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Navigating the Transition to Rooftop Solar in an Islanded Electricity System: a Western Australian Case Study

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This thesis is presented for the Degree of Doctor of Philosophy — Humanities
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Author’s Declaration

To the best of my knowledge and belief this thesis contains no material previously published by any other person except where due acknowledgement has been made.

This thesis contains no material which has been accepted for the award of any other degree or diploma in any university.

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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 HRE2017-0122.

Sam Wilkinson [redacted]

22………..June 2021

Statement of Contributions

I conceptualised and coordinated, as well as undertook data collection, analysis and writing for all publications contained within this thesis by compilation.

Wilkinson, S.; John, M.; Morrison, G. M. (2021). Rooftop PV and the Renewable Energy Transition; a Review of Driving Forces and Analytical Frameworks. *Sustainability*, 13, (10). doi:10.3390/su13105613

Wilkinson, S., Davidson, M., & Morrison, G. M. (2020). Historical transitions of Western Australia's electricity system, 1880-2016. *Environmental Innovation and Societal Transitions*, 34, 151-164. doi:10.1016/j.eist.2020.01.003

Wilkinson, S., & Morrison, G. M. (2018). Enablers of an electricity system transition. In Prasad Kaparaju, Robert J. Howlett, John Littlewood, Chandima Ekanyake, & Ljubo Vlacic (Eds.), *Proceedings of the 10th International Conference in Sustainability on Energy and Buildings (SEB'18)* (pp. pp. 464-477): Springer. doi:10.1007/978-3-030-04293-6_45

Wilkinson, S.; Maticka, M. J.; Liu, Y.; John, M. (2021). The duck curve in a drying pond: The impact of rooftop PV on the Western Australian electricity market transition. *Utilities Policy*, 71. doi: 10.1016/j.jup.2021.101232

Wilkinson, S., Hojčková, K., Eon, C., Morrison, G. M., & Sandén, B. (2020). Is peer-to-peer electricity trading empowering users? Evidence on motivations and roles in a prosumer business model trial in Australia. *Energy Research & Social Science*, 66. doi:10.1016/j.erss.2020.101500

Signed statements from all co-authors confirming my contributions to these papers are provided in Appendix 1.

Sam Wilkinson……………………………………

…22…June 2021

Abstract

This thesis by compilation is guided by the central research question: *Which transition factors should be focused on to ensure a stable electricity supply as the South West Interconnected System (SWIS) shifts from thermal coal and gas to a solar PV dominant system?* The SWIS is an islanded electricity system that has some of the highest global installation rates of rooftop PV (photovoltaic) in the world, which, together with its aging coal generation fleet provides insight into the transition issues to be navigated by other developed electricity systems as they confront similar challenges in coming years. The multi-level perspective (MLP) of transition theory is used to frame the research and understand the transition dynamics occurring within the SWIS and its supporting socio-technical regime.

Empirical research gaps related to islanded electricity systems that are being disproportionately impacted by the rapid uptake of rooftop PV are addressed. These gaps are filled through the study of the technical, economic and socio-political factors, together with regulatory and institutional aspects that affect the transition. Conceptual contributions are also made to MLP methodologies and in framing the role of prosumers during the energy transition. Mixed research methods have been applied, including separate historical analysis, semi-structured interviews, focus groups and surveys, together with parsimonious modelling.

In answer to the central question, the following factors should be focused on to ensure a stable electricity supply as the SWIS shifts from thermal coal and gas to a solar PV dominant system: 1) Understanding and addressing the historical lock-in mechanisms that influence the ability to transition; 2) Identifying and leveraging those landscape-level factors that can assist with reconfiguring regulations, institutions and socio-political factors within the socio-technical regime; 3) Identifying how and when to best engage prosumers with aspects of the transition; and 4) Implementing technical solutions with supportive markets to ensure system stability with consideration to the preceding three points. Each of these factors is explored in the papers that comprise this thesis by compilation.

The five research papers underpinning this thesis: 1) Explore the transition issues and theoretical frameworks associated with transitioning to high levels of rooftop PV; 2) Map historical transitions in the SWIS and associated lock-in mechanisms that influence the current transition; 3) Identify a plausible future generation profile and the transition issues to be managed to stabilise the SWIS under that profile; 4) Demonstrate the impacts that high rates of rooftop PV have on the wholesale energy market and identifies what changes are required to maintain a stable electricity supply; and finally 5) Present a theoretical framework of the role that electricity users can play during the energy transition through the world’s first trial of peer-to-peer (P2P) electricity trading across a live electricity market. The narrative linking these five papers is presented in this exegesis.

Acknowledgements

Thank you to Michael Reid and Tristy Fairfield for our early conversations back in 2015, which helped me identify worthy research topics. Your insights have proven themselves to be pertinent and current to this day. Thank you also for introducing me to many of the incredibly knowledgeable people across Western Australia’s electricity sector. I owe these anonymous experts so much for the information they shared so generously during the many hours of interviews. A very big thanks to you all.

To Michael Davidson, who took me on and provided supervision during the first part of this journey, thank you. Sharing your knowledge of electricity systems and markets was so valuable in turning my early journal readings into something that made sense in the real world. These conversations helped build a foundation upon which I could go forward.

Thank you to my Supervisor Greg Morrison for being available to act as a sounding board, for your rapid turn arounds on draft papers, for supporting me through the Curtin’s processes, accessing funding and bringing me into the RENewNexus project. Thankyou also for the many valuable introductions you enabled – such an important part of transitioning into a new professional field.

Thank you to Michele John, who agreed to provide additional supervision so late in my thesis. Your guidance and intellectual engagement in the project were first rate. Your structured approaches were very helpful and always added great value in tightening up my work and stepping the thesis and final papers towards submission.

Thank you also to Martin Maticka and Liu Yue for agreeing to work on our Duck Pond paper, and then adding such value and insights during its development. Our collaboration helped me get a better understanding of the SWIS and WEM - closing the gap between academic literature and real-world systems.

A big thanks to Kristina Hojčková, with whom I worked on the fifth paper in this thesis. Kristina, thank you for always pushing the paper, for constantly questioning and challenging our ideas, and for all the conversations around transition theories. Your insightful comments helped improve my other draft papers, for which I am very grateful.

And on a personal note, to my awesome partner Renee Webster and our two gorgeous boys, Fynn and Jesse. I am blessed to have you in my life and so thankful that you supported and encouraged me to take this break from the workforce and redirect my energy to understanding such a fascinating and rapidly evolving field. You made this journey so much fun, provide balance and all the while giving such love and support.

A special thanks also goes out to all my friends that provide the human connection so essential when working on a solo project for so many years. To the Blend cycling group, the Fremantle Mountain bike Collective / Downhill Valley Devils, the Vortex surf crew, and the community of White Gum Valley, for keeping me sane, fit, motivated and importantly, well connected within these communities of good humans, of good friends.

Dedication

To our children, to our now and our future.

Acknowledgement of Country

We acknowledge that Curtin University works across hundreds of traditional lands and custodial groups in Australia, and with First Nations peoples around the globe. We wish to pay our deepest respects to their ancestors and members of their communities, past, present, and to their emerging leaders. Our passion and commitment to work with all Australians and peoples from across the world, including our First Nations peoples, are at the core of the work we do, reflective of our institutions' values and commitment to our role as leaders in the Reconciliation space in Australia.

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Glossary

AEMO	Australian Energy Market Operator
AMI	Advanced meter infrastructure
BoM	Bureau of Meteorology
CAISO	California Independent System Operator
CSIRO	Commonwealth Scientific and Industrial Research Organisation
DR	Demand response (concept defined in Table 4.3)
ENA	Energy Networks Australia
ESB	Energy Security Board
IEA	International Energy Agency
ISO	Integrated System Operators
LRET	Large-scale renewable energy target
MLP	Multi-Level Perspective
MW	Megawatts
NEM	National Electricity Market
OLS	Ordinary least squares
P2P	Peer-to-peer (concept defined in Table 4.3)
PV	Photovoltaic
SLR	Structured literature review
S-SLR	Semi-systematic literature review
SWIS	South West Interconnected System
TEP	Techno-economic paradigm
TIS	Technological Innovation System
VPP	Virtual power plant (concept defined in Table 4.3)
VRE	Variable renewable energy
WA	Western Australia
WEM	Wholesale Electricity Market

Chapter 1 Introduction

This chapter presents the context for the research, the guiding questions and describes the theoretical framework within which the research is situated.

1.1 Research context

This thesis by compilation investigates factors that must be considered to ensure a stable electricity supply as Western Australia's (WA's) south west interconnected system (SWIS) transitions from utility coal fired production to an electricity system dominated by rooftop photovoltaic (PV) located within the distribution system. This transition is causing a myriad of challenges that affect the technical operation of the electric power system, the viability of market participants, and is redefining the roles of traditional electricity customers while regulatory settings attempt to stay relevant. A socio-technical research framework has been applied to help frame this research and, thereby, to interrogate the many factors required to guarantee the security of electricity supply during the transition. Section 1.1.2 outlines how this framework has been applied within the research. Background to the changes that are occurring in the SWIS and why this warrants further study is provided first, followed by specific research questions that have guided the research, which are presented in Section 1.2.

Electricity systems globally are changing. They are integrating ever higher rates of variable renewable energy (VRE) sources such as wind and solar. VREs have fundamentally different properties to traditional synchronous coal and gas fired generators around which existing electric power systems and their rules, regulations and financial underpinnings have been built (Ford and Hardy, 2020). In some places, such as Australia, electricity systems are already being forced to adapt their markets and control systems to stay operational in response to the rapid uptake of VRE sources. It is necessary for them to reconfigure to this change at a faster rate than market participants and regulators have done in recent decades (Bakke, 2016).

The need to integrate ever higher rates of VRE into the existing electrical power system has been driven at a global level through the challenge of climate change and to address national energy security concerns. When I began research on this thesis in early 2016, VRE sources required subsidies to compete with traditional thermal coal and gas generation. In the intervening years to 2020, the costs of VRE have fallen to the point that unsubsidised solar PV is supplying the cheapest electricity ever seen (IEA, 2020), particularly in regions such as Western Australia that have an abundance of wind and solar radiation. Along with the climate induced push to decarbonise, market forces have more recently become a twin driver that is accelerating the rate at which the SWIS is being impacted by VRE sources.

In this thesis I refer to VRE as encompassing renewable energy sources that are connected to the transmission and/or distribution system via an inverter. These are considered variable because their output varies along with their primary energy source (wind and sunlight) (Riesz and Milligan, 2015). Rooftop PV is a particular form of VRE in that it is connected within the distribution system. In the SWIS, where this research is applied, rooftop PV has been contributing over 50% of underlying system demand during some trading intervals in 2020 (AEMO, 2020e). Due to the system redefining characteristics of this form of VRE within the SWIS, its impacts and management are the primary focus of this thesis.

For the purposes of this thesis, the SWIS is considered to be “dominated” by rooftop PV when its historical technical rules, operating procedures and market settings can no longer ensure a stable electricity supply unless they are revised to specifically accommodate the integration of rooftop PV. Maintaining a stable electricity supply requires that the power system can continue to operate, regardless of the proportion of variable renewable energy, coal, gas or other energy sources, within security and reliability parameters as defined in Section 2 of the SWIS’s Technical Rules (Western Power, 2016)

1.1.1 The SWIS: an electricity system in transition

The increasing uptake of rooftop PV is changing the way electricity is generated, the function of distribution and transmission systems, and the operation of its supporting markets. The SWIS provides a unique insight into these challenges and serves as an excellent case study of global relevance. The SWIS has some of the highest levels of distributed rooftop solar PV system uptake anywhere in the world (AEMO and Energy Networks Australia, 2019; Shaw-Williams et al., 2019), which is challenging the technical and economic limits of existing synchronous generators and the functional operation of the supporting wholesale energy market (WEM). Due to its isolation from any other electricity system, the SWIS must balance instantaneous supply and demand without the support of a neighbouring electricity system, meaning there is greater urgency to find cost effective solutions before system security events manifest. For example, electricity from periods of excess generation cannot be exported for use in neighbouring systems and periods of shortfall cannot be met through imports, a luxury afforded to larger integrated electric power systems in Australia's National Electricity Market (NEM) (AEMO, 2020a; Energy Networks Australia and CSIRO, 2017; Finkel et al., 2017), the United States or Europe (Sioshansi, 2016a).

The high levels of rooftop PV in the SWIS is displacing output from and accelerating the retirement of some of the largest generators in this system (Johnston and McGowan, 2019; Synergy, 2017). As they retire, and their output is replaced by VREs, they remove the inherent properties of inertia, ramping, system strength and frequency regulation that they have historically supplied and around which the power system was designed to operate. The SWIS is spread across a dry and arid landscape that has negligible access to hydro or biomass energy sources. Most future renewable power sources connected to the SWIS will therefore be in the form of wind or solar energy. The research covered by this thesis explores the major socio-technical factors in the SWIS that require managing to cope with the rapid uptake of rooftop PV and loss of these traditional coal and gas fired generators over the coming decade.

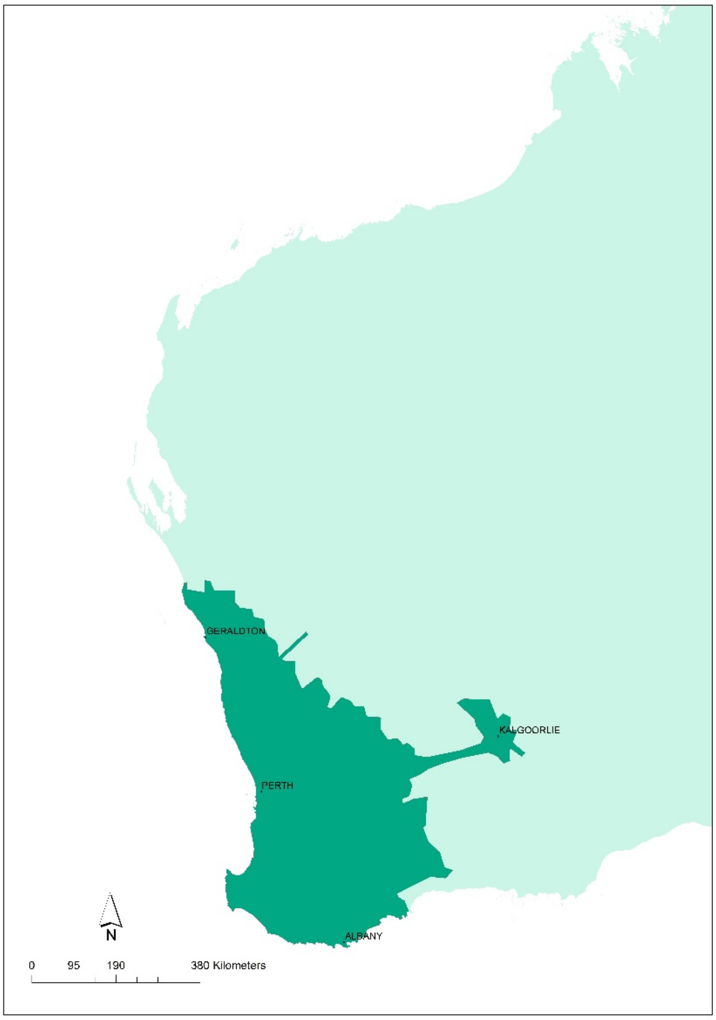

Figure 1.1: Location of the SWIS, shown as the dark area in southern WA. (Image supplied by Western Power) (from Research Paper III).

In 2015, when this research project was first conceived, WA regulators were beginning to recognise and plan for potential impacts from the increasing uptake of rooftop PV. Since 2015–16, installed rooftop PV has risen from approximately 500 to over 1300 megawatts (MW) and is projected to reach between 2600 and 3700 MW of rooftop PV installed in the SWIS by 2030 (AEMO, 2020b) (refer to Figure 1.2). This is in a system with a peak summer load of approximately 4000 MW and a typical spring/autumn load of 2000–3000 MW. This growth of rooftop PV, together with output from wind generators, reduced the demand from the existing coal fired generators by an average of 248 MW between 2015–16 and 2019–20 (AEMO, 2020e). AEMO (2020e) further noted that this reduction has been strongest during the middle of the day when rooftop PV output is highest, as shown in Figure 1.3.

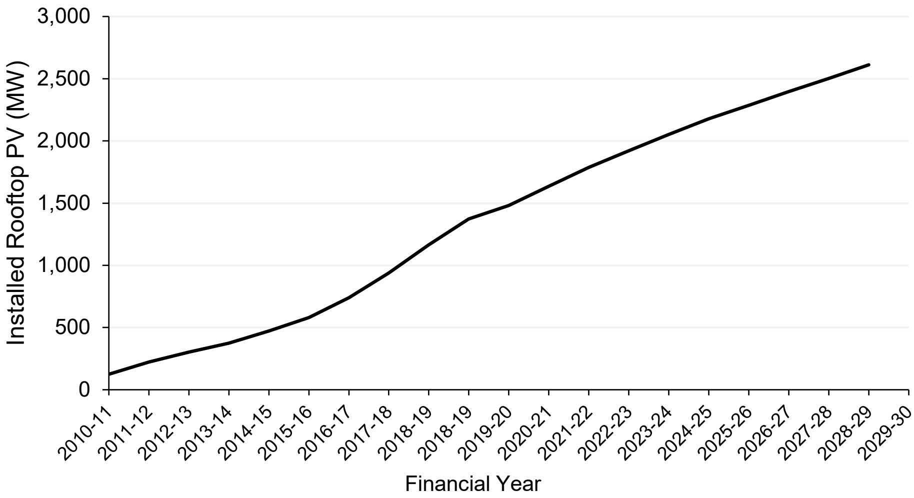

Figure 1.2: Installed rooftop PV capacity in the SWIS since 2010 and projected to 2030[1] (from Research Paper IV).

Figure 1.3 presents the average increase in solar PV and wind output over the years 2015–2020, but this underplays the significant impact that rooftop PV has been having on the operability of the SWIS during mid-day trading periods in 2020 and beyond. Impacts are accentuated during the middle of the day when solar output is highest and underlying network demand is lower. This can best be summarised by the ‘duck curve’, which is shown in Figure 1.4. The duck curve is the phenomenon first ascribed to the impact of solar PV on California’s electricity system (Sioshansi, 2016b). It is a graphical representation showing that as more solar PV is connected to the electricity system each year, the steepness of required evening ramp rates increases, reducing the minimum

[1] Graph produced using historical installed capacity data for the period 2010–11 to 2018–19 is sourced from Clean Energy Regulator and Australian PV Institute. Forecast installed capacity for the period 2019–20 to 2029–30 is sourced from AEMO 2020 WEM Electricity Statement of Opportunities report.

system load level (AEMO, 2020b) and increasing the amount of ancillary services, such as frequency regulation (Riesz and Macgill, 2013), needed to stabilise the power system. A failure to address these issues exposes the SWIS to security risks through the displacement of generators that currently supply inertia, frequency control, system strength and voltage control (AEMO, 2019b).

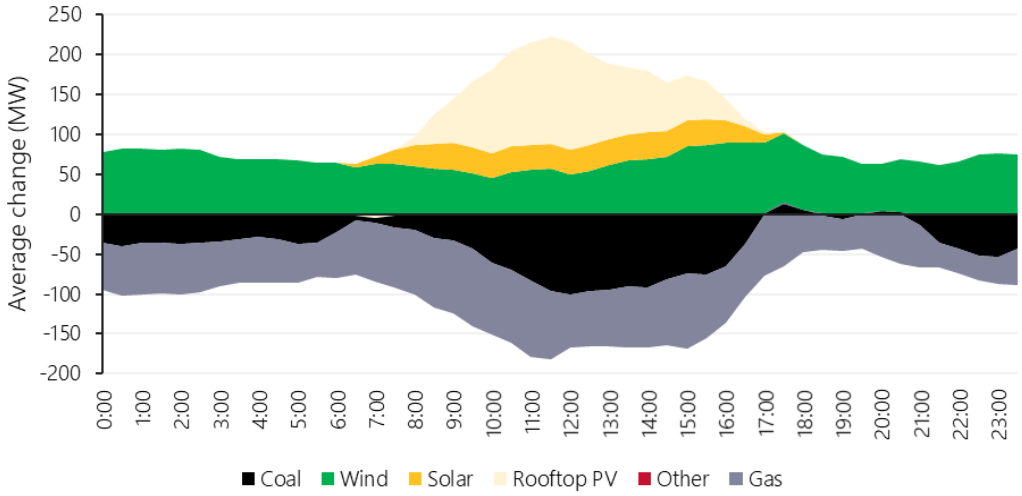

Figure 1.3: Average output (MW) of solar and wind generation showing how it has displaced gas and coal output from 2015–20 (Source AEMO (2020f)).

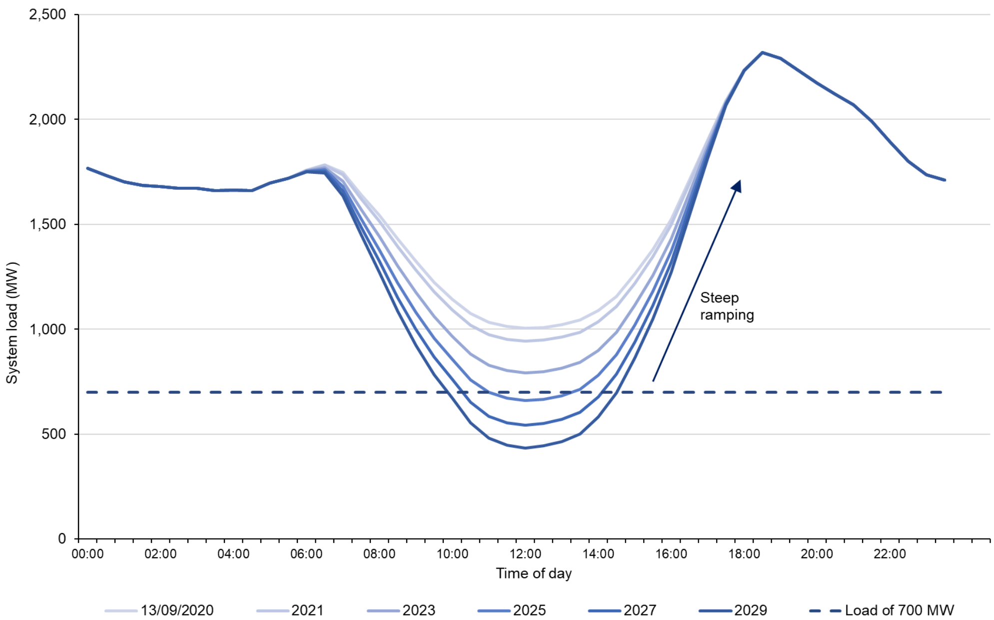

Figure 1.4: Growing of the duck belly as more rooftop PV is added to the SWIS[2] (from Research Paper IV).

[2] Note that all traces in the figure beyond 2020 are based on a projection.

The rapid and sustained uptake of rooftop PV in the SWIS is projected to push the system into higher operational security risk limits by 2022 (as indicated by a system load of 700 MW as annotated in Figure 1.4) (AEMO, 2019a), and is already creating market inefficiencies (AEMO, 2019b). The SWIS's isolation from other electricity systems accelerates the need to address ensuing problems sooner than similar systems globally. The integrated system operator (ISO) has advised that if not addressed, then managing the effects of falling minimum system load levels would result in the rolling curtailment of approximately 60,000 households in the SWIS during these periods by 2022, rising to 300,000 households by 2026 to avoid system blacks (AEMO, 2019b).

While the rate of uptake of rooftop PV in the SWIS has been faster than anticipated in the last few years, the transition unfolding in the SWIS is far from over. Issues identified in 2015 that require resolution to allow for a stable electricity supply under a high rooftop PV future have been progressed by regulators but remain fundamentally unresolved. As detailed in Research Paper IV, many of the technologies and control systems already exist and could be implemented to ensure a stable electricity supply under the changing generation profile. Much of the challenge rests in understanding what can be done to enable their implementation, including the creation of supporting markets.

Section 1.2 presents summary questions for the research. Before these questions are presented, the theoretical approach within which the research is situated is outlined.

1.1.2 Conceptualising electricity systems in transition

This research has been undertaken within the broader socio-technical research domain and framed by sustainability transitions literature. A central aim of transitions research is to explain and conceptualise how major changes can occur in the way societal functions are fulfilled (Köhler et al., 2019). It does so by identifying the interactions between the forces that aim to stabilise existing modes of operation and those that are driving radical changes (Köhler et al., 2019). In the context of this thesis, I focus on how electricity can continue to be reliably supplied as electricity systems shift away from carbon intensive coal and gas generators towards a system dominated by low carbon distributed rooftop PV.

There are a number of fundamental differences in how distributed rooftop PV dominated electricity systems would operate compared to one designed around large synchronous gas and coal generators (Ford and Hardy, 2020). These differences relate to the way that supporting electricity markets function under alternative energy generation models, the relationships of traditional energy customers with their suppliers, and energy distribution, transmission and control methods.

Within sustainability transitions literature, the multi-level perspective (MLP) is the dominant framework for interpreting energy transitions (Köhler et al., 2019) and was introduced to understanding the dynamics between the three analytical levels of niches (protected spaces and the genesis point of radical innovations), socio-technical regime (including institutions that lock-in practices) and the exogenous socio-technical landscape (including global and broad scale developments that influence both the regime and niches) (Geels, 2002; Geels and Schot, 2007; Smith et al., 2010). Within this framework, the actors and social groups in the MLP interact in accordance with entrenched norms of behaviour (Geels, 2004).

The regime structures and norms can lock-in existing practices but can also influence the way existing regimes respond to new innovations. In the electricity sector, the regime encompasses its full value chain including incumbent generators, product manufacturers, fuel supply chains, financial institutions, insurers, policy agencies, customers, media and government ministers. Interactions within the regime are governed by their internal norms of behaviour, which, in turn, can be affected by landscape level forces.

The way interactions occur within and between each of the three heuristic levels of the MLP influences transition pathways that can occur. In applying the MLP, Geels and Schot (2007) and Verbong and Geels (2010) presented five broad transition pathways to describe common ways in which transitions occur, which are distinguished based on the timing of interactions and the nature of those interactions. These pathways are transformation, reconfiguration, technological substitution, reproduction and de-alignment/re-alignment. By gaining an understanding of the current change pathways, it is possible to identify key mechanisms that should be targeted to effectively manage the transition towards a rooftop PV dominated system. The transition pathways are presented in Research Paper II and provide the theoretical basis for comparison with changes that have occurred since 1880 in the electricity system for the southwest of WA.

In the review undertaken by Sovacool et al. (2018) of energy transition research methodologies, they identify that social sciences need to improve their methodologies and policy relevance if they are to assist in the global transition towards decarbonised energy systems. Policy relevant research is required to assist in identifying impediments to transition, while also informing the discourse on how to move the transition forward.

In this thesis I interrogate the unfolding transition within the SWIS, with a focus on different critical socio-technical regime, landscape and niche factors to better understand the key change dynamics to be addressed as the SWIS transitions to incorporating very high rates of rooftop PV. This includes consideration of technical, economic, socio-political, and regulatory and institutionally related aspects of the regime. The following section details the research questions and how these fit within the MLP to answer the central research question.

1.2 Research questions and objectives

Within the above context, this thesis has been guided by the following research question:

> *Which transition factors should be focused on to ensure a stable electricity supply as the SWIS shifts from thermal coal and gas to a solar PV dominant system?*

Subsidiary research questions were posited to help answer the above question, which are presented in Table 1.1 along with their intended objective. This thesis by compilation addresses subsidiary questions in five separate papers. Research Paper I is a literature review and Research Paper II relies on secondary data from analysis of historical information, whereas papers III–V are based on original data. The structural logic that I have applied to these subsidiary questions, which links the five papers together, is summarised in the text below Table 1.1. The research methods used in each of the papers are summarised in Chapter 2 (Methods) followed by an abridged literature review based on Research Paper I. Combined results and discussion from Research Papers II–V are presented in Chapter 4. Chapter 5 (Conclusion) collates and integrates the findings from these papers to answer the central research question.

The five papers are summarised with research questions as follows:

<u>Research Paper I:</u> Wilkinson, S., & John, M. (2021). Rooftop PV driving Australia's renewable energy transition; a review of driving forces and analytical frameworks. Manuscript submitted to peer review journal, awaiting response.

Research Paper 1 is prepared as a semi-structured literature review (S-SLR) to analyse and consolidate key themes identified by existing literature reviews that address key enablers and blockers for the uptake of VRE generally and rooftop PV specifically. The focus extends to whole of system factors related to the energy transition. As this paper sets the scene for the thesis, it also explores different analytical frameworks for understanding energy transitions. Two questions were used to guide the S-SLR:

1. What factors enable and/or hinder the adoption of high levels of rooftop PV within advanced electricity systems?
2. Which theoretical frameworks are employed to analyse these transitions?

Table 1.1: Research sub-questions and objectives that supported the central research question, and associated publications.

Publications	Subsidiary questions	Objectives
I - Rooftop PV driving Australia's renewable energy transition; a review of driving forces and analytical frameworks	1. What factors enable and/or hinder the adoption of high levels of rooftop PV within advanced energy systems? 2. Which theoretical frameworks are employed to analyse these transitions?	To understand drivers for change towards VRE; frameworks for analysing the transition; and to identify associated research gaps.
II - Historical transitions of WA's electricity system, 1880–2016	3. Which transition pathways have characterised the development of the SWIS? 4. What lessons can we learn from historical transitions and how can we apply these lessons to current changes in the SWIS and other power systems globally?	To identify lessons from historical transitions in the SWIS for application to current dynamics.
III - Enablers of an Electricity System Transition	5. What are the main drivers for change in the generation profile over the past decade? 6. Do you agree with the CSIRO and Energy Network Australia's (ENA) projected generation profile for the SWIS in 2022 and 2027? 7. What are the main enablers required to allow a stable electricity supply under the agreed generation profile in 2022 and 2027? 8. What are the main blockers or impediments to realising a stable electricity supply under the agreed generation profile in 2022 and 2027?	To identify consensus on the likely electricity generation profile in 5–10 years, constraints that will result from this different profile, and to recommend a potential transition process to manage changes confronting the SWIS.
IV - The duck curve in a drying pond - the impact of rooftop PV on the Western Australian electricity market transition	9. Is there a statistically significant relationship showing that increasing rates of rooftop PV suppresses wholesale energy prices in the WEM? 10. If so, can the WEM continue to function without changes? 11. If not, what changes could be required to improve the WEM with a view to maintaining the ongoing stability of the SWIS?	To understand the implications of high rates of rooftop PV on the energy market and SWIS operability and to look at possible responses to address impacts.
V – Is P2P electricity trading empowering users? Evidence on motivations and roles in a prosumer business model trial in Australia	12. Who are the electricity users that are willing to experiment with P2P electricity trading and what motivates them? 13. What roles do electricity users play in shaping the P2P electricity trading-related innovation?	To understand the characteristics of prosumers who will be required to adopt new innovative business models that can enable effective integration of rooftop PV into the SWIS.

Research Paper II: Wilkinson, S., Davidson, M., & Morrison, G. M. (2020). Historical transitions of Western Australia's electricity system, 1880–2016. *Environmental Innovation and Societal Transitions*, 34, 151-164. doi:10.1016/j.eist.2020.01.003

To understand the present electricity system and the regime that supports it, it is important to first understand the historical factors that have helped shape the system (Arapostathis et al., 2013; Bennett, 2012; Bennett and Pearson, 2009). In this paper, I aimed to understand the factors that have both shaped the evolution of the SWIS and those that would influence the system's ability to adapt to rapid change in coming years. The MLP of transition theory was employed to look at the key actors and transition processes at societal, market, regulatory, political and technological levels. Two key research questions were posited to understand how history has shaped the ability of the SWIS to adapt to change:

1. Which transition pathways have characterized the development of the SWIS?
2. What lessons can we learn from the historical transitions and how can we apply them to current changes in the SWIS and other power systems globally?

Research Paper III: Wilkinson, S., & Morrison, G. M. (2018). Enablers of an electricity system transition. In: Prasad Kaparaju, Robert J. Howlett, John Littlewood, Chandima Ekanyake, & Ljubo Vlacic (eds.), *Proceedings of the 10th International Conference in Sustainability on Energy and Buildings (SEB'18)* (pp. pp. 464–477): Springer.

While Research Paper II explored the evolution of the SWIS since electricity was first introduced, Research Paper III narrowed the focus to the key drivers for change in the SWIS over the past decade and looked ahead to agree on a likely future generation profile and to understand the changes that can be expected in 5–10 years. The following four questions were asked to guide this component of the research:

1. What were the main drivers for change in the generation profile over the past decade?
2. Do you agree with the CSIRO and Energy Network Australia's (ENA) projected generation profile for the SWIS in 2022 and 2027? If not, why not?
3. What are the main enablers required to allow a stable electricity supply under the agreed generation profile in 2022 and 2027?
4. What are the main blockers or impediments to realising a stable electricity supply under the agreed generation profile in 2022 and 2027?

The focus was on understanding transitionary issues to be addressed in the SWIS rather than on the specific policy or technological end points that can be expected. This was an exploratory paper used to gain insights into drivers for change during a time when the electricity regime is at a definitive branching point. A point where it can either incorporate changes within its existing architecture or potentially be overtaken by evolving entrepreneur led business models aimed at coordinating rooftop PV interactions with the electricity system.

<u>Research Paper IV:</u> Wilkinson, S., Maticka, M. J., Yue, L., & John, M. (2021). The duck curve in a drying pond — the impact of rooftop PV on the Western Australian electricity transition. *Energy Utilities*, (undergoing second round of review).

Research Paper III identifies that the rapid uptake of rooftop PV will be a system defining niche technology. Building on this finding, Research Paper IV then explores the impact that rooftop PV will have on the electricity market and what changes will be required to allow for this technology to integrate into the SWIS and WEM. The following three questions guided this component of the research:

1. Is there a statistically significant relationship showing that increasing rates of rooftop PV suppress wholesale energy prices in the WEM?
2. If so (to question 1), can the WEM continue to function without changes?
3. If no (to question 1), what changes would be required to improve the WEM with a view to maintaining the ongoing stability of the SWIS?

Successful integration will be critical for maintaining system security and defining whether there is an orderly and controlled transition, or whether a more disruptive reconfiguration of the energy regime will occur. The paper is written in two parts. The first sought to confirm the effect of rooftop PV on energy spot prices and, by using an empirical analysis, demonstrate why distributed PV displaces utility PV generation. The quantitative modelling component of the paper was undertaken by one of the other co-authors on that paper. After modelling this relationship, the second part of the paper applies the findings of my semi-structured interviews to gain insights into the implications for the energy market and to identify what changes would be required to ensure the ongoing stability of the local power system as it integrates very high rates of rooftop PV.

<u>Research Paper V:</u> Wilkinson, S., Hojčková, K., Eon, C., Morrison, G. M., & Sandén, B. (2020). Is peer-to-peer electricity trading empowering users? Evidence on motivations and roles in a prosumer business model trial in Australia. *Energy Research & Social Science*, 66. doi:10.1016/j.erss.2020.101500

The focus for Research Paper V was guided by a finding from papers III and IV, which identified that new approaches that can allow for the integration of rooftop PV into both the operation of the power system and the supporting electricity markets will be key enablers to a successful transition. From this starting point, in Research Paper V, P2P[3] electricity trading models are conceptualised as a niche business model innovation within a broader transition to sustainable energy systems (Brown et al., 2019b; Cruz et al., 2018; Sopjani et al., 2019), and we place users as the focus of analysis. The aim of this study is to investigate the motivation and role users play in developing P2P electricity markets. This is done using evidence from the first real world example of P2P electricity trading via a blockchain platform in a trial located in Fremantle, WA. This research was guided by the following research questions and provided policy specific insights into the role that prosumers can have in enabling technology development and how they can best be leveraged for this purpose at different phases of an energy transition.

1. Who are the electricity users that are willing to experiment with P2P electricity trading and what motivates them?
2. What roles do electricity users play in shaping the P2P electricity trading related innovation?

1.3 Thesis organisation

The exegesis is presented as a logical progression, but not necessarily in the order in which the research was undertaken. This reflects the rapid change ongoing within the SWIS and is a challenge for industry and researchers alike. Chapter 2 details the methodological approach used to prepare this thesis. Chapter 3 provides a summary of the literature review that further contextualises this research. Chapter 4 presents and discusses the research papers' summary findings before Chapter 5 concludes with how these individual papers combine to answer the central research question, and presents recommendations for future research.

[3] P2P concept is defined in Table 4.3.

Chapter 2 Methods

This chapter provides an overview of the methods used across the research papers, which when taken together have been used to answer the central research question:

> *Which transition factors should be focused on to ensure a stable electricity supply as the SWIS shifts from thermal coal and gas to a solar PV dominant system?*

To understand change processes across the socio-technical domain, data collection processes were designed to capture insights associated with different aspects of the MLP. This included the use of surveys, semi-structured interviews and modelling to understand different drivers for change within and between the niche, regime and landscape MLP heuristics. Figure 2.1 describes the elements of the MLP that were tested in each of the papers and the broad method(s) used.

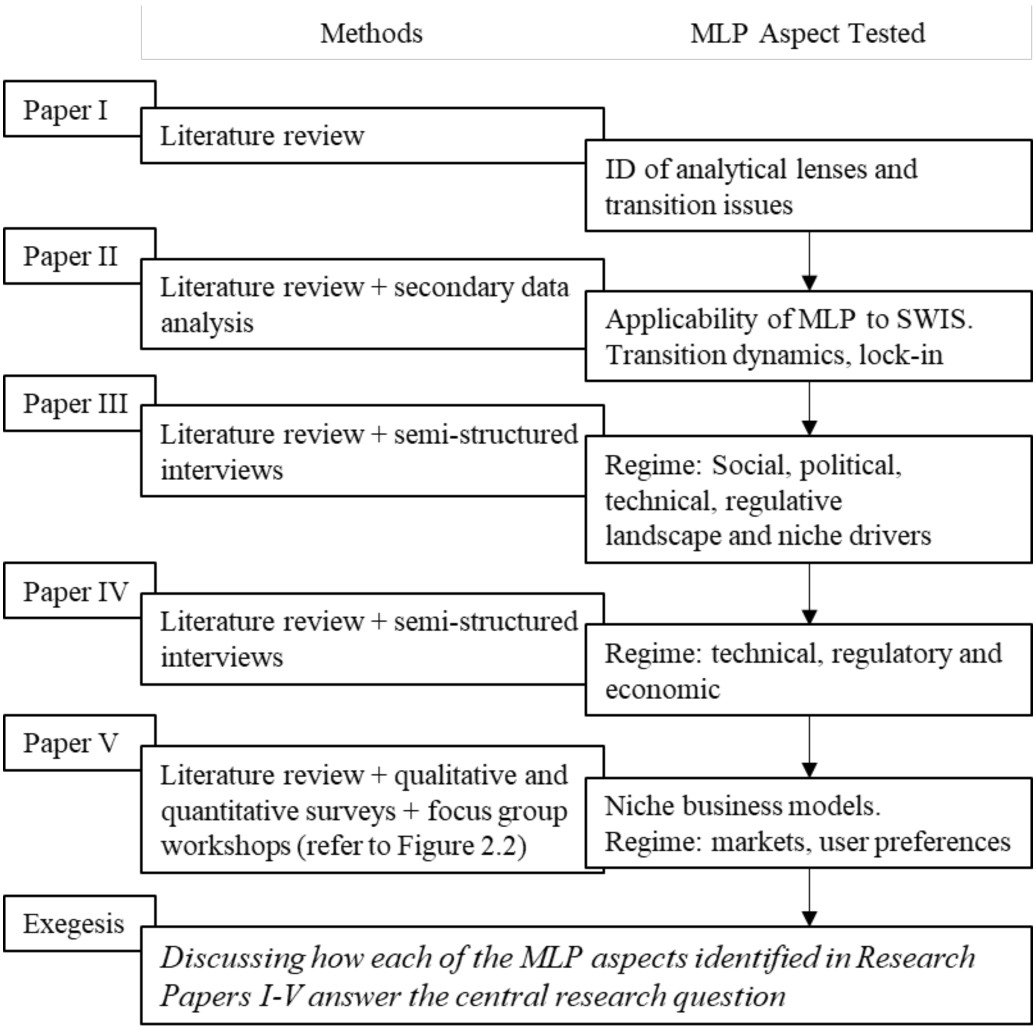

Figure 2.1: Methods used to answer the central research question and the aspect of the MLP tested in each paper.

An interpretivist approach was adopted, and a mixture of deductive and inductive inquiry was employed at different stages of the research. Research Paper II, in exploring the analysis of historical transitions in the SWIS, used deductive inquiry to test the suitability of the MLP for analysis of change processes in the SWIS. With the suitability of this framework for the analysis having been confirmed, the remaining papers adopted the MLP as the starting point for inductive inquiry (Massey, 2011) aimed at understanding the change dynamics and to build theories that could allow for policy relevant outcomes to be developed. For example, Research Paper V used inductive inquiry during initial data collection rounds to develop a novel analytical framework before refining and testing this framework through later rounds of data collection.

2.1 Research design and data collection

I applied a mixed methods research design (Baxter and Jack, 2008; Bazeley, 2018; Yin, 2011) selecting specific methods to interrogate subsidiary research questions as relevant to the Research Papers. The research methods used for addressing the central research question across the five Research Papers and exegesis are detailed separately in each of the following subsections, 2.1.1–2.1.6.

2.1.1 Literature review: transition issues and analytical lenses

The objective of the literature review (Research Paper I) was to gain an overview of the range of issues that both enable and hinder a transition from coal and gas based electricity systems to renewable energy based systems, and to identify an appropriate analytical framework for analysis of the energy transition.

