency ratios and performance of the battery storage system. The analysis was carried out by the lead author of Publication III. More detailed information regarding the analysis is provided in the publication (Syed, Hansen, & Morrison, 2020). The results of the analysis fed into the discussion in chapter 6 in line with the 5 phase process detailed in the previous section (4.5.1).

4.5.3 Quantitative analysis: RENeW Nexus

Agent-based modelling was used to simulate the dynamics of the RENeW Nexus P2P energy trading system. Details regarding the modelling exercise can be found in Publication IV (Monroe, Hansen, Sorell, & Zechman Berglund, 2020). To inform the simulation, the following analyses were carried out:

- Descriptive statistics of transactions recorded over the course of the trial were generated to gain an understanding of types (*e.g.* P2P or grid), frequencies, and amounts of electricity traded.
- Buying and selling rates set by participants were aggregated into daily and monthly averages per participant and type of rate (Peak buy; peak sell; off-peak buy; off-peak sell).
- Electricity consumption and solar PV generation (prosumers only) data was organised into 30 minute time intervals and formatted in accordance with the ABM framework. This was done with the support of the Curtin Institute for Computation.

The aggregate data was used as input into and a means of validating the agent-based simulation discussed in Publication IV. The ABM framework was developed by the collaborating lead author who also ran the simulation and aggregated the quantitative output. We then jointly discussed the implications of the results, with a focus on forging an interdisciplinary perspective based on our backgrounds in the social and engineering sciences.

FIVE |

Sharing solar energy: Findings from the field

The preceding three chapters provided the theoretical foundations of this research, and outlined the methodological approach to answering the research questions. This chapter revisits the empirical findings discussed in the publications forming part of this thesis. Its purpose is to provide an overview of learnings from the field and thus an initial understanding of how SRES function from a sociotechnical perspective. This chapter thus addresses the empirical sub-question: what are the sociotechnical elements and interactions that shape shared renewable energy systems? and how may they affect outcomes? The following chapter will then draw on the aggregate findings to develop conceptual foundations for the analysis and governance of SRES. Figure 5.1 illustrates how the discussions in chapters 5 and 6 are linked.

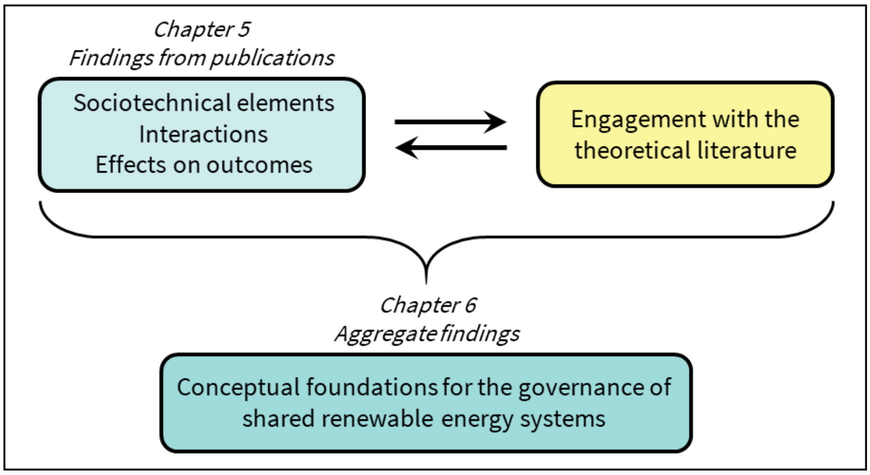


Figure 5.1: Findings from analyses of empirical data (presented in Chapter 5) were evaluated in the context of the theoretical literature to meet the overarching aims of the research. Chapter 6 presents these aggregate findings: a starting point for conceptual foundations to support the (analysis of) governance of SRES.

The chapter is divided into six sub-sections in line with the six publications included in this thesis. Each section begins with a short summary of the paper to provide context and then discusses the paper's contributions to understanding the sociotechnical elements, interactions and outcomes in SRESs. An exception is the first publication, which primarily served to inform the research design.

5.1 Publication I: Agent-based modelling and sociotechnical energy systems

A systematic literature review was conducted at the beginning of the research to explore the applicability of ABM to energy system studies and specifically within a sociotechnical paradigm (Hansen et al., 2019). The review found that the complexity resulting from the connections between social and technical sub-systems is an often cited reason for using the technique. Engaging with this literature early in the research process inspired the use of an agent perspective (*cf.* chapter 4) in the research design. Data collection and analysis (in particular the interviews) were subsequently designed to identify attributes and decisions of stakeholders and technologies (social and technical elements), mimicking the definition of agents in simulation studies. Another take-away that later fed into the planning of Publication IV was that there is a lack of empirical data being used in model initiation and validation.

5.2 Publication II: Digitalism and sociotechnical dynamics

This paper applied the SES framework to interview data from the WGV case study to examine the effect that digital technology has on the system (Hansen, Morrison, Zaman, & Liu, 2020). It also offered first insights into the general structure of the sharing arrangements at WGV. These are illustrated in figure 5.2 as a means of providing additional context and a point of reference for the WGV SRES.

Publication II helped gain insight into the characteristics and relevance of different system elements. Specifically, examining digital technology in more detail, revealed that the digital element, in the context of the paper's analysis, could neither be accounted for as a simple component of the system nor as a component attribute. Instead, it was found to be best described as a property of interactions.

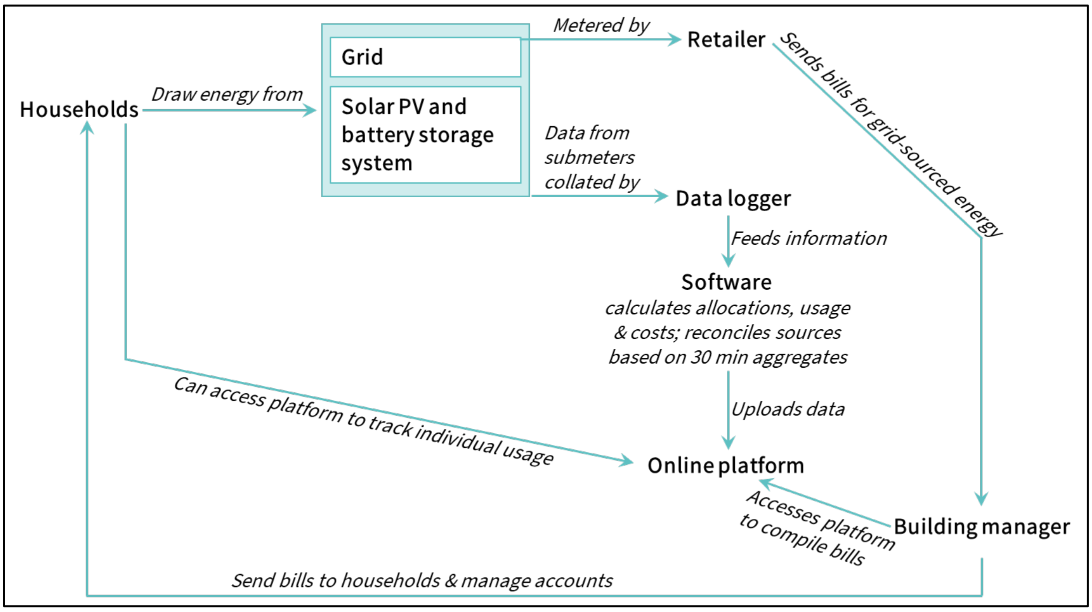


Figure 5.2.: Generalised governance structure for energy sharing at WGV , adapted from Hansen et al. (2020).

Figure 5.3 shows how interactions were conceptualised as occurring within and across physical and virtual spaces. While in the SES framework information sharing is a type of interaction, it was found to have the additional role of mediator between interactions and spaces in the case study analysis. The operation of the WGV SRES may be described as a continuous cycle consisting of information production, processing and management phases, with the information processing phase acting as an intermediate between physical and virtual spaces (figure 5.3).

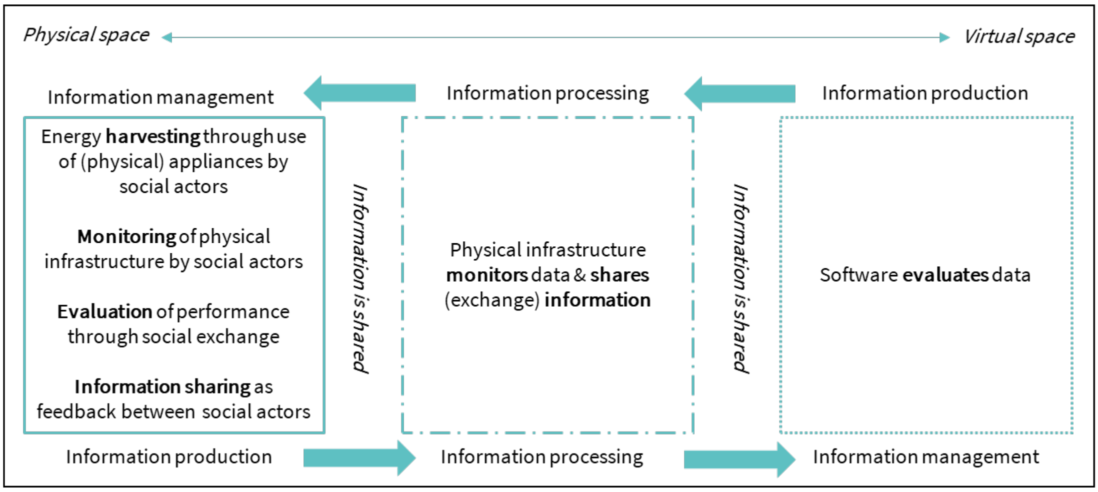


Figure 5.3: Interactions across physical and virtual spaces in the WGV SRES. Harvesting, monitoring, evaluative activities and information sharing were identified as important interactions based on the variables of the SES framework. Information was identified to act as a mediator between physical and virtual spaces. Adapted from Hansen et al. (2020).

In addition, applying the SES framework indicated, on the one hand, the need to differentiate system operation from other phases (*e.g.* implementation) when analysing interactions (harvesting, monitoring, information sharing and evaluation being most important); and on the other hand, that the interactions suggested in the framework are insufficiently precise in the context of SRESs. They do not specify the object of interaction, that is, what is being acted on or transacted.

Drawing on the outcome variables proposed in the SES framework (social performance measures, ecological performance measures), measures of system performance were established based on interviewees' expectations and evaluations. Overall, stakeholders agreed that cost savings for residents and positive environmental outcomes were primary indicators of success. Four themes of outcomes were observed in the case study; the emergence of new roles, an over-reliance on technology, missed communication and a lack of trust. Figure 5.4 illustrates how they related to the effects of digitalism on the performance of the SRES.

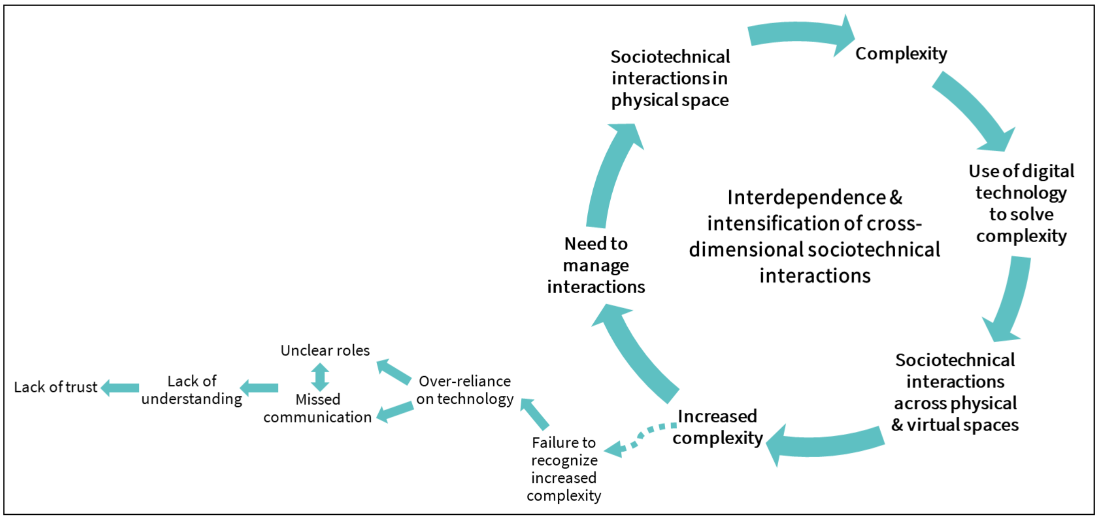


Figure 5.4: The use of digital technology to enable the sharing of solar energy at WGV led to a positive feedback loop of sociotechnical interactions occurring across physical and virtual spaces. Adapted from Hansen et al. (2020).

The use of the platform-based software at WGV was initially proposed to overcome the complex challenge of equitably sharing renewable energy in an apartment building. The operation of this technical solution, however, caused additional needs for monitoring and expert knowledge. These requirements in turn necessitated an increased involvement of social actors to manage the system (emergence of new roles).

Findings from the case study suggested that failure to recognise this increased sociotechnical complexity in digitally-enabled SRES may lead to unfavourable outcomes. At WGV, the resulting over-reliance on technology contributed to missed communication between the actors setting up the SRES, unclear roles, and eventually a lack of trust on the part of the residents. Digital technology may facilitate some interactions; but it also makes others more complex. To support the operation and performance of SRES, digital technology requires adequate management.

This finding is especially interesting considering the origins of the STS concept introduced in section 2.1.2. The concept of joint optimisation of social and technical subsystems arose from research into the organisation of work practices in the mining industry. Early observations suggested that many of the industry's problems

> "had resulted from the introduction of significant changes in the technical aspects of production *without* adequate attention to their appropriateness for a particular physical environment or their impact on social structure and needs" (Fox, 1995, p. 92).

5.3 Publication III: Getting to know the technical subsystem

The digital technology used at WGV to enable equitable sharing of solar energy is part of a larger technical subsystem. A study of the performance of the solar PV and battery energy storage system (BESS) at the Gen Y building provided an opportunity to gain an appreciation of the complexity of this technical subsystem (Syed et al., 2020). The shared energy microgrid evaluated in this article comprised of a range of physical and digital components and connections, each, in turn, with a separate set of operating principles and control methods. To illustrate, the principle components of this technical (sub-)system are the solar PV modules, the BESS, an inverter, electricity pulse meters, energy meters, interface modules, and a data logger. This physical infrastructure is supported by a cloud-based energy monitoring system, an energy server, a broadband internet connection and a bridging platform to manage the data.

Figure 5.5 shows the physical elements and interconnections of the shared energy microgrid, illustrating its complexity. The diagram also highlights how nested hierarchies manifest in SRES. What is broadly referred to as the technical subsystem is part of, and features numerous overlapping subsystems itself. The box labelled Grid in figure 5.5 represents a complex, large-scale electricity distribution network. The BESS is – as the name implies – a system consisting of the converter, inverter and storage unit. The elements shown in figure 5.5 are integrated with a software infrastructure required to make the SRES function. Examining the software infrastructure, in turn, requires a distinction to be made between the elements listed in the preceding paragraph, which were implemented by the electrical engineering firm; and the sharing platform created and run by the technology start-up.

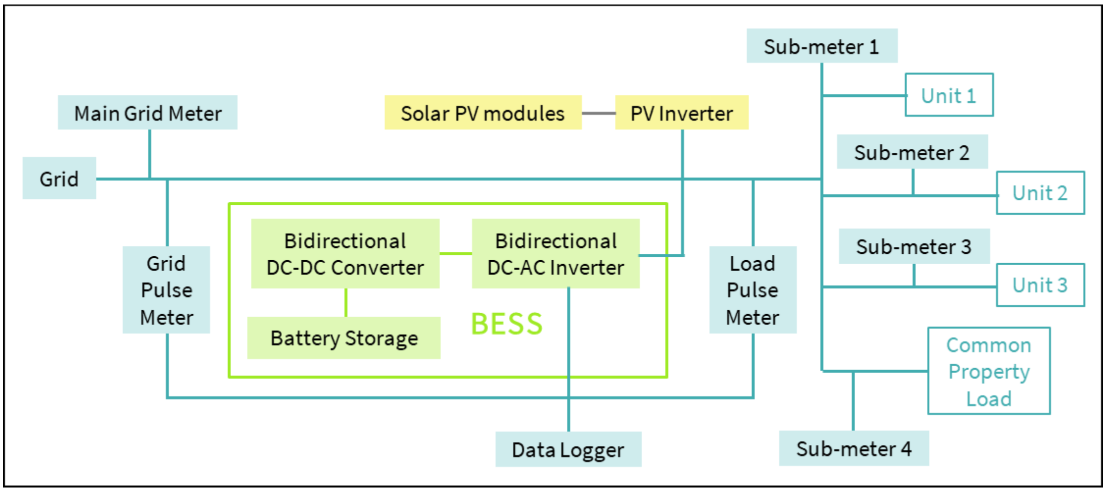


Figure 5.5: Simplified block diagram of the Gen Y shared energy microgrid to illustrate the complexity of elements and interconnections within and across nested hierarchies. Adapted from Syed et al. (2020).

This also demonstrates the intricate connections and dependencies between the social and the technical. A source of contention between the actors implementing the WGV system was the information processing phase shown in figure 5.3, namely, the question of who should be responsible for management and monitoring of data (Hansen et al., 2020). The data, and its management, represent the connection between the platform doing the financial accounting, and the rest of the system.

With respect to outcomes, the article concluded that while the BESS is central to creating a financially and technically viable shared system, the way it is used must be configured properly for it to add value to the system. Sizing the battery storage correctly is essential, and has to be considered in conjunction with the amount of available roof space, the resulting available PV generation capacity, and occupants' energy needs. Overall, however, the analysis of the microgrid's performance suggested a generally well-functioning system. Given that evaluations of system performance based on social actors' experiences consistently indicated sub-optimal results (Hansen et al., 2020; Hansen, 2020), this provides a text book example of the meaning of, and need for joint optimisation in sociotechnical systems.

5.4 Publication IV: An agent-based exploration of energy sharing

The RENeW Nexus trial tested the efficacy of P2P trading using the same sharing platform as the WGV SRES, and a tariff structure developed cooperatively by the organisations involved in the project (chapter 4). In Monroe, Hansen, Sorrell and Zechman Berglund (2020) the governance of the RENeW Nexus SRES was evaluated in terms of the effect that the tariff structure had on outcomes. It allowed for a better understanding of digitally enabled governance as pricing and trading rules were executed by the platform.

In contrast to the WGV SRES, the P2P trial allowed participants to actively trade their surplus solar electricity by adjusting their buying and selling prices as they pleased. Practically, the utility's rate for grid electricity and the market settling rules imposed a natural upper limit on the prices participants could set. As illustrated in the other articles, the effect of nested hierarchies, *i.e.* cross-level interactions, was important for the range of possible outcomes. In the case of the RENeW Nexus trial, the design of state-level electricity tariffs limited the design options for the trial and effectively led to economically adverse outcomes for trial participants. In the language of the Ostrom Workshop, the collective-choice process of designing the rules for the operational system was limited by constitutional rules.

This had a significant effect on outcomes. Given the limited flexibility actors had in setting the prices to include in the tariff structure, the rules were unable to offer a sufficiently large economic incentive to trial participants. At the beginning of the trial, participants adjusted their buying and selling prices as they got to know the system and the possibilities it could offer them. However, as the limited potential for economic rewards became apparent, participants optimised their own outcomes by minimising the time they invested into actively engaging with the platform. The trial offered a good illustration of the importance of financial incentives to actors participating in SRES; and of the impact that institutional constraints can have on outcomes at the operational level.

Furthermore, the modelling exercise offered insight into the pitfalls of digitally-enabled SRES. Examination of the data from the trial revealed that the algorithm of the trading platform itself had been insufficiently monitored by its human managing actor – it was found to have at times broken its own rules. This lends weight to the conclusion in Hansen et al. (2020) that the use of smart technology requires even smarter management if improved outcomes are to be achieved. It also provides an important lesson for governance in that it highlights the issue of potential opportunistic behaviour – trial rules created a principal agent problem by coupling transactions to the platform provider's revenue stream. In the trial, a $0.005 charge was attached to every (P2P) transaction. One error in the trading dynamics was that in some instances, the algorithm matched prosumers with themselves. This meant that these users effectively gave money to themselves (paid themselves for their own electricity), and incurred a transaction charge for this.

Within the scope of the RENeW Nexus trial, the income thus accrued to the platform provider was negligible and unlikely to have motivated the strategic use of such a trading pattern. However, these observations highlight the potential for opportunistic behaviour. The implications are twofold. First, in P2P-based SRES, the platform (or any service) provider's revenue stream should be decoupled from the number of P2P transactions. Second, and related to this, more consideration needs to be given to the question of monitoring, by both practitioners and researchers. Smart technology not only requires careful management, it also requires a more complex monitoring system.

Unravelling this issue further would likely provide material for further research. In keeping with the topic of the current one, it may mean that the polycentric structure of the energy system should relate not only to the governance of the physical infrastructure and associated resource flows, but should extend to the network of digital service providers to enable the notion of mutual monitoring. Just as the flows of energy and finances require the enforcement of rules, the information being generated, exchanged and fed into other processes and systems by digital infrastructure needs to be monitored to prevent system failures. Once again, this suggests that the use of digital technology, irrespective of its virtues, increases the responsibility of the system's human agents.

5.5 Publication V: Rules, interactions, and optimisation

Returning to WGV, the fifth publication explored the issue of joint optimisation – central to the original understanding of sociotechnical systems – in the context of SRES. To gain an integrated understanding of optimisation, it was proposed to focus on interactions rather than individual system components (*e.g.* solar PV). Further, sociotechnical interactions were conceptualised as rules, that is, as the institutional connections between different aspects of the system. The IAD framework was applied to examine the operational rules of the WGV SRES, and to explore their effect on system performance. This also allowed an understanding of how institutional arrangements may support (or inhibit) optimal performance.

With regards to outcomes, the analysis identified the criteria that were most important to stakeholders' evaluations of system performance. Using the language of the IAD framework, suboptimal system performance was indicated by measures of economic and resource efficiency, fiscal and redistributional equity, participation, and accountability. Building on these, main sources of inefficiencies were identified. Importantly, these were found primarily at the collective-choice and constitutional-choice levels, pointing once more to the implications of nested hierarchies.

In designing and implementing the sharing WGV sharing systems, the involved organisations did not consult or communicate sufficiently with the WGV residents, *i.e.* the users (and in some cases, owners) of the systems. This led to an information asymmetry that related not just to technical expertise but also the institutional structure of the systems. Although residents of the Evermore and Gen Y buildings were theoretically assigned the rights to change sharing rules, they were (initially) unable to act on this right because they were unaware they had it.

The problem arose from insufficient coordination at the collective-choice level. The organisations who collectively created the operational sharing rules did not have clearly defined roles and responsibilities. No actor, for example, was explicitly assigned the responsibility of passing the (essential) information of how sharing worked on to the residents. In addition, an incentive mismatch between the actors designing the sharing systems and its users emerged as a source of sub-optimality: commercial interests of involved organisations were at odds with the maximisation of benefits to the residents. This was exacerbated by constitutional-level rules that limited actors' choice of operational rules. For example, state electricity regulations made it difficult for the SHAC developer to offer the desired reductions in electricity prices to their tenants without jeopardising the financial viability of their business.

Based on these findings the paper also offers a more nuanced understanding of the finding from Publication II (Hansen et al., 2020) regarding the importance of the social subsystem to manage technology. Rules for the day-to-day operation of the SRES were largely enforced by technology. The challenge however was not in the technology itself but in the interactions of the participating organisations at the higher collective-choice level.

5.6 Publication VI: A polycentric perspective on impact at scale

While Publication III (Syed et al., 2020) focused in on the technical sub-system, Publication V (Hansen & Morrison, 2020) zoomed out and placed the WGV and RENeW Nexus case studies within a wider polycentric system. As outlined in chapter 1, SRES play an important in role in facilitating a transition to a low carbon energy system. This paper examined how local sustainability initiatives, such as the WGV and RENeW Nexus case studies, relate to wider system change from a polycentric perspective. The two projects were thus conceptualised as collective decision-making entities that may contribute to cumulative impact over time and were analysed by drawing on the presumed benefits of polycentrism (section 2.2.3). This offered an alternative to existing approaches based on the notion of scaling (-up). In particular, it allowed us to take the distributed agency of the different actors involved in the projects into account.

Figure 5.6 shows the identified pathways to impact within a polycentric conceptualisation. Of importance is the distinction between individual and collective direct outcomes and impact (those directly linked to the project) because it indicates the types of incentives motivating actors to participate, and subsequently directing their decision-making. Direct outcomes pertaining to an actor's individual organisation are processed *via* a pathway of divergent learning; for example, deciding whether to pursue a particular technology as a business opportunity. Convergent learning occurs when actors jointly evaluate outcomes for the collective – their understandings of problems and solutions converge. To maximise the potential contributions SRES can make, coordinating knowledge sharing across projects, initiatives and jurisdictions is essential. Coordinating mechanisms are needed to facilitate convergent learning. Because of the distributed agency of actors involved in local sustainability initiatives, pathways to impact are messy, non-linear, and multi-stranded.

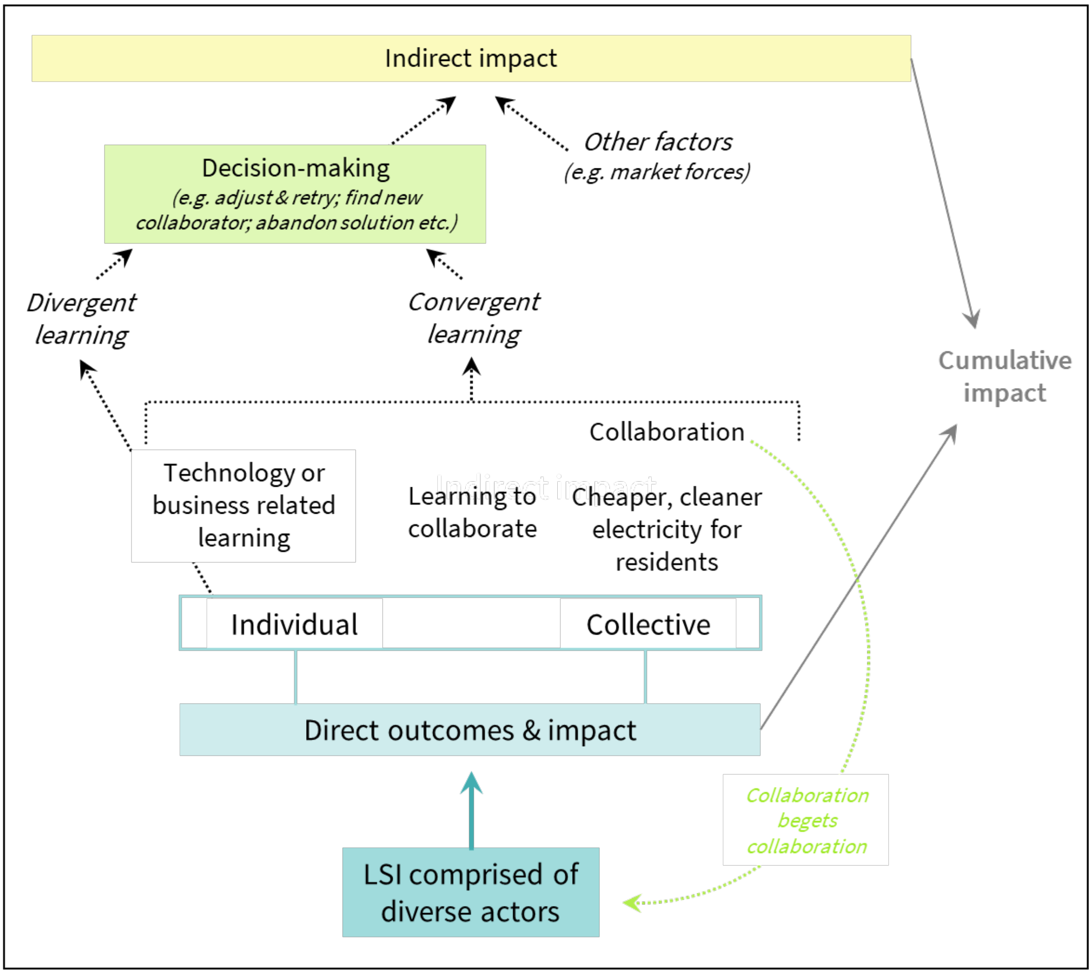


Figure 5.6: Possibilities for impact of local sustainability initiatives from a polycentric perspective. Adapted from Hansen and Morrison (2020).

In the context of this thesis, the analysis indicates that in addition to a system's structure, its purpose may affect what outcomes are generated and how they are evaluated. Experimental system set-ups such as the RENeW Nexus trial may be more concerned with learning experiences and/or commercial opportunities than technical performance as such. The analysis also pointed to another effect of nested hierarchies on system functioning and potential, namely different levels of power or authority different actors may have. The state-wide authority of the utilities involved in the RENeW Nexus Trial meant that the trial could not have happened without their participation (P2P trading across the network is not usually permitted); and that their evaluation of the trial (i.e. evaluation of the viability of P2P trading) will determine whether P2P trading will be used in future in Western Australia.

SIX |

Conceptual foundations for the governance of shared solar energy resources

This chapter builds on the empirical findings discussed in chapter 5 to advance conceptual foundations for the study and governance of SRES. While chapter 5 focused on learnings from the world of action (*cf.* chapter 1), this chapter is concerned with the resulting higher level learnings for the world of theory. It thus combines answers to the two research sub-questions to meet the first aim of the research, to operationalise the notion of sociotechnical dynamics in the context of SRES and to develop the conceptual foundations required to analyse and govern them effectively (*cf.* chapter 1).

In summary, the analyses of the WGV and RENeW Nexus case studies reveal the following implications for the structure and governance of sociotechnical SRES;

- Rules guide the behaviour of both social and technical parts of the system and rules designed to coordinate social interactions may be enforced and executed by technical system components
- Differentiating between physical and virtual spheres of interaction helps make sense of interactions and outcomes
- Recognising the presence and effects of nested hierarchies is critical to understanding structure as well as outcomes
- The motivations and intentions of social actors involved in the design and operation of SRES affect outcomes
- The types of interactions generally used in the existing literature are not sufficiently detailed to describe the structure of SRES

Building on these findings, section 6.1 presents and discusses a proposed structure for sociotechnical SRES. Before concluding the thesis, section 6.2 discusses (in more general terms than the individual papers) what has been learnt with regards to the second aim of the research (*cf.* chapter 1), *i.e.* exploring the applicability of insights from research on governing shared (natural) resources for sociotechnical energy systems.

6.1 Sociotechnical shared renewable energy systems

This research was guided by the principal question of how SRES function from a sociotechnical perspective. Applying a sociotechnical lens means understanding the structure of a system, *i.e.* what its elements are, and how they connect and interact with each other and understanding how this structure affects outcomes. This understanding forms the basis of the other dimension of how the system functions, *viz* system governance. Without a general understanding of the dynamics of a system, we cannot effectively coordinate them. Based on the findings outlined in chapter 5, this section builds on the tenets of systems thinking described in chapter 2 to present a structure of sociotechnical SRES, as illustrated in figure 6.1. Chapter 2 identified three building blocks of systems, *viz* elements, interconnections and function (Meadows, 2008). Elements and interconnections, as the structural aspects of a system, are discussed in section 6.1.1. Function is discussed in section 6.1.4. I will use the terms elements in a general sense to refer to any structural aspect of the system. The term component, in contrast, will be used to refer to a particular type of element. Figure 6.3 and section 6.1.2 further elaborate on this.

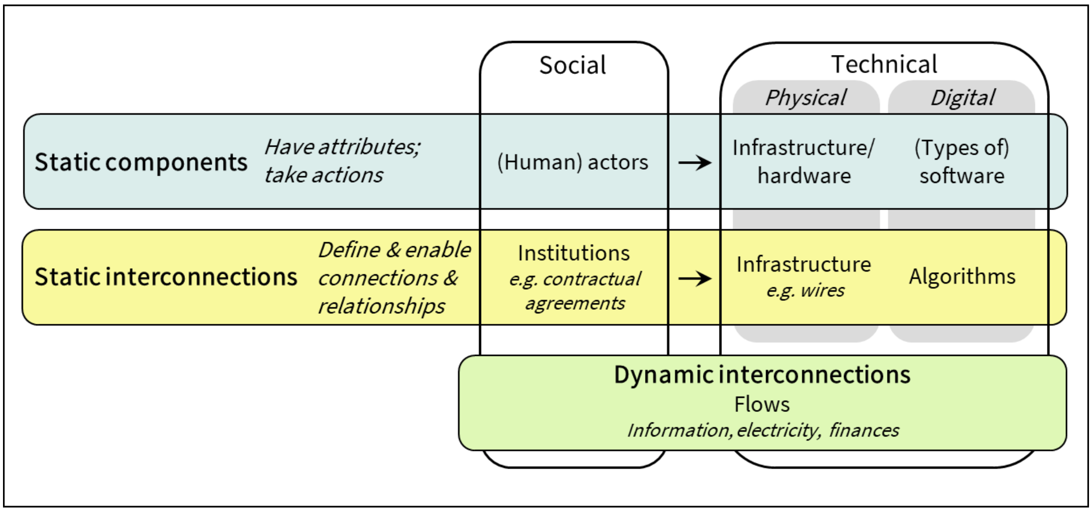


Figure 6.1: The structure of a sociotechnical SRES. The arrows indicate the control that social elements ultimately have over technical ones.

6.1.1 Elements and interconnections

The first building block of a sociotechnical energy system is named static components. They are those elements of a system that are either physically static, that is, cannot change their physical structure, for example, a solar panel or a battery, or that are conceptually or typologically static. In terms of the social subsystem static components refer primarily to the human actors involved in the system. The technical subsystem may feature two different types of static components, *viz* physical and digital. Hardware or a physical infrastructure, such as, for example solar panels, are physical static components. A particular type of software on the other hand may be described as a digital static component.

Static components have attributes and can take action. This is consistent with the approaches outlined in chapter 3 (*e.g.* agent properties in ABM; participants, positions and actions in the IAD framework; second-tier variables in the SES framework). Because of the indirect nature of many of the interactions between social actors and technical system components observed in the case studies, actions are understood primarily as initiators, or triggers, of processes. For example, the RENeW Nexus P2P trading trial was designed with a plan that Fremantle residents would wish to interact with each other to trade solar energy. However, and once residents had set the prices they were willing to buy and sell energy for, trading took place without residents having to do anything (often termed set and forget). Instead, their use of electrical appliances (an action that is not specific to the particular shared energy system) would activate a process of data being recorded and processed, with the initial action (*e.g.* boiling the kettle) being unidentifiable in the eventual record of trades and associated transactions. Another way to think about components as being static is that they have boundaries.

This is in contrast to interconnections. I differentiate between two types of interconnections, static and dynamic. Static interconnections specify the relationships between the components of a system. All SRES require a physical interconnection (*e.g.* wiring) between technical components to transport the generated electricity. In addition, rules, whether informal, *via* contractual agreements, or expressed as algorithms, define how the system's various parts function as a whole. Static interconnections may also be thought of as institutional interconnections. Institutions have been defined as the constraints that humans create to shape their interactions (North, 1990). In the case of sociotechnical systems, these constraints are devised to shape not only human but also human-technical and technical-technical interactions.

Dynamic interconnections, on the other hand, are the flows of resources in the system, that is, flows of energy, data and information transfer, and financial transactions. In the operation of SRES, flows occur primarily *via* a physical intermediary (infrastructure) and/ or virtually. Flows also contain the indicators social actors use to evaluate system outcomes. The case studies analysed in this research demonstrated that financial indicators were a key, explicit evaluative criterion for all organisational actors and system users. Flows of information served a more implicit indicator, expressed in missed communication between various actors, and a lack of knowledge pertaining to system functioning, particularly for the WGV residents.

The proposed structure implies a typology for the technical in sociotechnical energy systems, based on the distinctions between digital and physical, and static and dynamic. This is shown in figure 6.2.

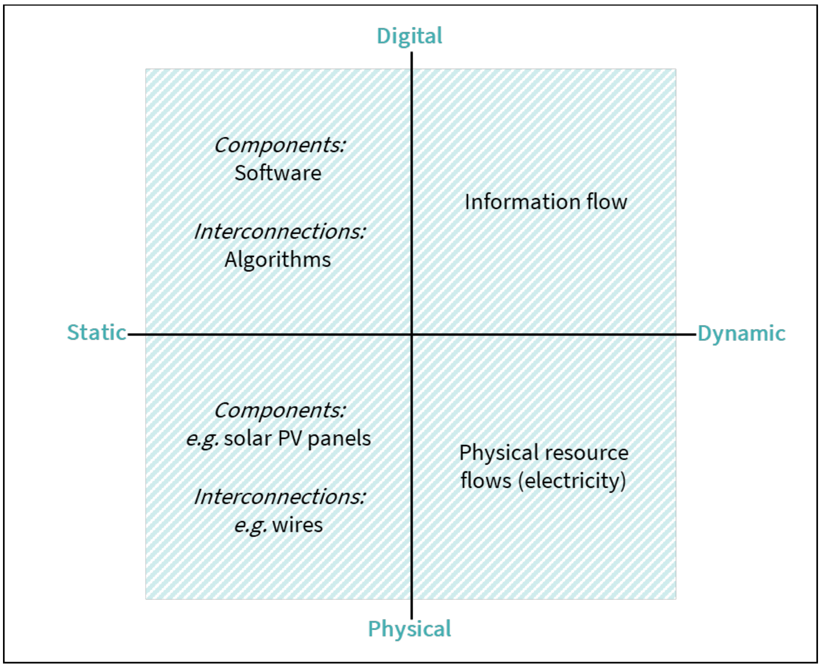


Figure 6.2: Typology of technical elements in sociotechnical SRES. Information flows may be both technical and social.

Although it is tempting to propose this typology as the sociotechnical system's counterpart to the four types of resources distinguished in the analysis of social ecological systems (section 2.2.1) [1], the implications for governance cannot be

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[1] *Resources are differentiated based on the cost of excluding beneficiaries and subtractability of supply, with combinations of these two criteria often shown in the quadrants in Figure 6.2.*

derived in the same manner. What may be suggested based on the evidence discussed in this thesis is merely that the top two quadrants in Figure 6.2 currently require more attention from practitioners and the research community. This research has shown that the digital elements in SRES (static components and interconnections, and dynamic interconnections) are a critical part of functioning of the system that despite their powers are ultimately at the mercy of its human agent.

The proposed structure of sociotechnical SRES offers a starting point for the development of a full framework for sociotechnical energy systems analysis. As it stands, figure 6.1 serves as a conceptual map (or part thereof) that specifies what we need to take into account when describing, communicating and comparing SRES.

6.1.2 A note on interactions

The above structure avoids the use of the term interaction for two reasons. The first reason is that the notion of an interaction suggests the presence of actions as well. However, this research found actions difficult to identify or specify, and that they appeared to relate, for the most part, indirectly to the dynamics of the system. In describing how elements of a system relate to each other, it may be more useful to refer to static and dynamic interconnections. On the other hand, and this is the second reason, the usefulness of the term and concept of interactions may be more useful at higher levels of aggregation, *i.e.* if higher levels are of interest to the analysis. For example, when planning the design of a novel SRES, we may highlight the need to specify types of interactions such as monitoring or information sharing processes. The result of such deliberation, however, should be a more nuanced description of the rules and physical connectors that shape them.

As such, the term interaction may be reserved for situations in which we cannot specify the structure of a system. For example, when conceptualising a system as sociotechnical in an article, we may start the investigation with a broad understanding of interactions between human actors, and digital and physical technical components (*i.e.,* static components). As we progress the analysis and our understanding, we may be able to specify the static and dynamic interconnections in the system. This hierarchy of systems terminology is illustrated in figure 6.3.

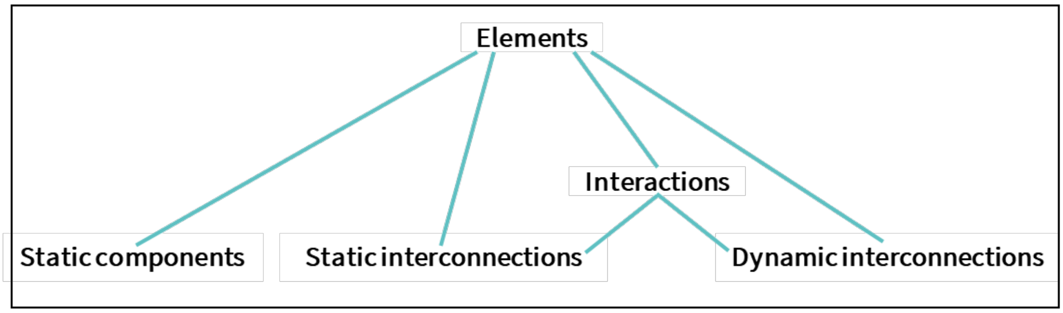

Figure 6.3: A proposed hierarchy of terminology to discuss SRES.

6.1.3 The role of nested hierarchies in defining structures and understanding outcomes

This leads us to the role of nested hierarchies in dealing with sociotechnical SRES. The main argument this thesis makes in this regard is that the presence and effects of nested hierarchies has thus far been under-appreciated in energy studies. Hierarchies are important from both a practical and theoretical point of view. Practically, in terms of both governance and engineering, dealing with a regional distribution network *versus* an embedded microgrid makes a difference. In a theoretical analysis, consideration of the higher and lower levels that the system of interest influences and is influenced by is likely to yield a more nuanced understanding. An illustration of this, for instance, is the effect of collective-choice processes on the functioning of the operational rule system (Publication IV).

This is in line with the discussion of hierarchies in chapter 2 (section 2.1.1). As expressed by the principle of excluded reductionism, a system can never be described completely using a single level of a hierarchy (Ropohl, 1999). The implication for the study of sociotechnical SRES is that identifying where one's research question or problem is situated at the beginning of the analysis may aid in recognising what other elements or levels of the system may have to be considered. Further development of a framework for sociotechnical SRES analysis should include the integration of the above structure with the principle (and effects) of nested hierarchies.

6.1.4 System function

As outlined in chapter 2, theory suggests that STS are comprised of elements, interconnections and function (*cf.* Meadows, 2008). Relating STS theory to SRES, system function may be understood as the purpose of the system, expressed as the outcomes it is designed to generate. Adding to the above propositions, the governance of SRES will typically be guided by social static components and physical static components and interconnections. While human agents and their attributes and decision-making determine the function of the system, their scope of possibilities may be delimited by physical technical infrastructure, for example, the capacity of generation sources. Digital and social static interconnections and digital static components are then selected to facilitate the specified outcomes.

Applying this logic to the WGV case study indicates why SRES that test new technologies may become problematic. A major source of inefficiency and suboptimal outcomes at WGV was the discrepancy between the stated objectives of actors and their actions. The organisations who implemented the systems effectively tested a technology to achieve equitable, low-cost, clean electricity for residents, instead of either testing a technology to assess its potential, or provide equitable, low-cost and clean electricity. The difference is in the outcomes for WGV residents. Because the means of achieving the desired outcome of equitable, clean electricity were selected without fully understanding how they worked, outcomes were not achieved. In contrast to this, the RENeW Nexus Trial had the explicit function of testing P2P trading. While the results of trading were not as financially beneficial as hoped, the SRES fulfilled its function of providing electricity system stakeholders with an improved understanding of P2P trading.

The example also offers a continuation into another aspect of system function, namely the relationship between those defining the desired outcomes, and those experiencing them, *i.e.* resource users. In line with Ostrom's design principles, the WGV case study suggests that including resource users in decision-making processes will likely improve system outcomes. However, a difference for social-ecological resources may lie in the heightened need for expert knowledge in designing, implementing and operating SRES. An awareness of the implications of different incentive structures is key to mitigating the collaboration of resource users and experts in system design. Contractual agreements for the provision of expert knowledge, for example, may help reduce the risk of vested interests and suboptimal results.

6.2 A return to common(s) foundations

Commenting on the potential of adapting the SES framework to social-ecological-technical systems (SETS), McGinnis and Ostrom (2014) speculated that the technical expertise required to construct and maintain them may imply a separation between the different types of actors that differentiate them from SES. While it is debateable whether the sharing of SES in today's world requires expert knowledge (I would argue that they do), the preceding discussion confirms that the differentiation between experts and users was a sensible suggestion.

Irrespective of whether this makes SRES different from other common resources, it does not affect the applicability of the Ostrom frameworks to STS. However, it likely has implications for the applicability and comparability of generalised findings that the literature on common resource governance offers. The SES, and particularly the IAD framework set out the basic structures affecting interdependent situations but do not define the specific attributes of, or relationships between actors. The relative importance of different types of actors to a particular situation is up to the analyst to identify and account for. However, given that the involvement of experts was of less importance to the situations studied by the Ostrom Workshop, its effect may not be adequately accounted for in their conclusions. An example of such conclusions are the design principles that were found to increase the likelihood of resource sustainability.

For the community of energy scholars interested in the application of Ostrom's legacy to energy systems, it simply means that we need to be mindful of the cases, reasoning or theory that underpin the concepts and approaches we wish to apply. While there appear to be many parallels between SES and SETS, including in terms of the design principles, the value of merging the two fields of research will be greatest if we start at the beginning. What I mean by mindful is for example the use of the concept of common-pool resources. The reason for the extensive discussions of CPRs was the particular problem of the collective action they create, and the implications of this for their sustainability. All too often however the concept seems to be used as a generic term to refer to the overall body of literature linked to the Ostrom Workshop.

Furthermore, the analyses undertaken as part of this thesis suggest firstly, that distributed renewable energy resources shared by a group of users do not exhibit the characteristics that make traditional CPRs problematic. Because of the need for technical, physical infrastructure to both establish and maintain access to the renewable source, shared energy systems have high barriers to access. Whether the supply of energy may be considered subtractable depends on the individual set-up. Generally speaking however, flows of electricity tend to be decoupled from financial ones (as in WGV) and (at least in grid-connected systems) the control users have over where their electricity comes from, at a given point in time, is limited. Secondly, as explained in the previous section, it may be the function of a SRES, rather than the resource, that provides the clues for their governance.

The implication is that further investigations into the applicability of the work of the Ostrom workshop to SRES should consider the incentives of actors participating in them because the nature of the resources they are dealing with is different from those previously studied. The problem(s) actors seek to solve by establishing SRES do not concern the potential depletion of that same resource. Nevertheless, as this thesis has suggested, by collaborating to establish and operate a SRES, actors realise the improved outcomes for all associated with collective *versus* individual action. As such, we should not assume that the same incentive structures theorised and employed in research on social-ecological resources necessarily apply to sociotechnical ones as well. Translating the knowledge from SES research to STS requires a re-examination of problem and incentive structures.

With regards to the SES and IAD frameworks, their application in this research is an insufficient basis for an in-depth discussion of potential adaptations. I will only comment that one useful adaptation for the analysis of SRES may be to simply consider actors as agents and allow them to be technical as well. Properties such as the generation capacity of the resource system, for example, would then not be a property of the resource system (as in the SES framework) but a constraint on the technical choice of actions by agents, imposed by collective-level decision-making. This may help shift the emphasis to the role and importance of human (social) agents in managing technology.

6.3 Conclusion

6.3.1 Limitations and recommendations for future research

The research discussed in this thesis is based on data from two case studies and as such shares the challenge of generalisability inherent to all case study research (Yin, 2009, 2010). The most important limitation of the research in this regard is the particular type of SRES studied. As outlined in the introductory chapter, SRES may vary widely with respect to technologies used, levels of community participation, geographic scope, and primary purpose, in addition, of course, to their regulatory environments. As such, the findings derived from the WGV and RENeW Nexus projects may not reflect the entire spectrum of possible SRES configurations. That said, the principle concern of the thesis was about uncovering the underlying structural elements of the systems rather than with their contextual embeddedness. The findings presented in this chapter are not based exclusively on the empirical evidence but on empirical evidence tested and compared with theory.

Furthermore, the aggregate findings are based on a mix of qualitative and quantitative data, and multiple analytical approaches which adds to the validity of the results (Sovacool et al., 2018). On the other hand, the application of the SES and IAD framework (in addition to polycentrism) means that the thesis provides only limited insight regarding the applicability of the approaches of the Ostrom Workshop to energy studies. With the aim of developing conceptual foundations, however, the use of various approaches was appropriate. While each approach offered a slightly different lens, their common theoretical foundations ensured the coherence of the emerging bigger picture.

The empirical findings and conceptual propositions highlight a number of avenues for future research. To begin with, more insight into collaborative decision-making in the specific context of SRES would be useful in strengthening the explanatory theoretical basis of SRES. By applying the SES and IAD frameworks, the thesis indirectly built on the theories of behavioural rational choice and collective action but it did not examine or evaluate them separately. To continue building on the congruence of sociotechnical systems and common resource governance research, an explicit integration of these theories into energy research would be useful.

One particular dynamic worth further investigation is the need to reconcile expert knowledge with the involvement of commercial enterprises, and the needs of resource users which this research has highlighted. Moreover, testing the viability of the proposed structure of sociotechnical SRES for different types of shared configurations deserves additional attention. Particularly interesting could be an examination of a SRES that is more community-driven to assess whether, or how, decision-making processes and their effects differ.

There may also be the potential to identify general patterns of organisational structure and performance for SRES. For example, one might hypothesise that if the actors establishing a shared system are the resource users themselves, the technical system elements will be less complex. In line with the argument of system function made in section 6.1.4, resource users will tend to choose the technologies that fulfil system function most efficiently. On the other hand, systems involving advanced, innovative ICT will be more likely to be overseen by commercial and or government actors. The benefit of identifying such patterns is that they would facilitate the formulation of recommendations for policy-making. The strategies for optimising the performance of different SRES will vary substantially.

6.3.2 Contributions of the thesis to energy research

This thesis has offered new insight into the sociotechnical structure of SRES and its relation to effective governance. In line with the aims of the research, the notion of sociotechnical interactions was operationalised as rules that guide the behaviour of social and technical agents which informed empirical data collection and analysis. This conceptualisation proved a useful approach to understand how SRES function as a whole and to enable the use of a variety of analytical tools. Highlighting the ontological principles that inform the thinking in sociotechnical systems and common resource governance research may in itself be a useful contribution. Agents and rules are a practical heuristic to address questions of structure and governance in sociotechnical SRES because it mimics the decision-making (behaviour) of technologies, allowing human and technical agents to be described in the same language. This could be especially helpful in making the virtual technical element more visible for analysts.

Building on the complementarity of sociotechnical systems theory and the theoretical underpinnings of common resource governance, this thesis developed a set of propositions as conceptual foundations for the study and governance of SRES. The thesis contributes to the advancement of interdisciplinary energy research by offering the research community a conceptual language that allows for an integrated examination of social and technical system elements, and may serve as a basis for the development of robust theoretical foundations. This is meant as a starting point to be tested, adapted and expanded. At the very least, the proposed conceptual foundations may help inspire others to reflect on, and engage more critically with terminology and concepts. In advancing the field of sociotechnical energy studies, the validity and applicability of describing energy systems as sociotechnical will depend to a large extent on whether we can foster a better appreciation of conceptual rigour in the academic community. This is particularly pertinent given the increasing interdisciplinarity in our efforts to address increasingly complex challenges.

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Publications

Publication I

Published/ Peer-reviewed journal article

Hansen, P., Liu, X., & Morrison, G. M. (2019). Agent-based modelling and socio-technical energy transitions: A systematic literature review. Energy Research & Social Science, 49, 41-52.

Energy Research & Social Science 49 (2019) 41–52

Contents lists available at ScienceDirect

Energy Research & Social Science

journal homepage: www.elsevier.com/locate/erss

Review

Agent-based modelling and socio-technical energy transitions: A systematic literature review

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ARTICLE INFO

Keywords:
Agent-based modelling
Transition
Socio-technical
Systematic literature review
Multi-level perspective

ABSTRACT

Agent-based modelling has the potential to provide insight into complex energy transition dynamics. Despite a recent emphasis of research on agent-based modelling and on energy transitions, an overview of how the methodology may be of value to understanding transition processes is still missing from the literature. This systematic review evaluates the potential of agent-based modelling to understanding energy transitions from a social-scientific perspective, based on a set of 62 articles. Six topic areas were identified, addressing different components of the energy system: Electricity Market, Consumption Dynamics/ Consumer Behaviour, Policy and Planning, New Technologies/ Innovation, Energy System, Transitions. Distribution of articles across topic areas was indicative of a continuing interest in electricity market related enquiries, and an increasing number of studies in the realm of policy and planning. Based on the relevance of energy transition specific complexities to the choice of ABM as a methodology, four complexity categories (1–4) were identified. Indicating the degree of association between the complexity of energy transitions and ABM's ability to address these, the categorisation revealed that 35 of the 62 studies directly linked the choice of ABM to energy transition complexities (complexity category 1) or were set in the context of energy transitions (complexity category 2). The review further showed that the greatest potential contribution of ABM to energy transition studies lies in its practical application to decision-making in policy and planning. More interdisciplinary collaboration in model development is recommended to address the discrepancy between the relevance of social factors to modelling energy transitions and the ability of the social sciences to make effective use of ABM.

1. Introduction

The notion of energy transitions has become increasingly relevant to policy-makers and academics alike [1], as efforts to reconcile the energy trilemma of affordability, security and environmental sustainability [2,3] have gained momentum over recent years [4]. The importance of technological innovation, and changes to the way energy is utilized, are common themes in the discourse on energy transitions [3] and is most evident in the discussion around renewable sources of energy. Current changes to social aspects of the energy system have also been observed, and include; increasing numbers and variety of stakeholders involved in the energy system [5], the importance of communities in facilitating the process of decentralisation [6], a general growth trend in community-based (energy) strategies [7]. The energy transition is defined here as the agglomeration of these (and related) concurrent trends.

In social scientific transitions research this occurrence of diverse changes to different parts of the energy system has been conceptualised as socio-technical dynamics. One theoretical approach that has been extensively applied to the study of transitions, especially that of energy systems [8], and is well-established in the transitions research community [9], is the multi-level perspective, or MLP [1,10]. The MLP structures the energy system into a multi-level nested hierarchy, in which an external landscape (macro-level), incumbent regimes (meso-level), and technological niches (micro-level) interact [3,4,8] (cf. Fig. 1). As the macro-level encompasses a multitude of possible regimes, which in turn may contain multiple niches, the system is described as a nested hierarchy.

Transitions occur when processes within and between all these levels align [11]. In line with this multi-level conceptualisation, the

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Abbreviations: ABM, agent-based model or agent-based modelling; MLP, multi-level perspective; SLR, systematic literature review; TPB, theory of planned behaviour

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https://doi.org/10.1016/j.erss.2018.10.021
Received 15 June 2018; Received in revised form 19 October 2018; Accepted 24 October 2018

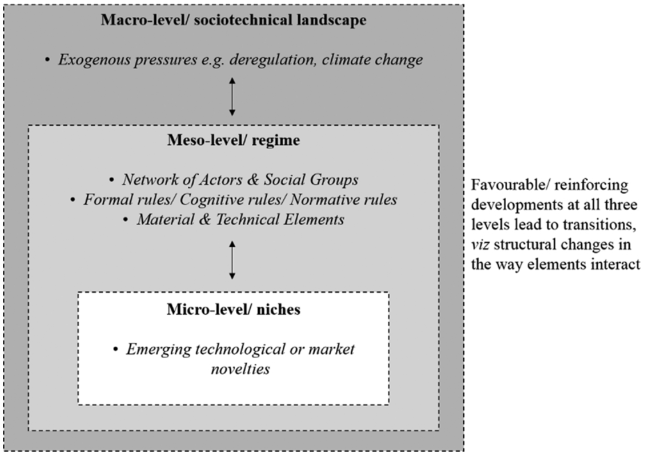

Fig. 1. Conceptualisation of the energy system following the Multi-level Perspective (adapted from [1,10]). As the three levels interact and influence each other, the energy system, in the present study, is understood as the whole of the three levels. This diagram is simplified in that it shows only one regime. However, multiple regimes can exist within the same landscape level.

energy system is understood here as the whole of all levels and their (relevant) constituent components which include networks of social groups and actors (such as household users and utilities); rules; technical and material elements (such as grid infrastructure); external pressures such as climate change [1,8,10]; and technological niches.

The interactions of technological and social system components, influenced by network and governance structures [2], has led to an increasing degree of complexity [5,11] in the energy system. At the same time, solutions to ensuring the sustainability of the energy system need to be multidimensional, involving changes in social, economic, institutional, political and technical spheres [12]. With a rising interest in understanding the dynamics underlying transitions [1] this complexity creates a need for research methods that can account for an individual phenomenon (*e.g.* a social trend in the energy system) as well as emergent phenomena arising from their interplay [2]. Traditionally, transition studies have largely relied on case study analyses [13,14]. Techno-economic approaches have also been employed in view of managing transitions [11]. While valuable insights have been gained from these approaches they are not suitable to addressing the dynamics between micro-level behaviour and macro-level emergence. Especially in techno-economic approaches, the multitude of actors involved in the energy system and its transition, and their decision-making cannot adequately be accounted for [11]. There is thus a need for research methodologies that can address the (increasing) complexity of confluent technical and social phenomena, diverse social actors, and nonlinearity [11].

Agent-based (ABM) modelling is a methodological approach which has the potential to deal with this complexity. As a computational simulation technique, ABM enables the modelling of individual, heterogeneous, autonomous agents – or, decision-making entities [15]. In addition to heterogeneity, a distinct feature of agent-based models is the ability to account for emergent patterns and self-organisation through simulation [16]. In short, ABM allows the modeller to observe the effect of interactions between agents whose behaviour is described (encoded) in simple rules [17]. With its origins in the study of complex adaptive systems, ABM is increasingly being recognised as a suitable tool for studying complex societal challenges such as energy transitions and has been applied across a wide range of academic and professional disciplines [16,17]. An insightful discussion on the synergies between energy studies and complex systems is provided in Bale, Varga and Foxon [2]. The application of ABM to the study of socio-technical systems is particularly promising, as it allows for the co-evolution of technical and social elements of a system, and the results of their interactions, to be modelled [7,18].

In the context of energy transitions, the specification of social and technical elements in a model, as well as the way they interact, may vary greatly. One may for example imagine individual households influencing each other's opinions or attitudes about a certain technology; or, in contrast, government actors and private firms making investment decisions depending on other actors' past performance. Bale, Varga and Foxon [2] referred to five co-evolving, (potentially) interacting systems as central to analysing complex energy transition processes; namely technologies, institutions (e.g. rule systems related to policy or investment), business strategies, user practices, and ecosystems (factors such as carbon emissions). As such, one may expect ABMs in the context of energy transitions to focus on any combination of interacting entities from these categories. Holtz [14] reviewed a selection of models in the context of transitions. In those employing ABM, the identified main model elements ranged from consumers, innovating firms, a product market and demand side networks; to power producers, physical assets, electricity markets; and households, their social networks and a variety of technology types [14]. Further illustrating the diversity of possibilities afforded by ABM, Heath, Hill and Ciarallo [19] conducted a comprehensive survey of ABM practices. Based on a model's purpose, they differentiated between generators (in which little is known about the system and the purpose is to generate hypotheses and theories about the real system), mediators (where the simulation provides insight into the real system) and predictors (the system is well understood) finding that generators and mediators were most commonly used.

With regards to the social sciences, the potential relevance of ABM is commonly linked to the unsuitability of other modelling approaches to solving social scientific research problems and the issue of emergence [20]. In addition, being based on (individual) agents may serve as a natural ontology for social sciences and could therefore offer a powerful formalism [20], and aid in the formal presentation of theories [14,21]. In the context of transitions research, Hoekstra, Steinbuch and Verbong [22] compared ABM with a range of other computational approaches and found that the agent-based paradigm was the only one able to model emergence, agent interactions, as well as agent learning. ABM (in contrast to equilibrium models) can represent complex (adaptive) systems, and can model pathways in transitions [22]. Similarly, Ponta, Raberto, Teglio and Cincotti [23] found that ABM may be an appropriate approach to modelling transitions (to low carbon economies) because it allows for such transitions to be studied as dynamic paths emerging from the interactions of heterogeneous agents – rather than equilibrium suboptimal solutions. Feedback mechanisms are another feature of transitions that ABMs can incorporate [24].

Discussing the interface of (computational) modelling and societal transitions, Squazzoni [21] concluded that the ideal way forward for transition studies would be "to strengthen formalization, modeling, theoretical parsimony and generalization, thereby avoiding the risk of formulating the societal transition models on weak social science theories" – an important implication of this is the *need* for interdisciplinary collaboration [21]. At the same time, others have pointed to the *potential* of ABM to be used in multidisciplinary collaborations [22]. Beyond the realm of academia, there have also been calls to enable participation of diverse actors in model development given the importance of establishing shared understandings of complexity [25]. Against this backdrop, the present study systematically reviews the literature at the interface of agent-based modelling and energy studies in view of understanding the methodology's past and possible future contribution to socio-technical energy transition research. While both fields of research have gained traction over recent years, a current systematic literature review (SLR) at the interface is missing from the literature. Holtz [14] noted that a lack of definitional clarity in transition research makes it difficult to discern the kinds of models that should be included in a review. In the present study, a systematic procedure is applied to identify literature at the interface of energy studies and ABM. To address the definitional challenge, a multi-level perspective is adopted to evaluate the contributions of studies to the overarching theme of energy transitions in Section 3.3. The complexities of energy transitions outlined in Section 1 are then compared with the complexities being addressed in the examined studies. Section 3.4 provides an evaluation of the (potential) contribution of ABM to the (social scientific) study of energy transitions.

2. Methods

A SLR procedure was applied to identify and select a relevant and representative set of literature to answer the research question and its sub-questions [26]:

> Research Question: How has ABM contributed to an understanding of energy transitions (as socio-technical processes)?
> Sub-Question 1: How is the choice of ABM linked to the complexities of the energy transition?
> Sub-Question 2: What is the potential of ABM to advance the social scientific discourse on energy transitions?

In line with the characteristics of a SLR, the procedure was designed to be replicable [27] and to reduce bias [28]. To meet these criteria, the first step was to construct a Boolean expression (search string) and apply it to three different online databases – ProQuest, Scopus, and GoogleScholar. Scopus and ProQuest were chosen as they are comprehensive and multidisciplinary databases. GoogleScholar was added as a control to potentially pick up any important publications missed by the other two databases. It was however shown to produce no additional articles and all selected articles were revealed through the ProQuest and/or Scopus searches.

As application of the Boolean expression to anywhere in the texts yielded an unfeasible number of articles (> 2000 articles per database), search queries were refined to apply the search to titles only (for GoogleScholar, Publish or Perish software [29] was used to run the query). The results of this are presented under Step 1 in Table 1. With the assumption that articles containing the chosen key terms in the title should be largely relevant to the topic under investigation, results from this query were then selected for further evaluation. At the same time, this provided 35, 142 and 54 relevant articles to be evaluated for the three database searches (see Table 1). This data was then exported to Excel to allow further analysis.

The key data points exported for each database included the title, author, date of publication, source, and URL. To clean the dataset, duplicates were eliminated, leaving a total of 191 publications. As scanning through the data showed inconsistencies with the original search query, Step 4 consisted of searching all titles for the terms energy and electricity. Another 23 results were then eliminated for failure to meet the original criterion of containing either of the terms in the title. As an emphasis was on quality, any result that was not a journal article (*e.g.* lecture notes, dissertations, conference proceedings) was also excluded. As an exception, three conference papers in the field of computer sciences were included because conference proceedings in this discipline are often peer reviewed and considered important in this rapidly changing field. Based on a manual review of the remaining titles, publications that could positively be identified as being off-topic, or were not written in English, were excluded. Those that could not be accessed due to paywalls were also eliminated. The dataset comprised of 53 articles.

To provide a full account for 2017, the search query was re-run in ProQuest and Scopus at the beginning of 2018. Applying the same criteria as above, an additional 8 journal articles were added to the selected set. Two more conference papers were also included based on an evaluation of titles and abstracts with regards to their potential usefulness to the study. The final dataset analysed in the following sections comprised of 62 scientific papers.

To ensure that the applied search method and the chosen set of articles is broadly representative of the field, an evaluation of related search queries was conducted. The results of this are provided in Appendix A. The assessment showed that despite the chosen search string's restrictiveness and the rigorous filtering, the literature discussed here is a good sample of the field. To the best of the authors' knowledge, no particular area or type of model was categorically excluded by the systematic method.

Table 1
Systematic process of selecting articles for analysis.

Step 1	Boolean expression: *("agent-based model*" OR "agent-based simulation") AND (energy OR electricity)* Directly applied to ProQuest and Scopus, and to GoogleScholar through Publish or Perish [29]			
Number of Results	Results in:	ProQuest	Scopus	GoogleScholar
	Anywhere	2,581	6,081	17,400
	Abstract only	393	662	/
	Title only	41	142	54
Step 2	*In title only* results selected for further evaluation and exported to Excel			
Step 3	Duplicates eliminated			
Number of Results	191			
Step 4	Filter 1: Titles searched for terms energy and electricity as verification of the Boolean expression.			
Number of Results	168			
Step 5	Filter 2: Include only journal articles In addition, include select conference papers and proceedings: most cited conference paper from computer sciences (1 article), (2 articles) most recent conference papers from computer sciences			
Number of Results	65			
Step 6	Filter 3: Exclude results that are: off-topic; unavailable for download due to paywalls or similar; published in languages other than English			
Number of Results	53 *(all selected articles appeared in the ProQuest and/or Scopus searches, meaning there was no added benefit of using GoogleScholar)*			
Step 7	At the beginning of 2018, the search string was re-applied to the Scopus and ProQuest databases to cover the full year 2017. Results were narrowed down to 8 journal articles and 14 conference papers and proceedings that had not previously been identified. The 8 journal articles were added to the selection. Two conference papers were selected for inclusion based on an evaluation of titles and abstracts with regards to their potential usefulness to the study.			
Number of results	62			

3. Results and discussion

3.1. Temporal distribution of studies

Fig. 2 shows the annual numerical article trend for the set of 62 studies. The graph suggests a clear growth trend over the past 17 years. Only 2 articles containing the key words agent-based modelling and energy or electricity in the title were published prior to 2007. Growth in the number of articles published was steady from 2014–17 (Fig. 2). More than a quarter of articles in the set were published in 2017.

This suggests an increased interest of applying ABM in the context of the transition to renewable energy in the past decade. This trend has been observed elsewhere as well (for example, see Macal [30]). A discussion of the possible drivers of the increasing use of ABM -beyond the growing recognition of limitations of traditional modelling approaches to the complexity of current research problems- is beyond the scope of this review.

3.2. Journal article sources

The identified articles were published in 43 different sources (including conferences). The most frequently occurring journals were Applied Energy (6 articles) and Energy Policy (6 articles). This was followed by 3 publications in Energy Conversion and Management, as well as Energy. All other sources (including conferences) had a

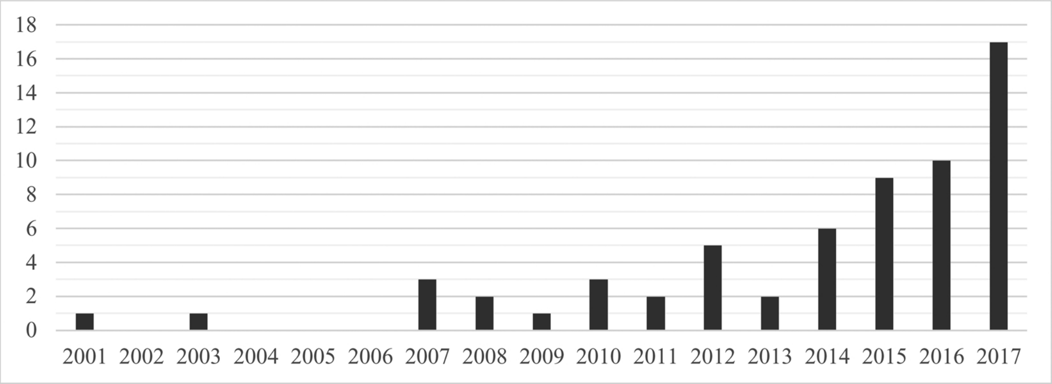

Fig. 2. Number of identified articles per year of publication.

maximum of 2 publications (34 had only 1).

While most of the journals that yielded more than one result have a technical focus, one of the two most frequently occurring sources was Energy Policy which focuses on the economic, social, planning and environmental dimensions of policy implications related to the supply and use of energy [31]. This large variety of sources indicates a wide range of areas of applicability. An interesting observation is an increase of publications in Energy Policy for the year 2017 – potentially pointing to ABM finding increased application in the realm of energy policy. Table 2 illustrates, for the nine sources that appeared more than once, the number of publications in each journal, and the years and count(s) of publications (for example, in the identified set of literature, four articles were published in Energy Policy in 2017).

3.3. Thematic relevance to (social scientific) transition research

The 62 identified articles were broadly categorised into 6 topic areas; Electricity Market (25), Consumption Dynamics/ Consumer Behaviour (12), Policy and Planning (9), New Technologies/ Innovation (7), Energy System (6), Transitions (3). To reduce bias, rather than superimposing pre-determined features of energy transitions onto the set of articles, the categories emerged after reading the selected articles. They represent thematic patterns observed independently of, and prior to applying any analytical lens. The topic areas therefore do not strictly follow the same terminology or interpretation as the definition of the energy system given in Section 1 (Fig. 1).

The set of 62 articles contained five review articles, four of which were placed in the topic area Electricity Markets. Interestingly, two of these were published in 2007 [32,33] – meaning they cover a period excluded by the systematic procedure applied in the present study. A control search run (see Appendix A) to verify the representativeness of the search results, and scanning of the reference lists in these two earlier reviews, suggests a combination of the term usage and spelling, and a focus on market-centric studies, to be responsible for the difference. Both lists of references also include a number of non-journal sources (*e.g.* technical reports) which were largely excluded here. In Sensfuß, Genoese, Ragwitz and Möst [33] the explicit purpose was to review a novel field of research. The premise for both review articles published in 2007 was similar to the one this study is based on: ABM is a promising tool to study the complex (and novel) changes to the electricity sector [32,33]. In contrast to the identified review articles which focused on particular components of the energy system, the present discourse considers the transition process itself (as defined in Section 1) and draws a map of how the energy transition has been approached with ABM.

3.3.1. Thematic analysis from a multi-level perspective of energy transitions

Given the popularity of the MLP in socio-technical transitions research, it was explored how the identified literature addresses energy transitions through this lens. The value of this is twofold: Firstly, energy transition is not a well-defined term [14]. The multitude of actors with potential stakes in it means that definitions vary. In the field of sustainability studies, the MLP is a well-established framework offering conceptual boundaries. An explorative application of the MLP to the identified literature may be valuable to scholars conceiving energy transitions as socio-technical processes. Secondly, a core premise of the MLP is that of interactions between different system elements, a concept for which ABM could provide a natural ontology. As the identified topic areas exhibit a certain degree of overlap with energy system components defined in the MLP (cf. Fig. 1), an exploration of themes in the literature through this lens offers a relational framework.

Technological innovations have the potential to affect systemic change when windows of opportunity open up [34] through tensions or mismatches between regime level components and/or the landscape level. These may be caused by factors such as changes to the landscape level (*e.g.* the effects of climate change); technical problems in the regime, leading actors to explore other options; changing user preferences; or the strategic behaviour of firms, where new technologies may provide a competitive advantage [34]. The niche level may be represented by the topic area New Technologies/ Innovation. Two

Table 2
Number of selected articles per journal and year, showing only journals that appeared more than once. For example, the selected set of literature contains a total of 2 articles published in Annals of Operations Research – one of these was published in 2003, the other in 2016.

Name of Publication/ Year of Publication	**2003**	**2009**	**2010**	**2012**	**2014**	**2015**	**2016**	**2017**	*Total*
Annals of Operations Research	1						1		*2*
Applied Energy				1	2	1		2	*6*
Energy		1				1		1	*3*
Energy and Buildings							2		*2*
Energy Conversion and Management					1	2			*3*
Energy Policy			1		1			4	*6*
Environmental Modelling and Software						1		1	*2*
IEEE Transactions on Power Systems						1	1		*2*
Journal of Computing in Civil Engineering				1				1	*2*

approaches to studying new technologies were identified in the selected literature: studies focused either on the techno-economic implications of a particular technology, such as storage [35], or electric vehicles [36]; or on processes of change and innovation adoption [37,38]. Ma and Nakamori [38] studied how technological change is treated in three different types of models (ABM being one of them). Their conclusions point to the ease of including adaptive behaviour, and especially adaptive decision-making behaviour, in ABMs. The appropriateness of ABM as opposed to traditional optimization models, however, depends on the decision-making context: ABM is concerned with possible future scenarios based on a given situation and set of assumptions (bottom-up); while traditional optimization models start with an end goal or objective (top-down) [38]. This suggests, firstly, that ABM is an appropriate technique for modelling energy transitions, given the definition applied here for them; but also, secondly, that in modelling energy transitions, the purpose of modelling may be more important than the applied definition of transitions. If the purpose is to develop an energy system towards a certain objective in a controlled manner, the study [38] suggested that optimization models may be advantageous. Similarly based on observations of change dynamics, Hodge, Aydogan-Cremaschi [39] investigated the mechanisms that cause change in energy systems, and how to integrate new technologies into the existing system. By representing each type of energy system entity (such as consumers, raw materials, researchers) as an agent, their framework can easily be translated into the MLP conceptualisation and may be understood as covering interactions between niche and regime level.

In Rai and Robinson [37] the adoption of solar PV was explored. The authors' primary concern however was with two methodological challenges in ABM, namely a lack of consistency in the theoretical and empirical foundations of models. This represents a valuable contribution to the methodological foundations necessary for any models. The study also presented a new approach for producing population-wide estimates for agent attitudes that is general in nature and may be used by other applications (ibid.). In another study of solar PV adoption, Robinson and Rai [40] investigated the effect of using empirical data and integrating behavioural, social and economic factors on model outcomes. Their findings suggested that behavioural and social factors were critical in accurately predicting demographic and spatial patterns; whereas focusing only on the financial factor predicted rate and scale well but not spatial and demographic patterns (ibid.). Overall, the inclusion of all elements let to better fit with empirical data *i.e.* increased the validity of the model [40]. As the study aimed for better prediction of the temporal and spatial patters of solar PV adoption, it implicitly pointed to a significant shortcoming of the MLP: that it largely disregards the spatial dimension of transitions and only vaguely touches on the temporal (transitions typically occur over long periods of time).

In addition to being interested in technology adoption, the above studies could also be conceptualised as micro-level by virtue of focusing on individual (household) level agents. Theory of planned behaviour (TPB) was used by various studies to define agent behaviour [37,40–42]. Zhang and Nuttall [42] compared TPB with four other social psychological theories (technology acceptance model, model of goal-directed behaviour, social cognitive theory, motivational model) in terms of their suitability for formalising agents. Based on this comparison they chose TPB because of the relative ease of translating it into code, and because is stresses psychological, sociological as well as environmental factors in agents' decision-making process [42]. The authors concluded that their model pointed to the benefits of directly integrating social psychological theory (ibid.). As the study [42] focused on the effect of government policy promoting smart metering on the diffusion of the technology, it falls between micro- and meso-level. While the model included micro-level individuals and an interest in technology diffusion, its overarching aim was to evaluate the effectiveness of government policy (ibid.). Interested in understanding how smart metering systems may impact on electricity stakeholders, Vasiljevska, Douw, Mengolini and Nikolic [43] concluded that a good policy for the promotion of smart metering technology should focus on passing information on advantages and disadvantages of the technology on to consumers so as to raise comfort and lower concerns.

The effect of policy interventions on the upscaling of niche innovations is a central concern in the Policy and Planning topic area (other studies focus on technical elements *e.g.* [44,45]). Busch, Roelich, Bale and Knoeri [46] investigated institutional barriers (and the removal thereof) to the upscaling of local energy infrastructure. Their study therefore represents a link between the niche level and the element of (formal) rules in the regime. Chappin, de Vries, Richstein, Bhagwat, Iychettira and Khan [47] found that given complexities such as cross-policy effects, differences in actor behaviour, imperfect foresight and path dependence, determining the side effects that policy interventions might have is difficult without ABM. Alfaro, Miller, Johnson and Riolo [48] took it one step further by aiming to facilitate the direct engagement of stakeholders in the decision-making process for energy planners through ABM. With a similarly practical motivation, Hinker, Hemkendreis, Drewing, März, Hidalgo Rodríguez and Myrzik [49] were interested in the creation of a framework to facilitate ABM in interdisciplinary teams. This in turn is deemed necessary for social factors to be successfully included in modelling efforts [49].

At the interface of Policy and Planning and Consumer Behaviour, Mittal and Krejci [50] evaluated how increased PV adoption affects a utility company's revenue, where consumers, based on financial and attitudinal factors, decide to either adopt rooftop PV, community solar, or a green pricing program. In the same line of research, Kowalska-Pyzalska, Maciejowska, Suszczyński, Sznajd-Weron and Weron [51] examined the adoption of dynamic tariffs based on the discrepancy between consumers' opinions on switching to dynamic electricity tariffs and their actual decision to do so. This was based on the premise that while dynamic tariffs can be beneficial to consumers, retailers and other electricity system stakeholders, convincing people to actually switch has proven difficult. The authors found that the intention-behaviour gap occurred (in the simulation) when levels of indifference were moderate to high regardless of the intensity of advertising [51].

The topic areas of Consumer Behaviour/ Consumption Dynamics, and Electricity Markets predominantly touch on all conceptual elements of the regime level. For instance, a cluster of studies emerged in the Consumer Behaviour topic area that is concerned with the behaviour of building occupants with regards to energy consumption [41,52–55]. Building occupant behaviour is essential to reducing building energy usage and emissions as the built environment accounts for a large percentage of global energy consumption [55]. These studies may thus be interpreted as implicitly incorporating the external landscape pressure of carbon emissions. Pointing once more to the importance of social factors to the energy transition, Azar and Al Ansari [52] investigated the impact of building occupants on a building's energy saving potential. Employing a social network structure, they found that connecting occupants with each other can lead to significant increases and stability in energy savings, suggesting that social connectivity could be leveraged to diffuse energy conservation behaviour. Another study [56] showed that the use of an individual's social network (in an eco-village) could lead to energy savings through the sharing of appliances; *i.e.* exploiting social networks significantly increased potential savings (ibid.). In a similar line of inquiry, Jensen, Holtz, Baedeker and Chappin [41] concluded that the heating energy consumption of a building may be reduced by addressing heating behaviour of occupants. Integrating socio-technical dynamics through the interactions of social agents with each other and with a feedback device, they found that in the case study city (Bottrop, Germany) the introduction of the feedback device (CO_2 meter) could have a significant (positive) effect on the energy efficiency of heating behaviour [41].

An important difference between studies in this topic area and those in Electricity Markets is the level of aggregation. While those in Consumer Behaviour/ Consumption Dynamics considered individual consumers or households, articles in the Electricity Markets were focused on interactions between organisations or firms. While the Electricity Markets topic area is the largest of all topic areas, accounting for about 40% of all articles, a majority of studies in it are of no direct relevance to energy transitions, particularly given the social scientific focus of this review. However, Liu [57] investigated the development of high and low carbon types of energy in relation to the number and performance of firms. Results point to the importance of developing low carbon energy to sustaining security of energy supply for firms [57]. Wittmann and Bruckner [58] focused specifically on the changing market against the backdrop of the diffusion of low carbon technologies and emission reduction targets, thereby providing a rather direct consideration of the transition in the topic area of Electricity markets. Changes in markets or increasing shares of renewables were also observed in [33,59–63].

In articles within the Energy System topic area, a particular focus on the technical components is evident. Whilst alluding to an energy transition to varying degrees in contextualising studies, articles here were centred on future power grids and energy networks [64–66]. As such, these studies provide less insight into the reinforcing dynamics between system components and levels, but instead illustrate the complexity of some of these components.

Three articles provided insight into how reinforcing developments across all three levels can lead to transitions. Despite this commonality, all three differ considerably in thematic focus. Firstly, Chappin and Dijkema [13] investigated energy infrastructure transitions based on the same ontology of socio-technical systems applied in the present study - defining transitions as the occurrence of structural change in technical as well as social parts of the system [13]. They posited that these transitions can be shaped, or managed, and contended that such transition management requires a set of strategies relating not only to technological innovation but also spheres, such as policy, regulation, finance and research – a set of strategies they term transition assemblage [13]. Based on the premise that modelling can enable the assessment of possible strategies or designs before implementation, the authors devised a typology to model transitions with ABM (ibid.). With the aim of assisting modellers in this, their typology suggested that the most useful model for the assessment of transition assemblages allow for the comparison of assemblage alternatives, and are also able to account for regulatory adaptability (ibid.). A key learning for the present study is that ABM can be used to evaluate strategic options for steering transitions.

Kraan, Kramer, van der Lei and Huppes [67] modelled the energy transition in terms of the mitigation of, *versus* adaptation to the issue of climate change. Given the uncertainties related to climate change effects on society and economy, different ethical perspectives exist on addressing climate change, which has resulted in different discount rates being applied to the problem in economic analyses (ibid.). Kraan, Kramer, van der Lei and Huppes [67] devised a proof of concept ABM in which different agents used cost-benefit analysis to evaluate the problem of adaptation *versus* mitigation of climate change. Different ethical perspectives are reflected in differing discount rates that agents apply in their cost-benefit analyses. Agents emitted CO_2 which they were able to mitigate [67], resulting in investments in mitigation technology. The overall system was described in terms of CO_2 equivalent emission levels and system costs. Kraan, Kramer, van der Lei and Huppes [67] built on existing literature interested in the climate-economy interface by combining Integrated Assessment Modelling – traditionally used in the field – with ABM, arguing that such an integration allows for more realistic modelling of the way in which society responds to climate change. ABM offers advantages over the underlying traditional economic paradigm relating to assumptions of stability and rational actor behaviour [40]. By connecting the landscape pressure of climate change with varied actors, and the option of investment into new technologies, they integrated all levels of the MLP. Compared with the study by Chappin and Dijkema [13] their model did not directly provide policy recommendations but rather an economic (and an environmental) indicator.

Shchiptsova, Zhao, Grubler, Kryazhimskiy and Ma [68] discussed a model of the global energy system based on the emergence of new energy technologies and demand for energy services. The model described how the energy system evolves based on six *response indicators*; demand for heat, mobility, modern services, non-fuel, total energy, and primary carbon. They noted that the carbon emissions variable served as an indicator of climate change, while the others described energy demand. Assessing the historical reliability of this model, they found that, concerning carbon emissions and energy demand, the model was not able to predict past developments in the energy system [69]. For the purpose of the present study, one may argue that landscape pressures are represented by the tracking of carbon emissions; and the regime is represented by other indicators and their interplay and influence on niches, which are in turn represented by new technologies.

In summary, the thematic contribution of the selected literature to the study of energy transitions lies more in addressing varied subcomponents of the energy system than in modelling whole transitions. From a social sciences perspective, studies have demonstrated that the inclusion of social and behavioural factors in models can, firstly, show improved outcomes, and secondly, lead to better model validity.

In terms of the MLP, most studies exhibited features or included elements of multiple system components and levels, particularly within the regime. Over and above a superficial thematic discussion, the MLP may not be the most suitable framework for agent-based transition studies as the multi-level structure, albeit based on the notion of scale, does not sufficiently account for the role of individual (agents). For example, studies in the New Technologies/ Innovation topic area were viewed as broadly representative of the niche level, while Consumer Behaviour/ Consumption Dynamics articles were placed in the regime because of the MLP conceptualisation of it (cf. Fig. 1). However, individual consumers arguably interact at a micro-level. This is not accounted for in the MLP.

Considering the three articles placed in the Transitions topic area, energy transitions, as multi-level, complex processes made up of many different interactions, can be addressed through the active management of the process [13]; an overall economic approach, whilst accounting for socio-cultural differences [67]; and/or historical trends based on technology uptake [68]. Moreover, the literature points to a possible role of ABM being its application to policy-making, advancing transition related decision-making practically, by offering a decision-support mechanism. Table 3 provides an overview of some key findings identified in the literature that are of relevance to, or demonstrate the relevance of, social sciences in modelling energy transitions.

3.3.2. Modelling complexity in energy transitions

Section 1 outlines how an increasing degree of complexity is a prominent feature of energy transitions. The present study is based on the premise that given this increased degree of complexity, ABM may be an appropriate means to investigate transitions. This argument appears well supported: The ability of ABM to account for complexity emerged as the predominant reason for the choice of this methodology across topic areas. Section 3.3.1 provided an overview of topic areas through a multilevel lens. Offering an alternative approach to evaluating the extent to which energy transitions have been addressed with ABM, this section compares energy transition complexities with the motivations for using ABM given in the selected set of studies.

The complexity of the research problem and the ability of ABM to deal with complexity was the most frequently cited reason for choosing ABM as a methodology across all topic areas. It was the most often cited reason in both the Electricity Markets [32,57,60–63,70–73] and Energy System [65,66,74] topic areas. As such, the interface of these two dimensions of complexity, as a feature of energy transitions and as a strength of ABM, was explored in more detail. It was found that the common theme of complexity can in fact serve to integrate the methodological choice of ABM with transition traits. Accordingly, articles

Table 3
Sample of findings illustrating the importance of social factors to modelling energy transition related problems, or otherwise of particular interest to social scientists.

Sample findings of particular relevance to the social sciences:
● Behavioural and social factors were critical in accurately predicting demographic and spatial patterns of solar PV diffusion [40] ● TPB may be more suitable for ABM than other theories because of the relative ease of translating it into code, and because is stresses psychological, sociological as well as environmental factors in agents' decision-making process [42] ● Directly integrating social psychological theories is beneficial for model outcome [42] ● Communication of a technology's advantages and disadvantages to consumers is important and should be the focus of a good policy for the promotion of smart metering technology [43] ● Interdisciplinary teams are necessary to successfully include social factors in modelling efforts [49] ● Connecting building occupants with each other can lead to significant increases and stability in energy savings [52] ● Exploiting an individual's social network (in an eco-village) could lead to energy savings through the sharing of appliances [56] ● ABM can be used to evaluate strategic options for steering transitions using a transition assemblage concept based on socio-technical systems [13] ● ABM can offer advantage in modelling society's response to climate change; mitigation versus adaptation decisions may be represented quantitatively through application of varying discount rates related to ethical views [67]

were placed in one of four categories depending on the degree to which the ability of ABM to treat complexity was relevant for choosing the methodology; and the degree to which the complexities of the energy transition (as defined in Section 1) were central to the study. The four categories may be understood as a continuum indicating the degree of association between the complexity of energy transitions and ABM's ability to address it in the given studies. As such, at one end, complex energy transitions and the ability of ABM to model these complexities are directly associated; while at the other, neither complexities in the transition nor ABM's ability to model them were of relevance to the study. This is illustrated in Fig. 3.

At the left of the spectrum (i.e., complexity category 1), articles were concerned with features of energy transitions which are described as complex. The choice of ABM as a methodology is linked to this complexity. For example, Chappin, de Vries, Richstein, Bhagwat, Iychettira and Khan [47] stated that challenges related to energy transitions include social elements (such as those noted in Section 1) which represent the type of complexities that ABM is suitable for, *e.g.*, uncertainty [51]. Deissenroth, Klein, Nienhaus and Reeg [75] explicitly discussed the complexity of energy transitions as including uncertainty, changing social configurations, increased numbers of actors, and more complicated market structures; and therefore deemed ABM the most suitable modelling technique [41].

In category 2, transitions or features thereof are still central to the study but the choice of ABM is not directly linked to this (Fig. 3). For example, while a global energy transition was the central topic in Shchiptsova, Zhao, Grubler, Kryazhimskiy and Ma [68], complexities such as an increasing number of actors (see Section 1) are not discussed. While ABM was described as a tool to analyse complex systems, this description is based on the general features and advantages of ABM as such. Hawasly, Corne and Roaf [56] discussed energy saving in an Eco Village: while the interest in energy saving can be linked to the characteristics of the current energy transition, the use of ABM in this study rested on the premise that any community setting in which people interact is complex. Complexity category 3 contains studies that may refer to the ability of ABM to account for complexity but these complexities are not linked to energy transitions or any features thereof as these are

Notation	(Increased) complexity is linked to (changing) structures of the energy system.	The study is set in the context of an energy transition or features thereof (such as climate change), but ABM is chosen for its ability to model complexity inherent in reality (it is not a new complexity).	Real-life systems are complex, and ABM allows for (more) realistic modelling (than other approaches).	The notion of complexity is not relevant to the study.
Description	The ability of ABM to model complexity was used to model (a) feature(s) of the energy transition that are viewed as complex or as adding complexity. This may be linked to the sociotechnical nature of transitions.	The study is motivated by a driver of the transition or is concerned with a feature of the transition. The choice of ABM however is linked to a pre-existing complexity.	Studies employ ABM for its ability to account for complexities which are inherent in real life. Energy transitions or any features thereof are not of concern.	Studies refer to neither the energy transition as a complex process or features thereof, nor to ABM's ability to model complexity.

Fig. 3. Complexity categories and topic composition per complexity category. The bar diagram shows the number of articles per topic area that were placed in each complexity category. Review articles were excluded from this. The notation summarizes the category criteria, while the description explains it in more detail. Given the great diversity of studies reviewed here, complexity categories are not to be understood as absolute. Rather, in category 1, complexity was relatively more central to studies, than in categories 2–4.

not of concern. Lastly, category 4 articles do not refer to complexity in any way. These studies were predominantly published in journals with a more technical focus, which may explain a narrower focus and less contextualisation of research problems (*e.g.* Journal of Computing in Civil Engineering, CIRP Annals - Manufacturing Technology, Energy and Buildings).

The exercise of grouping studies according to their two complexity dimensions provides only an estimate of the centrality of complexities to the selected set of literature. However, it demonstrates that ABM has been employed to cover energy transition complexities from a variety of thematic foci – *i.e.* all topic areas appeared in the first (and second) complexity categories. Although only three studies were placed in the topic area of transitions, when considering the notion of complexity, 18 were identified as addressing transition related complexities and therefore as being directly relevant to the topic under investigation in this study. Furthermore, six of a total of 17 (journal articles and conference papers combined) studies published in 2017 were placed in category 1, representing the largest share (of articles from that year) in any one category (4 in category 2, and 3 each in categories 3 and 4, 1 review article). As with the increasing numbers of studies identified over the past decade (Fig. 2), this might point to an increasing recognition of the relevance or usefulness of ABM for studying transitions.

3.4. Evaluation of evidence: using ABM to understand socio-technical energy transitions

Section 3.3 established the connections between the set of literature and its relevance to the study of energy transitions thematically. It was shown that varied parts, sub-components, and sub-processes of energy transitions have been addressed in the literature, and more so than the whole of the process; and that in a significant number of studies the choice of ABM was directly linked to its ability to address complexities of energy transitions. This section critically evaluates the potential contribution of ABM to the study of (socio-technical) energy transitions. Table 4 summarises the advantages and disadvantages of ABM identified in the literature.

In a practical evaluation of the state of the field of ABM (in general), Macal [30] proposed a set of four informal definitions of agent-based modelling and simulation. In order of increasing sophistication with regards to the individuality, behaviours, interactions, and adaptability of agents, he distinguished between individual, autonomous, interactive, and adaptive models [30]. In the latter case, agents are heterogeneous, their behaviours are autonomous and dynamic, interactions occur between different agents as well as with the environment, and they are adaptive, i.e. their behaviour changes over the course of the simulation [30]. Considering this differentiation, a large majority of studies examined here fall under the interactive or adaptive types, indicating a generally high level of sophistication and potential complexity. However, as pointed out by Robinson and Rai [40], the usefulness of an ABM (over other methodologies) rests on rigorous integration of theoretical and empirical foundations. As such, while the set of examined studies exhibit a generally high degree of sophistication, the degree of model implementation rigour is more varied.

One potential issue with regards to modelling energy transitions that emerged from the literature is a trade-off between model robustness and scale. Rai and Robinson [37] and Robinson and Rai [40] presented detailed and highly sophisticated models, addressing a lack of empirical data being used in initialisation and validation of models as well as the use of appropriate behavioural theories. While these studies have made an important contribution to the literature, the simulations were run on the 10 PF Stampede Supercomputer (at the Texas Advanced Computing Center) [37,40]. The rigorous design and validation of the models in these studies resulted in robust simulations of residential solar PV adoption in Austin, Texas.

The computing power required to execute them however suggests that modelling larger scale transitions involves a trade-off with the level of detail and model robustness – or, the collaboration with an institution with the necessary computing requirements. Holtz [14] asserted that reduced scope of a model improves the likelihood of good model performance. This supports the notion that the more methodologically robust contributions to modelling energy transitions will, or should, focus on parts of the system and processes. This also relates to an observation made by Hinker, Hemkendreis, Drewing, März, Hidalgo Rodríguez and Myrzik [49] - integrating social aspects appropriately in models is difficult because of their complexity – i.e. problems can never be modelled in all their complexity. Considering the complexities attributed to whole energy transition processes, including spatial, temporal, social and technical, this would certainly hold true for transition models. Moreover, the appropriate integration of empirical data in model initialisation and validation would arguably become increasingly difficult with increasing model scale.

The above example of a sophisticated model of Austin, Texas, also points to another issue present across the literature: as models are often case-specific, findings are difficult to generalise [47]. The way agent behaviour is modelled varies drastically and there is a lack of conventions regarding this (ibid.). In addition, a lack of consistent model descriptions throughout the literature makes it difficult to compare studies along the same criteria. While some studies use the ODD (Overview, Design concepts, Details) protocol originally proposed to address this issue, there is still a large number of studies not using it, and a considerable degree of divergence as to how its three components are addressed in individual studies. A possible partial solution to these problems could be the development of more generalizable models and conceptual frameworks. This would also play into the need for and potential of interdisciplinarity alluded to in Section 1. Two examples of generalizable frameworks from the reviewed set of literature are from the Policy and Planning topic area. One important advantage that is reflected in ABM applications to energy transitions is the possibility of determining the side effects of policies [48]. Building on this, Chappin, de Vries, Richstein, Bhagwat, Iychettira and Khan [47] presented EMLab (Energy Modelling Laboratory) which describes the impact that (EU) policies have on investment in the electricity sector in a flexible, open source platform. Alfaro, Miller, Johnson and Riolo [48] developed BABSTER, a model integrating technical, social and environmental factors, that is similarly aimed at enabling decision-makers to flexibly and easily test their strategies. This model is also interesting in that its development included participation by stakeholders, an important step to be addressed as outlined in Section 1.

Gallo [62] noted that in order to be able to model and build power systems (under high penetration of renewables) more accurately, a multidisciplinary approach is needed that includes all actors in the system. Similarly, Ringler, Keles and Fichtner [60] pointed out that an increased degree of multidisciplinarity would improve future work (on smart grids) through better integration of environmental, social, and technical elements. Hinker, Hemkendreis, Drewing, März, Hidalgo Rodríguez and Myrzik [49] argued that not just multi- but interdisciplinary work is needed to appropriately integrate social factors such as legal frameworks into optimization and simulation models; and that a common language is needed to enable this participation. Hence, rather than focusing on a specific topic, their study was concerned with the creation of models as such in interdisciplinary teams. Their proposed conceptual model is designed to enable interdisciplinary work in simulating socio-technical systems [49]. This is an important contribution to the advancement of ABM for energy transition studies for two reasons. Firstly, the study of energy transitions is inherently discipline-transcending, and, from a systems perspective, a model of a transition or part thereof should include social as well as technical components. The second reason relates to the accessibility of ABM for social scientists. Although the agent concept may be intuitive to the social sciences and provide a natural ontology [20], developing an ABM is not an easy task. Collaborations between social and computer scientists could therefore be particularly fruitful. Thus, interdisciplinarity

Table 4
Advantages and disadvantages of ABM as identified in the literature.

Advantages of ABM	Disadvantages & challenges of ABM
● Determining the side effects of policies [47] ● Accounting for role of communication in technology diffusion models; modelling household choice [76] ● Enables the modeller to build on practical and existing theoretical knowledge [41] ● Can represent complexities of energy demand such as social interactions [77] ● Attractive tool for study of human-technical systems because it can more flexibly describe detailed behavioural and structural system elements [37] ● Technological learning can be introduced without requiring large scale computational capabilities [38] ● Being able to focus on individual level rather than the whole system [55] ● Can address institutional and governance barriers [46] ● Agent autonomy and interaction skills; distributed/decentralized control; high flexibility in execution of tasks [64] ● Useful when dealing with various agents with diverse behaviour [53] ● Good to model complex behaviour of participants and for modelling large-scale systems where different types of participants interact [32] ● Can account for diverse heterogeneous actors making it suitable for studying dynamics of electricity systems undergoing transitions [75] ● Allows experiments to be run multiple times with varying market and agent characteristics [51]	● Challenges regarding validation, verification, calibration and model description [60] ● Lack of relevant empirical data [37] ● Difficulty of validation [73] [70] ● Lack of data for validation and calibration [46] ● In context of consumer behaviour: lack of spatial representation and validation [77] ● Integrating social aspects appropriately is difficult because of their complexity – i.e. problems can never be modelled in all their complexity [49] ● Behavioural rules are often ad hoc and not based on systematic theories of behaviour [37] ● When modelling human agents their 'soft' features (psychology, values, behaviour etc) are difficult to quantify [78] ● ABMs are often one-offs exploring specific cases, making insights difficult to generalise; ABMs difficult to develop and interpret; the way agent behaviour is modelled (theory or empirical basis) varies drastically which means models are diverse and there is a lack of conventions; ability of ABMs to analyse uncertainty in-depth makes it less relevant to policy-makers because it makes results less tangible [47] ● Despite advances in ABM and energy research models are still limited with respect to agent types, behavioural variety and interactions [53] ● In context of consumer energy technology adoption: integration of theory and empirical evidence in model structure, validation and initialization [40] ● Results are not optimal solutions but rather scenarios based on different assumptions [38]
Compared with other approaches	
● Compared with SD and game theory, ABM can integrate larger number of actors and their decision-making behaviour [69] ● Compared with game-theoretical models, ABM has the advantage of being able to model heterogeneous actors and observing dynamic evolutionary processes [79] ● Compared with equation-based diffusion models, ABM may be a better alternative for evaluating complex policies and targeted interventions aimed at increasing technology uptake [76] ● Compared with conventional discrete event simulation approaches ABM is more suitable for modelling complexity of electricity markets [32] ● Compared with field experiments, simulations are more cost-effective and require less bureaucratic efforts [52]	● Extent to which ABM is advantageous depends on the (rigour of) theoretical and empirical underpinnings being used [40]

is both a promising feature of, and a challenge for ABM; while various authors point to the importance of multi- or even interdisciplinary teams, few models are actually designed to enable this.

Lastly, the potential of ABM to aid in the formalisation of theories (such as transition theory, which is lacking formal presentation [14]) touched on in Section 1 could not be confirmed in this review. While Rai and Henry [77] discussed the importance of better theories (of energy demand of consumption) in advancing knowledge of complex energy systems, none of the identified studies focused on the testing or formalising of (new) theories. In this context, considering the integration of social factors into models, it was noted that behavioural rules are often ad hoc rather than being based on systematic theories of behaviour [37]. Related to this is the difficulty of quantifying features such as values or behaviour [78] that characterise human agents.

The value of current ABMs to the study of socio-technical transitions, based on this review, lies in its ability to address transition-related questions, and in modelling sub-components of the energy system. A particular appeal lies in the application of ABM to policy and planning and thus in aiding in the effective management of energy transitions. Models that enable collaboration between disciplines and sectors, thereby promoting knowledge sharing, and models that are easy to use by non-computer scientists, are promising areas for furthering energy transitions in practice. Nevertheless, the full potential of ABM in this respect has not yet been exploited.

4. Conclusion

The application of ABM to energy transition related questions is gaining popularity. The variety of identified topic areas illustrates, on one hand, a continuing prominence of technical and market focused studies; and on the other, an increasing share of studies interested in the application of ABM to policy and planning (as evidenced by the number of articles published in Energy Policy in recent years). The pattern of topics uncovered in the present study is similar to trends described by others, who have, as here, proposed that many different types of models may contribute to a partial understanding of energy transitions [14]. The application of a multilevel perspective to topics covered in the literature showed that regime-level interactions have received particular attention. Further application of the MLP in this context, beyond the explorative evaluation done here, may prove problematic, as the framework does not adequately account for individual agents and their roles. On the other hand, the complexity based evaluation of the relevance of studies to energy transitions in Section 3.3.2 showed that an increasing share of studies do link their choice of ABM to the complexities specific to energy transitions and therefore position themselves as contributing to this body of research.

A particularly valuable area of research in the energy transitions domain may be the application of ABM to policy and planning. This conclusion is motivated by two reasons. Firstly, studies in this topic area may contribute to practically driving energy transitions by informing (and improving) decision-making. Secondly, studies in this area identified here addressed the issues of interdisciplinarity and participation more directly than other topic areas. Given the relevance of policy-making to managing energy transitions, and the usefulness of ABM as a practical tool, it is likely that increasing numbers of studies will be in the Policy and Planning area. This is also suggested by temporal trends observed in this study, where 6 of 9 articles in this topic area were published in 2017. As the structure of the changing electricity market is high on the agenda of policy-makers and academics alike, it may also be expected that the importance of this topic in the context of energy transition studies will remain.

The increasing application of ABM to the policy and planning domain, and contributions to sub-components of energy transitions in general, support the promising contribution the methodology can make to the study of transitions. However, particularly from a social scientific perspective, areas of improvement were also identified. While the possibility of interdisciplinary research through ABM has been noted in the literature, the need for it has not been adequately addressed. An increase in interdisciplinarity will be needed if ABM is to advance as a transitions tool. This is, firstly, to ensure the appropriate integration of social elements into models. The reviewed literature has shown that such integration can have a significant effect on model outcomes; further, thus far, techno-economic problem statements are still more prominent than social ones in energy-related ABMs. Secondly, increased interdisciplinary collaboration will be needed to ensure the computationally adequate development and implementation of socially focused models. While the relevance of social factors to energy transitions and model outcomes has been demonstrated, the building of useful models still requires a considerable degree of ABM specific knowledge and skills. Collaboration could overcome this barrier to social scientists unfamiliar with computational techniques. This also implies a call for easily adaptable and understandable conceptual models to increase the accessibility of ABM to social scientists (and non-academic actors), and to potentially increase the comparability of modelling frameworks. In this regard, the authors recommend a review of socio-technical approaches used in ABM to complement the present study. These may exist outside the limited scope of energy specific studies.

While technical model specifications were not the focus of this article, the exercise of analysing studies nevertheless revealed the lack of consistency, or standardised formats, in which studies present and report on agent-based models. As has been commented by other authors (e.g. [60]), this makes it difficult to compare modelling studies across the literature through common criteria. Notwithstanding, future reviews of ABM and energy transitions would benefit from an in-depth evaluation of the technical details. Methodologically, it is also recommended that similar systematic reviews be conducted based on more comprehensive analyses of the quantitative data along the selection pathway to verify the temporal and topical patterns uncovered here.

In summary, ABM can advance energy transitions practically and will be particularly valuable in this area if issues of interdisciplinarity and accessibility are addressed; its potential to contribute to the theoretical foundations of energy transitions research could not be confirmed in this review but could be investigated further using alternative review approaches.

Conflicts of interest

There are no conflicts of interest to declare.

- The manuscript has not previously been published and is not currently under consideration with another journal.
- The submitted manuscript is an original piece of work.

Acknowledgements

This research is funded by the CRC for Low Carbon Living Ltd supported by the Cooperative Research Centres program, an Australian Government initiative; and received funding from the Australian Renewable Energy Agency as part of its Research and Development Programme. Paula Hansen received funding from the Australian Housing and Urban Research Institute through their research capacity building in form of a PhD top-up scholarship.

The funding bodies had no involvement in study design; data collection, analysis and interpretation; nor in the writing of the report. Permission to publish this research article was sought and granted from all three funding bodies prior to submission.

Appendix A. Testing search string robustness

To verify the representativeness of the selected sample of literature and evaluate search string effectiveness, three additional queries were run in ProQuest and Scopus (as the original search showed that GoogleScholar did not generate any results not already contained in the other two databases it was not used again) (Table A1). While the focus of this review is on energy (transitions), the word electricity was included to account for inconsistent and varied usage across the literature. A majority of studies containing the term electricity in the title are in the Electricity Market topic area. However, the term also appears in the Policy and Planning and Consumption Dynamics/ Consumer Behaviour topic areas. This illustrates that while the term is pre-dominantly used in market-centric studies, this is not always the case. Inclusion of the term therefore proved sensible.

Table A1
Alternative search query evaluation.

(agent-based OR multi-agent) AND (energy OR electricity)		
Results in	ProQuest	Scopus
Anywhere	23,612	34,195
Abstract only	2,701; peer-reviewed: 1,191	3,332; article, review, article in press: 1,234
Title only	645; peer-reviewed: 265 Of these 265 results, 10 were published between 1999-2007.	657; article, article in press, review: 238 Of these 238 results, 28 were published between 1999-2007.
→ This query was run to test the robustness of the search string applied in this study. The first expression is more flexible compared to the original (“agent-based model*” OR “agent-based simulation”). Scanning through titles within in the “titles only” search, results generally show little potential relevance to the topic under investigation; many seem highly technically focussed or centred on electricity markets. Limiting the date range to studies published before 2007 showed that the large majority of studies were published after 2007. This suggests that the date distribution observed in the present study is representative and not due to search string design.		
(agent-based OR multi-agent) AND (energy OR electricity) AND (transition)		
Results in	ProQuest	Scopus
Anywhere	10,963; peer-reviewed: 2,861 Date range of peer-reviewed results: 1992-2017; 491 results are from before 2007	4,141; limit to article, review, article in press: 3,025 Date range of peer-reviewed results: 1976-2017; 267 results are from before 2007
Abstract only	86; peer-reviewed: 46 These 46 include 20 duplicates; of the remaining set of 26 articles 4 are part of the selected literature in this study; a few others could be relevant	110; limit to article, review, article in press: 49 5 of these are included in the selection in this study; a few other could be relevant

(*continued on next page*)

Table A1 (*continued*)

Title only	5; 4 peer-reviewed; 2 of these results is an article that is included in this review (duplicate); the other 2 are not included and are relevant to the topic, however, 1 proofed to have been published in 2018 Date range of results: 2010-2017	5; 1 article, 1 review (3 conference papers); of the 2, one is included here, 1 is not but could be relevant Date range of results: 2008-2017
→ This query was run to test the robustness of the search string applied in this study. The first expression is much more flexible compared to the original (“agent-based model*” OR “agent-based simulation”). On the other hand, and in contrast to the above, a third expression, “transition”, was added. Unsurprisingly, the addition of the expression let to a smaller number of results in “anywhere” compared with above; and a drastic decrease in results when restricting the search to abstracts only (and even more when limited to titles only). 1 article was identified within the title search that suggests potentially high relevance to the topic under investigation. Within the abstract search, a few articles could be relevant based on their titles. However, none appeared to address a new topic area not covered here. In fact, a large portion of articles appeared market centric. The representativeness of the date range observed in the selected set of literature was verified with a majority of studies in the much broader search having been published after 2007.		
("agent-based computational" OR “agent-based spatial” OR "agent-based diffusion" OR "agent-based adoption" OR "agent-based analysis" OR "agent-based micro*") AND (energy OR electricity)		
Results in	ProQuest	Scopus
Title only	30; peer-reviewed: 21; duplicates eliminated, remaining: 8 results Of these 8, 5 contain the phrase “agent-based analysis” in the title; the other 3 are: “agent-based spatial”, “multi-agent based microgrid energy management”, “agent-based computational modelling”; 5 of 8 contain the word market in the title	16; article, article in press: 10; 5 of these 10 contain the phrase “agent-based analysis” in the title; “agent based computational economics”, “agent-based spatial simulation”, “agent-based computational economics simulation”, “Agent-based microsimulation”, “multi-agent based microgrid energy management”; 6 of the 10 contain the word “market” in the title
→ This query was applied to test whether a significant number of potentially relevant articles was lost by including only the restrictive phrases “agent-based model*” and “agent-based simulation” in the search string. The results suggest that this was not the case. Firstly, the majority of articles contained the term “agent-based analysis” rather than the more specific terms of diffusion or adoption. In ProQuest only 3 of the peer-reviewed articles contained other terms; these were “multi-agent based microgrid energy management”, “agent-based computational modelling”, and “agent-based spatial”. In Scopus, in addition to “agent-based analysis”, the terms “agent based computational economics”, “agent-based spatial simulation”, “agent-based computational economics simulation”, “Agent-based microsimulation”, “multi-agent based microgrid energy management” appeared. This shows that no articles containing the terms agent-based diffusion or adoption in the title were lost due to search string construction. Secondly, the majority of these articles appeared to be market-centric or technical studies; across ProQuest and Scopus, 11 of 18 results even included the word market in the title. They are therefore unlikely to have added insights to the present study, particularly given the focus on social components of the energy transition in this analysis.		

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Publication II

Published/ Peer-reviewed journal article

Hansen, P., Morrison, G. M., Zaman, A., & Liu, X. (2020). Smart technology needs smarter management: Disentangling the dynamics of digitalism in the governance of shared solar energy in Australia. Energy Research & Social Science, 60, 101322.

Energy Research & Social Science 60 (2020) 101322

Contents lists available at ScienceDirect

Energy Research & Social Science

journal homepage: www.elsevier.com/locate/erss

Original research article

Smart technology needs smarter management: Disentangling the dynamics of digitalism in the governance of shared solar energy in Australia

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ARTICLE INFO

Keywords:
Community energy
Digitalization
Energy governance
Energy transition
Shared renewable energy systems
Socio-technical interactions

ABSTRACT

This article argues that the need for a better understanding of socio-technical interactions in shared renewable energy systems (SRESs) is exacerbated by the relevance of digital technologies to their governance. Addressing the question of how the use of digital technology affects system governance, this study applies the social-ecological system framework to a case study in Perth, Western Australia. The analysis finds that although the digital element enables the sharing of energy in the case study, it also increases the complexity of the social subsystem. While technology is often heralded as the solution, successful governance of digitally enabled SRESs may be more dependent on recognizing the importance and complexity of social interactions needed to manage the technology. The findings of the study are useful in developing and implementing appropriate governance mechanisms for SRESs in Australia and other parts of the world.

1. Introduction

1.1. Background

Community energy initiatives have enjoyed rapid growth in popularity [1], both as a subject of academic inquiry and as a practical manifestation of renewable energy transitions. Having been attributed a role in facilitating the diffusion of decentralised renewable energies [2], and in mitigating climate change effects at the local level [3], a significant body of literature now exists with studies investigating themes as diverse as citizen engagement [4,5], the role of trust [6], energy consumption behaviour [3], and the technical feasibility of sharing energy from renewable sources (*e.g.*, [7–9]). The concept of prosumerism [10–12], the ability of an individual or group to perform both consumption and production activities [13], has also gained traction in this context.

Shared renewable energy systems (SRESs)[1] may be defined as socio-technical systems [14,15] in which social and technical elements, resource flows and infrastructure interact [14] to deliver the benefits of renewable sources of energy to a group or community of people. Such a definition underlines the complexity inherent in coordinating the interplay of various system components effectively. In fact, while it is widely acknowledged that the advent and diffusion of renewable energy technologies have led to new actors and business models [16], less attention has been directed towards the governance mechanisms that coordinate the effective operation of such new configurations. For new (sharing) models to be successful, the way that the various social and technical elements are managed needs to be better understood.