A semi-systematic literature review (S-SLR) research methodology was adopted to meet this objective for Research Paper I, following the steps presented in Figure 2.2. The S-SLR approach was adopted due to its suitability for gaining an overview of the research subject matter and analytical frameworks (Snyder, 2019), a central aim of Research Paper I. S-SLRs are useful for making qualitative comparisons between papers that have each used different methodologies to answer related but different research questions (Snyder, 2019). Systematic literature reviews (SLRs) and meta-analyses, by contrast, are best employed to quantitatively analyse comparisons of research paper findings that have each used similar methodologies (Davis et al., 2014; Snyder, 2019). Sovacool et al. (2018) report that SLRs are best employed when there are relatively narrow research questions rather than multi-dimensional or policy related problems.

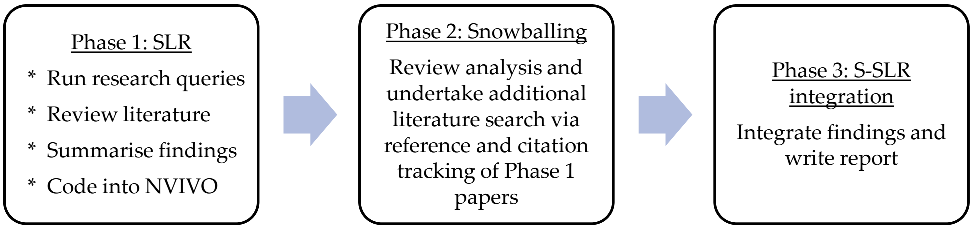

Figure 2.2: Semi-systematic literature review methodology (from Research Paper I).

A focus of the S-SLR was placed on reviewing prior SLRs and meta-analysis papers. This approach is used for rapid literature reviews and has been found to provide similar findings to the more comprehensive SLRs while requiring fewer researcher resources and less time (Abou-Setta et al., 2016; Lagisz et al., 2018; Nussbaumer-Streit et al., 2018); it is particularly useful for scoping issues at the commencement of a research process (Lagisz et al., 2018).

The search terms used in the S-SLR are presented in Table 2.1 and included a requirement for "systematic review" OR "systematic literature review" OR "literature" OR “review paper” OR "meta*analysis" to be located within the title or abstract of the research paper. Due to the rapidly evolving nature of the energy transition, papers were limited to those published since 2016 and available in English. Scopus was the primary database searched due to the breadth of results returned from searches within this domain and its improved functionality that allows bulk result downloads, which was not available for other databases under Curtin University licence arrangements. A comparative test for comprehensiveness was undertaken using the Web of Science database, which, when searched, only returned an additional four unique references, of which two were selected for further analysis. Papers that were focused on providing electricity to customers for the first time in developing countries were excluded to maintain the focus on understanding the transition of brownfield coal and gas based electricity systems towards VRE dominant systems.

Table 2.1: S-SLR search terms used and databases searched (from Research Paper I)

Database	Search Terms	Results*	Selected for further review
Scopus	"energy transition" AND *"electricity"* AND (*"system stability"* OR *"constraint*"* OR *integration* OR *"frequency regulation"* OR *"ancillary services"*) AND TITLE-ABS ((*"systematic review"* OR *"systematic literature review"* OR *"literature"* OR "review paper" OR *"meta*analysis"*) AND (*"solar"* OR *"PV"* OR *"distributed energy"* OR *photovoltaic* OR "duck-curve" OR "duck curve")) AND (EXCLUDE (SUBJAREA , *"MATE"*) OR EXCLUDE (SUBJAREA , *"MEDI"*) OR EXCLUDE (SUBJAREA , *"BIOC"*) OR EXCLUDE (SUBJAREA , *"AGRI"*) OR EXCLUDE (SUBJAREA , *"ARTS"*) OR EXCLUDE (SUBJAREA , *"CENG"*) OR EXCLUDE (SUBJAREA , *"CHEM"*) OR EXCLUDE (SUBJAREA , *"PHYS"*)) AND (LIMIT-TO (PUBYEAR , *2020*) OR LIMIT-TO (PUBYEAR , *2019*) OR LIMIT-TO (PUBYEAR , *2018*) OR LIMIT-TO (PUBYEAR , *2017*) OR LIMIT-TO (PUBYEAR , *2016*))	88	50
Scopus	"energy transition" AND "electricity" AND ("system stability" OR "constraint*" OR integration OR "frequency regulation" OR "ancillary services") AND TITLE-ABS (("systematic review" OR "systematic literature review" OR "literature" OR "meta*analysis") AND ("solar" OR "PV" OR "distributed energy" OR photovoltaic) AND (enable* OR allow OR assist OR facilitate OR encourage OR hinder OR discourage OR block* OR obstruct OR delay OR impede OR deter)) AND (LIMIT-TO (PUBYEAR,2021) OR LIMIT-TO (PUBYEAR,2020) OR LIMIT-TO (PUBYEAR,2019) OR LIMIT-TO (PUBYEAR,2018) OR LIMIT-TO (PUBYEAR,2017) OR LIMIT-TO (PUBYEAR,2016))	20 (6)	3
Scopus	"energy transition" AND "electricity" AND ("system stability" OR "constraint*" OR integration OR "frequency regulation" OR "ancillary services") AND TITLE-ABS (("systematic review" OR "systematic literature review" OR "literature" OR "meta*analysis") AND ("solar" OR "PV" OR "distributed energy" OR photovoltaic) AND (enable* OR allow OR assist OR facilitate OR encourage OR hinder OR discourage OR block* OR obstruct OR delay OR impede OR deter)) AND (LIMIT-TO (PUBYEAR,2021) OR LIMIT-TO (PUBYEAR,2020) OR LIMIT-TO (PUBYEAR,2019) OR LIMIT-TO (PUBYEAR,2018) OR LIMIT-TO (PUBYEAR,2017) OR LIMIT-TO (PUBYEAR,2016))	30 (8)	6
Web of Science	ALL=("energy transition" AND "electricity" AND ("system stability" OR "constraint*" OR integration OR "frequency regulation" OR "ancillary services")) AND AB=(("systematic review" OR "systematic literature review" OR "review paper" OR "literature" OR "meta*analysis") AND ("solar" OR "PV" OR "distributed energy" OR photovoltaic))	4(3)	2
	Papers excluded after detailed review		8
	Total brought forward for analysis		**53**

*Unique results not uncovered in preceding search are listed in brackets.

2.1.2 Case study: the SWIS as an electricity system in transition

A case study methodology centred on the SWIS was employed for each of the Research Papers II–V. The SWIS case study represents a globally advanced example of an electricity system that has very high contributions of electricity production from rooftop PV.

Case studies are useful for revealing a multitude of factors that interact in a real-world scenario (Thomas, 2003). While comparative case studies are often preferred over single-case case study research (Thomas, 2003), there are situations where the latter is beneficial, such as where a given case is exemplary in that it represents a unique instance not studied before and is, therefore, not available for direct comparison with other cases (Yin, 2011). The case chosen for Research Paper V on P2P users is an exemplary case, reflecting a real-life phenomenon that has not been studied in the past (Yin, 2011) — the world's first P2P electricity trading model across a public electricity grid. In our selection we made a paradigmatic choice (Flyvbjerg, 2006), one that served to develop a metaphor for the broader transition phenomenon being studied. This case study offers the first evidence of prosumer responses to the P2P market model, which, for the transition unfolding in the SWIS, is within the broader electricity system landscape, which has similar technologies, markets and control methodologies to those found elsewhere and, as such, the lessons learnt from this case are relevant to other advanced electricity systems globally.

2.1.3 Secondary data analysis: lessons from history that affect transition pathways in the SWIS

Within the qualitative research paradigm, raw data can consist of any information collected prior to analysis (Liamputtong and Ezzy, 2005). Data used for the analysis of the historical evolution of the SWIS was obtained from a review of archives (sound, video and written) at the State Library of Western Australia and the Universities of Western Australia, Curtin and Murdoch. This was undertaken to reveal material aligned to the conceptual framework of the MLP. Archives and secondary reports were selected based on their ability to illuminate the aspects of niche, regime, landscape and/or interactions between these heuristic levels associated with the electricity system between 1880 and 2016. Professional judgement was applied to identify the key change processes described in the archive material and to which heuristic level of the MLP they best related. Archives that did not illuminate these aspects were excluded from consideration.

Information relating to the above MLP conceptual framework were coded in five-year increments using the template presented in Table 2.2.

Table 2.2: SWIS historical analysis template.

Era	Key Landscape Characteristics and implications for system operability	Key Regime Characteristics and implications for system operability	Key Technology	Key Actors (state government, Local government, Consumers/public, Entrepreneurs)	Predominant Transition Pathway
Five-year increments starting in 1880					

2.1.4 Semi-structured interviews: identifying enablers and blockers to a transition

Semi-structured interviews, along with focus groups are among the most common form of data collection in energy social sciences (Sovacool et al., 2018). These methods enable inductive exploration and in-depth inquiry into different perspectives rather than testing specific hypotheses (Sovacool et al., 2018). The interviews were designed to capture a wide range of issues and the perspectives of those with expertise in the areas shown in Figure 2.3. Open ended questions, also referred to as 'loose questions', (Thomas, 2003) were used to support the inductive inquiry and thereby gain the broadest possible understanding of the range of issues affecting the energy transition. As shown in Figure 2.1, this methodology was designed to elicit information on the MLP's regime factors of social, political, technical and regulative and institutional, that could enable and/or hinder the energy transition. It also aimed to identify niche and landscape drivers for change. Interviews were used to support the research presented in Research Papers III and IV.

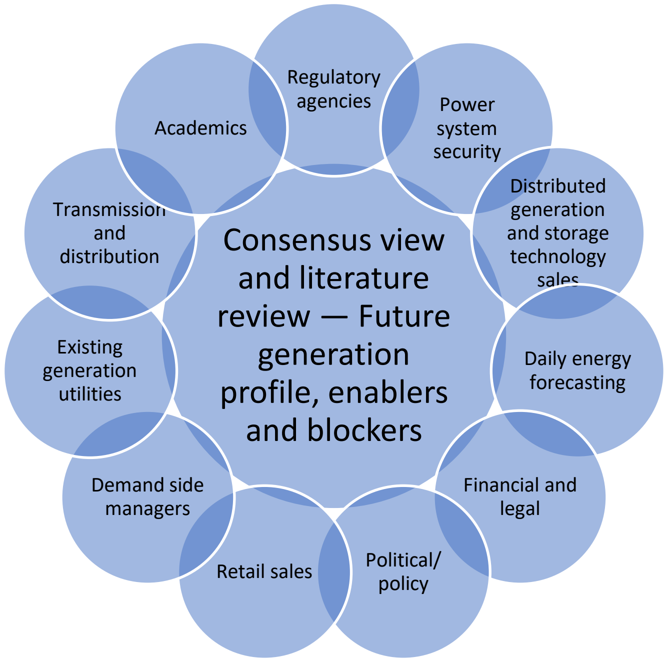

Figure 2.3: Semi-structured interview research design.

Two rounds of semi-structured interviews were conducted with industry experts. They were initially confined to experts within WA in Research Paper III, but were expanded to include international perspectives in Research Paper IV. Table 2.3 details the numbers of people interviewed and their areas of expertise. Participants were selected based on their detailed knowledge of electricity systems from a policy (including both rule makers and regulators), operational, legal or academic perspective. Many interviewees could have been equally categorised with expertise across many of these areas, however they were categorised based on their most recent role. The codes used in columns 1 and 2 of Table 2.3 are used identify participants during coding and to ascribe responses in the text of Research Paper III.

Ten people were interviewed during 2017 for Research Paper III, and an additional 17 in 2018-2019. All interviews (27) were considered relevant and were included in the analysis used for Research Paper IV. Each interview lasted between one and two hours and were held face-to-face with the exception of three, which were conducted over the phone. Twenty-four interviews were audio recorded after participants had signed appropriate university data-use ethics approvals agreements. Three participants were not comfortable with audio recordings and summary notes were made of these interviews.

Table 2.3: Area of expertise of participant in semi-structured interviews.

Paper III Participant	Paper IV Participant	Expertise
E1-E3	E1-E3	Current or past Chief Executive Officer of WA-based energy organisations
P1-P3	P1-P11	Senior management with current or recent policy and/or system operation related function in WA
C1-C2	C1-C4	Senior consultant to government and/or industry
A1	A1	Electricity sector academic
G1	G1-G3	Energy generator, wholesaler and/or retailer (one wind/solar generator, two generators with mixed portfolios that included wind, solar, gas and coal)
	In1-In4	International energy expert (two academic, one policy and one entrepreneur)
	L1	Legal

The first series of semi-structured interviews were undertaken during 2017 (and led to Research Paper III) and were guided by the questions detailed in Table 2.4.

Table 2.4: Questions used to guide the first round of semi-structured interviews including the future SWIS generation profile presented to interview participants for comment. Projections based on the CSIRO and ENA report on the Future Grid (Energy Networks Australia and CSIRO, 2017).

<table>
<tr><th>Question</th></tr>
<tr><td>1. Can you give me a brief overview of your recent involvement/role in the energy industry?</td></tr>
<tr><td>2. What do you see as the top three drivers for changes to the generation fleet in the SWIS over the past decade or so?
(Include consideration of market rules/codes/guidelines, contracting strategies, technological innovations, social and political changes, global energy prices/security, environmental concerns etc.)</td></tr>
<tr><td>3. I’m interested in your thoughts on what you believe the SWIS’s electricity generation profile will look like in five and ten years’ time (including both utility and behind the meter sources of power). The recent CSIRO and ENA report — “Electricity Network Transformation Roadmap” — indicates that they think the SWIS will then include:
<table>
<tr><th>By 2020</th><th>By 2025</th><th>By 2030</th></tr>
<tr><td>30% renewables</td><td>40% renewables</td><td>44% renewables</td></tr>
<tr><td>1 GW of rooftop solar</td><td>2.5 GW of rooftop solar</td><td>4 GW rooftop PV by 2030</td></tr>
<tr><td>Negligible domestic battery uptake</td><td><2 GW of on-site batteries</td><td>>2 GW of on-site batteries</td></tr>
<tr><td>Retirement of 240 MW of coal, 200MW of gas and 60 MW of liquid fuel generation[4].</td><td></td><td></td></tr>
</table>
CSIRO/ENA do not mention what the traditional generation profile will look like. Unless you disagree with the above, let’s assume they are as good a prediction as any, and consider what the remaining generation profile would consist of ...</td></tr>
<tr><td>4. What do you consider to be the top 3–5 enablers that would need addressing to allow your anticipated future electricity network to come about and for it to provide a stable and secure electricity supply? The focus of this response should be about resolving issues associated with the transition period rather than on the end state.
(Include consideration of market rules/codes/guidelines, contracting strategies, technological innovations, social and political changes, global energy prices/security, environmental concerns etc.)

<u>Stable and secure electricity supply</u> is taken to mean a continuation of the existing blanket reliability standards — if you think there’ll be a different standard in the future, then please explain.</td></tr>
<tr><td>5. What do you consider to be the top 3–5 blockers that would need to be removed to allow your anticipated future electricity network to come about and for it to provide a stable and secure electricity supply?
(Include consideration of market rules/codes/guidelines, contracting strategies, technological innovations, social and political changes, global energy prices/security, environmental concerns etc.)</td></tr>
</table>

The second round of semi-structured interviews were undertaken during 2019 and were guided by open-ended questions relating to managing a transition to higher rates of variable renewable energy sources within the SWIS. The questions used to guide those interviews are presented in Table 2.5.

[4] These retirements were announced by the WA Government mid-way through the series of interviews but had been expected by most participants already interviewed.

Table 2.5. Questions used to guide the second round of semi-structured interviews regarding a changing generation fleet, impacts and market solutions.

Question
1. Recent modelling is showing that distributed rooftop PV is reducing wholesale prices for all generators in the SWIS, with the most dramatic effects felt by utility solar facilities. There is also an increasing occurrence of zero or negative prices reflecting a near zero marginal cost of production from rooftop PV. What impacts do you think this will have on the generation fleet in the SWIS over the next five years?
2. What impacts do you think this change in generation fleet will have on the operability of the SWIS over the next five years?
3. Which of these impacts do you think can be addressed via the market and which via other mechanisms?
4. Can you explain how each of these mechanisms could work with particular focus on the market-based mechanisms?

2.1.5 Parsimonious modelling: implications of rooftop PV on the WEM

An ordinary least squares (OLS) modelling approach was applied to a parsimonious electricity market model in Research Paper IV to test for a statistically significant relationship that the increasing adoption of rooftop PV suppresses wholesale energy prices during the day in the WEM. This modelling analysis was undertaken by a co-author on Research Paper IV rather than by me. A description of this method is supplied here for completeness as the modelling was used to support the hypothesis in Research Paper IV.

Parsimonious modelling refers to the creation of a statistically relevant model with as few variables as possible to reflect a theoretical reality (Weron, 2014). Statistical models have been found to be effective in the investigation of the relationship between independent variables with a parsimonious structure used to describe a relationship (Weron, 2014). Such models perform poorly for predictive analysis, in particular the determination of price spikes (Weron, 2014), whereas OLS models are effective when the intent of the model is to understand the relative significance of different inputs (Fan and Hyndman, 2011). It is these relationships that were investigated in this paper and, as such, an OLS modelling approach was applied to a parsimonious electricity market model, which could allow more sophisticated models to be benchmarked (Aneiros et al., 2016; Weron, 2014) in future research if required.

Publicly available data from AEMO and Bureau of Meteorology (BoM) weather data was used as an input to determine the following approach and functional form. Following from the parsimonious model approach, data was sourced from daily Perth metropolitan readings for temperature, solar irradiance and rainfall (Bureau of Meteorology, 2018).

While all data was found to be clean with minimum missing data points, data still needed to be extracted and merged into a single dataset to be used for the analysis undertaken in this paper. Perth Metro Station 9225 was used as the reference point for analysis due to its central location in the Perth metropolitan region, but future work could consider using a model that includes all locational environmental data in the SWIS weighted to location of rooftop PV generation (AEMO, 2017). Correlation analysis was conducted on the data set and while minor correlation of data was found, relationships were as expected[5] or considered insignificant for the purposes of this research.

Wholesale energy data were available from when the WEM commenced in Western Australia (Government of Western Australia, 2004), with Balancing Data available from when that aspect of the market commenced in 1 July 2012 (Independent Market Operator, 2012).. This data was sourced from the AEMO website (AEMO, 2020d) and was found to be clean, although outlying data points in later years were identified during residual analysis.[6] Aggregated monthly PV capacity for the SWIS was sourced from AEMO (AEMO, 2020c) with the last data point (29th Feb 2020) used as the end point for analysis. Terminology is applied from the 'duck curve' naming convention using the noon demand point as a reference (Maticka, 2019).

2.1.6 Surveys and focus groups: engaging electricity users in the transition

Having identified, through Research Papers III and IV, that new business models would be required to facilitate the transition, Research Paper V investigated the motivations and characteristics of the first users of a P2P energy trading model. An inductive research approach was used for Research Paper V and, consequently, the paper's research design started with exploratory data collection that could guide the formation of suitable conceptual perspectives, which could then be used as a foundation for an analytical framework (Strauss and Corbin, 1998). Figure 2.4 summarises the research approach used for this paper.

Data was collected in three separate rounds using mixed methods to gain a broader perspective on the research object (Creswell and Plano Clark, 2007). Questions in the first survey and first focus group session (both were undertaken in August 2018 and are

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[5] Temperature and solar irradiation showed an expected relationship: long summer days drive high summer temperature conditions in WA.

[6] White tests were undertaken and a weighted regression using a bisquare method was explored to test the effect of outlining data points. This did not notably alter the statistical terms though, as expected, the predicted error range increased when using this method.

presented in Appendix B of Research Paper V) were exploratory and designed to suit a diverse range of research aims for the broader Renewable Energy and Water Nexus (RENeW Nexus)[7] project. Successive survey instruments (undertaken in October and November 2018, Appendices C and D of Research Paper V) and focus groups (held in August and October 2018) were designed to test emergent theories and the evolving analytical framework. The benefit of using different data collection methods is that it allows the triangulation of primary sources (Bazeley, 2018), especially given that secondary sources relating to users of P2P electricity trading models are still lacking (Creswell and Plano Clark, 2007). Figure 2.4 summarises both the focus of each data collection activity and the numbers of participants in each activity.

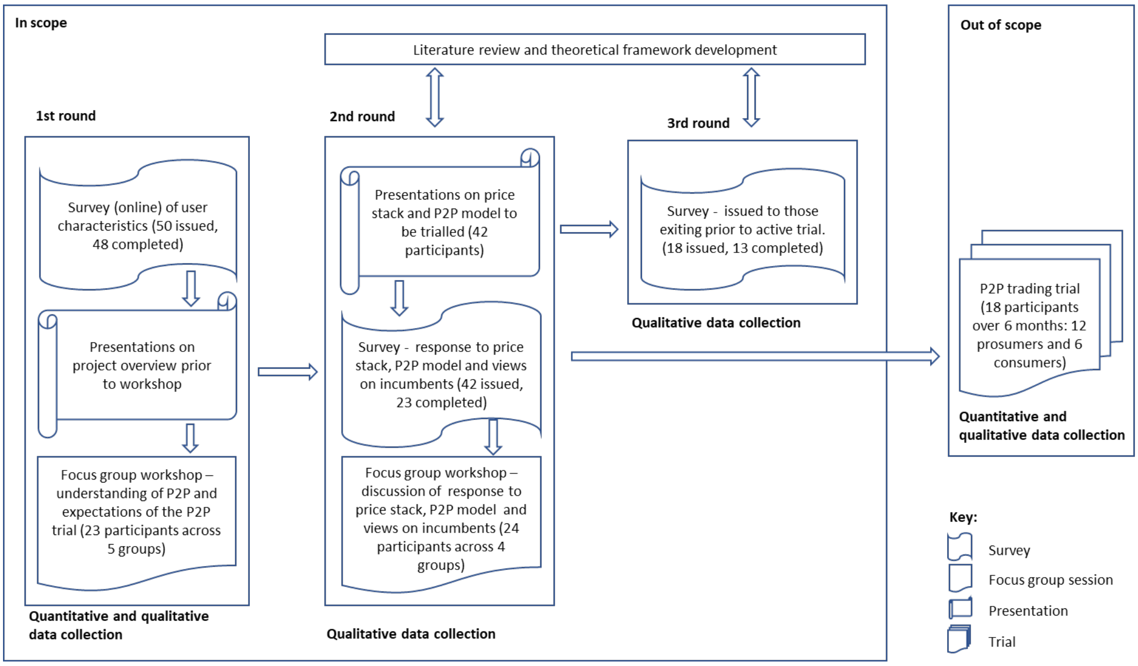

Figure 2.4: Stages of qualitative and quantitative data collection up to the commencement of the live P2P trial. This paper focuses on research findings stemming from the data collected in the *In scope* box. The P2P trading trial results are out of the scope of both Research Paper V and this exegesis (from Research Paper V).

Voluntary participants for the P2P trading trial in Fremantle were sought through announcements on social media and on the City Council's webpage, as well as through word of mouth between August and October 2018. A total of fifty participants were self-nominated for inclusion in the trial: forty prosumers and ten consumers. A participant represents a household rather than an individual. The choice of household-level analysis was influenced by the context of the electricity sector, where households remain the main unit of analysis. Prosumer participants are homeowners, which was necessary to allow

[7] RENeW Nexus project is the name given to the broader project within which the P2P energy user research sub-project for Research Paper V was undertaken. The aim of RENeW Nexus was to test both the technical and social aspects of P2P trading.

for the installation of updated metering infrastructure and was typically a precursor to having a solar PV system. As presented in Figure 2.4, the numbers of participants in the trial reduced to sixteen prosumers and eight consumers following a workshop presentation of the P2P trading tariff structures.

Research Paper V initially surveyed 50 householders who were interested in participating in the RENeW Nexus P2P trading trial, of which 48 responded via an online survey using Survey Monkey. This provided both quantitative and qualitative information with qualitative data related to householders' perceptions of incumbent utility companies. The survey instrument is presented as an attachment to Research Paper V.

Two sets of focus groups were held. The August 2018 workshop tested participants' understanding of P2P trading and their expectations of the trial. The objective of the second workshop, held in October 2018 together with the October survey, was to provide information around the P2P model tariff structure and to gather additional data on how the design aligned with expectations, how this influenced perception of incumbent utility companies and queries relating to participants' values and overarching expectations for the role of P2P in the energy transition. The third survey, in November 2018, was issued only to those that decided not to participate in the active P2P trading trial after tariff details had been revealed. The purpose of the last survey was to understand the motivations of people with an initial interest in P2P trading in choosing not to proceed.

There were five separate focus group tables at the first workshop and four at the second, each with one or two facilitators per table. Participants at each workshop were split into tables of four or five people. At the first workshop, each participant provided an independent written response to the two questions on post-it notes, each of which was then discussed on each table to identify common themes and areas for extrapolation. All written notes were later themed and coded within qualitative analysis software NVIVO 12, and at both workshops, audio recordings of the discussions at each table were transcribed verbatim into the same software. The same coding categories used for the written responses were then applied to each transcript. Coded themes from the written responses can be considered as more representative of individual thoughts whereas those mentioned during discussions can be considered as drawing out issues more important to the collective groups.

2.2 Data analysis

2.2.1 Qualitative analysis

2.2.1.1 Literature Analysis

Summary notes were made of the 53 papers identified by the systematic review for Research Paper I. These identified whether the papers were dedicated literature reviews or contained a literature review section and then whether the literature review was specific to rooftop PV adoption or covered VREs more broadly. The summaries also identified the broad analytical lens through which the paper considered the transition. Most papers were not explicit in their choice of analytical framework. However, if a paper was focused on modelling a technical issue, or based on a specific technology, then it was classified as adopting a technical lens. The classification lenses included technical, economic, socio-political, policy and institutional categories. Where a paper addressed more than one of these lenses, such as techno-economic or socio-technical papers, then their issues were assigned multiple times, to each of the relevant lenses. Coding was undertaken using NVIVO 12 social science software, which allowed issues to be grouped so that trends and research gaps could be more easily identified.

As the search terms used in the initial SLR process were focused on obtaining literature review papers, many papers that researched specific aspects of the energy transition were not identified. Additional references were then identified via a snowballing technique using reference and citation tracking. This was targeted at gaining deeper insights into the theoretical lenses for understanding the energy transition and for understanding the specific factors that could enable or hinder the uptake of rooftop PV in a transition to an electricity system dominated by renewables. Summaries of the issues identified through this process were then coded as for the SLR papers prior to writing Research Paper I.

A combination of SLR and snowballing using reference and citation tracking was similarly applied to each of Research Papers II–V.

2.2.1.2 Interviews and focus groups

All semi-structured interviews (Research Papers III and IV) and focus-group sessions (Research Paper V) were recorded and transcribed, with audio and transcripts loaded into NVIVO 12 social science software. Transcripts were coded for themes. As for Mayer et al. (2019), qualitative rather than quantitative assessment of importance was ascribed to issues raised by interviewees and focus group participants. While the number of times interviewees raised issues was used as a guide of importance, it was not the determining factor. This is because the additive nature of semi-structured interviews means that the interviewer is armed with additional information in later interviews and is able to interrogate new issues that may have equal or greater importance than issues mentioned in earlier interviews. This approach relies on the interviewer's understanding of the literature and systems, together with the totality of the information obtained in the interviews. This approach was also more relevant due to the duration over which the interviews were held. The first of the interviews was held in mid-2017, with the second in the second half of 2019. Given the speed of transition unfolding in the SWIS during this time, some of the technical and regulatory issues raised in the early interviews had either been resolved or overtaken by other emerging issues over the duration of the research process. The research design did not control for these transition processes but was able to observe them.

2.2.2 Quantitative analysis

2.2.2.1 Characteristics of first users in P2P markets

Relevant quantitative data from the first survey of P2P user characteristics was limited to participant income level, rooftop PV installation year and counts of electricity conservation practices. Simple averaging and percentage analyses were undertaken on this data. Coded themes from focus group workshops were taken from NVIVO summaries and used in Research Paper V to provide a quantitative count of the number of times a theme was mentioned.

2.2.2.2 Rooftop PV impacts on market clearing prices

The quantitative data analysis used in Research Paper IV to test the impacts of rooftop PV on mid-day energy balancing prices were undertaken by another co-author on that paper. The analysis approach used is presented below for completeness and has been taken from that paper.

The wholesale energy price value relationship proposed[8] was specified as follows for each trading interval:

$$B_0 = f(\,PV, T, S, R) + \epsilon_i \qquad \text{(equation 1)}$$

The estimate equation developed was as follows:

$$B_n = \beta_0 + \beta_p PV_d + \beta_p T_d + \beta_p S_d + \beta_p R_d + \beta_j SUmmer + \beta_f Winter + \beta_m Spring + \beta_{my} WeekendPH + \epsilon_n \qquad \text{(equation 2)}$$

Analysis has found that the following factors help explain the monthly relationship for the wholesale energy price and DPV in the SWIS where:

β_0: A constant term

n: Selection of the noon Trading Interval. A trading interval is the 30-minute period commencing on the hour or on the half hour. Noon trading interval is 12:00:00–12:30:00.

d: Calendar date. The calendar date was restricted from the WEM start to the last available rooftop PV installation data available at time of analysis, July 2012–February 2020.

B_n : Wholesale Energy Price (time of trading interval *n*) AUS$/MWh

PV_d: The amount of installed rooftop PV capacity in the SWIS area was based on postcodes and was sourced from AEMO (2020c). Monthly data was linearly smoothed to daily capacity in the SWIS at d. The sign was expected to be negative as the larger the amount of rooftop PV generation installed should reduce the wholesale energy price for all generation (MW).

T: Maximum temperature (Degree C), day. Perth Metro Station (9225) reading.

S: Daily aggregated global solar exposure (MJ/m*m). Used as a proxy for PV generation and reduces sessional variations. Perth Metro Station (9225) reading.

R: Daily rainfall at the Perth Metro Station. Used as a proxy cloud cover that affects rooftop PV generation in the Perth metropolitan area that contains the majority of rooftop PV in the SWIS. Perth Metro Station (9225) reading.

[8] While the daily rainfall amount (millimetres) was not a significant variable it was included in the model as the correlation of solar radiance may be considered as a suitable substitute, which would further complicate the seasonal relationship of environmental variables if excluded.

ϵ_n: Error term

The following dummy variables were used to account for seasonal and weekend/public holiday effects:

$Summer, Winter, Spring, with\ Weekend\ and\ public\ holidays\ combined\ to\ a\ single\ variable$: These variables have been selected to account for the seasonal and weekend/public holiday variation.[9] The lowest demand season of the autumn dummy variable was omitted in the OLS analysis as the base demand season and the expected result in all seasonal dummy variables was positive.

The resulting estimate equation was generated using the regression function in R for each point of the dataset. Modelling showed the relationship with the weather, with downward pressure on the wholesale energy price occurring on sunny days, which are periods of higher PV generation. As more rooftop PV is installed this effect will increase. On hot days, this corresponds with high demand and there is an upward pressure on the wholesale energy price. Rainfall was not found to be a significant variable but was retained for completeness of the model. This matches with expected results and follows basic economic principles as more of a product is produced the lower the price.

The overall fit of the equation could be considered low with an $\bar{R}^2$ value of 0.156 compared to the fit of System Load regression results of 0.666. This is unsurprising taking into consideration the variation of how prices are determined and the high amount of variability due to bidder and consumer behaviour, but what is more important is that the PV uptake relationship to the noon wholesale energy price is a significant contributor. The model did not show signs of omitted variable bias, which was a concern as electricity demand is an implied product (that is electricity is not directly usable).

2.3 Research constraints/limitations

As noted in Section 2.1.2, the ability to extrapolate findings from case case-study research that relies on a single-case case-study is less than those that rely on multiple-case case-studies (Sovacool et al., 2018). Triangulation of the research findings against

[9] Prior models considered for the paper included monthly dummy variables but found a seasonal approach provided more significant results and was aligned to how the market operator (AEMO) discusses variations in various formal publications, such as the WA Electricity Statement of Opportunities. Log-log models and lagged explanatory variables were explored as well as weighted linear regression to address relatively minor heteroscedasticity in the error terms. Another model used outage data as a predictor variable. As expected, system load did not show a significant relationship and the balancing price significance band was narrowed. As the approach taken in the analysis was to construct the simplest model to support the interviews, this model was not used. Investigated models produced minor improvements in $\bar{R}^2$ and the additional complexity to elucidate the results with the qualitative interviews outweighed the relatively minor improvements in the models.

reviewed literature has been used to ground and test for universal themes. Interviews were also held with industry experts in California and Germany to provide a broader context to research results. While each electricity system is relatively unique due to the variances in the generation profiles, market rules, institutional arrangements and societal expectations, the physics of each system is essentially the same. The aim of this research has therefore been to look at the broader transition dynamics that can be applied to electricity systems in transition. The findings of this research are most relevant to electricity systems in developed countries that are transitioning from legacy fossil fuel-based systems to those with very high levels of VRE generally and rooftop PV specifically.

Chapter 3 Literature review summary

This section presents the key outcomes from the Research Paper I — the literature review paper. This paper focused on answering the following questions:

1. What factors enable and/or hinder the adoption of high levels of rooftop PV within advanced energy systems?
2. Which theoretical frameworks are employed to analyse these transitions?

The first of these questions is answered in Section 3.1, with consideration of the theoretical frameworks discussed in Section 3.2.

3.1 Factors that enable and/or hinder the adoption of high levels of rooftop PV

The impacts of utility scale VRE facilities on energy systems and their associated markets is starting to be felt in many places globally and has been widely researched (Ford and Hardy, 2020; Gerres et al., 2019; Hirth, 2013; Woo and Zarnikau, 2019). However, some energy systems and associated markets, such as those in the southern and western parts of Australia are being disproportionately impacted by rooftop PV rather than utility scale projects and this phenomenon has been under studied (Maticka, 2019). The rapid uptake of renewable energy is redefining the way electricity systems and their associated markets can operate in Australia and, increasingly, around the world (Gerres et al., 2019; Hirth, 2013; Liebreich, 2017; Woo and Zarnikau, 2019).

Many of the effects of rooftop PV on electricity systems are like those from utility scale VRE, however some effects are particular to rooftop PV and warrant targeted research. Rooftop PV is located within the distribution network, rather than the transmission system, and produce energy by parties that have traditionally been electricity customers rather than energy wholesalers (Boscán and Poudineh, 2016; Castellini et al., 2020); and their output is neither visible to, nor controllable by integrated system operators (ISOs) (Gandhi et al., 2020; van Summeren et al., 2020). Further, any excess power produced by rooftop PV systems flows into the distribution network (Gandhi et al., 2020) and is not included in wholesale energy markets. Despite this, excess power is reducing prices that can be obtained on wholesale energy markets by other generators, causing the merit order effect (Abbott and Cohen, 2019; Boßmann and Staffell, 2015; Janko et al., 2016; Joachim et al., 2018; Sioshansi, 2016a; Woodhouse, 2016), which in turn is leading to the early retirement of many coal- and gas fuelled facilities (AEMO, 2019b). There is increasing evidence that rooftop PV can also disproportionately impact utility scale solar facilities due to the coincident mid-day output from these facilities (Maticka, 2019).

The economic drivers for installing rooftop PV systems are also different to those associated with other generation sources. Domestic and commercial premises installing rooftop PV systems peg their payback period against higher retail energy prices rather than the lower wholesale energy prices on which utility scale energy projects need to compete. The economic drivers for rooftop PV installation have, therefore, led to a rapid acceleration in the uptake of rooftop PV.

Very high rates of rooftop PV within electricity systems impose a series of challenges to the reliability of electricity systems. Table 3.1 presents a range of aspects, which have been grouped according to whether they are technical, economic, socio-political or regulatory and institutionally related. Managing the transition will require an understanding of each of these aspects and their interrelationships within the socio-technical regime. In categorising the themes identified within the literature review, I have defined the broad aspects as described within in Table 3.1, with the specific challenges that need addressing described in Table 3.2.. Research Paper I provides a complete version of Table 3.2 and includes a more complete explanation of each of the challenges.

Table 3.1: Categorisation of aspects that influence the uptake of VRE and rooftop PV based on specific elements of the socio-technical regime (from Research Paper I).

Aspect	Characteristic
Technical	The operational characteristics of the physical electricity production, conversion, distribution, transmission and control infrastructures and systems.
Economic	The financial drivers and investment impediments associated with the electricity system
Socio-political	Consideration of energy users and prosumers and their adoption of new technologies and business models. This includes ethical issues such as social justice and the political views and responses to issues.
Regulatory and Institutional	Primarily related to the regulative and normative behaviours and the ability of institutions to adapt to the changes related to niche innovations and business models. This extends to the regulatory and broad policy settings

Table 3.2: Aspects and associated challenges to be managed to transition to high rates of rooftop PV in electricity systems (from Research Paper I).

Aspect	Challenge
Technical	Mismatch between system load and ability of legacy generation to meet dynamic demand
	Lack of visibility and control of significant portions of generation
	Reduced system inertia as spinning generation exits the market
	More rapid frequency fluctuations from increased proportion of VRE
	Voltage regulation — insufficient synchronous generation to absorb the reactive power from rooftop PV, which is also causing a rise in real power in distribution systems.
	Loss of system strength[10]
	Ramp rate — more ramping required than of the historically flatter load profile
Economic	Merit order effect — near zero short run marginal cost renewables are reducing the clearing prices in energy markets, which is pricing base-load generators out of the market
	Missing money — VRE reduce the value and length of peak energy price periods that in turn reduce the financial viability of mid-merit and peaking plants
	Markets don't exist for new requirements such as battery services, virtual power plants (VPPs), P2P, demand response (DR), micro-grids, ramping fast-frequency response etc. (Note: refer to Table 4.3 for definitions of VPP, DR and P2P).
	Value of electricity — electricity as a societal right reduces ability to introduce tariffs at rates that could affect behavioural changes.
Socio-political	Changing societal roles/relationships with energy
	Energy justice — those without rooftop PV (who can least afford it) are left paying more for energy
	Public versus private — the role of governments
	Political balancing of divergent interests
	Conflicted interests — government ownership of legacy electricity assets that will be impacted during the transition
Regulatory and Institutional	Clarity of purpose — how best to address climate
	Ability for regulatory processes to keep up with changes
	Path-dependency — reduces ability of organisations to make rapid change
	Resources — accessing skilled staff to resolve emergent issues

3.2 Analysis frameworks for understanding transitions

Understanding the energy transition requires the coordination of multiple factors beyond technical and economic aspects (Gottschamer and Zhang, 2016; Sovacool et al., 2020). This can be aided by using theoretical frameworks, which are heuristic approaches that assist researchers to order and make sense of large amounts of information (Sovacool and Hess, 2017). The adoption of frameworks for ordering information is critical in understanding and managing the energy transition, since any changes to its production

[10] System strength is the available fault current at a specified location in the power system, where higher fault current indicates higher system strength AEMO, 2018. System strength requirements methodology: System strength requirements & fault level shortfalls. It represents the ability of the power system to both remain stable under normal conditions and return to steady state conditions following a disturbance AEMO, 2019b. Integrating Utility-scale Renewables and Distributed Energy Resources in the SWIS, in: Australian Energy Market Operator (Ed.).

and delivery will influence the institutions, political spheres, and normative behaviours of those using it.

In the study by Sovacool and Hess (2017), they considered 96 different theories and conceptual approaches that could be used to answer the following question: *What theories or concepts are most useful for the goal of explaining the adoption, use, acceptance, diffusion or rejection of new technology?* The adoption and integration of rooftop PV into electricity systems can be considered a new technology in this context. Sovacool and Hess (2017) found that the major theories integrate multiple theoretical perspectives to make sense of the differing factors that influence the diffusion or rejection of innovations. Pre-eminent frameworks for understanding transitions include the techno-economic paradigm (TEP) and socio-technical transitions theory. MLP is the dominant framework used to assess transitions within socio-technical transitions literature (Köhler et al., 2019). The TEP and MLP are further described below, in Section 3.2.1 and 3.2.2 respectively.

3.2.1 Techno-economic context

The techno-economic paradigm (TEP) (Freeman and Perez, 1988) focuses on the stable structures that result from institutions, technologies and beliefs (Geels, 2010). The TEP assumes that technical and economic forces act on institutions and the social framework, which then react to accommodate the initiative. This framing reflects the financial and technological focus of traditional corporate decision making such as with electricity utilities. While undoubtedly important in many situations, the TEP has been criticised for underplaying change dynamics that occur in response to social dynamics. It has also been used as a long-range theory for explaining transitions occurring over the course of 40–60 years (Schot and Kanger, 2018). Sustainability transitions, by contrast, are driven at the landscape level with strong social underpinnings, and promoting changes within the technological production processes, societal behaviours and supporting institutions, which is more aligned with the MLP construct.

The TEP is based on Schumpeter's principles of creative destruction where new technologies led by entrepreneurs enter the market (Mathews, 2013) and provide both economic change and change to market power. Shifts that occur under a TEP require the institutions, rules and social norms that have locked in existing technologies to make way for clusters of new technologies to diffuse in a manner that ultimately shifts the economy (Perez, 2009).

The concept of clusters of technologies that are required to support each other was originally introduced by Freeman (Freeman and Perez, 1988). The waves of transition under the TEP occur over several decades and were characterised as relating to five separate waves. These waves started with the industrial revolution (starting 1771), the shift to steam and railways (starting 1829), the age of steel and electricity (starting 1875), and the age of the automobile, oil and mass production (starting 1908) and the age of information technology and telecommunications (starting 1971) (Perez, 2009). While Schumpeter saw institutions, technologies and social organisations as external to the economy, Perez (2009) viewed these as internal to the waves of transitions that occur under TEPs.

The successful diffusion of an innovation is fundamentally underpinned by complementary technological innovations that are cost competitive and have a market that is willing to adopt and diffuse them, ultimately resulting in modifications to the socio-institutional structures (Perez, 2009).