The increased participation of households and consumers in energy systems brings a need for new techno-institutional arrangements [17]; and for the implications and opportunities for governance arising from new technologies to be better understood [10]. Thus far, studies focused on technical elements of energy systems often neglect the embeddedness of technological innovations in organisational structures, and how these may have to change [11,18]. Studies have also called for new approaches to enable the successful governance of prosumer communities specifically [13]. In short, if local energy initiatives are to achieve lasting results, organisational structures and visions for their

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[1] *Abbreviations used throughout the article:*
CPR(s): Common-pool resource(s)
I(C)T: Information (and communication) technology
SES(s): Social-ecological system(s)
SRES(s): Shared renewable energy system(s)
WGV: White Gum Valley

https://doi.org/10.1016/j.erss.2019.101322
Received 18 May 2019; Received in revised form 2 October 2019; Accepted 2 October 2019

governance - uniting new technologies with changed social dynamics - need to be further developed [19].

The need to take a closer look at the governance of SRESs is exacerbated by the role of digital technology in enabling them. Despite an emphasis on technology in transitions [20], the link to the digital revolution, a fundamental transformation of our daily lives and governance structures [21], is rarely explicitly acknowledged in energy governance studies. Yet, new collaborative economic models and the sharing economy [22,23] are driven and enabled by digital technology and infrastructure, and information and communication technology (ICT). Collaborative consumption has been defined, explicitly, as the peer-to-peer (P2P) based sharing of access to goods or services through online coordination [23]. As new types of online platforms and applications are facilitating exchanges between peers, traditional producer to consumer models are being subverted by the creation of alternative marketplaces [22].

With this pervasive impact on everyday life, digitalisation implies opportunities as well as challenges for sustainability [24]. In the context of the energy system, the integration of variable renewables, distributed energy resources, and the facilitation of P2P trading within local energy communities may be seen as opportunities [25]. On the other hand however, as a new way of mediating power and knowledge exchange processes, digital innovation may be at the very core of the increasing complexity of governance systems [26]. Given its novelty, it has been argued that digital infrastructure adds complexity as well as uncertainty to the operation of energy systems [27].

Positioning digitalisation in a similar manner as a driver rather than a mere characteristic of energy system change, Kloppenburg and Boekelo [16] argued that platforms have been an important driving factor behind such dynamics as new actors, new business models, and new technologies. While platforms act as enablers of new energy (sharing) models, the development comes with a host of new questions, such as how platforms affect the way people engage with energy infrastructures [16]. Understanding how online and offline behaviour interact has been identified as another challenge of studying such infrastructures [28].

In line with these observations, this article argues that the use of digital technology in SRESs affects their governance in important ways; and that these effects need to be discerned more clearly in order for researchers and practitioners to make informed decisions as to the potential success of a given sharing model. To exploit the potential SRESs may have in positively contributing to a more sustainable (energy) future, we need to first understand their governance mechanisms, evaluate their effectiveness, and in doing so, account for the significance of digital innovation [26]. Addressing this research gap, this paper uses a case study of a residential development in Perth, Western Australia, to study the effect of digital technology on the shared solar scheme's governance dynamics and long-term sustainability.

1.2. Conceptualising governance for analysis

The proposed undertaking necessarily gives rise to the question of what conceptual and analytical tools are available that may allow us to study the way that digital technology influences the effectiveness of shared energy governance systems. Governance is understood here as the purposeful orchestration of the interplay of the various system elements, including tangible and intangible, social and technical, with the express aim of enabling the sharing of energy among a group of people. Despite the plethora of approaches that have been employed to study different aspects of energy systems, the complexity of current energy transition dynamics, reflected in such a definition of governance, has led some to call for new analytical approaches [16]. Difficulties in studying infrastructure, including accounting for behaviour occurring both on- and offline, have also been noted [28], along with a call for new methods to understand the intersection of social and technical organisation (ibid.).

To overcome such challenges, we follow others [29,30] in conceptualising SRESs as shared resources that, in order to be sustained (to work effectively in the long-run), require suitable governance mechanisms. Such a view then opens up a wealth of well-established literature concerned with the governance of social-ecological systems (SESs). Although energy was not traditionally the subject of research into why and how communities may fail or succeed in governing their shared social-ecological resources [31], a new wave of commons research is now emerging that is concerned with human-made and technology-driven common-pool resources (CPRs) [31]. For example, it has been proposed that socio-technical infrastructure systems may be conceptualised as CPRs [32] or commons [13]. Electricity in community micro-grids has also been treated as a CPR, enabling the analysis of social and institutional factors through the lens of collective action and CPR scholarship [30]. Others have taken similar stances in analysing the successful management of smartgrids [13,33,34].

An important premise of commons research has been the potential of groups of people to self-organise to effectively and sustainably govern natural resources [31]. Ostrom [35] found that the likelihood of collective action and self-organisation to occur in social-ecological commons was affected by a range of variables. The social-ecological system framework was formulated to foster understanding of the factors that determine a complex SES' sustainability [36]. The framework is illustrated in Fig. 1. It is based on a set of first-tier categories: resource units and resource system, governance system, and actors [36]. Each of these contains a set of second-tier variables which serve as input into action situations where the interactions of different actors transform those inputs into outcomes [36]. The list of first and second-tier variables proposed by McGinnis and Ostrom [36] is given in Appendix A.

The SES framework provides scholars concerned with the sustainability of SESs with a common language and structure, offering a model to guide the analysis of complex and nested systems [36]. Given this same need applies to socio-technical energy systems, a growing community of researchers has been interested in the transferability of the SES framework (e.g. [29,37]). The need for an alignment of ecological and social systems addressed by the framework is analogous to that of technical and institutional coordination in energy systems [29].

The framework's original intention was to address the factors that promote the long-term sustainability of a SES [38]; and how a particular set of outcomes may emerge from a given governance structure [38]. Albeit in the context of a socio-technical rather than social-ecological system, determining how a given governance structure may lead to sustainability (stability) of its shared resource system, and how digital technology may factor into this potential, is the central concern of the present study.

Building on the above literature, we draw on the insights offered by commons scholarship to identify the dynamics that govern the sharing of energy in a case study system; and to discern how digital technology specifically affects the system's performance. The following section breaks down the methods used by first describing the case study (2.1) and then explaining the empirical (2.2) and analytical (2.3) approaches taken. Section 3 then presents and discusses the results. Section 4 concludes by making recommendations for policy and future research, and reflecting on the exercise of transferring the SES framework to a socio-technical system.

2. Methods

2.1. The White Gum Valley (WGV) case study

The WGV demonstration site is a residential infill development located in Fremantle, Western Australia. The One Planet Living accredited site offers a range of housing options [39] which include four (three built, one planned) apartment buildings in the otherwise low-density suburb. One of the collaborative projects at the site has been the implementation of shared solar PV and battery storage systems in the

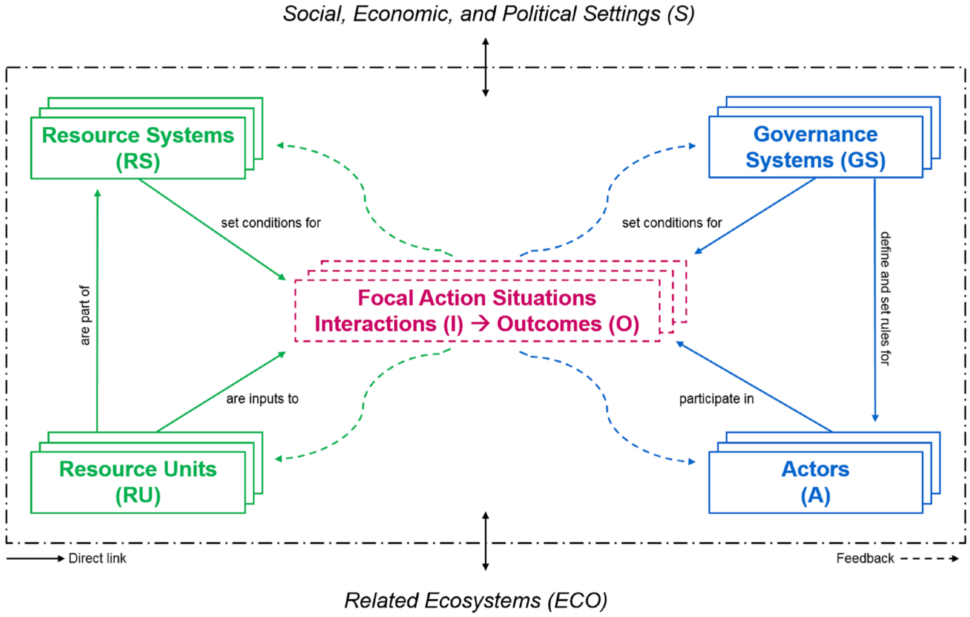

Fig. 1. Social-ecological systems framework, adapted from McGinnis and Ostrom [36].

site's apartment buildings. Australia is experiencing rapid uptake of solar PV [40]. However, due to technical, organisational, financial as well as regulatory barriers, the benefits of solar energy are not available to the large majority of the country's apartment dwellers [41].

Against this background, the three completed WGV apartment buildings (named Gen Y, SHAC and Evermore, Table 1) trial the use of a novel system configuration that aims to enable access to solar energy. The sharing solution's innovation lies in the inclusion of storage technology in addition to a rooftop solar array; and in its ownership and accounting structure [42,43]. As the sharing structures in these three buildings have been developed along the same principles, they are treated here as subunits of the WGV case; that is, with the intention of understanding the digital component, we focus on the general WGV sharing arrangement rather than the variations in rules per building. Table 1 provides an overview of the building typologies; Table 2 details the key stakeholders and their involvement.

In Australia, strata title allows a combination of individual and shared ownership to exist within the same property [44]. While lots (typically apartments) are owned individually, common property is owned by the owners corporation – a legal entity formed by the owners of individual lots (ibid.). This owners corporation acts as the management committee to govern the development's common areas [43]. As such, the energy infrastructure in Gen Y and Evermore is jointly owned by the respective apartment owners. In the cases of both Gen Y and Evermore, having sold the individual units, the respective developers transferred management of the premises to strata managers who act on behalf of the owners corporation. The renewable system at SHAC is owned and managed by the developer.

Gen Y was developed by the state land developer and subsequently sold to the current owners. In contrast, the Sustainable Housing for Artists and Creatives (SHAC) was conceived and built as a collaborative effort between the SHAC cooperative and an affordable housing provider and developer. Occupants rent from the developer, paying a fixed portion of their weekly income in rent – thereby accommodating for fluctuating income. Evermore was built by a commercial property development company with units gradually being sold to private owner-occupiers and investors. All buildings maintain a connection to the electricity network through one grid connection (and meter) per building.

2.2. Research design and data collection

The following research questions were formulated to guide the study:

RQ1: How does the use of digital technology affect the governance of a shared solar energy system?
1.1: What are the dynamics that govern sharing?
1.2: How is the system's long-term sustainability affected by the digital technology?
RQ2: How may the SES framework be employed or adapted to approach the above questions and what is its usefulness?

The case study method was applied as this allowed for the phenomenon of energy sharing across spaces to be studied in a real-world context [45]. In addition, case studies have been found to be especially useful in disentangling causal and complex processes [46] such as those implied in the topic under investigation. The specific case was chosen because of the explicit use of digital technology in its set-up. Moreover, the three apartment buildings within the WGV site allowed for an embedded case study design [47], in which the distinct buildings served as sub-units of analysis (ibid.) thus providing a larger evidence base.

Focused interviews with diverse stakeholders served as the main source of evidence and were supplemented with documentation and direct observation to corroborate findings, improving the validity of the findings [47]. This also served to gain an objective understanding of the implemented sharing structure. Participant information sessions were attended for the same purpose and allowed tracking of potential changes. Confirmation of the researchers' understanding of the shared structure was sought retrospectively from interviewees on multiple occasions.

Nine focused interviews of approximately one hour each were conducted with key project participants with the aim of understanding the process of energy sharing at the three sites. Table 2 lists the interviewed stakeholders, along with their involvement in the project. One interview was conducted in written form, where questions were emailed to the participating organisation's representative, and responses were emailed back after internal consultations. The oral interviews were audio-recorded and subsequently transcribed.

In addition, residents of the WGV apartment buildings were interviewed. After an initial round of three interviews with residents of Gen

Y (which were recorded and transcribed), a misunderstanding between project participants regarding the status of implementation of sharing structures became apparent. This meant that residents were largely unable to comment on their experiences with the systems under study. The subsequent nine interviews with residents (encompassing 10 households) were therefore deemed preliminary. Whilst they were audio-recorded and notes were taken by the interviewer, these interviews, being shorter and containing much less information, were not transcribed. A general interview guide is provided in Appendix B.

2.3. Analytical process based on the SES framework

Data were compiled in a database and then organised by question and answer per interviewee in Excel. Fig. 2 provides an overview of the analytical process. A first step consisted of establishing a baseline understanding of the system under study based on the interview data (2., Fig. 2). This is described in Section 3.1. The SES framework was then used to guide the analysis of how the use of digital technology affects the governance of a shared solar energy system. To address the complexity of this guiding research question, the process was broken up into six steps (3a – 3f, Fig. 2).

In elaborating on the SES framework, McGinnis and Ostrom [36] explained that any application of the framework to a particular case should begin with the identification of the types of interactions and outcomes most relevant to the research question under investigation. Given the boundaries already implicit in having selected the WGV shared solar energy system for analysis, this selection of a focal level of analysis was straight-forward (3a, Fig. 2). Nevertheless, to specify, we focus here on those aspects of governance that pertain to the system's day-to-day operation, and are less concerned with any possible external influences. Based on our general understanding of the system (2.), the WGV SRES was then translated into SES framework terms to unlock the framework's analytical powers.

In a second step (step 3c) in Fig. 2), measures of system performance were then determined [36] by consulting the interview data. Given our interest in the effect of digital technology specifically, this element had to then be isolated (3d). Based on this, and informed by the interview data, actual system outcomes were observed. To evaluate the (governance) system's overall sustainability, observed dynamics were then compared with the desired ones identified in step 3c).

3. Results and discussion

3.1. Description of the WGV system

The basic principle of energy sharing at WGV is that of allocation-based solar energy consumption coupled with a virtual transactive layer. Based on household allocations of available solar energy, the project uses the physical energy generation and storage technologies, metering devices per apartment and common areas, and software to enable the sharing of solar generated electricity. Fig. 3 offers a schematic overview of the sharing system illustrating the socio-technical connections between components of the system.

At Gen Y and Evermore households have an allocation of solar energy that is equivalent to their unit entitlement (that is, a percentage equivalent to their spatial ownership share). This solar electricity is assigned a price that is lower than the available retail tariff. Although apartment owners effectively own a share of the solar infrastructure, the monetary resource flow thus created is intended to feed into a sinking fund to finance future maintenance and replacement costs. Households using (less than) the allocated amount of solar energy pay the solar tariff. If a household requires more energy than what is allocated, the software enables P2P exchanges to occur within the building. A household that requires more energy may receive discounted solar from a neighbour within the same building who has not exhausted their allocated budget, creating an income for the neighbour. Reconciliation

Table 1
Overview of WGV case study buildings.

Building	Type	Number of apartments	Size of apartments	Solar PV	Battery storage	Occupation
Gen Y	Owner-occupied	3	1 bedroom	9 kW	10 kWh Li-Ion battery	Occupants moved in July & December 2017
Sustainable Housing for Artists and Creatives (SHAC)	The developer owns the building & energy infrastructure; occupants rent from them; social housing	12	1–3 bedrooms	19.6 kW	40 kWh Li-Ion battery	Majority of occupants moved between August & September 2017
Evermore	Owner-occupiers & renters	24	1–3 bedrooms	54 kW	150 kWh Li-Ion battery	Majority of occupants moved in September and October 2018

Table 2
Interviewed actors in the WGV case study, their involvement and data collected.

Actor	Involvement	Data *Gen Y*	*SHAC*	*Evermore*
Residents	Consume energy; SHAC: some residents involved in set-up of the cooperative and ensuing ideation of SHAC building; Gen Y and Evermore: council of owners may decide to manage electricity without external strata manager	3 audio-recorded & transcribed interviews (3 households)	2 preliminary audio-recorded interviews (1 individual, 1 group) with a total of 4 households	7 preliminary audio-recorded interviews with individuals from a total of 6 households
Strata manager	There are two strata managers, one at each Gen Y and Evermore. Employed by (two different) strata management companies, they are responsible for managing the electricity billing systems. At SHAC, this role is fulfilled by the developer.	1 audio-recorded & transcribed interview	–	–
		Direct observation (attendance at community information sessions); documentation (email correspondence)		
Affordable housing provider & developer	Developer of the SHAC building; own and manage the building and infrastructure, as well as the billing	–	1 audio-recorded & transcribed interview with project manager; email correspondence	–
Technology start-up/ transactive layer service provider	Provide the (blockchain-based) software application that calculates residents' bills – billing service provider.	1 audio-recorded & transcribed interview with senior executive/ co-founder		
Electrical engineering company	Designed and implemented the (physical) technical system; system maintenance; data monitoring	1 audio-recorded & transcribed interview with senior executive		
Network operator	The network operator for Western Australia; interested project observer	1 audio-recorded & transcribed interview with a manager		
State electricity retailer	Western Australia's electricity retailer; interested project observer	1 audio-recorded & transcribed interview with a manager		
State land development agency	Developed the Gen Y building and engaged the strata manager on behalf of the owners.	1 audio-recorded & transcribed interview with a senior development manager	–	–
Developer (Evermore)	Built Evermore and is selling the apartments; has handed over management to a strata manager	–	–	1 audio-recorded & transcribed interview with a director
Local Municipality	Local government for the WGV suburb and precinct; interested project observer	1 audio-recorded & transcribed interview with the mayor		
Government funding agency	Provided funding for research on increasing the uptake of solar PV and battery storage in strata residential developments in Australia	1 written interview, i.e. questions sent and responded to via email by Project Contract Management Services in consultation with their team		

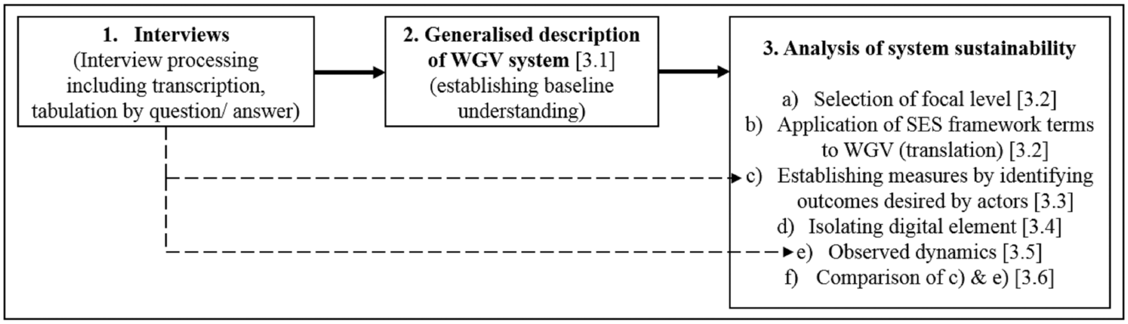

Fig. 2. Overview of analytical process. Interviews informed a general system description to serve as a baseline for analysis. In line with the research questions and based on the SES framework, system sustainability was analysed in a step-wise fashion. Numbers in parentheses indicate corresponding section in the text.

of energy data and tariffs takes place virtually on a 30 min aggregate basis. At SHAC, the power system infrastructure is owned by the developer who provides the discounted electricity to residents. Surpluses are shared on a needs basis and common areas electricity costs is covered by the developer.

3.2. Translating WGV's operative system into SES framework terms

To enable analysis using the SES framework, the system's different elements first needed to be translated into the conceptual language of the framework. To reiterate, the system's level of concern for this study is its day-to-day operation, i.e., the governance of the sharing of solar energy. Table 3 summarises how the categories of the framework (Fig. 1) correspond with the elements of the WGV system (Fig. 3). Table 4 list the interactions of the framework (Appendix A) that corresponded with key activities in the WGV operative system. Harvesting of energy, monitoring of consumption and generation, information sharing as well as evaluative activities emerged as central to the system's operation.

Other interactions such as investment activities, deliberation processes and networking activities (Appendix A) were found to be more relevant to the project set-up phase; while others, such as conflicts were deemed to arise occasionally without being an integral part of system governance as such. Another study [29] similarly differentiated between system creation, implementation and stability in applying the SES framework to an integrated community energy system. Having established how the categories and interactions of the SES framework relate to the case study, we now turn to the outcomes that the identified interactions should lead to in a well-performing system.

Table 3
Translation of SES framework categories into the WGV case study.

SES framework *categories*	Translation to WGV system components
Resource system	Energy supply system: Solar PV and battery storage; grid
Resource units	Energy in kWh, cost per unit
Actors	*Cf.* Table 2
Governance system	Sharing rules partly enforced by metering infrastructure, partly by software

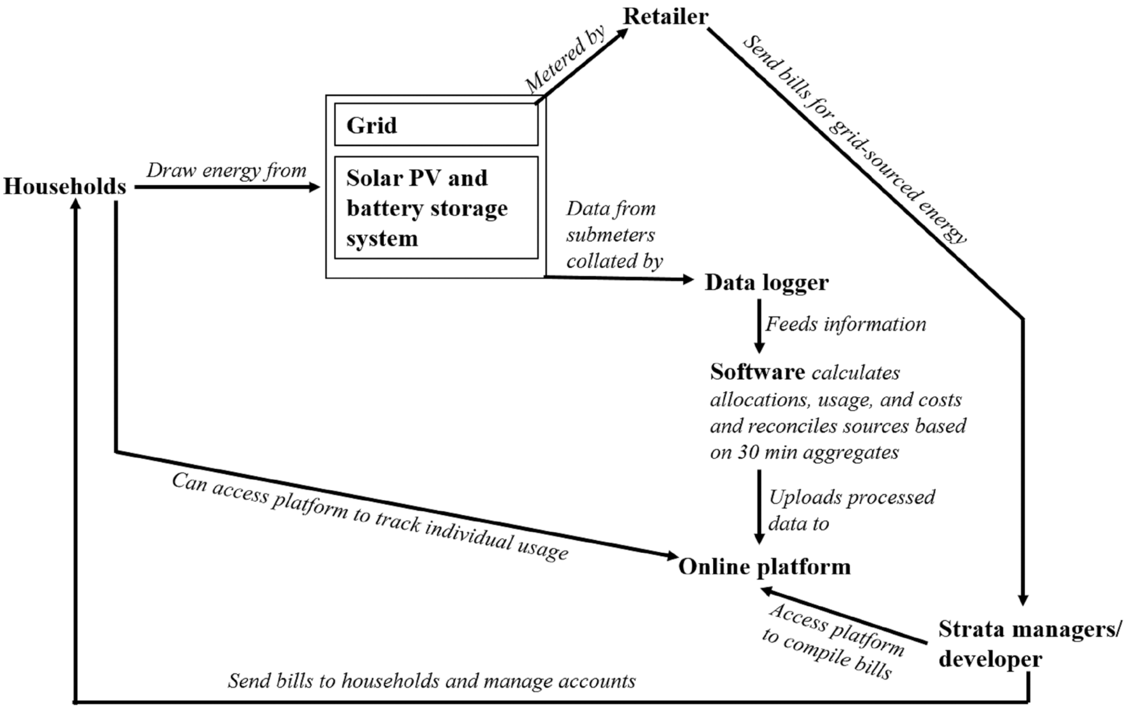

Fig. 3. Flow diagram illustrating the generalised WGV governance model in terms of the actions of different system components. Energy consumed by households is logged allowing the external software to calculate prices per unit of electricity according to their source and in relation to an individual's allocation. Managers as well as households can access an online platform showing usage and transactions with managers having access to all individuals' profiles. Given the single grid-connection point for the embedded network, grid-sourced energy is also metered by the retailer who then invoices the system administrator.

Table 4

Translation of SES framework interactions into the WGV' operative system. For the complete list of SES variables [36] see Appendix A.

Key SES framework *interactions* relevant to WGV operative system	Translation to WGV system interactions
Harvesting	- Energy consumption: harvesting of solar energy by residents (*cf.* also Acosta et al. [29]) - Feedback loop may be created in which access to energy consumption information *via* platform may influence a resident's actual consumption behaviour
Information sharing	- Data logger shares information with software: Information on energy consumption and generation serves as input into accounting software, allowing the software to determine who pays what for their electricity and to whom; reconciled data shared with system manager/developer - Retailer, platform, managers share information on electricity bills with managers/ residents
Monitoring	- Technical infrastructure & software track & monitor data - Prerequisite for translating consumption information produced by residents into the information required for billing - Performance monitoring of the technical sub-system & data generated by it
Evaluative activities	- Software reconciles data - Production of data used by stakeholders to evaluate (individual) project performance; (costs, energy generation and consumption)

3.3. Establishing measures of sustainability

To understand the nature of a successful governance system, interviewees were asked about their expectations, as well as about any measures they may take to evaluate whether it has been successful. As a first observation, the outcomes proposed by the SES framework were generally in line with interviewees' elaborations of what they hoped to achieve. The framework suggests three categories of outcomes which may be used to measure the success or sustainability of a system's governance structure (Appendix A): social performance measures, such as equity or accountability; ecological performance measures such as system resilience or sustainability; and externalities to other systems [36]. Across the data, an interest in cost savings for residents and positive environmental outcomes (social and environmental performance measures) were prominent.

The SHAC developer stated that lower costs for their tenants was their primary interest. Tariffs were to be reviewed every year to assess the financial sustainability of the model, for both developer and tenants. They also recounted that this aspect of the project had been frustrating for tenants thus far. Because of delays in getting the physical energy system up and running, the anticipated cost savings for tenants had not yet been achieved. The software company similarly asserted that the project was going to be successful when a "measurably beneficial outcome" in terms of providing low cost, low carbon energy had been proven. In addition to lower costs for households, the importance of demonstrating the affordability of new energy technologies was pointed to by the retailer.

Many residents' expectations similarly included lower running costs and savings on their electricity bills. While one interviewee stated that information material had specifically stated 80% of electricity would come from the solar storage system, most others were much less clear on this. Some expressed a degree of uncertainty as to whether cost savings would be achieved at all. Asked about the benefits of having a solar storage system, and motivations for moving into the development, there was a shared sentiment among residents as to its environmental benefits. Stated advantages included "fighting global warming", feeling better about the environment, helping establish a new paradigm and contributing to saving the planet.

Ecological performance measures were frequently mentioned by other interviewees as well. For example, the engineering firm's representative recognised the connection between the provision of a renewable energy system and the potential to reduce costs for tenants; but added that a main evaluative question was concerned with whether the embedded generation and storage system was working. Specifically, the renewable fraction of total energy consumed should be above 60%. They further stated that end use customer satisfaction was also important with regards to improving environmental sustainability and by creating access to a sustainable energy system in the first place. The municipality commented on their interest in identifying solutions to reduce carbon emissions.

In terms of potential externalities to other systems, the SHAC developer expressed an interest in seeing whether the business model could be transferable to other developments. They added that the project had been costly so far because of the additional management that had been required. The state land developer explained that a preliminary project review had already been undertaken to apply lessons to other sites with the project performing as per the business case. The potential of the project to facilitate the process of increasing uptake of renewables in strata developments was also noted, pointing out that apartments had sold well despite lacking features such as ocean views. As a project observer, the municipality was similarly interested in applying lessons learnt to other developments where sustainability and affordability were especially important.

To summarise, there appeared to be consensus among stakeholders that the sharing project would be successful if and/or when cost savings for residents, and positive environmental outcomes are achieved. Before examining how these goals may be linked to the use of digital technology used to operate the WGV system, the digital element needs to be placed within our analytical conceptualisation. This is done in the following section (3.4). Building on that, Section 3.5 analyses the observed impact of the digital element on the system, before any discrepancies between observed and desired outcomes are evaluated in Section 3.6.

3.4. Isolating the digital element

In order to be able to comment on the effect of the digital element, it, and its relation to the rest of the system, required clear identification. Unlike other technologies in the system (such as solar PV) however, the digital element does not pertain to a particular technological artefact: it cannot be definitively defined as any one system component, nor as a variable pertaining to any one of these components (tier-2 variable, Appendix A). Instead, the use of digital technology, in SES terms, may be described as pervading interactions. We found that the effect of digital technology on the system may most usefully be accounted for by relating it to the operative interactions – energy consumption (harvesting), monitoring, information sharing and evaluation (cf. Section 3.2).

Fig. 4 illustrates how SES interactions relate to interactions across physical and virtual spaces. Information emerged as the common denominator across spaces accounting for the role of digital technology. Interactions taking place in physical and virtual space serve to manage and produce information. For example, a resident consuming energy will produce the set of data needed by the software to reconcile it with other data and subsequently produce billing information. Between physical/ virtual spaces, the information processing phase serves to translate information between spaces.

The digital element in the examined SRES is thus represented by the information sharing interaction proposed in the SES framework. As in the SES framework, resource system and units, actors and governance system interact in harvesting, monitoring, evaluative and information sharing activities. Information sharing carries a second meaning however, in which it mediates the interaction of those very interactions. What is sometimes referred to as a digital overlay may be described as a master interaction – digitalism is not an attribute of any particular

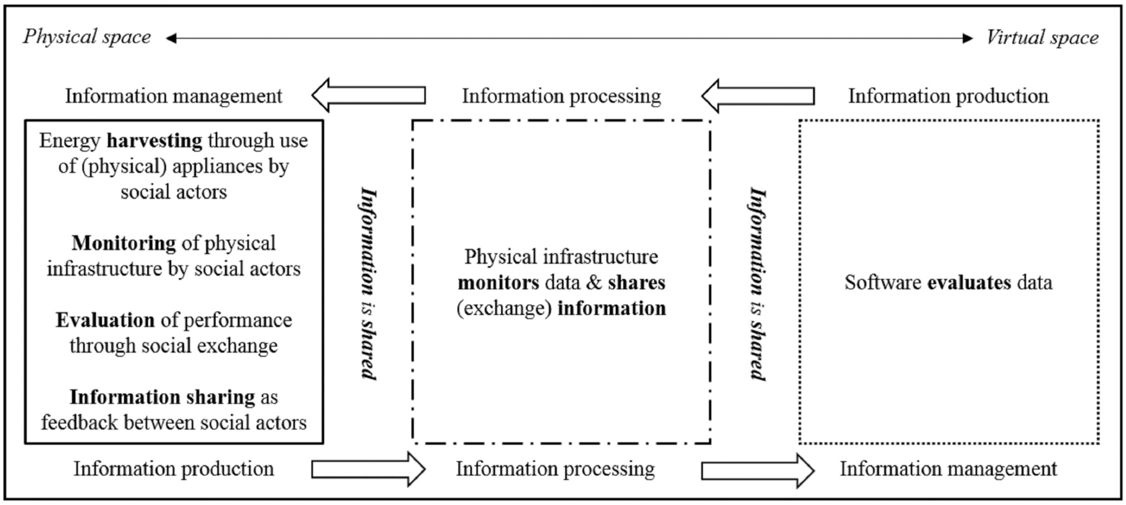

Fig. 4. Interactions occurring across physical and virtual spaces in the studied SRES. Information produced in physical and virtual space serve as inputs to be processed, and managed in the respective other space with an intermediary space serving as translator.

(technical) system component, but the enabler of interactions between components. Based on this understanding, the next section examines the dynamics that were observed at WGV.

3.5. *Observed dynamics*

Four themes emerged in analysing the outcomes of interaction in WGV. These are: emergence of new roles; over-reliance on technology; missed communication; and trust. Each is discussed in turn.

3.5.1. *Emergence of new roles*

Key to the innovation being trialled at WGV is the use of software to manage the complexity of multiple streams of data. The necessity for information to be transferred effectively affected the roles of social actors in the system. An interesting comment was made by the representative of the engineering firm. At the time of the interview, the responsibility for data management was with the engineers. However, given the experimental nature of the project and its organic development, this particular service had not been backed by a commercial arrangement. The significance of providing this service, and the role of the engineering firm in providing it, had not been anticipated. Thus, the novelty of the set-up with the digital transactive layer led to a need for new formal contracts and altered roles: the monitoring of data needed for the billing software represented an additional role for the engineering firm.

Moreover, the implementation of the software meant the addition of a new actor to the system, namely the software company. This implied a shift in responsibilities for billing: the management of strata energy bills shifted (albeit indirectly, in the form of maintenance of the software) from strata manager to the software company. As such, an implication of the use of a virtual component for the management of resource flows in WGV is the emergence of new roles linked, firstly, to the need for data monitoring; and secondly, to the expertise required to provide and manage the software. For the system to operate effectively, actors have to be aware of their own roles, and that of other operative agents. Given the complex interplay of technical and social elements in modern community energy systems, clear definitions of roles are a prerequisite for the effective coordination of resource flows [14].

3.5.2. *Fallacy of over-reliance on technology*

In contrast to our understanding of the digital element established in Section 3.4, stakeholders involved in the operation of the WGV systems did not identify it explicitly. Rather than referring to digitalism, interviewees talked about (a new) technology or software. The materialisation of digitalism as a technological artefact implicit in such language may have played a role in actors' failing to appreciate the importance of defining their own roles and responsibilities from the start. The importance attributed to the software in solving the complexity of sharing energy in strata developments led to an under-appreciation of social relations in successfully implementing the system.

An overdependence on technology has been described as an unintended consequence of the use of IT [48]. This fallacy of an over-reliance on technology seems to be a common theme in the popular discourse on prosuming. There is a commonly held view that prosuming increases user autonomy [49]; the term democratisation is frequently used to describe the transfer of power and control (back) to consumers, as they gain the ability to produce their own electricity [42,50]. The focus is on increased citizen-to-citizen interaction and reduced roles of (traditional) intermediaries [21], which may lead to the misconception of an overall reduced variety or importance of social actors. The term prosumer management [10] seems to sum up this dichotomy of interpretations, underscoring the need for external control in systems that assign increased internal control to consumers (making them prosumers).

We thus argue that while digitalisation (further) drives prosuming [49], it simultaneously drives a need for considerable expertise, perhaps shifting the prosumer's position from more power in some regards, to considerably less in others. The perceived importance of technology as a discrete enabler of new system configurations and changed power relations diverts the focus from the considerable expertise required to manage the technology. This requirement necessitates the involvement of social actors in successfully operating such systems. In this way, control over system operation is (further) removed from its actual users, the prosumers. Even more, looking specifically at blockchain technology, Buth, Wieczorek and Verbong [51] found that rather than being a panacea, the technology may create problematic shifts in power towards the software operator. While the provision and management of data are essential to the operation of a SRES, the digital infrastructure used to enable this requires itself a significant amount of management [27].

3.5.3. *Missed communication*

At WGV, an alienation of users from system operation became apparent in a striking lack of knowledge of the sharing system in interviewed residents. While most had some awareness of an intended sharing of energy, none had knowledge of the allocation-based (ownership and) management mechanism; some had insight into the new software being used for sharing. Because of delays in project implementation, at the time interviews were conducted, no induction sessions for residents had been held. This may explain why knowledge of the systems was lacking in residents at the particular point in time; but it also means that system

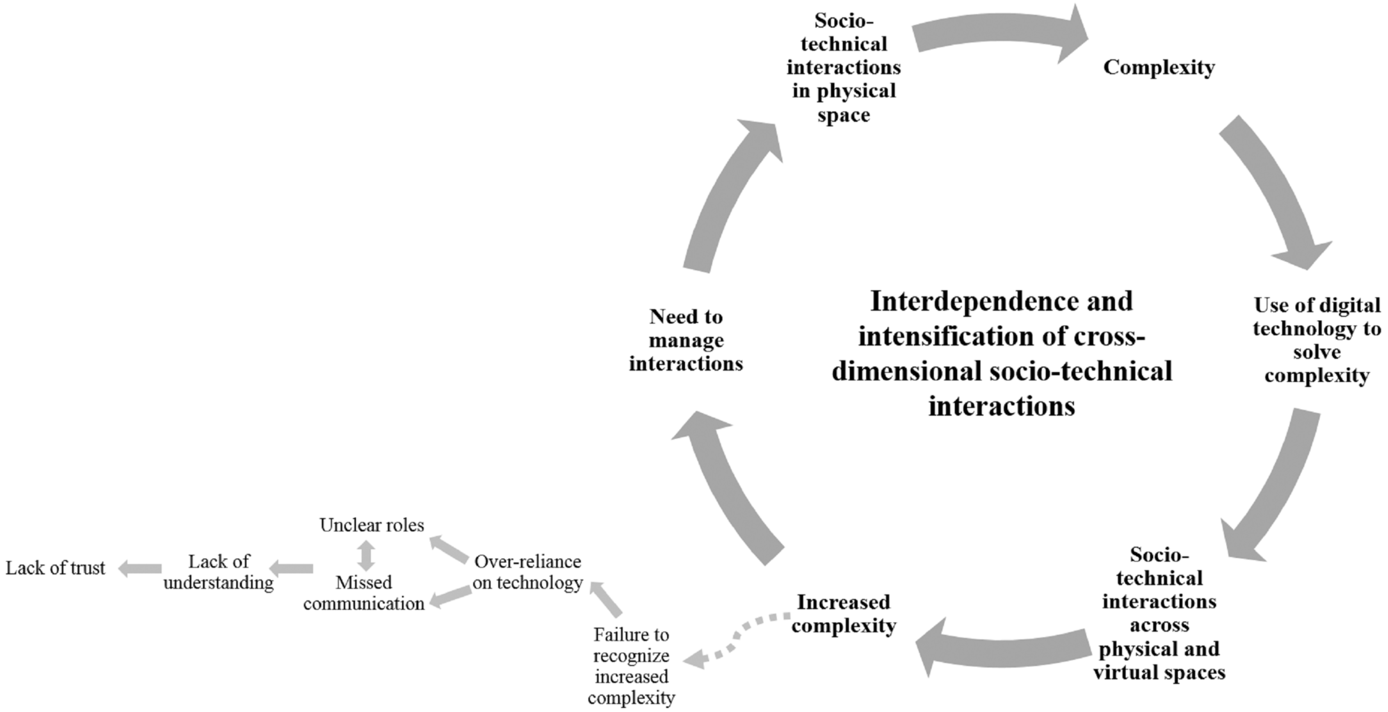

Fig. 5. Positive feedback loop of socio-technical interactions across physical and virtual spaces in the WGV case study. The complexity of sharing renewable energy in an apartment building led to the use of digital technology to solve the issue, leading to increased complexity through expertise and monitoring requirements; these in turn necessitate increased involvement of social actors in managing the system. If not managed appropriately, the re-enforced complexity may lead to unfavourable outcomes.

users were not involved in the development of the actual sharing rules and system set-up. Findings from other studies suggest that an accurate understanding of how the resource system works improves users' ability to assess benefits [52] and may lower the perceived costs associated with organising to sustain the resource [35].

A symptom of the over-reliance on technology in WGV was indicated by a lack of (social) communication amongst all project participants and this emerged as a theme in the interaction analysis. In one instance, failure to communicate effectively led to a dramatic misunderstanding between the Gen Y strata manager and the software provider. The interview with a strata manager revealed that they had deemed the sharing software unviable based on an inaccurate understanding of what it entailed, and had thus not put it to use. The benefit of the software was not apparent to the strata manager. The software provider on the other hand was unaware of the situation; and had in fact believed the system to have been implemented and working well.

This suggests that a misperception of the powers of the virtual component on part of the software provider may have contributed to this misunderstanding. Though the use of digital technology seemingly eliminates the need for social actors to communicate directly in terms of day-to-day decision-making, it does not remove the need to communicate, generally. Again, a parallel can be drawn to a study [48] on IT use in healthcare. The use of the IT in this study led to changes in the patterns and practices of communication, including a decline in some social interactions [48]. An illusion of communication was described, where an entry into the computer system was linked to the belief that somebody would receive it and act on it (ibid.). On the other hand, a large evidence base exists in the literature demonstrating the positive effect of communication on groups' problem-solving abilities [46], and on team effectiveness in creating sustainable local energy communities [19]. Janssen, Bousquet and Ostrom [53] even concluded that the mere possibility of communication was more important than the actual rules in determining the potential of resource management efforts.

3.5.4. Social and technical trust

The (technical) complexity of the WGV system, the need for experts, and the resultant alienation of stakeholders from the process, as well as the importance of data to the system, raises the issue of trust. A common theme in research on community resource governance, trust may affect the dynamics and outcomes of community renewable energy projects [6]. Face-to-face communication may increase trust and thereby increase the chances for commons governance projects to succeed [54]. In addition to this relevance of trust in social relationships, trust in data is also important. A comment made by the SHAC developer illustrates how the process of monitoring mediates this need. The interviewee recounted that they had asked the software provider to reconcile data from different meters on a regular basis to promote quality assurance as an initial lack of confidence in data presented a potential for tension between the developer and the engineering firm. Initial issues with the data loggers led to their reliability being questioned by the developer who required accurate data for billing purposes.

As such, although once set up, the technical system is expected to operate reliably, the fact that data is processed digitally and automatically means that this needs to be monitored for (some) actors to have trust in it; and that lack thereof may be a cause of conflict. The need for data sharing in system operation may also be grounds for privacy concerns [13]. On the other hand, one benefit of the digital technology in terms of trust may be the fact that (in the WGV case) it erases the risk of non-compliance. Because rules are enforced by the software, users do not have to monitor each other's behaviour with regards to, e.g., the inequitable use of allocated energy.

3.6. Evaluation of sustainability through comparison of desired and achieved outcomes

Section 3.5 showed that the complexity of coordinating social relationships is central to the system's functioning, and in parts under-appreciated [55]. While virtual interactions may resolve the mathematical complexity of compiling bills, the virtual component can only operate in combination with the (inter-) actions taken by social actors. Fig. 5 summarises this interdependency as a consequence of cross-dimensional interactions. At WGV, the complexity of socio-technical interactions (between energy users in apartment buildings and renewable energy infrastructure) instigated the use of digital technology. The resulting interactions across virtual and physical spaces have further driven complexity, which needs to be managed. Ultimately, this management requires human agents and therefore interactions in physical space. Consequently, the use of digital technology led to an intensification of the interdependencies between socio-technical interactions, in addition to pushing them beyond the physical realm.

Similar dynamics have been noted in the literature. Pallesen and Jacobsen [27] found that the introduction of smart technology to enable the system's operation in a Danish smart grid project led to new challenges and a significant increase in the infrastructure's complexity. In an analysis of disruptive innovation and transitions, Tyfield [26] observed a similar feedback loop and pointed to the complexity digital innovation brings to governance despite it being “generally evangelized as its panacea” (p.270). It is possible therefore that the dynamics observed in the case study are not unique to the WGV system, or even to shared energy schemes. New models using digital innovation should therefore be developed in a way that takes this increasing complexity into account [26]. In managing digitally enabled SRESs, a recognition of the complexity of interactions, and importance of social management efforts from the outset may be the single most important predictor of successful resource governance.

How do these findings relate to the desired outcomes stated by interviewees? In the SES framework, social and ecological performance is a function of system interactions. Our analysis has shown that the operative interactions of energy harvesting, monitoring, evaluation and information sharing led to an increase in system complexity that was not immediately apparent to actors in the system and led to the problems outlined above. In combination with delays observed by participants, at first instance, it can therefore be concluded that the digitally provoked complexity led to a delay in potential system benefits being delivered. Secondly, and interestingly, it may be argued that the desired outcomes of reduced costs and improved environmental footprint (through reduced grid-sourced energy) may be linked to system components (categories, Fig. 1) rather than (digital) interactions.

In the SES framework, properties define system components, and interactions define the outcomes that may result from them. In WGV, the portion of energy that each resident can source from the renewable system ultimately depends on the system's size and on the users’ ability to optimise electricity usage, where size and knowledge are properties of resource system and actors respectively. Achieving the anticipated outcomes can be theorised to be a process of managing interactions based on the set system properties, and adjusting either one until the optimal system state is reached. For properties of system components such as resource system and actors to promote desired outcomes, digitalism as a property of interactions needs to be accounted for. As shown, the effective operation of interactions may depend to a large degree on an appreciation of the complexity caused by the digital element. The system's stability in the long-term is likely to be the result of continuous micro-adjustments based on direct/ physical monitoring, information sharing and evaluative activities amongst social actors in the physical realm.

4. Conclusion

This study built on a small but growing body of literature applying insights from SES research to socio-technical energy systems. The exercise undertaken here does confirm other authors’ findings regarding the overlap of variables and general usefulness of such applications. In applying the SES framework to the WGV system, relationships between actors, governance system, resource system and units and the focal action situations remained unchanged: governance and resource systems set the conditions for action situations, while resource units serve as input and actors participate. Social, economic and political settings, as well as related ecosystems may still influence the system. Categories and interactions allowed to accommodate all relevant aspects of the system under study. A differentiation between phases of project development was found to be useful [29] in identifying interactions relevant to the actual day-to-day operation of the system. The most significant alteration to the original framework proposed here is the conceptualisation of digitalism as a property of interactions; and the ‘up-grading’ of the information sharing interaction to a master interaction. Though still relevant to interactions between system components in physical space, information sharing in the studied SRES also mediates interactions between interactions thereby encapsulating the nature of digital technology.

Although many studies have examined the use of a particular digital technology, or user interactions with a particular digital feature such as online platforms, to the authors’ knowledge none have thus far explicitly discerned the digital element in relation to other system features. Understanding the structural effect of digitalism is important however, for two main reasons: Firstly, as this study has demonstrated, digital technology has a significant effect on the governance of sharing. Analyses of the effectiveness of shared (or community) energy initiatives should therefore take such impacts into account. In this regard, our contribution is in having shown that digitalism can be conceptualised and analysed as a property of interactions within the SES framework, rather than a property of system components. Our second contribution in this regard relates to the notion of socio-technical interactions well-established in energy studies. Given the pervasive use of digital technology in modern energy systems, socio-technical conceptualisations may benefit from a more explicit consideration of physical-virtual dynamics.

It has been argued that the models of cooperation being trialled in living laboratories (such as WGV) are subject to significant uncertainty [56]. Experimental spaces therefore need to be made available that enable the exploration of novel cooperative models (ibid.). The degree of uncertainty inherent in such innovation implies that funding for research and innovation should account for (the possibility of) partial failure (ibid.). The feedback loop of increasing complexity may also serve to provide productive innovation – i.e., instead of increasing complexity, productive innovation may be accelerated [26]. This in turn may create the momentum necessary to break out of the carbon-lock in (ibid.). As such, in addition to accounting for potential failure, experimental undertakings of complex sharing schemes may benefit from an upfront framing of the initiative as an ongoing process, rather than merely the implementation of a pre-determined solution.

The case study nature of the investigation means that findings may not be broadly generalisable. Similar analyses of other shared energy systems would therefore be a beneficial contribution to this body of literature. Given the opportunity for discussion afforded by a single research paper, the study also lacks a level of detail that could add significant depth to our understanding of processes at WGV. Further analyses are currently being undertaken to discern the differences between the specific sharing structures at Gen Y, SHAC and Evermore at the micro-level. One may speculate that while the significance of the virtual component was demonstrated for a case study only, current trends regarding the integration of technology into everyday life may mean that its role is not unique to the WGV sharing system but is instead fundamental to the governance of any natural resource systems. It is therefore essential for a successful sustainability transition that more research on cross-dimensional interactions in SRESs (and other shared resource systems) be undertaken.

Funding

This research was funded by the CRC for Low Carbon Living Ltd supported by the Cooperative Research Centres program, an Australian Government initiative; and received funding from the Australian Renewable Energy Agency as part of its Research and Development Programme. Paula Hansen received funding from the Australian Housing and Urban Research Institute through their research capacity building in the form of a PhD top-up scholarship. The funding bodies had no involvement in study design; data collection, analysis and interpretation; nor in the writing of the report. Permission to publish this research article was sought and granted from all three funding bodies prior to submission.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Supplementary materials

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.erss.2019.101322.

Appendix A. SES framework variables

Table A1

Table A1
Social-ecological systems framework variables, adapted from McGinnis and Ostrom [36].

First-tier variable	Second-tier variables
Social, economic, and political settings (S)	S1 – Economic development S2 – Demographic trends S3 – Political stability S4 – Other governance systems S5 – Markets S6 – Media organizations S7 – Technology
Resource systems (RS)	RS1 – Sector (e.g., water, forests, pasture, fish) RS2 – Clarity of system boundaries RS3 – Size of resource system RS4 – Human-constructed facilities RS5 – Productivity of system RS6 – Equilibrium properties RS7 – Predictability of system dynamics RS8 – Storage characteristics RS9 – Location
Governance systems (GS)	GS1 – Government organizations GS2 – Nongovernment organizations GS3 – Network structure GS4 – Property-rights systems GS5 – Operational-choice rules GS6 – Collective-choice rules GS7 – Constitutional-choice rules GS8 – Monitoring and sanctioning rules
Resource units (RU)	RU1 – Resource unit mobility RU2 – Growth or replacement rate RU3 – Interaction among resource units RU4 – Economic value RU5 – Number of units RU6 – Distinctive characteristics RU7 – Spatial and temporal distribution
Actors (A)	A1 – Number of relevant actors A2 – Socioeconomic attributes A3 – History or past experiences A4 – Location A5 – Leadership/entrepreneurship A6 – Norms (trust-reciprocity)/social capital A7 – Knowledge of SES/mental models A8 – Importance of resource (dependence) A9 – Technologies available
Action situations: Interactions (I) → Outcomes (O)	I1 – Harvesting I2 – Information sharing I3 – Deliberation processes I4 – Conflicts I5 – Investment activities I6 – Lobbying activities I7 – Self-organizing activities I8 – Networking activities I9 – Monitoring activities I10 – Evaluative activities O1 – Social performance measures (e.g., efficiency, equity, accountability, sustainability) O2 – Ecological performance measures (e.g., overharvested, resilience, biodiversity, sustainability) O3 – Externalities to other SESs
Related ecosystems (ECO)	ECO1 – Climate patterns ECO2 – Pollution patterns ECO3 – Flows into and out of focal SES

Appendix B. Generalised interview guide

1 What do you know about the shared energy system generally (in terms of how it operates)?
2 Could you describe how you/ your organisation is involved in this trial?
3 What motivated you/ your organisation to be involved?
4 What is your goal or intention?
5 When will this trial be successful for you/ your organisation? What makes a successful project? How do you evaluate this? How do you define success?
6 Are there any formal rules, procedures, or regulations that prevent/ have prevented you from pursuing this goal? That support you in your activities?
7 How are you involved now? What do you/ your organisation do, how do you engage with the WGV system?
8 What were/ are the key activities? Any regular activities? How often, when, why, who, how?
9 What information are needed for that? And where do you get them?
10 Are there any formal rules, procedures, or regulation that you (have to) follow?
11 Do you use any physical component?
12 (How) do you/ your organisation interact – or has interacted – with other organisations or stakeholders in the project?
13 Do you interact with the users/ residents? … degree of interaction?
14 What do you expect to see when people start using the system/ have gotten used to using it?
15 If the overall trial is successful do you think it will be replicated/ applied to other sides in Australia? Should it be “scaled up”?
16 How important do you think it is to scale up projects like this?
17 What is your/ your organisation role in the project's overall success?
18 What do you think is the timeframe for this type of shared system in medium density developments to find mass uptake in Australia?
19 What will influence this (the most)?
20 Can the project facilitate this process? Why?
21 What is you/ your organisation role in facilitating mass uptake of this?
22 How has the project influenced you/ your organisation?

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Publication III

Published/ Peer-reviewed journal article

Syed, M. M., Hansen, P., & Morrison, G. M. (2020). Performance of a shared solar and battery storage system in an Australian apartment building. Energy and Buildings, 225, 110321.

Energy & Buildings 225 (2020) 110321

Contents lists available at ScienceDirect

Energy & Buildings

journal homepage: www.elsevier.com/locate/enb

Performance of a shared solar and battery storage system in an Australian apartment building

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ARTICLE INFO

Article history:
Received 12 April 2020
Revised 21 June 2020
Accepted 17 July 2020
Available online 22 July 2020

Keywords:
Shared energy system
Shared energy microgrid
Battery energy storage system
Energy performance analysis
Apartment buildings
Empirical analysis
Self-sufficiency
Solar PV

ABSTRACT

This study presents the energy performance of a three unit apartment building in Perth, Western Australia equipped with a shared energy microgrid. Although there has been a dramatic growth of residential rooftop solar PV across Australia, apartment buildings and their occupants are rarely able to access the benefits associated with onsite renewable energy generation and consumption. To address this, an apartment building in Perth was fitted with a PV and battery energy storage system, with metering architecture. The microgrid configuration enabled the sharing of energy between the apartment units. A one year dataset (December 2017-December 2018) obtained from onsite pulse meters was analysed. Load profiles were assessed and grid minimisation was evaluated through self-sufficiency metric. The three unit apartment showed a 22% reduction in average yearly energy consumption against the benchmark. The findings demonstrated an overall 75% dependency of the microgrid on renewables; and suggest that a shared energy microgrid may be more effective than separate supply connections.

1. Introduction

Increasing costs of network supplied electricity coupled with decreasing costs of solar panels [1] and policies supporting the uptake of renewables, have resulted in investments at scale in rooftop solar Photovoltaics (PV) [2]. An increase in installation capacity of 99% across Australia over the past ten years has led to more than 2 million dwellings with rooftop solar PV setups and a combined capacity exceeding 11 GW [3]. Western Australia is projected to experience the highest customer growth and the highest rate of growth in residential rooftop solar PV capacity in Australia, to reach 4.8 GW by 2025 [4]. Concurrently, a decline in grid sourced energy has been observed [5] as a result of a combination of a move towards less energy intensive industries, the effects of energy efficiency programs, and rising electricity prices. In addition, reduction in grid demand has also occurred with the expansion of rooftop solar PV and distributed generators [5]. The energy transition towards an embedded decentralised renewable energy system is further enabled by finance for renewable energy innovation such as efficient PV panels, battery storage technologies and smart metering [6].

While rooftop PV has widely diffused into the detached residential housing market, challenges with shared ownership, absence of a regulatory framework and cost incentives have impeded the uptake of PV and Battery Energy Storage Systems (BESS)[1] in multi-residential apartment and strata[2] developments [8]. Although utility networks have established technical guidelines to assess regulations and standards for grid connected renewable systems [9], PV and BESS configurations suitable for shared distribution in apartment buildings have not been reported. Only a few cases of multi-residential solar-storage developments with shared governance exist in practice; to the authors' knowledge no empirical analyses based on an implemented system exist in the literature. The aim of this paper is to present the energy performance of an apartment building designed for grid usage minimisation. The building is located in Fremantle, Western Australia and connected to a shared microgrid utilising solar PV and BESS combined with a metering architecture.

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[1] *Abbreviations: BESS – Battery Energy Storage System; CP – Common Property; IEG – Inverter Embedded Generator; Li-ion – Lithium-ion; LFP – Lithium iron phosphate; MPPT – Maximum Power Point Tracker; PV – Photovoltaic; SEM – Shared Energy Microgrid; SOC – State of charge*

[2] *Strata titled properties combine individual ownership of lots with shared ownership of common property through a legal entity referred to as strata company or owners corporation [7].*

https://doi.org/10.1016/j.enbuild.2020.110321

1.1. Issues concerning the uptake of renewables in apartment buildings

The growth in rooftop PV and BESS has occurred predominantly in freehold dwellings, with a limited number of residents of apartment buildings having access to solar energy [10-12]. A key reason for the exclusion of apartment buildings in these trends is the lack of governance structures that enable effective sharing of the costs, risks, and benefits of solar installations between households, developers, owners and utilities [10]. With nearly 9% of the Australian population living in apartments [13], sharing models need to address the split incentive issue. This arises when the benefit of reduced electricity bills is not accessed by the owner investing in the renewable source, but the tenant occupying their property, which leads to underinvestment in energy saving measures [14]. Physical limitations such as restricted roof space in proportion to numbers of residents combine with the complexity of conflicting interests of multiple households and thereby mean that the integration of solar PV in apartment buildings is a challenge. Despite all these problems, installation of solar PV can provide benefits in terms of reduced electricity bills [27] and significant reduction of carbon emissions [15]. Unlocking residential multi-dwelling developments to the benefits of solar energy could assist Australia in achieving carbon reduction targets of 441 $MtCO_2e$ by 2030 [16] and in an increase in self-consumption of the buildings [8].

1.2. Residential microgrid

Microgrids in general adopt PV as the main energy generation source along with other renewable technologies depending on feasibility [17] and also due to their enhanced design topologies, performance, efficiency and safety, all of which is improving with continued advancement in technology [18].

Recent developments in microgrids have focused on residential communities as ideal applications [19]. Whilst studies related to PV deployment in apartments have focused on technical performance evaluation [20] and techno-economic analysis of simplified microgrids with PV systems [8,21-25], few publications have studied apartment electricity loads in detail [26,27]. Shared microgrids containing PV and battery storage in multi-residential apartments have been relatively poorly investigated. A techno-economic study was performed by [28] to analyse the impact of PV-BESS systems using apartment interval data, although the deployment of actual PV-BESS on a particular apartment building has not been investigated.

In this context, we present a Shared Energy Microgrid (SEM) utilising a combined solar PV and BESS with metering architecture connected to apartment units. Energy performance is evaluated in its first year of operation; this is a significant contribution to the literature because apartment buildings are rarely discussed explicitly; performance data on these developments is scarce and such configurations provide a new and efficient way to enable the sharing of solar energy for residents. The paper begins with a descriptive approach to understand the problem; information about the systems is then presented, followed by methodology, analysis and finally discussion of results.

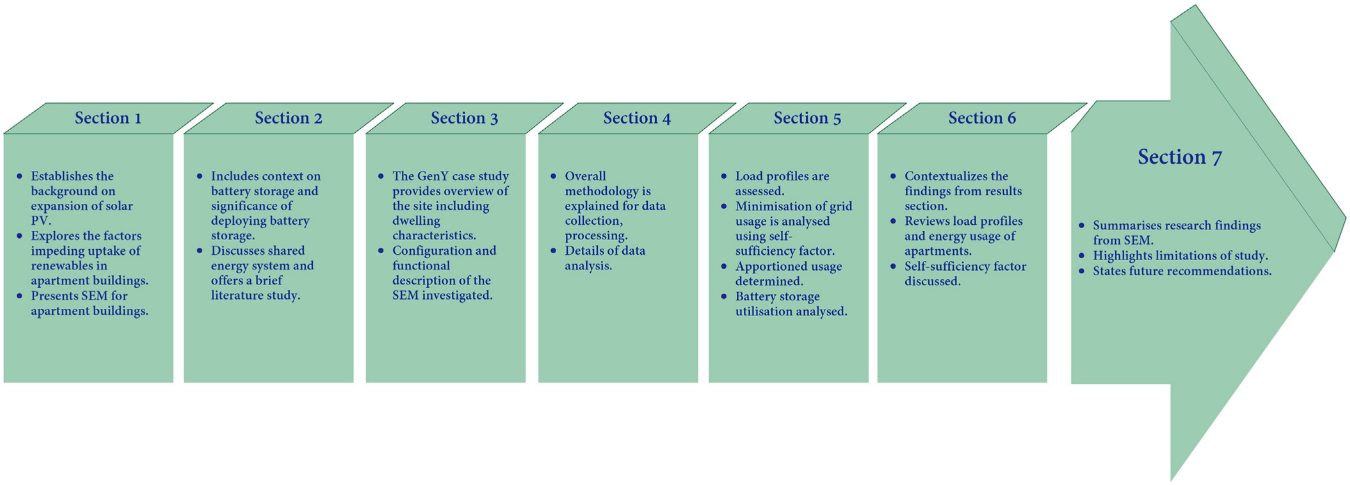
The paper is structured as illustrated by the arrow diagram of Fig. 1. The article begins from Section 1 by describing high level issues related to the uptake of renewables in apartment buildings which guides us to the background discussion of energy storage and shared energy systems covered in section 2. The significance of shared energy is also discussed with examples in different studies. On the basis of this context, we introduce the SEM in Section 3, with configuration details and technical description of the whole system. Section 4 discusses the methodology and analysis. The findings from the data analysis are presented in Section 5 with two main objectives. First, load consumption profiles from real time data were assessed for the apartment building with respect to average diurnal and monthly usage which has not been previously discussed in the literature. Secondly, the minimisation of grid energy usage is determined through the evaluation of self-sufficiency. The results also include the share of both sources in the load consumption, and battery utilisation in peak periods. Section 6 is a discussion of the analysed results. Finally, we conclude the paper by pointing out key findings and suggestions for future research in Section 7.

2. Battery storage and shared systems

2.1. Battery storage

The demand for battery storage is growing rapidly due to its potential to provide the backup for intermittent renewable sources. It is predicted that global installed battery storage capacity will increase from 29GWh in 2020 to 81GWh in 2024 [29]. Meanwhile in Australia household battery storage capacity reached 1GWh in 2019 [30]. Moreover, with the falling costs of batteries, hybrid systems are becoming increasingly attractive for Australian households [31].

Energy storage systems can increase the reliability and quality of power supply and self-consumption for end consumers [32] and can help defer grid extensions through reduction in peak



Section 1
- Establishes the background on expansion of solar PV.
- Explores the factors impeding uptake of renewables in apartment buildings.
- Presents SEM for apartment buildings.

Section 2
- Includes context on battery storage and significance of deploying battery storage.
- Discusses shared energy system and offers a brief literature study.

Section 3
- The GenY case study provides overview of the site including dwelling characteristics.
- Configuration and functional description of the SEM investigated.

Section 4
- Overall methodology is explained for data collection, processing.
- Details of data analysis.

Section 5
- Load profiles are assessed.
- Minimisation of grid usage is analysed using self-sufficiency factor.
- Apportioned usage determined.
- Battery storage utilisation analysed.

Section 6
- Contextualizes the findings from results section.
- Reviews load profiles and energy usage of apartments.
- Self-sufficiency factor discussed.

Section 7
- Summarises research findings from SEM.
- Highlights limitations of study.
- States future recommendations.

Fig. 1. Overview of article structure.

demand [12]. They reduce grid imported electricity by peak shaving [12,33-36] and through optimisation of the renewable source and battery operation [34,37-40].

Several battery technologies have been researched and compared in terms of their efficiency, costs, lifecycles and other parameters [41] however, for residential microgrids and small scale applications, Lithium-ion (Li-ion) battery technology has proven to be the most viable option [42]. Li-ion batteries have high energy density, improved life cycle, high efficiency and possess high power capability [43]. However, the cost factor is a major barrier in large scale deployment [35]. Due to expansion of the global electric vehicle market, Li-ion battery prices are expected to decrease over the next three years to $100/kWh [44,45].

A growing body of literature has evaluated BESS models for the purpose of curtailing grid reliance. An energy storage system design has been simulated to reduce electricity bills for a residential Zero-Energy Building in Portugal [32] which achieved a reduction of grid export and import energy by 76% and 78% respectively. Different battery storage models were compared by [46] through the use of measured electricity data from 99 Texas households. The peak demand power using a target zero method was reduced to 32% while a minimising power method reduced the peak demand to 8%.

2.2. Shared energy system

Given that 86% of the Australian population live in urban areas [47], the implementation of renewable energy sharing is a challenge in metropolitan environments where apartment buildings are in a space constrained area with ubiquitous availability of grid sourced electricity. Approaches to the integration of PV systems in apartment developments thus far have focussed either on connecting units to independent PV systems; on sharing the energy generated by a PV system through an embedded network; or on supplying energy to the common property (CP) only [11]. However, the business models that enable the sharing of energy via solar PV BESS [12] are not well developed. Energy sharing is usually discussed for multi-residential buildings in a community or more than one detached dwelling. In that regard, we establish our definition of SEM as an embedded network behind the main grid in which the renewable system is owned jointly by apartment owners for electrical supply while high level benefits such as cost reduction and lower environmental footprint are envisaged. We use the term SEM to differentiate between a conventional embedded network [27] and the case study, where an explicit focus on collective ownership of the infrastructure and the possibility of peer-to-peer trading guided the design of the system. The implemented governance structure is discussed in [60].Moreover, there is a minor difference between SEM and community microgrids: while both configurations rely on a centralised renewable source, a community microgrid is monitored in an aggregate manner whereas in SEM residential loads are monitored via sub-meters [48]. In the case of shared systems the energy consumption disseminates in a set of residential units, averaging out load variances to offer a cost effective storage solution resulting from the fact that someone in the community at any particular instant would be utilising energy from the battery [12]. If an occupant vacates, the allocated share could be sold to a new entity [49]. Therefore high self-consumption ratios and high self-sufficiencies are also achievable from a microgrid using a centralized resource approach with shared load configuration [50].

A SEM generates energy based on rated capacity, which is then de-multiplexed among different users through electrical distribution. Traditionally these loads decrease consumer accession costs by eliminating the requirement of several site assessments as compared to a single community site. In other words, entire residential units draw the utility and PV-BESS sourced power via a single connection point.

2.3. SEM in the literature

SEM has been the subject of many pilot studies around the globe however, there are very few instances of real-time operational sites. One study [51] allowed surplus renewable energy to be shared between prosumers in a neighbourhood through aggregated small scale batteries, thereby reducing 30% of energy cost compared to surplus PV exports. An investigation simulated the energy demand of a few households in a community using the Monte Carlo method to optimise the size and layout of a community shared solar PV system [52]. A discrete-time simulation model assessed the reduction in grid interaction from energy sharing in a net zero communal microgrid [53].

A number of studies have developed virtual energy sharing algorithms utilising PV and battery storage [54,55]. A simulation of an energy system model was performed by [56] from a simple household grid connection through to interconnected shared communal and individual PV with battery storage. In extension to this, [57] studied autonomy and environmental impacts due to shared generation, storage and communal consumption. Community formation was simulated using 15 minute interval consumption data in [58] and a framework was used to demonstrate storage selection. The authors discovered that community battery storage provides increased self-sufficiency and significantly reduces the surplus solar exports which are fed to the utility. A novel new energy management framework for a five unit communal PV and battery storage was presented in [59]. A multistage stochastic program was used to manage energy considering individual and shared control strategies. The proposed shared storage strategy reduced the overall electricity purchase costs and storage capacity compared with individual energy management of households. In addition to technical studies, socio-technical analyses of shared renewable energy systems have also emerged (e.g. [60]).

3. Case study - Gen Y demonstration housing

The Gen Y demonstration house project envisioned a design which encapsulated the sense of community, sustainability and affordability to suit 21st century living i.e. meeting the lifestyle demands of Generation Y. Built on an area of 250 m^2, it is a free-standing two storey, three apartment multi-residential dwelling nestled within the 2.2 ha White Gum Valley precinct located in the City of Fremantle, near Perth, the state capital of Western Australia. The size of Gen Y is significantly smaller than the average floor area of an Australian dwelling (240m^2) [61,62].

3.1. Dwelling characteristics

The Gen Y demonstration design incorporates a SEM fitted with a 9kWp solar PV and BESS with 10 kWh Lithium iron phosphate (LFP) in a microgrid topology [10]. LFP is considered as the most durable of Li-ion battery technologies [43]. The owners' corporation owns the solar PV and BESS and generated and stored electricity. The shared areas and facilities within the building are communally owned and managed by an agency nominated by the owner-occupiers. In the governance model, a fixed proportion of the PV generated electricity is allocated to each apartment in the building as well as to the CP [60]. Electricity bills are paid to strata management which use a blockchain billing system to allocate a fair distribution of energy generated on-site, and the margin earned can be used to offset strata levies. The SEM installed at Gen Y was projected to cover 60% of the energy demand through PV and

BESS, while the remaining 40% capacity would be provided through the electrical grid.

3.2. Energy system configuration

The SEM of Gen Y is comprised of a number of components in its design. Each component has its own operating principles and control methods. The system containing PV and battery storage (in line with distribution network guidelines [9]) is also defined as an Inverter Embedded Generator (IEG). There are several configurations to install IEG systems on the basis of applications but typically the arrangement contains two main elements i.e. PV source with or without storage medium and bidirectional DC-DC converter and then DC-AC inverter [9]. Generally two configurations for residential IEG systems are used (1) AC coupled where the PV and BESS comprised of bidirectional converters are connected on the AC bus and (2) DC coupled where the PV is connected on the DC bus with BESS and AC side is connected to BESS inverter. Fig. 2 illustrates the AC coupled configuration deployed at Gen Y.

One advantage of this connection is integration of different AC compatible converter systems to the loads and grid and a second advantage is that this configuration can be easily expanded to meet increasing energy demand. Moreover, the battery storage component can function independently of PV source [18]. All IEG systems connected to the utility network as a rule comply with the Australian standard AS/NZS 4777 [9]. Component ratings and pulse metering information for this microgrid are provided in Table 1. Roof mounted PV panels of 9 kWp PV were connected in a combination of 36 × 250 W (poly-crystalline) PV modules. The system consisted of two Maximum Power Point Tracker (MPPT) circuits coupled with 12 separate strings of three PV modules each, six strings for the 1st MPPT with six strings for the 2nd MPPT. A Sunny Tripower inverter,labelled as PV Inverter in Figure 2 is an integral part of this AC coupled system which converts PV generated DC into AC output which is then fed into the BESS.

3.3. SEM operation

Each apartment connects to the microgrid in an embedded configuration with a centralized BESS as shown in Fig. 3. The main objectives of commissioning the microgrid were (1) Store PV generated energy during daylight hours in LFP batteries (2) Supply on site loads and (3) Feed excess energy back to the grid while releasing the stored energy to supply loads during the night time or when there is no availability of PV. If the load demand exceeds available solar PV generation and battery storage capacity, then the loads are also fed from the grid. A bidirectional inverter inside the BESS charges the battery. It also provides the path for PV generated AC power to supply the load, and transfers excess power to the grid. Generally the battery is not charged from the grid when it is configured for self-consumption with excess export [9] however, the BESS in SEM is charged through the grid to maintain a minimum operational State of Charge (SOC). The bidirectional inverter provides dynamic functions such as protection, synchronization and anti-islanding. Metering plays a central role in the measurement of bidirectional energy flow, generation as well as electricity consumption of households. The pulse metering used at Gen Y consists of KMP1-50 sub-meters connected to monitor residential loads with pulse weight of 1000 imp/kWh and class B precision of 1%, whereas IEM3255 pulse energy meters are used to measure bidirectional energy flow from grid and PV-BESS. IEM3255 meters hold pulse weight of 5000 imp/kWh and class C precision of 0.5%. All meters are connected to a ComX'510 data-logger which has data resolution of 15 minutes. This combination of pulse meter and data-logger records temporal measurements of load consumed and energy generated. Therefore much like smart meters, they may help in predicting the optimised load profiles based on obtained data thus reducing electricity costs and also incentivising prosumers to forecast the best period for selling excess PV energy to the grid [63].

Table 1
Gen Y SEM component specifications.

Sub-meter	KMP1-50
Pulse energy meter	IEM3255
Interface Modules	SIM10M
Data logger	Com'X 510
BESS	BYD 10kWh
Solar PV Modules	9kWp Hanwa Q cells Poly Crystalline
PV-Inverter	SMA Sunny Tri power

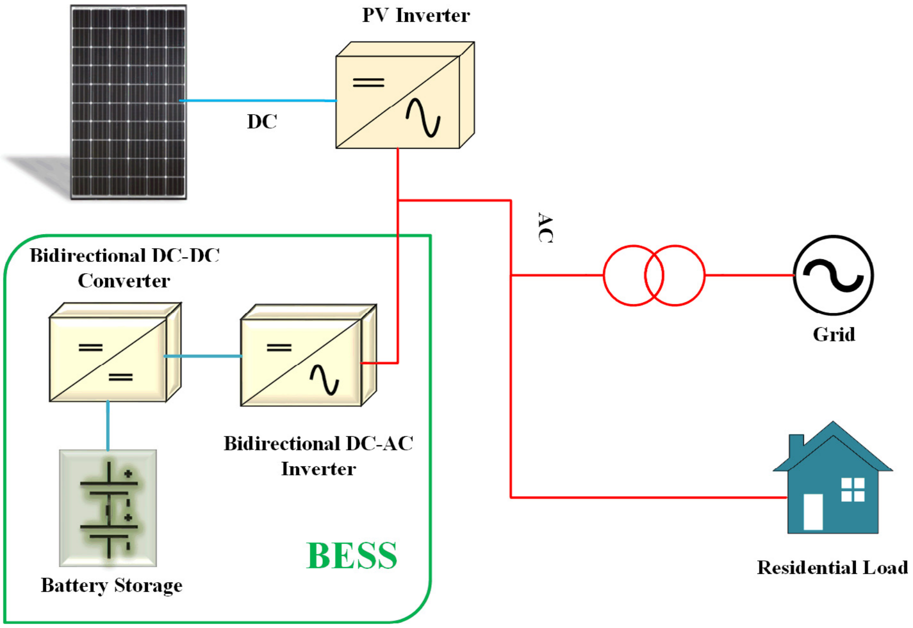


Fig. 2. AC-coupled system used in Gen Y configured as IEG topology.

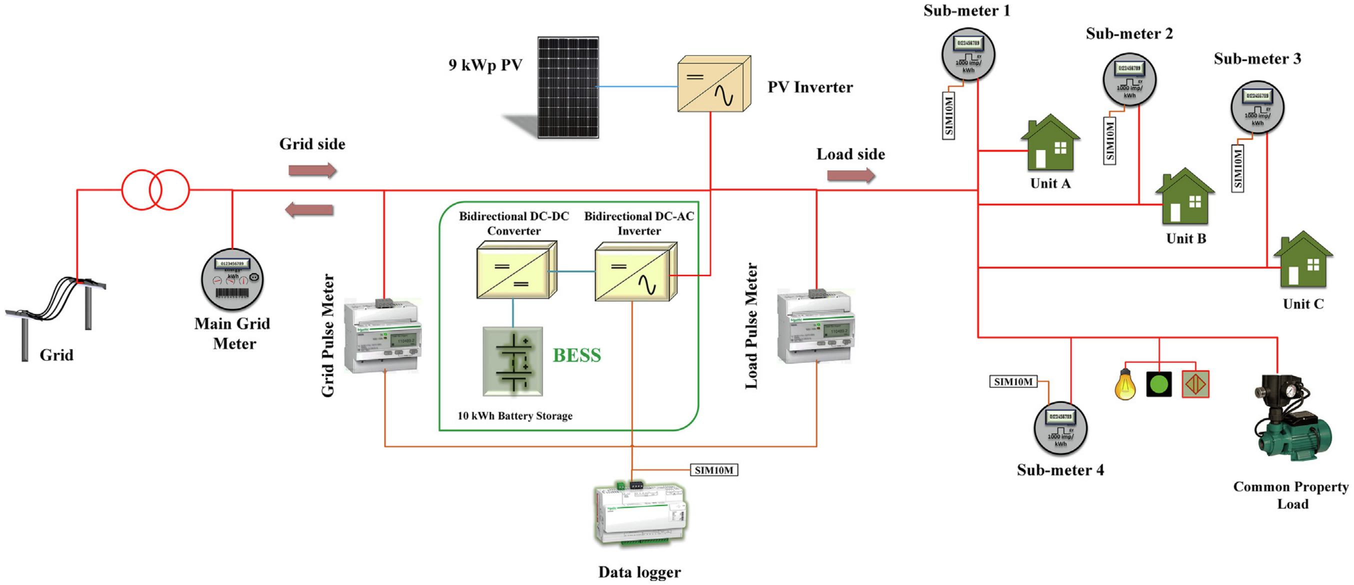


Fig. 3. The block diagram of Gen Y SEM.

The installation of SEM pulse meters was arranged in parent and child configuration [64]. Electricity passes through the loads from the grid *via* main grid meter and grid pulse meter IEM3255 and individual apartments are wired by means of KMP1-50 pulse sub-meters. For reconciliation, another load pulse energy meter was also installed to measure the total load measurements.This metering configuration balances load distribution as well as eliminates multiple grid connections which provides significant cost savings. The hybrid metering network protocol used in Gen Y is Modbus-RS485. All meters used for electricity billing are approved and meet NMI Regulations[3]. Moreover, a cloud based energy monitoring system including a ComX'510 data-logger system was configured to collect and measure electricity consumption from onsite meters [65] and the resolution set for obtaining data from the data-logger is 15 minutes.

4. Methodology

4.1. Data collection

This section describes the overall methodology used for data collection, processing and analysis. The methodological scheme is shown in Fig. 4. The consumption data from the three units were taken from on-site pulse meters through an interface module (SIM10M) and data-logger. The metering network communicates *via* Modbus-RS485 which terminates at the data-logger. Pulse meters employ internal Modbus registers to measure different parameters which are then stored in ComX'510. The network is also connected to an interminable onsite broadband internet as a means to transfer and store the data to the web server. The web server is hosted by a project participant organisation which runs Schneider PME application which is the bridging platform for managing data using a SQL database. The SQL database manages data in the form of tables and each metering device added has a unique ID identifier for inputs. An external script extracts information from the SQL database and pushes it to the big-query database which utilises Google studio with proper validation and indexing to remove any discrepancies before providing the data to researchers in CSV form.

4.2. Analysis

As illustrated in Fig. 3 the case study depends on pulse-metered electricity data for three apartments in the Gen Y building. The apartments are named Unit A, Unit B and Unit C. The dataset was collected over the period of one full year from December 2017-December 2018 and the data was analysed in time series. Initially, the characterisation of data and variables was based on resolution, location and type of equipment whilst missing values and outliers were identified and removed. Owing to the pioneer status of this demonstration, benchmark data for such developments is scarce. Therefore, the monthly energy usage plot in section 5.1 is compared with the average consumption of a three person household across Australian detached houses, except Western Australia[4]. Consumption data was taken from [66] with consideration that those houses also utilised gas for cooking and electricity to run the rest of the appliances in a similar manner to Gen Y. As the metering architecture is comprised of pulse meters, the dataset containing energy values are mostly cumulative whilst parameters such as Power (Watts) and SOC are instantaneously recorded. In order to get the desired interval output from the cumulative data, equation (1) was applied.

$$\Delta X_n = Y_n - Y_{n-1} \tag{1}$$

Where n is the number of a particular interval whilst X and Y are defined as output and cumulative data values, respectively.

Given the data resolution is 15 minute, 24-hour data in a day generates 96 intervals. To calculate daily values the output from equation (1) was added to provide equation (2).

$$Energy_{kWhperday} = \sum_{n=0}^{95} (\Delta X_n) \tag{2}$$

4.3. Self-sufficiency

Self-sufficiency can be defined as the ability of the microgrid to operate on its own sources (PV and battery) without relying on grid electricity [21], and is also often referred to as energy autonomy [67]. This metric is sometimes confused with self-consumption,

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[3] NMI regulates and maintains measurement system standards in Australia

[4] Western Australia is not connected to the National Energy Market (NEM) and has its own separate regulatory arrangements and electrical infrastructure. Residential electricity consumption datasets from Western Australia are not currently available.

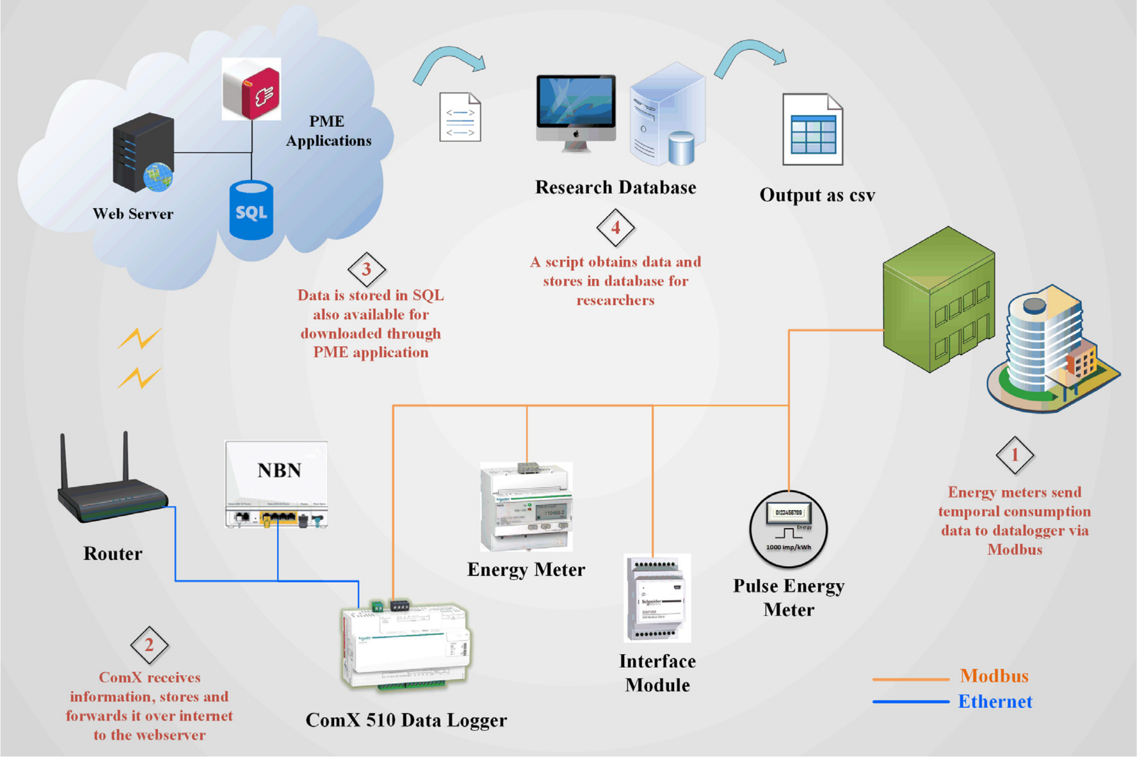

Fig. 4. Representation of the system methodology used in this case study.

which is the ratio of PV use by loads to total PV generation [68]. The self-sufficiency ratio can be calculated from the autonomy requirement equation given in [69] as:

$$\mathrm{Self-Sufficiency}(\%) = \left(1 - \frac{\sum_{n=0}^{95} E_{grid}}{\sum_{n=0}^{95} E_{load}}\right) \times 100 \tag{3}$$

Where n denotes the number of intervals in a day whilst E_{grid} and E_{load} represent temporal grid imported energy and total load consumption respectively. For calculating monthly self-sufficiency, the number of intervals would depend on the total number of days in each month, e.g. in January the maximum value of n would be 2976. Self-Sufficiency also facilitates an understanding of the overall share of both sources in the total load consumption and subsequent cost benefits could be identified in order to increase or decrease the renewable system size.

Similarly apportioning of energy usage would be insightful to examine the share of both sources i.e. grid and PV-BESS, in individual load consumption of apartments. Although the main benefits of apportionment are allocation of energy bills and management of energy demand contingent on desired system output, we can also apply this method in the present scenario where energy has to be fragmented from multiple sources i.e. grid and renewables terminating on a single AC coupled bus. Various approaches have been employed to determine apportioned usage such as clustering [70], non-intrusive load monitoring [71–73] as well as static apportionment [73,74] and controlled switch energy sharing in [75]. However we apportion grid and PV-BESS usage for each of the three residential units by first itemising total load consumption into self-sufficiency percentages of sources (grid or PV-BESS) as given in Eq. (4),

$$\mathrm{Source}\% = \frac{\mathrm{Source\ (PV + BESS\ or\ Grid)consumption\ (kWh)}}{\mathrm{Total\ Load\ (kWh)}} \times 100 \tag{4}$$

Subsequently applied percentages will disaggregate individual units' consumption into two additional measurements, i.e. consumption from PV-BESS and grid supply represented as apportioned consumption in Eq. (5).

$$\mathrm{Apportioned\ consumption,\ (kWh)} = \mathrm{Source}\% \times \mathrm{Unit\ Consumption(kWh)} \tag{5}$$

This rationale provides a realistic figure relative to the usage of a particular unit, i.e. an apartment which consumes a certain amount of energy is billed or incentivised based on the ratio of both energy sources. The method satisfies the numerical composition of total energy, i.e. the sum of all individual loads was equal to total load supplied by the grid and PV-BESS.

5. Results

In this section, we present the energy performance results obtained from operating the SEM in Gen Y apartments. Performance is analysed by initially looking into energy consumption of apartments. Seasonal load profiles illustrate diurnal consumption patterns while the monthly energy usage plot is compared with the benchmark. Power profiles of summer and winter days indicate PV generation and load consumption from grid and PV-BESS. Results from the CP load are also shown because it constitutes an important part of most multi-unit developments. Subsequently grid minimisation is assessed by evaluating the monthly self-sufficiency ratio, and based on outcomes; the share of each source in consumption is shown. Finally we will look into battery storage performance in different periods which plays an important role in meeting the load demand.

5.1. Apartment load profile

The seasonal diurnal load profile of the Gen Y building as shown in Fig. 5 was segregated into four different periods of the year to observe power consumption against hour cycle. The baseload remained under 300W throughout the average 24-hour period cal-

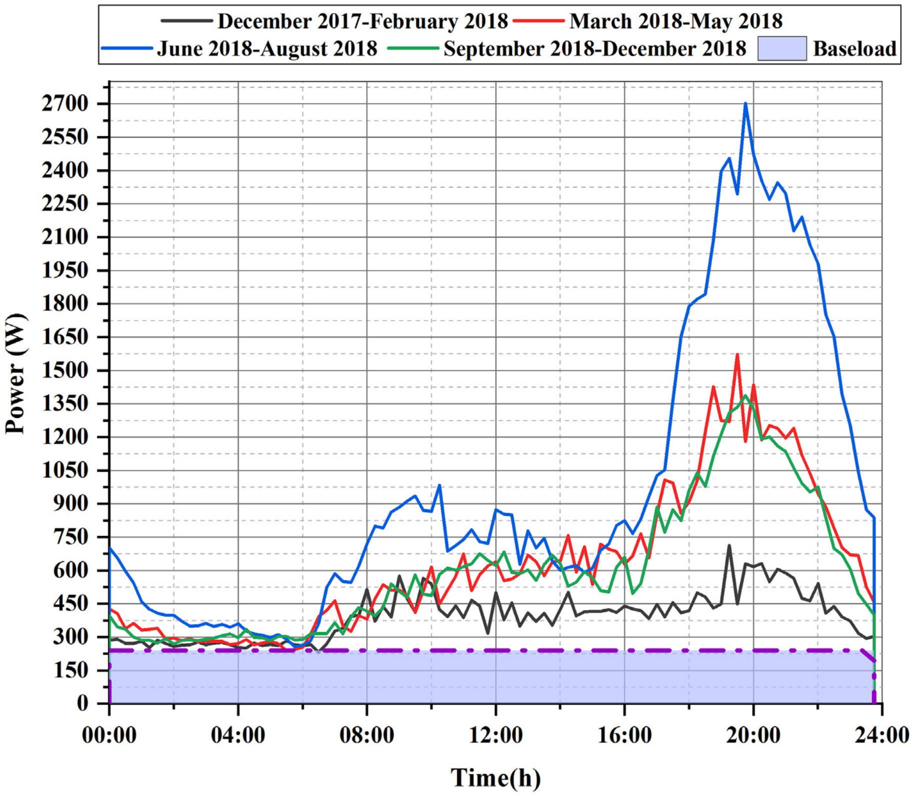

Fig. 5. The seasonal load profiles during four periods of the year (December 2017-December 2018).

culated through lowest values and considering seasonal variation as identified by [76]. The load profile shows commonly recognised peaks in the morning and evening, with the highest demand occurring in the winter period (June 2018-August 2018) as a result of consumption from heating appliances [56].

The decreased load power during the summer period (December 2017–February 2018) as opposed to the other three seasons is a result of occupancy behaviour; the resident of Unit A travelled during that period. Consumption between midnight to early morning hours (6:00 am) in all periods remained under 500 W, with exception of load power in period June-August decreasing from 700W at midnight to 264 W at 6:00 am. The average usage during this period (315W) confirms that the bulk of activity occurs during the day time. The highest consumption during morning peak hours in the dataset was observed between 8:00 am-11:00 am, particularly during the winter period (982W). Similarly, evening peak hours (7:00-9:00 pm) show increased usage, with winter consumption among the highest (2700W), whilst shouldering months (March 2018-May 2018 and September 2018-December 2018) in comparison, exhibited idiosyncrasies.

Fig. 6 represents monthly consumption of all three units in comparison with the average consumption of a three person household in Australia. This benchmark data from [66] was quantified taking per day consumption values across four quarters of a year. The consumption of the three Gen Y units is compared to the benchmark values of one house given the equal number of occupants, i.e. three. The benchmark values are not tailored to characteristics of the dwellings such as floor space.

However the energy consumption at Gen Y is still found to be lower considering the size of units, total of 3 units (Gen Y) to one house (benchmark). The overall average consumption of three units at Gen Y was 22% lower than the benchmark consumption, except for the month of May 2018 and the period of July 2018-September 2018 when the total consumption of all apartments remained 14% higher than benchmark values. The overall lower consumption average may be attributed to energy efficiency features of the building (cross ventilation, access to natural light, light wells, louvres and energy efficient bulbs), and smaller than average living spaces. Occupancy factor should not be overlooked while analysing load profiles. For example, in contrast to the other two units, Unit B does not show any variation in consumption trends over 12 months. This is largely due to the fact that the resident of Unit B worked full time during the day and remained conscious of electricity consumption throughout the year. In comparison, the other two residents worked from home most of the times and would therefore have used heating appliances during the day in winter.

Western Australia boasts an abundance of sunshine, with an irradiance ratio of 5.22kWh/m^2/day [77] and approximately 8 hours per day of sunlight availability. Fig. 7 (a) shows the power profile of a sunny summer day. Clearly a large portion of PV generation (87%) was fed back to the grid between 10:00 am-6:00 pm whilst the remainder was utilised by the loads and for charging the battery. Due to excess PV generation and large availability of battery storage, grid imported power remained minimal throughout the day as shown in Fig. 7(a). The PV+BESS consumption parameter was calculated by subtracting the grid imported power from total consumed power. Similarly, energy consumed from battery storage in the evening shown as BESS Consumption was computed using the same method however, it excluded PV day generation (i.e. calculated between sunset and sunrise). Further details of this battery storage utilisation is given in section 5.4.

The winter day profile is quite dissimilar to the summer period as shown in Fig. 7 (b) and reveals a major portion of grid imported electricity while the battery comes into play later in the day. The major influencing factors on low PV power production are the rainy season, lower availability of solar radiation, changed winter sun path causing shorter sun hours. Consequently, the lower avail-

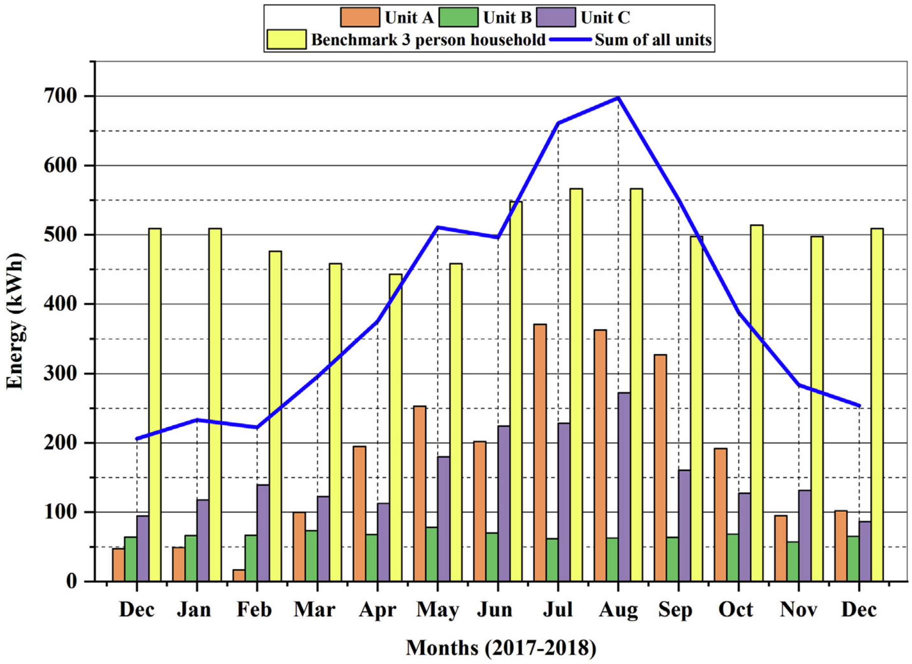

Fig. 6. Monthly energy usage of individual units in Gen Y apartment.

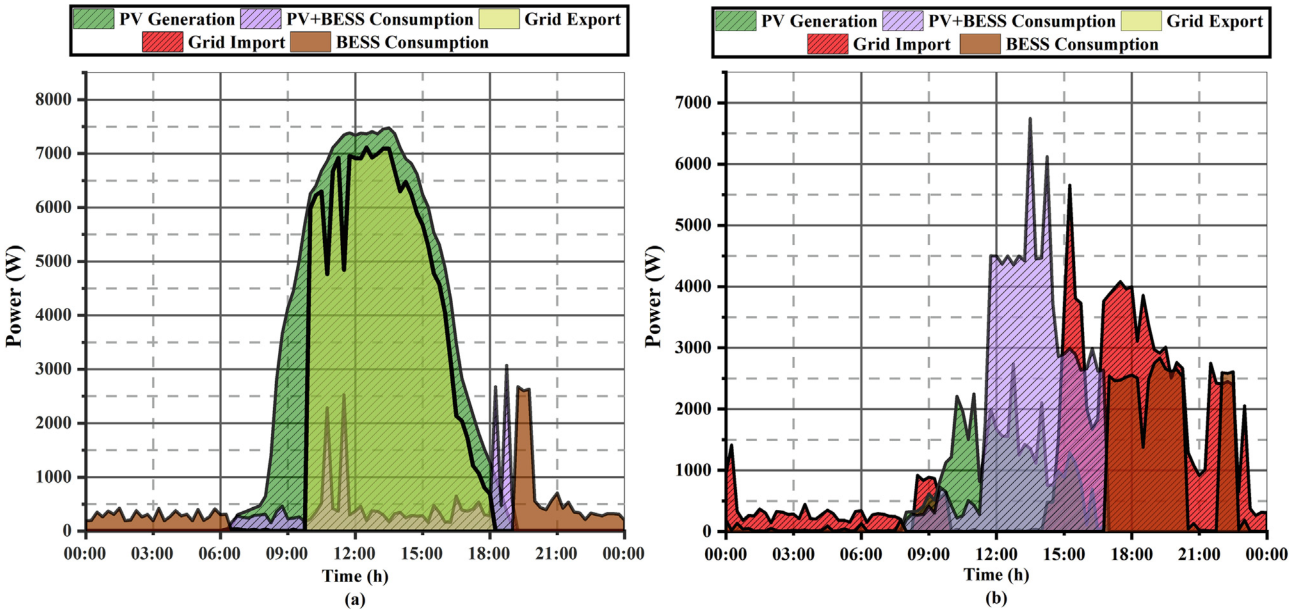

Fig. 7. Power profile of Gen Y on (a) Summer day (Dec-10 2018). (b) Winter day (July 15, 2018).

ability of PV output in winter affects PV generation to consumption ratio [56]. On the other hand, the battery stores less energy and hence loads rely on utility power [78-80]. Nevertheless, the Gen Y SEM maintained the battery and supplied 24% of electricity to the load during peak hours for the worst performing day as shown in Fig. 7 (b). Such a response highlights the significance of the BESS installation in parallel to PV, which provides a backup under extreme seasonal conditions.

5.2. CP load profile

The CP load at Gen Y consists of walkway lights, parking sensors, and entry lights. Contrary to large developments where the CP requirements constitute a significant portion of energy consumption [81] the CP load at Gen Y is relatively small. CP demand in previous studies [21,82] was only covered by grid and PV. In comparison, the available proportion of grid and PV-BESSin SEM meet CP demand at Gen Y. As illustrated in Fig. 8 (a), the CP load demonstrates an average yearly profile operating mostly throughout the night while baseload remains around 80W to keep the control supplies energised for sensors during the day time. The profile does not distinguish weekdays and weekends as given in [11] however, it does exhibit an identical pattern differing only in amplitudes (110–120W). The power value increment after 6:00 pm and the drop after 5:00 am in the morning reflects the load control sequence implemented through a programing relay which oper-

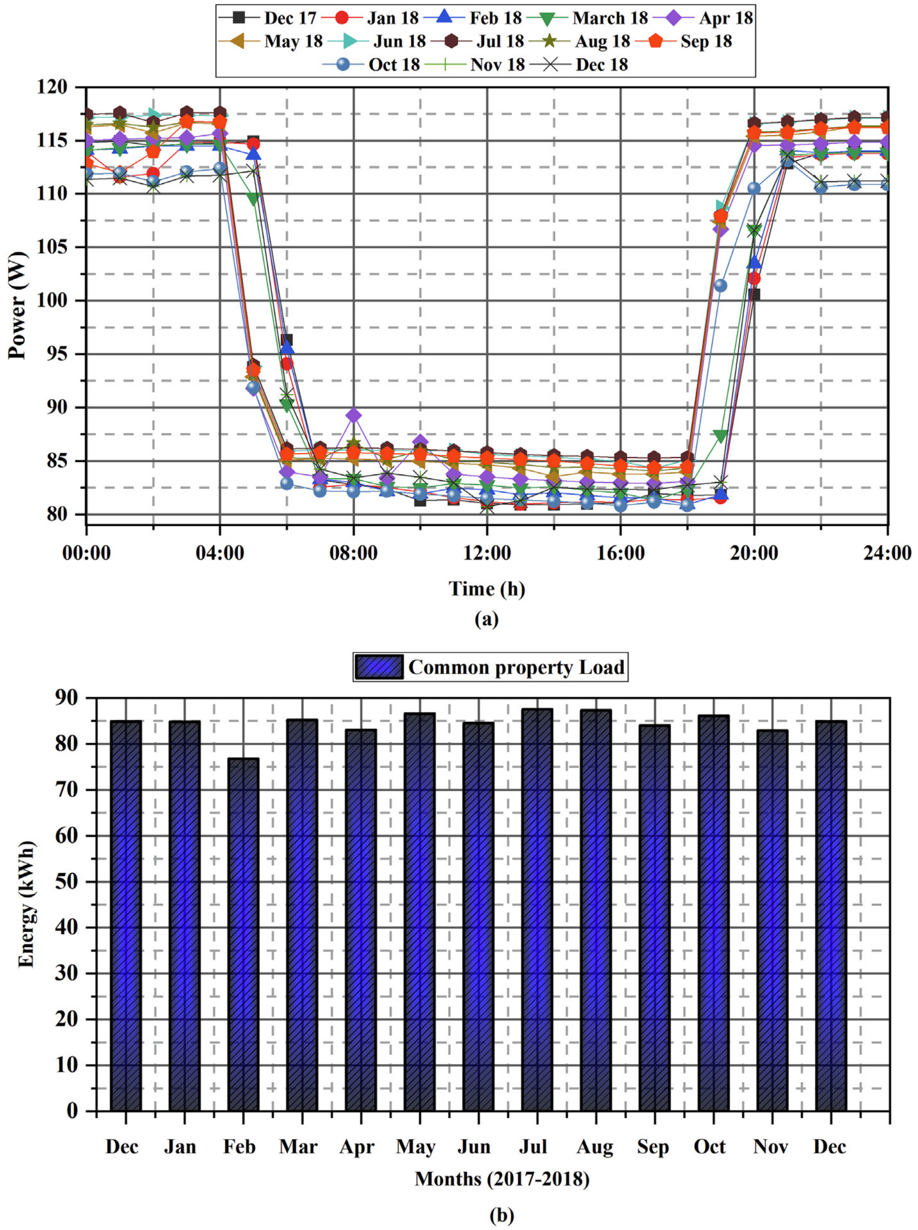

Fig. 8. (a) CP yearly average load consumption profile. (b) Monthly energy consumption of CP load.

ates according to seasonal daylight hours. It can be deduced that the CP load, despite its profile specificity, contributes to the total baseload level (in Fig. 5) with standby mode for other residential loads. Fig. 8 (b) shows the monthly chart clearly indicating an average CP consumption of 85kWh (2.8kWh/day) which constituted 37% of the total load during the first three months of data, with a decrease to 22% for the remaining period. The reason for the increased percentage during the first quarter was an overall lower consumption from individual apartments (forming the total load together with CP) which increased the CP consumption ratio of the total load. Likewise, the remaining quarters observed a steady share (22%) due to increased energy usage of other primary apartment loads which lowered the CP portion.

Therefore CP load, despite following the identical yearly load pattern as shown in Fig. 8(a), contributes to overall consumption upon aggregation with apartments' load which vary during different periods as shown in Fig. 5. This demonstrates the importance of SEM's embedded metering, which contains all loads including CP, connected in a shared arrangement rather than separate electrical connection [64]. As long as renewable capacity to consumption ratio is higher or equal, the CP load as part of the overall load will be supplied by PV and BESS, thus reducing grid reliance and also avoiding additional cost of separate connection.

5.3. Self-Sufficiency

The yearly self-sufficiency ratio obtained from equation (3) in Fig. 9 reflects on average 75% dependency of the microgrid on PV-BESS and 25% on the grid. The system maintained a self-sufficiency of 80% for half of the year while the poorest period for the achievement of satisfactory percentages were the winter months (June, July, and August).

The lower self-sufficiency ratio in winters can be improved using various optimisation strategies however we can also apply export limitation method as a facile solution. Considering the availability of battery storage in later hours of the day, if we regu-

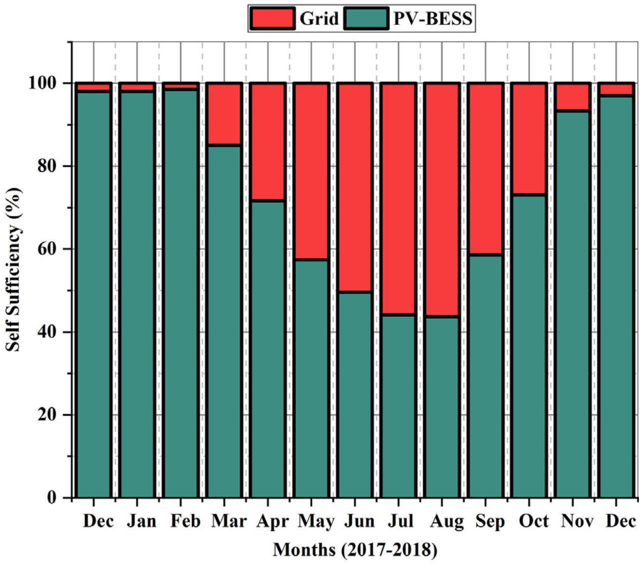

Fig. 9. Monthly self-sufficiency ratio of SEM.

late the SEM on export limitation(zero export) during excess generation hours, the results will suggest overall increased self-sufficiency with more PV-BESS consumption and less grid percentage. Fig. 10 (a) shows average export pattern during four winter months (May-August), while the total export energy per month is plotted in Fig. 10(b). Subsequently if this exported energy is utilised to supply residential loads, the self-sufficiency ratio reflected in Fig. 10(c)increases for the months of May-August to 88%, 74%, 66% and 82% respectively.

On the other hand, the presence of an individual dweller at any particular instant is not guaranteed which could further improve the energy performance metrics i.e. the possibility of even less grid consumption if an occupant moved out frequently during winters and created a surplus storage capacity for other units. The method is helpful in underlining the effectiveness of a shared system and it further offers improvements for system optimisation.

The energy fraction of each load resulting from from the apportionment method is shown in Fig. 11 which reveals that Unit A and Unit C consumed more renewable energy in total (1286kWh and 1252kWh respectively) than Unit B which consumed only 611kWh.

In the same manner when the apportionment method was applied to determine CP energy fraction, an increasing grid consumption response was noticed during winter increasing from 40kWh in May to 53kWh in August. Since the majority of CP load operates during night hours, an increased grid usage can be observed in winters with less availability of battery storage.

5.4. Battery storage in SEM

Fig. 12 illustrates the average daily SOC over three different periods in the calendar year (December 2017-December 2018). To preserve usable battery lifetime, the depth of discharge of the BESS is set to 80%, i.e., 8kWh of usable capacity, which means the illustrated graphs represent 8kWh of maximum battery capac-

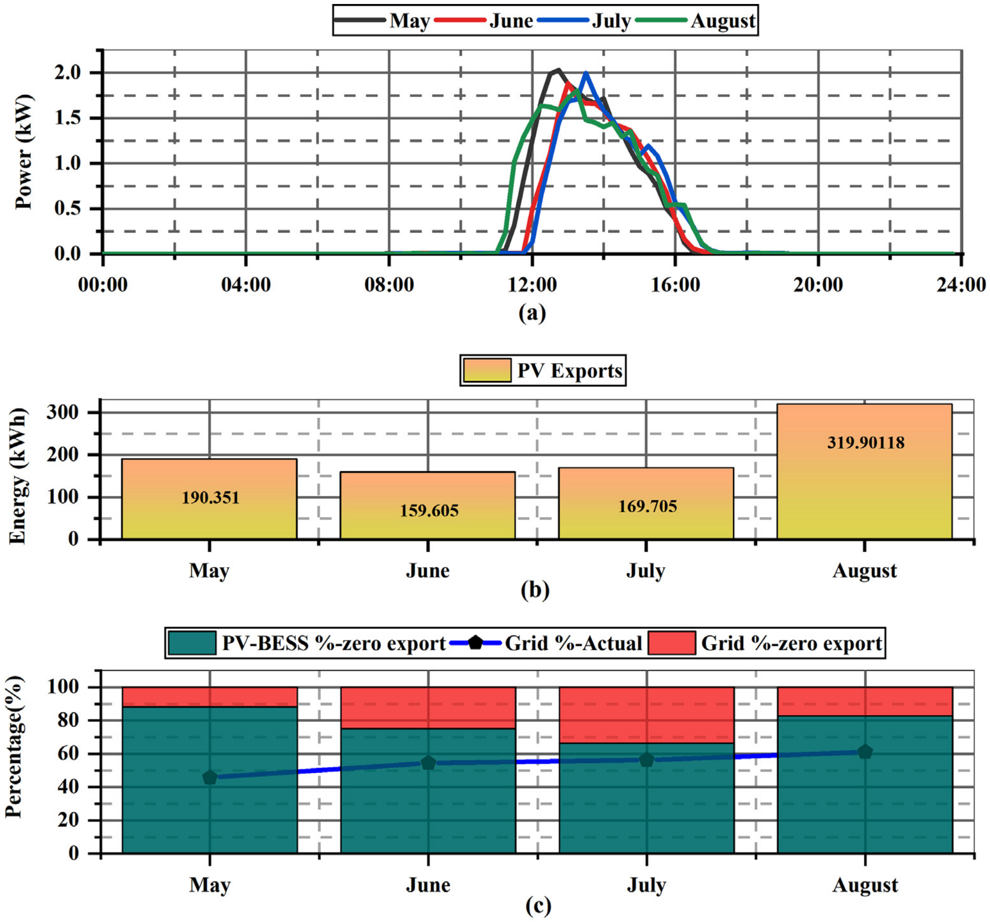

Fig. 10. Resultant self-sufficiency ratio after zero export limitation (May to August): (a) Average PV export pattern in winters (b) Monthly PV exported energy (c) Self-sufficiency ratio after zero export.

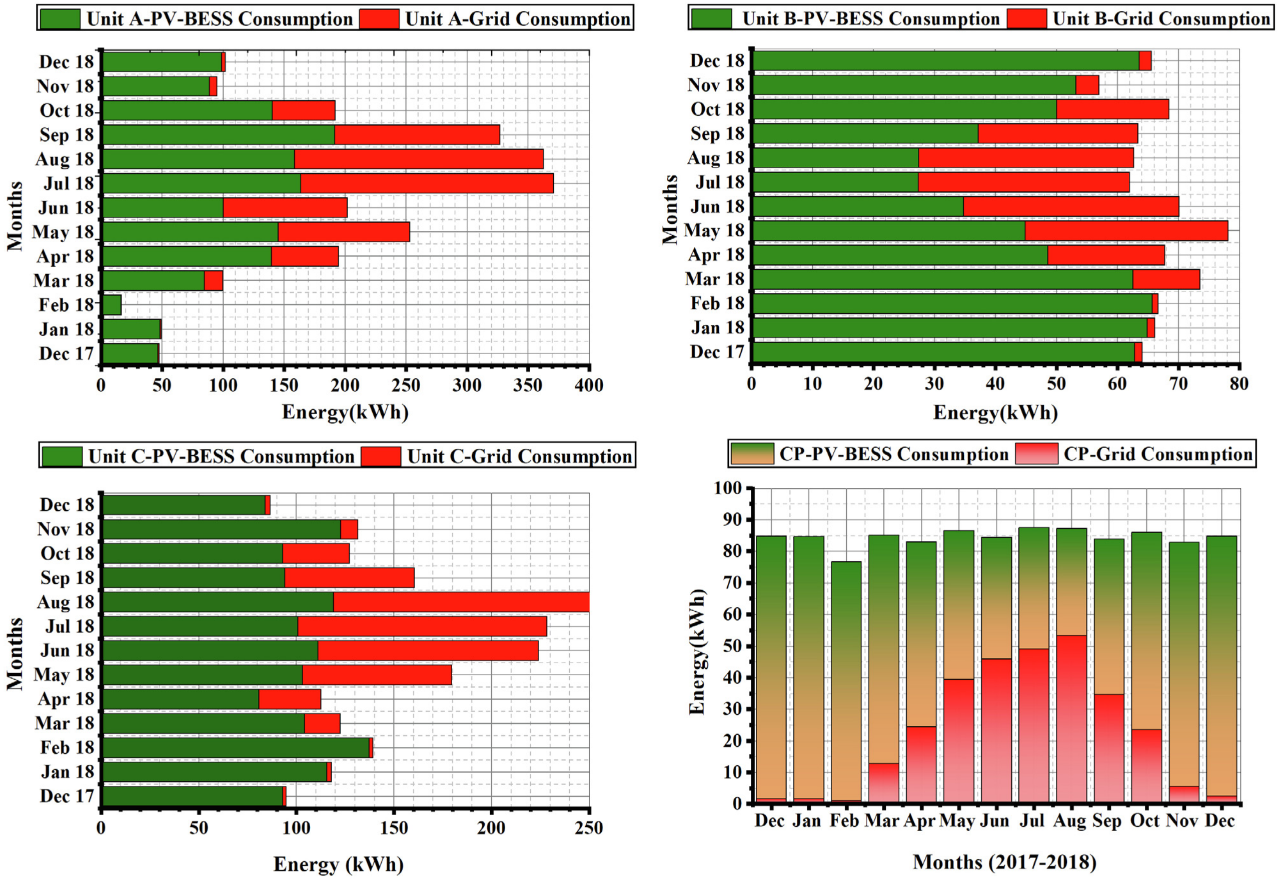

Fig. 11. Energy fraction of residential units and CP load according to apportionment method.

ity at 100% SOC. Self-consumption ratios of PV-BESS vary greatly with changing seasons which is apparent from the plot. The summer (December 2017- February 2018) and spring (September 2018-December 2018) profiles exhibit a high level of storage capacity over a longer period, which aids in shaving the peak load and reduces grid imports.

Usually, on-site loads are supplied by PV and BESS during the daytime in summer; however, it is generally the peak demand period which affects the electricity bills. During summer the SOC remained at 80% on average during the peak load period (6:00 pm-9:00 pm). Hence, 6.4kWh of battery capacity was available to cover load demand for the total load and self-sufficiency of more than 80% during this period was achieved. The SOC profile for winter (June 2018-August 2018) shows a low percentage of storage due to the lower availability of PV unable to fully charge the battery.