The TEP has been criticised for undervaluing the roles played by civil society, users, scientists, engineers, media and other social groups, and for placing most attention on financial institutions and governments in creating the space for turning points to occur (Schot and Kanger, 2018). An assumption of techno-economic transitions is that economic decisions are fundamentally rational (Geels et al., 2016), which contrasts with socio-technical transitions which make allowances for multifaceted decision-making processes that can include social, political and other factors, and are not necessarily rational (Li et al., 2015). The need to consider these other factors is highlighted by issues identified in Table 3.1 and Table 3.2. Authors such as Freitas Gomes et al. (2020); Gosens et al. (2020); Kang et al. (2020) and Wolsink (2019) identified the importance of users, scientists and civil society in the transition to VRE. The TEP has also been criticised for a lack of emphasis on political contexts and broad landscape factors (such as wars and climate change), over emphasis on the role of the state (assuming that transitions emerge at the level of the state) and the lack of provision of detail on what happens to the existing paradigm of technologies (Schot and Kanger, 2018). Each of these factors have been identified through Research Paper I as being important in VRE transition.

3.2.2 Socio-technical context

The MLP is derived from evolutionary economics, institutional theory and the sociology of innovation (Geels et al., 2016; Köhler et al., 2019). It has often assessed the feasibility of low-carbon transition pathways through analysis of niche, regime and landscape developments that have occurred in the recent past, which can then be used to identify drivers and barriers in the present and, therefore, to inform assessments of the future (Geels et al., 2016).

The strength of the MLP is its recognition of multi-dimensionality and multi-actors involved in transitions over time and geographically (Köhler et al., 2019). This is particularly relevant for sustainability transitions, which require fundamental shifts in socio-technical systems rather than just technological fixes (Köhler et al., 2019). The MLP has received criticism for how it addresses geographical space (Chandrashekeran, 2016; Coenen et al., 2012; Hansen and Coenen, 2015; Wells and Lin, 2015), the boundaries between niche, regime and landscape (Zolfagharian et al., 2019) and for the ambiguous methodology that is weighted towards bottom-up change models (Geels, 2011; Sovacool and Hess, 2017)

Sovacool and Geels (2016) have argued that while understanding history is useful it is not necessarily predictive of either the future or the pace at which future transitions may unfold. This has relevance to the energy transition, which is being driven by energy costs and environmental pressures associated with climate change, and has been led by rooftop PV in the SWIS at a scale that is much smaller and quicker to implement than historical large utility scale energy projects.

The scope of the MLP has expanded in recent years to include the importance of political drivers in socio-technical transitions, including through the works of Rosenbloom et al. (2018), Kern and Markard (2016), Geels et al. (2014); Hess (2016); Meadowcroft (2009, 2011), Kuzemko et al. (2016), and Lawhon and Murphy (2011). Political forces are evident at key branching points, which can affect the shape of a transition either through the imposition or removal of inertia (Foxon et al., 2013; Kivimaa and Kern, 2016; Rosenbloom, 2017; Rosenbloom et al., 2018).

As with the TEP, the MLP is focused on multi-decadal change processes. Rooftop PV was initially introduced in the late 1970s (Booth and Coulter, 1980) and, as such, its study using TEP and MLP frameworks can be considered appropriate. The system building role of users in breaking down the existing regime during the energy transition was proposed by Schot et al. (2016). However, their research is focused on multi-decadal transition dynamics and does not pay sufficient attention to the micro dynamics and agency between users associated with innovations at a local scale (see, for example, Research Paper V).

The diffusion of innovations literature, first developed by Rogers (1958), provides a framework for considering the roles that users can play, such as the uptake of rooftop PV, at shorter timeframes than occurred within the transition phase. Under Rogers

(2003) framework, adopters of new innovations are characterised along a bell curve based on their level of innovativeness, from the most innovative and earliest adopters of a technology to the slowest to adopt. Those in the middle of the bell curve represent the early-majority and late-majority of users. This has similarities with Geels (2004) cognitive, normative and regulative rules, which represent users' patterns of behaviour that can crystallise a regime's architecture. By understanding the roles of users within a regime architecture, change agents may be better equipped to affect the directionality of energy transitions. Authors such as Kivimaa et al. (2019b) and Kivimaa et al. (2019a) also considered the roles that specific groups of users, who they term intermediaries, have in shaping or influencing transitions.

Transition thinking has recently been refined by integrating business model innovation ideas (Bolton and Hannon, 2016; Brown et al., 2019c). Existing transition studies have focused on the roles of firms, entrepreneurs, managers and advocacy organisations when implementing new business models in the context of a sector in transition (Bidmon and Knab, 2018; Bolton and Hannon, 2016; Boons and Lüdeke-Freund, 2013; Brown et al., 2019a; Brown et al., 2019c). In transition literature, business models are traditionally regarded as integral to firms for delivering customer value, with customers seen as passive business model adopters. If the dominant business model logic in the electricity sector is to be broken and/or breaks, more knowledge is needed concerning the role users can play in business model innovation as they evolve from being mere consumers to key actors in the electricity market.

Alternative perspectives can be used to study socio-technical transitions, including technological innovation systems (TIS), strategic niche management and transition management. These, however, are less well suited to long running historical analyses. As noted by Köhler et al. (2019), TIS also tends to focus on the emergence of niche innovations rather than the stability of existing systems, which is a necessary feature in the development of electricity systems. As TIS is focused on the development and emergence of niche innovations, it typically considers national and international influences as external to a study's boundary (Bergek et al., 2015). While this thesis looks specifically at the SWIS, which is a local case study, the adoption of rooftop PV is intrinsically linked to PV pricing and climate change policy settings that occur at a national and global level.

The MLP has been identified and carried forward as the central analytical framework in this thesis due to its suitability for ordering the breadth of issues that are relevant to the energy transition (Table 3.2). It has been augmented, as necessary, through integration with diffusion of innovations frameworks where a more granular approach is required to consider the role of users in the adoption of rooftop PV is considered (Research Paper V). Research Paper IV focusses on the technological and market related changes that are required to manage the energy transition. Whilst these are aspects within the socio-technical regime of the MLP, the focus given to them in Research Paper IV reflects pre-eminence of TEP thinking within business decision makers – who are central to the energy transition.

Chapter 4 Results and discussion

This section presents key findings from Research Papers II to V[11] to answer each of the sub-questions, which collectively answer the overarching research question:

> *Which transition factors should be focused on to ensure a stable electricity supply as the SWIS shifts from thermal coal and gas to a solar PV dominant system?*

Due to the integration of electricity within every aspect of society, there are a great many factors to consider in transitioning the electricity system from one dominant technology to another. It is therefore, beyond the scope of this thesis to capture all aspects. I have, however, sought to understand the shape that the transition is taking, the implications for this transition on the electricity system, electricity market and the role that prosumers can take in assisting with the transition. This was done by exploring a subset of factors across the MLP heuristics. There are a great many more technical, system operability, policy implementation, legal, market, social justice and political aspects within the MLP that could equally have been explored. The major aspects that have been described in the literature, together with the views obtained during interviews have guided this thesis.

The research papers can be found following this exegesis. Section 4.1 identifies the historical factors in the evolution of the SWIS that influence the ability to adapt to the current transitionary forces. Section 4.2 identifies the consensus views on the future generation profile for the SWIS and the socio-political factors that must first be addressed to manage the transition. Section 4.3 presents the techno-economic findings on the market impacts of rooftop PV, and the drivers and possible solutions to high rates of rooftop PV in the SWIS. Section 4.4 identifies the roles that electricity users can play in adopting innovative business models that may be required to enable higher rates of rooftop PV in electricity systems.

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[11] Noting that findings from the literature review paper (Research Paper I) has been presented in Section 3.

4.1 Evolution of the SWIS that shapes the future direction

Sub-section 4.1 discusses the key findings from Research Paper II as an answer to the following research questions and Figure 4.1 shows the MLP aspects considered within this paper:

1. Which transition pathways have characterised the development of the SWIS?
2. What lessons can we learn from historical transitions and how can we apply these to current changes in the SWIS and other power systems globally?

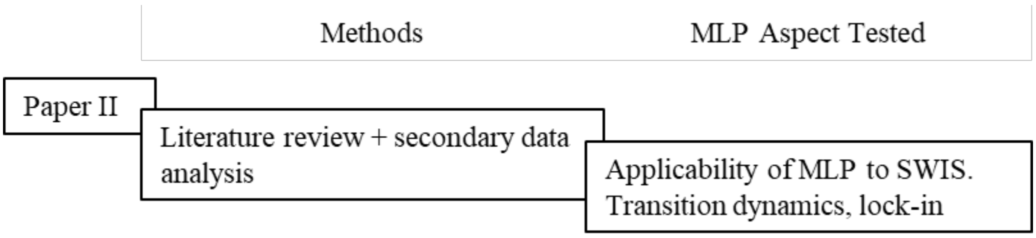

Figure 4.1: MLP aspects considered in Research Paper II.

Understanding the transition factors that should be considered starts with understanding the historical factors that have shaped the current day electricity system. The SWIS has evolved over the course of more than 100 years to keep pace with the growing demands of Western Australians for a stable electricity supply. Electricity within southern WA began as a series of intertwining microgrids in the early 1900s. Generators were relatively small, located close to the end users and produced electricity in response to customer demands. These demands were met by stand-alone generators providing electricity for tram services on a peaky morning and afternoon load, and separate generators and networks to service evening domestic lighting requirements. The progressive use of electric motors and lighting in workplaces were facilitated by electricity tariffs that evolved to encourage energy use 24 hours a day and match the output of larger coal generators. Generators became larger and were located closer to coal supply centres in response to improving economies of scale. These were then connected to demand centres by transmission lines. Integrated within these were fault protection and control systems designed around rotating synchronous generators. Both the transmission systems and large coal and fuel oil generators required large capital investment, undertaken by the state, with multi-decadal payback periods.

Society's relationship to electricity evolved from one of considering access to it being a privilege to becoming a societal right. This has led to an engineered system that guarantees security of supply using historically available electricity generation and transmission approaches. Designing a system that guarantees security of supply has led to high infrastructure costs that are supported by self-reinforcing rules. Collectively these factors make incumbents within the regime less nimble and poorly prepared to adapt to the rapid changes currently occurring in the generation landscape.

In answer to the first sub question, analysis of historical transitions shows that the SWIS has been through many phases, including de/re-alignment from a decentralised system in the early 1900's to the centralised system that has been promulgated by the local regime from around 1916 through to the current day. The initial period of de-alignment and re-alignment was driven by entrepreneurs pushing to introduce innovative electric lighting in the face of the established gas lighting regime. The evolution of the electricity system for around a century has been dominated by incremental changes driven by local state actors and vertically integrated utilities at the local-regime level. It is plausible that a return to either a fully decentralised system or a hybrid of the two systems in the future is possible.

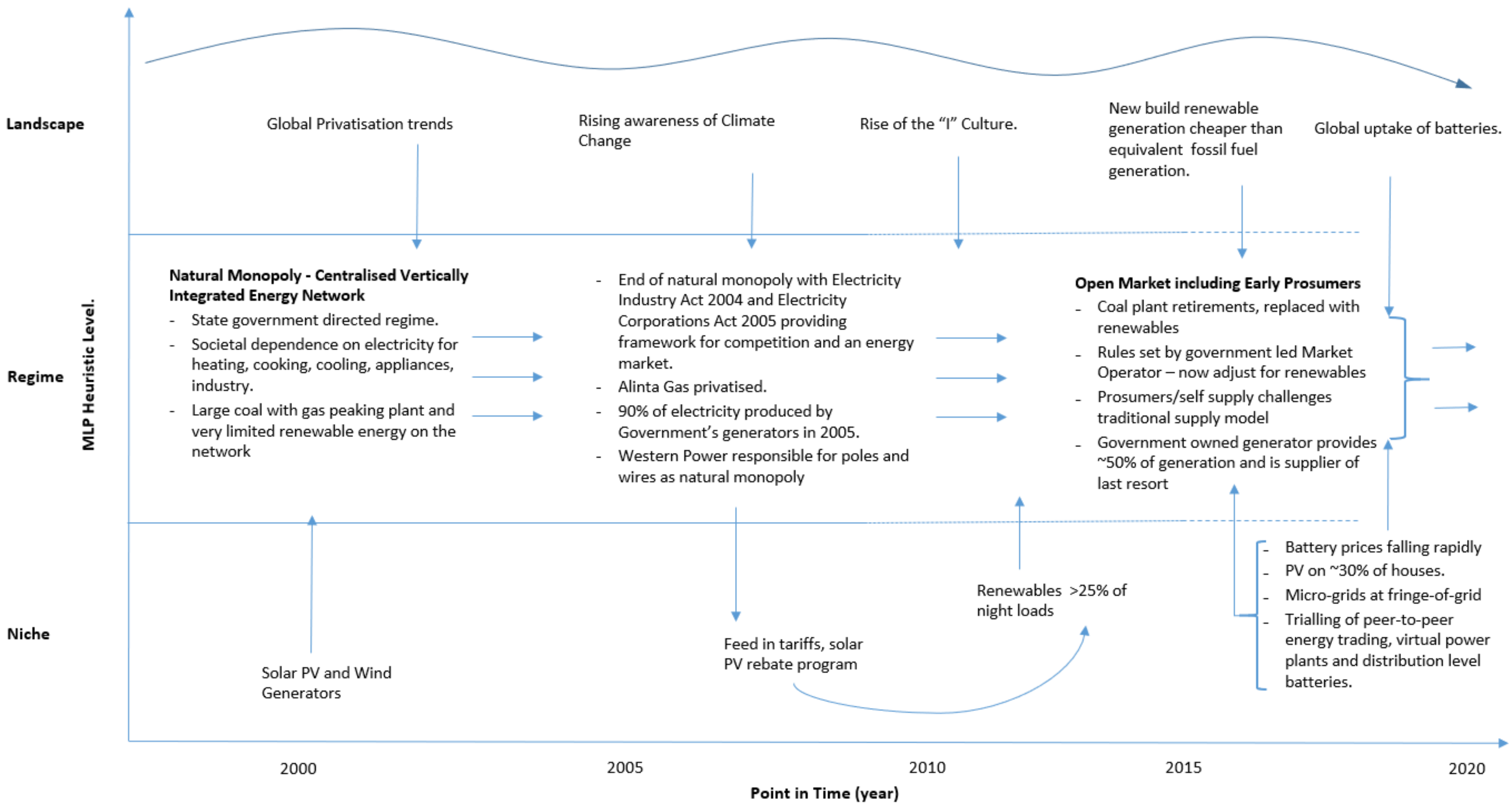

Figure 4.2: Key MLP change processes that mark the ongoing re-alignment of electricity supply in southwest WA since 2005 in response to landscape and niche pressures. (Key: arrows indicate direction of push/pull; solid/dashed or absence of line indicates strength of boundary between regime and landscape and/or niche) (from Research Paper II).

Electricity demand grew at a relatively steady but slow pace throughout the 1900s, allowing for the progressive planning and building of the electricity system. The long-running evolution of the system has been dominated by incremental changes by state actors and vertically integrated utilities at the local-regime level. This began to change in the early 2000s when, for the first time, electricity demand reached a plateau and then began to fall. Figure 4.2 from Research Paper II, shows the key MLP change processes that characterise the transition towards a VRE and rooftop PV dominated system that is currently unfolding in the SWIS. The following key changes marked the beginning of the current energy transition:

- A growing awareness of the need to address climate change, which resulted in policy initiatives at a national and state level in Australia to support renewable energy production (such as feed in tariffs for rooftop PV and the large-scale renewable energy target (LRET) for utility scale VRE projects) and to encourage energy efficiency.
- A global financial crisis that suppressed growth in energy demand, particularly from industrial energy users in the SWIS.
- Existing coal generators approaching end-of-design life.
- Falling costs for wind, solar and battery generation resulting in a boom in the installation of rooftop PV and progressive installation of utility wind projects.
- An aging fringe of grid that was progressively needing replacement and prompting a rethink of system design. This is leading to the installation of stand-alone renewable energy power stations on economic grounds rather than replacing some transmission and distribution lines; and
- Discussions around the disaggregation of the electricity market that is creating the space for entrepreneurs to progressively define new market segments that can address emerging challenges associated with the energy transition.

These changes were opposed by the following countervailing forces within the regime:

- Tariff equalisation policies implemented in the 1970s make current day tariff reform difficult to achieve. This is because the requirement for all electricity consumers, regardless of location in WA to be able to purchase electricity at the same price, makes it harder to a) implement cost reflective tariffs[1] and b) to implement competition for the supply of retail electricity. Cost reflective tariffs can be useful in

[1] It is noted that having tariffs that did not fully reflect the underlying costs initially aided the uptake of rooftop PV. This is because it paid prosumers higher than market prices for their excess energy fed back into the network, thereby shortening rooftop PV pay-pack periods. This also encourage prosumers to consume less energy during periods of high solar output maximise their returns for energy exported to the network.

affecting behavioural changes such as encouraging mid-day energy use and decreasing energy use during peak afternoon periods. The lack of ability to introduce competition into the retail sale of electricity hinders innovative business models such as VPPs, DR, aggregators and P2P trading models (the need for tariff reforms to help stabilise the grid becomes apparent in Research Papers III and IV. Definitions for VPPs, DR and P2P are presented in Table 4.3.)

- The gas pipeline from the gas fields in northern WA and the coal mines in the south of the state both have long-term contracts that have underwritten their viability and affect the all-in costs to society of changing fuel sources.
- Political disagreement in Australia on the realities of climate change and any need to address it have resulted in policy uncertainty for investors in longer term energy assets. The lack of political leadership on climate change has also made policy formation difficult, resulting in state-based agencies tending to make policies on a reactive rather than proactive basis.
- Existing electricity rules have been written to support prevailing technologies and do not allow for the participation of VRE and batteries from some electricity market segments. The WA government is also the state's largest owner of generation capacity, meaning they stand to lose the most should these generators become non-economic through a shift to alternate VRE sources.
- Control systems have been designed around small numbers of large synchronous coal and gas generators located on transmission lines rather than many hundreds of thousands of inverter-based technologies located predominantly within the distribution network.

Collectively, these forces answer the second sub question on lessons from historical artifacts that have influenced the direction and form that an energy transition in the SWIS could take.

4.2 Managing the transition to high rates of distributed rooftop PV in the SWIS

Sub-section 4.2 presents data from Research Paper III in answer to the following questions, which informed my understanding of the MLP aspects shown in Figure 4.3:

1. What have the main drivers for change been in the SWIS's generation profile over the past decade?
2. Do you agree with CSIRO and ENA's projected generation profile for the SWIS in 2022 and 2027?

3. What are the main enablers required to allow a stable electricity supply under the agreed generation profile in 2022 and 2027?
4. What are the main blockers or impediments to realising a stable electricity supply under the agreed generation profile in 2022 and 2027?

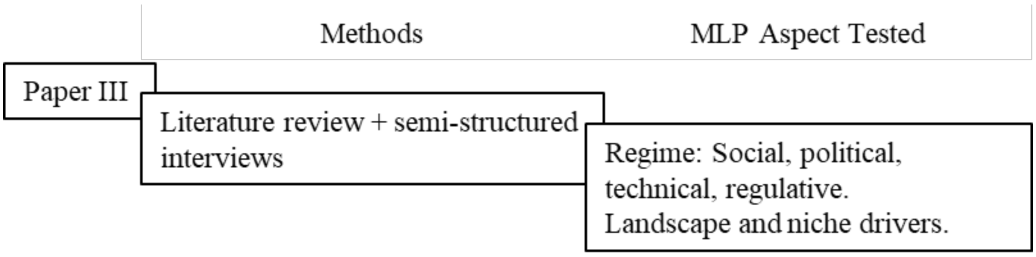

Figure 4.3: MLP aspects considered in Research Paper III.

4.2.1 Drivers for change in the generation profile

The interviews undertaken to answer these research questions were the first in this thesis and, as such, were exploratory in nature. A key finding was that the main drivers for change in the generation profile related to landscape level factors, including falling global prices for renewables, an increasing awareness of climate change and a decline in the demand for electricity from the network. At a regime level, the falling demand for electricity since the 2008 global financial crisis, together with improvements in energy efficiency allowed utility scale VRE to be safely added to the electricity system during a period of low demand growth, which may have otherwise been met by thermal generators under a high growth scenario. Increased societal acceptance of the need to address climate change was also considered important in encouraging the introduction of renewable energy stimulating policies at the regime level.

The most consistently mentioned drivers for change at the regime level during the interviews undertaken in 2017 were the state-based capacity mechanism[2] and the federally implemented large scale renewable energy target (LRET). The latter scheme was considered to be driving the wave of renewable projects that are expected to connect to the network over the next five years (Table 4.1). Very generous state-based feed in tariffs, together with federal grants, were recognised as the drivers for the rapid early uptake of rooftop PV.

[2] The WEM's capacity mechanism provides annual payments to facilities based on their guaranteed availability to produce electricity during peak network demand periods. The scheme is designed to avoid system shortfall and associated blackouts during peak system demand periods that typically coincide with the hottest summer afternoons.

4.2.2 Generation profile 2017 and 2027

The changing generation profile was viewed as trending toward:

- a fall in coal generation;
- a stable, to increasing level of gas; and
- a marked increase in wind, centralised solar and rooftop solar (referred to as 'behind the meter solar' in Table 4.1).

Interviewees expected to see a marked uptake in battery storage, which would be essential to counteract the effects of rooftop and utility scale PV, whose mid-day output could exceed network demand if not arbitraged by batteries.

Table 4.1: Consensus view[3] on the generation capacity on the SWIS in 2022 and 2027 based on interviews in 2017 (from Research Paper III).

Generation type	2007	2017	2022	2027
Coal (MW)	1044	1787	1550	750
Gas (MW)	1749	3370	3240	3670
Dual Gas/Coal (MW)	509	0	0	0
Diesel (MW)	48	196	70	70
Wind (MW)	70	392	700	1000
Solar (MW)		10	1100	1500
Behind the meter PV (MW)		860	1200[4]	2500
Solar thermal (MW)		0	0	200
Wave (MW)		0	0	200-250
Battery (MWh)		~	300	1500

Interviewees expected that the high-level uptake of rooftop PV was likely to create the greatest system risks and cause the introduction of new problems associated with low underlying mid-day system demand coincident with rooftop PV output. The likelihood that this generation profile would accelerate the removal of coal generation was consistently raised as was the impending need for generation that could ramp quickly and cycle on and off throughout the day. It was this finding that focused the next two Research Papers on the impacts of rooftop PV. Other challenges raised that could be introduced from this altered generation profile included frequency regulation, inertia, fault

[3] Projections were based on the interviewer's interpolation of the collected data rather than an average of responses received. This is because some interviewees had access to additional information on certain generation types (e.g. the pipeline of wind or solar projects).

[4] At the time of writing the exegesis in early 2021, installed rooftop PV was over 1300 MW and had already exceeded the levels predicted in 2017 for 2022. Impacts associated with rooftop PV predicted in this early paper are already being experienced and, in some instances, addressed.

current, voltage regulation and ramp rate. Concerns were also raised about the current inability to monetise various battery services into the WEM. Technical system operability challenges associated with the removal of traditional thermal generators from the SWIS were further explored in Research Papers I and IV, and summarised in Table 3.2. Research Paper IV also explored solutions to these technical issues and the need for markets to support their implementation. These results are presented later, in Table 4.4.

4.2.3 Enablers and blockers to stable electricity supply in 2022 and 2027

Table 4.2 presents the summary of the social, political, regulative and technical issues identified by the interviewees that will need addressing to ensure a stable electricity supply under the agreed future generation mix. A central finding was that the role of electricity users would change under the future generation profile and that long-term programs would need to be put in place in preparation for this change (refer to issue S1 in Table 4.2). This could involve communications programs to inform them of the changes, in preparation for the introduction of new supportive infrastructure (advanced meter infrastructure — AMI, updated inverters, battery integration), revised business models and retailer relationships. This result was then taken forward for investigation in Research Paper V. While technical constraints were inevitable from the forthcoming generation mix, these were considered resolvable, provided the social, political and regulatory issues were first progressed and/or addressed (refer to issues P1, R1-R4 and T1-T4 in Table 4.2). This could be greatly assisted by early agreement at a political and societal level on the need to address climate change.

Table 4.2: Core actions raised by interviewees that need addressing for the market to provide a stable electricity supply under the future generation mix (from Research Paper III).

No.	Regime factor	Core Outcome
S1	Social	A multi-year communications program that informs the community that an energy transition is underway, that their relationship in the electricity market is evolving, that rooftop PV and battery interactions with the network will need to be controlled, and that AMI will need to be installed and enabled.
P1	Political	Bipartisan political support for a move to cost-reflective pricing, agreement on the structure of the gentailer[5] and retail contestability, and a transparent pathway towards achieving these.
R1	Regulative	A carbon price and/or a long-term clean energy target.
R2		Assign accountability for system planning and modelling to allow for long-term planning and policy formation.

[5] A gentailer is an organisation that acts as both an electricity generator and an electricity retailer. In the SWIS, all retail sales of electricity must be purchased from Synergy, which is the state owned gentailer.

R3		Streamlining of rule-making processes such that regulators can deal with the rapidly changing energy marketplace.
T1	Technical	The need for control devices, such as AMI on premises with rooftop PV and/or batteries.
T2		The need for a more automated dispatch engine, and for the gentailer's generation fleet to individually bid into the market rather than doing so on a whole-of-portfolio basis.
T3		A means to address low fault current on transmission lines when there are high levels of non-synchronous inverter-based generation in a region.
T4		How to compensate for loss of inertia that is currently provided by rotating machines such as coal and gas turbines
R4	Regulative	Clarification of the access arrangements, whether constrained or unconstrained, for new generation to connect onto the SWIS.

4.3 Implications of rooftop PV on the energy market and system operability

Research Paper IV focused on the technical, economic and regulatory aspects associated with integrating high levels of rooftop PV within the SWIS (Figure 4.4) and was guided by the following questions:

1. Is there a statistically significant relationship showing that increasing adoption of rooftop PV suppresses wholesale energy prices during the day in the WEM?
2. If so, can the WEM continue to support the ongoing operability of the SWIS without change?
3. If not, what changes could be required to improve the WEM with a view to maintaining the ongoing operability of the SWIS?

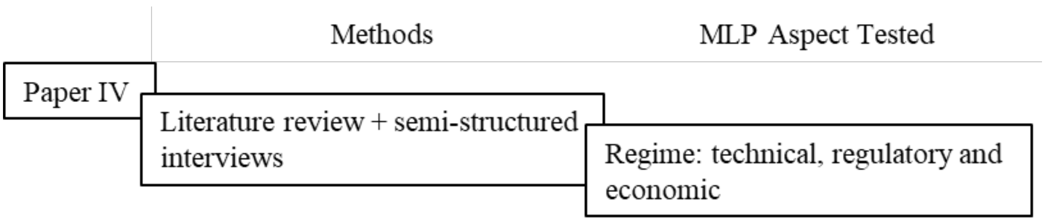

Figure 4.4: MLP aspects considered in Research Paper IV.

4.3.1 Rooftop PV suppresses energy prices

Figure 4.5 from Research Paper IV shows the mid-day wholesale energy price and the output of the predicative model. The mean downward sloping trajectory of the wholesale energy price is reflected in the downward pressure of rooftop PV in the model. While the longer-term effect of high rates of rooftop PV in the WEM is complex, the results are clear — greater uptake of rooftop PV will continue to put downward pressure on WEM prices under the current market design. This modelling of price impact is supported by AEMO, which has estimated that over 40% of October trading intervals in the WEM will be negative as soon as 2021 (AEMO, 2019b). These findings support the notion that increased uptake of rooftop PV will undermine the profitability of thermal coal and gas generators, and that a reduced contribution from these generators can be expected in the SWIS in coming years.

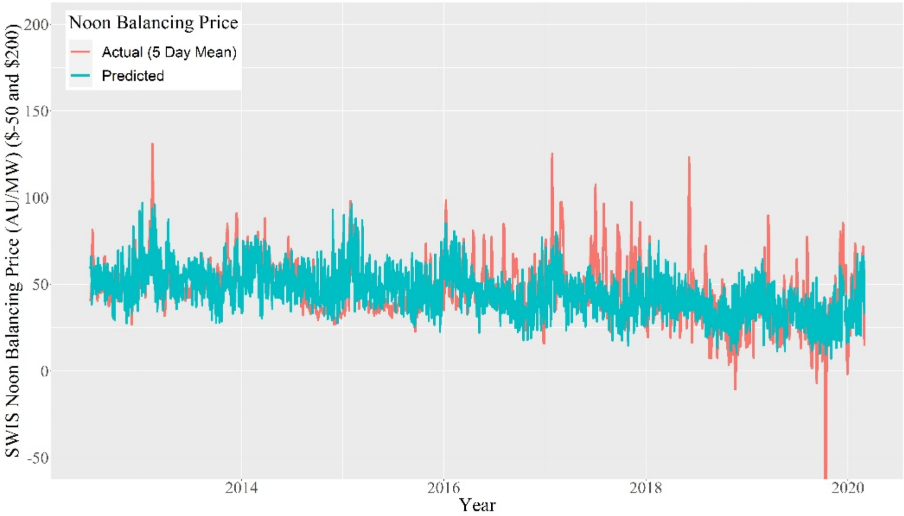

Figure 4.5: Regression model showing noon wholesale energy balancing (five-day mean) price in the SWIS versus the predicted noon wholesale energy balancing price (y-axis) gradually decreasing between 2012 and 2020 (from Research Paper IV).

4.3.2 Total market failure if not changed

As shown in Research Paper IV, the continued uptake of rooftop PV results in the growing duck belly and its drying pond (Figure 4.6). The growing duck belly metaphor refers to system impacts of increasing rooftop PV output during the middle of the day, whereas the drying duck pond metaphor refers to market impacts associated with rooftop PV. The expected system impacts, as the duck belly grows and the duck pond dries up, are detailed in Table 3.2. These impacts are already occurring and are expected to require material changes to existing modes of operating and associated market rules over the next 2–5 years (Research Paper IV). As reported in Research Paper IV, the market that underpins the SWIS if left unchanged, "... will result in complete market failure" (response from interview participant). A market failure would result in the system becoming inoperable.

These findings support the assertion that the SWIS is undergoing a transition, away from carbon intensive coal and gas generators towards a system dominated by low carbon distributed rooftop PV.

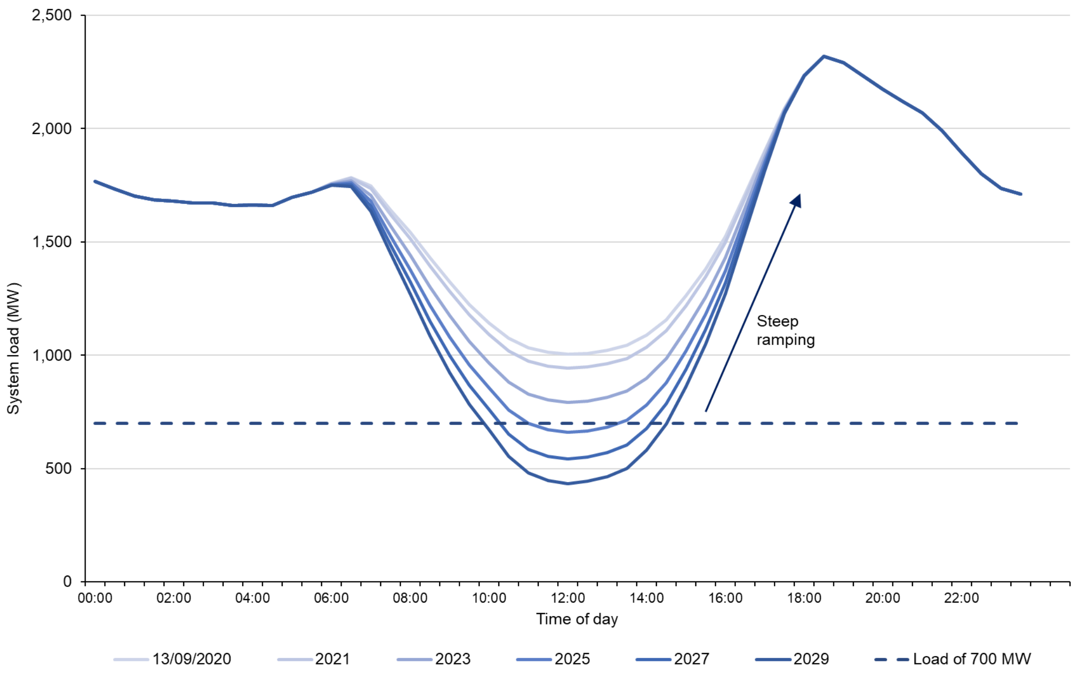

Figure 4.6: Growing of the duck belly as more rooftop PV is added to the SWIS (from Research Paper IV).

Market failure would likely start with increasing occurrences of zero and negative daytime prices, which would reduce the profitability of baseload generators and accelerate their departure from the market. As detailed in Table 3.2, and as described by interviewees, loss of these generators removes the grid stabilising properties of inertia and system strength (reduced ability of protection systems to see faults) that they currently inherently provide. Over generation on the distribution system from rooftop PV systems would create operational and safety constraints associated with voltage and reactive power management.

The WEM's capacity market was seen as no longer fit for purpose on the basis that it rewards generation in the wrong locations and of the wrong type to redress current and future system constraints. The current capacity market rewards generator availability during peak demand periods. While this may continue to be relevant, other emerging issues, such as capacity that can operate during minimum demand periods and/or address voltage issues within the distribution network, are becoming increasingly relevant. Further, the current ancillary services markets were described as failing to reward required services (e.g. inertia, ramping and rate of change of frequency) while also excluding alternative technologies (e.g. batteries) and approaches (e.g. DR, VPPs and P2P — refer to Table 4.3 for definitions of DR, VPP and P2P) from playing a role in maintaining system security. Current volumetric retail tariff structures were also identified as failing to incentivise customers to change their electricity consumption patterns, which would be useful to increase mid-day consumption and reduce evening peaks, thereby flattening the load curve to slow growth of the duck belly.

From a system management perspective, there is also limited visibility and control of rooftop PV systems by the ISO, which makes it harder to maintain frequency within safe operating bounds.

Table 4.3: Definitions for DR, VPP and P2P in stabilising the electricity system.

Mechanism	Definition
Demand response (DR)	Changes in electricity usage by "customers from their normal consumption patterns in response to changes in the price of electricity over time, or to incentive payments designed to induce lower electricity use at times of high wholesale market prices or when system reliability is jeopardized" (Sperstad et al., 2020)
Virtual power plant (VPP)	Active power control across a fleet of assets (e.g. behind the meter prosumer batteries) to provide grid services that are independent of the specific location of each asset, for example feeders or circuits (Enbala, 2018). Prosumers typically receive payment for allowing external control and access to their assets' services.
Peer-to-peer (P2P) trading	Allows prosumers and consumers to trade directly with each other or a third party without needing a traditional electricity supplier or retailer as middleman (Parag and Sovacool, 2016; Tushar et al., 2018).

4.3.3 Changes required to improve the WEM and maintain operability of the SWIS

Literature reviewed within Research Paper IV corroborated the interview findings regarding relevant technical and market resolutions to problems expressed by the duck curve. The first measure to be implemented should include updating inverter standards and the roll-out of advanced meters. Both these measures could be undertaken without the need for regulatory reforms and would be required prior to any consequent market and system control mechanisms being implemented that could utilise rooftop PV for network support purposes. While viewed as technological solutions, changes to prosumer meters and inverters have caused significant social push back in many jurisdictions due to privacy and cyber security concerns associated with these technologies. As mentioned in Research Paper III, prior societal and political agreement on climate change and, therefore, the need to make changes would be beneficial at a landscape level before attempting to implement changes that affect all prosumers.

New regulated markets will be required that can incentivise and reward investment in technologies and approaches for stabilising the SWIS. This will include new ancillary services markets that supply inertia, fast frequency response, ramping and system strength, and that open up the provision of these services to newer technologies and approaches. Batteries are currently excluded from providing these services, as are approaches that utilise prosumer resources such as VPPs, DR and P2P trading schemes. Re-organising the regulatory regime to allow for these new business models has historically been met with resistance due to concomitant impacts to existing market participants, the largest of whom is the state government through its electricity generation and sales business.

Table 4.4 presents a summary of the solutions identified by interviewees in Research Paper IV to address impacts described by the growing duck belly and drying duck pond. These are focused at the regime level of the MLP at technical and market solutions. A key focus of these measures is using multiple approaches to flattening the load curve while introducing new technologies and enabling markets that can address the generation variability introduced by VRE and rooftop PV.

An outcome of Research Paper IV was the finding that the implementation of new markets, such as DR, P2P and VPP, could be used to support the involvement of prosumers and that research is required on the role of prosumers in shaping of these new markets and taking them from niche business models into the mainstream market so that they can achieve the desired system supporting objectives. Definitions for DR, P2P and VPP are presented in Table 4.3, with the mechanism by which they can support the transition presented in Table 4.4.

Batteries, VPPs, DR and P2P can each be used to provide system security, but also to help flatten the demand curve and address the greater impacts of the growing duck belly such as frequency and voltage regulation. The other main approach for flattening the duck belly involves tariff reforms. Electricity has long been held as a societal right, with social justice issues associated with keeping electricity prices low. As identified in both local and Californian interviews, policy makers have thus been limited in their ability to raise electricity tariffs to the point that they can drive behaviour changes. The literature reviewed in Research Paper IV found conflicting evidence of the ability of variable tariffs to affect load profiles. The most effective tariffs for flattening the demand curve were associated with time varying tariffs that were linked to in-home automation technologies that can shift loads in response to even small price variations.

Table 4.4: Summary of interviewee solutions to high levels of rooftop PV (from Research Paper IV).

Change Mechanism	Specific Mechanisms[†]	What it does
Technical requirements	Inverter connection standards [ϕδβσ]	Allows ISO to control interaction of rooftop PV with distribution and transmission system, voltage control, reactive power management and/or for inverters to respond with automatic droop control.
	Synchronous condensers [σ]	Provide inertia and fault current.
	Minimum short-circuit capability [δσ]	Grid security.
	Transmission and distribution-level control systems[*ϕδβσ]	Increase automation and control of increasingly distributed generation profiles and associated interactions with grid architecture. Specific measures may also increase visibility and controllability of rooftop PV.
Markets	Ancillary services markets[*ϕδβσ]: • Inertia • Frequency (rate of change of frequency, primary response, load rejection, spinning reserve, black start) • Ramping • System strength	Incentivises availability of services that can provide grid security and stabilisation.
	P2P trading[ϕσ]	Allows localised retail pricing that incentivises local energy consumption to decrease transmission and distribution bottlenecks. Can form basis of DR programs.
	DR / aggregators/ VPPs[*ϕδβσ]	Supplies ancillary services, enables short term load shifting.
	Capacity payments*	Incentivises generation in appropriate locations and of a type that is suited to future load profiles. Reducing impacts of "missing money" problem.
	Intra-day storage[*ϕδσ]	Flattens load/energy arbitrage, provides ancillary services. Supports transmission and distribution networks.
	Seasonal storage [σ]	Reduces variation in loads between summer/winter and shoulder periods.
Flattening load profile	Transmission[*σ] and distribution level storage[*δσ]	Flattens load/energy arbitrage, provides ancillary services. Supports distribution network.
	Time and load varying tariffs[*ϕδβσ]	Provides incentives for load flattening — reducing the peak and raising mid-day minimums.
	Domestic storage incentives	Incentivise load flattening and potentially voltage regulation.
	Smart loads / automation [ϕδ]	Provides ancillary services and maximises benefits achievable via tariff reform.
	DR and/or VPPs[*ϕδσ]	Provides ancillary services and allows for load flattening.
	P2P trading [ϕσ]	May incentivise behaviour change around energy use and reduce the rates of rooftop PV installation.

† Symbols against text in the "specific mechanism" column indicate that mechanisms have also been identified in key work programs by the following related industry reports *=CAISO (2020a, 2020b). ϕ = ESB (2019, 2020); δ = Energy Transformation Taskforce (2020); β=Distributed Energy Integration Program (2020); and σ = AEMO (2019b, 2019c, 2020g).

Battery storage technologies were also seen as critical for addressing many of the challenges represented by the duck curve. Larger batteries located within distribution and transmission systems were identified as more economically efficient than behind the meter storage while also allowing for additional distribution network support services to be provided to reduce the likelihood of bulk curtailment events (Energy Transformation Taskforce, 2020).

Broad measures aimed at improving energy productivity were also identified as important for flattening the demand curve. This would have the effect of reducing evening peaks rather than flattening the duck belly. Energy productivity could include improved building efficiency standards resulting in reduced heating and cooling demands. It could also include electrical product efficiency standards.

The final area that will need addressing relates to control technologies and architectures associated with millions of generating devices located within the distribution system. The current system is designed around tens of generators, all located within the transmission system, which are visible and predominantly dispatchable by the ISO. This is not the case with rooftop PV. This may require a greater reliance on artificial intelligence to coordinate its integration into what is becoming an exponentially more complex system (Tayal, 2017). Price signals aimed at prosumers and coordinated via VPP and P2P schemes have also been proposed as a proxy control mechanism. The ability to enrol prosumers in these programs remains an area of great uncertainty and was the focus of Research Paper V.

4.4 Engaging electricity users in the electricity transition

Sub-section 4.4 presents the key findings from Research Paper V in answer to the following questions:

1. Who are the energy users that are willing to experiment with P2P electricity trading and what motivates them?
2. What is the role of the energy users in the innovation processes towards a P2P electricity trading model in WA?

Figure 4.7 shows the MLP aspects that were considered in Research Paper V:

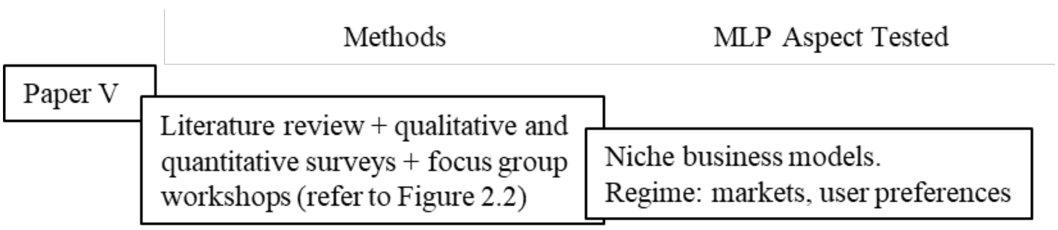

Figure 4.7: MLP aspects considered in Research Paper V.

These questions were asked to interrogate findings from the preceding research papers. Research Paper III reported that long running communications programs would be required to prepare prosumers for their evolving roles in the electricity system. Preparing prosumers for this change could also serve to de-risk the space for politicians to amend the regulatory regime. This will continue to be important while there is a lack of agreement on the need to address climate change.

As found in Research Paper IV, significant changes will be required to the WEM to maintain system operability during the transition to higher rates of rooftop PV. These changes focus on flattening the load curve and addressing minimum system load issues. The main mechanisms identified to achieve this included tariff reform, new ancillary services, automation, storage, energy productivity and targeted markets to match energy supply to the new demand curve, together with enabling technologies such as improved inverter functionality and control systems.

Studying all the mechanisms required to achieve these changes was beyond the scope of this thesis. I therefore elected to focus on a case study of one niche business model that had the potential to address many of these issues and could serve as an example of how policy makers could engage and leverage prosumers in the transition. The analytical framework developed in Research Paper V provides a framework for targeting initiatives specific to different users at different phases in a transition. The key learnings from this framework are presented in Section 4.4.2. The trial researched the first test globally of P2P electricity trading within a real-world marketplace across the public electricity network.

If new innovations are to be introduced to the market, it is important to understand how this can be done successfully. Transitions literature identifies that many niche innovations do not make it through to the socio-technical regime (Geels and Raven, 2006). Similarly, the diffusion of innovation literature finds that many innovations do not make it through to the mainstream market (Rogers, 2003). This is because the early adopters of a technology that often trial the associated technology and/or business models may not be representative of mainstream users (Moore, 2014). Therefore, in answering these questions I sought to understand the role that users can play in assisting niche business models to break through and challenge the dominant socio-technical regime. Answering these questions could also inform policy on how to best engage users in different phases of the energy transition.

4.4.1 Characteristics of first users of a niche business model

Users in the P2P trading trial had the following characteristics (refer to Research Paper V for full results on the user characteristics):

- financially secure households with a high interest in social equity and transitioning to decarbonised energy systems;
- a good knowledge of their local context and issues that they would like to help resolve;
- typically, a good understanding of renewable energy technologies and their consumption and production patterns;
- strongly motivated to learn about their own electricity use and broader innovations in the electricity sector without being discouraged by initial complexities and financial losses; and
- a desire to be ahead of the curve and have first-hand experience of cutting-edge technology.

The trial participants fell into two categories, each of whom play different roles in the energy transition. These included:

- those that were willing to stay in the trial despite a likely financial disadvantage; and
- those with a high interest in participating but who withdrew from the trial once they were made aware that they would be financially disadvantaged through participation.

4.4.2 Roles played by users in allowing uptake of enabling niche business models

An analytical framework was developed with my co-author, Kristina Hojčková, in Research Paper V to answer the second sub-question — *What is the role of the energy users in the innovation processes towards a P2P electricity trading model in WA?* The theoretical framework was based predominantly on sustainability transitions and diffusion of innovation literature. The former characterises four phases of innovation across time, which are summarised in Table 4.5, and helps with understanding the current phase of the broader renewable energy transition. By combining this with the diffusion of innovation literature, allows a more time-sensitive analysis. The diffusions of innovation literature are focused on individual innovations, however, when taken collectively, they constitute the MLP niche within the broader energy transition. The integration of these two concepts is presented graphically in Figure 4.8 and forms the basis of the analytical framework that underpins Research Paper V.

Table 4.5: Summary Four phases of system innovation, adapted from Geels (2005) (from Research Paper V).

Phase	Characteristic
Phase 1. Emergence of novelty	An innovation emerges to solve a problem or offer a new alternative to the dominant regime, i.e. sector. It is nurtured by a small actor network (of technology pioneers and innovators) sharing expectations of the future performance of the innovation. To improve the innovation's price and performance, they experiment to improve the design and accommodate user preferences.
Phase 2. Probing and learning	The supporting network evolves into an established group or community of specialists, producers and consumers. These actors work together to improve the innovation through learning about market preferences and understanding the necessary legislative change.
Phase 3. Breakthrough and wide diffusion	With the help of external pressures and internal momentum, the innovation gains more actor and legislative support, which improves the price/performance ratio and achieves economies of scale and learning. The linkages and co-development of new system elements increase, building new infrastructures, new governmental agencies and professional organisations.
Phase 4. Stabilisation of the new regime	A new socio-technical regime is created around the innovation with new infrastructure and new widely adopted user practices, policies and regulations.

In identifying the roles that users play in energy transitions, we built on the work of Schot et al. (2016), together with a broader review of transitions and diffusion literature to look for commonalities in how users are characterised. A multitude of terms are used in the literature and have been consolidated in Table 4.6; the terms have been taken from Research Paper V. The naming conventions adopted are as defined under the user role column of Table 4.6. The relevance of these roles to trial participants is outlined in the following paragraphs.

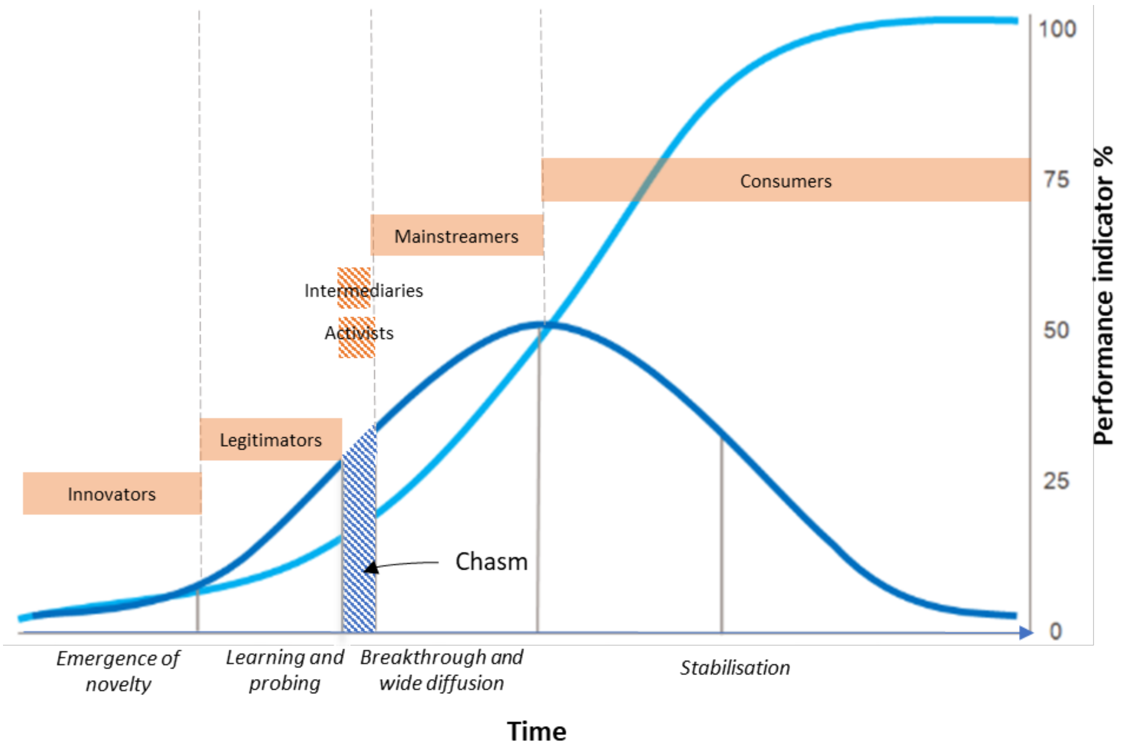

Figure 4.8: User roles (graph labels) across four phases of innovation (x-axis labels), showing the innovation phase in which each user type is most active. This schema includes the chasm to be crossed to move from learning and probing to breakthrough and wide diffusion with the assistance of user–intermediaries and activists (from Research Paper V). The performance indicator represents the maturity of the innovation and relates primarily to the s-curve (light blue line). This same concept is conceptualised by the area beneath the bell curve (dark blue line).

Analysis of the results against the analytical framework shows the trial participants correspond with *legitimator* and *mainstreamer* categories. The former relate to those that were willing to proceed with the trial despite financial loss because they wanted to learn about the innovation and help embed it in the local context. As defined in Table 4.6, they strongly believe their participation could increase outside expectations and therefore support the transition to a more socially equitable and local renewable energy system through demonstrating the P2P model. The *legitimators* can be of benefit to policy makers and innovators as they help legitimise a new concept, which is critical before it can be adopted by broader mainstream users. However, for this to occur, the innovation must first cross the chasm (Rogers, 2003) (as shown in Figure 4.8) before it is adopted more broadly by the *mainstreamers* and general *consumers* (refer to Table 4.6 for definitions of these user types and descriptions of how they contribute to the innovation and transition process).

The high attrition rate in the trial was reflective of the misalignment between participant expectation, the trial consortium's design and the characteristics of the users that self-enrolled for the trial. Many trial participants viewed themselves as an active part of creating the niche by contributing to learning and probing as *innovators* and *legitimators*, whereas the project consortium viewed the participants merely as *consumers*, playing a role in consuming the new market product. This may have been one of the biggest contributors to the high drop-out rates within the trial.

Table 4.6: Summary of user roles across the transition phases with descriptions of how they contribute to the innovation and transition process (from Research Paper V).

Transition phase	User role	User role defined in the existing literature[†]	Contribution to the innovation and transition process
Emergence of novelty	Innovators	• User–producers • Innovators • Product designers • Energy enthusiasts	• Invent and create new technical and organisational solutions and routines • Use supporting institutions (e.g. tax reductions and subsidies) • Enthusiasm for new ideas, understand and apply complex technical knowledge • Look for ideas outside the local context • Can cope with high uncertainty • Have substantial financial resources
Probing and learning	Legitimators	• User–legitimators • Early adopters • User–entrepreneurs, entrepreneurial lead users • Opinion leaders	• Embed innovation in the local context • Reduce uncertainty by making errors and learning • Convince and increase expectations of the relevance and significance of the innovation • Stimulate acceptance of the innovation among their peer networks
Breakthrough and wide diffusion	Intermediaries	• User–intermediaries • Energy user communities	• Create space for alignment of new actors, institutions and technologies • Voice expectations, interpretations and uses of new technologies to regime actors • Enrol new actors, creating networks between them • Cooperate with other actors such as firms and (non)governmental organisations
	Activists	• User–citizens • Grassroots movements • Activist groups	• Involved in transition politics • Mobilise social movement for reform • Actively try to overcome resistance of incumbent actors • Dissatisfied with current regime
	Mainstreamers	• Early majority users	• Important in creating network effects among users • Adopt just before the average member of a system • Seldom hold an opinion-leadership position • They have great willingness to adopt but seldom lead
Stabilisation of the new regime	Consumers	• User–consumers • Late majority users • Market product consumers • Market participants • End users • Consumers with preferences, needs, behaviours, and practices	• Buy products and embed them in their daily practices • Adopt just after the average user, after innovation-related uncertainty is reduced • Use the innovation due to peer pressure or because it has become the dominant choice

† Refer to Research Paper V for a complete version of this table containing the source references.

Those that withdrew early from the trial have been characterised as *mainstreamers* (refer to Table 4.6 and Figure 4.8) as they were not willing to participate until the financial uncertainties and risks improved. *Mainstreamers* could be more effectively engaged in creating network effects for wider diffusion in a later stage of innovation, after the legitimacy has been improved and a better price/performance ratio has been achieved.

From a policy perspective, the results and analytical framework point to the importance of actively engaging with each of the user categories during trialling and implementation phases of niche innovations and business models relevant to the energy transition. Identification and engagement of *activist* and *intermediary* users (Table 4.6) will be of utmost importance as they are the ones that *mainstreamers* consider as credible sources of information that they will listen to when deciding whether to adopt the niche innovation/business model.

Understanding who can fulfil these roles will be both context specific and dependent on the stage of the transition process (x-axis in Figure 4.8). For example, if the niche innovation is something that must be adopted by existing energy utilities, then an *intermediary* may be an existing supplier in whom the utility has a positive working relationship, or who has done reputable work for an esteemed peer organisation. If the niche innovation must be adopted by prosumers, then the relevant *activist* or *intermediary* may be a prominent community leader/personality, consumer rights group or other entity whose opinions mainstream prosumers will trust. However, mainstream users can be considered distinct from *early adopters* and *legitimators*, and therefore may not value their product endorsements as highly as they would those coming from *activist* and *intermediary* organisations.

Further studies should be undertaken to test the broad applicability of the analytical framework described in Figure 4.8 for engagement of users in different aspects of the transition. This could be focused on innovative business models, tariff structures or technologies at different phases of development. In the case of managing the transition within the SWIS, the role of incumbent energy organisations, such as the retailer (Synergy) and grid operator (Western Power), together with leading renewables advocates/activists should also be pursued. If the analytical framework described by Figure 4.8 holds true, then the inclusion of these users could assist in bridging the chasm between *innovator* and *legitimator* users and the broader mainstream.

Chapter 5 Conclusions and recommendations for future research

5.1 Answering the Central Research Question

This thesis by compilation has sought to answer the following central research question through 13 subsidiary questions in five separate Research Papers:

> *Which transition factors should be focused on to ensure a stable electricity supply as the SWIS shifts from thermal coal and gas to a solar PV dominant system?*

The five Research Papers collectively demonstrate that a transition is unfolding in the SWIS and is primarily being driven by the installation of rooftop PV systems within the distribution network. Managing the transition requires consideration of the interaction between technical, economic and socio-political factors, together with regulatory and institutional aspects. The interaction of these aspects can be considered as a socio-technical regime that is subject to landscape forces and niche developments. Through secondary data analysis in Research Paper II, it is evident that the electricity system has been through a period of de-alignment from decentralised micro grids in the early 1900s and a re-alignment towards a centralised hub-and-spoke system centred on large coal and gas generating units. It is not clear what the final system architecture will look like as retiring coal and gas generators are increasingly replaced with rooftop PV and other VRE generation sources.

The transition is occurring because inverter-based rooftop PV are increasingly connecting within the SWIS and have different operating characteristics to the large coal and gas synchronous generators around which the legacy electricity system and its supporting market were built. As shown by the growing duck belly and drying duck pond (Figure 4.6) from Research Paper IV, rooftop PV is putting pressure on existing coal generators, whose operating characteristics are no longer matched with the changing residual system load and this is creating both the missing money and merit order effects that affect the profitability of coal and gas generators.

As uncovered through empirical contributions in Research Papers III and IV, the existing wholesale energy market is no longer fit for purpose and will require a fundamental redesign if it is going to continue to support the SWIS. It will need to provide services that are not currently catered for, such as inertia, fast frequency response, ramping and system strength, which will increasingly be required as synchronous coal and gas generators are replaced by output from inverter controlled VRE technologies.

To succinctly answer the central research question within the context of the MLP, the following high-level factors should be focused on to ensure a stable electricity supply as the SWIS shifts from thermal coal and gas to a solar PV dominant system:

1. The historical lock-in mechanisms and other artefacts that can both enable and block the reconfiguration of the socio-technical regime to allow in high levels of rooftop PV (refer to Research Paper II).
2. Landscape level factors that may be leveraged to enable a reconfiguration of the socio-technical regime (refer to Research Paper III).
3. Implementing key technical solutions and any supporting markets (refer to Research Papers III, IV and V).
4. How and when to best engage prosumers in transition activities (refer to Research Papers III and V).

Each of these four points are summarised in Section 5.1.1–5.1.4, below.

5.1.1 Historical artefacts

The transition pathway from an electricity system designed around synchronous coal and gas generators to one dominated by inverter connected rooftop PV will be heavily influenced by historical artefacts that both block and enable changes. In the SWIS, these include all aspects of the socio-technical regime, whether it be the WEM design, technical control systems, the financial capital sunk into existing infrastructure, long-term gas and coal contracts or customers' relationships with the electricity sector and their associated tariff structures. The lock-in and self-reinforcing nature of these socio-technical regime artefacts have indicated that the transition is more likely to go in one of two ways. The first involves an incremental adoption of niche rooftop PV within the existing regime architecture by existing utilities, whereas the alternative is a more disruptive change process that results in a reconfiguration of the existing regime. Total reliance on electricity within modern society implies that a disruptive change is not an acceptable outcome either socially or politically.

This thesis has undertaken a relatively high-level review of the historical artefacts that influence the ability to effectively manage the transition. It is recommended that policy makers in the SWIS and WEM continue to identify historical artefacts that are influencing the transition processes. Understanding these artefacts, together with an understanding of landscape forces (Section 5.1.2) may inform a pathway of least resistance for managing the energy transition.

5.1.2 Leveraging landscape forces to enable socio-technical regime changes

Landscape level forces have created the space for the rapid uptake of rooftop PV. This has primarily been due to cost reductions in VRE technology resulting from economies of scale through their global uptake as nations seek to address climate change and improve their energy security through diversification.

Interviews during this thesis identified that national and state level agreement on the need to tackle climate change would be a key enabler for a smooth transition. Without societal agreement on climate change in Australia, government and regulators lack the political capital to re-organise the electricity sector's socio-technical regime around rooftop PV. This is because the breadth of change is substantial and may require new organisations, disruptions to existing workforces and possible changes to customer/prosumer relationships with existing electricity retailers. Any politician attempting to make changes of this scale will need societal agreement on their necessity, which could be supported by societal agreement on the need to tackle climate change and to decarbonise the electricity sector.

An absence of this agreement could require those within the socio-technical regime to rely more heavily on technical fixes to the growing duck belly and to implement these on a reactive, rather than proactive basis. This approach may be more disruptive and costly and makes addressing the drying duck pond issues associated with market failure, harder to address.

In the absence of societal agreement on climate change and the need to transition, it is recommended that those within the electricity industry, such as retailers, and network operators run long-term communications programs preparing prosumers for the need for change. These programs would seek to de-risk the political decisions required to support changes within the policy and the institutional regime required to stabilise the electricity system with high rates of rooftop PV. Other measures to prepare prosumers for change and to de-risk political decisions, such as trialling new prosumer focussed business models are discussed in Section 5.1.4, below. Unfortunately, there is now insufficient time for long running communications programs given issues of high rates of rooftop PV are already evident in the SWIS. It is noted that the premise in this thesis, that there is an absence of societal agreement on climate change and the need to transition the electricity sector is anecdotal and requires further verification and focussed research prior to the development of any targeted communications strategies by electricity retailers, network operators and/or policy makers This may best be undertaken as longitudinal studies.

5.1.3 Technical problems need resolving with the support of new markets

What is almost certain, is that stabilising the electricity system with a deepening duck curve and drying duck pond will need to be addressed from multiple directions, and that a single solution is not on the immediate horizon. This may involve allowing participation of new business models in the market that reward technologies (such as batteries) and business models (such as P2P, VPP and DR), which can assist in stabilising the electricity system. New control systems, capable of coordinating the millions of inverter-connected generation points embedded within the distribution system and the remaining large generators and VRE sources in the transmission system are going to be required. New tariffs and other supporting financial incentives will be required to incentivise a flattening of the duck curve.

Table 5.1, summarised from Research Paper IV, presents the range of mechanisms needing to be implemented to allow a stable electricity supply during a transition. These are grouped according to whether they are technical, market or load flattening change mechanisms. The shift to a generation profile dictated by rooftop PV promotes an initial incentive to flatten the load's profile. It is uncertain whether this will be a long-term solution or an interim measure that gives policy makers additional time to implement other measures to stabilise the electricity system during the transition. Quantitative modelling will be required to determine the extent that each of these change mechanisms can contribute so that policymakers can prioritise enabling regulatory reforms required for their introduction. These studies will be unique to each electric power system in supporting the market's transition.

Table 5.1: Summary solutions to high levels of rooftop PV (summarised from Research Paper IV).

Change Mechanism	Specific Mechanisms
Technical requirements	Inverter connection standards Synchronous condensers Minimum short circuit capability Transmission and distribution level control systems
Markets	Ancillary services markets: • Inertia • Frequency (rate of change of frequency, primary response, load rejection, spinning reserve, black start) • Ramping • System strength P2P trading DR / aggregators/ VPPs Capacity payments Intra-day storage Seasonal storage
Flattening load profile	Transmission and distribution level storage Time and load varying tariffs Domestic storage incentives Smart loads / automation DR and/or VPPs P2P trading

5.1.4 Enrolling prosumers in the transition

Research Papers I–IV showed that socio-political factors are important aspects within an energy transition. Research Paper III identified that enabling a successful transition could be helped if political decision making could be de-risked, in addition to leveraging landscape level changes through agreement on climate change, as discussed in Section 5.1.2. The successful implementation of trials that can validate policy options and familiarise stakeholders with new approaches would be another way of facilitating this. Research Paper IV showed that new markets would be required to stabilise the electricity system with high rates of rooftop PV, and that one option could be the introduction of innovative business models such as P2P energy trading. The RENeW Nexus P2P trial brought these concepts together and tested the motivations of users interested in P2P electricity markets, identified their characteristics and the roles they could play in building those markets. We found that if P2P trading is to enter the mainstream market, the assistance of other actors (e.g. *intermediaries* and *activists*) is important to cross the chasm to reach mainstream users and move from a learning and probing phase to breakthrough and wide diffusion. The analytical framework developed through this research is presented in Figure 4.8 and can be used to target participant recruitment for trials and other transition related initiatives.

It is possible that prosumers may not want to actively assist with stabilising the SWIS through P2P, VPP or DR programs. It was difficult to find prosumers willing to engage in P2P energy trading during the RENeW Nexus project. This, as we proposed in Research Paper V, may have been due to the stage of the P2P model's development, a misalignment between participant and consortium expectations, the design of the trial or the lack of suitably credentialed forerunners from which potential participants would take product recommendations. Or, alternatively, it could just be that electricity customers are most comfortable in their passive historical role of obtaining stable, reliable electricity from a retailer and they are happy to invest in rooftop PV if this can further reduce their energy costs.

As detailed in Section 5.5, it is recommended that electricity retailers, policy makers and entrepreneurs undertake more research to determine the potential to engage prosumers in grid stabilisation services in the future. If prosumers are unwilling to change their traditional roles, it is further recommended that ISOs and electricity utilities evaluate how they can actively maintain system security on behalf of passive prosumers throughout the transition. If, however, prosumers can be engaged in grid-stabilising business models, then the theoretical contribution developed in Research Paper V provides a basis for designing these trials and taking the niche innovations into the mainstream. As identified in Research Paper V, additional research is required to validate the theoretical framework presented in Figure 4.8 related to user roles in the energy transition.

While the uptake of rooftop PV may progress on a linear basis, it is unlikely that transition dynamics within the socio-technical regime will do likewise. Rather, managing the transition will need to be an iterative process that is done in consideration of all aspects of the socio-technical regime.

5.2 Conceptual contributions to the MLP

The MLP is an effective analytical framework for guiding and ordering the analysis of aspects relevant to the current energy transition. The MLP has evolved from the study of multi-decadal transitions that can occur on a global scale. Its application has, therefore, not always been best suited for use in smaller electricity systems undergoing transition, such as that currently occurring within the SWIS. Research Paper II contributed to the MLP literature through the adoption of a methodological approach that built on the work of Wells and Lin (2015), allowing change processes to be more accurately attributed at a local, national or international/global scale. This is important as change processes can proceed at different speeds depending on whether they occur at a local or international scale. This was operationalised in the thesis by mapping change processes and actors as they related to the landscape, regime or niche based on whether this was predominantly occurring at a global, national or local level. This methodological contribution helps to address geographic and temporal weaknesses that have been identified with MLP research (Chandrashekeran, 2016; Coenen et al., 2012; Hansen and Coenen, 2015).

Research Paper V provides a further conceptual contribution through the integration of diffusion of innovation and transitions literature. This integration allows the role of both individual and institutionalised users to be analysed both in terms of user to user (Rogers, 2003) and user to the rest of the socio-technical system (Schot et al., 2016) in all stages of the sustainability transition process. This allows for a more granular study of the role of energy users within different phases of innovation. When integrated with the MLP, this framework can be used to guide transition policy through an improved understanding of the roles users perform at different phases of innovation and how this relates to the broader transition. Research Paper V shows that users can also support the transition by adopting the innovation and collaborating with other project actors, providing it appears to align with their idealised vision for the future and/or is financially beneficial. Users need not be part of a collective movement but, rather, they can be organised and assisted by another intermediary actor in the system.

5.3 Empirical contributions

Electricity systems that are being disproportionately impacted by rooftop PV rather than utility scale projects have been under studied in peer-reviewed literature (Maticka, 2019). The transition unfolding in the SWIS provides an exemplary case study as it is islanded from other electricity systems, meaning that any impacts of high rates of rooftop PV will be experienced sooner and need resolving quicker than in other systems that are connected to neighbouring systems. Research Papers III and IV provide empirical contributions to this research gap through study of the technical, economic, socio-political, and regulatory and institutional aspects affecting the transition within the SWIS.

Research Paper V provided an empirical contribution in identifying the motivations for why users were interested in joining a P2P market trial. This was the first time globally that P2P energy had been traded on a public electricity market and had been analysed.

5.4 Concluding comments

Navigating the transition as the SWIS shifts from thermal coal and gas to a solar PV dominant system requires the management of multiple factors to ensure that a stable electricity supply is maintained. Addressing the technical and market solutions so they better match the new inverter connected technologies embedded across the distribution system will be critical. However, these technical and market solutions are but two aspects within the socio-technical regime. Integrated approaches that consider all elements of the socio-technical regime, including their relationship to other landscape forces and emerging niche innovations will be required. Many of these factors have been explored and expanded upon in the papers that comprise this thesis and can be summarised by the following four factors:

1. Understanding and addressing the historical lock-in mechanisms that influence the ability to transition.
2. Identifying and leveraging those landscape level factors that can assist with reconfiguring regulations, institutions and socio-political factors within the socio-technical regime.
3. Identifying how and when to best engage prosumers with aspects of the transition.
4. Implementing technical solutions with supportive markets to ensure system stability with consideration to the preceding three points.

5.5 Recommendations for future research

This thesis has been far ranging, which is appropriate given the integration of electricity within all aspects of modern society. Consequently, it has had a relatively light touch on many aspects of the transition and targeted research will now be required into specific aspects of the transition. Change processes within the regulatory regime have evolved alongside the historical electricity system. This has resulted in processes that can, in many instances, take a decade to implement. This is not adequate to keep up with current rooftop PV installation rates and associated system and market impacts. Applied research is required into how policy development and implementation processes can be modernised to keep pace with rapid technological changes.

As prosumers continue to install rooftop PV, they are inadvertently impacting the operability of the electricity system. More applied research is required by electricity retailers, policy makers and entrepreneurs into how and/or if prosumers will be willing to participate in managing these impacts. Answers to these questions could greatly influence the range of transition solutions available to policy makers and system operators in the near to medium term. A lack of interest points to a reliance on technological solutions (such as batteries), whereas an active or potential interest opens the door to a broader range of solutions (such as tariff reforms, VPPs, P2P trading schemes and DR programs).

The conceptual framework presented in Research Paper V would benefit from being tested within case studies that provide longitudinal empirical analysis in different geographies and sectors. This should look at identifying the characteristics of users and the roles they take in innovation and transitions.

The speed at which individual energy systems will need to adapt to the changing energy landscape will likely be system specific. Each system will need to develop transition roadmaps with priorities dependent on the VRE make-up, local markets, system architecture and user relationships to the changing niche innovations, landscape and regime.

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Appendix 1: Signed contribution statements

Appendix 1: Signed contribution statements

Research Paper I:

I Sam Wilkinson contributed 80% to the paper:

Wilkinson, S., John, M., Morrison, G. M. (2021). Rooftop PV driving Australia's renewable energy transition; a review of driving forces and analytical frameworks. Manuscript submitted to peer review journal, awaiting response.

Specifically, I contributed the following:

Conceptualisation and design, acquisition of data, contribution of knowledge, analysis and interpretation of results, drafting, revising and final approval of the paper.

Signature of candidate:..Date: 16/3/21

I, as co-author, endorse that the level of contribution by the candidate indicated above is appropriate:

Michele M. John:..Date: 22 March 2021

G.M. Morrison

Gregory M. Morrison:...... ....Date: 16/03/2021

Research Paper II:

I, Sam Wilkinson contributed 85% to the paper:

Wilkinson, S., Davidson, M., & Morrison, G. M. (2020). Historical transitions of Western Australia's electricity system, 1880-2016. *Environmental Innovation and Societal Transitions*, 34, 151-164. doi:10.1016/j.eist.2020.01.003

Specifically, I contributed the following:

Conceptualisation and design, acquisition of data, contribution of knowledge, analysis and interpretation of results, drafting, revising and final approval of the paper.

Signature of candidate:……………………………………..Date: 16/3/21

I, as co-author, endorse that the level of contribution by the candidate indicated above is appropriate:

Michael Davidson:…………………………………………...Date 23rd March 2021

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Gregory M. Morrison: .Date: 16/03/2021

Research Paper III:

I Sam Wilkinson contributed 85% to the paper:

Wilkinson, S., & Morrison, G. M. (2018). Enablers of an electricity system transition. In Prasad Kaparaju, Robert J. Howlett, John Littlewood, Chandima Ekanyake, & Ljubo Vlacic (Eds.), *Proceedings of the 10th International Conference in Sustainability on Energy and Buildings (SEB'18)* (pp. pp. 464-477): Springer.

Specifically, I contributed the following:

Conceptualisation and design, acquisition of data, contribution of knowledge, analysis and interpretation of results, drafting, revising and final approval of the paper.

Signature of candidate:……………………………………….Date: 16/3/21

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Gregory M. Morrison: **Date: 16/03/2021**

Research Paper IV:

I Sam Wilkinson contributed 75% to the paper:

Wilkinson, S., Maticka, M. J., Yue, L., & ~~Michele,~~ John, M. J. (2021). The duck curve in a drying pond - the impact of rooftop PV on the Western Australian electricity transition. *Energy Utilities*, (undergoing second round of review).

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Research Paper V:

I Sam Wilkinson contributed 50% to the paper:

Wilkinson, S., Hojčková, K., Eon, C., Morrison, G. M., & Sandén, B. (2020). Is peer-to-peer electricity trading empowering users? Evidence on motivations and roles in a prosumer business model trial in Australia. *Energy Research & Social Science*, 66. doi:10.1016/j.erss.2020.101500

Specifically, I contributed the following:

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Gregory M. Morrison: **Date: 16/03/2021**

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Review

Rooftop PV and the Renewable Energy Transition; a Review of Driving Forces and Analytical Frameworks

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Abstract: Rooftop solar photovoltaics (PV) are accelerating the transition towards low carbon electricity systems in many countries, particularly in Australia. This review paper provides an overview of the (1) technical, (2) economic, (3) socio-political, and (4) regulatory and institutional aspects that should be considered concurrently when navigating the transition towards a rooftop PV-dominated electricity system. We consider the suitability of two prominent long-range transitions theories for understanding the importance and interaction of elements within these four aspects during the transition. The multi-level perspective (MLP) of transitions theory is considered best suited for this task as it addresses fundamental shifts in the socio-technical systems, rather than being weighted towards technological and/or economic solutions. We find that relatively little research has been undertaken where the renewable energy transition is being driven by the uptake of rooftop PV within the distribution network of established islanded electricity systems. These islanded electricity systems will be the first to experience system impacts from high levels of rooftop PV. This review provides further analysis of important gaps in understanding the rooftop-PV-led energy transition and the implications for policy makers in maintaining stable electricity supplies during the transition.

Keywords: rooftop PV; variable renewable energy (VER); energy transition; techno-economic paradigm (TEP); multi-level perspective (MLP)

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1. Introduction

Australia's transition towards an electricity system dominated by renewable energy sources is unfolding faster than many would have expected, particularly given the deep political divide over the need to address climate change in the country. Blakers, et al. [1] reported that Australia is installing wind and solar energy at a rate that is four to five times faster on a per capita basis than is occurring in China, the United States, Japan or the European Union. They further project that, at this rate, Australia would reach 50% renewable electricity in 2024 and 100% in 2032. Rooftop photovoltaic (PV) systems are now installed on over a third of homes in some Australian states [2,3]. The rapid uptake of renewable energy is starting to redefine the way electricity systems and their associated markets can operate in Australia and many places around the world [4–8].

Many of the effects of rooftop PV on centrally controlled electricity systems are similar to those from utility scale wind and solar variable renewable energy (VRE) sources, such as their limited dispatchability and inherent variability. There are, however, many effects that are unique to rooftop PV, requiring specific measures and targeted research. Rooftop PV is located within the distribution network, rather than the transmission system [9]. It is produced by parties that have traditionally been electricity customers rather than energy wholesalers [10,11] and their output is neither directly visible to, nor controllable by the integrated system operators (ISOs) [9,12]. The very low short-run marginal cost of energy produced by rooftop PV reduces the prices that can be obtained in wholesale energy markets by other generators, causing the merit order effect [13–18]. This effectively reduces the profitability of many coal- and gas-fuelled facilities, which then contributes to their early retirement [19]. Whilst this may be viewed as the effective functioning of a market, it has the potential to cause significant system security problems if the traditional thermal generators exit the market quicker than the techno-economic, socio-political, regulatory and institutional challenges can be addressed. Failure to make the timely policy adjustments could result in the need to occasionally disconnect electricity users in some parts of the distribution system to protect the broader electricity system from collapse or to severely limit the numbers and locations of new rooftop PV connections [19,20]. Both are politically and socially unpalatable outcomes.

The economic drivers for installing rooftop PV systems are also different to those associated with other generation sources. Domestic and commercial premises installing rooftop PV systems peg their pay-back period against higher retail energy prices rather than the lower wholesale energy prices that utility scale energy projects need to compete with. As a result, there is an acceleration in the uptake of rooftop PV and consequent early retirement of traditional coal and gas generators occurring in some Australian electricity systems [19]. As these traditional generators exit the market, they take with them properties such as inertia, system strength, load following and fault current that they inherently supplied to stabilise the electricity system. Whilst many technical solutions exist to address the loss of these properties from electricity systems, markets do not currently exist that allow for many of these technical solutions to be monetised and therefore enabled. For example, Australian markets do not have mechanisms by which batteries or other distributed energy resources can participate in energy markets or be paid for their network stabilising services. Other mechanisms, such as demand response (DR) programs, virtual power plant (VPP) operators or peer to peer (P2P) trading schemes are also ineligible to bid into electricity markets [21,22]. Managing the transition must therefore consider a number of technical and economic aspects.

Making the market changes to introduce new system-stabilising services will inevitably influence the viability of existing participants and those intending to enter the market. This introduces politically contested spaces that can rely on prior societal acceptance of the need to change if the transition is to be managed in a timely and effective manner [23,24]. The scale of this challenge can be amplified with the new role of prosumers, who effectively expand the number of market participants from tens of generators to the millions of generators that will be directly affected by policy shifts. Socio-political factors must also therefore be managed to allow for the rapid uptake of rooftop PV within the distribution system to occur without compromising the security of the electricity system during the transition.

Whilst industry and researchers know that significant electricity system change is occurring and at an accelerating rate, the electricity sector does not have recent experience in dealing with such rapid and significant change [25]. Electricity demand has historically steadily risen, with increasing demand met through slow and well-planned additions of generation and transmission capacity that could be safely implemented within five- to ten-year time horizons [25]. In the case of rooftop PV, much of this change is being exerted upon the incumbent regime by their traditional customers and is requiring substantial infrastructure augmentation to be financed, designed, built and made operational within time periods ranging from months to years [19]. Rooftop PV generation is also being built in an unplanned manner across the distribution system, rather than through the centrally controlled transmission system [26]. This duality combines to represent a fundamental reconfiguration of the relationship between markets, electricity consumption and production patterns and electricity transportation.

With such a fundamental and transformational shift in the provision of energy as an essential service, more knowledge is needed to allow policy makers to understand how the transition can be managed under accelerating timeframes [27] and in a way that guarantees continuity of supply, financial sustainability and supportive prosumer focused business models. Managing the rapid uptake of rooftop PV within the distribution system must therefore also address the regulatory and institutional changes that can enable or hinder the transition.

This paper uses a semi-systematic (S-SLR) literature review methodology to identify the key enablers and blockers of a transition to a rooftop PV-dominated electricity system. The primary purpose is to identify, at a high level, the factors that should be considered by policy makers in electricity systems where the transition is being underpinned by rapid adoption of rooftop PV. The primary themes uncovered through the review include the need to consider (1) technical, (2) economic, (3) socio-political, and (4) regulatory and institutional aspects that can either enable or block the transition process. Key factors within each of these aspects are outlined in Section 5 of this paper.

The secondary purpose of this paper is to identify which theoretical frameworks are best used to understand the relationships between the four key aspects identified through the S-SLR and how these relationships inform and assist the transition towards electricity systems dominated by rooftop PV. The objective is to aid policy makers and energy system planners to develop roadmaps of key factors to be considered during the transition and how they relate to each other.

This paper found that the literature uncovered by the search terms either explicitly or implicitly considered transition factors using techno-economic or socio-technical perspectives. In Section 4, the merits of these two long-range analytical frameworks for understanding and guiding policy in the current transition are discussed. Both the techno-economic perspective (TEP) and multi-level perspective (MLP) of socio-technical transitions theory are considered. The TEP has strengths in considering the technical and market related drivers of transitions, whereas the MLP has strengths in integrating the multi-dimensionality and multi-actors involved in spatial and temporal transitions [28]. A key difference between these theories lies in the TEP's underlying philosophy that economic decisions are fundamentally rational [29], whereas socio-technical transition theory makes allowances for decision making processes that can include social, political and other factors that are not necessarily rational [30]. Recommendations for future research into which transition factors should be considered to ensure a stable electricity supply, as brownfield electricity systems shift from traditional thermal coal and gas to systems being dominated by solar PV, are then presented.

In the following section, the methods used to undertake the S-SLR are described. This is followed by an overview of the results obtained from the review in Section 3. Section 4 then investigates frameworks for considering the large amounts of information and multiple aspects relevant to the transition. The aspects identified in the literature that require resolution to enable very high rates of solar PV within electricity systems are then discussed in Section 5. These are discussed as they relate to the technical, economic, socio-political, and the regulatory and institutional aspects. The conclusions drawn from this work and how the aspects are conceptualised within the MLP are then presented in Section 6, along with recommendations for further research.

2. Methods

This paper is grounded in a positivist ontology based on an underlying assumption that a transition is occurring within the electricity sector towards a lower carbon-emitting generation profile. An inductive approach is used [31] within the literature review to identify key themes and issues associated with this energy transition.

A S-SLR process was followed due to its suitability for studying topics that have been conceptualized differently by researchers across diverse disciplines using predominantly qualitative methodologies [32]. As described in Figure 1, this approach combines a systematic literature review (SLR) together with additional references obtained via a snowballing approach using reference and citation tracking of the papers identified by the SLR. This compares with the meta-analysis undertaken within SLRs, which are best employed to quantitatively analyse comparisons of research paper findings that have each used similar methodologies [32,33]. Sovacool, et al. [34] also reported that SLRs are suited to studies with relatively narrow research questions rather than multidimensional problems. The S-SLR process, by contrast is useful for obtaining an overview of issues and analytical frameworks used to interpret research problems [32].

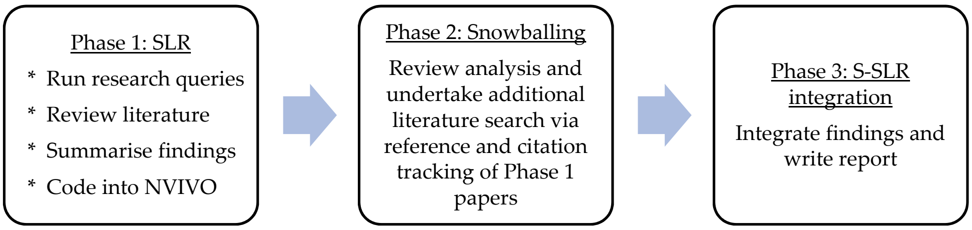

Figure 1. Semi-systematic literature review methodology used in this paper.

As described by Figure 1, the review was undertaken in three phases. The first phase followed a SLR process using the search terms contained in Table 1. These terms were formulated to answer the central research question of: what factors enable and/or hinder the uptake of rooftop PV within brown field electricity systems and which analytical frameworks have been used? The search criteria focused on identifying literature review papers as these can assist in rapidly identifying key themes, research approaches and gaps in a scientific field [35], which was a key aim of this exploratory research. Results were limited to peer-reviewed literature published in the past five years. Key themes identified through the SLR were coded into NVIVO 12 social science software in accordance with themes that emerged through their review.

Table 1. Search terms used for the SLR, the number of returned results and the number of papers consequently selected for further review and synthesis.