These findings are comparable to the simulations of [32] on a similar scale where seasonal variation affected the SOC profiles. Despite these limitations the battery still maintained a stored capacity between 1.6kWh and 3.2kWh over the peak period to supply loads which were complimented by grid imported energy when required. Besides SOC information, it is also important to understand temporal battery energy usage in the peak seasons i.e summer and winter. In Fig. 13, the time considered for the plot ranges from evening to early morning (6:00 am-6:00 pm). The summer consumption during peak period maintained a threshold of 2kWh from midnight to the rest of the period whilst in winter the trend shows 40% higher usage.

Since the configuration at Gen Y employs a standard flat rate tariff, the possibility to apply any time-of-use pricing for charging the battery through the grid is not applicable here. However, it is feasible to consider different BESS scheduling strategies for the peak periods in order to achieve high self -sufficiency and reduce costs. Moreover, the battery utilisation depends strictly on load demand and high consumption. Fig. 13 suggests that deferring battery utilisation to a later part of the evening would be beneficial to achieve high self-sufficiency in winter. As battery utilisation during the daytime in SEM is supported by solar PV, discharging the BESS in the evening peak period would reduce large grid imports. Our current operational method closely resembles the evening discharge strategy modelled by [28], although the latter discharges the battery in the evening.

6. Discussion

The shared diurnal load profile of the apartment building indicates discernible characteristics independent of the sources' impact on consumption. The minimum baseload threshold remained consistent on a 24-hour scale, i.e. values were lowest around 6:00 am in the morning throughout the year whilst the highest occurred between 4:00 pm-11:00 pm. These findings differ from those of [83], who reported that 50% of lowest consumption intervals occurred during midnight to 8:00 am and also showed that baseload variation was significant among different dwellings. Nonetheless, the observation from the Gen Y metering data gives key information about the consumption intervals and minimum energy value (approximately 7.2kWh/day) required to operate appliances. In a shared context, benefits to manage a shared connection are greater than separate loads. This is due to the fact that individually connected loads are subject to several factors such as occupancy and user behaviour [84-87].

If distribution of power is considered, average load power of all profiles would occur at less than 800W which bears a close resem-

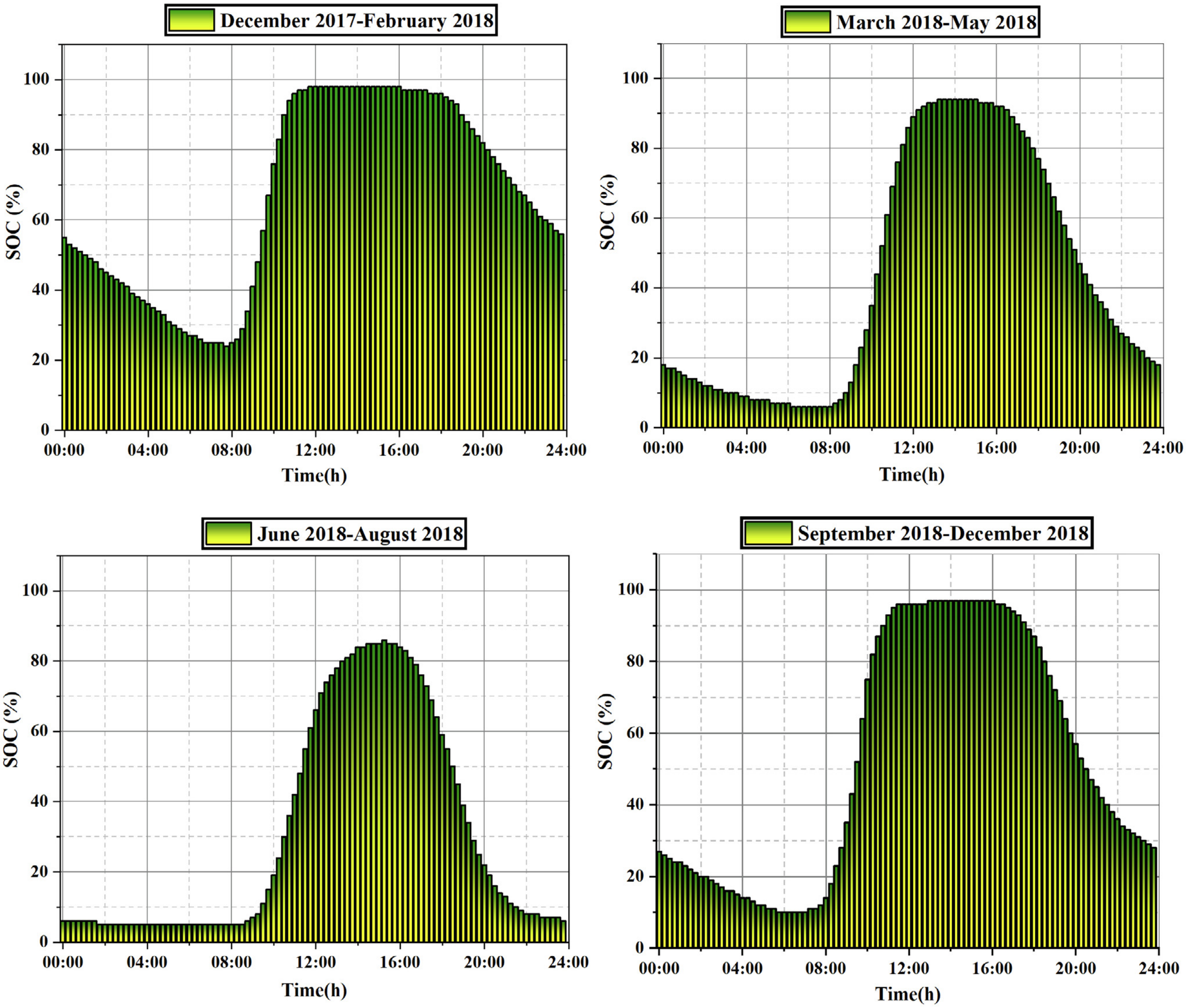

Fig. 12. Average diurnal SOC profile for four different periods.

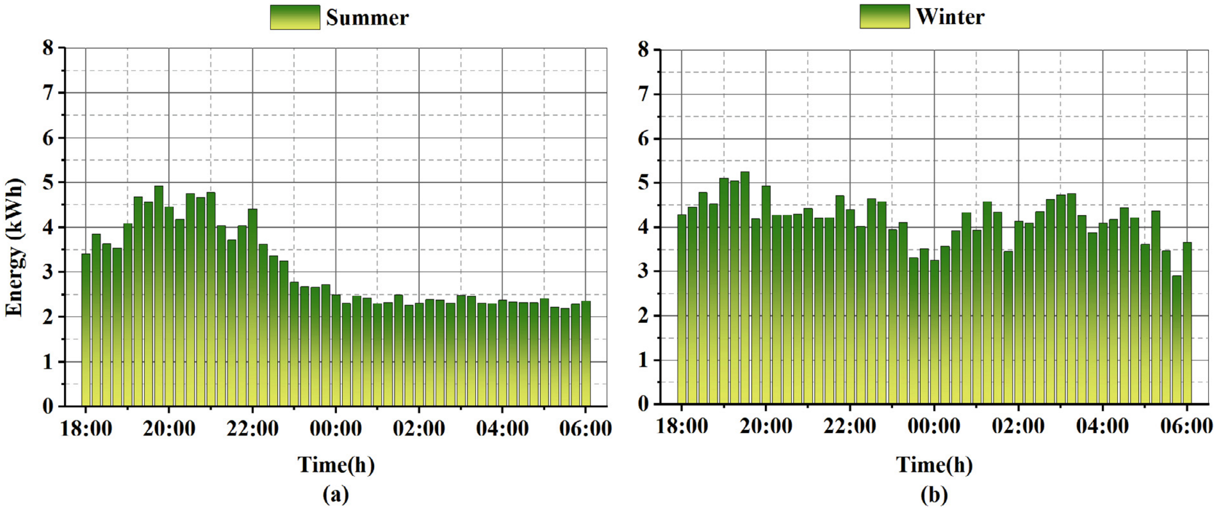

Fig. 13. Average battery consumption in evening hours for (a) Summer (b) Winter.

blance to the one reported by [88]. However, these authors strongly emphasized the use of high temporal resolution (less than 1 minute) data for instantaneous power because even 15 minute intervals could lose the valuable peaks which occurred during high consumption periods. Nevertheless, the pooling of households from 15 second resolution data matched precisely with conventional 15 minute pulse meters. Due to the lack of load profile data from Australian apartments, this remains subject to further studies.

Overall, the sum of the three units' energy consumption over the period of one year was 22% lower than benchmark values for a 3 person detached dwelling, as given in Fig. 6. While household sizes, occupancy behaviour and dwelling characteristics affect electricity consumption, load profile data illustrates positive energy performance for the building in summer due to the abundance of PV generation. In contrast, high electricity usage in winter implies that space conditioning constitutes a large portion of energy consumption in Australia, as identified by [89]. To achieve cost savings during winter, consumption patterns from this dataset could be analysed and extrapolated to apply demand response strategies by utilising battery storage during peak periods alone.

To capitalise on the commissioning of SEM for meeting load demand, PV-BESS utilisation was measured against the grid reliance. The self-sufficiency ratio throughout the year remained higher as a result of available battery storage in the evening peak hours. Even though an increased PV size as a renewable source could have improved the self-sufficiency ratio, numerous studies have discovered that the inclusion of a battery storage significantly reduces the grid dependency [68,90,91]. In this context, the research findings have focused more on detached housing, and hence shared energy systems in apartment buildings need to be studied further. It is highlighted by [92] that centralised battery storage in a shared residential setup could effectively increase self-consumption and reduce grid reliance. Moreover [28] having simulated different models and strategies, stressed the usefulness of embedded networks with PV-BESS in reducing peak demand and increasing self sufficiency. On the other hand, four operational strategies suggested in [93] are also plausible in proposing a method to improve self-supply, reducing peaks and also proposing a control strategy to lower investment costs.

7. Conclusion

The study provides energy performance results for an apartment building connected to SEM. Pulse metering played a vital role in providing real-time performance of the shared system since each electricity distribution and consumption node was monitored that helped in energy analysis. It also provided an accurate representation of a customer's electricity usage pattern over different periods. The lower consumption of Gen Y apartments than benchmark value could involve multiple factors such as number of households, occupancy behaviour, dwelling infrastructure and improved thermal performance features. Further research into the effects of occupancy behaviour on energy consumption, and empirical assessments of the effect of construction design in the context of apartment buildings is needed.

Our findings also indicate that utilisation of SEM has increased self-consumption and achieved an overall self-sufficiency of 75%. Certain imperfections such as excess availability of renewable energy during summer and lack of battery storage in winter require further exploration. Comprehensive optimisation modelling would be an interesting research topic for studies in this subject area. A hybrid energy system with an energy sharing mechanism [94] could be modelled to resolve the seasonal consumption issue however, such a system would not prove to be cost effective. Improved results may be achieved on different apartment sites by zero export or export limitation during particular periods or deploying optimal BESS control and scheduling strategies backed by load forecast.

We also analysed the results from the BESS which in parallel to PV, played a key role in meeting the majority of load demand. As apartment construction designs vary significantly, identification of the single best battery type for a particular apartment is premature. Moreover, BESS optimisation strategies must be deployed before searching for other options because if BESS usage is not configured properly, even optimal capacity may not result in increasing self-sufficiency and cost savings.

The SEM configuration in Gen Y, if replicated in other apartment buildings, might be helpful in curtailing lgrid imported electricity and bringing financial benefits however, the reduced surface area of the roof might become a limitation to generating enough PV energy and therefore adequate battery storage sizing is integral to support limited PV generation. The insights provided by the Gen Y data may be relevant to other jurisdictions with similar system capacity and network design guidelines, however individual load performance, different climate conditions and dwelling characteristics should be considered during system design.

Funding

This research was supported by; the Australian Renewable Energy Agency (ARENA) as part of its Research and Development Programme; the CRC for Low Carbon Living Ltd which is an Australian Government initiative; the Australian Housing and Urban Research Institute.

CRediT authorship contribution statement

Moiz Masood Syed: Conceptualization, Investigation, Methodology, Formal analysis, Data curation, Visualization, Writing - review & editing. **Paula Hansen:** Conceptualization, Writing - review & editing. **Gregory M. Morrison:** Writing - review & editing, Supervision, Project administration.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.enbuild.2020.110321.

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Publication IV

Published/ Peer-reviewed journal article

Monroe, J.G., Hansen, P., Sorell, M., Zechman Berglund, E. (2020). Agent-based model of a blockchain enabled peer-to-peer energy market: Application for a neighbourhood trial in Perth, Australia. Smart Cities, 3, 1072–1099.

smart cities

MDPI

Article

Agent-Based Model of a Blockchain Enabled Peer-to-Peer Energy Market: Application for a Neighborhood Trial in Perth, Australia

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Received: 24 July 2020; Accepted: 18 September 2020; Published: 19 September 2020

Abstract: The transfer of market power in electric generation from utilities to end-users spurred by the diffusion of distributed energy resources necessitates a new system of settlement in the electricity business that can better manage generation assets at the grid-edge. A new concept in facilitating distributed generation is peer-to-peer energy trading, where households exchange excess power with neighbors at a price they set themselves. However, little is known about the effects of peer-to-peer energy trading on the sociotechnical dynamics of electric power systems. Further, given the novelty of the concept, there are knowledge gaps regarding the impact of alternative electricity market structures and individual decision strategies on neighborhood exchanges and market outcomes. This study develops an empirical agent-based modeling (ABM) framework to simulate peer-to-peer electricity trades in a decentralized residential energy market. The framework is applied for a case study in Perth, Western Australia, where a blockchain-enabled energy trading platform was trialed among 18 households, which acted as prosumers or consumers. The ABM is applied for a set of alternative electricity market structures. Results assess the impact of solar generation forecasting approaches, battery energy storage, and ratio of prosumers to consumers on the dynamics of peer-to-peer energy trading systems. Designing an efficient, equitable, and sustainable future energy system hinges on the recognition of trade-offs on and across, social, technological, economic, and environmental levels. Results demonstrate that the ABM can be applied to manage emerging uncertainties by facilitating the testing and development of management strategies.

Keywords: peer-to-peer energy trading; distributed generation; electricity markets; energy storage; sociotechnical systems; agent-based modeling; blockchain; distributed ledger technology; smart contracts

1. Introduction

Distributed energy resources (DER) are transitioning modern electric grids by shifting generation from utilities to the end-users [1]. Solar photovoltaics (PV) and battery storage systems collectively empower traditional utility customers to become prosumers [2], or end-users, who can consume energy and sell excess electricity back to the grid [3]. The introduction of the prosumer has the potential to place a large share of the generation market into the hands of those at the grid edge [4]. This transfer of market power has created the need for a system that can better manage distributed generation (DG) of electricity [1,5]. One concept for facilitating DG is peer-to-peer (P2P) energy trading [6].

P2P electricity trading is the exchange of surplus renewable energy among pro- and consumers [6,7]. By assigning a value to units of surplus renewable energy, a virtual marketplace is created that overlays the physical infrastructure and flow of electricity with a financial accounting structure [8]. P2P energy trading provides a free-market system for prosumers to exchange excess electricity with neighboring consumers at a pre-arranged price [6,9]. Online P2P energy trading platforms may add new value to renewable electricity generation while also encouraging conservation of natural resources [4,8,10]. Moreover, the reconciliation of multiple users' energy and pricing information may enable equity in consuming energy from renewable sources [11]. Advocates of virtual energy trading stress its potential in making green energy more affordable and more accessible to larger shares of the population [4].

While P2P offers economic and environmental benefits, little is known about the effect of P2P interactions on realized net electricity costs of households [12]. As P2P markets are an emerging and novel type of energy system configuration, new research is needed to explore how alternative electricity market structures and individual decision strategies affect the dynamics of neighborhood electricity exchanges and the performance of the market [1,10]. There are few analyses of real-world applications [6], and discussions around the virtues and shortcomings of P2P energy trading rest predominantly on theoretical analyses to date (*cf.* [13,14]). Systematic, empirically-based investigations are needed [12] to move beyond theoretical discussions and to advance our understanding of the effects of P2P energy trading on participants and infrastructure alike (*cf.* [10,15–17]).

The goal of this research is to explore how alternative governance structures affect the performance of a P2P market in the context of a real-world case study. We use an agent-based modelling (ABM) approach to simulate consumer and prosumer agents that enter the market equipped with storage solutions, forecasting algorithms, and willingness-to-buy and accept values. ABM is a computer simulation technique that uses an in silico approach to model micro-level actions and interactions to study the emergence of macro-level phenomena for complex adaptive systems [18]. Here, we simulate the interactions of prosumers and consumers with the physical, technical, and financial aspects of P2P systems to generate insight about the emerging dynamics of electricity prices [4,14,19]. The ABM framework is applied using empirical data to simulate decentralized electricity trades in an existing residential neighborhood in Perth, Western Australia. The ABM is developed using data about 18 consumer and prosumer households that participated in a P2P market trial. Data describing energy consumption profiles, energy generation profiles, and willingness-to-accept and willingness-to-pay values for excess solar generated power are used as input for the ABM.

The contributions of the study are twofold. This research addresses a gap in the literature by applying an ABM for observations of an existing P2P market; other applications of ABM for P2P energy trading have not been validated for real-world data observed for P2P markets [1,5,6,20]. In validating the ABM, we find that the structure of transaction fees led to market failure and a lack of engagement among consumers and prosumers in bidding. There is some discrepancy between the modeled outcomes (e.g., electricity price and energy exchanged) and the observed outcomes due to the implementation of the market: rules that were specified to limit trading were not enforced throughout the trial. Secondly, the validated ABM framework is applied to explore the performance of alternative electricity market structures that use different approaches to forecast energy generation and alternative storage solutions. As such, it explores how adaptations to the set-up of the Perth trial may change market outcomes. Results are analyzed to assess the effect of forecasting approaches and storage on untraded excess and the price of electricity. This paper develops new insight about the potential market gains, based on buyer and seller electricity price, that can be achieved through alternative market designs and structures. The model that is developed here can be applied for other systems to test potential market designs and select market governance structures for new applications.

This paper is organized as follows. Section 2 describes the theoretical foundation of blockchain-enabled P2P energy trading and the use of ABM to simulate the integration of renewables in smart grids. Section 3 characterizes the case study of Perth, Western Australia and the trial of P2P energy trading in the Fremantle residential neighborhood. Section 4 describes the ABM of the electricity market to simulate decentralized P2P energy trades and its implementation using the multi-agent simulator of neighborhoods (MASON) open-source toolkit [21].. Section 5 explains the modeling scenarios simulated in the study. Section 6 lists a set of results from the analysis of alternative electricity market structures, the use of storage, and the clustering of trial participants. Section 7 provides a discussion of the impact of governance structures on the dynamics of P2P energy systems and the scale at which they are most effectively managed. Finally, Section 8 presents the conclusions of our study.

2. Background

2.1. Peer-to-Peer Energy Trading

With the growing prominence of small-scale and local generation of renewable energy, community energy initiatives and new market models have emerged [22] to address the need for innovative management mechanisms. Given its potential effectiveness in managing DER [20], P2P energy trading as one such mechanism is expected to become a key element of future power systems [23]. Although a variety of potential P2P market configurations exist, it may generally be described as the flexible trading of excess energy from small-scale DER among customers in a neighborhood [23].

A number of benefits have been linked with P2P energy trading, including better overall system efficiency [4] and the potential to improve social cohesion and sense of community (ibid.). Energy matching, uncertainty reduction, and preference satisfaction have been identified as potential value streams offered by P2P energy trading platforms [10]. It has further been argued that the emergence of prosumers may contribute to the viability of P2P trading through increases in diversity and variability of energy demand [10]. Importantly, a central motivator for the transdisciplinary interest in P2P trading has been cost optimization, and potential cost savings for communities and their members are frequently cited (e.g., 4, 5).

Some evidence of cost savings is beginning to emerge (e.g., 20, 7), but so are indications of challenges. One study found that cost savings that can be achieved through P2P trading are highly sensitive to a range of factors that are, as of yet, poorly understood [7]. For example, it was found that higher PV penetration led to lower cost savings for households with PV systems, and that batteries only increased savings if the PV systems was sufficiently large [7]. Challenges also exist regarding the practical implementation of P2P energy trading. For example, to calculate bills, near-real-time information on amounts of electricity produced, types of trades, and time of trades is required [6]. Other questions pertain to sub-optimal economic outcomes [2,10], privacy and security concerns [13], and adequate prosumer engagement and education [2,10].

Lastly, research on P2P energy trading thus far has had limited access to empirical evidence to validate expectations. Given the novelty of the field, only a small number of practical demonstration projects and trials have been discussed in the literature, with the most frequently cited ones being Vandebron in The Netherlands [4,10,24], sonnenCommunity in Germany [4,10,24], Piclo in the UK [4,10,24], and the Brooklyn Microgrid (US) [4,6,10]. In addition to the relatively small pool of potential sources of data, projects differ substantially in focus and design [25]. As a result, literature on P2P energy trading currently suffers from a lack of empirical grounding. Simulation studies have therefore served as an important tool and source of information for researchers and practitioners.

2.2. Blockchain Technology for Facilitating Peer-to-Peer Energy Trading

Blockchain technology has garnered interest as an information and communications technology capable of addressing some of the challenges in implementing a P2P electricity market [5]. Blockchain technology promises to offer new opportunities and innovation in decentralized generation and energy markets [13,26] through improved means of managing and controlling decentralized and digitized systems [26]. Providing immutable records of all transactions in a decentralized and distributed ledger, the technology promises security, accuracy, authentication, and traceability of transactions [9,13].

A blockchain is an ever-growing data structure that is shared among member nodes in a decentralized network. This distributed ledger offers a platform for digital transactions and applications to proceed without using a trusted third-party organization for authentication. Blockchain technology enables a trustless decentralized peer-to-peer electronic cash payment network with minimal transaction cost [27]. Transactions facilitated by a blockchain are mutually agreed upon and secured by nodes through a distributed consensus, which is the process of adding new blocks of data to the blockchain data structure [26,28]. Blockchain data structures are both immutable and cryptographically verifiable [27].

The possibility of secure management of transactions without the need for a third party is a distinct feature of public blockchain platforms [10]. Blockchain-based trading platforms are differentiated from other platform models for P2P trading that focus on delivering particular benefits, such as raising awareness around community microgrids or creating a value-added service [10]. Others have highlighted the wide range of possible use cases for blockchain technology in the context of P2P trading and decentralized energy, including, for example, business-to-business trading, community energy, and coordination of virtual power plants [26]. Despite the potential benefits, Andoni et al. [26] pointed out that a key challenge in this application area is integrating trading systems into the existing network.

2.3. Agent-Based Modelling in the Context of Peer-to-Peer Energy Trading

The complex, dynamic nature of energy systems has made simulation studies, and ABM in particular, a viable approach in the study of emerging energy system structures. ABM has the ability to account for the complexity of interactions in real-world settings [29]. This makes it uniquely suited to simulating energy systems [30,31] and an important tool for the management of power systems [16]. Using ABM, dynamic processes and their emergent properties can be simulated effectively based on interactions among heterogeneous, autonomous agents. ABM is applicable for emerging P2P markets that are formed through interactions between rational and distributed decision-making units [16,17].

There is a growing body of literature dedicated to applications of ABM to energy systems. Electricity markets in particular have been the focus of many ABM applications [30,32] and include those based on P2P interactions. Mengelkamp, Notheisen, et al. [33] found that blockchain technology can be employed to design decentralized, local energy markets and confirmed the potential of these markets to lead to electricity cost savings (ibid.). An evaluation of the simulated performance of three different sharing mechanisms was conducted by Zhou, Wu, and Long [1] and indicated a potential of residential P2P energy sharing to generate economic benefits. Long et al. [20] proposed a sharing mechanism aimed at ensuring economic benefits for all individuals in a community. Analyzing these benefits further, they showed reduced costs for the community as a whole, reduced electricity bills for individuals, and an increase in both self-consumption of PV energy, and in self-sufficiency [20].

Zhang, Wu, Cheng, Zhou, and Long [34] also demonstrated the potential of P2P energy trading to balance demand and generation in a local market. Lüth et al. [6] analyzed how electricity storage in a local P2P market may benefit end-users. Proposing two different market designs—one with decentralized (prosumer-level) and one with centralized (community-level) storage—they analyzed the value of their models in a heterogeneous prosumer group that differed in terms of demand patterns as well as available technology (ibid.). Findings in this study showed that, while both models were economically viable, the centralized storage design yielded slightly lower cost savings, but more trades [6]. These dynamics were found to be primarily driven by the type of market design. The trade-off between higher independence of the main grid or higher levels of integration of storage and P2P trade suggests that, when designing markets in practice, the market's primary objective should be considered (ibid.).

These ABM studies provide valuable insight into possible designs and dynamics of P2P energy markets. As applied to other types of studies on P2P energy trading, there is a need to establish better empirical foundations and improve the integration of empirical data into model design and analysis.

The first issue lies in the type of data used in simulations. Data used to simulate trading models is often based on averages (e.g., 33, 1), may stem from various different sources (e.g., 33), or may be artificially simulated (e.g., 22). Various authors call for the use of real consumption data [33], or of local demand and generation data [1], in future research. Secondly, there is a lack of empirical data being used in the validation of ABM (*cf.* 35). ABMs should be rigorously grounded in theoretical and empirical foundations [35].

Another dimension of the missing empiricism is a disregard for the stakeholders involved in P2P energy trading markets. Engaging the stakeholders of local energy markets is essential to improve public acceptance of such systems, especially when both the market design and the ICT (e.g., blockchain) are new [33]. Formulation of shared visions about the objectives and operation of microgrid energy markets may help increase communities' acceptance (ibid.). It has further been argued that end-users and their active participation in markets have received insufficient attention in market designs [6,16]. The fact that the behavior of the actors involved in such markets has not yet been sufficiently studied contributes to the current uncertainty regarding the configuration of future energy systems [31]. The imperfect communication and forecasting abilities that agents hold in the real world should be considered in modeling studies [1].

This article makes several contributions at the interface of P2P energy trading and ABM research. We contribute to the burgeoning literature on P2P energy trading by analyzing the dynamics arising from the interactions of heterogeneous pro- and consumers with an empirically tested pricing structure and trading mechanism. To the authors' knowledge, this is the first post-hoc agent-based study of a real-life P2P energy trading trial. Methodologically, we thereby address the lack of empirical data for modelling and validation in ABM studies by presenting a framework and simulation based on a real-world trial. Using available data, real consumption and generation data was used to run the simulation, and simulation results were validated against observed dynamics. Finally, the validated ABM was used to assess alternative market structures in the context of the case study.

3. Case Study: The RENeW Nexus Trial in Perth, Western Australia

3.1. Case Study Description

The present study combines the capabilities of ABM with empirical data from the Renewable Energy and Water Nexus (hereafter RENeW Nexus) P2P energy trading trial conducted in Perth, Western Australia, between August 2018 and June 2019. As part of the Australian Government funded RENeW Nexus project, the trial was run by a consortium of research, government, and industry partners, including the state utilities, and a blockchain-based energy trading start-up company. Electricity consumption and solar generation data were initially collected from 50 households recruited through an expression of interest process. Eighteen of these households subsequently signed up to the P2P electricity trading trial conducted in the Perth suburb of Fremantle between November 2018 and June 2019 (Figure 1). A discussion of why participants decided to withdraw from the RENeW Nexus study is provided by Wilkinson et al. [36]. Only data from the 18 households were used in the simulation application described here.

Perth enjoys a mild climate with an annual mean temperature of approximately 24 °C (based on 1993–2019 data) [37]. Annual mean global solar exposure in Fremantle in 2019 was 5.5 kWh m^2, with a low of 2.7 kWh m^2 in June and a high of 8.3 kWh m^2 in December [38]. An estimated 23% of dwellings in the Fremantle Local Government Area (LGA) have rooftop solar PV systems, with an installed capacity of approximately 11,280 kW [39]. This is compared to 19.5%, 23.7%, 27.3%, and 33.2% of dwellings with rooftop PV systems in the neighboring LGAs of Mosman Park, East Fremantle, Melville, and Cockburn, respectively. The state-wide average for Western Australia is 28.8%.

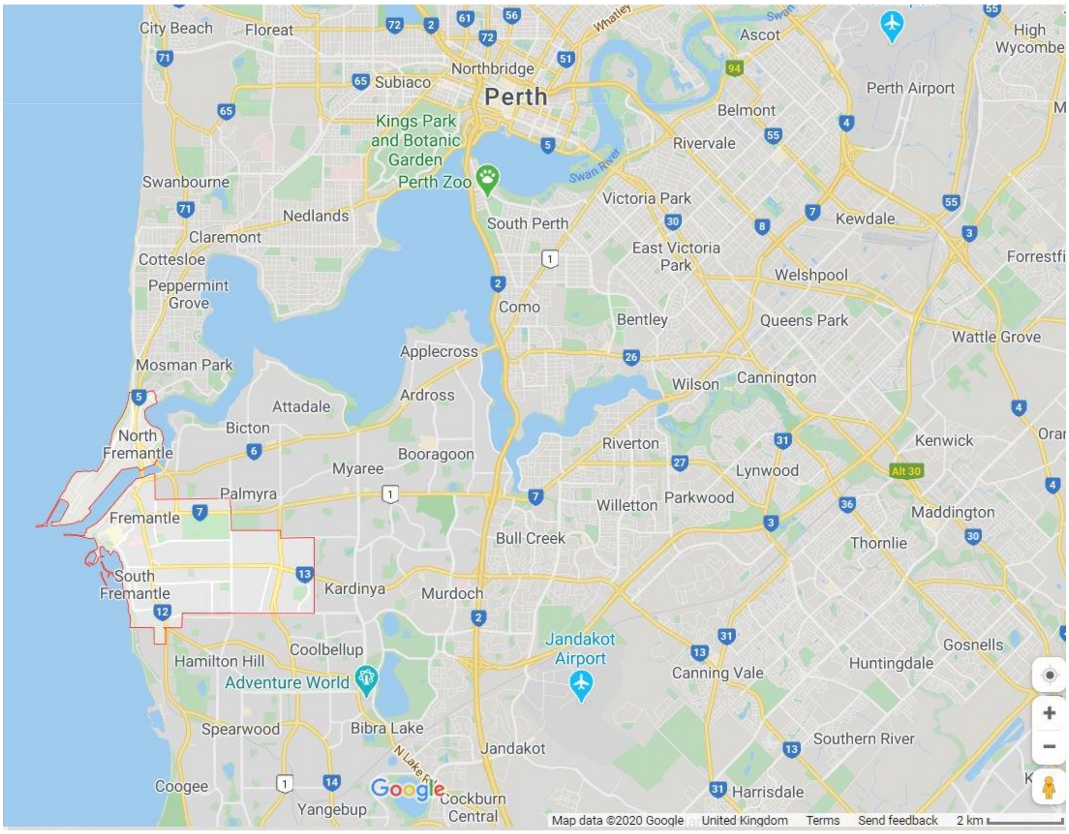

Figure 1. Map showing where Fremantle (local government area) is located within the greater Perth area. Screenshot taken by the authors. Map data: Google, 2020. Accessed on 21 May 2020.

3.2. Neighborhood Characteristics

The trial cohort of 18 participants comprised of 6 consumers and 12 prosumers, i.e., participants with a rooftop solar PV system installed at their home. As part of the wider RENeW Nexus project, a number of surveys and workshops were administered to varying (sub-)groups of participants that provide additional background information. 14 trial participants responded to questions about household characteristics (four households elected not to participate), leading to the following statistics: average household size within the trial cohort was 2.6 adults and 1.5 children (0–18 years). Homes had an average of 3.4 bedrooms, 2.2 bathrooms, and 2.4 living areas and were built between 1945 and 2018. Solar PV system capacities averaged approximately 4–5 kWh, ranging from 1 to 10 kWh (Only 11 out of 12 prosumers provided system size; average of 4.64 kWh based on these 11). Further information on neighborhood characteristics and an analysis of qualitative data from the RENeW Nexus project is available in Wilkinson, Hojckova, Eon, Morrison, and Sandén [36].

All trial participants had access to an online trading platform that allowed them to set and adjust their buying and selling prices at any time. Set rates remained active until the next change was made. Prices to be set were peak and off-peak rates for maximum buying and minimum selling prices per kWh of excess solar energy. In addition, the following prices (in Australian Dollars) applied:

- Rate for grid-sourced energy: $0.0572 per kWh (off-peak); $0.0990 per kWh (peak/3 p.m.–9 p.m.)
- Retailer rate for purchase of any unsold excess: $0.04 per kWh
- Retailer daily capacity charge: $1.10
- Daily network operator charge: $2.20
- Platform transaction fee: $0.005 per kWh purchased through trading

3.3. Observations of P2P Market Performance

Monthly electricity consumption and solar energy generation for 18 households are shown below for the trial system (Figure 2). The results indicate that there are seasonal gradients for both profiles: a general decrease in generation and increase in consumption from November to June. The negative gradient in solar generation can be attributed to the decrease in direct solar irradiance from the end of spring in November to the beginning of winter in June, which is consistent for geographic areas in the southern hemisphere. The positive gradient seen in the profile for electricity consumption is likely due to the general increase in household space heating from late spring to early winter. It is important to note that, in Western Australia, the penetration rate of household space heating systems (90%) is higher than that for air cooling systems (79%), which shows that the electricity consumption in the trial system is probably driven more by heating than cooling [39]. The solar generation dominates electricity consumption in the system from November to April, with the opposite being true in May and June.

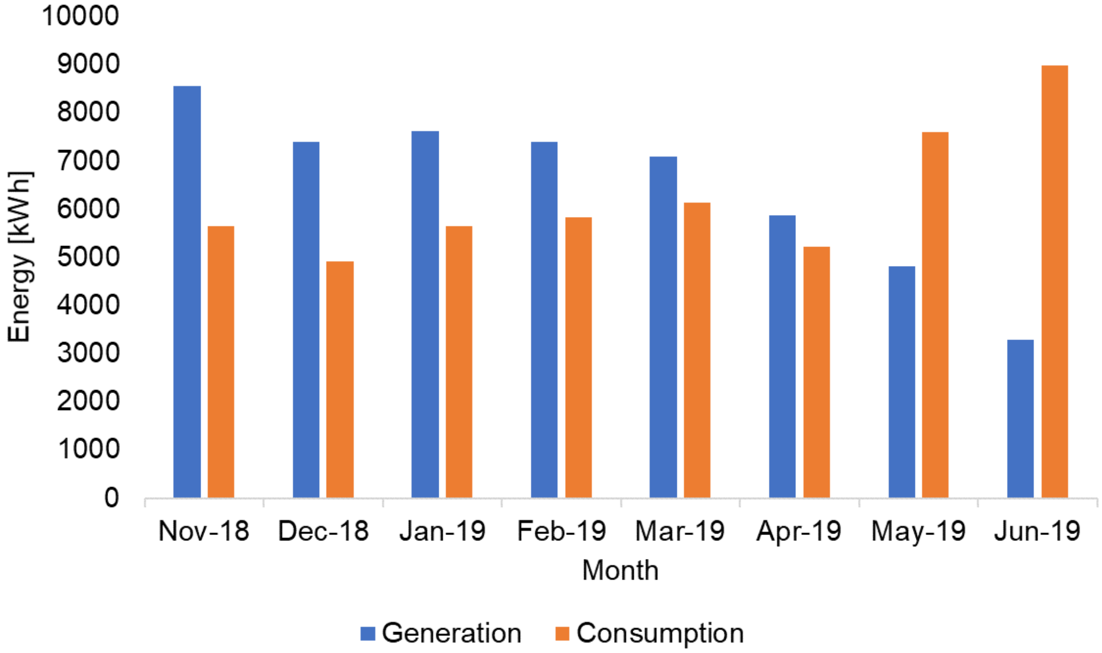

Figure 2. Monthly electricity consumption and solar energy generation for 18 households in the trial system.

The temporal profile of daily total changes to willingness-to-pay and willingness-to-accept values for all participants are shown below for the entire length of the market trial (Figure 3). Participants were highly engaged early on, with the largest peak in activity occurring on the day of the launch. Changes within the first month and a half of the trial can be attributed to the learning curve effect and early emails from program administrators with tips on how to use the trading system. Additionally, a few of the trial participants were onboarded to the market system in mid-December, which can account for some of the dynamics during that time. The profile of bid pricing updates becomes mostly static after mid-January. The decrease in the dynamics of bid pricing is likely due to apathy of engagement because of poor economic opportunities from participation resulting from high monthly fixed fees, which is described below. A lack in understanding of how to use the online trading system by some participants also likely influenced the decrease in bid pricing dynamics.

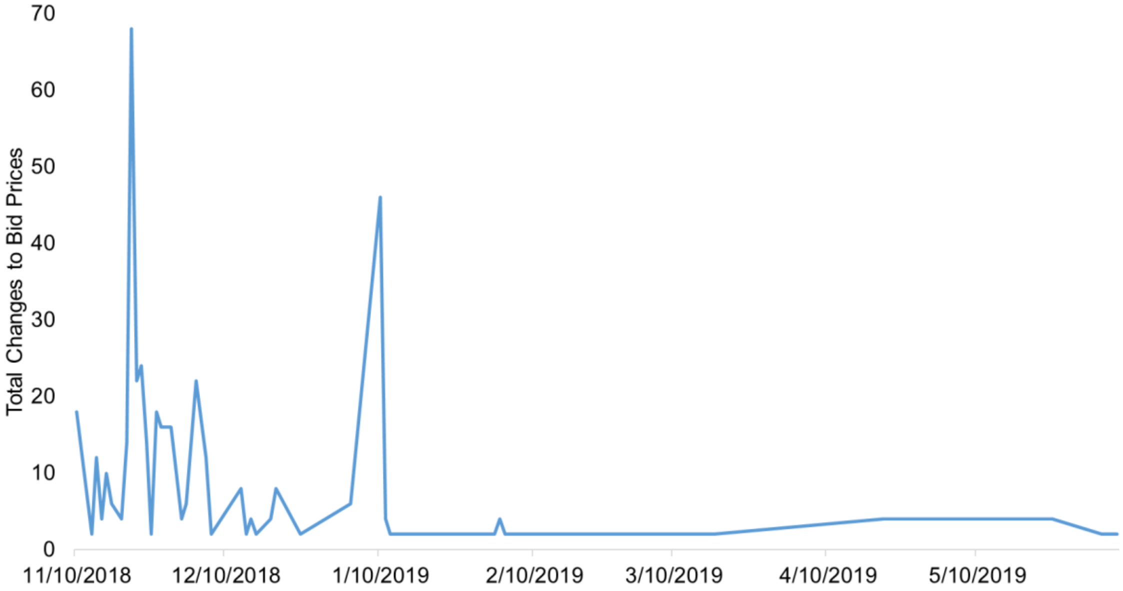

Figure 3. Daily total changes to willingness-to-pay and willingness-to-accept values during the trial market system.

4. Agent-Based Modelling Framework

An ABM framework was developed to simulate the dynamics of a peer-to-peer energy market to model electricity exchanges and prices for the RENeW Nexus trial system in the Perth suburb of Fremantle. A set of consumers, a set of prosumers, the Power Ledger trading platform, and an electricity retailer were simulated as agents; their interactions were simulated to assess market dynamics and the value of electricity in a local peer-to-peer system (Figure 4). The framework also simulated household-level battery energy storage with multiple scenarios of varied functionality; the framework simulated automatic battery unit charging and discharging, predefined schedules for charging and discharging the battery unit, and no battery energy storage. Automatic charging and discharging provide full flexibility over battery resources, allowing energy storage units to charge whenever irradiance is present and to discharge whenever there is available capacity. Predefined schedules for charging and discharging energy storage units constrain the flow of electricity to and from battery banks to daily timelines set by the household; electricity is not allowed to flow into battery units outside of the charging timeline, and electricity is unable to flow from the units outside of the discharging timeline. The framework was constructed using the MASON agent-based modeling open-source toolkit [21]. A complete summary of the market and energy storage dynamics simulated in the ABM framework is provided below according to the ODD protocol [40].

4.1. Overview

Purpose: The purpose of the model was to assess the value of electricity as determined by the dynamics of a residential peer-to-peer energy market.

State Variables and Scales: A set of prosumer households and a set of consumer households are represented as dynamic agents in the model. The state variables for the prosumer and consumer agent types are listed below in Table 1. Additionally, the platform is represented as an oracle agent, and the retailer is represented as a retailer or utility agent; their state remains static and their behaviors are outlined below in process overview and scheduling. The model was simulated for one month with a step period of 30 min, which was the trade interval length used in the RENeW Nexus trial system.

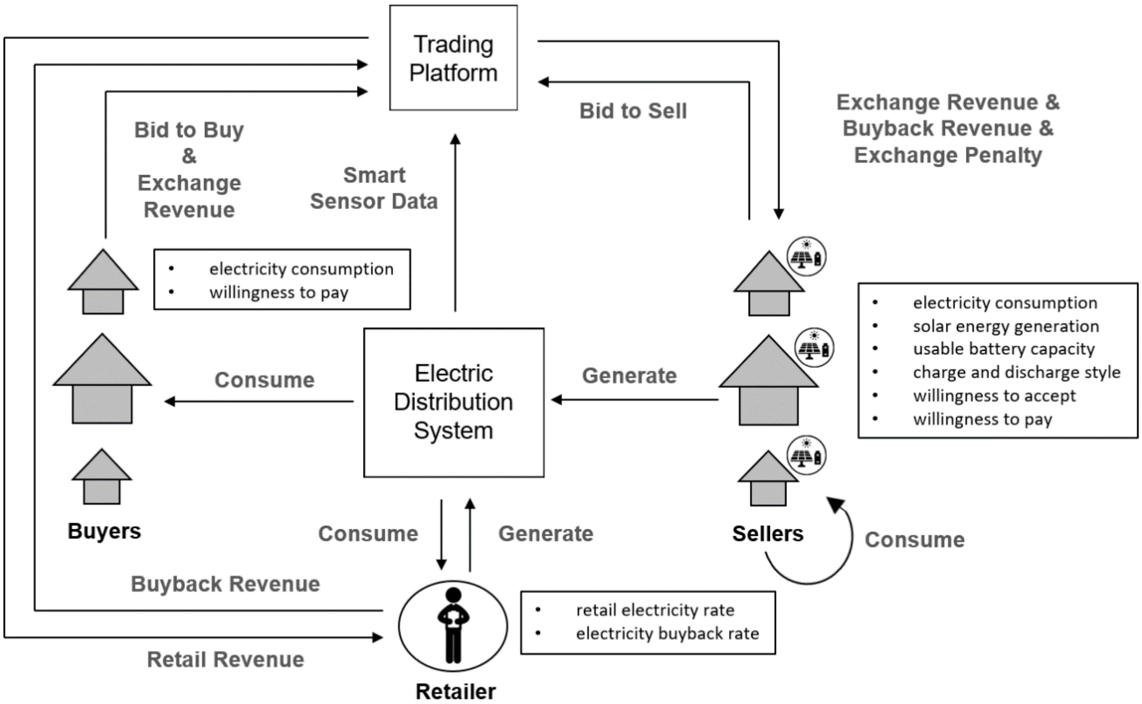

Figure 4. Agent-based modelling (ABM) framework simulates a peer-to-peer energy market to model electricity exchanges and prices for a trial system in the City of Perth. Agent attributes are shown in boxes.

Table 1. State variables for prosumer and consumer agents, which are updated at each time step *j*.

Prosumer Agent	Consumer Agent
Generation in interval j–G_j	Consumption in interval j–C_j
Generation forecast in interval j–GF_j	Willingness to pay of interval j–WTP_j
Consumption in interval j–C_j	
Storage available at beginning of interval j–S_j	
Willingness to accept of interval j–WTA_j	
Willingness to pay of interval j–WTP_j	

Process Overview and Scheduling: At each time interval, the order of operations in the ABM were executed for the RENeW Nexus system rules using the set of steps described below. For a scenario with no forecasting, the following steps were applied.

Step 1. Discharge initial storage: Available storage was initially discharged at the beginning of the current interval to satisfy prosumer household demand. If the time of day was outside of discharge hours, then there was no initial storage discharge for the predefined storage method.

Step 2. Communicate bid prices: Prosumer agents communicated their willingness to accept (WTA_j) for surplus electricity. Consumer agents communicated their willingness to pay (WTP_j) for surplus electricity.

Step 3. Perform market exchanges: Buyers and sellers were aligned in a bilateral exchange market based on their WTP_j and WTA_j values. Trades were successful if the WTP_j value of the buyer was greater than or equal to the WTA_j value of the seller; transactions were cleared at the buyer's WTP_j value. The trade agreement was defined so that the seller could exchange up to the buyer's full demand or their total excess generation for the upcoming interval. If two or more sellers had the same WTA_j value, sellers bid together, and their upcoming excess were grouped in the same exchange. If two or more buyers have the same WTP_j value, buyers bid together, and their demand values were grouped in the same exchange.

Step 4. Satisfy prosumer demand remaining after initial discharge: Prosumers used their energy generation, G_j, to satisfy demand remaining after initial storage discharge.

Step 5. Execute electricity exchanges: Seller generation remaining after demand and energy storage remaining after initial storage discharge was routed to the grid to satisfy electricity trade agreements made by sellers in the peer-to-peer market. If there were multiple sellers on the same exchange, then sellers sold all surplus electricity for the upcoming interval if the amount was smaller than the upcoming demand from the buyer(s). If the upcoming demand of the buyer(s) was smaller than the combined surplus of the sellers, then sellers exchanged an equal amount of surplus electricity between those on the same exchange, up until the seller with the smallest amount of surplus had exhausted their resources; this process repeated down the order of sellers until the demand of the buyer(s) was fully satisfied. If there were multiple buyers on the same exchange, then buyers all bought surplus electricity up to their demand for electricity for the upcoming interval if their combined demand was smaller than the total amount of surplus from the seller(s). If the upcoming amount of surplus from the seller(s) was smaller than the combined demand of the buyers, then buyers purchased an equal amount of surplus electricity between those on the same exchange up until the buyer with the smallest demand had filled their demand; this process repeated down the order of buyers until the surplus from the seller(s) had been fully purchased. Exchanged electricity from the seller(s) was first supplied by the available storage remaining after initial discharge; sold electricity could not be supplied by storage with the predefined storage method if outside of discharge hours. Solar generation remaining after prosumer demand was then supplied for the trade agreement made with the buyer(s).

Step 6. Fill battery energy storage unit: Any generation remaining after satisfying electricity exchanges in the market was routed into the battery bank. If there was more solar generation remaining than storage capacity available, then the battery bank was charged to maximum capacity, and leftover generation was routed to the local grid at the buyback rate set by the retailer. Battery energy storage was not charged by remaining generation for the predefined storage method if outside of charging hours; in this case, all leftover generation was routed to the local grid at the buyback rate set by the retailer.

Step 7. Satisfy buyer remaining demand: Any demand remaining for buyers after satisfying electricity exchanges in the market was supplied by the utility at the retail rate.

Steps were changed slightly for the solar forecasting scenario, as follows.

Step 1. Discharge initial storage: Available storage was initially discharged at the beginning of the current interval to satisfy prosumer household demand. There was no initial storage discharge for the predefined storage method if outside of discharge hours.

Step 2. Communicate bid prices: Each prosumer agent checked if GF_j would satisfy remaining scheduled demand for the interval; calculations for GF_j are outlined below in the sub-models section. If loads could not be satisfied, then the prosumer communicated the remaining demand amount to the market along with the WTP_j value. If demand could be satisfied, then the prosumer checked to see if there as any surplus. If there as surplus between remaining storage and GF_j, then this amount was communicated to the market with the WTA_j value; storage was not included in the surplus calculation for the predefined storage method if outside of discharge hours. If there as no surplus, then the prosumer did not go to the market. Consumer agents communicated their upcoming demand to the market with their WTP_j value.

Step 3. Perform market exchanges: Buyers and sellers were aligned in a bilateral exchange market based on their WTP_j and WTA_j values. Trades were successful if the WTP_j value of the buyer was greater than or equal to the WTA_j value of the seller; transactions were cleared at the buyer's WTP_j value. Trading was repeated until all demand was exhausted, surplus was completely bought, or the highest WTP_j value of the buyers was smaller than the lowest WTA_j value of the sellers.

Step 4. Satisfy seller demand remaining after initial discharge: Prosumers used G_j to satisfy demand remaining after initial storage discharge.

Step 5. Execute electricity exchanges: Seller generation remaining after demand and storage remaining after initial storage discharge were routed to the grid to satisfy electricity trade agreements made by sellers in the peer-to-peer market. Sold electricity was first supplied by the available storage remaining after initial discharge; sold electricity could not be supplied by storage with the predefined storage method if outside of discharge hours. Any sold electricity that was left over was then supplied by solar generation remaining after demand. The amount of electricity that was sold could be higher than what the household could supply to the local grid based on forecasting errors. In this case, all remaining storage and solar generation was injected into the grid; storage was not injected into the grid with the predefined storage method if outside of discharge hours. The utility supplied the amount of sold electricity that remained after all prosumer energy resources were exhausted, which the prosumer had to pay for at the retail rate.

Step 6. Fill battery energy storage unit: Any generation remaining after satisfying electricity exchanges in the market was routed into the battery bank. If there was more solar generation remaining than storage capacity available, then the battery bank was charged to maximum capacity and leftover generation was routed to the local grid at the buyback rate set by the retailer. Battery energy storage was not charged by remaining generation for the predefined storage method if outside of charging hours; in this case, all leftover generation was routed to the local grid at the buyback rate set by the retailer.

Step 7. Satisfy buyer remaining demand: Any demand remaining for buyers after satisfying electricity exchanges in the market was supplied by the utility at the retail rate.

4.2. Design Concepts

Emergence. The system price of electricity emerged from the interactions of the prosumer and consumer agents.

Heterogeneity. The prosumer and consumer agents both had a different consumption profile as well as different willingness-to-pay and willingness-to-accept values. The prosumer agents also had differing generation profiles.

Prediction. Prosumers predicted their solar production at the beginning of each trading interval using a simple forecasting model.

Sensing. Both the prosumer and consumer agents were aware of their demand profile.

Interactions. The prosumers and consumers could communicate energy bids if surplus electricity existed, and bids could be accepted or rejected based on the willingness-to-pay and willingness-to-accept values.

4.3. Details

Initialization: The agent-based modeling framework was initialized with values for number of prosumers as well as charging and discharging timelines for the predefined storage method. The default numbers of prosumers and consumers were 12 and 6, respectively. For the predefined storage method, default charging and discharging timelines were set as hours 09:00–14:59 and 15:00–20:59, respectively.

Input: The input data provided for the agent-based modeling framework included the consumption schedule for each household, generation profile of households with solar PV, and the timelines of willingness-to-accept and willingness-to-pay values for excess solar generated power. The input values were all taken from data recorded by the Power Ledger blockchain platform. These data for the RENeW Nexus system are shown in Section 3.3 above.

Forecasting Sub-Models: There are two forecasting models that prosumers used to predict upcoming solar production for each trading interval, including the perfect and simple forecasting models. The perfect forecasting model assumes that the prosumer knows exactly the solar production for the upcoming trade interval. The simple forecasting model calculates GF_j for the current interval using Equation (1), which multiplies the generation value of the previous trade interval by a forecasting parameter.

$$GF_j = G_{j-1} * P_F \tag{1}$$

where:

GF_j = Generation forecast for the current trade interval
G_{j-1} = Generation value of the previous trade interval
P_F = Forecasting parameter

5. Modeling Scenarios

The ABM framework was applied to the 18-household trial market system using the RENeW Nexus, perfect forecasting, and simple forecasting market structures; the framework was simulated with 12 prosumers and 6 consumers. The input data that was used in each modeling scenario included generation and consumption data, as well as WTP and WTA data recorded during the actual RENeW Nexus trial. The simple forecasting market structure was modeled with a forecasting parameter (P_F) of 75% and 100%. Each market structure was simulated with automatic, predefined, and no storage methods; household battery energy storage systems were modeled after the Tesla Powerwall 2.0 with a 13.5 kWh maximum capacity and a 70% depth of discharge [41]. A summary of settings is provided in Table 2 below.

Table 2. Summary of modeling scenarios and parameter settings.

Scenario Name	Market Structure	Storage Method	Forecasting Parameter (P_F)
RN-N	**RENeW Nexus**	No Storage	NA
RN-A		Automatic Storage	NA
RN-P		Predefined Storage	NA
PF-N	**Perfect Forecasting**	No Storage	NA
PF-A		Automatic Storage	NA
PF-P		Predefined Storage	NA
SF-N_{75} SF-N_{100}	**Simple Forecasting**	No Storage	75% 100%
SF-A_{75} SF-A_{100}		Automatic Storage	75% 100%
SF-P_{75} SF-P_{100}		Predefined Storage	75% 100%

A prosumer-to-consumer ratio analysis was performed for the RN-N and RN-A scenarios, where the number of prosumers was increased from 1 to 12; prosumers were chosen in each scenario by descending order of total solar generation over the entire market trial. A discharge timeline analysis was performed for the RN-P scenario in which the following timelines were tested: 15:00–20:59; 16:00–21:59; 17:00–22:59; and 18:00–23:59; a charging timeline of 09:00–14:59 was held constant for all scenarios in the discharge timeline analysis.

6. Results

The ABM was applied to simulate the existing RENeW Nexus trial and to explore alternative market structures that can affect market outcomes, based on electricity price and the amount of energy exchanged in the market. Research questions that are addressed in these results are summarized in Table 3.

Table 3. Summary of research questions.

Research Question	Section
How did the RENeW Nexus market perform?	6.1
How accurately does the ABM simulate prices and exchanged energy that were observed in the RENeW Nexus market?	6.2
How would storage affect the performance of the RENeW Nexus market?	6.3
How would combined strategies of storage and forecasting affect the performance of the RENeW Nexus market?	6.4
How does the ratio of sellers to buyers affect the performance of the RENeW Nexus market?	6.5

6.1. Analysis of Electricity Price in the RENeW Nexus Market

The ABM was executed to simulate the RN-N scenario, which most closely represents the RENeW Nexus market trial as it was implemented. This scenario simulated the generation, consumption, and exchange of energy for the eight months of the trial without the use of storage or forecasting approaches to improve market efficiencies. The simulated monthly seller and buyer average prices are shown below for the RN-N scenario (Figure 5); the prices include transaction fees as well as monthly generation and network fees. Average prices for buyers were calculated using simulated purchase data for all 18 participants, while the seller average prices were calculated using simulated sell data for the 12 prosumers that were involved in the trial. Buyer average prices were extremely high at multiple orders of magnitude greater than typical prices paid to the utility. The economic incentive for a buyer to participate in the market was the slim margin of savings that was made possible through a prosumer that underbids the retail rate of electricity; however, the fixed monthly generation and network fees overshadowed the marginal savings accrued in the peer-to-peer market. Negative values can be seen for seller average prices, indicating that sellers had to pay to send their excess onto the grid; this happened because the fees were greater than the revenue gained from exchanging excess solar power. Seller prices were much lower than buyer prices, because prosumers received revenue from consumers in the peer-to-peer market and buyback payouts from the utility for untraded excess. There was no economic benefit for either group to participate in the trial, as consumers paid substantially more than typical rates for electricity, while prosumers paid to send their excess power onto the grid.

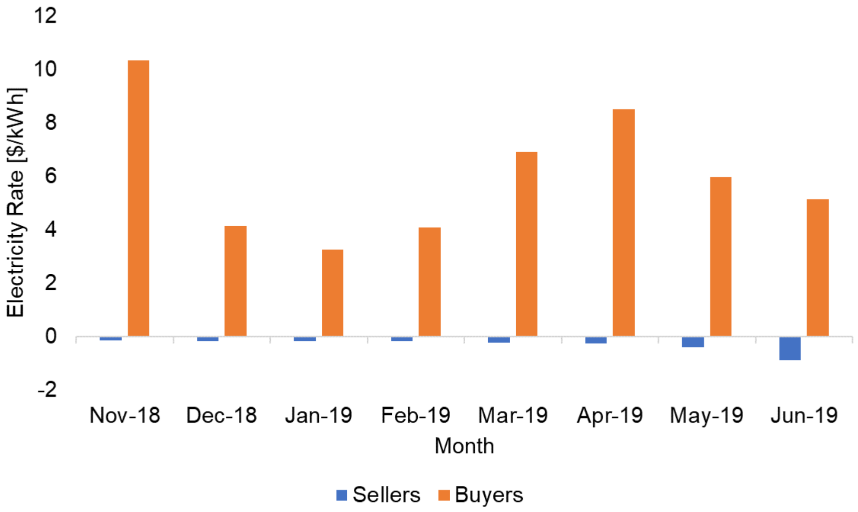

Figure 5. Modeled monthly seller and buyer average price of electricity in the trial system. Negative seller prices indicate that sellers pay to put energy on the grid. Results are shown for the RN-N scenario. Prices shown here include monthly generation and network fees. Transaction fees are also included in the prices shown.