Database	Search Terms	Results *	Selected for Further Review
Scopus	"energy transition" AND *"electricity"* AND (*"system stability"* OR *"constraint*"* OR *integration* OR *"frequency regulation"* OR *"ancillary services"*) AND TITLE-ABS ((*"systematic review"* OR *"systematic literature review"* OR *"literature"* OR "review paper" OR *"meta*analysis"*) AND (*"solar"* OR *"PV"* OR *"distributed energy"* OR *photovoltaic* OR "duck-curve" OR "duck curve")) AND (EXCLUDE (SUBJAREA, *"MATE"*) OR EXCLUDE (SUBJAREA, *"MEDI"*) OR EXCLUDE (SUBJAREA, *"BIOC"*) OR EXCLUDE (SUBJAREA, *"AGRI"*) OR EXCLUDE (SUBJAREA, *"ARTS"*) OR EXCLUDE (SUBJAREA, *"CENG"*) OR EXCLUDE (SUBJAREA, *"CHEM"*) OR EXCLUDE (SUBJAREA, *"PHYS"*)) AND (LIMIT-TO (PUBYEAR, *2020*) OR LIMIT-TO (PUBYEAR, *2019*) OR LIMIT-TO (PUBYEAR, *2018*) OR LIMIT-TO (PUBYEAR, *2017*) OR LIMIT-TO (PUBYEAR, *2016*))	88	50
Scopus	"energy transition" AND "electricity" AND ("system stability" OR "constraint*" OR integration OR "frequency regulation" OR "ancillary services") AND TITLE-ABS (("systematic review" OR "systematic literature review" OR "literature" OR "meta*analysis") AND ("solar" OR "PV" OR "distributed energy" OR photovoltaic) AND (enable* OR allow OR assist OR facilitate OR encourage OR hinder OR discourage OR block* OR obstruct OR delay OR impede OR deter)) AND (LIMIT-TO (PUBYEAR,2021) OR LIMIT-TO (PUBYEAR,2020) OR LIMIT-TO (PUBYEAR,2019) OR LIMIT-TO (PUBYEAR,2018) OR LIMIT-TO (PUBYEAR,2017) OR LIMIT-TO (PUBYEAR,2016))	30 (11)	8

Table 1. *Cont.*

Database	Search Terms	Results *	Selected for Further Review
Web of Science	ALL = ("energy transition" AND "electricity" AND ("system stability" OR "constraint*" OR integration OR "frequency regulation" OR "ancillary services")) AND AB = (("systematic review" OR "systematic literature review" OR "review paper" OR "literature" OR "meta*analysis") AND ("solar" OR "PV" OR "distributed energy" OR photovoltaic))	5(1)	1
	Papers excluded after detailed review		8
	Total		**51**

* Unique results not uncovered in preceding search are listed in brackets.

References were limited to those relevant to the adoption of renewable energy in brownfield electricity systems and excluded literature pertaining to the adoption of these technologies in developing countries that did not have pre-established centralised energy systems. As noted by Sareen and Kale [36], the issues facing developing and developed countries can be markedly different from each other.

After analysis of the literature uncovered by the SLR, broader literature was then identified via a snowballing technique using reference and citation tracking of the SLR papers. This approach was used to further interrogate the specific enablers, blockers and analytical frameworks identified through the SLR and to gain additional context on issues uncovered through the initial literature search. Results from phases one and two were then integrated for the final report write-up.

3. Overview of SLR Papers and Their Theoretical Framing of the Energy Transition

Of the 51 papers analysed via the SLR, only five were dedicated literature review papers specific to the uptake of rooftop PV. This is not surprising given that rooftop PV is a relatively new and developing area and is consistent with the literature reviews within the remaining papers. These five papers analysed the energy transition by focusing on socio-political factors [37], economic factors [38] or combined socio-technical issues including, technical, economic, social, political, regulatory and institutional factors [39–41]. A further 22 of the papers were dedicated literature reviews, however these were generic to the energy transition, rather than being specific to rooftop PV adoption. The remaining papers contained literature reviews that were generic to various aspects of the energy transition.

The review of all papers uncovered by the SLR found that managing the energy transition has been studied through the separate consideration of technical issues, economic/financial factors, socio-political issues and/or regulatory and institutional issues. These factors are defined in Table 2, along with an indication of the number of papers that included those aspects within their analysis. A complete breakdown of which SLR papers considered these aspects is presented in Appendix A.

The literature also, either implicitly or explicitly, presented analyses within either socio-technical or techno-economic theoretical framings. These frameworks emphasise the relative importance that the aspects identified within Table 2 provide in terms of influencing the energy transition. Section 4 details the strengths and weaknesses of these two theoretical frameworks. A summary of how the literature considers the four factors in Table 2 that enable and/or hinder the uptake of very high levels of rooftop PV is then summarised in Section 5.

Table 2. Categorisation of aspects that influence the uptake of VRE and rooftop PV based on specific elements of the socio-technical regime. The third column shows the number of papers uncovered in the SLR that addressed the respective aspects (note that papers typically addressed more than one aspect).

Aspect	Characteristic	No. of Papers
Technical	Studies that investigate the operational characteristics of the physical electricity production, conversion, distribution, transmission and control infrastructures and systems.	30
Economic	Studies that consider the financial drivers and investment impediments associated with the electricity system	31
Socio-political	Consideration of the politics of energy together with its intersection with electricity users and prosumers and their adoption of new technologies and business models. It includes ethical issues such as social justice.	25
Regulatory and Institutional	Primarily related to the policy and regulatory settings and the ability of institutions to adapt to the changes related to the niche innovations and business models.	16

Overall, articles were sourced from 25 different journals, reflecting the breadth of journal disciplines that are providing coverage of the renewable energy transition and the divergent factors that are relevant to the energy transition. The foci of the journals were also broad, with the majority taking an extended triple bottom line sustainability focus. Journals included those with a focus on the economic, policy, social sciences or technical/applied aspects. Of the 52 articles selected for inclusion in the review, 10 were sourced from *Renewable and Sustainable Energy Reviews*, 7 from *Applied Energy* (7) and 5 from *Energy Research & Social Science* (5) (Figure 2). A further 17 articles were sourced from 17 different journals, with the balance coming from journals that supplied 2–3 articles.

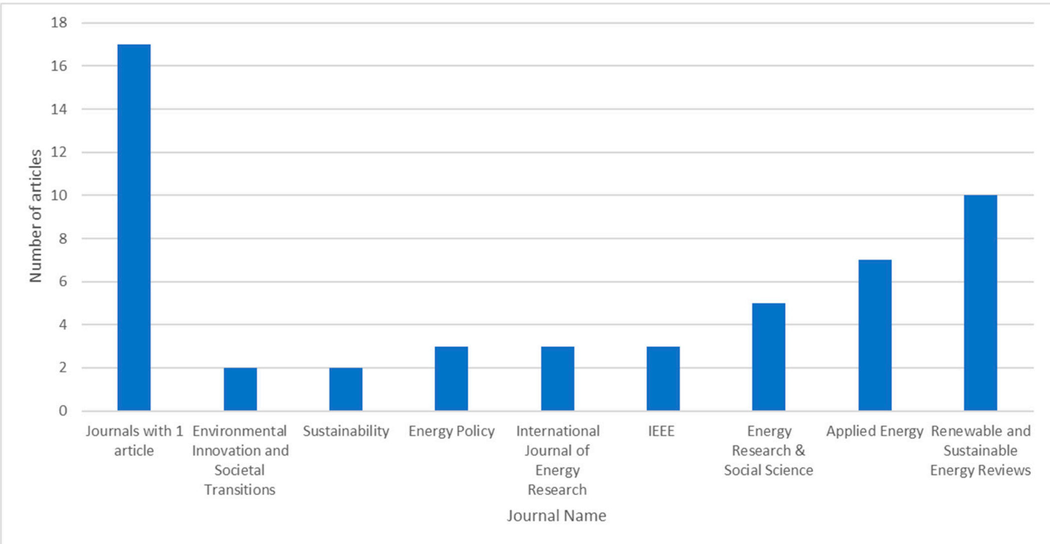

Figure 2. Journals from which SLR articles were sourced.

4. Analytical Frameworks for Understanding Renewable Energy Transitions

This section considers two prominent long-range theories used to consider energy transitions—the techno-economic paradigm (TEP) and the multi-level perspective (MLP) of socio-technical transitions. Understanding the energy transition requires the coordination of multiple factors beyond technical and economic aspects [42,43]. This can be aided by using theoretical frameworks, which are heuristic approaches that assist researchers to order and make sense of large amounts of information [44]. The adoption of frameworks for ordering information is critical in understanding and managing the energy transition, since any changes to its production and delivery will influence the institutions, political spheres, and normative behaviours of those using it.

Sovacool and Hess [44], considered 96 different theories and conceptual approaches that could be used for explaining the *adoption, use, acceptance, diffusion or rejection of new technology*. The adoption and integration of rooftop PV into electricity systems can be considered a new technology in this context. They found that the major theories integrate multiple theoretical perspectives to make sense of the differing factors that influence the diffusion or rejection of innovations such as solar PV adoption. The MLP was the most popular theory amongst their interview respondents and is considered to be the dominant framework used to assess transitions within the socio-technical transitions literature [28]. By comparison, the TEP is a dominant framework that gives pre-eminence to technological and economic factors as drivers for a transition, which were the most regularly researched aspects uncovered in this review.

4.1. Techno-Economic Paradigm (TEP)

The TEP is based on Schumpeter's principles of creative destruction, where new technologies, led by entrepreneurs enter the market and catalyse the shifts in supportive technologies [45]. Shifts that occur under a TEP require the institutions, rules and social norms that have locked in existing technologies to make way for clusters of new technologies to diffuse in a manner that ultimately shifts the economy [46]. The concept of clusters of technologies that are required to support each other was originally introduced by Freeman [47]. The waves of transition described under the TEP occur over several decades and were characterised as relating to five separate waves (these waves started with the industrial revolution (starting 1771), shifting to steam and railways (starting 1829), the age of steel and electricity (starting 1875), the age of the automobile, oil and mass production (starting 1908) and then the age of information technology and telecommunications (starting 1971) [46]). Whilst Schumpeter saw the institutions, technologies and social organisations as external to the economy, Perez [46] viewed these as internal to the waves of transitions that occur under TEPs.

The successful diffusion of an innovation is fundamentally underpinned by complementary technological innovations that are cost competitive and have a market that is willing to adopt and diffuse them, ultimately resulting in modifications to the socio-institutional structures [46]. Use of the TEP to order information relevant to the energy transition would therefore focus on how to foster supporting technologies and associated markets, whilst acknowledging the need to modify supporting institutions.

Technological aspects were the focus of 30 of the 52 papers identified during the SLR component of this review, whilst economic and financial aspects of renewable energy uptake was considered relevant within 31 of the papers. These were the most consistently researched aspects of transitions towards higher rates of renewables within electricity systems, which reflects the weighting towards these factors within the TEP's theoretical framing.

4.2. Multi-Level Perspective (MLP)

The MLP is derived from evolutionary economics, institutional theory and the sociology of innovation [28,29]. It has often assessed the feasibility of low-carbon transition pathways through analysis of historical niche, regime and landscape developments. Analysing historical transitions can inform our understanding of the enablers and blockers to currently unfolding transitions and can provide insights into potential future transitions pathways [29].

The premise of the MLP is based on sustainability transitions being influenced by dynamics within and between the heuristic levels of the niche, landscape and regime [48]. In the context of the MLP, the niche is where technological innovations can grow and emerge [49–51]. The ability of niches to expand into the regime is influenced by the forces at play within both the socio-technical regime and the overarching landscape. The socio-technical regime is the structure that accounts for the dynamic stability of the socio-technical system and is made up of the rules, actors and behavioural norms of the socio-technical system [52]. This can include separate but intertwined policy, science, technological, user and market and socio-cultural regimes [52,53]. The relationships between these socio-technical regime elements can be self-reinforcing, which can lock-in existing technologies and block the breakthrough and diffusion of emerging niche innovations unless there is an internal regime requirement for the innovation or there are external landscape forces that force a reorganisation of the socio-technical regime, thereby creating the space for the innovation [54,55]. Examples of landscape forces include climate change, war, global pandemics or recession, which drive social and political changes that encourage a reorganisation of the socio-technical regime to adopt the innovation. The actors and groups within the heuristic levels interact in accordance with cognitive, normative and regulative rules [48] and, in so doing, they influence the transition pathways, which can unfold over a number of decades.

4.3. Strengths and Weaknesses of the MLP and TEP

Both the MLP and TEP are focused on change processes that occur over decades. Rooftop PV was initially introduced in the late 1970's [56] and as such, its study using these frameworks can be considered appropriate. The system building role of users in breaking down the existing regime during the energy transition has been proposed by Schot, et al. [57]. However, these changes are focused on multi-decadal transition dynamics and do not pay sufficient attention to the micro dynamics and agency of the users associated with innovations at the local scale [58]. In situations where niche innovations such as rooftop PV are breaking through into a phase of wide dispersion within the socio-technical regime, further research should be undertaken into how long-range theories can be augmented by shorter-range theories with finer granularity.

The strength of the MLP is in its recognition of the multi-dimensionality and multi-actors involved in spatial and temporal transitions [28]. This is particularly relevant for sustainability transitions, which require fundamental shifts in the socio-technical systems, rather than just technological fixes [28]. However, the MLP has received criticism for how it addresses geographical space [59–62], the boundaries between niche, regime and landscape [63] and for its ambiguous methodology, weighted towards bottom-up change models [44,52].

An important assumption of techno-economic transitions is that economic decisions are fundamentally rational [29], which contrasts with socio-technical transition theory, which makes allowances for multifaceted decision making processes that can include social, political and other factors that are not necessarily rational [30]. The TEP has been criticised for undervaluing the roles played by civil society, users, scientists, engineers, media and other social groups, whilst placing most attention on financial institutions and governments in creating the space for turning points or shifts to occur [64]. The need to consider these additional factors is supported by this paper's SLR, which identified the importance of users, scientists, and civil society [40,65–67] in the transition to VRE. The TEP has also been criticised for its lack of emphasis on political contexts and broad landscape factors (such as wars and climate change), the over emphasis on the role of the state (assuming that transitions emerge at the level of the state) and that it doesn't provide details on what happens to the existing paradigm of technologies [64]. Each of these factors have been identified through the full S-SLR as being important in a VRE transition (refer to Table 3 for a weighting of how each of the MLP and TEP considers the factors that should be considered during the transition).

Table 3. Weighting of the MLP and TEP strengths in integrating the key aspects identified in this literature review.

Aspects	Multi-Level Perspective	Techno Economic Paradigm
Technical	High	High
Economic and financial	Medium	High
Socio-political	High	Medium
Regulatory and Institutional	High	Medium

To summarise, key aspects that should be considered when making sense of a transition towards high rates of rooftop PV within an energy system include: technological aspects; economics and markets; users and associated behaviours; global shifts together with political, regulatory and institutional settings; and the interaction between all these aspects. The two long range theories considered above, can frame these multi-dimensional factors in the unfolding energy transition. However, the TEP's emphasis on rational decision making associated with economics and technology decisions make it a less well nuanced framework than the MLP of socio-technical transitions theory. The MLP is well suited for use by researchers and policy makers seeking to understand the multi-faceted dynamics within an energy transition. The MLP may need augmenting by those researchers and policy makers seeking to understand rapid change processes driven by emerging niche technologies such as rooftop PV that can operate at the scale of sub-national electricity systems or within those systems.

5. Challenges Associated with Transitioning to Very High Rates of Rooftop PV within Electricity Systems

Very high rates of rooftop PV within electricity systems impose a series of challenges to the operational reliability of electricity systems. Table 4 presents the broad range of challenges, which have been grouped as technical, economic, socio-political and regulatory and institutional. Managing the transition will require an understanding of each of these challenges and their interrelationships within the socio-technical regime.

Table 4. Issues associated with high rates of rooftop PV in electricity systems.

Issue Type	Challenge	Cause
Technical	Mismatch between system load and generation capabilities	More thermal generators (e.g., coal and gas) will fall below their minimum generation level during midday hours, causing them to either cycle on and off [1] or to pay other generators not to run. This may result in generation being unavailable to support afternoon ramping and/or evening peak loads whilst also removing the additional system support services that they inherently supply (as summarised in the remainder sub-section of this table).
	Lack of visibility and control of significant a portion of generation	As for the above challenge, a significant portion of midday demand will be supplied via inverter-connected rooftop PV systems that are neither visible nor controllable by the ISO. The ISO is only able to dispatch utility scale generators (those greater than 10 MW) for maintaining system security.
	Reduced system inertia	Traditional thermal generators have high spinning inertia, which can resist the rate of change in frequency [68,69]. Exit of these generators results in a reduction in inertia, which makes systems more vulnerable to frequency variation.
	More rapid frequency fluctuations	Uncontrolled VRE without storage respond almost instantly to changes in cloud cover (PV) and wind speed (wind turbines). As a result, inter-interval generation can vary significantly pending changing weather conditions, requiring additional frequency regulation services [69].

Table 4. *Cont.*

Issue Type	Challenge	Cause
	Voltage regulation	As the minimum system load drops, there is expected to be insufficient synchronous generation on-line to absorb the elevated reactive power that results from rooftop PV systems exporting into the distribution system [19] in some electricity systems.
	System strength [2]	Synchronous generators inherently supply system strength, which contributes to system security and is needed most at the centre of the system [70]. Inverter-connected VRE's produce very low levels of system strength and, in the case of rooftop PV are located on the distribution network close to demand centres. Conversely, the existing thermal generators, around which the existing system has been designed, are located further out on the transmission network.
	Ramp rate	The new system load profile characterised by the duck curve with low midday demand and high evening peak requires substantially more ramping than the historically flatter load profile.
Economic	Merit order effect	Near zero short run marginal cost renewables are reducing the clearing prices in energy markets, which is pricing base-load generators out of the market [13–18] and can exacerbate the technical issues identified above.
	Missing money	Renewable energy sources reduce the value and length of peak energy price periods that, in turn, reduces the financial viability of mid-merit and peaking plants [6,71–74] and can exacerbate the technical issues identified above.
	Markets do not exist for new requirements	Many wholesale energy markets do not have rules that would allow the following to monetise their services that could address many of the technical issues identified above [4,75,76]: Chemical energy storage batteries; Distributed demand response programs (including via virtual power plants (VPPs) and peer to peer (P2P) energy trading schemes); Micro-grids.
	Value of electricity	Electricity has become a societal right and politically must be available to all at a minimal cost [15]. Low-cost electricity reduces the potential effectiveness of tariffs that could change behaviours and therefore flatten the system load.
Socio-political	Changing societal roles/relationships with energy	Households have traditionally been electricity customers; however, they are now suppliers of energy to the system and will increasingly be called up to help manage and stabilise the electricity system in a role as prosumer [77].
	Energy justice	Grid defection by those able to afford rooftop PV and/or batteries is driving up costs for those that remain connected to the grid. [78–81].
	Public versus private	With electricity becoming a societal right, renewed arguments arise over the role of government provision requirements [15]. In many systems, the government owns a significant portion of the existing generation and/or transmission and distribution system. Any policy changes allowing further development of renewable energy can negatively impact government assets and revenues, which can lead to inefficient decisions.
	Balancing divergent interests	Political decisions have been shown to be major determinants of the form that energy transitions take [36,82,83].
Regulatory and Institutional	Clarity of purpose	Lack of climate and energy targets, resulting from lack of agreement on the realities of climate change, creates investment and policy uncertainty.
	Speed of change	Traditional generation and network planning and implementation cycle of 5–10 years is too long to handle urgent challenges created by high level PV penetration.

Table 4. *Cont.*

Issue Type	Challenge	Cause
	Strong network problems and path-dependencies	Self-reinforcing constructs exist where firms have critical exchange partners with whom they prefer to conduct business, that are closed to outsiders. Their effective regime of suppliers, customers, funding bodies, regulatory groups, trade associations and the general public can create a lock-in mechanism that reduces the ability of organisations to make rapid change [84].
	Human resources	As change is occurring at such a rapid pace, there is often not enough appropriately skilled staff to resolve emergent issues [39].

[1] Cold or warm re-starts cost in the order of AUD 350/MW or AUD 120/MW, respectively, for coal units. With units ranging in size from 120 MW to 330 MW, these restarts can cost AUD 14,000 to AUD 40,000 per warm restart and AUD 42,000 to AUD 115,000 per cold restart depending on the individual unit sizes. [85] These costs do not include the increased maintenance costs associated with cycling these units.
[2] System strength is the available fault current at a specified location in the power system, where higher fault current indicates higher system strength [71]. It represents the ability of the power system to both remain stable under normal conditions and return to steady state conditions following a disturbance [19].

The largest body of available literature was focused on the technical integration of rooftop PV systems (30 of 51 articles) and the economic problems and/or opportunities that this presented to the electricity system and its users (31 articles). The following sections provide additional information on the technical, economic, socio-political and regulatory and institutional challenges posed by high levels of rooftop PV specifically and VRE generally.

5.1. Technical Aspects

In traditional centralised energy systems, electricity is transmitted across the network in an alternating current that changes frequency at a rate of 50 or 60 hertz (dependent on the jurisdiction). The frequency is used as a measure of the system's balance and must be maintained within a close band of approximately plus or minus 0.5 hertz to avoid system collapse. The system's frequency will drop when a generator trips off, or customers turn on equipment that draws power. The centralised integrated system operator (ISO) responds in these situations by dispatching generators up or down to bring the frequency back to a safe level and thereby ensure that the instantaneous supply and demand for electricity is balanced. To do so, the ISO has historically had visibility over the operating parameters of all generators in the power system and the capacity to dispatch them up or down in response to system requirements.

Rooftop PV, however, is not visible to ISOs and is also not controllable or dispatchable by them [86,87]. This has not been a problem in power systems where rooftop PV contributes relatively small amounts to the electricity system. This creates several problems for ISOs where a significant proportion of instantaneous energy demand is coming from self-generated rooftop PV systems during some trading intervals. It can push the midday energy demand below the minimum operating levels of the larger coal and gas generators, forcing some of them to switch off, leaving ISOs with fewer options to dispatch and control for frequency variations. Some generators can cope with this fluctuation, such as gas turbines, which can cycle on and off over the course of the day, but for large steam-driven generators, such as coal and open cycle gas turbines, cycling on and off within a day may not be a viable option. These generators have been required to meet the afternoon and evening peak demand periods and therefore have been required to stay on during the midday low demand periods to avoid cycling costs. To do so, they have increasingly been forced to bid negative prices into the energy market, effectively paying to displace low priced utility scale wind and solar facilities to discourage them from producing. The larger steam generators have also introduced high levels of inertia into the power system, which has further slowed the rate of change in frequency due to changes in load and/or generation. Displacement of these generators by rooftop PV from the energy system reduces system inertia.

Rooftop PV can fluctuate rapidly in response to cloud movements and the rising and setting sun, giving rise to the term variable renewable energy (VRE) source. Whilst the rising and falling of the sun is entirely predictable, it often occurs close to the system's peak demand periods, which accentuates the concurrent steep ramp rate and requiring market participants to rapidly supply energy at those times. This becomes more challenging when rooftop PV has displaced these generators from the market during the middle of the day. The effects of cloud movements can largely be predicted and controlled with accurate weather forecasting [74,88]. It does, however, introduce additional variability that needs to be increasingly managed by ISOs and, if done poorly, can result in market inefficiencies [74,88].

As the minimum system load drops with additional rooftop PV, there can be insufficient synchronous generation on-line to absorb the elevated reactive power and voltage levels that result from rooftop PV systems exporting into the distribution system [19]. The increasing proportion of inverter-connected devices together with the removal of traditional thermal generators reduces fault current and therefore system strength [89]. System strength is the available fault current at a specified location in the power system, where higher fault current indicates higher system strength [71]. It represents the ability of the power system to both remain stable under normal conditions and to return to a steady state condition following a disturbance [19]. Inverter-connected energy sources, such as rooftop PV and utility scale wind and solar facilities effectively supply no fault current.

ISOs currently lack control systems that can deal with the shift from tens of generators that were located on the transmission system towards one that has a very large number of small inverter-connected rooftop PV systems generating significant portions of the energy from within the distribution system. This will require improved coordination between the distribution system and transmission system operation [26] and the development of automated control mechanisms [90].

ISOs also lack technologies, such as improved inverter and metering technologies, that can allow them to control the rooftop PV systems located across the distribution system, [91,92]. The absence of these devices has also been identified as an issue that impacts the ability to implement time of use tariffs, or to be externally controlled by third parties via demand response (we have adopted the definition for demand response as used by [93]: "Changes in electric usage by end-use customers from their normal consumption patterns in response to changes in the price of electricity over time, or to incentive payments designed to induce lower electricity use at times of high wholesale market prices or when system reliability is jeopardized") programs or to participate in distributed energy markets such as VPPs and P2P schemes [94]. These programs and markets have been proposed as mechanisms that could incentivise load shifting and reduce ramp-rate requirements [14,95]. These programs and markets may also be used to address short-term energy supply and demand imbalances and to meet requirements for additional frequency response [7,76].

Much of the research into technical impacts and solutions to high VRE and rooftop PV impacts on power systems is focused on electricity systems that have interconnections to neighbouring power systems or in very small standalone micro-grids. Limited research has been undertaken on electricity systems servicing several million customers that have very high rates of VRE, including rooftop PV and that are islanded from any neighbouring electricity system. These islanded systems are likely to demonstrate the impacts of rooftop PV sooner than larger systems that can import support from neighbouring electricity systems and therefore islanded systems warrant further research.

5.2. Economic Aspects

The costs of rooftop PV and other VRE sources have dropped dramatically over the past decade, with the International Renewable Energy Agency reporting that 80% of PV and wind projects commissioned from 2020 will produce electricity cheaper than fossil fuel alternatives [96]. Similarly, the cost of lithium ion battery packs has fallen 87% between 2010 and 2019 [97], with rooftop PV prices falling 79% in the same period [98]. At the same time, electricity prices purchased from the grid have typically been increasing, which further incentivises customers to invest in self-generation and the accelerated uptake of associated batteries. The International Energy Agency projects that 80% of the growth in energy demand will be met by solar PV over the next decade [99]. They also note that PV is now cheaper than both gas and coal generation in most countries and that it is producing electricity at the lowest costs ever recorded [99]. These landscape-level price changes can be expected to accelerate rooftop PV uptake and intensify the need to address the associated impacts.

Rooftop PV and utility scale VRE sources have been shown to suppress the clearing price in energy markets, reducing the profitability of traditional base-load generation in many energy markets around the world [13–18,100]. This phenomenon is referred to as the merit order effect (MOE). In addition, these renewable energy sources reduce the value and length of peak energy price periods causing the "missing money problem" which reduces the financial viability of mid-merit and peaking plants [6,72–75]. Whilst this may be viewed as the effective functioning of a market, it has the potential to cause significant system security problems if the traditional thermal generators exit the market quicker than the techno-economic, socio-political, regulatory and institutional aspects can be addressed.

Whilst many technical solutions exist to address the challenges introduced to system operation by rooftop PV, energy markets do not currently exist that allow for many of these technical solutions to be monetised. For example, many markets do not have a mechanism by which distributed energy resources can participate in demand response programs, nor for aggregators, VPP operators or P2P trading schemes to bid into a market [21,22]. Similarly, batteries are excluded from participating in many energy markets. Market rules in some jurisdictions were developed to only allow generators to provide system support services, thereby excluding the use of batteries and other non-synchronous technologies [101,102]. This is a legacy issue reflecting the times in which the rules were originally written, but updating these rules introduces political and vested interest debates that can take many years to resolve.

Tariff reforms aimed at flattening the load curve can be an effective mechanism for reducing evening peak ramping requirements and raising the mid-day minimum system load [14,103,104]. This can be helpful to slow the speed at which traditional coal and gas generators need to exit the market due to a miss-match between their operating characteristics and the new system load. This provides policy makers with additional time to address the technical, economic, regulatory, institutional and socio-political factors required to maintain a stable electricity supply with increasing rates of rooftop PV. However, with electricity now considered an essential service and societal right, politicians must ensure that it is available to all at a minimal cost [15]. By supplying electricity at a very low cost, the potential effectiveness of tariffs as a mechanism for changing behaviours that flatten system loads is diminished.

Managing the transition will therefore require market mechanisms that can value potential solutions to the challenges posed by introducing new technologies and removing/reducing historical and legacy dominant technologies. Doing so requires an understanding of the interplay between the socio-political, techno-economic, technical, regulatory and institutional mechanisms that have developed and locked in the legacy regime.

5.3. Socio-Political Aspects

Nearly half of the references within the SLR identified the importance of user acceptance of renewable energy technologies and/or enabling business models for a successful transition. Socio-political acceptance relates to community acceptance at the broadest level [24] and can be reflected in the decisions that politicians make within democratic countries. Each of the technical and economic challenges identified in the preceding section will need to be addressed to allow for a successful transition, which will be dependent on prior political and social acceptance [23,24] to enable their introduction. This section presents the S-SLR findings related to how political and social acceptance are high-level enablers and blockers to the adoption of significant rates of rooftop PV.

Low levels of rooftop PV uptake can be facilitated without many regulatory changes, however, as penetration levels become significant, as is occurring in Australia, political support to enable the required policy and regulatory changes becomes increasingly critical. Hess and Lee [8] argued that there are often convoluted political policy logics in play, which has allowed conflicting policy proposals to be argued for by both incumbent and emergent technologies. This has the effect of slowing the transition process.

Policies to support technologies such as rooftop PV, batteries and electric vehicles typically lag behind both the technological advancements and rates of implementation currently experienced with these technologies [40]. This points to the importance of political support for policy development, a factor supported by research into the adoption of distributed energy resources in the United States [83], UK [78], as well as PV in India [36], and Africa [105]. Huang [84] found that policy support in China was most effective when it occurred consistently across each level of government.

Political decisions have been shown to be major determinants of the structural form that energy transitions take on [36,83,84]. Sareen and Kale [36] noted that many political decisions are made to promote certain renewable technologies without consideration of their relationship to the broader electricity system and other renewable energy sources. Lenhart, Chan, Forsberg, Grimley and Wilson [83] showed that political relationships were the greatest determinant of the amount and type of renewable energy adopted within municipal utilities in the United States.

Jurisdictions affected by rapid adoption and penetration rates of rooftop PV in their electricity systems must therefore identify and implement mechanisms for empowering politicians to lead the transition processes. Democratically elected politicians must be empowered by their voters and media to make the changes that can allow for a reconfiguration of the socio-technical regime. This could be through the setting of carbon reduction targets but must focus on allowing implementation of the enabling technologies, such as batteries, control systems and infrastructure, together with supporting markets and tariffs to allow for their successful implementation. The extent to which politicians are empowered to make these changes will vary on a jurisdictional basis.

Despite being responsible for catalysing a potential re-configuration of the electricity system, prosumers have limited avenues to interact with energy markets and/or assist in managing their impacts on electricity systems. Many new business models to integrate distributed energy resources (DER), including rooftop PV, into the electricity markets, such as via VPPs, P2P trading and demand response programs, have been proposed. However their implementation could require energy users to change their production, consumption and purchasing behaviours [78] and little is known about their willingness to do so [21,78].

The literature review undertaken by Freitas Gomes, Perez and Suomalainen [40] found that user acceptance was a key variable in determining whether people will invest in rooftop PV systems. Kang, Wei, Liu, Han, Yu and Wang [66] identified that more research is required to understand the roles played by individuals, businesses and communities in the energy transition. Ahl, Yarime, Tanaka and Sagawa [21] also reported that relationships between electricity users and blockchain-based P2P business models (and vice versa) have not been empirically studied.

Whilst transitioning current consumers into becoming prosumers makes sense in theory, actual behaviours may not conform to predictive models. Real-life trials have shown that those with solar PV's may use more energy during the day than prior to PV installation, and therefore there will be less PV-generated energy available for load shifting [38]. Behaviours may also vary for those with rooftop PV with batteries that are at home during the day versus those working away from home. The energy use behaviours of these households have the potential to influence the effectiveness of different policy responses, and therefore needs to be better understood. The S-SLR has shown that, to manage the transition to high rates of VRE, understanding the actual energy users, their acceptance of new technologies and enabling business models, together with users' actual responses to these, are all critical factors to be considered.

Another key theme emerging from the S-SLR was the need for an energy transition to address social justice issues [36,83,106,107]. This is because rooftop PV is more readily available to those users who own their own home. Energy consumers who rent or cannot afford to install rooftop PV are left to pay increasing energy prices, particularly as those installing rooftop solar start to add batteries and pay less towards the maintenance of the distribution infrastructure. This can result in a phenomenon referred to as the death spiral, where electricity supply prices rise as less energy is purchased from network providers, who have already invested in their infrastructure, whilst those remaining on the grid are left to pay for the grid infrastructure as the number of grid users diminish [79–82]. Some utilities are starting to promote restrictions on the number of rooftop PV systems that can be installed as a means to reduce social justice impacts [83]. Whereas some authors, such as Sareen and Kale [36], consider that addressing social justice issues must be considered in the early phases of transition planning by policy makers.

5.4. Regulatory and Institutional Aspects

The need for locally specific regulatory and policy support was identified in the S-SLR [83]. The adoption of distributed energy resources and enabling markets can vary between neighbouring countries, demonstrating the importance of regulatory, policy and institutional factors in designing energy systems [78]. Policies that were consistently and longitudinally applied were found to be most effective in supporting VRE uptake [65,108]. Research shows that policy affects innovations and the innovations then affect policy settings in an iterative process [84].

Electricity provision has become a societal right in recent decades, which has renewed arguments on the role of markets versus governments in supplying this essential service [7,15]. As the list of services required to stabilise the electricity system grows with the uptake of rooftop PV, further policy research will be required to define the changing roles for governments, institutions and associated markets in electricity provision. This is particularly the case where new approaches are required to replicate services such as inertia, which was inherent to thermal generators but will be increasingly required throughout the transition. The role of government is further complicated in many systems, given that it often owns a significant portion of the existing generation and/or transmission and distribution system. Any policy changes allowing further development of renewable energy can negatively impact government assets and revenues, which can lead to inefficient decisions and further complicate the transition process.

Theo, et al. [109] noted that many regulatory and institutional barriers exist that preclude renewables from some market segments (such as providing ancillary services). As mentioned in Section 5.2, market rules in Western Australia were written to only allow generators to provide system support services, thereby excluding the use of batteries and other non-synchronous technologies [101,102]. This is despite energy storage being considered one of the most important mechanisms by which excess rooftop-PV-generated energy can best be integrated into existing power systems [110–112], in a state which has some of the highest daytime solar radiance in the world.

There are many factors that influence the speed at which enabling regulations and policy can keep pace with the uptake of VRE generally and rooftop PV specifically. Electricity systems in the developed world have been continually adjusting since at least the early 1900s to maintain reliable electricity supply as they have expanded to meet society's growing demand for electricity [25]. Society's relationship with electricity has also changed over this period from being a privilege, to an expected societal right [25]. The regulatory structures and technologies have co-evolved to promote reliability and stability, which has then reinforced a specific path-dependency. Whilst this has undoubtedly resulted in societal benefits through the provision of safe reliable electricity supplies, it has contributed to rigid regulative and normative practices that are ill equipped to respond to the current rapidly changing energy marketplace in Australia and elsewhere. In addition, as change is occurring at such a rapid pace, there is often insufficient appropriately skilled staff to resolve emergent issues [39].

6. Conclusions: Integrating the MLP with the Four Aspects Uncovered in the SLR

Electricity systems are changing with the installation of VRE sources. One form of VRE includes rooftop PV systems, which have unique impacts and require specific responses to manage their effects on the electricity system. The very high adoption rate of rooftop PV in some systems is forcing regulators, system operators, market participants, customers, technology providers, politicians and others associated with the electricity value chain to change their systems, practices and technologies at a pace that the electricity sector has not been exposed to since electricity was first introduced. To navigate the transition and maintain security of supply, policy makers must not limit their focus to the technical and/or economic parameters but must also consider the associated socio-political, policy and institutional changes that must be managed concurrently.

Theoretical frameworks can assist researchers to order and make sense of large amounts of multi-disciplinary information associated with an energy transition. Of the two long-range transitions theories reviewed in this paper, MLP and TEP, we consider the MLP to be more useful for policy makers with an interest in maintaining the security of electricity supply during a transition to high rates of rooftop PV. In this regard we support Schot and Kanger [64]'s criticism of the TEP for undervaluing the roles played by civil society, users, scientists, engineers, media and other social groups, whilst placing most attention on financial institutions and governments for creating the space for turning points to occur. This paper has identified many of the major technical, economic, socio-political and regulatory and institutional aspects that must be managed during a transition dominated by rooftop PV systems. The MLP of transition theory provides a useful framework in considering these multi-dimensional aspects.

Our research suggests that the transition frameworks must also be able to consider the rapid rates of change that are being dictated by the accelerating uptake of rooftop PV in some electricity systems. In systems where the transition is being led by rooftop PV adoptionit, is occurring at a smaller scale and faster pace than was possible with large electricity infrastructure associated with historical energy transitions. Whilst the MLP has been particularly effective in considering multi-decadal transitions, the accelerating rate of rooftop PV installations in some electricity systems may require a more time sensitive approach to framing these change processes. The impacts of rooftop PV on electricity systems will be, and is being, felt very soon in islanded networks with no interconnectors to neighbouring electricity systems. Research into managing the transition should therefore have a prioritised focus on islanded systems. Despite this, the literature reviewed in this paper uncovered very limited research into managing transition in islanded electricity systems with very high rates of rooftop PV uptake.

To assist policy makers in managing the transition, a deeper understanding of the technical and economic impacts of rooftop PV on wholesale energy markets and the associated physical electricity system will be required. Any policy changes made in response to these improved understandings will be constrained by lock-in mechanisms that have evolved as the incumbent energy systems have developed and should also be understood by those intending to manage a transition. This will include gaining a deep understanding of the political, social, regulatory and institutional aspects that can be leveraged to enable a transition or that need addressing so they do not block the successful change processes from occurring.

Whilst there has been significant research into the impacts of utility-scale renewable energy projects on established electricity systems, very little research has been carried out into systems where the transition is being driven by new supply from within the distribution network due to prosumer uptake of rooftop PV. Consequently, more research is required into the evolving roles of prosumers and how their participation can best be harnessed to assist in stabilising the newly developing electricity system. To do so could require an improved understanding of the evolving role of prosumers, both in their capacity to interact in energy markets, but also to facilitate change within the socio-technical regime through their support for niche technologies and markets that will be required to stabilise the effects of rooftop PV systems.

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Appendix A

Table A1. Literature identified in the structured literature review component of the research and taken forward for further review. The table indicates whether each paper identified technical (Tech), economic (Econ), socio-political (Socio-Pol), and/or regulatory and institutional (Reg & Inst) aspects within their research.

Reference	Aspects Considered			
	Tech	Econ	Socio-Pol	Reg & Inst
Adil, A.M., Ko, Y., 2016. Socio-technical evolution of Decentralized Energy Systems: A critical review and implications for urban planning and policy. Renewable and Sustainable Energy Reviews 57, 1025–1037.	1		1	1
Ahl, A., Yarime, M., Tanaka, K., Sagawa, D., 2019. Review of blockchain-based distributed energy: Implications for institutional development. Renewable and Sustainable Energy Reviews 107, 200–211.	1	1	1	1
Al Arrouqi, R.A., Ellabban, O., Rasheed, M.B., Al-Fagih, L., 2019. An Assessment of Different Electricity Tariffs on Residential Photovoltaic System Profitability: Australian Case Study. IEEE, pp. 1–6.		1		
Alipour, M., Salim, H., Stewart, R.A., Sahin, O., 2020. Predictors, taxonomy of predictors, and correlations of predictors with the decision behaviour of residential solar photovoltaics adoption: A review. Renewable and Sustainable Energy Reviews 123.		1	1	
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Berg, A., Lukkarinen, J., Ollikka, K., 2020. 'Sticky' Policies—Three Country Cases on Long-Term Commitment and Rooting of RE Policy Goals. Energies 13.	1	1	1	1
Bhatt, B., Negi, A., 2018. Analysis of Rooftop Solar Photovoltaic System Across the Indian States: Learnings for Sustainable Infrastructure, Sustainable Development Research in the Asia-Pacific Region, pp. 393–419.	1	1		1

Table A1. *Cont.*

Reference	Aspects Considered			
	Tech	**Econ**	**Socio-Pol**	**Reg & Inst**
Castellini, M., Menoncin, F., Moretto, M., Vergalli, S., 2020. Photovoltaic Smart Grids in the prosumers investment decisions: a real option model. Journal of Economic Dynamics and Control.		1	1	
Fontenot, H., Dong, B., 2019. Modeling and control of building-integrated microgrids for optimal energy management – A review. Applied Energy 254.	1			
Freitas Gomes, I.S., Perez, Y., Suomalainen, E., 2020. Coupling small batteries and PV generation: A review. Renewable and Sustainable Energy Reviews 126.	1	1	1	1
Gandhi, O., Kumar, D.S., Rodríguez-Gallegos, C.D., Srinivasan, D., 2020. Review of power system impacts at high PV penetration Part I: Factors limiting PV penetration. Solar Energy.	1			
Gosens, J., Binz, C., Lema, R., 2020. China's role in the next phase of the energy transition: Contributions to global niche formation in the Concentrated Solar Power sector. Environmental Innovation and Societal Transitions 34, 61–75.	1	1	1	1
Grøttum, H.H., Bjerland, S.F., Granado, P.C.d., Egging, R., 2019. Modelling TSO-DSO coordination: The value of distributed flexible resources to the power system. IEEE.	1			
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Huang, P., 2019. The verticality of policy mixes for sustainability transitions: A case study of solar water heating in China. Research Policy 48.			1	1
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Table A1. *Cont.*

Reference	Aspects Considered			
	Tech	Econ	Socio-Pol	Reg & Inst
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Lenhart, S., Chan, G., Forsberg, L., Grimley, M., Wilson, E., 2020. Municipal utilities and electric cooperatives in the United States: Interpretive frames, strategic actions, and place-specific transitions. Environmental Innovation and Societal Transitions 36, 17–33.			1	1
Lenhart, S., Nelson-Marsh, N., Wilson, E.J., Solan, D., 2016. Electricity governance and the Western energy imbalance market in the United States: The necessity of interorganizational collaboration. Energy Research & Social Science 19, 94–107.		1		
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von Wirth, T., Gislason, L., Seidl, R., 2018. Distributed energy systems on a neighborhood scale: Reviewing drivers of and barriers to social acceptance. Renewable and Sustainable Energy Reviews 82, 2618–2628.		1	1	1
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Totals	**30**	**31**	**25**	**16**

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Historical transitions of Western Australia's electricity system, 1880-2016

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ABSTRACT

We present a historical analysis of the evolution of southern Western Australia's electricity system between the 1880′s and 2016. By applying a multi-level perspective (MLP), we identify historic actions that impact the system's ability to successfully transition towards higher rates of distributed energy. The adopted methodology seeks to address geographic and temporal weaknesses in the MLP approach. We found that the system is at a definitive branching point between a de/re-alignment (radical change) or reconfiguration (incremental change) pathway as up to 50% of the network's energy requirement comes from distributed energy. Political and policy decision-making inertia at local, national and international levels increases the chances of returning to a decentralized electricity system reminiscent of those in place during the early 1900′s. The management of the transition in this small islanded system can provide lessons for larger systems that are yet to experience significant impacts from distributed energy.

1. Introduction

In Western Australia (WA), and to a variable extent globally, renewable electricity generation is challenging the business models that have underpinned the evolution of base-load power since the early 1900′s (Bakke, 2016; Rochlin, 2016; Tayal and Rauland, 2017). In South Australia, high rates of wind and solar generation have helped displace coal generation from the market (McConnell and Sandiford, 2016), while in WA rooftop solar photovoltaic (PV) has been a key factor driving change in the generation profile (ERA, 2017). Electricity systems in Australia as well as other countries are currently transforming from systems dominated by large thermal generators, to diverse distributed and decentralised systems with prosumers who now interact with the system as both producers and consumers of electricity (AEMO, 2018b, e; Shackley and Green, 2007).

Navigating change in the generation mix whilst maintaining a stable electricity system will likely involve a series of policy and technology changes (Ahlstrom et al., 2015; Riesz et al., 2015; Riesz and Macgill, 2013; Riesz and Milligan, 2015; Riesz et al., 2016; Tayal and Rauland, 2017). As previous literature demonstrates, policy and technology changes at present depend on the historical sequence of events that led to the current generation mix (Arapostathis et al., 2013; Bennett, 2012; Bennett and Pearson, 2009; Foxon, 2013). From this standpoint, learning lessons from the historical evolution of the existing electricity system can help us to better prepare for the future. This paper analyses the historical evolution of an islanded electricity system in south west Western Australia and applies the multi-level perspective (MLP) to socio-technical sustainability transitions.

The MLP is a dominant theoretical framework for understanding sustainability transitions (Köhler et al., 2019), which has its roots in evolutionary economics, systems of innovation and research on co-evolution (Essletzbichler, 2012; Geels, 2002; Rip and Kemp,

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1998; Smith et al., 2010). The MLP is particularly useful in providing a framework for understanding the agency of stakeholders in historical transitions and the relations between new entrants and incumbents (Geels, 2018). It provides a framework for interpreting the relationships between MLP levels comprising the niche innovations, the regulative, social and institutional norms of the existing regime and broader landscape forces. Through an understanding of agency and the historical lock-in mechanisms, the MLP can also provide a framework for understanding transitions that are currently underway (Sovacool and Hess, 2017). Within this study, it is used to provide a framework for identifying developments and key lock-in mechanisms that influence the ability of incumbent utility operators, politicians, policy makers and society to respond to evolving technologies, business models and norms throughout the evolution of the electricity system in southern WA.

The aim of this study is to understand the factors that have both shaped the evolution of the electricity system and that will influence the system's ability to adapt to rapid change in coming years. Two key research questions have been posited for the study. First, which transition pathways have characterized the development of the South West Interconnected System (SWIS)? Second, what lessons can we learn from the historical transitions and how can we apply these lessons to current changes in the SWIS and other power systems globally? We address our research questions by providing evidence from a review of the historical records that map the evolution of the SWIS, the electricity system in southern WA.

The case-study is situated in an advanced economy with centralised energy markets and dispatch systems which are similar to other energy markets globally. The energy system currently has over 50 per cent of electricity coming from roof top solar PV during some periods in spring and autumn (AEMO, 2018a). This is causing technical and financial issues for the operationally inflexible coal generators, which are consequently expected to exit the market in coming years (Wilkinson and Morrison, 2018). Loss of large legacy coal assets, around which the system has evolved, will have technical and financial implications for the system. Further, the rooftop solar PV is invisible to system controllers, which makes managing system stability increasingly difficult. As reported by Wilkinson and Morrison (2018), technical solutions can be found to enable a smooth transition to higher rates of distributed renewable energy, however the key to the transition will be enabling these to be implemented by first creating suitable socio-political environments. Managing the transition to higher rates of distributed energy within this system serves as a valuable window into the likely future of many electricity systems elsewhere in the world.

While transition research has predominantly been conducted in the context of Western European countries, Americas and increasingly in the countries of the Global South, there have been limited socio-technical transition studies into the Australian electricity system (Chandrashekeran, 2016; Gui and MacGill, 2018; Quezada et al., 2013; Simpson, 2017; Tayal, 2016), and no studies have been undertaken of the long-term transitions within WA's islanded electricity system (SWIS, the South West Interconnected System). It is in this space that this paper contributes to the socio-technical transition literature.

2. Background

Within the broader socio-technical research domain, we have situated this research within the sustainability transitions literature. Within this literature, the MLP is the dominant framework for interpreting energy transitions (Köhler et al., 2019) and was introduced as a framework for understanding the dynamics between the three analytical levels of niches (which are protected spaces and the genesis point of radical innovations), socio-technical regime (which includes the institutions that lock in practices) and the exogenous socio-technical landscape (which includes global and broad scale developments that influence both the regime and niches) (Geels, 2002; Geels and Schot, 2007; Smith et al., 2010). Within this framework, the actors and social groups in the MLP interact in accordance with cognitive, normative and regulative rules (Geels, 2004). By identifying the key actors operating within the three MLP layers during the evolution of electricity systems along with the predominant cognitive, normative and regulative rules, it is a useful framework for understanding the key factors that have influenced changes in a system over multiple decades. Whilst its strength lies in interpreting historical transitions, it can also be used to inform transitions currently underway (Sovacool and Hess, 2017).

Alternative perspectives can be used to study socio-technical transitions, including technological innovation systems (TIS), strategic niche management and transition management. These, however, are less well suited to long running historical analyses, which is the primary focus of this paper. As noted by Köhler et al. (2019), TIS also tends to focus on the emergence of niche innovations rather than the stability of existing systems, which was a feature of the SWIS's development. Further, the current study is consistent with the MLP approach in which global landscape factors are within the study's boundary. This contrasts to a TIS analysis approach, which would typically consider the national and international influences as external to a study's boundary (Bergek et al., 2015).

From outside the sustainability transitions field, other approaches such as actor network theory and path dependency were also considered. As with the MLP, actor network theory (ANT) would also include broader landscape factors as being within scope (Latour, 1997), however the hierarchical structure of the MLP provides a clearer analytical framework for analysis than might be provided by ANT. Path dependency concepts have been considered within the scope of the current study. Whilst the concept of increasing economic returns is a central concept that influences the direction of path dependency (Pierson, 2000), we have considered the developmental pathways to be broader than this and to include all elements of the socio-technical framework as described by the MLP, particularly within the cognitive, normative and regulative rules within the regime heuristic.

In applying the MLP, Geels and Schot (2007) and Verbong and Geels (2010) presented five broad transition pathways to describe common ways in which transitions occur. These are summarised below and are used in answering this paper's first research question and provides the theoretical basis for comparison to changes that have occurred since 1880 in the south west of Western Australia:

1 Transformation - This pathway is driven by external pressure at a landscape level and results in reorientation of existing regimes *via* gradual increments. The transformation is driven by regime actors, who can be influenced by changing public opinions and consumer practices. This can result in new environmental policies to support the transformation. Niche developments are typically not yet well enough developed to take advantage of the changes that are occurring. The change pathway is characterised by gradual changes to the old regime through "cumulative adjustment and reorientation" (Verbong and Geels, 2010).
2 Reconfiguration - In this pathway, innovations of the niches are more likely to occur when there are problems with the regime and pressures are occurring within the landscape. These niche innovations can cause a gradual reconfiguration of the regime, eventually changing its basic architecture. Verbong and Geels (2010) state that one difference between reconfiguration and transformation pathways, is that reconfiguration results from cumulative adoption of new components, which substantially alters the architecture of the regime. Further, the reconfiguration pathway differs from the reproduction pathway in that the former is instigated by landscape level pressures.
3 Technological substitution - In this pathway, niche innovations gather momentum and start entering larger markets, thereby competing with the incumbent regime actors. This can occur through landscape pressures that induce issues with the regimes.
4 De-alignment and re-alignment – This pathway sees a major change in the landscape and a restructuring of the system. The regime becomes destabilised and there is uncertainty about which of the innovation pathways will take pre-eminence. One option eventually wins and results in "new actors, guiding principles, beliefs and practices" (Verbong and Geels, 2010).
5 Reproduction - is a pathway essentially devoid of landscape pressures, thereby diminishing opportunities for any niches to break through and providing an environment for the existing regime to reinforce itself and internally solve any emerging issues.

The MLP has been criticised, including for how it addresses geographical space (Chandrashekeran, 2016; Coenen et al., 2012; Hansen and Coenen, 2015; Wells and Lin, 2015) and for its methodological ambiguity weighted towards bottom-up change models (Geels, 2011; Sovacool and Hess, 2017). We attempt to address the geographic space and methodological ambiguity through the adoption of local, national and international scales as used by Wells and Lin (2015). Wells and Lin (2015) applied the landscape, niche and regime MLP drivers separately at each of the local, national and international scales. National scale relates to niche, regime and landscape pressures that are occurring at the country level. Local scale relates to niche, regime and landscape related pressures that are influencing at the local/region/state level. The methodological approach adopted for this purpose is detailed in Section 3, whilst Fig. 1 shows the sub-categorization of the MLP at each level within the current study and identifies the SWIS's physical boundaries. This more granular and nuanced approach is particularly useful for improving the attribution of agency, including the political drivers, to change processes within a studied system at sub-national scales. The approach can also assist in more accurately attributing drivers for change that occur outside the study's boundary to a niche or regime level rather than defaulting to the generality of the landscape. The success of new niches can be place dependant (Coenen et al., 2012). For example, local political and

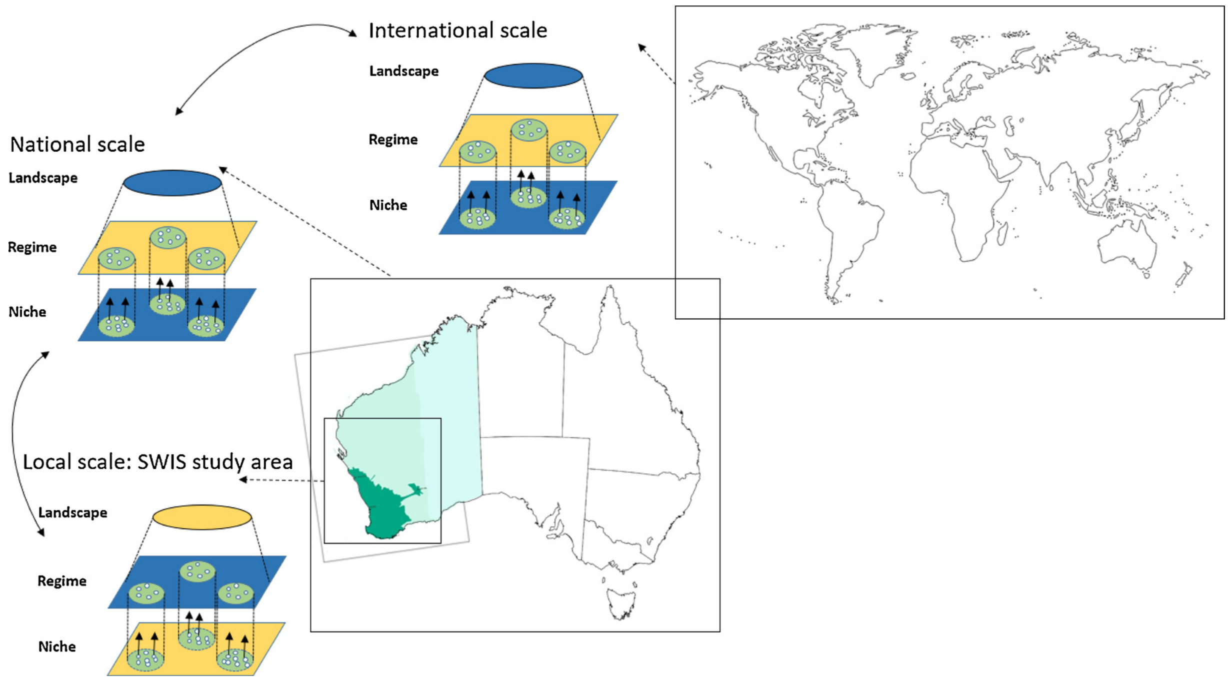

Fig. 1. Location of the South-West Interconnected System (SWIS) displayed as the dark area in southern Western Australia. The SWIS study boundary is at the local scale and is nested below the national and international levels. The MLP heuristic levels of niche, regime and landscape will apply at differing ways at each local to international levels. The blue shading indicates the predominant MLP heuristic operating at the local, national or international level (SWIS image supplied by Western Power, scalar images adapted from Wells and Lin, 2015).

associated regime level support may be more forthcoming for local niche firms than for similar technologies from other regions or nations. Consequently, transitions can occur more rapidly at the local scale than is the case for broader national or international level transitions.

The importance of political drivers in socio-technical transitions has broadened the scope and addressed some criticisms of the MLP in recent years, including through the works of Rosenbloom et al. (2018); Kern and Markard (2016); Geels et al. (2014); Hess (2016); Meadowcroft (2009, 2011); Kuzemko et al. (2016) and Lawhon and Murphy (2011). The effects of political forces can be felt when they are aligned around enabling a transition at key branching points. They can also influence the shape of a transition if there is inertia and lack of alignment of political and institutional parties (Foxon et al., 2013; Kivimaa and Kern, 2016; Rosenbloom, 2017; Rosenbloom et al., 2018). In the case of competing goals, politicians must inevitably make decisions creating both winners and losers.

As reported by Wilkinson and Morrison (2018), political decisions will be central to navigating transitions to higher rates of renewable energy within the studied system. As with transitions elsewhere (Kuzemko et al., 2016), Western Australian politicians have often waited for a crisis to emerge to give sufficient mandate to address the dissenting cries of those negatively impacted by the changes. This is a high stakes strategy for an essential service which cannot be allowed to falter as it undergoes technological transformation.

3. Procedure

3.1. Methodology

In a qualitative paradigm, data can take the form of any raw information collected prior to a subsequent analysis (Liamputtong and Ezzy, 2005). On that basis a review of historical archives (sound, video and written) at the State Library of Western Australia and the Universities of Western Australia, Curtin and Murdoch, was undertaken to reveal material aligned to the conceptual framework of the MLP.

Archives and secondary reports that did not illuminate the niche, regime, landscape and/or interactions associated with the electricity system were excluded. Information relating to the above MLP conceptual framework were coded in five-year periods between 1880 and 2016. Consequently, a deductive approach was followed as we sought to test the data's fit with the pre-existing theoretical framework (Strauss and Corbin, 1998) of the MLP. For each period, the information was categorised as relating to either the niche, regime, or landscape (at each of the local, national or global/international level) and/or descriptions on the drivers for change between these heuristic levels. Data at the regime level was further sub-categorised into regulative, formative and normative groupings to inform understanding of the regime's predominant lock-in mechanisms. Key actors relating to each phase of the SWIS's evolution were identified. Actors were identified as collectives, such as organisations, levels of government (local, state or national), companies, entrepreneurs and society/community rather than as specific individuals. Once collated, data was analysed to determine key branching points and drivers associated with periods of regime reorganisation during the SWIS's evolution.

3.2. Case study

The electrical power system in southern Western Australia, known as the SWIS, has been selected as the case study, and covers the geographic area indicated by the dark area within Fig. 1. Whilst power systems on the east coast of Australia are meshed into the National Electricity Market *via* a series of interconnectors, the SWIS is an islanded system. Any imbalances in the SWIS's power system must be met through internal balancing and cannot rely on power injections or balancing services from neighbouring jurisdictions. Over the past 10 years there has been a large increase in the proportion of less-schedulable renewable energy sources in the SWIS (Figs. 2 - A and B). The energy market currently has over 1200 megawatts (MW) of installed roof top solar PV in a network that can have a minimum daytime demand of 1200 MW in spring and autumn months (AEMO, 2019b). Roof top PV is not visible to the

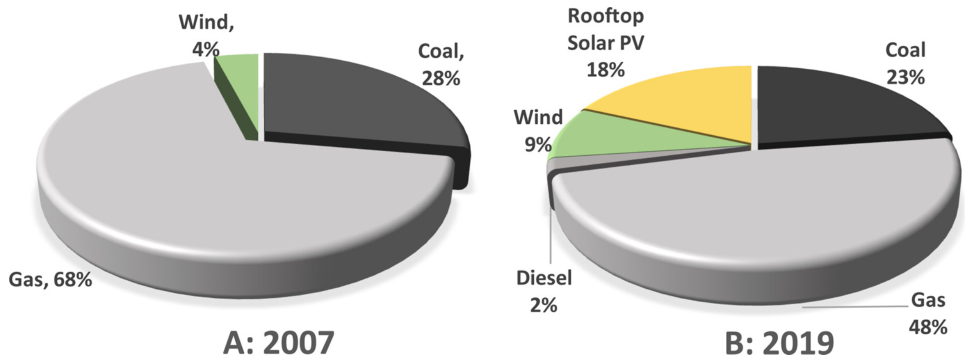

Fig. 2. Graph A shows the proportion of generation capacity on the SWIS in 2007 according to fuel type; Graph B shows generation capacity on the SWIS in 2019 by fuel type, with wind and rooftop solar photovoltaic (PV) comprising the greater proportion of installed capacity. (Data sourced from:[dataset] (AEMO, 2018c, d, 2019a; Australian PV Institute, 2019)).

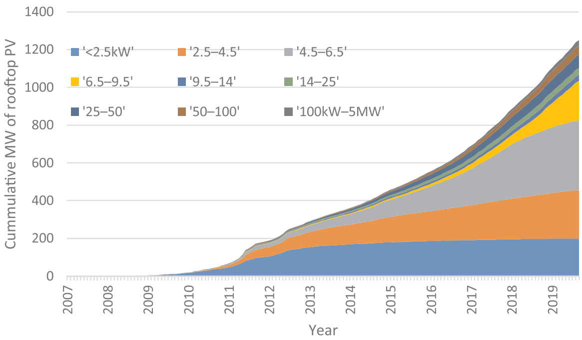

Fig. 3. The rapid uptake of rooftop solar photovoltaic (PV) systems since 2007 in Western Australia, with installed units becoming progressively larger (MW = Megawatts) (Data sourced from: [dataset] Australian PV Institute (2019)).

system operator, which makes the real time balancing of supply and demand necessary for frequency regulation increasingly difficult. Fig. 3 shows the rapid uptake of small-scale PV systems and the increasing size of these systems. Continuation of this trend is likely to have significant implications for future management of the SWIS.

Together with the retirement of traditional thermal generators these changes are making it harder for system operators to meet reliability standards (AEMO, 2018b). These effects are more pronounced in a smaller islanded system than in larger interconnected systems that can rely on broader system dynamics for frequency and voltage stabilisation. In this regard, the SWIS can be considered a valuable test case for power systems globally that are transitioning to higher rates of non-synchronous renewable generation with diminishing rates of synchronous generation.

3.3. Analytical boundaries

As for Bergek et al. (2015) and Andersson et al. (2018), the analytical boundaries of this case study are bounded spatially, temporally and within socio-technical domains. The spatial boundaries of the SWIS are limited to southern WA as shown by the dark areas within Fig. 1. The spatial boundary of the SWIS sits at a local scale as defined by Wells and Lin (2015) and is nested within the national and international scales. The regime level unit of analysis is predominantly at the local level, whereas niche and landscape influences are derived predominantly from the national and international scales. For example, emerging niche technologies and business models may have developed outside the SWIS's spatial boundary, as will have the broad landscape forces, however the interlocking regime is predominantly at the local level of analysis. The temporal and socio-technical boundary included the generation capacity and market within the jurisdiction of the Western Australian State Government and as influenced within a national and global energy supply landscape between 1880 and 2016.

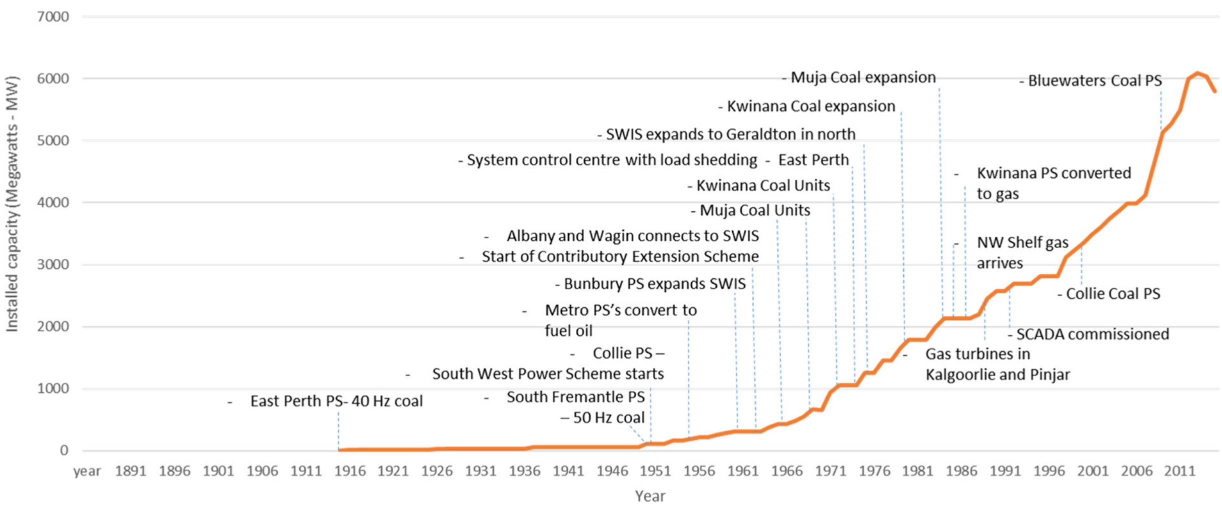

Fig. 4. Technological growth of the generation capacity within the SWIS, Western Australia from 1880′s to 2016 (PS = Power station).

4. Results and discussion

4.1. Historical transitions in the SWIS

This section characterises the changes in the SWIS from 1880 through to 2016 against the socio-technical transition pathways of Geels and Schot (2007) and Verbong and Geels (2010). Fig. 4, shows the long and slow technological uptake of electricity in Western Australia between the start of the twentieth century and the 1950′s. After this point, the generation capacity steadily increased to meet a constantly growing demand for electricity. It was not until around 2011 that energy efficiency measures, together with self-generated electricity from domestic solar photovoltaics (PV) led to the abatement of network energy demand (ERA, 2017).

The remainder of this section describes the MLP transitions that have occurred during the evolution of the electricity system in south-west Western Australia. A de-alignment from gas street lighting and a re-alignment towards electric street lighting occurred between the 1890′s and 1916. This was followed by a period of transformation from micro-grid generation and networks towards an early version of a centralised vertically integrated energy network from 1916 through to 1938. A long period of reconfiguration then followed between 1938 and 2005, during which the local-regime responded to global-landscape pressures. Privatisation and an energy market were introduced in 2005, followed shortly thereafter by policies favourable to renewable energy technologies. It is unclear whether this will result in another period of de-alignment and realignment towards a less centralised energy model; or whether the existing regime will maintain control of the transition and extend the phase of reconfiguration. The series of historical decisions and policy settings, together with political and regime responsiveness and electricity-user preferences will help determine which of the pathways are most likely to occur. The remainder of this paper is dedicated to the analysis of these factors.

4.1.1. 1890′s-1916: A period of de-alignment and re-alignment

Shove and Walker (2014) state that a discussion on energy transitions should first consider what the energy is used for. In this regard, our focus for the period of 1890–1916 is on the supply of metropolitan street lighting as it was street lighting that underpinned the first attempts to introduce electricity into Western Australia (Boylen and McIlwraith, 1994), and as such related to a technological shift within society.

From a lighting supply perspective, the period from the late 1880′s through to around 1916, is consistent with a de-alignment and re-alignment pathway (Fig. 5). At the start of the period of de-alignment, the gas lighting regime was dominated by the Perth Gas Lighting Company (PGC), which had monopoly rights for the supply of gas street lighting (Gregory and MacKinny, 2011). As illustrated in Fig. 5, the landscape pressures emanating from the gold rush in the late 1800′s and the emergence of the multiple niche uses of electricity led to a re-alignment towards an electricity-based lighting paradigm.

Limitations of the gas street lighting, including labour requirements, brightness and cost became apparent, allowing

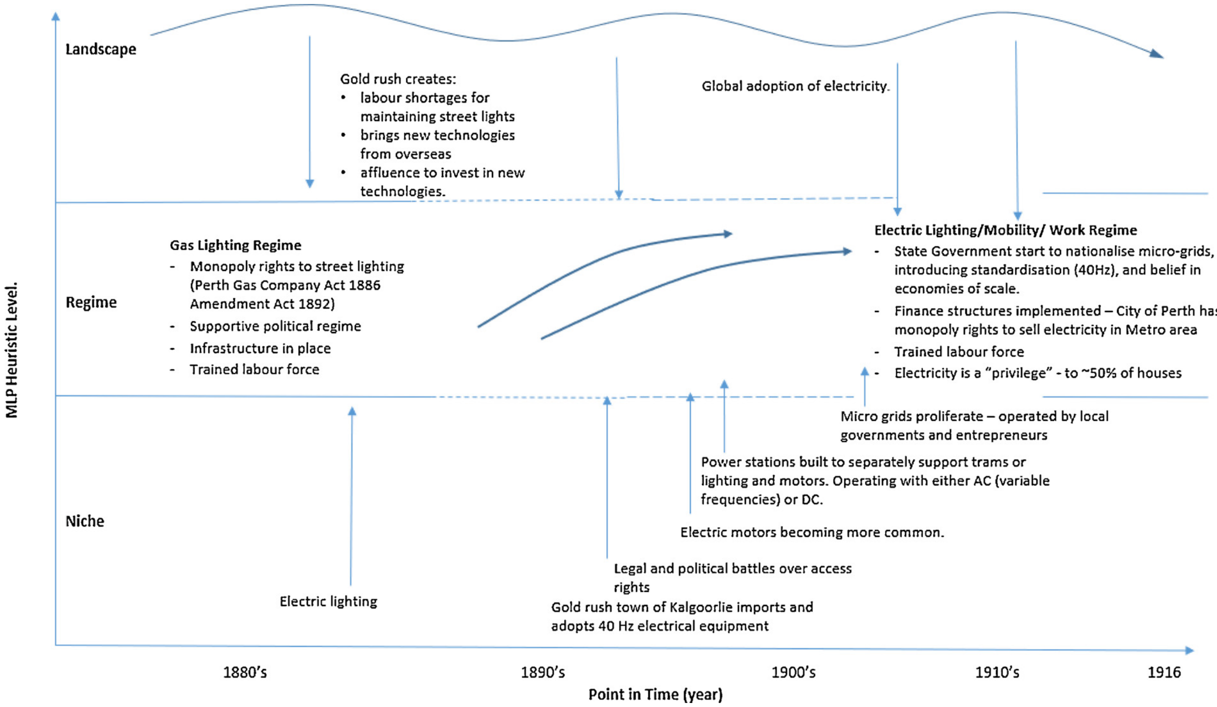

Fig. 5. De-alignment and re-alignment of lighting in Perth, Western Australia, showing how the landscape and niche interacted to diminish the regime's protective mechanisms, which allowed for a re-alignment of the lighting regime to occur. (Key: arrows indicate direction of push/pull; solid/dashed or absence of line indicates strength of boundary between regime and landscape and/or niche.).

entrepreneurs to resolve these limitations through the provision of electric lighting. Growing societal desire for electricity forced local Council's to build and operate local power stations and networks (Harman, 2011). Parallel electricity networks were developed to service trams, as well as for domestic and commercial lighting. The multiple uses of electricity built momentum within the niches to push into a newly forming regime despite efforts by the incumbent Perth Gas Company (PGC) to prevent the technology.

The PGC hotly contested any threats to their monopoly access rights through legal and political means (Boylen and McIlwraith, 1994; Gregory and MacKinny, 2011). Whilst access for an alternative street lighting technology was being battled out in the courts, entrepreneurs were finding and marketing alternative uses for electricity (Booth, 2003; Harman, 2011). Generation and distribution infrastructure was built individually for each of these purposes, resulting in a convoluted mesh of distribution wires and operating practices (Harman, 2011).

Once society had embraced the multiple uses of electricity, and Perth was faced with a complex network of distribution wires, the State Government took responsibility for public electricity supply through the introduction of the Electric Light and Power Agreement Bill 1913 (Bodycoat, 1994). This led to the standardisation of the electrical frequency at 40 hertz and the start of the consolidation of electricity supply infrastructure. The State Government established a central power station that would eventually supply all electricity to metropolitan Perth. This was done on the basis that a single large power station was considered more efficient than multiple smaller power stations (Harman, 2011). The State Government also bought out the PGC and gave the City of Perth monopoly rights for the sale of electricity (Boylen and McIlwraith, 1994). Following its purchase, the replacement of gas with electric lighting accelerated, with approximately 50% of urban houses being connected by 1914 (Boylen and McIlwraith, 1994; Gregory and MacKinny, 2011). At this point it became a rapid re-alignment around electric lighting and an associated local regime. Introduction of the Electric Light and Power Agreement Bill and the consequent centralisation marked a clear temporal marker between the period of de/re-alignment and the consequent transition period. The de-alignment from decentralized electricity supply towards central government control has parallels with activities currently underway within the SWIS. The difference being that current changes are introducing decentralisation back into the grid, potentially reversing a long-standing centralisation model. This is discussed further in the Section 4.1.4.

4.1.2. 1916– 1937: A period of transformation

From an electricity supply perspective, the period from 1916 to 1937 aligns with the transformation pathway. Fig. 6 illustrates the transformation of 1916 through 1937. The arrows in Fig. 6 show the predominant direction of the interaction between the heuristic levels of regime, landscape and niche. The dotted line between the heuristic levels represents the porosity between the levels at that point in time, whereas a solid line marks a period of relative stability of a regime not subject to change from the landscape or niche.

Between 1916 and the late 1930′s, the global landscape saw a broad adoption of electricity, in both households and industry (Bakke, 2016). This global trend fed down to the local-niche level in Western Australia, where householders increasingly adopted

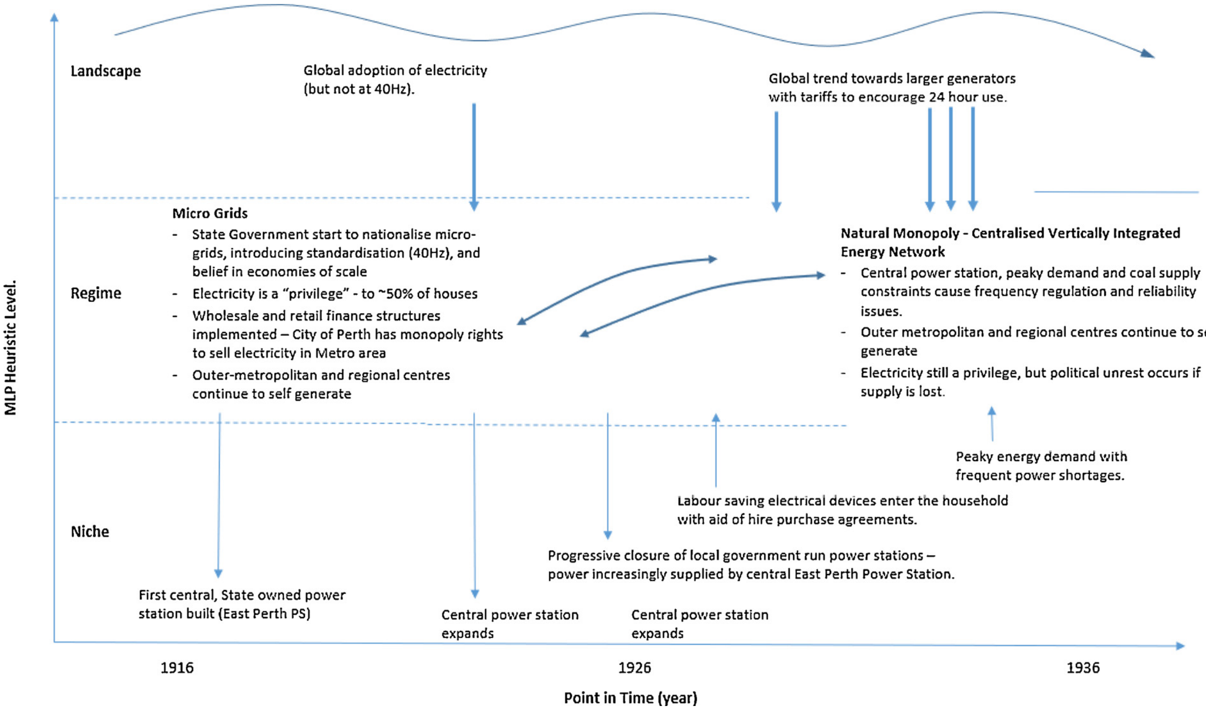

Fig. 6. Transformation of electricity supply in Perth, Western Australia 1916–1937 in response to landscape pressures on the regime, which put pressure on, and drew the niche elements into the regime. (Key: arrows indicate direction of push/pull; solid/dashed or absence of line indicates strength of boundary between regime and landscape and/or niche.).

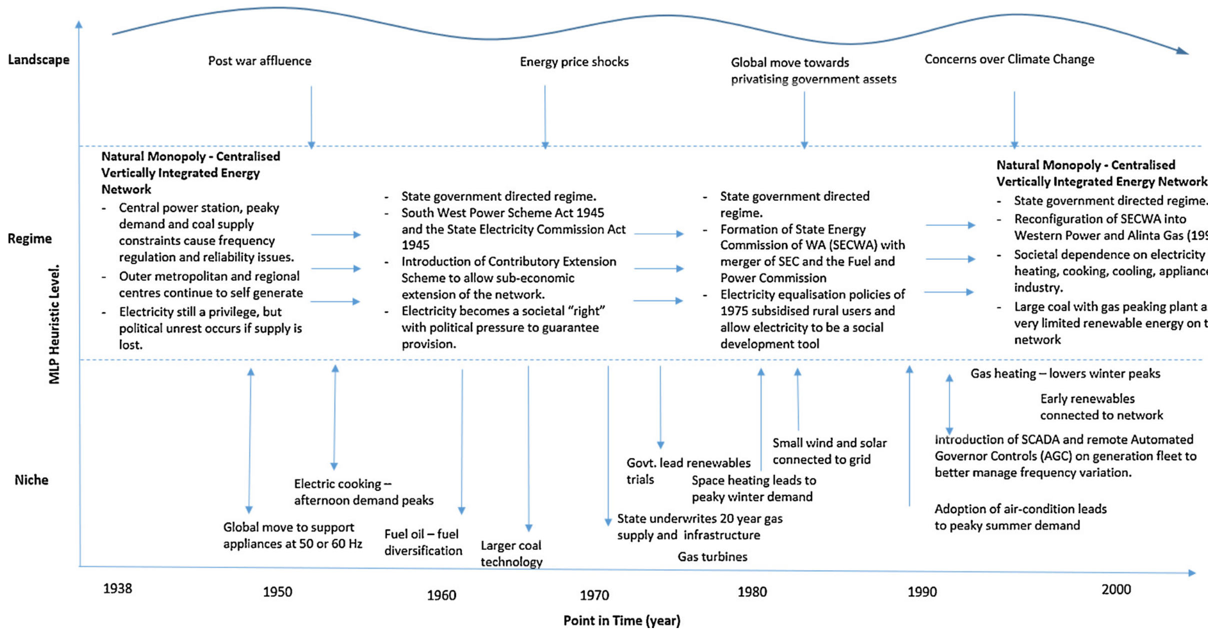

Fig. 7. Reconfiguration of the electricity supply in south-west, Western Australia 1938–2005 (Key: arrows indicates the predominant direction of push/pull; solid/dashed or absence of line indicates strength of boundary between regime and landscape and/or niche.).

electrical appliances, which in turn drove demand for more electricity. This was aided by the introduction of hire purchase agreements that allowed more people to purchase appliances such as radios and irons (Bulbeck, 2011). The local-regime that coalesced at the end of the period of re-alignment was forced to transform to account for the broadening user-consumer demand for electricity. Schot et al. (2016) define user-consumers as the people that help stabilise and consolidate new energy systems through adoption and legitimisation. In this way the period aligns with the transformation pathway which is characterised as being driven by external pressure at a landscape level and results in reorientation of existing regimes *via* gradual increments. The transformation was driven by the local-regime actor - the State Government - who was influenced by changing international public opinions and consumer practices.

Increasing demand for electricity saw a transformation of the local regime in metropolitan Perth through vertical integration of electricity generation, supply and sale into the State-run enterprise. This led to progressive closure of Council run power stations throughout the 1920′s (Harman, 2011). The local-regime structures existing at the end of the period were subject to cumulative reorientation and adjustment – a key characteristic of the transformation pathway.

4.1.3. 1938– 2005: Period of reconfiguration

A set of problems arising from energy shortages in the late 1930′s and over reliance on a single coal generating power station led to a rethink of the local-regime architecture and a move from the transformation pathway to a reconfiguration pathway. It was these energy shortages and consequent implications for the socio-political relationships to electricity that demarked the boundary between the period of transformation and the long running period of reconfiguration, commencing in the late 1930′s.

Three phases of reconfiguration are noted over the period 1938–2005. The key characteristics of these phases are shown in Fig. 7 and discussed below. This period is predominantly one of structural and institutional evolution rather than technological shift. The length of time this reconfiguration took was underpinned by the strength of the regime controlling the transition. This has been described by Turnheim and Geels (2013) as the triple embeddedness framework (TEF), a concept for describing how firms in an organisational field have critical exchange partners. These include their effective regime of suppliers, customers, funding bodies, regulatory groups, trade associations and the general public. Turnheim and Geels (2013) contend that firms prefer incremental change within the parameters of the existing regime due to the action of the above lock-in mechanisms.

4.1.3.1. First Phase:1940′s to 1970′s. Whilst the way electricity was generated, and the technologies used to generate it did not change during this reconfiguration, the local-regime's structure and institutional character was forced to respond to changing energy sources and a growing demand for electricity. At all landscape levels, there was continuing uptake of electricity both for domestic and industrial purposes (Bakke, 2016).

Post 1945 governments were taking a more interventionist pathway on the basis of economic efficiency (Booth and Coulter, 1980). Similar centralised structures were pursued elsewhere in Australia (Moran and Sood, 2013) and in many other countries, including the United States (Bakke, 2016) and Europe (Wilkenfeld and Speerritt, 2004). This saw the enactment of the State Electricity Commission Act of 1945 and the South West Power Scheme (SWPS) Act of 1945, which signified a change in the regulative regime for electricity distribution in the metropolitan area, following the national and international-level regime changes occurring elsewhere. When the SEC was formed in 1946, it was given powers to purchase Council run power stations, operate their distribution networks and sell electricity to customers (Harman, 2011). They also bought out the City of Perth's electricity sale rights, thereby creating a truly integrated utility with full control over power generation, transmission, distribution and sales. In regional areas, this signalled a change in both the generation and distribution functions of local Councils. By vertically integrating the electricity system, the Government was able to effectively control the responses of the regime to landscape forces, the integration of niche innovations and to shape new niches. This can be seen in Fig. 7 through the direction of arrows linking the regime with the landscape and niche heuristic levels.

The passage of the SWPS Act also led to the purchase of the Collie power station in 1946, and connection of this regional coal mining town to the metropolitan area (Booth, 2003; Harman, 2011). By 1957 the network of interconnected power stations had extended beyond the metropolitan area, to include several towns, including Bunbury, over 200 kilometres away (Edmonds, 2000; Harman, 2011). This marked the start of the South West Interconnected System (SWIS) and allowed greater flexibility for load following in a network with increasing peaks in electricity demand. It also marked a change in which electricity was transported to the demand centres *via* transmission lines rather than transporting the energy (coal) to the demand centres.

A major change in the local socio-economic regime's relationship to electricity supply occurred in 1959 with the introduction of the Contributory Extension Scheme (Booth and Coulter, 1980). For the first time, the SWIS could be extended to rural and marginal metropolitan areas on a subsidised basis (Booth, 2003). Prior to this, electricity had been provided based on economic return. This marked a change from electricity as a privilege to electricity being considered a societal right and showed the Government starting to use electricity as a tool for State development. This created a new normative regime for energy users, which has locked the State Government into providing electricity on a subsidised basis ever since.

On a technology level, gas turbines were introduced after a serious system collapse in 1971, which exposed the drawbacks of a system reliant on a few very large generating units. It was also realised that providing enough spinning reserve to protect against the unexpected loss of a large generator would be too expensive (Edmonds, 2000). We consider these changes represented the local regime (*via* the Sate owned electricity utility) adopting new technologies and operating practices in response to changing societal and landscape pressures – a key feature of the reconfiguration pathway.

4.1.3.2. Second Phase: 1970 to early 1990′s. The second phase is marked by international level regimes reconfiguring in response to energy shocks after the 1973 OPEC oil crisis. At the local level, this included bringing together the State's electricity utility with the raw energy supply commission – to form the State Energy Commission of WA (SECWA).

Perhaps the greatest local level regime change during this period was the introduction of the 1975 standard electricity tariffs across Western Australia, with country customers paying the same as, and thereby being heavily subsidised by, metropolitan customers (Booth and Coulter, 1980; Public Utilities Office, 2014). This cross subsidisation, at a regulative regime level, was largely able to occur because the electricity system was a vertically integrated government activity that could be used to give effect to government policy.

The equalised pricing policy further entrenched the societal normative regime of electricity being a societal right and government service rather than a commodity. This change marked a branching point that has locked the government into supplying subsidised electricity to society and has hampered later efforts to introduce competition into the energy market. It also hampered the introduction of time-of-use tariffs, demand response and load control by accentuating the view that electricity pricing and demand response are indicative of rationing and shortages rather than tools to manage network utilization.