6.2. Comparison of Observed and Simulated Trading Data

The observed and simulated time series of daily energy exchanged in the peer-to-peer market are shown below for the entire time period of the trial system (Figure 6); the simulated data is based on the RN-N scenario, which is the scenario that most closely resembles the structure of the actual system. There is a large error between the two series, as the actual energy exchanged was higher than simulated values. Over the trial period, the actual energy exchanged was approximately 6900 kWh, while the simulated energy exchanged was 2600 kWh, which is 62% lower than the observed energy exchanged. The error can be attributed to differences between the rules that were modeled for energy exchange and the actual implementation of the trading algorithm. The Power Ledger trading algorithm specifies that (1) prosumers cannot both buy and sell excess generation in the same trade interval, (2) prosumers cannot buy excess generation from themselves, and (3) prosumers cannot enter into more than one exchange per trade interval. The simulated series of energy exchange shows the temporal profile of the trial system with strict adherence to the rules outlined for the Power Ledger trading algorithm. Inspection of the trading data reveals that these three rules were violated in the implementation of the Power Ledger trading algorithm, which inflated the amount of energy that was exchanged in the peer-to-peer market. While there is a discrepancy in the magnitude of values between the actual and simulated energy exchanged, the pattern of peaks and troughs in the temporal profiles are similar.

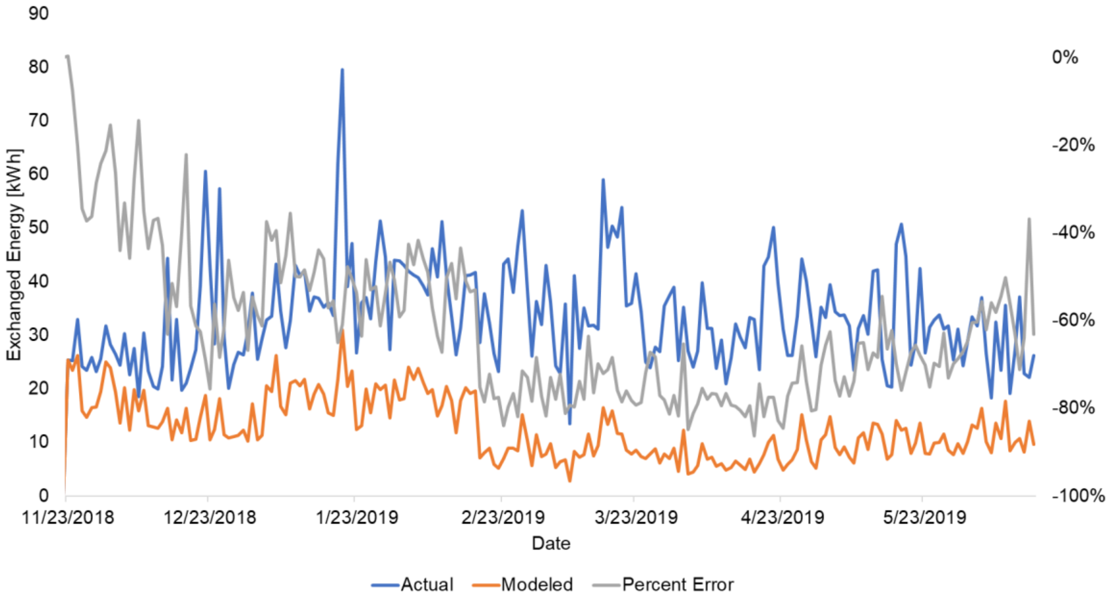

Figure 6. Actual and modeled daily energy exchanged in the peer-to-peer market system. Modeled data is shown for the RN-N scenario. Percent error of the modeled energy exchanged relative to the actual energy exchanged is also provided.

The actual and simulated daily average price of electricity exchanged in the peer-to-peer market is shown below for entire length of the trial system (Figure 7); the simulated data is representative of the RN-N scenario and only includes transaction fees. Both series keep the price of electricity reasonably close to retail rates, although they can be higher than the on-peak rate during some periods of the year. All prices shown are greater than the 4 ¢/kWh utility buyback rate for excess solar generation. The modeled data matches the observed data well over the trial timeline, although the modeled temporal profile overvalues the actual profile from early January through mid-February and undervalues the actual profile from mid-March through late May.

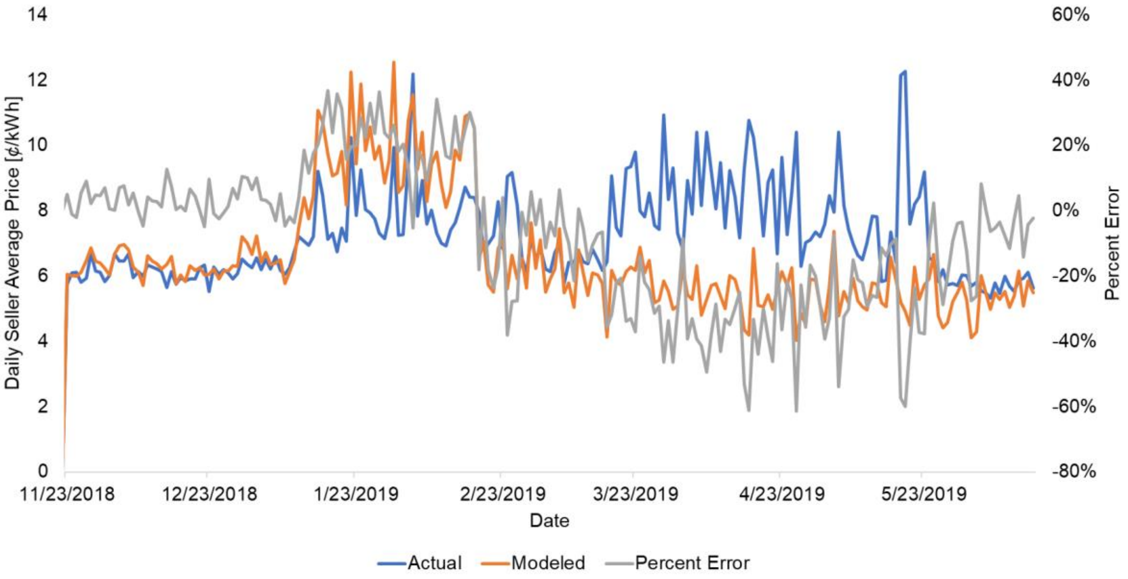

Figure 7. Actual and modeled daily seller average price of electricity exchanged in the peer-to-peer market system. Modeled data is shown for the RN-N scenario. Prices shown include transaction fees but do not include monthly generation and network fees. Percent error of the modeled price relative to the actual price is also provided.

6.3. Evaluating the Effect of Storage on Market Performance

The simulated seller average price of electricity traded in the peer-to-peer market is shown below from November 2018–June 2019 for the RN-N, RN-A, and RN-P scenarios (Figure 8). Prices shown were similar between November and April, with the peak during the month of January. The seller average price increased substantially in the months of May and June for the RN-A and RN-P scenarios, likely due to the increase in electricity consumption for these months. The range in price for each of the RN scenarios across the months was 4.06–4.55 (4.29 mean) ¢/kWh for RN-N, 4.14–6.89 (5.31 mean) ¢/kWh for RN-A, and 4.10–6.05 (4.85 mean) ¢/kWh for RN-P. Automatic and predefined storage capabilities increased prices relative to the RN-N scenario in each month except for November, which was caused by early market inefficiencies from poor bids, or the learning curve effect. The RN-A scenario dominates the RN-P scenario in all months; however, shifting the discharge timeline later in the evening could marginally improve the seller average price for the RN-P scenario (shown in Figure A1). Each monthly seller average price shown here was greater than the standard 4 ¢/kWh utility payout.

The buyer average price of electricity traded in the peer-to-peer market and the proportion of solar generation sold in the peer-to-to peer market are shown in the Appendix A for the RN scenarios (Figures A2 and A3, respectively). The highest average prices emerged in the months of January and February, though prices during other months were in a similar range. The range of price for each RN scenario across the months simulated was 5.85–9.42 (6.97 mean) ¢/kWh for RN-N, 6.30–9.28 (7.55 mean) ¢/kWh for RN-A, and 6.62–9.40 (7.86 mean) ¢/kWh for RN-P. Prices were lowest for the RN-N scenario, because the electricity had to be purchased earlier in the day during off-peak hours of demand. Monthly prices were highest for the RN-P storage scenario, because prosumers were able to place bids during on-peak pricing hours.

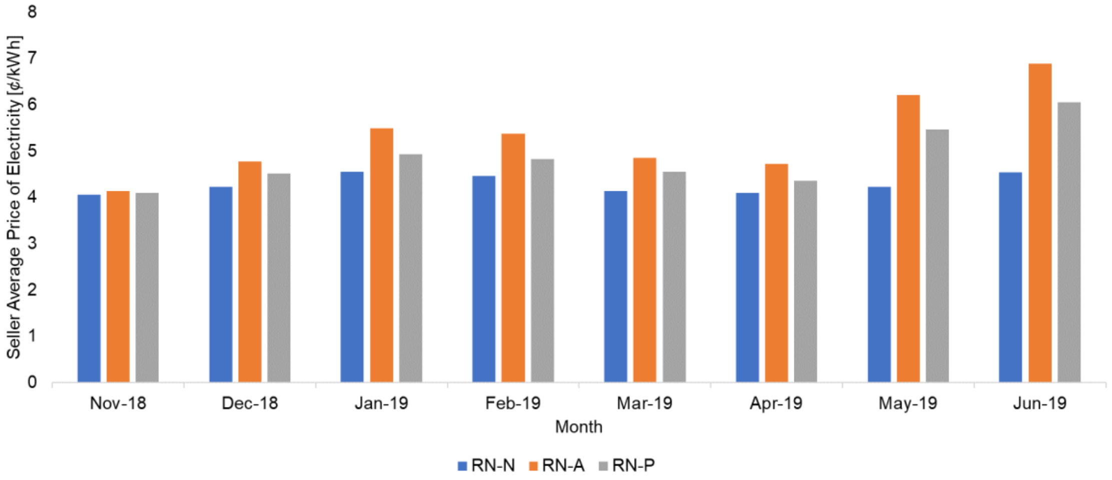

Figure 8. Seller average price of electricity in the trial market. Results are shown for the RN-N, RN-A, and RN-P scenarios. Prices shown here do not include monthly generation and network fees or transaction fees.

The proportion of excess solar generation that was sold in the peer-to-peer market is shown below for simulations of the RN-N, RN-A, and RN-P scenarios (Figure 9). The values shown here correlate well with those seen for the monthly seller average price of electricity. The month of November showed much smaller values compared to the other months, because households were learning how to use the platform and efficiently conduct trades early in the trial. The proportion of sold excess was similar from December through April, then increased in May and June. Both the automatic and predefined storage capabilities increased the proportion of excess generation sold relative to the RN-N scenario, with automatic storage dominating predefined storage. Results for the RN market structure represented a lower bound of performance for the market structures that are tested in the following sections.

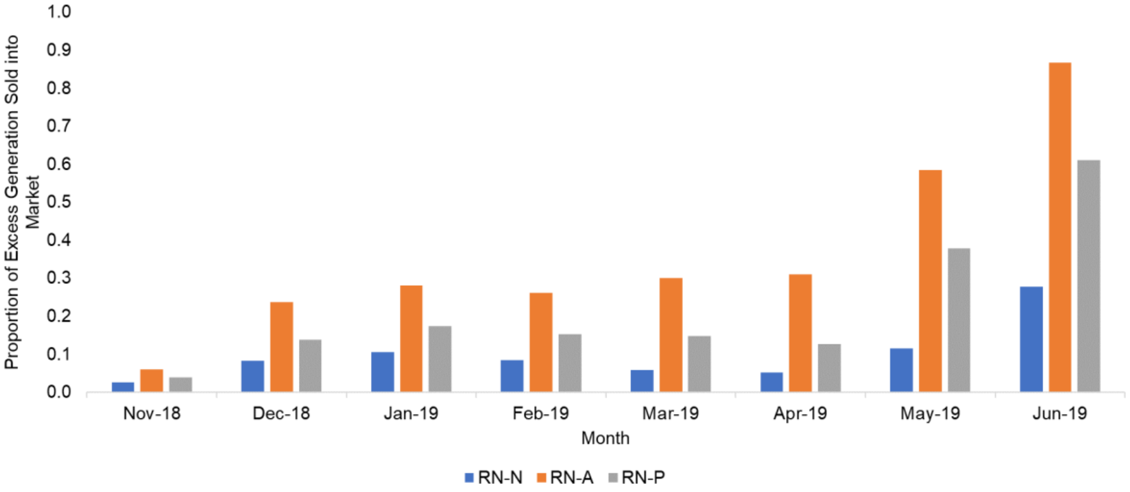

Figure 9. Proportion of excess solar generation sold in peer-to-peer market. Results are shown for the RN-N, RN-A, and RN-P scenarios.

6.4. Evaluating the Effect of Forecasting on Market Performance

The ReNEWS Nexus system was modeled using two alternative rules for forecasting energy production, as shown in Table 2. Simulation results for the PF (perfect forecasting) scenarios represented an upper bound of performance of all the scenarios tested; the percent increase in performance of the

PF scenarios relative to the RN scenarios in terms of the proportion of excess generation sold in the peer-to-peer market is shown below for all months and storage scenarios (Figure 10). PF generates a positive increase in sold excess generation for each month and storage scenario. For all months except November, the order of increase in performance of the storage scenarios from largest to smallest was no storage, predefined, and automatic, respectively. The range of increase for each storage scenario across the months was 35–71% (57% mean) for no storage, 6–51% (35% mean) for predefined, and 22–44% (29% mean) for automatic.

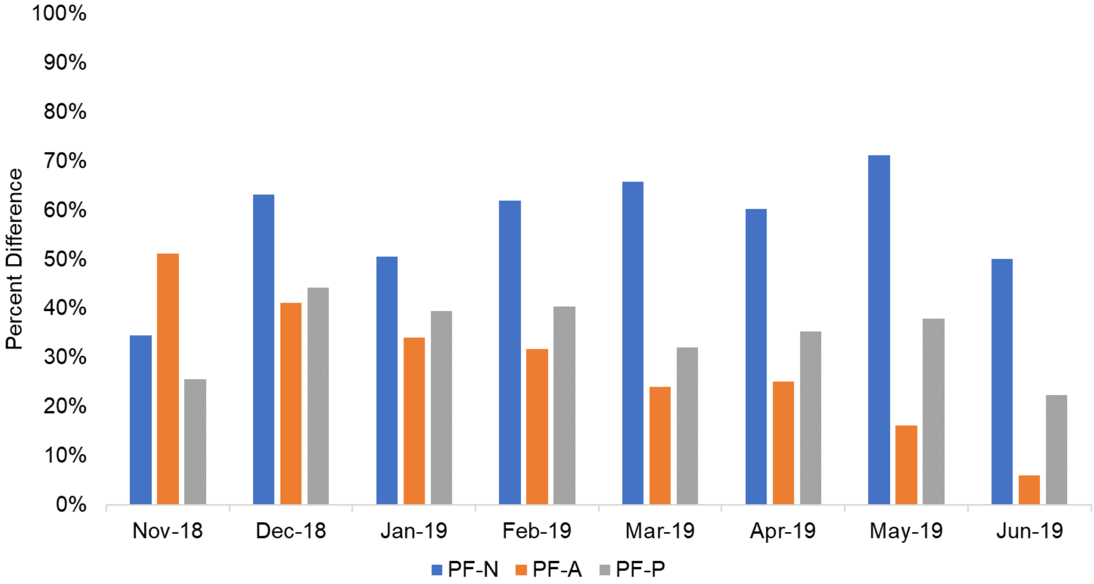

Figure 10. Percent difference in proportion of excess solar generation sold in peer-to-peer market between the forecasting parameter (PF) and RENeW Nexus (RN) market structures. Results for the PF-N, PF-A, and PF-P scenarios are shown. The percent difference shown is for the increase in performance of the PF scenarios relative to the RN scenarios.

Results for the SF (simple forecasting) scenarios represented the middle ground between the RN and PF scenarios; the percent increases in the proportion of excess generation sold in the peer-to-peer market relative to the RN scenarios are shown in the supplemental information for a forecasting parameter value of 75% (Figure A4) and 100% (Figure A5). Similar to the PF scenarios, the SF-N_{75}, SF-A_{75}, SF-P_{75}, SF-N_{100}, SF-A_{100}, and SF-P_{100} scenarios lead to a positive increase in excess generation sold relative to the RN scenarios for all months simulated. The mean increase in performance for the SF-N_{75}, SF-A_{75}, and SF-P_{75} scenarios across the months simulated was 45%, 31%, and 29%, respectively; the SF-N_{100}, SF-A_{100}, and SF-P_{100} scenarios result in a mean increase of 35%, 29%, and 27%, respectively. Limiting the forecasting parameter to a value of 75% lead to a larger proportion of excess sold into the market on average than a value of 100% for each SF storage scenario, because the 75% SF scenario underestimated upcoming solar generation and limited shortfall penalties. This allowed prosumers farther down the sell list to exchange their excess generation instead of prosumers higher up on the list filling buyer demand with an inaccurate amount of generation that must be eventually supplied by the utility. Both PF and SF market structures improvde performance of the no storage scenario greater than the automatic and predefined storage scenarios relative to the RN market structure.

6.5. Evaluating the Effect of Prosumer-to-Consumer Ratio on Market Performance

As shown in Figure 2, the amount of energy generated by prosumers was greater than the energy required by consumers during some parts of the year. The amount of energy produced and consumed should be balanced to improve market inefficiency, and the ratio of prosumers to consumers engaged in the market has a significant effect on this balance. The proportion of excess solar generation sold in the peer-to-peer market versus the number of prosumers in the market is shown below for three months (Figure 11). Results are shown for the RN-N scenario (Figure 11a) and the RN-A scenario (Figure 11b). Additionally, results are shown for the PF-N scenario (Figure 11c) and the PF-A scenario (Figure 11d). For each scenario, the total number of households simulated in the market was held at 18, while the number of prosumers increased from one to 12.

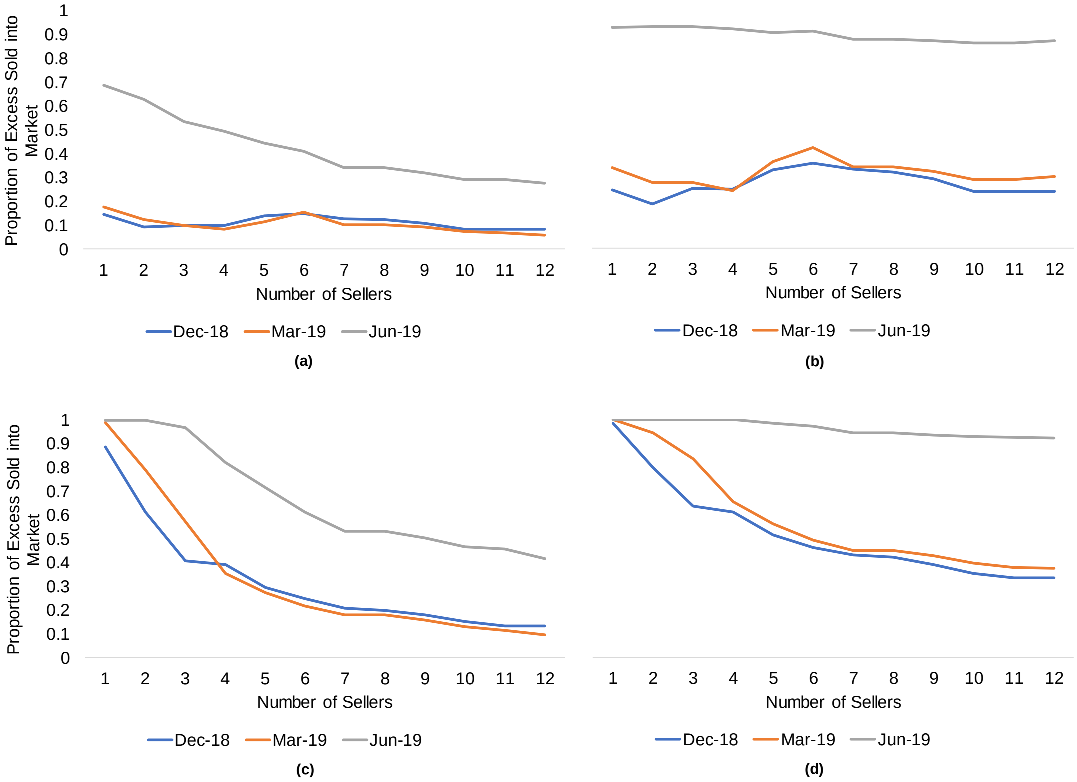

Figure 11. Proportion of excess solar generation sold in the peer-to-peer market versus the number of sellers. Results are shown for the (**a**) RN-N and (**b**) RN-A scenarios. Results are also shown for the (**c**) PF-N and (**d**) PF-A scenarios. Values are shown for the months of December, March, and June.

For the RN-N scenario (Figure 11a), March and December followed similar trajectories; the trend dipped within the first few numbers of prosumers, then increased until six prosumers, and finally decreased all the way through 12 prosumers. The odd profiles seen for March and December were likely due to a combination of low demand and the restrictive rule of one exchange per prosumer per trade interval; as the number of prosumers increased, more consumers could participate in exchanges to meet more demands through decentralized production. The month of June showed an expected trajectory with a decreasing trend from one to 12 prosumers. The proportion of sold excess generation was higher in June than in March and December, because June was a higher demand month, and each consumer was able to buy a larger share of available excess, leading to increased market efficiency. The RN-A scenario demonstrated that automatic storage functionality substantially increased the proportion of excess generation sold in the peer-to-peer market (Figure 11b). March and December followed trajectories similar to those seen in the RN-N scenario, decreasing within the first few numbers of prosumers, then increasing to the peak at six prosumers, and decreasing thereafter. The month of June showed, in general, a slightly decreasing trend from one to 11 prosumers, but the overall efficiency stayed around 90% of excess energy, compared to the RN-N scenario, in which efficiency dropped to nearly 30% in the month of June for 12 prosumers. The market created overproduction of solar generation for all months at each setting for the number of prosumers, for both RN-N and RN-A scenarios.

For the PF-N scenario (Figure 11c), the market efficiency was higher than for the RN-N scenario, which did not use forecasting. For a small number of prosumers in the PF-N structure, the market efficiency was very high, between 90–100% for all three months. This demonstrates that forecasting can significantly improve market performance, even without storage, for markets with few prosumers. For the PF-A scenario (Figure 11d), the proportions sold were much higher than those seen for the PF-N scenario, and in the month of June, nearly 100% of excess generation as sold in the peer-to-peer market for 1–4 prosumers in the market. Market efficiency remained high for the month of June across the number of prosumers in the market.

7. Discussion

The validation of the ABM for the RENeW Nexus case study provided the foundation for a critical analysis of P2P energy market structures. Building on the congruence of simulated and empirical observations, systematic experimentation, and the availability of supplementary information on the trial, this section discusses the efficacy of P2P trading as a means to manage DG. Though the number of households that participated in the RENeW Nexus trial limited its success, important lessons can be extracted from the trial and from the ABM that was developed in this research. The P2P electricity trading trial succeeded in giving prosumers more control on the price of their excess generation, and the trial revealed some important tradeoffs between the decentralized and centralized paradigms of electric distribution. The decentralized system of business gives end-users more financial control over their distributed energy resources, but the time commitment of participation, combined with high fixed costs, severely limits market activity. The centralized paradigm eliminates the time burden of household participation and provides a stable price point for electricity rates, though it gives prosumers less control over the value of their excess generation and limits the ability for communities to cultivate sustainable cultural norms. Fee and market structure changes are necessary to keep decentralized energy markets from drastically raising the price of electricity for consumers and lowering the value of excess generation for prosumers. Creating the opportunity for net positive financial outcomes will likely incentivize activity in decentralized markets and increase their economic efficiency; this, in turn, may embolden morale for P2P electricity systems and household renewable energy technology.

We provide an overview of the RENeW Nexus model and lessons learned through the ABM application, followed by a discussion of limitations and future work.

7.1. *Ratio of Prosumers to Consumers and Engaging Participants*

Efficiency of the P2P market system depends on the balance between consumer and prosumer households, and the ratio of prosumers to consumers limited the success of the RENeW Nexus trial. The disparity between the count of prosumers to consumers created market inefficiency and, thus, large amounts of untraded excess. Using the ABM, we explored how the seller to buyer ratio affects excess solar generation, and analysis revealed that the market became oversaturated when there were only a few prosumers participating in the system. The performance of the market was sensitive to the season, and the use of storage and automatic discharging during summer months allowed a higher number of prosumers in the market. Forecasting also permitted more prosumers in the market, though storage solutions were more effective at increasing the efficiency of the market.

Qualitative data from the RENeW Nexus trial suggests that understanding differences in motivations between consumers and prosumers may help develop targeted recruitment strategies to create a more balanced market population. Financial incentives were found to be of high importance to participants [36]. As such, improving the perceived satisfaction of consumers with potential economic outcomes will likely increase their participation and enhance P2P market efficiency.

Economic payoffs appeared to gain relevance for all (consumer and prosumer) participants once the initial decision to join had been made. This is suggested by the drastic reduction in changes made to buying and selling prices. Though pro-environmental attitudes may have initially motivated participants to join, the size of the economic rewards led to a decline in market engagement. As participants realized the limited scope of potential economic outcomes, they optimized their net benefits by minimizing their time investments. As a result, rate changes stagnated. Adequate overall engagement, as well as increased market participation, may thus require the provision of sufficiently large economic incentives within the tariff structure.

7.2. Implications of Regulatory and Incentive Structures

In the case of the RENeW Nexus project, existing rules within the Western Australian electricity system significantly limited the possibilities for efficient tariff design. The rules of the RENeW Nexus trial were set to create a simplistic bilateral exchange system, where only one transaction could take place each trade interval for all sellers and buyers. The single transaction setup limited the ability for sellers to exchange all of their excess solar generation. An alternative electricity market structure involving solar forecasting was tested using the ABM framework. The alternative structure allowed for multiple transactions to take place so more energy can be exchanged. While forecasting rules have the advantage of allowing prosumers to sell more of their excess generation, penalties for incorrect forecasts are possible, which can lower the value of that excess. The forecasting scenario was adapted to create more conservative projections, which limits shortfall penalties and increase the amount of energy sold relative to the RENeW Nexus scenario. Simulation of alternative electricity market rules with constrained forecasting shows that simple changes can be made to the platform exchange structure to improve market efficiency.

The simulation and analysis of the RENeW Nexus trial demonstrates that the viability of a P2P market depends on the adequacy of incentives for participating household agents. As described above, fees were structured in a way that led to high costs for consumers and prosumers, and participants did not engage in bidding in the market due to the lack of incentives. To optimize outcomes of P2P trading in practice, collective action and design is needed to develop a fee structure that encourages participation.

7.3. Effects of Integrating Storage into Market Design

Flexibility of solar generated energy resources can be improved with the use of energy storage technology. A lack of energy storage forces prosumers to sell the majority of excess in the middle of the day during off-peak hours of demand. Further, the absence of storage leads to a considerable amount of reverse power flow, which can negatively affect the power system and make network operations more difficult for utility managers.

The ABM framework as used to evaluate the advantages of using energy storage, and results showed that energy storage can increase the amount of excess generation that is sold in the P2P market, with significant gains in summer months. Both the automatic and predefined storage scenarios allowed prosumers to shift the discharge of excess solar generation to time periods of higher demand, which reduced high levels of reverse power flow during off-peak hours and increased the value of solar power for sellers. The predefined storage scenario allowed prosumer households to pinpoint the discharge of excess during the peak price hours for retail electricity, resulting in higher prices for sold electricity. Adoption of energy storage units at residential households can give prosumers the ability to employ temporal arbitrage in the decentralized market and limit the effects of reverse power flow during off-peak periods of system demand.

7.4. Limitations and Future Work

We describe as follows some components of the ABM approach and the P2P market that can be explored in further research.

7.4.1. Agent-Based Modeling of Consumers and Prosumers

Consumers and prosumers were simulated in the ABM described here as simple automata that exchange energy when they are matched through a bi-lateral market, based on reported values for willingness to pay and willingness to accept. New research is needed to simulate the decision-making process that consumers and prosumers use to form values of exchanged solar energy. Some consumers value environmental externalities of using solar energy, while others make decisions based on price alone. Households vary in their expertise of using technology and may also vary in perceptions, such as attitude, social norms, and perceived control around using new technology. Perceptions and attitudes of households engaged in the RENeW Nexus trial are explored by Wilkinson et al. [36]. Including heterogeneity among consumers and prosumers based on characteristics, abilities, and skills is needed to more realistically simulate agents and the emerging performance of P2P energy markets. Consumers and prosumers learn as they participate in a P2P market, and they may adapt and update their bids based on past success or failure to secure an exchange. New agent-based modeling approaches can be integrated within the modeling framework developed through this research to simulate agents that optimize bids based on feedback from the market.

The population of agents that is simulated in this research consists of 18 agents, and further research is needed to explore how the size of the market can affect the emergence of market performance. A larger group of participants could create more competition, leading to an efficient market. On the other hand, some households that lack the time or expertise to compete effectively may disengage from the market.

7.4.2. Aggregation Services

Alterations to the P2P market structure can be evaluated through further development of the ABM developed in this research. An increase in economic and technical efficiencies can be achieved by transferring management to aggregation service providers who have expertise in the operation of renewable energy technology. Aggregation services eliminate the time burden for households and can decrease the uncertainty in payments for excess generation by offering a predetermined rate for solar production. However, aggregation service providers can negatively perturb electricity prices for consumers in decentralized markets if they gain enough market power; aggregators can do this by withholding energy storage capacity and manipulating the supply curve of electricity, similar to Enron in the early 2000s [42]. New research can simulate aggregation services and explore their impact on market performance.

7.4.3. Automated Trading Algorithms and Smart Contracts

A different method of solving the time burden for prosumers and consumers could be the development of an automated trading algorithm. Automated trading algorithms can be built on smart contracts. Smart contracts, which are simple scripts that perform automated algorithmic steps using data logged by the blockchain [43,44], can be used with the ledger of bids and transactions to validate that constraints are being met and to restrict market exchanges between participants. They also allow for the automatic execution of payments and their real time settlement [26]. An algorithm that automatically updates bid pricing for households can be made possible through the use of machine learning technology. Machine learning can be applied to data on historical bid success and failure as well as system-level demand data that is made available by the online trading platform to make improved decisions on P2P energy bids. Machine learning can also be applied to meteorological data to make more accurate solar forecasts during the bidding process. Automated trading algorithms can increase the technical efficiencies of decentralized electricity exchanges and defend consumers against price manipulation induced by aggregation service providers by keeping market power in the hands of individual household prosumers.

Automation may offer an alternative—or complementary—approach to improving market participation. By removing the time commitment barrier, economic outcomes may still be optimized. In addition, automated adjustment of buying and selling rates could help address potentially low levels of technological and electricity market literacy by offering participants the possibility to delegate decision-making to algorithms. Automated services can be simulated within an ABM framework to explore how they might impact market performance and provide guidance for adopting these technologies within a P2P market.

7.4.4. Using Tokens within Blockchain Technology

Decentralized electricity systems must be regulated at both the virtual market and physical distribution levels. An important issue for regulation is developing a platform solution for enforcing system-level policies, and the RENeW Nexus trial uses blockchain technology to enable trades. A novel feature of blockchain platforms is the ability to create assets and sub-assets, or tokens that represent virtual or physical objects. Asset tokens can be issued by users of a blockchain protocol that supports asset creation; they can be used for a number of purposes including representing gold bars, energy credits, concert tickets, and gift card credits [45]. Assets can also be used to represent organizations and businesses; sub-asset tokens can be created under those assets and used to develop sub-networks within the blockchain platform that, for example, facilitate the public trading of stocks for subsidiary companies, or manage boarding passes and frequent flyer miles. In the context of P2P energy trading, an asset can be created to support a decentralized electricity platform, and sub-asset tokenization can be used to regulate the virtual energy market. For example, tokens can be created and passed to prosumers for each kWh of excess generation sold in the P2P market, which can be used to enforce rules for maximum power flow. Additionally, tokens can be passed to prosumers for each kWh of energy storage that is bid into the P2P market to institute a constraint for the minimum amount of storage that must be offered each interval, which would be a defense against the gaming of aggregated energy storage resources. The feature of blockchains to support sub-asset tokenization can be employed to regulate a P2P energy trading platform and ground the virtual market into the physical constraints of the grid and protect consumers from electricity price manipulation.

7.4.5. Secondary Markets for Decentralized Energy Systems

P2P energy trading allowed prosumers in the trial to create higher value for their excess generation. However, the extra value was overshadowed by the high fixed costs of participating in the trial. Participants could accrue other value with their distributed resources if secondary markets were established in the platform. Secondary markets can be created for frequency balance, ancillary services, and peak shaving to help facilitate grid stability; this can add more value for prosumers if they own a household energy storage system. Further, secondary markets can be enabled through sub-asset tokenization of energy resources and smart contract technology. The addition of secondary markets could completely change the game theoretical approach of households that participate in the market. More simulations should be performed to determine the additional value that is created through secondary markets and to assess their impact on the dynamics of decentralized electricity systems.

7.4.6. Physical Constraints of Electric Distribution Infrastructure

The simulation framework developed here models a virtual P2P electricity market but does not consider the constraints of the physical infrastructure. P2P electricity exchanges could, however, adversely impact the power system dynamics of the distribution system. Future work can couple an electric distribution system model of the infrastructure with the ABM to perform power system analyses and determine the constraints of the grid. This insight can be valuable in planning infrastructure operations and regulating market exchanges. A better understanding of the network layout and a map of the physical vulnerabilities can help facilitators draw boundaries for sub-market systems that are more appropriate for infrastructure. Determining the physical constraints of the system can also be used to develop appropriate network and generation fees for participants.

7.4.7. Sub-Market Boundaries and Neighborhood Clustering

The geographic displacement of the participating households along with the disparity between the number of prosumers and consumers together raise an important challenge in how to appropriately scale decentralized electricity markets. As the number of participants increases, it will become important to facilitate decentralized markets at an adequate scale. Decentralized markets can be scaled by aggregating participants into clusters that function as sub-market systems. Boundaries for the sub-markets may be drawn according to power system boundaries to better facilitate grid stability. Sub-market boundaries may also be assigned through neighborhood zoning to foster community connections in decentralized electricity systems. Boundaries for sub-markets should consider the ratio of prosumers to consumers; parity between prosumer excess generation and sub-system daytime demand is necessary to ensure market efficiency. The boundaries may be redrawn over time based on market outcomes and comparing historical willingness-to-pay and willingness-to-accept values for P2P electricity. Clustering households to scale decentralized markets may induce gains in economic efficiency and help to better manage power system integrity.

8. Conclusions

An ABM framework is demonstrated here to simulate P2P electricity trades in a decentralized electricity market. The framework is applied to data from a real case study in Western Australia to validate modeling assumptions. Simulations are performed to determine the impact of alternative governance models on the dynamics of the trial system. Battery bank systems are modeled in the framework to determine the effect that energy storage can have on market performance.

The work presented here can be extended in the future to enhance the insight that is gained from using ABM. For example, the modeling framework can be applied to a P2P electricity system that allows residential apartment units to trade excess generation within and between buildings. Clustering schemes of households in the community can be tested to evaluate the scale at which to conduct decentralized energy trading. The ABM can be used to simulate the withholding of household energy storage capacity from the P2P market to determine the ability of individuals and aggregation service providers to manipulate energy prices. Though the platform used in the trial was based on blockchain technology, none of the observed outcomes could be linked directly to this feature. However, blockchain technology does provide promising features in the context of regulation and governance of decentralized energy systems. Sub-asset tokenization can be modeled to assess its ability in enforcing market constraints for limiting price manipulation and protecting grid integrity. The extent to which blockchain technology may be able to mitigate potential privacy and data accuracy concerns in the context of power control could be another possible avenue of research. Commentary regarding the usefulness of platforms in improving user engagement is beyond the scope of this study but may be an important avenue for future research. Although low engagement was observed, the study design does not allow for inferences to be made in this regard. Future studies should also consider including more heterogeneity in behavior and allow for the assessment of behaviors within social systems.

Designing and implementing an efficient, equitable, and sustainable future energy system requires collective and coordinated action from a diverse set of actors. Its success hinges on the recognition of trade-offs on, and across, social, technological, economic, and environmental levels. ABM helps manage the resulting uncertainties by facilitating the testing and development of alternative management strategies.

Author Contributions: Conceptualization: J.G.M. and E.Z.B.; methodology: J.G.M.; formal analysis: J.G.M., and P.H.; resources: M.S.; data curation: P.H.; writing—original draft preparation: J.G.M., and P.H.; writing—review and editing: M.S. and E.Z.B.; supervision: M.S. and E.Z.B.; project administration: E.Z.B. All authors have read and agreed to the published version of the manuscript.

Funding: The RENeW Nexus project was supported by the Australian Government through the Smart Cities and Suburbs Program. Paula Hansen is funded by the CRC for Low Carbon Living Ltd. supported by the Cooperative Research Centres program, an Australian Government initiative; the Australian Renewable Energy Agency as part of its Research and Development Programme; and the Australian Housing and Urban Research Institute through their research capacity building in the form of a PhD top-up scholarship. The funding bodies had no involvement in study design; data collection, analysis, or interpretation, nor in the writing of the report. Jacob G. Monroe is funded by the United States National Science Foundation Graduate Research Fellowship Program [Grant No. 2016223977] and the Hood Fellowship, funded by Ed Hood Jr. and his wife, Kay. Any opinions, findings, and conclusions or recommendations expressed in this material are those of the authors and do not necessarily reflect the views of the United States National Science Foundation or the views of the Hood Family.

Acknowledgments: The authors would like to thank Daniel Marrable and Rebecca Lange at the Curtin Institute for Computation for their assistance with data management and provision and Gregory M. Morrison at the Curtin University Sustainability Policy Institute for his support in enabling this collaboration.

Conflicts of Interest: The authors declare no conflict of interest.

Abbreviations

ABM	agent-based model(s) or agent-based modelling;
DG	distributed generation;
DER	distributed energy resource(s);
ICT	information and communication technology;
LGA	local Government Area;
P2P	peer-to-peer; PV–solar photovoltaic(s).

Appendix A. Supplemental Results

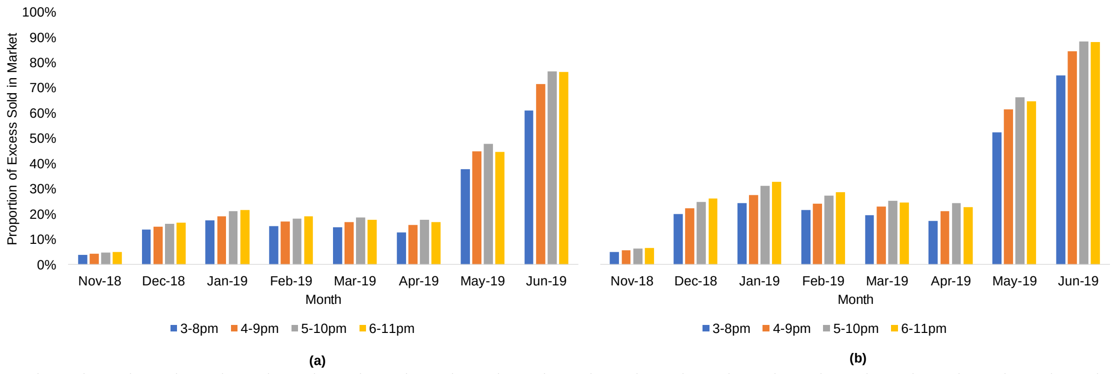

Figure A1. Proportion of excess solar generation sold in the peer-to-peer market versus the predefined storage discharge timeline for the (**a**) RN-P and (**b**) PF-P scenarios. Values are shown for the months of December, January, February, March, April, and May.

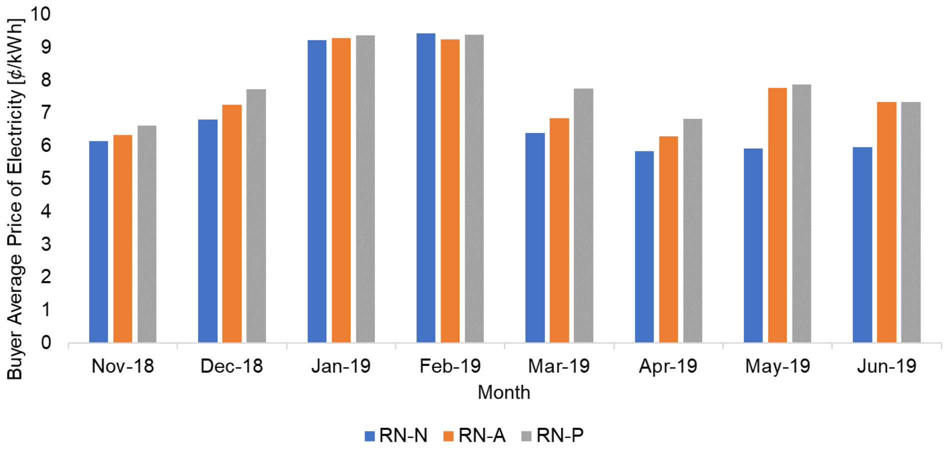

Figure A2. Buyer average price of electricity in the trial market. Results are shown for the RN-N, RN-A, and RN-P scenarios. Prices shown here do not include monthly generation and network fees. Transaction fees are also not included in the prices shown.

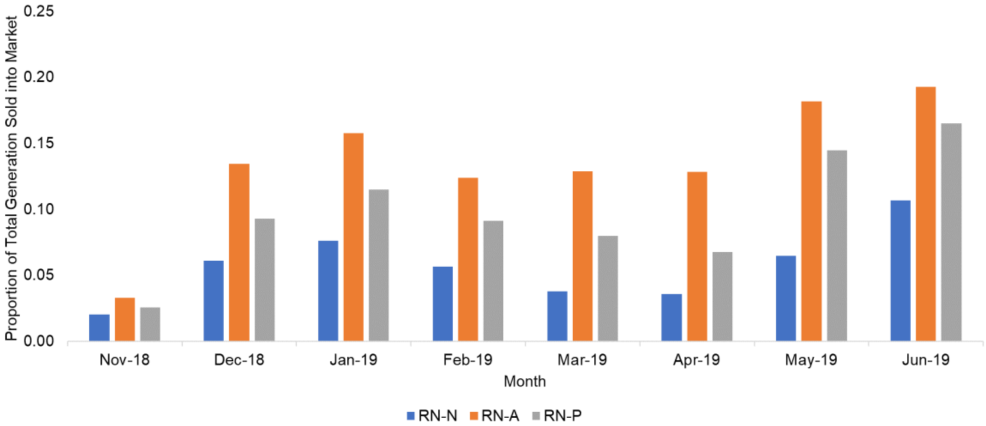

Figure A3. Proportion of total solar generation sold in peer-to-peer market. Results are shown for the RN-N, RN-A, and RN-P scenarios.

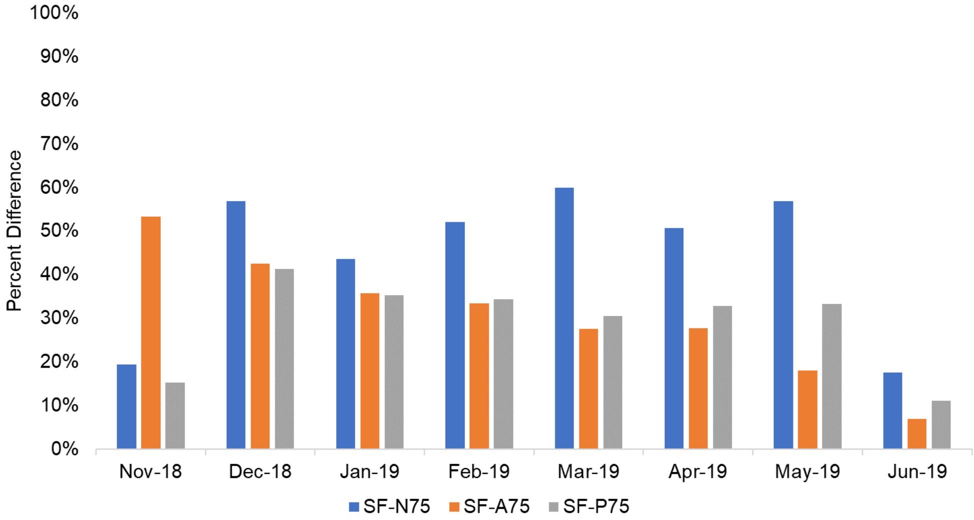

Figure A4. Percent difference in proportion of excess solar generation sold in peer-to-peer market between the SF and RN market structures. Results for the SF-N_{75}, SF-A_{75}, and SF-P_{75} scenarios are shown. The percent difference shown is for the increase in performance of the SF scenarios relative to the RN scenarios.

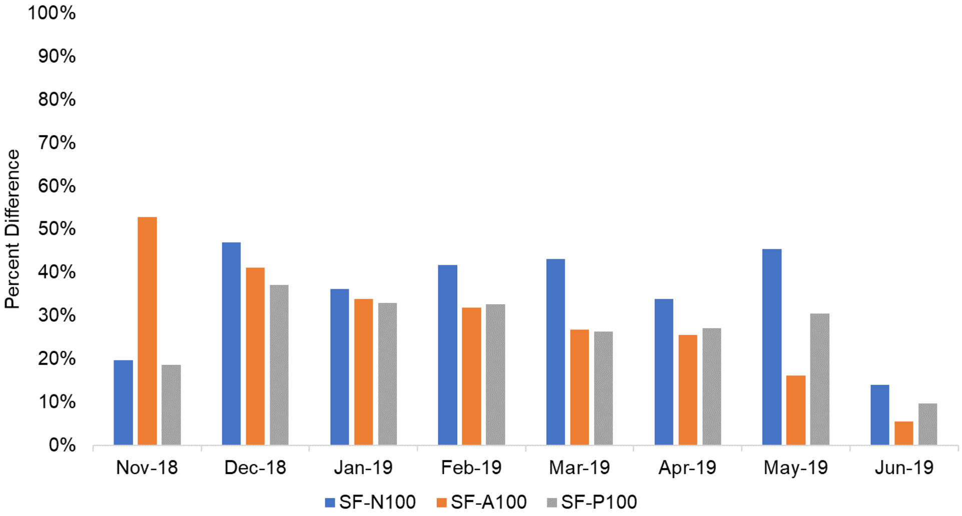

Figure A5. Percent difference in proportion of excess solar generation sold in peer-to-peer market between the SF and RN market structures. Results for the SF-N_{100}, SF-A_{100}, and SF-P_{100} scenarios are shown. The percent difference shown is for the increase in performance of the SF scenarios relative to the RN scenarios.

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Publication V

Manuscript under review for publication in peer-reviewed journal

Hansen, P. & Morrison, G.M.: Beyond local scale: Action and impact of sustainability initiatives from a polycentric perspective. Under review in Heliyon.

Energy Research & Social Science

Optimising shared renewable energy systems: An institutional approach

--Manuscript Draft--

Manuscript Number:	
Article Type:	Research Paper
Section/Category:	Energy institutions and governance
Keywords:	institutional analysis; community energy; shared resource systems; collective action
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Optimising shared renewable energy systems: An institutional approach

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Abstract

The potential of shared renewable energy schemes to optimise outcomes for communities and the larger energy system has inspired a surge of collective action by diverse stakeholder groups. Existing evaluations of community energy systems tend to focus on the performance of separate system components in isolation. This is at odds with the sociotechnical conceptualisation of energy systems that social energy research commonly draws on. This article posits that institutional arrangements, as the mechanisms, both coordinating sociotechnical interactions and governing sharing, may offer an improved integrated understanding of optimal system performance. The Institutional Analysis and Development framework was applied to a three-part case study to identify the institutional arrangements used, and the conditions that enabled and inhibited optimal system performance. Analysis showed that a well-performing collective-choice process of designing the sharing arrangements is a prerequisite for optimal outcomes at the operational level. Moreover, the involvement of expert organisations for the operation of complex energy systems may lead to incentive mismatch, followed by socially suboptimal outcomes. The study demonstrated that institutional factors have a considerable effect on the performance of shared energy systems.

Key words: institutional analysis; community energy; shared resource systems; collective action

Declarations of interest: none

Acknowledgements: This research is funded by the CRC for Low Carbon Living Ltd supported by the Cooperative Research Centres program, an Australian Government initiative; and received funding from the Australian Renewable Energy Agency as part of its Research and Development Programme. Paula Hansen received funding from the Australian Housing and Urban Research Institute through their research capacity building in the form of a PhD top-up scholarship. The funding bodies had no involvement in study design; data collection, analysis and interpretation; nor in the writing of the report. Permission to publish this research article was sought and granted from all three funding bodies prior to submission where applicable.

The author would like to thank Professor Gregory M. Morrison, Dr. Atiq Zaman and Dr. Xin Liu for their feedback on earlier versions of the manuscript.

Abbreviations:

IADF – Institutional Analysis and Development Framework
CPR – Common-pool resource
SHAC – Sustainable Housing for Artists and Creatives
SRES – Shared renewable energy system(s)
WGV – White Gum Valley

Word count: 8055 (excluding references)

1 Introduction

The global quest for a low-carbon energy system has increasingly led to individuals and organisations taking part in collective action to create and operate small-scale renewable energy systems [1, 2]. To support society's efforts to optimise energy systems, this study suggests the use of an institutional approach to evaluate the structure and performance of shared solar energy systems.

Optimisation is a prominent theme in the literature on shared renewable energy systems (SRES) [3] [*e.g.* 4, 5]. The act of sharing energy has the potential to enable optimisation of the integration of renewables into grid operation [4, 6], reduce capital expenditures, lower electricity costs [*e.g.* 4, 7], change consumption practices [8], improve social cohesion [9, 10] – and, ultimately, contribute to the low carbon energy system of the future. This positive impact of community energy on the function of future energy systems can only be fully realised if the shared small-scale systems themselves operate optimally [*cf.* 11]. As such, the behaviour, performance and optimisation of a variety of primarily economic and technical aspects of shared renewable energy systems has also been studied [3, 12].

Although useful, evaluations of individual components as an indication of system performance are at odds with the prominent socio-technical conceptualisation of energy system dynamics. Viewed through a socio-technical lens, elements not only co-exist, but interact with each other [13]. Consumers, producers, and managing actors are connected to, and through, physical network infrastructures, wires, and generation plants; control systems, and flows of energy, information and finances [*cf.* 2, 11]. Given this complex interplay between different elements, studying an individual element requires accounting for the others as well [14]. Thus, achieving optimal outcomes requires effective coordination of interactions [*cf.* 15]. The need for coordination among actors has been exacerbated by the increasing number, diversity and complexity of energy system actors and generation sources [16]. It follows that our ability to optimise the sharing of renewable sources of energy, and subsequently reap larger-scale benefits of shared systems, hinges on an understanding of coordinating mechanisms.

These mechanisms may be defined as institutions – prescriptions that serve to organise the structured interactions within shared systems (Ostrom, 2005). Institutions are organised social practices [11] that constrain and facilitate individual choices and their consequences [17]. In shared energy systems, these social practices may address, for example, the allocation of costs and benefits, degrees of power and control, and responsibilities held by different actors [16]. Institutions are critical to structuring repetitive social situations [15]. This study uses an institutional approach to reframe optimal performance as the outcome of interactions among elements. Only limited understanding of institutions in the context of community energy currently exists [12, 13, 18]. Knowledge gaps exist regarding the institutional conditions that may enable the optimisation of renewable energy communities [19]; and regarding the formation of institutional arrangements for energy systems [13] and their potential influence on technical system performance [16].

This paper contributes to closing this gap by applying an institutional approach based on collective action theory to a three-part case study of shared solar energy systems in Perth, Western Australia. Focusing on the performance of interactions, rather than individual components, should offer insights into optimality that are more in line with the widely accepted notion of socio-technical complexity. This paper aims to improve the understanding of how energy sharing works by identifying the institutional arrangements used for the sharing of solar energy in the case study; and analysing which institutional factors support and inhibit the performance of the shared systems. The following section provides the background to the study by outlining its theoretical roots in collective resource governance (2.1), and briefly reviewing how this literature and its most prominent analytical tool (2.1 and 2.2) have been applied to energy studies.

2 Background

Novel energy system configurations are marked by the diversity of actors involved in their operation [16, 20]. Interdependent situations, such as the sharing of energy, in which multiple actors with (potentially) diverging interests interact, may face problems of collective action (or, social dilemma). If actors independently pursue their own maximum short-term benefits in an interdependent situation, outcomes will be suboptimal for all [21]. When actors take collective action and coordinate their strategies, the social dilemma can be avoided and mutually beneficial outcomes achieved [22].

This potential of groups of actors to organise and overcome problems of collective action has been empirically validated and extensively discussed in the context of common-pool resources (CPRs) [*cf. e.g.* 15]. Resources are defined as common-pool when it is difficult to exclude potential beneficiaries from accessing them, and one person’s usage subtracts from the supply available to others [23]. These characteristics mean that without coordinated efforts, the resource may be depleted, representing a suboptimal outcome for all. Groups can achieve the socially optimal outcome of sustainable resource use by establishing institutions that constrain and enable actions, choices, and consequences [24].

Shared energy systems have been conceptualised as CPRs because they, too, are concerned with optimising the use of natural resources [*cf.* 11] and managing their overuse and access [10, 25]. Similarly, enabling and managing the operation of systems of energy co-production and co-consumption requires institutional arrangements to facilitate the necessary collective action [1].

Addressing institutional factors in the context of shared renewable energy systems is essential to design effective management strategies and policies [*cf.* 26, 27].

Emerging systems of shared energy resource ownership and use are in contrast to an established provisioning system based on private ownership structures [28]. Choosing the right ownership structure for energy sharing can help optimise collective outcomes by influencing the risks, uncertainties and incentives faced by actors [12]; and by addressing questions of control, cost and benefit distribution, and responsibilities [16]. Further, the degrees of control available to actors is likely to impact how accepting actors will be of novel system configurations [11]. Given the differences in incentives offered by different governance regimes, further inquiry into the way they affect actors' interests, and the costs of energy consumption and production is needed [28].

Systematic analysis of institutional arrangements and their effectiveness may be facilitated by the Institutional Analysis and Development framework (IADF) [*e.g.* 23, 29]. Developed to support the study of how governance systems may promote and facilitate collective problem-solving [23], the IADF guides analysts through the complexity of institutions, and towards an understanding of their operation and evolution [24]. In the context of SRES, the IADF allows a deconstruction of complex sociotechnical systems into their component parts [26]. As a result, insights into the interactions between community characteristics (such as their attitudes towards the environment), policies, choices of technology and availability of resources (*e.g.*, hours of sunshine and solar irradiance) can be gauged [15]. It also enables the identification of strategies used by actors to devise and change rules of collaboration [30] and emphasises their importance [1].

Although applications are still limited, there is an increasing recognition of the IADF as a valuable tool for energy transitions research [16]. One recent study applied the IADF to identify institutional factors that may support or inhibit decision-making processes concerned with the establishment of smart energy projects [16]. Similarly, and through an interest in analysing local level development processes, Newell, Sandström and Söderholm [30] used the typology of rules proposed in the IADF to understand the institutional context that influences social networking processes, and in turn, enables investment in renewable energy projects. Heldeweg and Lammers [1] combined the IADF with legal scholarship to analyse discrepancies between existing legislation and the increasing numbers of community microgrids. Using the IADF to analyse the effect of rules, biophysical conditions and attributes of the community on energy transitions, Koster and Anderies [15] proposed a set of institutional drivers for energy transitions. Their study found that energy transitions face a social dilemma that requires the introduction of well-designed institutions.

This paper uses the IADF to identify the structure and rules of energy sharing in a case study of three apartment buildings. Aspects of the institutional arrangements that enable or disable optimal performance are identified. This understanding of what does and does not work in practice is paramount to reforming the energy system [*cf.* 27]. The following sections explain the research design; describe the case study (3.1) and data collection methods (3.2); and outline how data was analysed using the IADF (3.3).

3 Research design

The principal research question addressed in this article is: What are the institutional arrangements for energy sharing in the case study, and how do they support and inhibit optimal performance? The aim is to gain an understanding of how sharing works by focusing on the interactions that require coordination in sociotechnical energy systems.

3.1 Case study: The White Gum Valley development

The case study discussed in this article is the White Gum Valley (WGV) precinct located in Fremantle, a suburb of Western Australia's state capital Perth. Featuring a number of sustainability initiatives, the site serves as a demonstration project of how medium-density and sustainability can be integrated into Perth's low-density landscape. This includes a government-funded project concerned with making solar PV more accessible to apartment dwellers. The three apartment buildings on the site were fitted with rooftop solar PV and battery storage systems, metering infrastructure, data monitoring capabilities, and an online platform for financial accounting.

The apartment buildings are named Gen Y, Evermore and SHAC (Sustainable Housing for Artists and Creatives). Gen Y is a three-unit building developed by the state's land development agency with the aim of demonstrating the possibility of sustainable, modern living in apartments. The units are owner-occupied. Evermore is a 24-unit complex developed by a commercial property developer, and with the units privately owned. As at Gen Y, the infrastructure is commonly owned by the owner's corporation and apartment owners are allocated shares of solar energy in proportion to their units' size. SHAC was developed by an affordable housing provider after being approached by the SHAC cooperative. The intention was to offer an alternative housing solution for local creatives that have been increasingly driven out of the Fremantle area by rising rental prices. The building comprises 12 units of varying sizes and two artist studios. Units and energy infrastructure are owned by the developer who sells the renewable energy to tenants.

3.2 Data collection

Semi-structured interviews with various organisational stakeholders, as well as WGV residents, form the empirical basis for this study. The research questions addressed in this paper form part of a larger study on shared solar energy systems. Only those actors (and interviews) relevant to this study are described and discussed here.

Table 1 shows the timeframe within which interviews were conducted with each of the relevant stakeholders (round 1, 2, and 3) and the type of data formatting applied. In addition to the listed interview processing strategy, notes were taken by the interviewer throughout all interviews and rounds. After the first round of interviews, it became apparent that there were significant delays with the implementation of the sharing structures; that (Gen Y) residents had little information about their system; and that transcriptions of these resident interviews had very little value for the researchers (largely due to the lack of explicit information obtained). Consequently, interviews with other residents and the Evermore developer were postponed and held at the end of 2018 (round 2); and resident interviews were no longer transcribed.

Round 3 interviews were conducted towards the end of 2019. With regards to the present paper, the main purpose of this third round of interviews was to verify that (given delays and changes to the project) the information obtained during rounds 1 and 2 were still correct. The following limitations should be noted:

- The strata management company[1] for Gen Y changed over the course of the research. Because the current firm only became active in November 2019 and had very limited understanding of the system, no additional interview was conducted with them.
- The Evermore strata company declined our invitation to be interviewed on the grounds that they would unlikely be able to provide useful information. Before the strata management company was engaged, management was with the developer who was interviewed during the second round. The necessary information was thus taken from this earlier interview with the developer.
- The technology start-up providing the software for sharing in all three buildings provided written answers to interview questions by email in February 2020. Because this was outside the original timeframe of the data collection and analysis process, these responses were integrated into the analysis retrospectively where appropriate.

Table 1: *Actors interviewed about the WGV sharing systems and the data processing format adopted for each interview. Round 2 interviews were conducted after round 1 interviews revealed a lack of information from some actors which appeared at least in part tied to a delay in project delivery. SHAC residents were therefore interviewed towards the end of 2018, together with*

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[1] *Company employed to manage the owners' collective interests (represented by the owners corporation), which may include managing utility bills. Strata titled property combines private ownership of some parts (e.g. apartments) with common ownership of others (e.g. garden, parking lot). The owners corporation is the legal entity, and comprises of the owners of all private lots.*

Evermore residents, who moved to the development after round 1 interviews were conducted. Round 3 interviews were organised the following year to confirm findings.

Interview participation						
WGV Actor	**Interviews Round 1** *April – July 2018*		**Interviews Round 2** *October – December 2018*		**Interviews Round 3** *November – December 2019*	
	Participation	*Data*	*Participation*	*Data*	*Participation*	*Data*
Strata manager Gen Y	✓	Audio-recorded and transcribed	-	-	-	-
Developer Evermore	-	-	✓	Audio-recorded and transcribed	-	-
Strata manager Evermore	-	-	-	-	*Declined citing lack of relevant information*	-
SHAC developer	✓	Audio-recorded and transcribed	-	-	✓	Interview conducted over the phone, notes taken by interviewer
Electrical engineering firm	✓	Audio-recorded and transcribed	-	-	✓	Audio-recorded and transcribed
Residents Gen Y	✓ (3 people/ households)	Audio-recorded and transcribed	-	-	✓ (1 person/ household)	Notes taken by interviewer
Residents SHAC	-	-	✓ (4 households/ people)	Audio-recorded, notes taken by interviewer	✓(1 person officially interviewed, commentary provided by)	Notes taken by interviewer
Residents Evermore	-	-	✓ (6 households/ 7 people)	Audio-recorded, notes taken by interviewer	✓(4 households/ 5 people)	Notes taken by interviewer
Technology start-up	✓	Audio-recorded and transcribed	-	-	✓	Interview answers provided by email in February 2020

3.3 Data analysis

The IADF discussed in section 2 was used to guide the analysis as it serves as a “multi-tier conceptual map” [23, 27] that specifies the structural variables and relationships found in institutional arrangements (ibid.); and aids in the diagnosis of (sources of) dysfunction [23, 24]. *Figure 1* illustrates the main components of the framework. The action situation, and the interactions and outcomes that arise from it, is the focal point of the IADF [27]. Action situations contain seven main components, shown underlined in *figure 1*. Three clusters of exogenous variables [23], or contextual factors [24] affect the action situation: attributes of the community, biophysical conditions, and rules [23, 24].

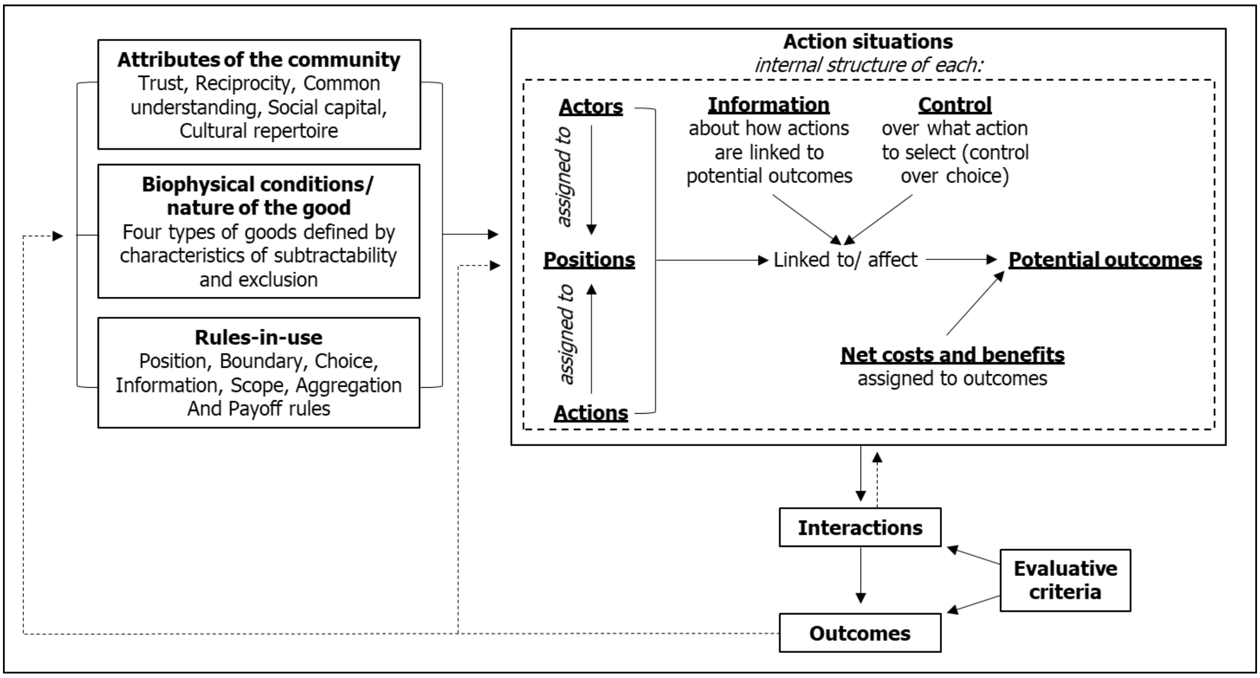

Figure 1: *Combined illustration of the IADF and the internal structure of an action situation, adapted from [27] and [24].*

Rules are classified according to the components they affect [24] (see *Box 1*). Rule systems and action situations tend to be nested within higher level systems, and as such, multiple levels of analysis exist [23]. Three levels are typically differentiated: operational, collective-choice, and constitutional-choice levels. In order of increasing scope, the operational level is concerned with day-to-day activities and decision-making (*e.g.* production, distribution, consumption of a resource) (ibid.); the collective-choice level is concerned with constructing institutions and making policy decisions [24]; and constitutional-choice processes stipulate who is eligible to participate in the collective-choice situation, and the rules they are to use in creating collective-choice rules [23].

Based on the structure offered by the IADF, the analysis focused on:

- Identification of the action situation(s);
- Definition of the seven components of the action situation(s);
- Identification of the rules that affect these components and constitute the coordination mechanisms for the sharing of solar energy at WGV;
- Insight into actors' motivations and evaluations of outcomes;
- Identification of attributes of community, environment, rules and actors that affected outcomes;
- Derive enabling and disabling conditions.

NVivo [31] was used for preliminary coding of interview data that served primarily to organise the information contained in the interviews. Categories and nodes used for coding were based on the IADF and are provided in Appendix A. The information identified in NVivo was then summarised and transferred into a Microsoft Excel [32] file. The resulting database was used in conjunction with the IADF structure and literature to identify the above information of interest in an iterative process. The action situation of primary interest to the present study is the sharing of solar energy. The theory of collective action noted in section 2.1 complemented the analysis and discussion by providing the theoretical underpinnings. Section 4 describes the identified structures and summarises outcomes. Section 5 then discusses the factors and conditions that acted to support and inhibit system performance. Section 6 concludes.

Rules	specify:
Position	Positions to be filled by ***actors***
Boundary	Eligibility to enter a ***position***; process determining who may/ must enter/ leave a position
Choice	Permitted/ prohibited/ obligatory ***actions*** linked to a position
Aggregation	Level of ***control*** participants have over actions, *i.e.* whether selection of action depends on other actors' decisions
Scope	Outcome variables affected by actions, and scope of ***potential outcomes***
Information	(Level of) ***information*** available to participants
Payoff	***Costs and benefits***, *i.e.* rewards/ sanctions linked to actions or outcomes

Box 1: *Classification of rules affecting components of the action situation (shown in bold and italics) [23].*

4 Institutional arrangements at WGV

I begin the presentation and discussion of results by providing an overview of the wider institutional structure identified in the case study (4.1). Based on this conceptualisation of observations within the IADF, the institutional design of the sharing arrangements at the three sites is presented (4.2.1). Stakeholder evaluations are then summarised to provide an indication of perceived system performance (4.2.2). The factors supporting and inhibiting their performance are then discussed in section 5.

4.1 Nested levels of analysis for energy sharing

Attempts to identify the relevant action situations in the case study confirmed the complexity and on-going change that systems of human organisation have been shown to exhibit [23]. As a result, the following analysis conceptually places the observed processes within nested levels of analysis. Inputs, interactions and outcomes were linked vertically [*cf.* 23] across (predominantly) the collective-choice and operational level. *Figure 2* illustrates the way in which energy sharing at WGV is conceptualised within the IADF.

At the collective choice level, developers, engineers, the software firm and strata managers (and to a lesser extent, the residents), interacted to construct the institutional arrangements to govern the sharing of energy in the three buildings. Nested within the higher-level choice arena of rule-making, is the operational choice situation of energy sharing. Operational-choice rules that coordinate the sharing of energy are understood to have emerged as the outcome of interactions in the adjacent collective-choice situation [*cf.* 24].

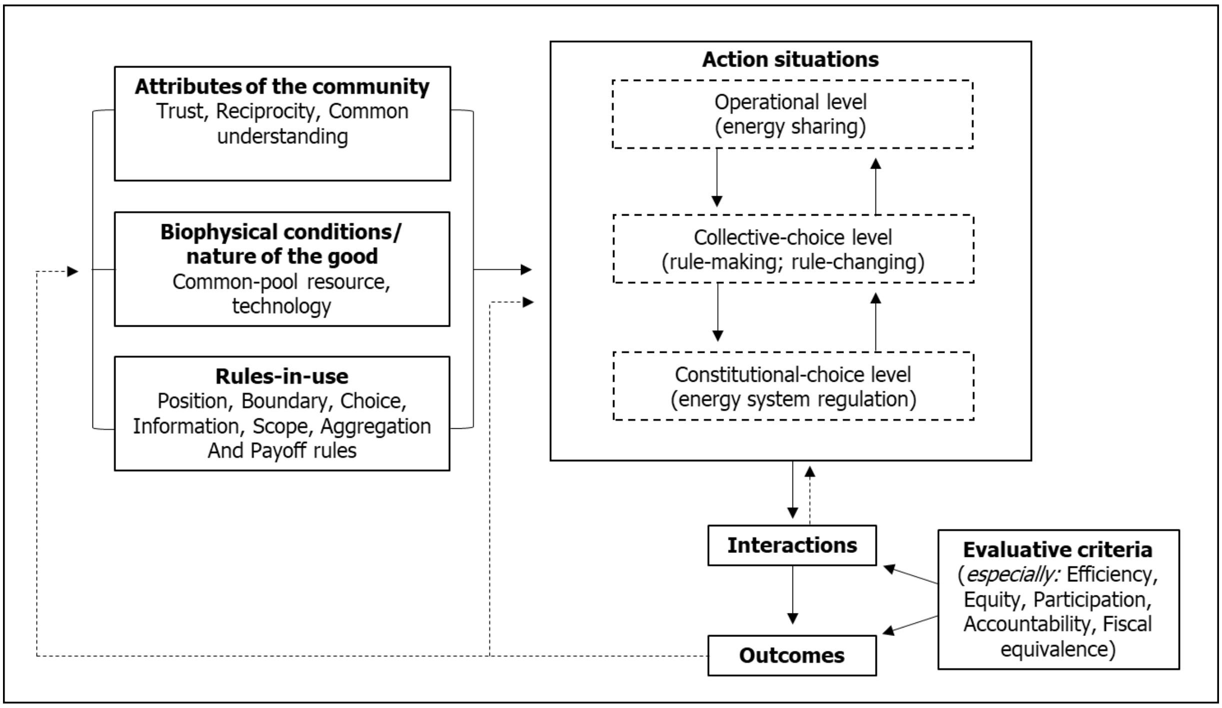

Figure 2: *Nested system of linked action situations for the sharing of energy in WGV. The dotted lines denote potential feedback and learning processes. Specifications of community and resource attributes, rules-in-use, action situations and evaluative criteria reflect findings discussed further in the main body of text. The figure is adapted from Ostrom [27] and McGinnis [24] with author's own additions.*

4.2 Operational-level energy sharing in WGV

4.2.1 Institutional arrangements at WGV

The formal sharing systems at WGV can be described using the seven components of an action situation and the rules that affect them (see section 3.3). The components and rules most central to the institutional arrangements for energy sharing at Gen Y, Evermore and SHAC are described in the following. A complete list of all identified components and rules is provided in Appendix B. To provide a better contextual understanding, *Table 2* summarises actors' main motivations for participating in the systems.

At all buildings, residents gain the position of (energy) user by occupying the apartments. The number of apartments represents a boundary rule delimiting the number of users. The main action of the users is the consumption of electricity. Decisions concerning when to consume are limited by work schedules or other regular activities. A resident that understands how the solar storage system operates and is interested in its efficient use, may choose to shift consumption accordingly. Residents have limited control regarding the amounts of electricity consumed. This is influenced by the number of people in the household, their habits, and the appliances they use.

At Gen Y and Evermore, apartments are privately owned and residents may therefore also hold the position of owner. Owners may change the rules of sharing. Control over affecting such changes is delimited by the owners corporation, whose agreement acts as an aggregation rule. A change of strata management company was undertaken at Gen Y. As the first firm was not providing bills according to the proposed structure, a new one was brought in through an owner's initiative.

Table 2: *Actors involved in operational-level energy sharing and excerpts of their key motivations for participation and moving to WGV.*

Actor taking part in operational-level energy sharing situation	**Actor's key motivations & characteristics**
Gen Y & Evermore residents	*Commonly cited reasons for moving to WGV:* Sustainability features generally and solar storage systems specifically, living in a community of like-minded people *Commonly cited benefits of having solar storage system:* potential/ expected cost savings
SHAC residents	SHAC cooperative aimed to address need for affordable housing for artists in the area
Technology start-up	Enabling access to renewable energy for apartment dwellers, blockchain-based energy trading platform for neighbours trading may generate revenue stream, incentivising the uptake of renewables in embedded networks through the platform
Electrical engineering firm	Creating technical solution, supported by commercial model, to enable more effective, transparent, user-based, genuine way of sharing solar energy; making a market in embedded network space/ demonstrate business case Government grant enabled participation/ project
SHAC developer	Reduce cost of living for tenants, have positive environmental impact; goal: offer 20% discount on electricity bills; test business model Government grant, discounted land and subsidy enabled participation/ project (no capital outlay)
Strata management companies (Gen Y & Evermore)	No particular reasons for involvement, hired by other actors *Evermore developer:* Government grant enabled participation/ project

Potential outcomes of central concern for residents are the amounts of consumed energy attributable to the solar storage system, sharing, or the grid. The net costs and benefits are the electricity costs, with rates for solar, shared and grid energy representing the payoff rules. The scope of outcomes is bound by an initial allocation of solar electricity that each apartment has (based on size). At Gen Y and Evermore, energy consumed within this allocation is priced the lowest (rate 1). Monies generated from rate 1 flow into a sinking fund held by the owners corporation for future asset maintenance purposes. If a resident consumes more than the allocated amount of energy, the algorithm will allocate surpluses from other residents first, before attaching the grid tariff to all additional units of electricity. This peer-to-peer rate is set slightly higher than rate 1 to incentivise users to consume within the allocated amount. At SHAC, surpluses are distributed on a needs basis and are charged at the same rate as allocated solar.

The amounts of electricity consumed per apartment, generated, stored and exported by the solar storage system, and sourced from the grid are monitored and recorded by a data monitoring system operated by the engineering firm. Data is accessed by the technology start up's software, which compiles aggregate datasets on a 30 minute basis. An algorithm then reconciles the information of electricity consumed and generated with the relevant rates and allocations. This information is provided to the strata managers and SHAC developer for billing purposes.

In addition to managing billing, the SHAC developer also takes the position of system owner and can thus set the prices of solar electricity to charge tenants. Their choice of rates was significantly delimited by regulation. While the developer is charged a business tariff for grid-sourced energy, they can only charge their tenants up to the amount of the residential tariff. On a per unit basis, this is slightly cheaper than the business tariff, implying a loss to the developer for every unit of grid-sourced electricity consumed in the building. As a result, the rate selected for solar energy needs to make up for this loss, in addition to contributing to future maintenance costs.

4.2.2 Performance of the WGV sharing systems based on stakeholder evaluations

To evaluate the performance of these institutional arrangements, evaluative criteria given by participants, and statements related to outcomes were identified in the interview responses. These were complemented by the evaluative criteria suggested by the IADF literature [*e.g. cf.* 23, 27]. Of these, economic and resource efficiency, fiscal and redistributional equity, participation, and accountability (*cf.* 17, 23, 27] emerged as most relevant for the WGV systems.

Participation emerged as a critical indicator of (currently) sub-optimal system functioning at all sites. Importantly, this criterion represents a lack of knowledge and actions available to the users of the solar energy systems. During the first round of interviews, none of the interviewed residents had specific information about the sharing systems; many were unaware of the organisations involved, and the intended use of allocations, software and an online platform. A high degree of uncertainty remained in the second interviews. A lack of communication was explicitly lamented by many residents across all sites. At Evermore, multiple residents explained that they had been promised a meeting about their energy system months ago that had not been scheduled. Others commented that any updates or emails at all would be appreciated, or that “nothing is coming through”.

Difficulties in accessing more specific information was also a key issue for the residents. For example, one resident stated that access to overall energy data would be nice to gauge the performance the building as a whole. Others had not been able to access the online platform to check their own consumption, or were unaware of the option. At Evermore and Gen Y, even those residents with the highest level of understanding were unable to state the prices of electricity with certainty.

Economic efficiency emerged as a crucial evaluative criterion for the majority of interviewed residents. Many linked their ability to evaluate this outcome for themselves to the receipt of an electricity bill. At Gen Y, no bills had been received. At Evermore, issues arose after the first bill had been sent out. A second one had not been received. At SHAC, residents found their bills to be relatively high. They explicitly commented that there was no incentive to change their energy consumption behaviour as the discount was only about AUD$ 0.04. Economic efficiency depends, in part, on the efficiency of the resource system. The more solar is available, the more energy will be available at cheaper rates. This in turn will depend on the size of the solar PV and battery storage systems. At all buildings, actors expressed doubts about the efficient performance of their solar PV and battery storage systems. Size and efficiency were called into question.

In addition, system delivery was delayed. At SHAC, this delay became a significant problem: without an operational system, the SHAC developer was unable to offer electricity at reduced rates to residents. There were uncertainties and misunderstandings between the SHAC developer and the electrical engineering firm with regards to the performance of the system. While the developer stated that it was not meeting expectations in terms of the amounts of solar energy available, the engineering firm explained that the assumptions used for sizing had been inadequate. A lack of prior experience and regulatory constraints meant that achieving the 20% target discount within a sensible business model was difficult and inhibited economic efficiency.

Overall, the project had cost more time and effort than usual. The electrical engineering firm also acknowledged that project participation had cost more money than expected. The Evermore developer on the other hand asserted that it was too early to tell whether the energy model was working. Residents at Evermore noted that, despite their dissatisfaction, the providers of the energy system seemed to be happy with outcomes. Others agreed that it seemed as though the technology start-up and the Evermore developer continued to promote the development as successful – but had missed the issues affecting residents. Another resident speculated that the providers were so hard to reach because they knew they were not doing a good job and were “hiding” (*i.e.,* avoiding confrontation). According to residents, none of the participating organisations had sought their feedback. From the system users' perspective, there was no accountability.

Enabling the fair sharing of energy was frequently noted as a desired outcome by stakeholders. This implies that equity should be considered in evaluating outcomes. Two types of equity are discussed in the literature, namely redistributional equity and fiscal equivalence [27]. Redistributional equity is concerned with differences in individuals' abilities to pay (Ostrom 2011), and may be achieved by providing, or facilitating access to resources for poorer individuals or groups (Ostrom 2011). The SHAC developer's intention of reducing tenants' costs of living and offering discounted electricity is in line with this notion but comments from the developer and SHAC residents suggest that it not perceived as having succeeded.

In comparison, fiscal equivalence considers benefits to individuals in proportion to their contributions (ibid.). The operational rules used at all three sites are based on this concept. Allocations of energy are based on the occupied space, where energy demand is assumed to increase with an increase in living space. In line with the notion that those who benefit from the resource also pay for it, in addition to equity in allocations, residents only pay for the amounts of energy they actually consume.

The importance of incorporating these principles in the sharing rules was illustrated by an owner-occupier at Gen Y when interviewed at the end of 2019. The aforementioned change in the strata management company was motivated by this resident's perception of unfair sharing practices. The strata manager initially hired by the developer had not conformed to the proposed rules and instead had simply divided the building's total consumption by the number of units. The interviewed resident thus felt that they had unfairly been paying for other people's consumption. This view was exacerbated by the fact that they had a very conservative energy demand, making a conscious effort to reduce consumption and promote sustainable practices.

5 Towards optimal system performance

The above account of outcomes and evaluations suggests that the sharing arrangements at Gen Y, SHAC and Evermore are currently performing sub-optimally. This section highlights which aspects of the system worked well and which were problematic. In working towards an understanding of (more) optimal system performance, I draw on the explanatory potential of exogenous variables (community and resource attributes, rules) and actor behaviour. I start by discussing conditions that were found to inhibit system performance, and then turn to those that supported optimality. Before concluding (section 6), section 5.3 weighs up the evidence in view of moving the field of community energy towards optimality.

5.1 Disabling conditions

5.1.1 Asymmetric information

The complexity of technology involved in the operation of community energy systems means that expert knowledge is essential to their operation [12, 33]. To some extent, an asymmetric distribution of information amongst involved actors may therefore be viewed as a necessary evil. However, asymmetric information becomes problematic when it relates not only to technical specificities but extends to structural system components. An observation in the case study was the lack of information regarding the institutional sharing arrangements held by actors, most notably, residents.
Although residents are the users of the energy systems, and, at Gen Y and Evermore, also the system owners, their knowledge of sharing rules and ownership rights was very limited.

This had an interesting implication. The institutional arrangements for Gen Y and Evermore stipulate that owners of the energy infrastructure have permission to change the sharing rules. For residents to be able to take this action however, they require knowledge of this right. Ostrom [23] explained that permission rules only confer a right if there is another rule that assigns another actor the duty to ensure that those with permission are able to act on it. In the absence of a rule assigning this duty to an actor in the situation, the permission rule merely establishes eligibility (ibid.) –
residents who meet the criterion of being owners of a unit, are eligible to demand a change in rules. However, they do not, strictly speaking, have the right to do so.

As such, the lack of information provided to residents at WGV effectively inhibited parts of the intended sharing mechanisms from working. As the project evolved, some residents gained more information. At Gen Y, the aforementioned owner-occupier who initiated the change of strata management company, was gradually enabled to act on their right. These observations raise two questions. The first question is whether owners need (should have) the right to knowledge about the energy system and sharing rules. If the answer is yes, the question arises of who should have the duty to inform and educate residents.

I argue that if the institutional arrangements are designed to assign residents ownership of the energy infrastructure, then their ability to maintain a robust sharing system over time requires the possibility to make changes to the system configuration. Without adequate knowledge of existing rules, owners may – as was the case at WGV – be unable to even initiate a potential rule-changing process. Although knowledge of their right to this action would be a minimum requirement, the ability to then make informed decisions demands access to a more comprehensive set of information. As such, the collective-choice rules guiding the design and implementation of the shared system need to assign the obligation to pass on relevant information to one of the actors involved in the collective-choice process.

5.1.2 Missing position rules at the collective-choice level

A lack of position rules at the collective-choice level meant that none of the actors involved in the design and implementation process felt obliged to inform and educate residents. The organisations involved in the trials gained their positions through the official project agreements with funding agencies. This involvement in turn, seems to have been largely driven by personal connections to other involved parties. The SHAC developer for example stated that their involvement in the SHAC building and energy sharing project evolved out of an existing collaboration with the SHAC co-operative.

The interviewee of the electrical engineering firm talked about conversations with a co-founder of the technology firm that eventually led to project proposals and their collaboration. This interviewee further pointed out how various parts of the project had evolved organically, pointing specifically to how the technology start-up developed from concepts to a legal business entity over the course of the collaboration. This organic evolution of the project meant that the roles (positions) organisational participants were to take in the action situation of sharing energy, as well as in the collective-choice situation, were at times ill-defined.

The electrical engineering firm explicitly identified the lack of clarity regarding one particular position. The time-intensity and complexity of the data monitoring needed to enable the energy sharing only emerged over time. The need for an explicit, additional data monitoring position arose. Instead of a well-defined rule for establishing the position, the engineers' work on the data monitoring component up to that point in time led to them assuming, or having to assume, the additional role. This additional need for expertise and the associated resource expenditures may be viewed as a separate inhibiting factor [33]. Partly motivated by this experience, the engineering interviewee stated that the need for clear definitions of roles from the outset was one of their major lessons learnt.

5.1.3 Lacking user participation

Linked to the lack of clearly defined roles in system design and operation is the lack of user engagement in these processes. Insufficient resident participation throughout the project also feeds into the problem of the knowledge gap identified above. The involvement of system users in the design of shared resource systems as an essential condition for success is well-established in the literature (*e.g.* 12, 23, 34, 35]. Participation of users reduces uncertainty [12]. Reduced uncertainty, in turn, has been linked with a greater potential for maintaining resources over time [36].

Participation may also have an important effect on the efficiency of the technical system by increasing awareness of energy consumption. This was indicated by interviewed residents who (implicitly and explicitly) exhibited a poor understanding of the workings of solar energy systems (*e.g.*, when best to use appliances). The efficiency of solar storage systems can be optimised when users understand the connections between their own consumption and system efficiency. In line with the sociotechnical perspective, lacking institutional provisions for user engagement may thus have a negative effect on technical system performance.

Participation also enhances the likelihood of reciprocity, trust, and shared understanding among stakeholders. As attributes of the community, these directly affect action situations, interactions and outcomes (*cf. figure 1*). Resident interviews suggested that community trust in the organisations providing the shared system was low. Some interviewees explicitly commented that organisations were not acting to support the community's best interest. For systems to enable collective benefits for the community, and rules in line with local conditions, cooperation and communication are crucial [19].

Communication is particularly important in establishing a shared understanding of the problems to be addressed among participants [23]. Communication may be facilitated when shared mental models exist among actors [37]. While they may be challenging to achieve, shared visions of a project's goal are necessary for effective collaboration [5]. Arguably, this applies to the involvement of residents as well as the collaboration among other actors. At WGV, a lack of resident engagement resulted in distrust, lack of understanding and operational inefficiencies. Establishing a shared understanding between users and external actors would likely alleviate these adverse outcomes. A lack of common ground among the group of external actors may have additionally contributed to the lack of collective-choice rules to guide system design and implementation.

5.1.4 Incentive mismatch

Diverging interests and a resulting incentive mismatch likely contributed to these inadequate levels of participation, trust and shared understanding. While WGV residents are interested in the benefits of having access to a shared solar storage system, other involved actors were interested in the benefits of being involved in the systems' implementation and operation. Commercial interests are at odds with the maximisation of the community's social welfare (*cf.* 12]. There was agreement among interviewees that collaboration was critically important to setting up and delivering the project. Despite this recognition (and the initial commitment to joining the collective effort) however, the commercial interests of actors appear to have contributed to sub-optimal outcomes.

The engineering firm interviewee commented on this complexity, pointing to the need for clearly defined roles, responsibilities and commercial agreements. Other studies have similarly suggested that the increasing diversity of expertise needed in energy systems has led to increasing complexity of governance arrangements and unintended consequences [14]. In short, the actors involved in designing and implementing the solar storage systems and institutional arrangements for sharing at WGV did not act to achieve socially optimal outcomes for the community of residents, but to maximise their own short-term benefits, leading to sub-optimal outcomes [21]. This is not surprising given the commercial nature of their businesses.

The problem of sub-optimal outcomes in WGV may thus be described as a second-order collective action problem. Rather than stemming from the nature of the CPR (as in the traditional literature), incentive mismatching causing sub-optimality occurs at the collective level where the operational rules of sharing are devised.

5.1.5 Constitutional-choice rules limiting the scope of possible outcomes

As the final disabling condition identified in the WGV case study, constitutional-level rules negatively affected outcomes. A health and safety regulation that the engineering company had to adhere to led to delays. The SHAC developer's tariff design was impacted by regulation necessitating them to pay the business tariff to the retailer whilst charging the (lower) residential tariff to residents. An initial idea of peer-to-peer trading between (rather than within) buildings was abandoned because of regulation prohibiting trading across the regulated network. This means that information sharing, user participation and collective-choice rules can only contribute to optimal system performance if the prerequisite of congruence with constitutional rules is met.

5.2 Enabling conditions

5.2.1 Biophysical conditions/ nature of the good

Shared renewable energy systems may be understood as CPRs within the physical boundaries of the infrastructure. In the social-ecological literature, the social dilemma associated with CPRs lies in the potential destruction of the resource as selfish individuals act to satisfy their own needs, in the face of a highly subtractable supply and many potential users. Although the attributes of the solar energy resource are similar, the physical structure of the system serves as a boundary to unauthorised access. At WGV, only those residing in one of the buildings can access the resource. It is physically impossible for outsiders to compete. Similarly, once the wiring and metering infrastructure is in place, exploitation by any one resident is impossible so long as an accounting system exists. Because residents cannot control the flow of energy at any given point in time, they cannot choose whether to source solar or grid energy.

Consequently, renewable energy CPRs do not face the same dilemma as other CPRs traditionally discussed in the literature. Instead, the deciding attribute is their technical complexity and the resulting need for experts. The challenge of sustainably managing renewable energy CPRs arises from the diverging interests of resource users and the expert organisations necessarily involved.

5.2.2 Technology automates rule enforcement and facilitates equitable sharing

In contrast to other CPRs, rule enforcement is achieved through the physical technical infrastructure (governing flows of energy), and an algorithm (governing financial accounting). This means that cheating as such is not possible; and sanctioning rules may not be needed. The use of technology to enforce rules may be an advantage as it removes the irrationality and unpredictability of human behaviour to a large extent. In addition, because rules for flows of energy and associated equitable sharing operate independently, resource access can be maintained even if the institutional arrangement fails.

5.2.3 External funding enabled participation

All organisations commented that government funding enabled the project and their participation. The initial financial risk of participation was significantly reduced. However, government funding does not necessarily, or automatically, make a project financially viable for participating organisations.

5.3 Trade-offs

While the factors identified in the preceding two sections support and inhibit optimal system performance, an overall evaluation of institutional arrangements should also take trade-offs into account [23]. An important one concerns economic efficiency and arises when the marginal cost of use of a good is zero, but funds are required to maintain the good over time [23]. Economically efficient pricing would mean that the price equals the good's marginal cost of use – zero [27]. Generating the funds necessary for maintenance thus means that the price cannot, by definition, be economically efficient.

This applies to the institutional arrangement at SHAC. Even though the cost of every additional unit of energy generated or consumed is zero for the SHAC developer, solar energy is still priced above zero. As owner of the infrastructure, this enables the developer to accumulate funding for future maintenance; and to defray the costs of grid-sourced electricity that they cannot fully pass on to their tenants. As a result, a trade-off had to be made between the economic efficiency of owning and operating the system and the desired size of the discount residents receive on their electricity. The outcome is suboptimal – economically inefficient – for both parties: while the developer needs to manage a system that is not financially viable, residents receive a negligible discount.

The idea of trade-offs, especially regarding economic efficiency, may also be relevant to the evaluation of innovative or experimental structures more generally. As novelty implies the absence of a knowledge base on which to draw, risk and uncertainty increase. The outcomes analysed here illustrate how the process of creating the WGV sharing structures came at the cost of economic (and process) efficiency for some of the involved actors. Both the SHAC developer and the engineering firm explicitly talked about the impact that novel features of the envisioned systems had on their organisations' time and cost expenditures. On the other hand, actors referred to the learning experience and the potential for market expansion, indicating an expectation of future payoffs. Creating the possibility of growth for one's business that is associated with learning through experimentation will likely imply having to make concessions in economic efficiency.

The same line of reasoning may apply at a broader level. Improving the economic and resource efficiency of the larger energy system in the long-term comes at the risk of inefficiencies in the short-term. This may become problematic when actors discount future benefits in pursuit of short-term profits. The analysis of WGV showed that the interests of commercial entities may inhibit the socially optimal performance of shared energy systems. Yet, these organisations committed to joining the project despite the high degree of uncertainty associated with novelty. This willingness and motivation to learn, and potentially forego short-term benefits, suggests that collective action for energy system change is possible and has the potential to create longer-term benefits to society.

6 Conclusion

This study addressed the need for an understanding of the institutional arrangements of energy sharing by applying the IADF to a case study of three community energy systems. Conditions that inhibited and supported the performance of these systems were identified, and demonstrated that institutional factors have a substantial effect on performance. This underscores the importance of studying institutional arrangements in the context of shared energy systems. A purely economic or technical focus on optimisation or performance evaluations is insufficient and may result in misleading interpretations of outcomes.

The analysis suggests that the creation of socially optimal, sustainable community energy systems poses a collective action problem. The problem is not, however, in defining the best set of operational rules. Instead, there is a dilemma in how socially optimal outcomes can be achieved for shared energy systems when their creation requires the expertise, and thus involvement of, actors driven primarily by economic optimality. The challenge for community energy scholarship is the creation of incentives that motivate the necessary collective action on the ground.

One avenue is an assessment of shared energy systems in which investment has come primarily from the community of resource owners. Based on the discussion of the present study, one may hypothesise that if the community was the service providers' direct client, outcomes would be more likely to approach a social optimum. Contractual arrangements between the community as the principal and service providers as the agents would establish a sense of accountability, if not an obligation, for the agents to deliver the principal's desired results. At the same time, this would provide the necessary economic incentive for service providers. Participants could thus pre-empt the principal-agent problem that contributed to the suboptimal outcomes observed in WGV. In terms of policy-making, this could imply that government funding for shared energy schemes may be better directed to the communities themselves.

In accordance with other studies, engaging the users of the shared (energy) system in the design of rules may be critical to achieving optimal outcomes. The analysis further suggests that the rights to knowledge of system components and rules is a prerequisite to the possibility of optimal outcomes for owners. Participatory approaches to rule-making and project design may aid in establishing these rights. Constitutional-level support in the form of government funding was critical in enabling organisations to participate in WGV by lowering financial risks. It did not however remove the knowledge uncertainties that led to delays and mistakes.

To reduce such uncertainties for future collective action, (government) funding organisations need effective knowledge sharing mechanisms. Sharing lessons learnt from individual small-scale projects with communities and the (technical) expert organisations involved will improve the likelihood of optimal outcomes being achieved fast in future community energy systems. By implication, the positive effects of energy sharing on the wider system could also be optimised.

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Appendix A: Categories and nodes for organising interview data

Category 1: Problem and solution

Key words/ themes: solution; problem; motivation

Category 2: Structure of the action situation

Key words/ themes: structure generally; sources of information; interactions; roles; information needed; information available or level of understanding; enabling conditions; costs/ disadvantages/ limitations; benefits/ advantages/ successes; actions; tasks; responsibilities

Category 3: Rules in detail

Key words/ themes: rule-making; rule barriers/ challenges; pricing and allocations; ownership; common areas; changing rules

Category 4: Outcomes

Key words/ themes: perceived outcomes; learnings; evaluating outcomes

Appendix B: Operational-level components and rules

***Table B.1**: Working components of the energy sharing action situations at Gen Y, Evermore and SHAC and the rules affecting each component. Dotted lines separate rules and the component they affect; bold lines separate pairs of working components and rules. Rule descriptions in brackets are adapted from Ostrom [27].*

Boundary rules (number, attributes & resources of participants, conditions of entry & exit)	Number of units & bedrooms limits number of participants; need financial means to purchase unit (if unit for sale) or rental agreement with owner	One firm at any time, exiting stipulated in formal agreement (*at Evermore:* contract is for 2 years)	Number of units & bedrooms limits number of participants; qualify as low-income creative; have allocation of solar energy based on unit size	Government grant, subsidy & discounted land enabled project participation; approached by SHAC cooperative; ownership of building & units	One firm at any time, exiting stipulated in formal agreement (termination of contract); Government grant enabled project participation	
ACTOR	**Gen Y & Evermore Residents**	**Gen Y & Evermore Strata management company**	**SHAC Residents**	**SHAC developer**	**Tech./ software firm**	**Electrical engineering firm**
Position rules (establish roles actors take in situation)	Occupancy establishes user position; legal ownership of unit gives owner's rights	*At Gen Y:* By virtue of profession; selected by council of owners *At Evermore:* Contracted by Evermore developer; council of owners may select	Occupancy	Funding (ownership); nature of business	Project participation	By virtue of profession & data monitoring capabilities (by default)
POSITION(S) assigned to actor	User; Owner	Manager of residents' shared interests	User	Owner of physical infrastructure; manager; generating retailer	Software system manager; Sharing platform; (billing) service provider	Physical system provider; data monitor

Choice rules (permitted, obligatory, prohibited actions linked to positions)	Occupancy; Rights of ownership; decision by council of owners	As per retailer's billing cycle; agreement with residents (council of owners)	Occupancy	Billing as per retailer's billing cycle; rate changes at own discretion; strata management statement	Service agreement with strata/ SHAC developer; nature of business; responsibility for own product	Fault alarming triggers action; nature of technical infrastructure & business; responsibility for own product
ACTIONS associated with position	Consume electricity; call for meeting of council of owners (*e.g.* to discuss/ change rates); pay bills for electricity consumed in own unit; pay strata levies	Generate invoices; send invoices to residents; pay electricity for common areas using strata levies; settle accounts with retailer for grid-sourced energy	Consume electricity; pay bills for electricity consumed	Billing tenants for electricity usage (sell electricity); paying retailer for grid-sourced electricity; selection of rates to charge for solar & grid-sourced electricity; operational *e.g.* maintenance; pay for common areas electricity usage; pay service fee to platform service provider	Translate sharing mechanism into algorithm; provide data in format required for billing to manager; platform allocates appropriate solar rate(s) or grid rate to units of electricity; (reading meters, aggregation in 30min intervals, conversion into transactions) *at SHAC:* reconcile data sources for quality assurance/ ensure data reliability	Ensure physical solar PV, battery storage and metering infrastructure are working properly; maintenance & attend to system faults & failures; monitor & manage energy data
Information rules (information available to position)	Information linked to control	Induction/ communication with platform provider	Information linked to control	Software to provide billing information; novelty of project meant no experience to draw on	Require access to meter data	
INFORMATION	(currently) limited Residents can access the online platform to track their own consumption & trades	Knowing how to use platform	(currently) limited Residents can access the online platform to track their own consumption & trades	Varying		Based on project set-up experience
Aggregation rules (how much control actor in position has	Work schedule affects time electricity is used; understanding of efficient usage of solar system;	Service agreement with strata/ council of owners	Work schedule affects time electricity is used; understanding of efficient usage of solar system;	Retailer must be paid; choice of rates for tenants depends on costs for grid electricity (set by retailer) to	Service agreement; 30min intervals aligned with wholesale market; [technology-dependent]	Network operator's technical rules & compliance with energy safety regulation; service

over action selection)	appliance being used affects amounts of electricity consumed		appliance being used affects amounts of electricity consumed	be recovered, size of solar storage system & levels of consumption; Strata regulation (only one meter, business tariff); tenants may not be charged above retailer's residential tariff; compliance as generating retailer (*e.g.* affects billing format)		agreement; technical expertise
CONTROL	limited	limited		limited	[automated]	limited
Scope rules (delimit scope of potential outcomes)	Allocations of solar energy based on unit entitlements; amounts of solar generated and stored; amounts consumed by other occupants; rates set for solar within allocation & solar traded	Ease of use of platform; financial viability	Allocations of solar energy based on unit entitlements; amounts of solar generated and stored; amounts consumed by other occupants	Solar storage system size & performance (changing system size requires additional funding or investment); retail prices for electricity; amount of electricity consumed; technology & compliance	Software and data provision are working; customer permission to access data; Falling costs of distributed renewables; growing interest in positive effect of low carbon energy supplies	Physical limits of the system; amounts of solar used during day
POTENTIAL OUTCOMES	Amounts of electricity consumed and their source: within allocation/ traded/ grid; Building up fund for asset replacement/ maintenance; Fair cost sharing	Bills provided to residents; Increased service flexibility & value	Amounts of electricity consumed: within allocation/ shared/ grid	Aim to balance financially viable business model with reduced costs of electricity for tenants – viable business model, making financial losses, residents satisfied or unsatisfied	Bills/ datasets provided to manager; Group can assign different rates to different sources of electricity; sharing is fair; Consumers (generally) have incentive to invest in renewables; platform provides measurable benefit in ability to access/ provide low cost low carbon energy	Amount of solar available (for sharing); Degrees of system autonomy (at SHAC: 60% self-sufficiency target); degree to which this is in line with expectations/ predictions; Technical solutions developed can be applied elsewhere
Payoff rules (benefits & costs of	Rate for solar energy within allocation; rate for	Growing uptake of renewables,	Rate for solar energy; rate for	Need to break-even; offer reduced cost of electricity	Service agreement with manager/ strata	Time & cost outlay

action-outcome combinations, incentivise/ deter action)	solar energy traded with neighbour; rate for grid-sourced energy	likely expansion to strata space	grid-sourced energy	for tenants; offer 20% discount on power bills		
NET COSTS & BENEFITS of potential outcomes	Cost of electricity: within allocation (solar rate 1 only), traded (solar rates 1 & 2), grid (solar rates 1 & 2, grid rate); low to high and/ or lower/ higher compared to previous home; reduced CO_2 emissions Expenditures (& potential savings) in line with own consumption; emotional aspect of sustainability	Experience/ learning in management/ administration of shared energy systems	Cost of electricity: within allocation (solar rate only), shared (solar rate only), grid (solar & grid rate); from low to high and/ or lower/ higher compared to previous home; reduced CO2 emissions; Expenditures (& potential savings) in line with own consumption; emotional aspect of sustainability	Reduced costs for tenants; positive environmental impact; scaleable business model; learning & experience; dissatisfied; financial losses; tenants pay (more than) standard tariff	Fee for services rendered (income)	Commercial benefits; losses

Conflict of Interest

Declaration of interests

☒ The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

☐The authors declare the following financial interests/personal relationships which may be considered as potential competing interests:

Publication VI

Manuscript submitted for publication in peer-reviewed journal

Hansen, P. & Morrison, G.M.: Beyond local scale: Action and impact of sustainability initiatives from a polycentric perspective. Submitted to Heliyon.

Heliyon

Beyond the local scale: Action and impact of sustainability initiatives from a polycentric perspective

--Manuscript Draft--

Manuscript Number:	
Article Type:	Original Research Article
Section/Category:	Social Sciences
Keywords:	sustainability; collective action; polycentrism; scaling; local sustainability initiatives
Manuscript Classifications:	90.230.110: Human Geography; 90.230.120: Nature Conservation; 90.230.130: Natural Resource Management; 90.230.140: Sustainable Development; 90.230.150: Urbanization; 140.160.260: Stakeholder Analysis; 140.170.200.100: Sustainable Development; 140.190.120: Social Organisation; 140.190.120.110: Social Networks
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Abstract:	Local sustainability initiatives play an important part in facilitating and driving the transition to a sustainable, low-carbon future. However, there is a lack of understanding regarding how local collective efforts contribute to wider system change. While notions of scaling and scaling up processes offer insight into intentional and strategic efforts at increasing impact, they do not account for how impact may develop organically, nor for the diversity of actors involved in local sustainability initiatives. This article proposes a polycentric perspective as an alternative conceptualisation of impact. Building on the literature on polycentrism, two case study energy projects in Perth, Western Australia, are analysed with a view to how they relate to wider system change. Conceptualising these initiatives as multi-actor decision-making units brings into focus the struggle between the individual and the collective inherent in such projects; and allows for a more nuanced understanding of the challenges as well as opportunities that collaborative Local Sustainability Initiatives provide to system-wide sustainability.
Suggested Reviewers:	
Opposed Reviewers:	

Beyond the local scale: Action and impact of sustainability initiatives from a polycentric perspective

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Abstract

Local sustainability initiatives play an important part in facilitating and driving the transition to a sustainable, low-carbon future. However, there is a lack of understanding regarding how local collective efforts contribute to wider system change. While notions of scaling and scaling up processes offer insight into intentional and strategic efforts at increasing impact, they do not account for how impact may develop organically, nor for the diversity of actors involved in local sustainability initiatives. This article proposes a polycentric perspective as an alternative conceptualisation of impact. Building on the literature on polycentrism, two case study energy projects in Perth, Western Australia, are analysed with a view to how they relate to wider system change. Conceptualising these initiatives as multi-actor decision-making units brings into focus the struggle between the individual and the collective inherent in such projects; and allows for a more nuanced understanding of the challenges as well as opportunities that collaborative Local Sustainability Initiatives provide to system-wide sustainability.

Keywords:
sustainability; collective action; polycentrism; scaling; local sustainability initiatives

1 Introduction

The global quest for a sustainable, low-carbon future has given rise to a growing number and diversity of, as well as interest in, small-scale, local built environment projects and initiatives applying novel social and technical innovations (Hermans, Roep, & Klerkx, 2016; Hewitt et al., 2019). There is consensus that collective action at the local level plays an important role in mitigating, and adapting to a changing climate, and in building resilient, low-carbon economies (Dóci, Vasileiadou, & Petersen, 2015; Hermans et al., 2016; Meelen, Truffer, & Schwanen, 2019; Parag, Hamilton, White, & Hogan, 2013; Tosun & Schoenefeld, 2017). Grassroots innovations (Hermans et al., 2016), initiatives (Dóci et al., 2015), organisations or experiments (Tosun, 2018; Tosun & Schoenefeld, 2017) may empower communities and lead to more sustainable developments locally, while also contributing to change at higher system levels (Hermans et al., 2016).

However, there is a lack of a clear understanding regarding the impacts local level initiatives may have on the wider system (Bulkeley, 2010; Dewald & Fromhold-Eisebith, 2015; Moss, Becker, & Naumann, 2015; van Doren, Driessen, Runhaar, & Giezen, 2018). Discerning how small-scale initiatives may affect, or contribute to changes, at larger scales may enable a faster and more efficient sustainability transition (Dóci et al., 2015; van Doren, Giezen, Driessen, & Runhaar, 2016). This article addresses this issue through a polycentric systems perspective by exploring how the interplay of various actors involved in local sustainability initiatives (LSIs) affects the collective endeavour and its potential impact on the wider system. The polycentric lens allows an emphasis on the role of multi-level, multi-scale, distributed decision-making. We propose that this enables an understanding of links between lower and higher system levels with regards to action and impact.

LSIs may be conceptualised as instances of collective action (Bird & Barnes, 2014). While climate change is often described as a global collective action problem (Bodin, 2017; Bulkeley, 2015; E. Ostrom, 2010) that has arisen from the cumulative impact of many, small, local and individual actions over time, it has also been suggested that the cumulative impact of many small initiatives may lead to a multiplier effect of positive, mitigating outcomes (E. Ostrom, 2010; Wilbanks & Kates, 1999; Wyborn & Bixler, 2013). It has further been suggested that problems faced by large groups may in fact be more easily managed when broken into, and addressed by, smaller units (Bauwens, 2017; E. Ostrom, 2009; Wyborn & Bixler, 2013).

In a seminal report to The World Bank, E. Ostrom (2009) offered a variety of examples of successful local action when she famously argued that “multiple benefits are created by diverse actions at multiple scales”. There is widespread agreement that positive change to mitigate global sustainability challenges will be driven by individual and local-level actions (Anderies, Folke, Walker, & Ostrom, 2013).

However, what their effect at a wider system level is, or how this occurs, is thus far not well understood (Anderies et al., 2013; Bird & Barnes, 2014; Moss et al., 2015).

Since Ostrom's 2009 publication, LSIs have become characteristic of global efforts at decarbonising societies (Bernstein & Hoffmann, 2018; Schoon & Cox, 2018). Such initiatives have, in turn, been characterised by fragmentation that is, in part, driven by the multi-locational nature of innovation and technology development (Dewald & Fromhold-Eisebith, 2015). In addition, the growth of LSIs has been accompanied by the rise of decentralised and distributed governance systems (Hamilton, Mayne, Parag, & Bergman, 2014; Hölscher, 2019; Tosun & Schoenefeld, 2017), and linked to this, distributed agency (Hermans et al., 2016). Agency may be understood as the power of individuals or groups to change processes or outcomes (Biermann & Pattberg, 2008), or the ways through which this change is achieved (Hölscher, 2019); and is generally regarded as an important element of transition processes (Dóci et al., 2015).

The distributed agency of multiple groups or actors may help counteract the problem of local context dependency that many innovations have (Hermans et al., 2016). It implies, however, that the ability of actors to plan scaling processes are hampered (ibid). It also implies that when layered onto the complicated structures that need to be considered for scaling, building the mass, unity and momentum necessary to create change, going to scale becomes difficult (Hermans et al., 2016). Moreover, local actions for sustainability are rarely perceived to be directly connected to global phenomena (Kates & Wilbanks, 2003), which illustrates a lack of appreciation of structure and agency on the ground. Not surprisingly then, the question of how local agency relates to global change has, thus far, been under-explored (Dóci et al., 2015; Hölscher, 2019; Wilbanks & Kates, 1999).

These trends provoke an important question: how can large numbers of diverse initiatives be structured and coordinated to enable and achieve collective, long-term, sustainable outcomes at scale? (Hölscher, 2019); and further, how can their potential be harnessed and leveraged effectively? Given the multiple benefits at multiple scales previously observed, E. Ostrom (2009) proposed that a polycentric perspective may be a suitable response to these questions. This suggestion has recently inspired a growing interest in the concept of polycentrism, or polycentricity (Thiel, Garrick, & Blomquist, 2019). A polycentric system is characterised by the prevalence of multiple, self-organising and semi-autonomous centres of decision-making (Carlisle & Gruby, 2019; Morrison et al., 2019; E. Ostrom, 2010). It follows that polycentrism has served as both a means of describing the phenomenon of fragmentation, and a response to its emergence (Thiel et al., 2019).

As the complexity and multidimensionality of climate change and its mitigation has highlighted the limited ability of traditional modes of governance to address the problem (Kivimaa, Hildén, Huitema, Jordan, & Newig, 2017; E. Ostrom, 2009), polycentrism has been proposed as a viable alternative (ibid) and as a useful analytical approach to sustainability-oriented governance (E. Ostrom, 2010).We argue that a polycentric lens may also assist inquiry into the above questions regarding the impact LSIs may have on the wider system. In a polycentric system, collective benefits and costs result from the interplay of diverse organisations in, and across, multiple geographic and jurisdictional positions (McGinnis, 2016). If LSIs are conceptualised as instances of collective action taken by a diverse group of actors, then their potential for impact may be understood in terms of these actors' individual and collective interactions.

Reframing the scaling question in terms of higher order collective outcomes shaped by multiple, diverse, self-organising decision-making units may enable accounting for the complex, constituent hierarchies that embed and link local initiatives. Consequently, framing LSIs as self-organised decision-making units may allow for a better understanding of local agency and using polycentrism as an overarching analytical lens may aid in identifying the connections between the local and the wider system structure. To examine this conjecture, we begin by outlining the need for an alternative conceptualisation of scaling in the context of sustainability transitions (section 2.1); and by highlighting how a polycentric perspective fits into the discussion (section 2.2). Two shared renewable energy projects in Perth, Western Australia are used as case studies to explore the application of a polycentric perspective. The article is guided by the research question: How do local sustainability initiatives relate to wider system change from a polycentric perspective?