The State Government underwrote a contract in 1977 to bring natural gas from the north of the state to the demand centres in the south (Edmonds, 2000; Harman, 2011). This has underpinned the rapid uptake of gas generators in the WA electricity market, which accounted for two thirds of the installed capacity by 2007 (AEMO, 2016a). Gas turbines were first introduced after the 1971 system collapse (Edmonds, 2000). They were also able to support the increasingly peaky demand that developed in the 1980′s with the broad uptake of electric domestic space heating. These changes led to the local regime adopting new technologies and operating practices in response to changing societal and landscape pressures.

The OPEC oil crisis also drove investigation of global niche renewable energy technologies that were not yet sufficiently developed and would not make significant inroads into energy supply for some decades. The SECWA was keen to adopt these technologies, as evidenced by their Remote Area Power Supply (RAPSI) project, and the later Solar Energy Research Institute of WA (SERIWA), which was established by SECWA to undertake works relevant to energy conservation, management and use of renewable energies (Boylen and McIlwraith, 1994). In 1980, RAPSI reported that with rising oil costs, wind power was already cost competitive with diesel generators and that solar would be competitive in the longer term (Booth and Coulter, 1980). However, with the fall in oil prices and introduction of gas to the WA market through the 1980′s, wind and solar made little inroads on the SWIS over the next two decades.

4.1.3.3. Third Phase: Early 1990′s to 2005. In the 1980′s a global trend towards disaggregation and privatisation of public utilities (Henney, 1987), resulted in the 1995 disaggregation of SECWA (Public Utilities Office, 2014). The SECWA was split into Western Power – responsible for electricity generation, distribution, transmission sales – and Alinta Gas, responsible for gas transmission and distribution (Public Utilities Office, 2014).

Loads picked up in the early 1990′s when the metropolitan rail network was electrified, and greater use of gas turbines was enabled by completion of the pipeline from the far north of the state to the demand centre in the south. Smaller cheaper gas generators meant an end to the economies-of-scale argument that had supported government monopoly of electricity generation through large coal-fired power stations (Harman, 2011; Henney, 1987). An abundant supply of gas also allowed for domestic gas heating – lowering the pattern of winter peak demand, whilst continuously increasing air conditioner uptake reinforced peak summer network loads (System Controllers, 2016). This translated into new norms of air-conditioning (cooling) becoming a societal right – leading to increased loads in regional areas, pressure on the rural network and intense pressure on utilities to protect vulnerable customers. Increasing use of industrial motors also drove continual growth of power loading throughout this period. The nature of the generation fleet within the network therefore continued to adapt to the evolving energy use patterns. These patterns were encouraged by the regime *via* policies to increase gas use. Reconfiguration of the local level regime architecture was driven by global-landscape trends towards privatisation and a desire to introduce competition between the local coal and gas energy suppliers, both of which were enabled by the State Government and it's agencies.

It was during this period that an embryonic renewables sector took root in the SWIS. At the time, it contributed a very small amount of power to the existing system, thus representing no challenge to the rules, structures or functioning of the existing regime.

4.1.4. 2005 Onwards: A return to de-alignment and re-alignment, or further reconfiguration?

2005 may have seen the commencement of a different transition pathway, one that started to revert to structures reminiscent of those during the last period of de-alignment and re-alignment over a century earlier. In the early 1900′s, there was a move from multiple smaller generators and grids controlled by a mix of public and private enterprise towards vertically integrated state ownership of a single electricity system. Fast forward to 2005, mechanisms were put in place to allow the disaggregation of the central public utility, with establishment of a wholesale electricity market aimed at allowing for introduction of competition (Public Utilities Office, 2014). Rapidly falling solar PV and battery storage prices have allowed households and businesses to start generating their own power, which has seen rapidly decreasing demand on the centralised electricity system. The high rates of rooftop solar PV has also prompted trials of distributed power systems, grids and energy trading schemes to manage the voltage and frequency impacts caused by PV generation.

A growing awareness of climate change at all landscape levels, together with policy initiatives from all regime levels to encourage uptake of renewable energy technologies have been key factors in this period of transition. Policy initiatives included: the Australian Government's solar PV rebate program that ran through the 2000′s and resulted in a sixfold increase in PV generation capacity (Macintosh and Wilkinson, 2010); introduction of the 2020 Renewable Energy Target in 2009; and State and National solar feed-in-tariffs (Biggs, 2016; Moran and Sood, 2013). Fig. 3 shows how successful these programs have been in stimulating the uptake of rooftop solar PV, which were more successful than the government or utilities had anticipated. Macintosh and Wilkinson (2010) and Geels (2018) note that radical innovations that form a technical basis for a new socio-technical regime often require protection as they are often non-cost competitive and can be non-complementary to the existing socio-technical regime. This is certainly the case within the current case study.

Fig. 8 shows the alignment of multiple niche and landscape factors allowing them to propel into the existing regime. These include falling prices for battery storage, new forms of energy pricing and peer-to-peer transaction, de-risking of renewable energy financing, social acceptance/normalisation of both self-generation and new generation-distribution models (AEMO, 2018b, e). The need for

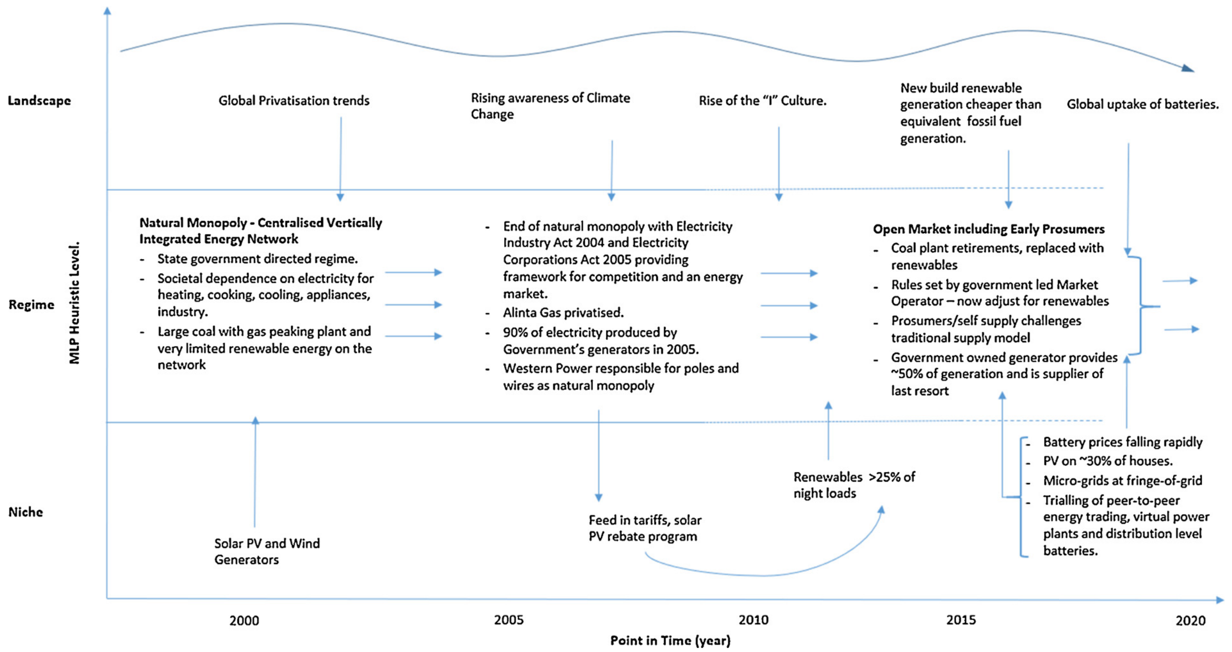

Fig. 8. Reconfiguration or De-alignment and ongoing re-alignment of electricity supply in south-west, Western Australia since 2005 in response to landscape and niche pressures. (Key: arrows indicate direction of push/pull; solid/dashed or absence of line indicates strength of boundary between regime and landscape and/or niche.).

multiple innovations and multidirectional interactions between the heuristic levels of the MLP to allow re-alignment to occur is recognised in the works of Berkers and Geels (2011); Markard (2018) and Geels (2018). Whilst it is unclear if a full-scale re-alignment is occurring in Western Australia's electricity sector, the confluence of factors that could enable this are building. In Schot et al. (2016)'s article, the normalisation of rooftop solar PV and, to an increasing extent, battery storage, is described as moving the electricity user experience from one of a user-producer, to that of a user intermediary. The user-intermediaries "create spaces for the appropriation, shaping and alignment of the various elements of emerging socio-technical systems, such as products, infrastructures and regulatory frameworks" (Schot et al., 2016).

Policy makers and generators at both the local and national levels had thought that the additional renewables entering the system would be used to meet the ever-increasing demand for electricity (Nelson et al., 2015; Simshauser, 2014). However, growth in electricity demand from the networks across Australia halted in around 2011, resulting in over capacity (Nelson and Orton, 2016; Nelson et al., 2015; Simshauser, 2014). The near zero short-run operating costs of renewables means that the higher cost coal generators have suffered financially (Nelson and Orton, 2016; Nelson et al., 2015; Simshauser, 2014). The output of solar PV has further stressed the established local and national regime operators by reducing peak demand and suppressing wholesale electricity prices (Nelson et al., 2015). A central concept of path dependency is one of increasing returns (Pierson, 2000). From this perspective, the pathway that has locked in traditional thermal generation, and the associated business models based on economies of scale are starting to unwind, or in MLP parlance, to de-align and re-align towards other business models.

Market reforms and renewable energy policies are also important to the discourse of the current transition in the electricity system for several reasons. Firstly, uptake of renewable energy creates a need for different market structures that reward products not required in a coal and gas dominated electricity network, such as faster ramping rates, which have not been required by the high inertia steam driven units of the past (Ahlstrom et al., 2015; Miller et al., 2013) and shorter dispatch intervals (Ahlstrom et al., 2015; Riesz et al., 2015; Riesz and Macgill, 2013; Riesz and Milligan, 2015). Secondly, the increase in self-generation is reducing demand on the electricity network (Figs. 2A, B and 3 demonstrate this trajectory) and enabling a move from single centralised power systems to smaller localised distribution grids. Thirdly, a move from vertically integrated public to disaggregated private ownership, makes reconfiguring the regulatory regime more litigious and hotly contested by a larger number of market participants.

Whilst underlying residential electricity consumption continues to rise, consumption from the network has been falling in real terms since 2010 as house owners turn to self-generated solar PV (Figures 2B and 3) (AEMO, 2016b, 2018b). The commercial customers on the SWIS make up over 70% of the market and are only just starting to adopt solar PV and self-generation (AEMO, 2016b). The large-scale adoption of solar PV, together with battery storage is likely to further reduce the daytime demand for electricity from the SWIS (AEMO, 2019b, c; ERA, 2017). This is causing the phenomenon known as the duck curve, where minimum demand for electricity from the network is increasingly occurring during the middle of the day, followed by a steep ramp in network electricity demand when the sun goes down (causing a rapid fall in solar generation capacity), coincident with people coming home from work to heat or cool their homes.

Miller et al. (2013) and Markard (2018) in their review of next generation renewable energy policy instruments, cite that whilst first generation renewable energy policy was mostly able to ignore major system interactions, the next stage of policy development will not have this luxury. In short, the rules developed over time to support the existing regime will need to be changed to support an orderly transition to the new energy landscape. While regulatory agencies in Western Australia and elsewhere, are working on policy solutions, their progress is falling behind the pace of technological rollout and new entrepreneurial business models (Wilkinson and Morrison, 2018). As noted by Hess (2016), it will be the local level State Governments that will affect the pattern of niche-regime strategies and interactions.

As occurred with the Perth Gas Company in the early twentieth century, the incumbent energy operators in the SWIS are resisting at political, policy and legal levels changes to policy settings that could be favourable to new niche technologies and protagonists. As with many electricity systems globally, the largest incumbent in the SWIS is the State Government, which is itself, the rule maker. Whilst the State has sought to reduce its presence in the electricity sector by pursuing a privatisation agenda since 2005, further introduction of renewables into the SWIS has the potential to diminish profitability of their generation assets and thereby increase State debt levels, which reduces the incentive to facilitate this transition. Notwithstanding the above, the State's share of the generation market in the SWIS has reduced from around 90% in 2005 (Public Utilities Office, 2016) to less than 50% in 2016 (AEMO, 2016b).

The move from electricity as a privilege to a right during the period of reconfiguration in the 1950′s has also been confounded by the move to privatise electricity provision. The requirement to supply electricity has been bound in the regime's rules, and transferred from the public to the private sectors, which has limited the sector's ability to operate on a purely commercial/unsubsidised basis (Tayal and Rauland, 2017). Somewhat paradoxically, the rigid regulative regime has created the environment for the de-alignment and re-alignment to occur. This is because the rigid structures have locked the existing large-scale generators and network operators into providing electricity – as a societal right - across a geographically large, sparse and costly network and they have been slow to respond to a rapidly evolving consumption – generation – distribution nexus. Whilst historic regulatory and cognitive norms at the local regime level make it difficult for incumbents to evolve their business models to accommodate the niche technologies, these same regulatory structures are also actively prohibiting new technologies and business models from entering the market.

As occurred in the re-alignment from gas lighting to electric lighting in the early 19th century, entrepreneurs are trialling new products for entry to the electricity market. This includes: self-sufficiency *via* battery supported PV systems on domestic and commercial premises; centrally controlled virtual power plants made up of distributed PV and battery systems; and local, or peer-to-peer trading; each of which can substantially challenge the current electricity provision paradigm (Bragg, 2014; Green and Newman, 2017; Hall and Roelich, 2016; Hojčková et al., 2018; Vorrath, 2016). Under local, or peer-to-peer trading scenarios, residential customers could trade excess solar PV generation between themselves over the distribution network. An entrepreneur led model of this peer-to-peer trading system is being trialled in a new development in Western Australia (Green and Newman, 2017). In time, this could move a significant portion of the SWIS from a centralised utility-to-customer paradigm, to a distributed supply chain (Green and Newman, 2017). Another trial which began in mid-2018 incorporates both the system's sole energy retailer and network operator and the peer-to-peer trading system. This is an important development, as it marks an attempt by regime level operators to participate at the disruptive niche level. Whilst existing regulations prohibit the integration of peer-to-peer trading or other distributed energy resource (DER) business models into the local electricity market, it may simply be a matter of time before legal loopholes and workarounds are found, which enable their introduction and uptake. This was the case with the introduction of electric lighting over a hundred years ago, and more recently with the advent of other similar peer-to-peer platforms such as Uber and AirBnB. This marks a key juncture that could determine whether a de/re-alignment or reconfiguration pathway will unfold. The pathway followed will also depend on the ability of the regulative regime and political decision makers to incorporate the learnings from these trials and adjust the regulatory regime to allow for these innovations.

The changing relationship of traditional energy users to taking on a joint role of producer and consumer (also known as prosumer) is causing landscape level pressures on the electricity system (Biggs, 2016). Biggs (2016) questions whether prosumers, who are projected to invest $A21 billion in residential PV (Warburton et al., 2014), will coalesce. If so, this landscape change may pull the niche technologies into a new regime architecture. Coalescence around DER models such as peer-to-peer trading, virtual power plants, DER management systems and distribution level batteries could collectively negate much of the business model underpinning the existing regime (Biggs, 2016) triggering another de-alignment and re-alignment.

Should the existing local regime operators prove unable to incorporate evolving DER models, within their architecture, it is plausible that a de-alignment and re-alignment pathway would ensue. The adversarial political system in Western Australia is not well suited to proactive decisions that create clear winners and losers. A slow-to-respond legislature is also plausible given the government's strong vested interests, who could be the greatest financial loser in the short term; and its political stake with the energy users who stand to win or lose from the changes. This de-alignment / realignment pathway, should it occur, would be reminiscent of the early era of electricity, where power was supplied by multiple parties and distribution infrastructures. In this event, the central monopoly run utility model, which has served largely unchanged for the past 100 years would be undone. A realignment of this magnitude would see a reshaping of the political, social, and cultural dynamics of the energy regime.

5. Conclusion

This paper has added an Australian electricity system to the body of case studies applying the MLP of transition theory. Due to its isolation from interconnecting electricity systems, together with the very high rates of rooftop solar PV, the SWIS provides an early indication of the likely challenges to be faced by larger electricity systems into the future. Whilst specific drivers and constraints will vary for each system's transitionary processes, the nested local, national and international/global level methodology adopted in this study can be broadly applied elsewhere. The use of nested levels is useful in allowing scholars to determine which findings are attributable to the local level, *versus* those that are generalizable to the national or global level. This reduces the opportunity for any MLP heuristic level, particularly at the national or global level to be used as a broad bucket for generalised drivers. Given transitionary processes can operate at much faster paces at the local rather than national or global scales, the three level approach also allows temporal variations in transitions to be better interrogated.

The analysis has highlighted the multiple policy, political and electricity user interactions at the local level that have contributed to system change as well as its stabilisation. The analysis of historical transitions shows that the SWIS has been through many phases, including de/re-alignment from a decentralised system in the early 1900′s to the centralised system that has been promulgated by the local regime from around 1916 through to the current day. The initial period of de-alignment and re-alignment was driven by entrepreneurs pushing to introduce innovative electric lighting in the face of the established gas lighting regime. The evolution of the electricity system for around a century has been dominated by incremental changes driven by local state actors and vertically integrated utilities at the local-regime level. Historical decisions driven by society's changing relationship to energy at all levels – from a privilege to a right – has reinforced the local regulatory and normative regime and its broad architecture. This stability is providing both political and regulative resistance to new entrepreneurial business models, whilst simultaneously providing space for the entrepreneurs to work within. This is because the incumbents are less nimble than newer local-niche participants with their innovative business models.

Growing normalisation and acceptance of distributed rooftop solar PV will increasingly challenge centralized regime architectures. The nature of the ongoing transition will depend on the course of action of the incumbent local regime. If they decide to participate and incorporate new entrepreneur-led business models (such as peer-to-peer trading, distributed energy management systems, virtual power plants or microgrids), the transition is more likely to resemble the reconfiguration pathway. This will keep the hegemony of the centralized system management but adapt to incorporate the increasingly distributed elements of the electricity system. If the incumbent local regime doesn't act fast enough or resists, this could lead to disruptive action from the local niche start-ups and communities of prosumers, leading to the de-alignment and re-alignment pathway unfolding. As noted in Wilkinson and Morrison (2018), the slow-moving nature of the regulatory regime is not equipped to keep pace with the rapidly evolving business models of the current day energy transition. Political and policy decision makers should be decisive in their preferred pathway and seek to understand the ramifications of each alternative. Failure to decide increases the chances of history repeating itself - heading back to an increasingly decentralized system reminiscent of those in the early 1900′s *via* an uncertain and inevitably tumultuous transition pathway.

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Enablers of an Electricity System Transition

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Abstract. This research reveals a plausible future generation profile for the electricity network in southern Western Australia and seeks to understand the enablers and blockers to maintaining a stable electricity supply during a transition to that generation profile through to the late 2020's. Transition theory is used as the theoretical framework for understanding the challenges for this transition and is supported by a series of semi-structured interviews with industry executives. The future profile will see the retirement of a significant proportion of synchronous coal fired generation, replacement with an equivalent capacity of solar and wind generation and at least as much distributed rooftop solar PV generation. Mid-day solar PV output will dominate the consumed energy and diminish network demand to levels that are expected to threaten the profitability of much of the existing baseload generators. Rooftop solar PV has limited visibility to and uncontrollable by the system control center, which under current market settings will struggle to maintain system frequency under the future generation profile. Wholesale market reforms will be required to maintain energy security, including to; tariff structures; ancillary services markets; connection codes; public generator bidding and ownership structures; and the role of consumers in the future market. These reforms are heavily confounded by the adversarial political system; legacy decisions around uniform tariffs; incumbency; and uncertainty over the willingness of society to accept third party control of their personal loads, solar PV output or battery services. The key to the transition will be creating the social and political space within which reforms can be made.

Keywords: Electricity transition · Multi-level perspective · SWIS WEM · Smart meter

1 Introduction

The rapid uptake of renewable energy has tipped the Wholesale Electricity Market (WEM) in southern Western Australia into a period of transition [1, 2], mirroring similar transitions elsewhere in Australia and globally [3, 4]. The WEM is transitioning from a recently disaggregated vertically integrated hub and spoke system architecture that has been largely unchanged for over 100 years, towards a system struggling to integrate a profusion of distributed renewable generation. Much of the new generation is from household level solar PV systems that are currently uncontrollable by system operators and are increasingly impacting on the system's security. This change is occurring at a time when network energy demand is falling after a century of near-continual growth [3, 5, 6].

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Navigating the change in the generation mix within the WEM whilst maintaining a stable electricity system will involve a series of policy and technology changes [7–12]. The transition introduces destabilizing effects in the form of intermittency, variability, low fault current, voltage regulation, market reorganization, threats to incumbents and a need for new planning accountabilities. If politicians get this wrong, either overtly, or through lack of action, then the implications for system stability are severe.

The importance of political forces is widely reported on in the transitions literature [13–19]. It has been found that the nature of the political voting system can influence the ability of a country to undertake transition management, with two-party political systems, such as that found in Western Australia promoting a more adversarial approach [17]. Whilst electricity transitions rely on technological evolution, it is society's relationship to the technology that underpins how the transition will unfold. This study uses the socio-technical framework of transition theory to guide interpretation of the research findings.

The changing relationship of traditional energy consumers to taking on a joint role of producer and consumer is causing landscape level pressures on the electricity system [20]. Biggs [20] argues that if prosumers, who are projected to invest $A21 billion across Australia by 2030 in residential PV, coalesce, then this landscape change could pull the niche technologies into a new regime architecture. New models of peer-to peer trading systems are being trialed in the WEM [21]. If change coalesce around this, or other innovative new electricity supply models, then the de-alignment and re-alignment pathway would be followed, negating business models that underpin the existing regime [20]. This could point to a new electricity system, whose architecture is still nascent.

This paper discusses the key drivers for change in the South West Interconnected System (SWIS) over the past decade and looks ahead to the coming decade to answer the key questions of what the future generation profile on the SWIS will look like and what the enablers and blockers to a stable electricity supply are under that profile. The focus is on understanding the transitionary issues to be addressed rather than on the specific policy or technological endpoints that can be expected. The paper reports on a point in time where the regime is at a definitive branching point. A point where it can either incorporate the changes within it's existing architecture, or potentially be overtaken by the evolving entrepreneur led business models such as those of peer-to-peer trading.

2 Theory and Methods

2.1 Theory

From within a positivist ontology, the study has used the multilevel perspective (MLP) of transition theory to ground the research. A key concept of the MLP is that transitions in systems, such as the electricity system, are a result of relationships between three different societal system levels: landscape; regime and niche [22–29]. Landscape is the macro level context within which the system operates, such as macro-economic and macro-political trends and guiding environmental values [22]. Regime relates to the supporting mechanisms that provide the rules, standards and governance arrangements to support the incumbent technological players [23, 25–27]. It is the regime that provides the lock-in mechanism for a set of technologies, and has been categorized by Geels [23] as being in the form of a regulative, formative and normative mechanism. Niches are the spaces where various technical, social and organizational innovations are created and tested [22]. Institutional governance structures, whether they be fully centralized or decentralized, will often start as a niche idea prior to stabilizing into the regime architecture. A more thorough description of the socio-technical framework, beyond the basic landscape-regime-niche categories, is outlined in Geels [24], Smith, Voß [30].

2.2 Case Study

The WEM in south-west Western Australia was chosen as the case study. This market covers the SWIS that stretches from Kalbarri in the north, inland to Kalgoorlie and as far south as Albany - the area covered being the darker area in Fig. 1. Figure 2, shows the changing generation profile on the SWIS between 2007 and 2017, with a marked increase in wind and behind the meter solar PV over the past decade. The SWIS is an islanded electricity system, meaning that it must rely on its own internal generation to maintain system security without the aid of regional interconnectors.

Fig. 1. Location of the South-West Interconnected System (SWIS) displayed as the dark area in southern Western Australia. (Image supplied by Western Power).

Electricity Sector Governance Arrangement

The electricity system in southern Western Australia was subject to a series of reforms in the mid-2000’s to introduce competition to a government run vertically integrated

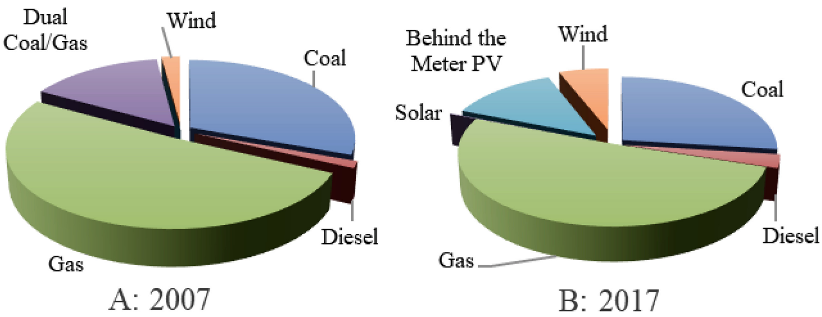

Fig. 2. Graph A shows the proportion of generation capacity on the SWIS in 2007 according to fuel type; Graph B shows generation capacity on the SWIS in 2017 by fuel type, with wind and behind the meter solar photovoltaic (PV) taking a significant market share from coal and gas. (Data sourced from: [1, 32, 33]).

system. These reforms have led to the current-day, comprising of government corporations: Synergy –the electricity retailer and generator of last resort; and Western Power - the monopoly networks operator. Electricity pricing is set by the Government on advice from the Economic Regulation Authority, with rules developed by the Public Utilities Office (PUO), and system administration and system control undertaken by the Australian Energy Market Operator (AEMO). Limits were placed on the generation capacity of Synergy in the mid-2000's to encourage new capacity to come from new participants, who now comprise approximately 50% of the generation capacity on the SWIS [31].

Large customers in the WEM are permitted to purchase electricity via bilateral trades and/or on the short-term energy market (STEM) and balancing market. Small use customers (less than about $40/day) are only permitted to purchase electricity from Synergy, the State run gentailer. The load following ancillary services (LFAS) market is also operated by AEMO for system stability. The gentailer has significant market power as the majority provider of LFAS and is permitted to bid its entire generation fleet into the markets on a portfolio basis. The portfolio is dispatched under agreed run priority and in compliance of the Market Rules order by the system controller. Other potential LFAS providers must bid individual generators into the LFAS market.

AEMO operate a capacity market, with payments made to generators to ensure there is sufficient generation capacity on the network to meet projected peak system demand [31]. Retail electricity prices are standardized under the uniform tariff policy that was introduced in 1975, which sees country customers paying the same as, and being heavily subsidized by, metropolitan customers across WA [34]. The tariff equalization contribution was budgeted to cost $198 million in 2018/19 [35]. The gentailer typically runs at a significant loss due to government's suppression of tariff price increases below the cost of production over the past decade.

2.3 Data Collection and Analysis

Using a qualitative research methodology, the study has undertaken in-depth interviews with 10 industry executives to gain insights into current and future issues within the SWIS. Participants were selected based on a mixture of their detailed and high-level understanding of the issues and are summarized in Table 1.

Table 1. Interview participants

Participant	Expertise
P1–P3	Current or past CEO of Western Australia based energy organizations
P4–P7	Senior management with current or recent policy and/or operational related function in Western Australia
P8–P9	Senior consultant to government and industry
P10	Electricity sector academic

One or two interviews were held with each participant and were guided by the following open-ended questions:

1. Description of their formal training and work history.
2. Thoughts on the main drivers for change in the generation profile over the past decade.
3. Comments on the plausibility of CSIRO and Energy Network Australia's (ENA) projected generation profile for the SWIS in 2022 and 2027 (Table 2).
4. Main enablers required to allow a stable electricity supply under the agreed generation profile in 2022 and 2027.
5. Main blockers or impediments to realizing a stable electricity supply in 2022 and 2027.

Table 2. Future generation profile presented to interview participants for comment. Projections based on CSIRO and ENA report on the Future Grid [36]

By 2020	By 2025	By 2030
30% renewables	40% renewables	44% renewables
1 GW of rooftop solar	2.5 GW of rooftop solar	4 GW rooftop PV by 2030
Negligible domestic battery uptake	<2 GW of on-site batteries	>2 GW of on-site batteries
Retirement of 240 MW of coal, 200 MW of gas and 60 MW of liquid fuel generation[a]		

[a] These retirements were announced by the WA Government mid-way through the series of interviews but had been expected by most participants already interviewed.

Each interview was between one and two and a half hours in duration. Questions 4 and 5 are similar, but from a different direction, intended to draw out alternate thinking concerning the transition.

All interviews were transcribed into the social sciences software package, NVIVO 11. Transcripts were coded to identify key themes, which were then assigned to each interview question for each interviewee. A consolidated group of themes was then prepared for each of the guiding interview questions and a record made of which of the respondents mentioned each of the key themes at some point during the interview. Responses to questions 2, 4 and 5 were categorized in accordance with Fig. 3 to identify key areas of the MLP of transition theory that were relevant to past and future transitions.

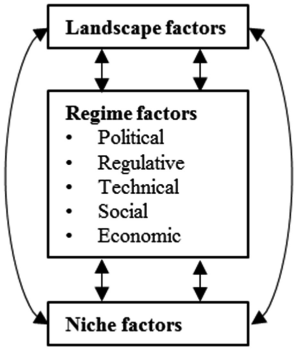

Fig. 3. Factors from each heuristic level of the multilevel perspective (MLP) were used as the basis for categorizing interviewee responses to questions.

3 Results and Discussion

3.1 Drivers for Change Since 2005

Interviewees stated that the change in the generation profile over the past decade has been largely driven at a landscape level by falling prices for renewables, an increasing awareness of climate change, and a decline in the demand for electricity from the network. One respondent was adamant that the fall in demand allowed the regime to safely allow renewables onto the network. Had there been a continuation of strong growth in underlying demand, then energy providers would have met this demand with thermal generators. It was also important to the uptake of renewables that the growing awareness of climate change allowed for the introduction of renewable energy stimulating policies at the regime level.

The most consistently mentioned drivers for change at the regime level were the State based capacity mechanism and the federally implemented large scale renewable energy target (LRET). The latter scheme is driving the current wave of renewable projects that are expected to connect to the network over the next five years (Table 3).

Table 3. Generation capacity on the SWIS 2007, 2017 and as anticipated in 2022 and 2027.

Generation type	2007	2017	2025	2030
Coal (MW)	1044	1787	1550	750
Gas (MW)	1749	3370	3240	3670
Dual Gas/Coal (MW)	509	0	0	0
Diesel (MW)	48	196	70	70
Wind (MW)	70	392	700	1000
Solar (MW)		10	1100	1500
Behind the meter PV (MW)		860	1200	2500
Solar thermal (MW)		0	0	200
Wave (MW)		0	0	200–250
Battery (MWh)		~	300	1500

3.2 Generation Profile and Implications

Generation Profile

Table 3 shows the generation profile expected by interview participants on the SWIS by the late 2020's. The trends are toward: a fall in coal generation; a stable, to increasing level of gas; and a marked increase in wind, centralized solar and behind the meter solar. Some participants also expected to see a greater diversity of energy sources, with the introduction of solar thermal and wave-based generation technologies towards the latter part of the study period. A marked uptake in battery storage is also expected, and this will be essential to counteract the effects of solar PV, whose mid-day output could exceed network demand if not arbitraged by batteries.

Of equal or greater importance than the generation profile, is consideration of the network demand profile. Forward-looking reports by the system operator, which are used to set capacity payments, are focusing on how to meet peak energy demand [31]. However, the most likely limiting factor in the future will be maintaining network stability in the middle of the day when solar capacity factors can be up to 0.74 in summer months [31] and the coincident network demand is likely to be less than solar PV and wind's combined output. This should accelerate the removal of coal from the network unless their operators can either cycle on and off throughout a day; solar output is curtailed or precluded from connecting to the network; or energy is arbitraged in the middle of the day using a form of energy storage such as batteries or pumped hydro. This altered demand profile will require generation services that can ramp quickly and cycle on and off throughout the day [37]. Interviewees raised other challenges that can be expected under this generation profile related to frequency regulation, inertia, fault current, voltage regulation and ramp rate. Concerns were also raised about the current inability to monetize the various battery services into the WEM.

Reforms to Enable Frequency Control

The variable nature of renewable generation makes it harder for the existing network operators to maintain a stable frequency and voltage using existing ancillary services

[10, 38]. The ancillary services are used to support the reliable functioning of electricity systems by balancing the short-term energy supply and demand [38–40]. With rooftop PV systems currently invisible to the system controllers, this generation cannot be dispatched or controlled to manage system frequency. The need for improved frequency control ancillary services is expected to increase dramatically in coming years [7]. One interviewee summed up the existing ancillary services market as follows:

> "We don't actually have a clear boundary between balancing and our real energy dispatch and load following. We need to sort that out, because the product's going to become more important as will the distinction between the two."

The WEM currently favors Synergy as essentially the only provider of ancillary services. Interviewees consistently mentioned the need to open the ancillary services market up to other participants as a key step in maintaining a stable electricity supply under a high renewables scenario. Historical decisions during the evolution of the WA electricity sector, particularly the uniform tariff policies from the 1970's [34], facility bidding practices, and retail tariffs that are not reflective of true costs have made the introduction of a fully functioning energy and ancillary services market particularly complex.

To unwind the existing lock-in mechanisms, the steps presented in Table 4 are considered necessary by interviewees. Addressing these could then assist in allowing the reforms required to address stability issues under a future generation mix.

Subject to the items in Table 4 being addressed, it could be possible to have coherent policy that allows developers to know the price of carbon, the reserve capacity revenue stream and for the various elements of the ancillary services stream to be transparently costed in a co-optimized energy and ancillary services market. Addressing the issues in Table 4 would allow core technical issues raised by interviewees to also be resolved (Table 5).

Table 4. Core actions raised by interviewees that need addressing for the market to provide a stable electricity supply under the future generation mix.

No.	Regime factor	Core outcome
S1	Social	A multi-year communications program that informs the community that an energy transition is underway, their relationship in the electricity market is evolving, that rooftop PV and battery interactions with the network will need to be controlled, and advanced metering infrastructure (AMI) will need to be installed and enabled
P1	Political	Bipartisan political support for a move to: cost reflective pricing; agreement on the structure of the gentailer and retail contestability; and a transparent pathway towards achieving these
R1	Regulative	A carbon price and/or a long-term clean energy target
R2		Assign accountability for the system planning and modelling to allow for long term planning and policy formation
R3		Streamlining of the rule-making processes such that regulators can deal with the rapidly changing energy market-place

Table 5. Core technical issues raised by interviewees that need addressing for the market to provide a stable electricity supply under the future generation mix.

No	Regime factor	Core outcome
T1	Technical	The need for control devices, such as AMI on premises with rooftop PV and/or batteries
T2		The need for a more automated dispatch engine, and for the gentailer's generation fleet to individually bid into the market rather than doing so on a whole-of-portfolio basis
T3		A means to address low fault current on the transmission lines when there are high levels of non-synchronous inverter-based generation in a region
T4		How to compensate for loss of inertia that is currently provided by rotating machines such as coal and gas turbines
R4	Regulative	Clarification of the access arrangements, whether constrained or unconstrained, for new generation to connect onto the SWIS

3.3 Transition to a Future Regime

As one respondent said:

> "It's the way that the transition is managed rather than the particular solutions, because I'm not sure the particular solutions are known."

Transition theory can be used to make sense of the transition process currently unfolding in the SWIS. The MLP of transition theory focusses on the interactions between the heuristic levels of landscape, regime and niche [22–29]. The remainder of this paper discusses the issues raised in Tables 4 and 5 within the framework of the MLP.

Uncertainty currently resides around the role and structure of the gentailer in the market, the market structure itself, and how to transition towards certainty within the confines of the existing regime. Many of the interviewees considered it likely that government was essentially paralyzed to make decisions that would result in significant losers and would more likely make change on the back of almost inevitable crisis resulting from outages and associated community outcry. Whilst interviewees did not favor this approach, it was considered a plausible eventuality. A more proactive strategy to engage the public in a long-running communications plan to seed public and political acceptance for the essential changes was raised by one interviewee. Installation of advanced meter infrastructure (AMI)/smart meters was considered essential by interviewees for allowing system management to control behind the meter solar and for aggregation services to be provided. However, application of these devices would require community acceptance, which may currently be lacking.

It is evident from Table 4 that the key elements of managing the transition are within the social, political and economic domains, rather than a technological one. The influence of consumers on the reliability of the future power system will be huge. This is because of the increasing influence of their solar PV on the distribution system, and also on the ability for their load and battery storage devices to be used to stabilize the system [37]. An international electrical power system engineering peak body, CIGRE, has recommended that definitions of system reliability need to be updated to reflect the new role of prosumers in the power system [37]. Historically, the energy utilities have simply needed to focus on how to provide more electricity to customers. Now, they are being forced to also consider the end-users preferences, as the customers actively interact as both customers and producers [41].

In order for the prosumers to fulfill their potential in supporting system reliability, they must first understand and value how they can interact with the power system. Jones, Curtis [42] report that implementation of smart meters was a gentle and successful first step in the electricity reform processes in California and Massachusetts. The smart meter roll-out in the state of Victoria, on the east coast of Australia was met with significant community backlash and was considered politically disastrous [43]. Several interviewees referred to the Victorian experience, which has dampened political enthusiasm in WA for a similar roll-out. It is for this reason that a long-term communications strategy is required to assist customers in understanding the value of the devices and to pave the way for them agreeing to have smart meter functionality activated (S1 in Table 4). Having the community broadly understanding these factors de-risks political support for this infrastructure rollout (P1 in Table 4). Other successful pathways include the use of demonstration trials to familiarize the public with the opportunities and thereby de-risks political decision making [44].

Market reforms are required to enable prosumers to actively participate in the market, both in providing ancillary services and real energy. This would require cost reflective pricing to be introduced into the WEM, a precursor to allowing third parties to provide ancillary services on a competitive basis. However, cost reflective pricing requires a substantial increase in domestic electricity tariffs, which unsurprisingly is politically and socially unpalatable. Long running communications plans and iconic projects that point to the future will likely be important steps in softening resistance to contentious political decisions ahead of them being made.

There is an acceptance in other countries that meeting climate change goals is efficiently done via a carbon price and that this can result, at least in the short term, in higher electricity costs [45]. Australia has vacillated on setting a carbon price, largely though lack of community support, which has translated into political inaction. Most interviewees saw the high-level need for a carbon price to be set, which can then send the correct pricing signals to the market and underpin social acceptance for increased pricing that flows from associated market restructures (R1 in Table 4). In the absence of this, the Australian energy consumers are seeing electricity costs increase, without having overtly signed onto a clean energy reform agenda. The long-term communications strategy will therefore need to help the community better understand that an energy transition is underway, the role they are playing in this transition, the reasons for the cost impacts and most importantly, what is in it for them. Without this understanding, any major political decisions are likely to be met with strong resistance.

Recent governance changes in the WEM has inadvertently resulted in no single party being left accountable for long-term system modelling and planning. Without understanding what a potential future could look like, it is not possible to plan and articulate a roadmap for industry to follow. Several interviewees were keen to see this function assigned promptly (R2 in Table 4).

Interviewees were also adamant that market reforms must be clear on the longer-term reform pathway for the gentailer, capacity mechanism and markets for energy and ancillary services. To these ends, there was a strong desire for bipartisan support for a move to: cost reflective pricing; agreement on the structure of the gentailer and retail contestability; and a transparent pathway towards achieving these (P1 in Table 4).

Many of the technologies to manage high rates of variable renewable generation already exist, however the market structures are not in place to incentivize their application [46]. It is the market, and the regulatory settings that need to be updated to deal with the accelerating pace of technological advancement and societal uptake of these technologies [6].

Transition theory posits several transition pathways that can occur, each differentiated by how the regime responds to changes at the landscape and niche level. The most radical changes occur under the de-alignment and re-alignment transition pathway. This pathway is defined as having a major change in the landscape and a restructuring of the system; where the regime becomes destabilized and there is uncertainty about which of the innovation pathways will take pre-eminence; and where one option eventually wins and results in new guiding principles, actors, practices and beliefs [25, 27, 29]. It can occur when the regime is altered due to its inability to keep pace with the changes resulting from new niche and landscape factors. Whilst this form of transition can be regenerative, it is disruptive to the incumbent regime.

The need to streamline regulatory decision making and effect associated change was acknowledge as a key issue by AEMO [47]. This was the first issue presented in AEMO's submission to the federal Government review into the future security of the national electricity market [47]. It was also acknowledged by the ERA in their report to the Minister for Energy earlier in 2018 on the WEM [48]. To avoid significant disruption, it will be essential for the regime to find a way to address decision making and rule change processes whilst still retaining sufficient stability to allow for investment decisions to be made (R3 in Table 4).

The predominantly technical challenges facing the energy network of the future, as presented in Table 5, should be solvable by the existing regime provided there is a social understanding of the issues, political alignment and sufficient political and institutional capacity to make the requisite changes in a timely fashion. With this foundation laid, market reforms can be implemented, and technical solutions provided in a manner guided by the existing regime.

If the existing regime can successfully lay the foundation, the transition pathway could be a continuation of the reconfiguration pathway, which has been occurring in WA since the late 1930's [49]. The reconfiguration pathway of transition theory results from cumulative adoption of new components, which substantially alters the architecture of the regime and is subject to landscape pressure [27]. The difference between this and de-alignment/re-alignment is that reconfiguration is more guided by the regime in response to the changes rather than new regimes emerging out of the coalesced niches. In the absence of the social and political foundations outlined above, it is most probable that a less directed transition pathway will be followed, one that could result in new guiding principles, actors, practices and beliefs.

It will be critical for the existing regime to prime society for their role in the future network. If the plausible electricity crisis eventuates, it will be essential that space has been created for society, and therefore politicians to make sensible decisions. As several interviewees stated, “My concern over here is that the simple solution will ban them… or put up such barriers that they’re effectively banning it”. Given the momentum and cost benefits of self-generation, the regime can’t afford to take this strategy if it wants to avoid a de-alignment/re-alignment transitionary pathway.