2 Background

2.1 The notion of scaling

Research on increasing the impact of local sustainability initiatives, and particularly of energy-related projects, has drawn heavily on the concept of scaling (usually, but not necessarily, scaling up). Concepts and frameworks from the literature on socio-technical transitions, innovation and innovation diffusion, and social-ecological systems have been particularly influential in informing empirical studies on scaling processes (Lam et al., 2020; van Doren et al., 2018) in the context of grassroots innovations (Hermans et al., 2016), system innovations or experiments (Kivisaari, Saari, Lehto, Kokkinen, & Saranummi, 2013; Meelen et al., 2019; Naber, Raven, Kouw, & Dassen, 2017; Wigboldus & Brouwers, 2016), community energy niches (Ruggiero, Martiskainen, & Onkila, 2018), and novel policies and practices (Bernstein & Hoffmann, 2018).

However, there is a lack of consistency in how the concept of scaling is interpreted and applied (Lam et al., 2020; van Doren et al., 2018). Although some inroads have been made to improve our understanding of how sustainability initiatives scale, effective advancement of the field is hampered by the disparate use of the terminology of scale and underlying theories (Dijk, De Kraker, & Hommels, 2018; Lam et al., 2020). One particular shortcoming is a lack of conceptual clarity (Lam et al., 2020; van Doren et al., 2018) and many publications fail to define the concept altogether. Where explicit interpretations and explanations are given, they vary significantly within and across disciplines and schools of thought (Lam et al., 2020; van Doren et al., 2018).

In an effort to integrate some of the seemingly disparate approaches in the literature, Lam et al. (2020) proposed a typology of three main categories of processes aimed at increasing the impact of sustainability initiatives (which they referred to as amplification processes). They differentiated between those that focus on a specific initiative by, for example, accelerating or prolonging impact (i.e. amplifying within); those that aim to increase numbers of participants or beneficiaries, and increase geographic reach (i.e. amplifying out); and those that target higher institutional levels or value change as a means of increasing impact (i.e. amplifying beyond) (Lam et al., 2020). van Doren et al. (2018) similarly sought to address the obscurity of the concept and process of scaling low-carbon initiatives, and distinguished between horizontal and vertical scaling up; processes aimed at increasing spatial coverage or numbers of beneficiaries (horizontal), or using lessons from one initiative to inform institutions at higher levels (van Doren et al., 2018).

Although these studies seek to address challenges in terminology for the scaling literature, they share an assumption of intentionality which is an important limitation common with other conceptualisations. This is illustrated in Lam et al.'s (2020) review, where scaling processes (amplification processes) are explicitly defined as the intentional actions taken by sustainability initiatives in collaboration with other actors for the purpose of increasing the impact of the initiative. Others have expressed this notion by referring to scaling as a strategy aimed at making the benefits of a given initiative more widely available (Wigboldus & Brouwers, 2016) or by asserting that a LSI cannot contribute to sustainability unless it is scaled up (Dijk et al., 2018).

Conceptualising and studying the scaling and impact of LSIs solely in terms of planned, intentional processes arguably limits our understanding of scaling to an extremely small sub-set of cases. In fact, specificity to local context is what makes widespread impact difficult to achieve for many LSIs (Hermans et al., 2016). On the other hand, it would be foolish to assume that instances of strategic scaling are the only way local initiatives have impact. While they may represent or be followed up with strategic means to reach diffusion benefits, they may also have an intrinsic value and/or no aspiration to scale (Pesch, Spekkink, & Quist, 2019). An assumption of intentionality tends to ignore the non-linear nature of the processes by which innovative technologies and practices have been observed to diffuse (Wigboldus et al., 2016).

Moreover, empirical research has suggested that the distributed agency of actors involved in initiatives significantly limits the possibilities for planned scaling processes to occur (Hermans et al., 2016).

Different interests and framings of the innovation in question may instead lead to multiple divergent pathways (ibid). (Moss et al., 2015) similarly pointed out that institutional change depends, in part, on how actors interact with each other and their contexts and that some actors may act strategically in their own interest while others may be more interested in collective benefits to the community (ibid). The agency of diverse actors often involved in LSI is another shortcoming of the scaling literature and arguably one of the sources of complexity in understanding and generalising LSIs and their scaling. Although it is commonly acknowledged that actions for sustainability are often based on the collaboration of multiple, diverse actors, complexities arising from their attributes and interactions are not usually taken into account in discussions of intentional scaling processes.

In a similar vein, it has been argued that approaches to scaling rarely take into account that many contemporary sustainability initiatives are based on complex, systemic innovations (Wigboldus et al., 2016). This characteristic implies that their increased uptake depends on a diversity of contextual, infrastructural, institutional and social factors (Meelen et al., 2019). Despite a general consensus that the systems and subsystems of interest to sustainability scholars tend to be of a complex, sociotechnical, multi-actor and dynamic nature (Ruotsalainen, Karjalainen, Child, & Heinonen, 2017), this insight has not been explicitly translated into the study of scaling processes.

2.2 An alternative conceptualisation of scale

In contrast, in a different stream of literature, it has been suggested that it may be more useful to frame the question of impact and scaling processes as a challenge of managing complexity, rather than scaling up (Berkes, 2006). Understanding how the interactions of a small number of actors may be scaled to interactions within large groups or many actors has been framed as one of the main challenges facing contemporary social sciences (Janssen & Ostrom, 2006). These lines of thought originate from the literature on social-ecological systems and global environmental change. In contrast to the literature reviewed above, conceptualisations of scale in this stream of research are less concerned with concrete processes, and offer an alternative to framing the impact of local-level sustainability initiatives in terms of an intentional scaling process. Instead, we may view LSIs as self-organised, local-level governance systems that may cumulatively contribute to managing change at a global level (Huitema, Jordan, Munaretto, & Hildén, 2018; E. Ostrom, 2010).

Arguing that a lack of clarity regarding the concept of scale in the social sciences was an impediment to productive, interdisciplinary endeavours to understand and address global environmental change (and in particular, its human dimensions), Gibson, Ostrom, and Ahn (2000) provided a useful, frequently cited set of definitions. The concept of scale in the social sciences, they argued, was particularly important in observing and identifying problems and patterns, explaining them, generalising findings, and optimising processes (Gibson, Ostrom, & Ahn, 2000). Scale was defined as an analytical dimension such as time, space or quantity, as units of analysis, with levels specifying locations on a given scale (Cash et al., 2006; Gibson, Ostrom, & Ahn, 2000). Scaling up was defined with regards to generalisability, applying the explanations of phenomena observed at one level to phenomena at higher levels (Gibson et al., 2000).

Three common scale challenges have been identified, in which interactions across scales and levels hinder the successful, resilient management of a human-environment system (Berkes, 2006; Cash et al., 2006). The challenge of plurality, namely the failure to recognise the heterogeneity of how different actors perceive and value scales differently (Berkes, 2006; Cash et al., 2006), is particularly relevant here as it adds weight to agency. In practical terms, effective resource management requires an appreciation of the heterogeneity of involved actors, and of how this heterogeneity may translate into divergent interpretations of scale. In the context of policy experimentation and governance specifically, there has also been a call to consider the effects that experiments may have on the norms and learning of the actors organising them (Huitema et al., 2018).

Moreover, reflecting on the links between local and global action and change, Wilbanks and Kates (1999) asserted that gaining a better understanding of local agency required investigation into what local actors actually can and want to do about global change. This is particularly pertinent given the emerging range of new actors and agency involved in sustainability initiatives, who, directly or indirectly, contribute to the governance of global environmental change (Biermann & Pattberg, 2008). It has further been argued that insufficient attention has been directed towards the links between various scales of (common resource) management, despite their importance (Berkes, 2002). This has been referred to as the scale challenge of ignorance: the failure to recognise interactions across the diverse dimensions of complex human-resource systems (Cash et al., 2006) Berkes 2006).

The scale challenge of mismatch refers to a persistent mismatch between the scale of problems and of the solutions applied to them (Berkes, 2006; Cash et al., 2006). Understanding the fit between an environmental problem and the collaborative arrangement addressing it has been found to be crucial, and implies that governance solutions should be devised at a level appropriate for the scale of the problem (Bodin, 2017; Goldthau, 2014; Wyborn & Bixler, 2013). In the context of environmental governance, distributed, multi-level institutional structures are commonly proposed to address issues of scale (Wyborn and Bixler 2013). In this respect, polycentrism has received recent attention as a type of governance system applicable to these challenges, at least in theory (Jordan et al., 2015; Thiel, 2017; Thiel et al., 2019). Polycentric systems are defined by the presence of multiple, independent or semi-independent centres of decision-making (E. Ostrom, 2010; V. Ostrom, Tiebout, & Warren, 1961). The interplay of these different organisations in and across multiple geographies and jurisdictions affects the overall collective benefits and costs of the system (McGinnis, 2016). With the increasing pace and significance of changes in social, economic and environmental systems, polycentrism has become more prevalent over recent years (Thiel et al., 2019).

While the polycentric term was originally coined in the context of collective action and the provision of public goods and services (E. Ostrom, 2010; Sovacool, 2011), there is now a range of interpretations and applications (Thiel et al., 2019). Importantly, it has been proposed as a useful analytical perspective to understanding interactions between various actors or organisations in solving societal problems (Andersson & Ostrom, 2008; E. Ostrom, 2010; Thiel et al., 2019). Specifically and in support of the introduction to this paper, (E. Ostrom, 2009); E. Ostrom (2010) proposed that polycentrism is a useful perspective to conceptualising climate change mitigation efforts. Applying a polycentric perspective to the question of climate change mitigation highlights the complexity of the issue and challenges the belief that benefits are derived solely from local or global measures (E. Ostrom, 2009). As diverse actions to counteract the adverse effects of climate change are being taken, "multiple benefits are created […] at multiple scales" (E. Ostrom, 2009, p. 35).

A number of benefits are typically linked with polycentrism. One important benefit is that actors can make use of local knowledge and tailor solutions to their specific context (E. Ostrom, 2009, 2010). Evidence also suggests that when knowledge is shared and actions are coordinated across diverse levels and scales, governance outcomes improve (Vervoort et al., 2014). Moreover, polycentric systems offer more opportunity for experimentation and innovation (Morrison et al., 2019). Experimentation, in turn, facilitates and enhances learning processes (e.g. Tosun, 2018). In summary, polycentric systems tend to "enhance innovation, learning, adaptation, trustworthiness, levels of cooperation of participants, and the achievement of more effective, equitable, and sustainable outcomes at multiple scales" (E. Ostrom, 2010, p. 552).

In this article we use a polycentric perspective to conceptualise LSIs as self-organised units of decision-making embedded within a complex multi-scale, multi-level, interactive structure. Change at a global level is thus understood as the outcome of the interplay of actions within and across scales of time, place and jurisdiction, and their levels. We adopt a polycentric perspective as an alternative to existing approaches concerned with the strategic scaling of LSIs or their products. Instead of assuming a homogenous group of actors, clearly defined outcomes, or an intention of scaling, this paper explores the implications of the distributed, multi-scale, multi-level agency of LSIs for how they may affect change. The polycentric perspective is applied here not in a prescriptive sense as an aim of policy-making, but as a conceptual approach to explore the relationship between the multi-actor nature of LSIs, and the impact of the initiatives on the system. The paper is not concerned with the specific rules created by the actors in the case studies but with what the diversity of actors involved has meant for its impact.

Building on the presumed benefits of polycentrism, we conceptualise these benefits as the potential contribution to change, i.e. impact that LSIs may have. From this perspective, two types of impact may be differentiated; impact as the direct output of a LSI (e.g. a more equitable and/or lower carbon energy system for a community); potential impact *via* pathways such as learning or increased levels of trust that improve the future decision-making of actors. Figure 1 provides a simplified schematic of this polycentric conceptualisation of potential impact. In this conceptualisation, the LSI may be linked across scales and levels to other decision-making units, either formally, through the jurisdiction it falls under, or informally, *via* the different actors involved. The analysis in section 4 will build on the distinction between the what and the how of outcomes and impact, In other words, what outcomes and impact have been achieved and may be in the future; and how future ones may be arrived at.

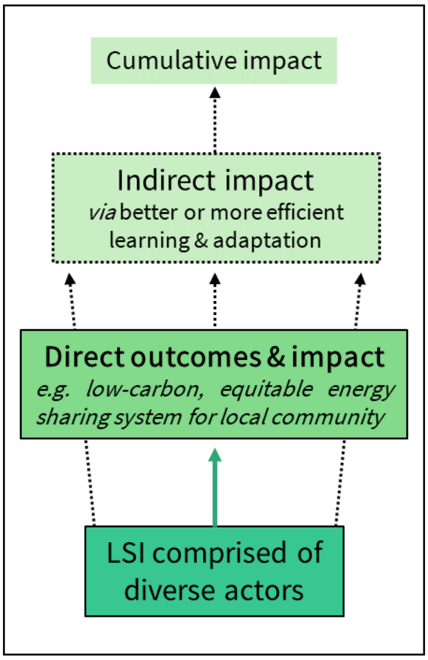

Figure 2: Conceptualisation of how LSIs may contribute to change in the wider system using a polycentric perspective.

3 Application of the polycentric perspective to shared energy systems

This section introduces the case studies used in this study and describes how data were collected and analysed. We draw on two interrelated LSIs concerned with testing novel renewable energy system configurations. The proposed polycentric perspective may be particularly relevant in the context of renewable energy systems because they have been explicitly recognised as having polycentric characteristics (Goldthau, 2014; Sovacool & Van de Graaf, 2018; Tosun, 2018). While the term decentralisation is often used to describe the emerging pattern of energy generation, the term polycentric also accounts for the concurrent decentralisation of decision-making (Moroni & Tricarico, 2018;

Skjølsvold, Ryghaug, & Berker, 2015; Wolsink, 2020). On the one hand, the distributed generation source operates in conjunction with the larger distribution network (effectively, a higher level of technical rules), while on the other hand, the community using the energy generated by the resource creates the rules of how energy is shared – so long as they are in accordance with the various levels of regulation.

In line with the discourse that problems are better solved at the scale at which they occur, it has also been argued that energy infrastructure should be governed in a polycentric manner because it involves resources at local through to national dimensions (Goldthau, 2014; Koster & Anderies, 2013). Moreover, a polycentric perspective on energy systems may provide the openness to learning and adaption needed to facilitate a low carbon transition (Goldthau, 2014) and can thereby also impact the rate of implementation of energy technologies (Koster & Anderies, 2013).

3.1 Case study

This research draws on two interrelated projects concerned with the implementation and testing of new energy sharing arrangements in Perth, Western Australia. The RENeW Nexus Trial involved the use of a blockchain enabled trading platform to enable residents in the City of Fremantle to sell excess solar energy produced by their rooftop PV systems to residents without such systems (and each other). This trading of energy between prosumers and consumers is termed peer-to-peer (P2P) trading. The RENeW Nexus P2P trading trial ran as part of the RENeW Nexus project, a transdisciplinary research project funded by the Australian government. This involved the state's utilities, technology and software companies, and a research organisation testing the feasibility and viability of sharing solar energy through P2P trading across the grid in the City of Fremantle.

The White Gum Valley (WGV) is a residential precinct that was designed to include a number of sustainability features. Among these is the integration of solar PV and battery storage systems in three multi-residential apartment buildings to enable residents of the individual apartments to share and access the benefits of solar energy. In contrast to the RENeW Nexus trial, WGV has been described as a demonstration project. The fundamental idea of enabling solar energy to be shared within multi-unit dwellings through the integration of storage, smart metering and platform technologies was implemented with varying ownership models in the three buildings (Hansen, Morrison, Zaman, & Liu, 2020).

Figure 2 illustrates the stakeholders relevant to the present study and their links with the two projects. WGV may be regarded as a precursor to the RENeW Nexus project. The software platform used for trading in the RENeW Nexus trial (developed by the technology start-up) was also used for accounting purposes in the WGV project. Western Australian utilities were also involved in both projects, albeit more actively in RENeW Nexus. The project manager was employed by the participating research organisation. At WGV, additional actors were the developers of the three apartment buildings. An electrical engineering company designed and implemented the solar PV and battery storage systems at WGV. One of the three systems is described and evaluated in detail in Syed, Hansen, and Morrison (2020). Hansen et al. (2020) provide more insight into the governance arrangements at WGV; further information and analysis on the actors in the RENeW Nexus trial, including household participants, can be found in Wilkinson, Hojckova, Eon, Morrison, and Sandén (2020).

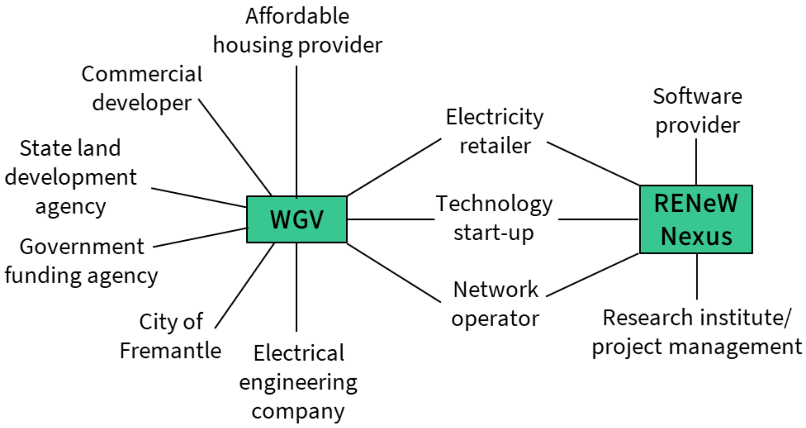

Figure 1: Links between actors and the two projects with respect to the present study.

3.2 Approach to data collection and analysis

Semi-structured interviews with the WGV and RENeW Nexus stakeholders were conducted over a two year period as part of a larger research project. This paper draws on a total of 16 of these interviews, including 11 different stakeholders representing organisations, and 13 different individuals/ representatives. Table 1 shows the interviews conducted according to stakeholder type. The timing of the interviews was influenced by project timelines. Stakeholders in the RENeW Nexus trial were interviewed after the trial was completed, at the end of 2019. Some WGV actors were re-interviewed at the same time, to verify earlier findings. Interviews were audio-recorded and transcribed, with the exception of two written responses and one telephone interview.

Table 1: Overview of interviews that informed the analysis in this paper.

Stakeholder	**Interviewed regarding:**	**Date interview was conducted:**	**Interview recording & processing methods**
Electricity retailer	WGV	April 2018	Notes taken, audio recorded & transcribed
	RENeW Nexus	November 2019	
Network operator	WGV	April 2018	Notes taken, audio recorded & transcribed
	RENeW Nexus	December 2019	
Technology start-up	WGV	April 2018	Notes taken, audio recorded & transcribed

	RENeW Nexus	February 2020	Written (email)
Electrical engineering company	WGV	April 2018	Notes taken, audio recorded & transcribed
		November 2019	
Government funding agency	WGV	April 2018	Written (email)
City of Fremantle	WGV	April 2018	Notes taken, audio recorded & transcribed
State land development agency (Gen Y developer)	WGV	April 2018	Notes taken, audio recorded & transcribed
Affordable housing provider	WGV	April 2018	Notes taken, audio recorded & transcribed
		November 2019	Via telephone, notes taken
Evermore developer	WGV	October 2018	Notes taken, audio recorded & transcribed
Research institute/ project manager	RENeW Nexus	November 2019	Notes taken, audio recorded & transcribed
Software provider	RENeW Nexus	November 2019	Notes taken, audio recorded & transcribed

An iterative process of reading interview notes and transcripts, and writing memos to identify patterns and themes constituted a first step in the analysis. A set of six general themes relevant to the present article were identified and related to; the problem being addressed; the solutions being applied; expected and perceived outcomes; challenges; interpretations of scaling (processes); and the importance of collaboration. By going back and forth between the data and the polycentric conceptualisation, differences between individual actors and the collective of project stakeholders were identified. Findings were then related to the proposed types of impact, i.e. arising from direct project outcomes and arising indirectly through learning and adaptation. The findings are discussed in the following.

4 Results & discussion

We address the research question of how LSIs relate to wider system change (from a polycentric perspective) in two steps. First, we examine what the interviewed stakeholders suggested was relevant in this regard, i.e. what the (tangible or intangible) product or outcome is, and what constitutes impact. Secondly, the question of how is explored, that is how this impact may be achieved.

4.1 What: Exploring outcomes and impact

4.1.1 Individual *versus* collective interest and outcomes

Examining the interests that the different actors had in participating in the WGV and RENeW Nexus projects offered an illustration of the heterogeneity of actors in LSIs. A number of different framings of problems being addressed, and associated anticipated outcomes were identified. There were varying degrees of specificity regarding the projects' roles, ranging from testing a particular solution to addressing a general problem. At the same time, this overlapped in many cases with whether the projects promised benefits were of an individual or collective nature.

For example, the government agency that supported the WGV project described a broad and collective beneficial outcome stating that the central point of the project was to accelerate the uptake of solar PV into apartment housing. Similarly, the technology start-up referred to the inability of residents of apartment buildings to access distributed energy resources (DERs) as the key problem being addressed at WGV. Scaling demonstration projects like WGV was important to address energy poverty. The state development agency expressed an interest in growing the levels of acceptance that buildings should be more sustainable, while the local municipality asserted that "It's just a really important step toward a decentralized renewable energy based grid".

These views reflect a general ambition amongst the WGV stakeholders to affect positive change at a collective level for wider society. While few interviewees considered WGV residents in describing collective benefits, the technology start-up, the engineering company, and the Evermore developer expressed in general terms that customer satisfaction was important to them. The affordable housing provider on the other hand specifically described their primary interest as reducing the costs of living for their tenants. This was followed by reducing CO_2 emissions. Finally, there was also an interest in testing a new business model as a benefit to their organisation, but it was stressed that this came last.

In line with the chief business of their organisation, other actors indicated a focus on the technical aspects of the project. While the technology start-up referred to their trading platform as a solution to enabling the uptake of DERs in apartment buildings, the electrical engineering company was concerned with creating an integrated energy system to allow the equitable sharing of electricity across multiple residents and buildings. The network operator wanted to gain an early understanding of how behind the meter DERs affect the network and how its utilisation might change; while the state land development agency saw an opportunity to improve understanding of the effectiveness of batteries in apartment buildings and demonstrate their application in this context.

The tendency towards a focus on benefits to the individual organisations, as well as the focus on technical aspects, became more pronounced in the RENeW Nexus project. There appeared to be a greater specificity in the overarching problem definition, with all actors referring to P2P electricity trading as the principal interest of the project. The project manager explained that the leading question of the trial was how P2P trading may be done across the South West Interconnected System (SWIS), Western Australia's main electricity network. As the provider of the trading platform, the technology start-up stated that the trial served to gain a better understanding of how platforms may support solving current challenges such as the need to ensure grid stability and a low cost energy system. For them the trial served to assess blockchain technology to facilitate P2P trading across the grid as a potential solution to these challenges, and in doing so, also evaluate the potential of and for their technology in this context.

The electricity retailer and the network operator specified the electricity system challenge they thought the trial addressed, referring to the problem of matching demand and supply. In contrast to the technology start-up, their interest was not in the technical potential of blockchain-based P2P trading. These organisations were interested in finding out whether customers were generally interested in and/ or engaged with P2P trading and digital platforms; and in whether there would be any observable behaviour change. The electricity retailer explained that while this particular trial used a platform, it was only one option to address the issue. As such, the solution being trialled was not the platform itself but the concept of creating an opportunity for customers to buy and sell to each other. In a similar vein, the software provider intermediary also referred to P2P trading as a concept being tested in the trial. As the retailer, they described P2P trading and blockchain technology as one of many new digital energy technologies entering the market. Their organisation's interest was in applying software to facilitate all or any of these digital technologies.

These observations give an indication of the potential difficulties of planning and implementing an intentional scaling process and suggest that the notion of impact is often abstract, even at the local level, and long before it becomes cumulative. These first findings may also be understood as a manifestation of the plurality challenge noted in section 2.2: actors often have different perceptions regarding the most important scale or level of a given problem (Cash et al., 2006). The case studies exhibited a plurality of perspectives on problems and solutions. Boundary organisations that act as intermediaries are typically proposed as a means to address the scale challenge of plurality (Cash et al., 2006).

The need for such an intermediary was recognised by the electrical engineering company involved in the WGV project. They explained that the project had lacked structure, especially with regards to clearly defined roles and responsibilities (Hansen et al., 2020). While this project had been an experiment with high degrees of uncertainty and novelty at the beginning, more commercially focused arrangements would require clearer project management. They pointed to the evolution from WGV to RENeW Nexus, with the latter having a designated project manager. The RENeW Nexus project manager affirmed that having the research institute as a non-commercial party in the collaboration was extremely important. The network operator referred to this as the glue between the different partners. Both the retailer and the network operator commented that having a dedicated project manager was attractive, specifically to facilitate communication between the research and commercial actors.

4.1.2 Collaboration

Perhaps not surprisingly and given the awareness of actors of the plurality of interests in their group, collaboration in itself was seen as a positive and important outcome by a majority of interviewees. The RENeW Nexus project manager emphasised the importance of collaboration as an outcome in and of itself. Achieving a collaboration between the technology start-up, the retailer and the network operator specifically was a success that many in the sector had doubted would be possible. This was affirmed by the software provider, who argued that while there may be different views on whether the project had been successful, getting the utilities and the technology start-up to sit down together and negotiate tariffs was, in their view, a good starting point and a satisfactory outcome.

Collaboration as a beneficial outcome also had a more individualistic dimension. Building relationships with industry actors was part of the motivation of the research partner for involvement and continued relationship building was a desired outcome of the project. Similarly, the software firm described their newly established relationship with the university in particular as a great outcome for their organisation in view of future opportunities, they found it exciting to participate in a project with important stakeholders.

As well as being important as an outcome, there was agreement that collaboration had been critical to enabling the two projects in the first place. In the case of RENeW Nexus, the retailer and the project manager pointed out that the project could not have happened without collaboration, and specifically, not without the involvement of the utilities, as P2P electricity trading across the network was not permitted within the existing regulatory framework. This had been observed earlier in the WGV interviews as well, when the state land development agency noted that the challenge for P2P trading was its application across the grid.

In addition to this institutional support, technical expertise was also an important aspect of collaboration. The retailer explained that they will usually seek collaborators if their own organisation does not have the necessary technical understanding. With regards to the RENeW Nexus trial, they viewed their own contribution as their experience with engaging customers and understanding their wants and needs, and regulatory expertise. The technology start-up pointed out that that all of the actors involved in the RENeW Nexus trial were important players in the energy system and its transition. They also noted that all other projects they engaged with involved collaboration with local utilities and/or renewables developers.

Despite the consensus that collaboration was critical to carrying out the projects, actors also raised the point that collaboration was only a first step. For example, the affordable housing developer argued that collaboration was important but that things should not stop there. While getting the collaboration going in the first place presented an opportunity, there was a need for people to invest time, come together and work towards aligning the system more closely with the initial vision as the project progressed.

This is again indicative of the issue of plurality. While the RENeW Nexus project sought to address this by involving a project manager and non-commercial party, the diversity of actors and associated plurality of perspectives was still viewed as the main source of difficulties.

The RENeW Nexus project manager pointed explicitly to the differences in the ideas and expectations of the stakeholders in asserting that the collaborative effort had been challenging at times. The issue of plurality meant that it was difficult to come to an agreement at the beginning of the project. This lack of agreement repeatedly led to disagreement throughout the project and resulted in diverging interpretations of outcomes. Many other actors also commented on the challenges of collaboration. The electricity retailer, for example, pointed to the need to be clear about shared objectives, while the network operator described the coordination of collaborative efforts as naturally difficult. The technology start-up commented that collaboration was essential to ensure that all relevant viewpoints were taken into account in setting up and evaluating the project.

4.1.3 Experimentation and learning

One of the proposed benefits of polycentrism is that it promotes and facilitates experimentation and learning through the use of local knowledge and networks (Morrison et al., 2019; E. Ostrom, 2005; Tosun, 2018). The analysis of the case studies suggested that experimentation was in fact facilitated by virtue of actors knowing each other. Moreover, participating in the WGV and RENeW Nexus projects was regarded by many actors as a learning opportunity. In discussing the WGV project, both the retailer and the network operator expressed that learning was, in fact, the most important outcome for their organisations, more important than whether the tested setup actually worked. Similarly, the state land developer explained they had been motivated to provide funding for the WGV project by providing finance for one of the battery and solar PV systems, because it provided an opportunity for research. They stressed that they had not been looking for a commercial payback. These examples highlight the importance of outcomes that are intangible and difficult to measure in our exploration of how LSIs may contribute to wider system change.

With respect to learning and experimentation, there was also evidence that effective learning was more difficult to achieve in the context of experiments. Regarding the RENeW Nexus trial, the network operator stated that learning was difficult because, given the novelty of the technology and trial set-up, there was no means of comparison. As such, while experimentation is an opportunity for learning, the extent to which this increases system efficiencies depends partly on whether the set-up, available knowledge and rigour in evaluation allow for useful insights to be gained. Another challenge of learning experiences is the high level of knowledge required to implement innovative systems or projects. The state land development agency for instance noted that they had experienced obstacles at WGV as regular electricians and builders lacked knowledge on how to install novel systems (e.g. systems including additional metering).

4.1.4 Value creation

A market-based conceptualisation of impact emerged as a fourth theme in terms of what an LSI's contribution to wider system change may consist of. This emerged in relation to interview questions about understanding by the actors of the scaleability of the project or innovation. The RENeW Nexus project manager considered scale to mean that something is offered as a service as part of the overall system. The electricity retailer had a similar view, explaining that (regarding the RENeW Nexus trial) what goes to scale is the opportunity of P2P trading being offered to more customers, i.e. beyond the trial cohort. An innovation can be considered scaled when there are a significant number of people using it. According to the network operator, scale meant that there was a larger benefit to more people, and the product or service was available to a larger cohort.

The notion of value creation was central to this understanding, that is, scaleability was understood to depend on whether value is created for customers and for the organisation. The software provider referred to the consumer market as the key to impact. They elaborated that it was not about reaching a specific number or percentage of people but rather about the potential reach, i.e. if it was offered as a product or service by the retailer then it would be considered to have had a significant effect on the system, even is only a small number of customers took it up. The interviewee drew a parallel to VHS technology for watching movies, "it wasn't about the technology at all, it was about watching movies". What goes to scale is the service.

This section explored the ways in which the case study LSIs were seen to make their potential contribution to the wider system. The diversity of actors constituting the WGV and RENeW Nexus projects was reflected in a plurality of views regarding the principal interests and outcomes of the projects. A distinction between beneficial outcomes to the individual organisations and a larger collective emerged. Given the heterogeneity of group composition, collaboration was seen as an important outcome of the projects. Collaboration was also essential for enabling the projects, and thus played a role in creating the opportunity for learning through experimentation. Lastly, findings showed a focus on the consumers and the marketplace as an indicator of impact.

4.2 How: Pathways to impact

Building on the findings discussed in the previous section and our initial conceptualisation of a polycentric perspective on impact (figure 2), pathways to impact were identified. Based on the evidence from the case studies, the conceptualisation was then revised. Figure 3 illustrates a proposed conceptualisation of how the potential of LSIs to contribute to change in the wider system may be understood from a polycentric perspective.

4.2.1 Direct outcomes and impact

We differentiate between direct outcomes and impact, and indirect impact. Direct outcomes refer to those described in the previous section that is outcomes that actors directly associated with the projects, such as having achieved collaboration, or having had an opportunity for learning. Direct impact may be understood as measurable effects such as a reduction in CO_2 emissions resulting from the WGV systems. The goal of the affordable housing provider to achieve lower electricity costs for their tenants may be understood as a reference to a direct impact.

As alluded to in the previous sections, figure 3 further differentiates between individual and collective direct outcomes and impact. Collaboration is a collective outcome because it provides benefits to groups of collaborators. One example of an individually beneficial outcome is insight gained by a given organisation regarding their business operation or product. In between the two, the outcome learning to collaborate may be interpreted as having both an individual and collective dimension. Being a skilled collaborator will contribute to greater efficiencies in future collaborations which is a benefit to the actors themselves as well as others they collaborate with. The state land developer stated that for their organisation, lessons learned related primarily to collaborating with a large number of different partners. The retailer also commented that the lessons learned regarding collaborating with a number of different partners were going to be valuable in the future.

The distinction between individual and collective outcomes is important with regards to existing notions of scaling (up), as well as with regards to understanding impact. For the former, the distinction brings the heterogeneity and distributed agency of actors involved in LSIs to the fore, and thus conceptually addresses the shortcomings of existing approaches. With regards to impact, the distinction leads to the recognition of a multitude of potential ways in which an LSI may contribute to change.

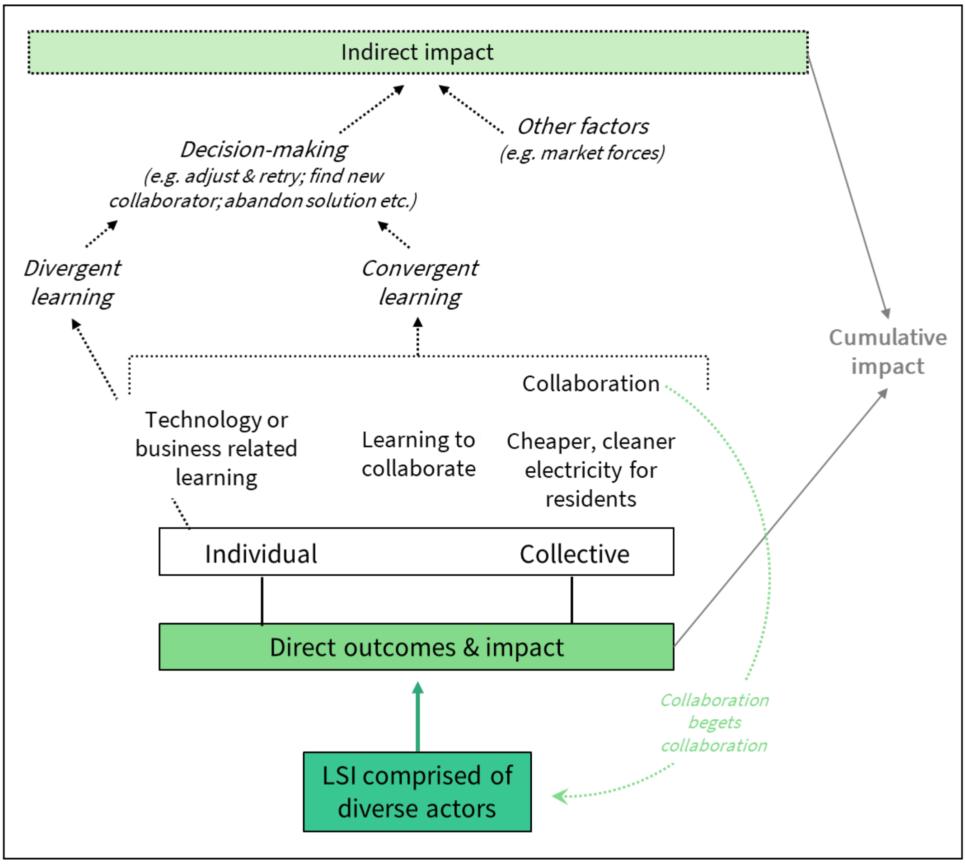

Figure 2: Possibilities for an LSI's impact, i.e. contribution to wider system change, with divergent and convergent learning as the most important pathways.

4.2.2 Learning as a vehicle for change

In line with contemporary literature on polycentrism, our conceptualisation suggests learning as a main vehicle for impact (Tosun, 2018). The principle idea is that what was learned, and how, influences the decision-making of actors regarding future action. Two different modes of learning – divergent and convergent – may affect how outcomes go to scale. Divergent learning is based on individual outcomes and is the process by which actors relate learning to their own organisation. For example, the electrical engineering company may decide that solar PV and storage systems for apartment buildings present a viable opportunity to expand their service offering. Convergent learning on the other hand occurs when project outcomes are jointly evaluated by the participating actors.

Convergent learning results in a shared understanding of project outcomes, their implications for the problem being addressed, and desirable next steps. This may also extend beyond the initial group of collaborators. The case studies suggested that convergent learning is an important element in enabling a LSI to have impact beyond its direct outcomes. For example, the state land development agency asserted that it was important to apply lessons learned from WGV and apply them to larger sites. They also reported that in contrast to their expectations, their next project (following WGV) had not been easier to develop, and that different actors will have varying levels of understanding: “It was still… almost like you've got to go back and rewrite all those same arguments for why we should be doing this and not business as usual”. As such, while their organisation had incorporated individual lessons into their decision-making, other actors had not had access to the same information or experience. As the developer noted, information is (generally) not being shared or advertised. The local municipality stressed the importance of this, stating that sharing the learnings from projects such as WGV with other local governments was crucial, and a first step to mainstreaming.

4.2.3 More collaboration, more impact

In addition to learning as a main pathway to impact, collaboration may be considered a pathway to impact in the sense that collaboration begets collaboration. This was illustrated by the WGV collaboration paving the way for RENeW Nexus, i.e. collaboration was important in linking actors and projects with each other and over time. In terms of the application of P2P trading, cross-references were frequently made between the two projects. The software provider recalled that they became involved in the RENeW Nexus trial because they had previously worked with the retailer, who brought them into the consortium. Numerous interviewees also commented on the importance of continued relationship building. The technology start-up stated that the connections established through the RENeW Nexus project could be expected to continue in the future.

4.2.4 Other factors determining impact

Asking actors how projects may have impact revealed that many viewed this as dependent on market dynamics. Many referred to the cost of technologies in terms of new technologies usually being expensive when first entering the market and in terms of price determining mass uptake. With reference to P2P trading, the electricity retailer asserted that its potential ultimately depended on whether value was being created for the customer. Albeit noting that broader uptake also required regulatory change, the network operator stated that once P2P trading was proven to be viable, it was down to economics, and how fast and significantly prices for solar PV panels and batteries drop. Others also argued that a product needs to have genuine value, that is, the value proposition cannot rely solely on novelty, it must make financial sense and, in the end, it comes down to marketing. Both the retailer and the software provider made explicit reference to Rogers’ diffusion of innovation theory (Rogers, 2003), describing the key challenge as overcoming the chasm between early adopters and the early majority of technology users. Achieving this required a pipeline of products to meet mass market demand, and research and development at the same time.

4.2.5 Implications and indirect impact

The above sections have sought to illustrate that in addition to an LSI's direct outcomes they may contribute to change through the knowledge gain for actors through participation. Indirect impact is achieved through these multi-stranded learning and decision-making pathways, in addition to external factors such as market forces. The notion of cumulative impact, as proposed by Ostrom, is thus comprised of direct (more tangible) outcomes and impacts, as well as indirect ones. What some refer to as scaling (up), is the accumulation of messy, non-linear learning and decision-making processes within and across organisations and collectives. The distributed agency of actors involved in grassroots innovation was found to lead to divergent pathways for further development by Hermans et al. (2016). Peng, Wei, and Bai (2019) stressed the complexity of learning from, and building on, experiments, asserting that applying learning to a new project may even be considered an innovation in itself.

An important implication of the distributed agency of actors involved in the case study projects was the effect of different levels of authority on the potential for impact. Following their interest in seeing whether P2P trading would lead to observable behaviour change, the network operator and the electricity retailer joined the technology start-up for a second iteration of the P2P trading trial. Because no behaviour change (and no evidence of no behaviour change) had been observed in the first trial, the decision was made to re-test whether this was due to P2P trading as a mechanism, or a result of the types of participants in the trial cohort. The network operator explained that the outcomes of the first and second trial would then inform their decision-making. If benefits for customers and the network is apparent then a wider rollout would be considered. If no benefits were apparent, their next step would be to try and understand why this was the case, i.e. whether a change to the setup could lead to benefits, or whether "it's simply not there" (at the time of the interview, the second iteration was not completed).

Because the Western Australian utilities are owned by the state government, their decision determines whether P2P trading will become part of the state's electricity system. As such, regardless of the effectiveness of learning processes, varying levels of power may have an overriding effect on the future of a given solution, product, service or practice. A LSI may thus also have indirect impact through the elimination of a particular solution. In a similar vein, it should be noted that experiments like the RENeW Nexus trial may be very different from other types of initiatives. The purpose of an initiative is not necessarily to have a direct impact, but to test the potential of a particular solution.

The analysis points to the importance of overarching mechanisms to coordinate the distributed efforts of different actors. This is a central pillar of polycentric governance and without coordination between the various collective decision-making entities, the efficiency of systems may decrease rather than increase (Bauwens, 2017). This was demonstrated for example by the lack of comparable experiences to evaluate the results of the P2P trading trial and by the state land developer commenting that their own new knowledge did not make ensuing collective projects easier because their partners were missing the relevant experiences. Regarding the difficulty of convergent learning, it has been suggested that effective collective learning from collaborative actions constitutes a collective action problem in itself (Bodin, 2017).

5 Conclusion

This paper proposed a polycentric perspective on how LSIs relate to wider system change to better account for the distributed agency of actors typically involved in local collective sustainability efforts. Conceptualising LSIs as decision-making entities comprised of heterogeneous actors highlights the challenges and opportunities of collaborative undertakings and points to a messy, non-linear, and multi-stranded pathway to impact. It also shows that not scaling or replicating initiatives does not necessarily mean it has failed or cannot have any impact as, on the contrary, success depends on how well individuals and the collective learn.

One may speculate that the maximum scale (extent) of impact a LSI may have will be achieved when both divergent and convergent learning takes place. If actors are able to implement a collective learning strategy and share their (collective) knowledge, in addition to each individual actor integrating their new knowledge into their decision-making, then positive outcomes will be maximised. Convergent learning does not occur automatically but requires actors to take collective action in formulating and executing a shared strategy. This will likely be facilitated if clear shared understanding has been established at the start of the original project. In addition, top-down coordination of knowledge sharing would improve the efficiency of these processes. In this regard, an option could be for government funding agencies to require more rigorous reporting on shared understandings at the end of a project, in addition to acting as the coordinator of knowledge exchange activities amongst the projects in their portfolio.

The analysis suggests that in LSIs, even in those that are established collaboratively, the characteristics of the individual actors involved in terms of their goals and interest can be a more powerful determinant of impact than the observed collective results. The polycentric perspective enables us to see that multiple pathways exist because of the diversity of actors involved, but also that the agency of individual actors can be a critical determinant of the scale of impact.

This article explored the usefulness of a polycentric conceptualisation of notions of scaling. The application produced valuable insight in relation to the case studies and may offer a starting point for the development of a more complete framework. One area for further investigation are the implications for polycentric governance from a political science perspective. The effect of different types of LSIs also warrants further research, for example regarding differences between initiatives testing a particular solution, and those taking the opposite approach of wanting to address a specific problem. Related to this is also the question of participating actors. While the case studies involved a mix of public and private actors, many LSIs also involve citizens. Lastly, mapping how existing conceptualisations of intentional scaling complement the polycentric perspective would generate a fuller picture of the myriad of ways in which LSIs cumulatively support sustainability-oriented change.

Funding acknowledgements:

This research is funded by the CRC for Low Carbon Living Ltd supported by the Cooperative Research Centres program, an Australian Government initiative; and received funding from the Australian Renewable Energy Agency as part of its Research and Development Programme. Paula Hansen received funding from the Australian Housing and Urban Research Institute through their research capacity building in the form of a PhD top-up scholarship. The funding bodies had no involvement in study design; data collection, analysis and interpretation; nor in the writing of the report. Permission to publish this research article was sought and granted from all three funding bodies prior to submission where applicable.

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Appendix A: Co-authors' statements of contributions

I, Paula Hansen, contributed 80% to the publication entitled:

Agent-based modelling and socio-technical energy transitions: A systematic literature review

Specifically, I contributed to the following:

Conceptualisation; methodology; data collection and analysis; validation; writing (original draft); writing (review and editing); data visualisation.

Signature of Candidate: [redacted] **Date: 22/07/2020**

I, as a co-author, endorse that the level of contribution by the candidate indicated above is appropriate.

Co-author 1.

Gregory M. Morrison

Signature: [redacted] **Date:** 10/08/2020

Co-author 2.

Xin Liu [redacted]

Signature: **Date: 17/07/2020**

I, Paula Hansen, contributed 80% to the publication entitled:

Smart technology needs smarter management: Disentangling the dynamics of digitalism in the governance of shared solar energy in Australia

Specifically, I contributed to the following:

Conceptualisation; analytical approach; literature review; data collection and analysis; writing (original draft); writing (review and editing); figures and diagrams.

Signature of Candidate [redacted] **Date:** **21/07/2020**

I, as a co-author, endorse that the level of contribution by the candidate indicated above is appropriate.

Co-author 1.

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Date: 17/07/2020

I, Paula Hansen, contributed 35% to the publication entitled:

Performance of a shared solar and battery storage system in an Australian apartment building

Specifically, I contributed to the following:

Conceptualisation; literature review; writing (original draft); proof-reading.

Signature of Candidate: [redacted] **Date:** 22/07/2020

I, as a co-author, endorse that the level of contribution by the candidate indicated above is appropriate.

Co-author 1.

Moiz Masood Syed

Signature: [redacted] **Date:** 22/07/2020

Co-author 2.

Gregory M. Morrison

Signature: [redacted] **Date:** 10/08/2020

I, Paula Hansen, contributed 40% to the publication entitled:

Agent-based model of a blockchain enabled peer-to-peer energy trading trial in Perth, Australia

Specifically, I contributed to the following:

Conceptualisation; data management; preliminary data analysis, aggregation and formatting; literature review; writing: introduction, background, case study, discussion, conclusion; editing.

Signature of Candidate: [redacted] **Date:** July 13, 2020

I, as a co-author, endorse that the level of contribution by the candidate indicated above is appropriate.

Co-author 1.

Jacob G. Monroe

Signature: [redacted] **Date:** 02 JUL 2020

Co-author 2.

Matthew Sorell

Signature: [redacted] **Date:** July 2, 2020

Co-author 3.

Emily Zechman Berglund

Signature: [redacted] **Date:** July 2, 2020

I, Paula Hansen, contributed 90% to the publication entitled:

Beyond the local scale: Action and impact of sustainability initiatives from a polycentric perspective

Specifically, I contributed to the following:

Conceptualisation; analytical approach; literature review; data collection and analysis; writing (original draft); figures and diagrams.

Signature of Candidate: [redacted] **Date:** 10/08/2020

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Co-author 1.

Gregory M. Morrison

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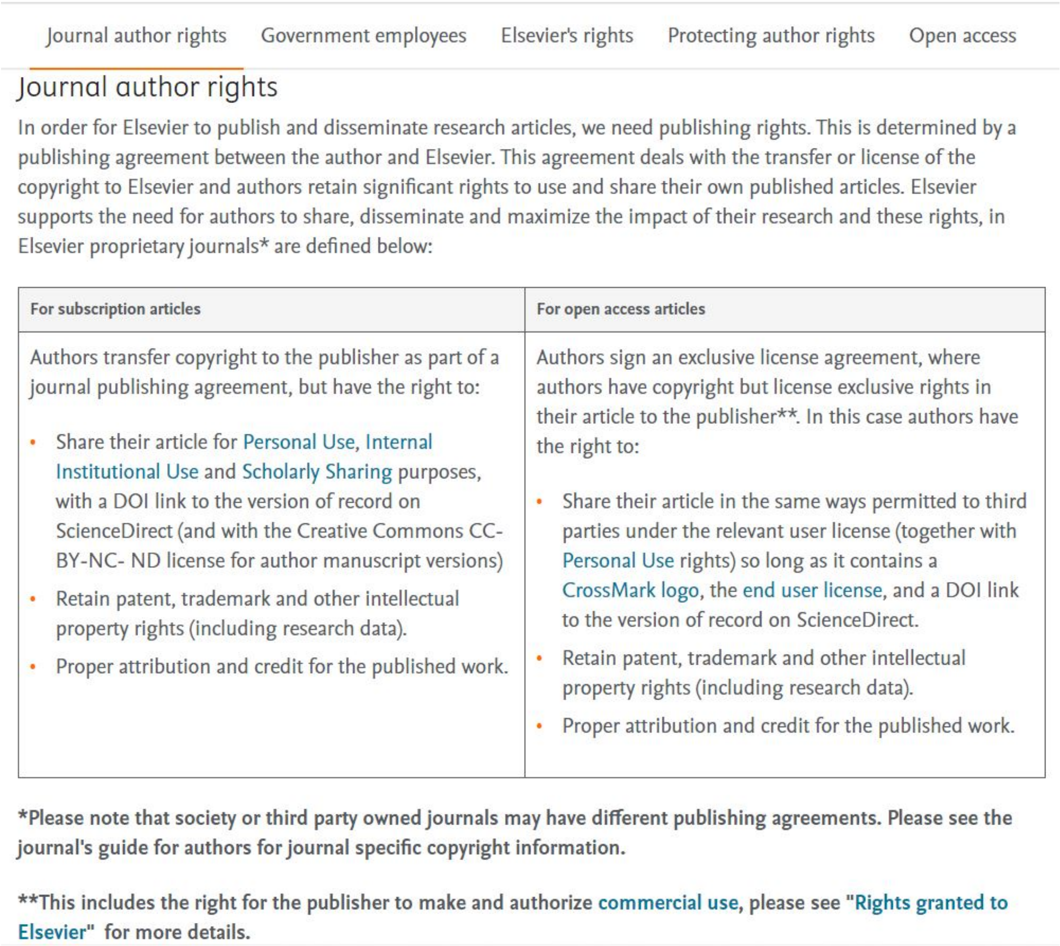

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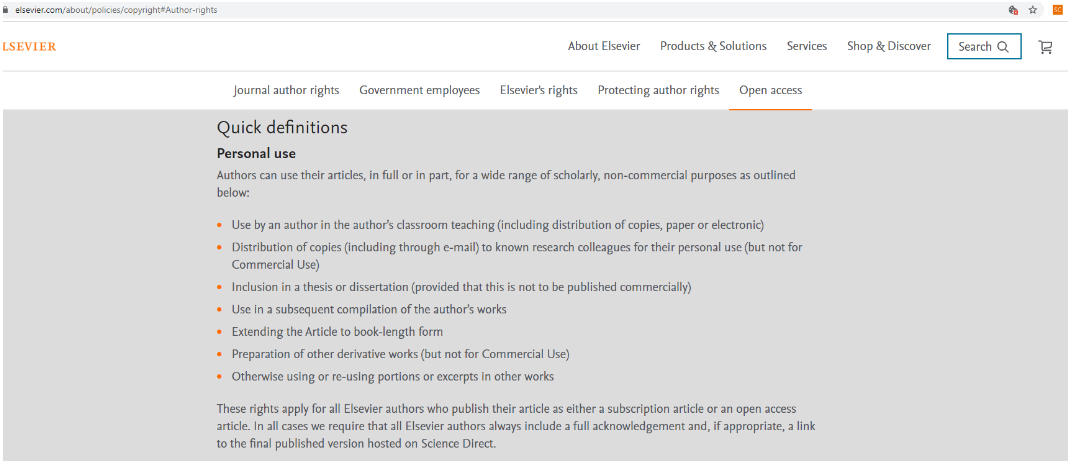

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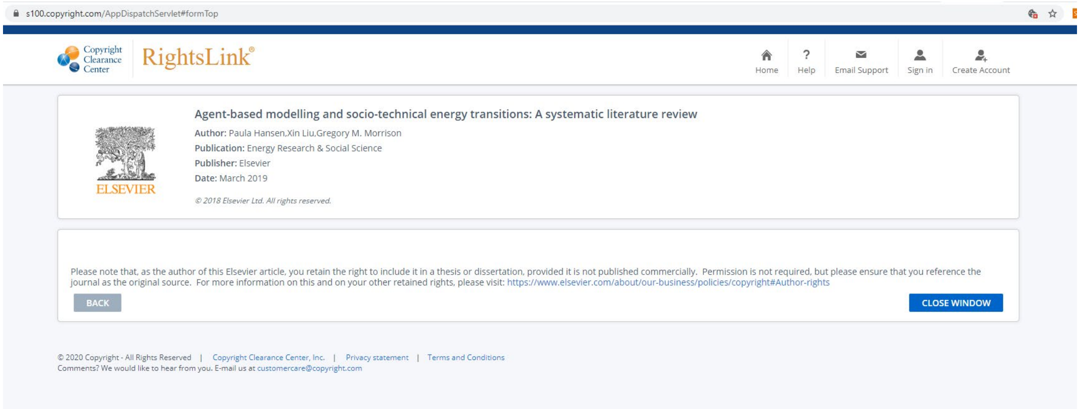

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Author: Paula Hansen,Xin Liu,Gregory M. Morrison
Publication: Energy Research & Social Science
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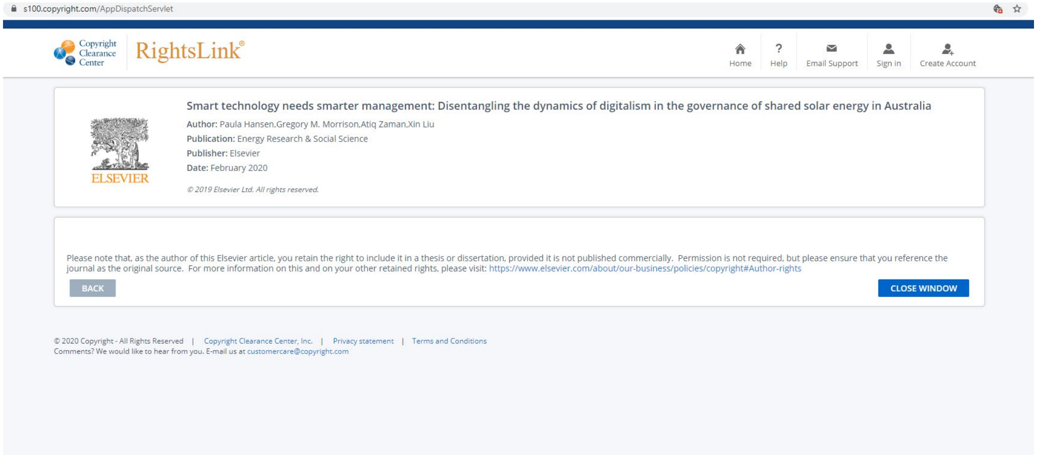
Published in Energy Research & Social Science, 60, 101322.



Smart technology needs smarter management: Disentangling the dynamics of digitalism in the governance of shared solar energy in Australia

Author: Paula Hansen,Gregory M. Morrison,Atiq Zaman,Xin Liu

Publication: Energy Research & Social Science

Publisher: Elsevier

Date: February 2020

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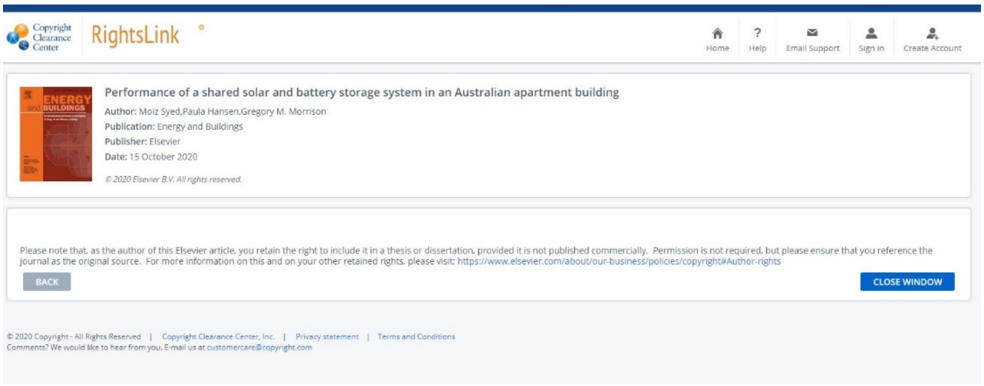
Publication III:

Syed, M. M., Hansen, P., & Morrison, G. M. (2020). Performance of a shared solar and battery storage system in an Australian apartment building.
Published in Energy and Buildings, 225, 110321.



Performance of a shared solar and battery storage system in an Australian apartment building

Author: Moiz Syed,Paula Hansen,Gregory M. Morrison
Publication: Energy and Buildings
Publisher: Elsevier
Date: 15 October 2020

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