4 Conclusion

The electricity generation profile in the SWIS is fast evolving to incorporate high rates of renewable generation, much of which is currently invisible and uncontrollable by system management. This will result in system stability issues, which will be visible earlier in the SWIS’s islanded system than could be expected in larger, interconnected systems elsewhere in the world. Lessons stemming from transitions within the SWIS are therefore important to the global energy transitions discourse.

Political decisions will be required at an increasing rate to evolve the market to maintain a stable electricity supply over the coming decade. It will be critical for existing operators and regulatory agencies to help customers understand their evolving role within the future electricity market, which will assist in de-risking political decisions affecting energy consumers. Regulatory agencies must also find a pathway towards accelerating the rule change processes. If they succeed in these tasks, then the market reforms can be made and the necessary technical fixes related to frequency regulation, inertia, fault current, voltage regulation and ramp rate can be implemented. A controlled transition of this type would result in a continuation of the hegemony of the existing regime. If, however, the decision-making processes cannot keep pace with the rapid deployment of renewables, then it is highly possible that a new regime could coalesce out of evolving business models.

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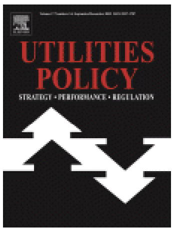

The duck curve in a drying pond: The impact of rooftop PV on the Western Australian electricity market transition

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The duck curve in a drying pond: The impact of rooftop PV on the Western Australian electricity market transition[☆]

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ABSTRACT

Rooftop solar photovoltaics (PV) are significantly influencing the electricity market and system operability in Western Australia. Qualitative methods are used to determine likely impacts and solutions to associated technical and market challenges in this islanded electricity system. Solutions focus on flattening the load curve and addressing minimum system load issues, including via; tariff reform, new ancillary services, automation, storage and energy productivity; targeted markets to match energy supply to the new demand curve; together with enabling technologies such as; improved inverter functionality and control systems. A parsimonious model demonstrates the impacts of rooftop PV on the local mid-day wholesale energy prices.

1. Introduction

Electricity systems and market settings that have been effective for the past 100 years in the economic provision of electricity are beginning to falter in response to the uptake of variable renewable energy (VRE) sources (Bakke, 2016; Gerres et al., 2019; Hirth, 2013a; Liebreich, 2017; Woo and Zarnikau, 2019) particularly rooftop photovoltaic (PV). This trend is seen by decreasing mid-day system loads resulting in the increasing number of negative price intervals in electricity markets in response to the uptake of VRE sources (AEMO, 2020f; Maticka, 2019). On a per-capita basis, more rooftop PV has been installed on Australian residential and commercial premises than anywhere else in the world (AEMO and Energy Networks Australia, 2019; Shaw-Williams et al., 2019), and this is contributing to the early retirement of many traditional thermal generators and putting remaining generators under some financial stress (AEMO, 2020f; Johnston and McGowan, 2019; Synergy, 2017). International Energy Agency (IEA) modelling suggests that this trend is likely to accelerate, with combined rooftop and utility PV projected to overtake coal as the single largest installed capacity globally by 2040 (IEA, 2018). The trend is being driven jointly by government policies to address climate change and the continuing fall in the cost of VRE, with solar PV, in particular, now supplying some of the cheapest electricity prices ever seen (IEA, 2020). These changes are placing pressure on the operability and financial viability of traditional electric power systems, which calls for the transition to be effectively managed (AEMO, 2018a, 2019b, c, 2020a, g; Energy Security Board, 2019; Energy Transformation Taskforce, 2020; ESB, 2019, 2020; Finkel et al., 2017; Wilkinson et al., 2020a; Wilkinson and Morrison, 2018) to ensure that the supply of electricity continues uninterrupted.

The near-zero short-run marginal cost[1] (SRMC) of VRE reduces market-clearing prices for traditional baseload generators, reducing their profitability, a phenomenon described as the merit-order effect (MOE) (Abbott and Cohen, 2019; Boβmann and Staffell, 2015; Janko et al., 2016; Joachim et al., 2018; Sioshansi, 2016a; Woodhouse, 2016). In addition, it reduces the length and value of peak energy price periods causing the ‘missing money problem’ that in turn reduces the financial viability of mid-merit and peaking plants (International Energy Agency, 2016; Martin de Lagarde and Lantz, 2018; Tveten et al., 2013; Woo et al., 2016; Woo and Zarnikau, 2019). The natural outcome of this in systems with very high proportions of solar VRE is the removal of higher-cost thermal generators from mid-day trading intervals followed by their gradual decommissioning from the market on economic

☆ The views expressed are those of the author and do not necessarily reflect those of my employer.

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[1] SRMC is defined as the change in short-run total cost for an extremely small change in output ERA, 2008. Short Run Marginal Cost - Discussion Paper, in: Authority, E.R. (Ed.). Economic Regulation Authority.

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grounds. As they exit the market, the electric power system loses inherent services such as inertia and system strength[2] that are importantly supplied by these generators (AEMO, 2019a). This transition requires careful management to ensure electric power systems can continue to function as they change from systems based on small numbers of large and centrally controlled power generators to ones containing millions of small distributed energy resources (DER) connected to the electric power system via inverters that currently provide limited network support.

The South West interconnect system (SWIS) in Western Australia (WA) represents a good case study for examining the electricity transition. The SWIS has some of the highest levels of installed rooftop PV, an aging thermal generation fleet, and due to its isolation from any other electric power system (AEMO, 2019a; Energy Transformation Taskforce, 2020), it will need to resolve these challenges within the next two to five years. The learnings from this case study can be applied to other electricity systems globally. As shown in Fig. 1, the SWIS displays advanced characteristics of the "duck curve," the phenomena first ascribed to the impact of rooftop PV on California's electricity system (Sioshansi, 2016b). As manifested in the SWIS, the duck curve is characterised by an urgent need to manage steepening ramp rates, system loads approaching minimum system demand level and increasing ancillary service requirements to maintain system stability (AEMO, 2019b; Maticka, 2019). The rapid and sustained uptake of rooftop PV in the SWIS is projected to push the system into higher operational security risk limits by 2022 (AEMO, 2019a) and is already creating market inefficiencies (AEMO, 2019b). The SWIS's isolation from other systems means that electricity from periods of excess generation cannot be exported for use in neighbouring systems, and periods of shortfall cannot be met through imports, a luxury afforded to larger integrated electric power systems in the United States, Europe (Sioshansi, 2016a) and National Electricity Market (NEM) in eastern Australia (AEMO, 2020a; Energy Networks Australia and CSIRO, 2017; Finkel et al., 2017). This isolation requires all instantaneous supply and demand imbalances to be resolved internally, meaning there is greater urgency to find cost-effective solutions

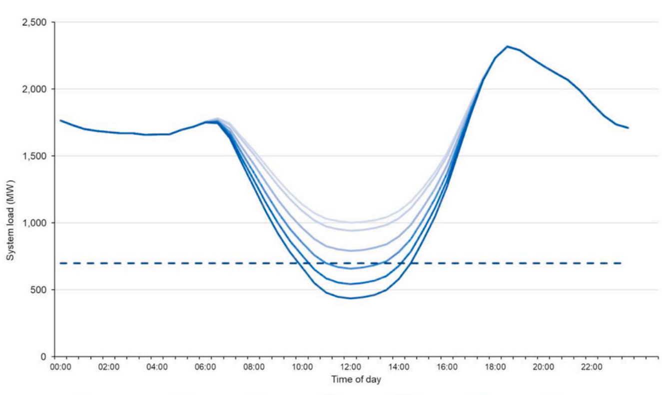

Fig. 1. Deepening of the duck's belly as more rooftop PV connects to the SWIS.

before system security events manifest. Lessons learned from safeguarding this electrical power system can be applied to other systems globally as they progressively encounter these challenges when their systems decarbonise to meet their respective Paris Agreement commitments.

This paper explores the technical and market operating challenges associated with the increasing size of the 'duck belly' as rooftop PV energy production increases to the extent that it displaces utility power production resulting in a 'drying duck pond'[3] in the SWIS. In this paper, we refer to the reduction of mid-day instantaneous system load as a 'drying duck pond,' a metaphor describing the electric power system and market impacts as the system load diminishes in the mid-day and the belly of the duck curve increases with further rooftop PV energy self-sufficiency (Fig. 1). There is a growing body of technical reports from system operators and regulators that aim to understand and respond to these issues and reflect the urgency of the transition challenge. See for example the following reports that address issues on both WA's Wholesale Energy Market (WEM) and the NEM AEMO (2019b, 2019c, 2020g); Distributed Energy Integration Program (2020); Energy Networks Australia and CSIRO (2017); Energy Security Board (2019); Energy Transformation Taskforce (2020); ESB (2019, 2020); Finkel et al. (2017) and California's Independent System Operator (CAISO, 2020a, b). The peer-reviewed literature includes few papers that specifically address the linkage between high penetration rates of rooftop PV, wholesale markets, and system operability of electric power systems in islanded networks.

There is significant literature demonstrating the MOE resulting from VRE installation both in Australia (Bell et al., 2017; Cludius et al., 2014; Csereklyei et al., 2019; Forrest and MacGill, 2013; Gilmore et al., 2015; McConnell et al., 2013) and internationally (Azofra et al., 2014; Bublitz et al., 2019; Clò et al., 2015; Figueiredo and Silva, 2019; Hirth, 2013a, b; Hirth et al., 2016; Janda, 2018; Joachim et al., 2018; Kyritsis et al., 2017; Sorknæs et al., 2019; Tveten et al., 2013; Woo et al., 2016). While the MOE impacts are well researched, there are limited empirical studies explicitly testing the effect of rooftop PV on wholesale energy markets. The exceptions we are aware of include a study showing that rooftop PV reduced hourly median wholesale energy prices by 7–8% in California based on historical data (Craig et al., 2018); and a study by Cole et al. (2016) who found that rooftop PV was a natural competitor to utility PV. They modelled that rooftop PV would likely result in a 1:1 displacement of utility PV. A further study by Maticka (2019), specific to WA, provides further evidence that rooftop PV results in a MOE, with the effect most strongly impacting utility PV profitability.

This paper initially tests for a statistically significant relationship between rooftop PV output and wholesale energy prices in the WEM for the SWIS to provide a supportive context to the WEM case study. A relatively simple and established approach has been applied using empirical data and looks at the mid-day energy trading interval to examine the displacement of marginal cost generators as the duck 'belly' grew in the SWIS. The results of this analysis, taken together with recent modelling from the WEM's independent system operator (ISO), are used to highlight the urgent need to understand what changes would be required to ensure the ongoing stability of the electric power system as it transitions, or adapts to these changes. The second half of the paper applies semi-structured interviews to gain insights into the implications of the MOE for the energy market and electric power system and to identify changes required for effectively managing the transition. These interviews are cross-checked against recent ISO and regulatory reports from across Australia and California.

The following section discusses specific challenges faced in the SWIS,

[2] System strength is the available fault current at a specified location in the power system, where higher fault current indicates higher system strength AEMO, 2018b. System strength requirements methodology: System strength requirements & fault level shortfalls. It represents the ability of the power system to both remain stable under normal conditions and return to steady state conditions following a disturbance AEMO, 2019b. Integrating Utility-scale Renewables and Distributed Energy Resources in the SWIS, in: Australian Energy Market Operator (Ed.).

[3] The drying of the duck pond in the WEM context is the reduction of demand not supplied by ancillary services. The WEM Balancing market, while energy only also contains the provision of spinning reserve and load following ancillary services.

while section 1.2 reviews the literature on global responses to these issues. Section 2 details the methods used to address the research objectives, and section 3 presents the results, followed by the discussion in section 4. Conclusions and suggestions for future research are presented in section 5.

1.1. The Western Australian context

An ISO operates the WEM for the SWIS in WA that comprises energy trading and capacity components. The former is a net pool energy market with day-ahead and real-time wholesale energy markets and a limited ancillary services market. The State's legacy thermal generation utility dominates the market with over 40% of the system's installed generation and provides most ancillary services. The retail electricity market is restricted to a single state-run retailer with retail tariffs set on a volumetric basis.[4] Commercial customers can access multiple tariff options via a competitive market. The capacity component is like that employed by PJM[5] in the United States and provides payments based on capacity availability during peak intervals, which in the SWIS has historically coincided with hot summer afternoons and evenings.

Fig. 2 shows the installed capacity (left-hand side) and the electricity generated in the WEM (right-hand side) as of mid-2020. Rooftop PV is not included in these figures as it is not traded in the WEM, nor is it controllable by the ISO. Despite this, approximately 1,300[6] MWs of rooftop PV are already installed (AEMO, 2020b), making it the largest energy source at almost four times the size of the largest single dispatchable (coal) generator (Energy Transformation Taskforce, 2020) in the SWIS. The limited visibility and control of this resource create increasing operational challenges for the ISO (AEMO, 2019b) (Table 1).

Over 30% of dwellings in WA already have rooftop PV installed (Australian PV Institute, 2020), with adoption rates projected to continue at a linear rate (Gerardi and O'Connor, 2017) to reach 2600

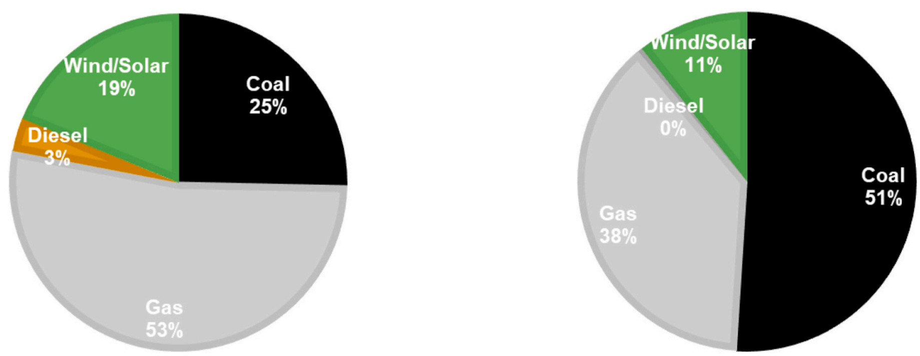

Fig. 2. Installed generation capacity as of 2020 (left-hand side) and the percentage of electricity generated in the WEM in 12 months to August 2020 by fuel type (right-hand side). Note: Rooftop PV is not included in these figures as it neither visible nor controllable by the ISO. Source (AEMO, 2020b, d).

Table 1
SWIS transition challenges created by the loss of traditional thermal generation capacity (from.Wilkinson et al. (2021)).

Challenge	Cause
A mismatch between system load and generation capabilities	More thermal generators will fall below their minimum generation level during mid-day hours, causing them to either cycle on and off[8] or pay other generators not to run. This may result in generation being unavailable to support afternoon ramping and/or evening peak loads while also removing the additional system support services they inherently supply (as summarised in the remainder of this table).
Limited visibility and control of a significant portion of total generation	As for the above challenge, a significant portion of mid-day demand will be supplied via inverter connected rooftop PV systems that the ISO has limited visibility and control of (Energy Transformation Taskforce, 2020). The ISO can only dispatch utility-scale generators (those greater than 10 MW) for maintaining system security.
Reduced system inertia	Traditional thermal generators have high spinning inertia, which can resist the rate of change in frequency (Austin, 2020; Riesz and Macgill, 2013). Exit of these generators results in a reduction in inertia, making systems more vulnerable to frequency variation.
More rapid frequency fluctuations	Uncontrolled VRE without storage responds almost instantly to changes in cloud cover (PV) and wind speed (wind turbines). As a result, inter-interval generation can vary significantly pending on weather conditions, requiring additional frequency regulation services (Riesz and Macgill, 2013).
Voltage regulation	As the minimum system load drops to around 700 MW, there would be insufficient synchronous generation online to absorb the excess reactive power that results from rooftop PV systems exporting into the distribution system (AEMO, 2019b).
System strength	Synchronous generators inherently supply system strength, contributing to system security, which is needed most at the system's centre (AEMO, 2018b). Inverter connected VRE's contribute little to system strength and, in the case of rooftop PV, are located on the distribution network close to demand centres. Conversely, the existing thermal generators, around which the existing system has been designed, are located further out on the transmission network.
Ramp rate	The new system load profile characterised by the duck curve with low mid-day demand and high evening peak requires substantially more ramping than the historically flatter load profile (Fig. 1).

[4] These are customers that consume 50 MW h or less of energy per year and represent approximately 28% of energy consumed in the SWIS. AEMO, 2018c. Wholesale Electricity Market Fact Sheet. Australian Energy Market Operator.

[5] PJM is a regional transmission organisation that coordinates the movement of wholesale electricity across the states of Pennsylvania, New Jersey, Maryland, Delaware, Ohio, Virginia, Kentucky, North Carolina, West Virginia, Indiana, Michigan, Illinois, and the District of Columbia.

[6] In terms of impact, the peak generation of the combination of all these installations will not total the nameplate value listed. This is due to several reasons, including but not limited to shading, faulty installation, failed PV cells, age of solar panel, temperature rerating, and orientation.

MW over the coming decade (AEMO, 2020b). Fig. 3 shows the rapid uptake of rooftop PV in the SWIS since 2011. These installations are termed as “behind the meter” and offset consumption, with rooftop PV generation typically observed in the wholesale market as reduced system load. As a result, output from rooftop PV is reducing the operational load to be supplied by other market generators, contributing to wholesale energy prices then clearing lower on the price stack as it effectively moves the demand intersection down the merit order (refer to Fig. 4, which provides a graphical representation of the MOE). VRE sources typically bid into the WEM at negative prices down to the price floor of

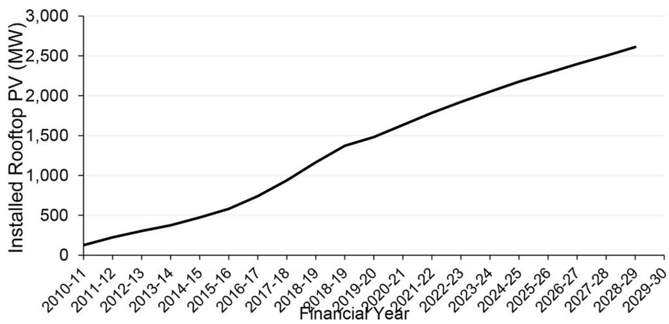

Fig. 3. Installed rooftop PV capacity in the SWIS since 2010 and projected out to 2030. (Historical installed capacity for 2010–11 to 2018–19 is sourced from the Clean Energy Regulator and Australian PV Institute. Forecast installed capacity for the period 2019–20 to 2029–30 is sourced from the AEMO 2020 WEM Electricity Statement of Opportunities report).

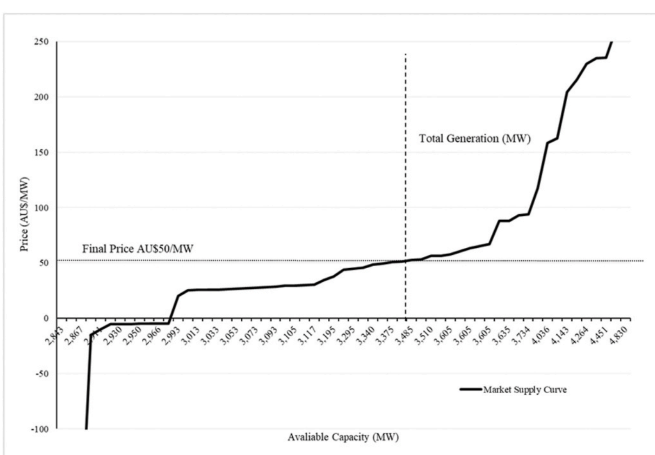

Fig. 4. Market supply curve showing the merit order effect created by zero short-run marginal cost rooftop PV reducing the residual load and pushing the wholesale energy price lower. (Source: WEM Balancing Market Merit Order summary).

negative AU$1,000,[7] as do thermal generating units contracted to supply frequency control ancillary services (load following, spinning reserve, and black-start capability). Coal generators seeking to avoid cycling costs also often bid into the market at the price floor. The output from these rooftop PV systems has already created significant negative wholesale energy price intervals, with negative prices increasing from 4.8 to 6.2 per cent of trading intervals from 2019 to 2020 (AEMO, 2020f).

As more rooftop PV connects to the SWIS, the minimum mid-day system load will transition toward higher operational security risk limits (estimated to be 700MW) by 2023–24 (AEMO, 2020b) and decrease further to 100 MW by 2026 (AEMO, 2019b) without intervention. These projections do not consider the likely new installation of utility PV and wind facilities over this time horizon to a system with a projected peak system load of less than 4000 MW by 2029–30 (AEMO, 2020b). This situation creates a mismatch between the generation capability and the underlying system load. Table 1 summarises the challenges created by this mismatch in supply and demand. Section 1.2 then summarising the literature on how these challenges get addressed globally. The challenges identified in Table 1 have also been identified in work programs addressing the integration of high levels of DER in the WEM and NEM (AEMO, 2019b; 2020a; Distributed Energy Integration Program, 2020; Energy Transformation Taskforce, 2020; ESB, 2019) and can be expected to confront other electricity systems globally as their proportion of rooftop PV increases.

1.2. *Managing the growing duck belly and drying pond*

This section reviews the literature on key measures being undertaken globally to manage the electricity system’s transition and addresses issues inherent in the drying duck pond. It is noted that the MOE and associated reduction in demand for energy from traditional thermal generators do not represent a market failure but rather point to an energy system in transition.

A first step in managing the transition to a VRE dominant system is to clarify the roles of government and markets during and after the transition. While electricity systems globally have been progressively privatised over recent decades, consideration is increasingly being given to what is a public and private good regarding electricity supply (Liebreich, 2017) and, therefore, the best ownership model moving forward. A public good is typically supplied to all members of society rather than a private good, which is supplied based on a customer’s willingness to pay. Abbott and Cohen (2019) argue that electricity supply is a private good, whereas the security of supply is a public good. Access to electricity has become a societal right and relies on physical infrastructure, control systems, and ancillary services for this to occur (Wilkinson et al., 2020a).

In contrast, the amount of electricity consumed (beyond a minimum societal amount) is a privilege or private good (Abbott and Cohen, 2019). Understanding this distinction can assist in creating the correct market settings and address social equity issues that occur during the energy transition. This process can include defining the role of governments and associated market controls associated with the growing list of system services inherent to traditional thermal generators and have increased relevance during the transition phase.

[7] Minimum Short-Term Energy Market Price, see: https://aemo.com.au/en/energy-systems/electricity/wholesale-electricity-market-wem/data-wem/price-limits.

[8] Cold or warm re-starts cost in the order of AU$350/MW or AU$120/MW respectively for coal units. With units ranging in size from 120 MW to 330 MW, these restarts can cost AU$14,000 – AU$40,000 per warm restart and AU $42,000 to $115,000 per cold-restart, depending on the individual unit sizes. GHD, 2018. AEMO costs and technical parameter review. These costs do not include the increased maintenance costs associated with cycling these units.

1.2.1. A mismatch between network demand and generation capabilities

Like those employed in the WEM and PJM, capacity reserve mechanisms ensure enough capacity will be available during times of scarcity and help solve the missing money problem, which occurs when there are insufficient high-priced periods to recover costs for peaking plants (Bublitz et al., 2019; Milstein and Tishler, 2019; Woo et al., 2016; Woo and Zarnikau, 2019). Capacity reserve mechanisms provide income to generators to guarantee their availability during trading periods of known system vulnerability, such as on the hottest or coldest days. They are, however, not without their detractors who claim they can be politically motivated to support incumbent generators (Auer and Haas, 2016), interfere with effective market function (Bublitz et al., 2019) and can result in significant overpayment and/or over capacity (McCullough et al., 2019). Notwithstanding these criticisms, well-designed capacity payments are widely regarded as providing a safety net during the transition (International Energy Agency, 2016; Kraan et al., 2019). They can be targeted to ensure sufficient generation capacity and ancillary services are invested in and will be available at times of future scarcity (Byers et al., 2018; Gerres et al., 2019; Joachim et al., 2018) while addressing the missing money problem that would have otherwise precluded investment in these products. The need for ancillary services, such as providing ramping and frequency regulation services, increases as more VRE connects to electric power systems due to the variable nature of renewable energy and their lack of inertia. To address the market-distorting criticism of capacity markets, Auer and Haas (2016) believe that effective demand response[9] (DR) can provide similar system benefits and can do so by introducing price discovery (Bublitz et al., 2019). This is because customers effectively set a price for avoided generation capacity when receiving payment for forgoing energy use.

Using pricing signals to shift customers' energy use behaviours has been a feature of the electricity market for over 100 years (Bakke, 2016). The ongoing success of this measure is needed to affect a better matching of daytime energy consumption and rooftop PV output while also incentivising customers to reduce consumption at other times. However, some research argues that tariff reform may have less potential in future years given that the elasticity of demand has fallen over the past three decades as the majority of available energy efficiency and load shifting opportunities have already been implemented (Bublitz et al., 2019; Hobman et al., 2016; Joachim et al., 2018). Other researchers have found that households have a limited response to electricity price changes, particularly those with higher ambient temperatures, such as in the Gulf (Atalla and Hunt, 2016; Matar, 2019).

Despite this criticism, utilities globally are continuing to use innovative tariff structures to incentivise desired behaviour changes such as through real-time pricing (RTP), critical peak pricing, and peak demand tariffs (Joachim et al., 2018; Satchwell et al., 2015; Tayal and Evers, 2018) with a general move away from the volumetric charges that are used for most retail customers in the SWIS. Critical peak pricing and peak demand tariffs focus on reducing power system costs associated with peaks. While dealing with system peaks has been a key policy driver in WA, future drivers must be more focused on managing minimum demand periods to address the issues that occur during maximum rooftop PV output, such as congestion at the distribution level. RTP has the greatest potential to address this issue through its ability to expose prosumers to the wholesale electricity market. A downside to these tariffs is that they can be politically unpalatable due to their potential to result in large bill increases for the electorate (Mills and Wiser, 2015; Tayal and Evers, 2018). Effective implementation of RTP is also maximised when linked with automation technologies that can switch equipment on or off in response to price signals (Lo et al., 2019). Mills and Wiser (2015) reported that a 10% increase in wholesale prices seen via RTP tariffs resulted in a 1% decrease in energy consumption. These figures would indicate that these tariffs, on their own, may not be enough to address the issues described by the drying duck pond that are challenging the SWIS and the effective functioning of its electricity market.

In Sherwood et al. (2016) 's review of the literature, they found no studies showing any relationship between maximum demand charges and behavioural changes that would flatten the load profile. By contrast, they also found strong evidence that well-structured time of use (ToU) tariffs can effectively drive behaviour changes. Some Australian retailers are introducing "solar soak" tariffs that charge 25% of the standard tariff to encourage energy use during daylight hours (SA Power Networks, 2020). A similar mechanism has also been piloted for the WEM as part of the Energy Transformation Taskforce's Distributed Energy Resources Roadmap. The WEM, however, implements variable renewable energy buyback rates (lower during sunlight hours and higher at other times), which aim to change the energy use patterns of rooftop PV owners and potentially better reward those that install battery systems.

The most promising approaches occur by combining time-varying tariffs, automation, storage technologies, and market structures that allow prosumers to participate in a wholesale market. Business models such as DR, virtual power plants (VPPs) via an aggregator, or peer-to-peer (P2P) trading have been suggested as effective mechanisms for prosumers to participate in markets and be exposed to effective price signals (Parag and Sovacool, 2016; Say et al., 2019). The benefits of DER, such as rooftop PV participating in energy markets, has been identified as a key transition issue in Australia's NEM and California's energy market reform programs, where pathways to introduce these market mechanisms are being developed (CAISO, 2020a, b; Distributed Energy Integration Program, 2020; ESB, 2019; FERC, 2020).

Energy productivity can also flatten the load profile and address supply and demand imbalances (CEC, 2020a; Finkel et al., 2016). This approach comes in the guise of product design standards for improving energy efficiency and building design codes, which can reduce peak system loads. California's Loading Order guides the implementation of Californian energy policy and places energy efficiency and DR as high priorities (Woo et al., 2016). DR, such as switching to efficient electric hot water storage, can also shift electricity loads to daylight hours, thereby raising mid-day demand and lowering evening peaks (Rodríguez-Molina et al., 2014). Satchwell et al. (2015) found that many of the measures adopted for driving energy efficiency are equally relevant in offsetting the negative impacts of rooftop PV on traditional power production systems.

1.2.2. Technical requirements: system strength, inertia, voltage, and frequency

As described in Table 1, traditional thermal generators provide some inherent services typically not priced or sufficiently valued by electricity markets. If the MOE pushes these generators from the market, services such as inertia, frequency regulation, and ramping will need to be supplied via other means. Thermal generators provide dispatchable energy to ISOs, which can be ramped up and down to maintain supply and demand balances and control frequency. As in the WEM, a resolution to these problems has occurred in deregulated energy markets through a mixture of technical rules and markets. Technical rules have set the

[9] We adopt the following definition for demand response: "Changes in electric usage by end-use customers from their normal consumption patterns in response to changes in the price of electricity over time, or to incentive payments designed to induce lower electricity use at times of high wholesale market prices or when system reliability is jeopardized" as referred to by Sperstad, I.B., Degefa, M.Z., Kjølle, G., 2020. The impact of flexible resources in distribution systems on the security of electricity supply: A literature review. Electric Power Systems Research 188.

minimum requirements for devices connected to the system, ensuring reliability standards are met. Markets have been used to ensure enough generation capacity, and ancillary services meet demand and system requirements. However, markets currently either do not exist for some of these services in many electric power systems, or they are inefficiently designed to the point that they are unlikely to provide for sufficient quantities of ancillary services to meet the needs of the future high VRE systems.

Network operators globally have been adopting advanced metering infrastructure and inverter standards. When used together, these can allow for a combination of market-based strategies and can provide direct controls over rooftop PV's interactions with the distribution network (AEMO, 2019b; CAISO, 2020a, b; Department of Energy and Climate Change (DECC), 2014; Energy Networks Australia and CSIRO, 2017; FERC, 2020; Glass et al., 2019; Knieps, 2016; Mengelkamp et al., 2017). Inverter standards are also being adopted to allow for rooftop PV to assist in the management of frequency, voltage, and reactive power fluctuations in the distribution system and assist prosumers to access potential future markets for these services (AEMO, 2019c; FERC, 2020; Giraldez et al., 2018; NREL, 2012).

Advanced metering infrastructure, or smart meters, are a precursor to allowing rooftop PV owners, down to the household level, to participate in the wholesale energy markets via DR, VPPs, and/or P2P trading models (Parag and Sovacool, 2016). These evolving business models can be effectively integrated into ancillary service markets, such as for primary frequency responses (Bertolini et al., 2018; Liebreich, 2017) while providing the market signals to flatten the load curve (Rodríguez-Molina et al., 2014). These signals can be used, for example, to decrease evening electricity use and increase day time consumption, such as by turning on pool pumps, electric hot water storage, commercial air conditioning, and incentivising day time electric vehicle charging (Joachim et al., 2018). This approach has the benefit of improving economic efficiency, lowering carbon emissions, and enhancing power quality.

Storage technologies have the potential to shift loads from periods of high PV output to those of high demand, directly addressing the drying pond conundrum. Market structures are required to reward the investment in these technologies at a household, distribution, and transmission level. Regardless of who pays for storage, its integration into power systems and electricity markets has the potential to be transformative (Azzuni and Breyer, 2018). On a technical level, batteries can supply peak load shaving, congestion management, frequency control, and "harmonic compensation" (to improve the overall power quality and prevent further injection of harmonics into the grid) (Azzuni and Breyer, 2018; Das et al., 2018, 2019; Sperstad et al., 2020; Yazdani et al., 2017). Opportunities are also being explored to develop new markets for reactive and active power for voltage regulation to manage rooftop PV impacts on the distribution system (Anaya and Pollitt, 2020). From a market perspective, batteries can reduce the daily price spread (Auer and Haas, 2016) and allow more effective integration of DR, VPPs, and P2P trading schemes.

Inverter connected rooftop PV systems use synchronous generators as the reference for frequency and power phase angles (AEMO, 2018b). Austin (2020) proposed that with a 100% inverter-based wind and solar power system, all frequency could be set against a reference GPS clock (which can be accurate to 25 billionths of a second). Under this scenario, instead of frequency slowing or speeding up, it would stay steady, and voltage would go up or down depending on instantaneous supply and demand imbalances, requiring controllers to manage voltage in a future system rather than frequency. Of more immediate concern to systems such as the SWIS is ensuring that inverter connected rooftop PV systems can support system security rather than acting independently, causing large voltage and frequency variations that destabilise the electrical power system (AEMO, 2019c). This concern can be managed by requiring inverters to be regulated with tighter standards on how they respond to frequency variations and voltage fluctuations in the distribution system (AEMO, 2019b, c; Giraldez et al., 2018; Prabakar et al., 2019; Yazdani et al., 2017).

2. Methods

A mixed-method research approach was adopted for this case study analysis. As presented in section 1.2, a literature review was undertaken to understand the impacts of rooftop PV systems on energy markets and electric power systems, focussing on WA, Eastern Australia, and California. A parsimonious hybrid model with statistical analysis was used to supply supporting details for the interviews by demonstrating the impact of rooftop PV systems on wholesale energy prices in the WEM. Qualitative methods were then used in conjunction with the literature review results to answer the remaining research objectives on the impacts and required responses to very high levels of rooftop PV in the SWIS (Section 2.2).

2.1. Quantitative analysis approach and data sources

This paper initially tests for a statistically significant relationship between rooftop PV output and wholesale energy prices in the WEM to provide a supporting context to the WEM case study. A parsimonious hybrid model with a statistical analysis approach was selected. Statistical models effectively investigate the relationship between independent variables with a parsimonious structure. Using a minimal number of independent variables decreases the dependency on dataset availability using this approach (Weron, 2014). Such models perform poorly for predictive analysis, particularly with the determination of price spikes (Weron, 2014). In contrast, ordinary least squares (OLS) models are useful when the model intends to understand the relative significance of different inputs (Fan and Hyndman, 2011). The relationships that are investigated in this paper, and as such, an OLS regression model have been used. Such a model could be used to benchmark more sophisticated models (Aneiros et al., 2016; Weron, 2014) in future research if so required.

OLS analysis and examination was undertaken using R Programming language on publicly available data. The OLS regression analysis equations and sources of input data used for the analysis are presented in Appendix A.

2.2. Qualitative data and analysis

A total of 27 semi-structured interviews were undertaken to gain insights into current and future issues resulting from the MOE occurring in the SWIS due to high rates of rooftop PV installation. Twenty-three industry executives with expertise in the WEM and SWIS were inter-

Table 2
Composition of interview participants based on their area of expertise.

Participant	Expertise
E1-E3	Current or past CEO of WA based electricity organisations
P1–P11	Senior management with current or recent policy or system operation related function in WA
C1–C4	Senior consultant to government and/or industry
A1	Electricity sector academic
G1-G3	Energy provider (including those with renewables and mixed renewable and thermal generation portfolios)
In1–In4	International energy expert (2 academic, 1 policy maker, 1 entrepreneur)
L1	Legal

Table 3
Results of the OLS regression model for each noon trading interval – System Load and Wholesale Energy Price - July 2012 to February 2020.

Predictors	System Load			Wholesale Energy Price		
	Estimates	Confidence Interval.	Signif.	Estimates	Confidence Interval.	Signif.
(Intercept)	1670	1617–1723		27.34	19.77–34.90	
Rooftop PV Installed (MW)	−0.49	−0.51–−0.47	***	−0.02	−0.03–−0.02	***
Solar Irradiation (day - MJ/m*m)	−21.91	−23.51–−19.98	***	−1.42	−1.67 - - 1.17	***
Max Temperature (°C)	41.73	39.70–43.76	***	2.28	1.94–2.52	***
Daily Rain Fall (mm)	5.11	3.81–6.49	***	0.11	−0.08–0.31	
Summer (Dummy variable)	302.84	273.47–332.20	***	11.91	7.706–16.11	***
Winter (Dummy variable)	168.41	143.40–193.41	***	7.72	4.14–11.30	***
Spring (Dummy variable)	76.95	50.85–103.04	***	7.20	3.46–10.94	***
Weekend/Public Holiday (Dummy variable)	−300.55	−317.19–−283.92	***	−10.75	−13.13 - - 8.36	***

Number of Observation (N): 2786.

System Load Adjusted R-Square ($\overline{R}^2$) : 0.666 Wholesale Energy Price Adjusted R-Square ($\overline{R}^2$) : 0.156
Significance Codes: '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1.

viewed, along with four experts from the United States and Europe. International experts were recruited based on their specialised knowledge in integrating high rates of rooftop PV into electricity systems and their regulative, academic, and entrepreneurial perspectives from outside the immediate study. As such, the inclusion of international experts was not intended to provide an exhaustive compendium of issues and possible solutions. All participants were selected based on a mixture of their detailed and executive-level understanding of the issues. Their functional areas of expertise are summarised in Table 2.

At least one in-depth interview was held with each participant. Interviews were guided by open-ended questions about managing a transition to higher rates of variable renewable energy sources within the SWIS. All interviews were transcribed into the social sciences software package, NVIVO 12. Transcripts were coded to identify key themes. As with Mayer et al. (2019), the number of times participants mentioned each theme, while used as a guide, was not ultimately used to ascribe importance to a theme. Instead, the analyst's understanding of the systems and literature, together with the totality of the interviews, was used in the analysis. The additive nature of semi-structured interviews also means the interviewer is armed with additional information for latter interviews than for earlier ones.

The representative number of interviews was considered to have been completed once relative saturation of issues raised was reached (Guest et al., 2016; Malterud et al., 2016). A cross-check was made between interview responses and issues raised by stakeholders in recent industry reports investigating the impacts of rooftop PV on energy markets and electricity systems[10]. Industry reports were selected for WA, Australia, and California that comprised broad stakeholder views on transitioning their electricity systems to integrate large quantities of DER generally or rooftop PV specifically.

Research findings were analysed within a sustainability transitions framework, leveraging off earlier works Wilkinson et al. (2020a); Wilkinson et al. (2020b); Wilkinson and Morrison (2018). Within this theoretical framework, understanding the energy transition requires consideration of all aspects across the socio-technical domain, including the social, technological, political and regulatory contexts and consists of actors, institutions, and infrastructure (Wilkinson et al., 2020b).

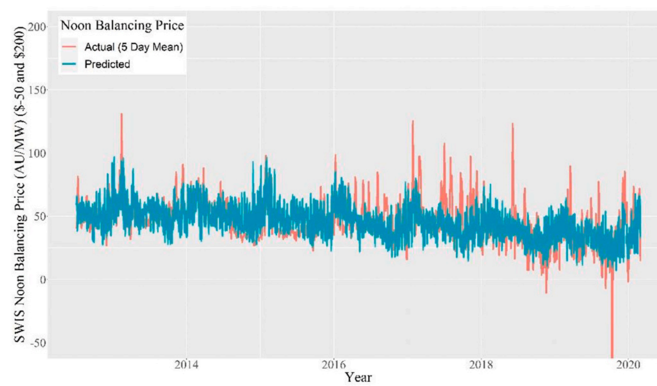

Fig. 5. Regression model showing noon wholesale energy (5-day mean) price in the SWIS versus the predicted noon wholesale energy price (y-axis) decreasing gradually between 2012 and 2020.

3. Results

3.1. Empirical analysis - distributed PV placing downward pressure on wholesale electricity prices

The parsimonious model provides contextual material for the case study, demonstrating statistically significant impacts of rooftop PV on the local mid-day wholesale energy prices. An examination of the entire dataset found that the wholesale energy price data is significantly more dynamic over a month than is evident from looking at single days or isolated periods. Average figures across the entire year do not correlate well with a single day. Monthly data is presented in graphical form in Appendix B, which shows a comprehensive description of the price profile in the SWIS. The thumbnail figures show the daily wholesale energy price curves for each month from 2012 to 2020 with the functional mean highlighted. The regression analysis undertaken is presented in Appendix A and was based on the System Load[11] and Wholesale Energy Price[12] of the midday price interval (12:00–12:30), as this corresponds to the period of maximum solar irradiation (and thus PV generation) in the SWIS.

The results in Table 3 show the OLS statistical relationship at the noon trading interval. The analysis shows that with each additional megawatt

[10] This includes the review of 2019 and 2020 reports by: Australian Energy Market Operator (AEMO); Distributed Energy Integration Program; Energy Transformation Taskforce; Energy Security Board (ESB) Californian Integrated System Operator (CAISO); and Californian Energy Commission (CEC).

[11] System load refers to the total of all actual generation in the SWIS as provided by AEMO and is used to determine the final balancing price and is based on non-loss adjusted SCADA data.

[12] The final balancing price, representative of the cost of providing the balancing energy, is sourced from the Operator - AEMO.

Table 4
Summary of interviewee solutions to high levels of rooftop PV. Symbols against text in the "specific mechanism" column indicate if that mechanism has also been identified in key work programs by the following related industry reports * = CAISO (2020a, 2020b). ϕ = ESB (2019, 2020); δ = Energy Transformation Taskforce (2020); β = Distributed Energy Integration Program (2020); and σ = AEMO (2019b, 2019c, 2020g).

Change Mechanism	Specific Mechanisms	What it does
Technical requirements	Inverter connection standards $^{\phi\delta\beta\sigma}$	Allows the ISO to control interactions of rooftop PV with distribution and transmission system; voltage control; reactive power management; and for inverters to respond with automatic droop control.
	Synchronous condensers $^{\sigma}$	Provide inertia and fault current.
	Minimum short circuit capability $^{\delta\sigma}$	Grid security.
	Transmission and distribution level control systems$^{*\phi\delta\beta\sigma}$	Increase automation and control of increasingly distributed generation profiles and associated interactions with the grid architecture. Specific measures may also increase the visibility and controllability of rooftop PV.
Markets	Ancillary services markets$^{*\phi\delta\beta\sigma}$: Inertia Frequency (rate of change of frequency, primary response, load rejection, spinning reserve, black start) Ramping System strength	Incentivises availability of services that can provide grid security and stabilisation.
	P2P trading$^{\phi\sigma}$	Allows localised retail pricing that incentivises local energy consumption to decrease transmission and distribution bottlenecks. Can form the basis of DR programs.
	DR/aggregators/VPPs$^{*\phi\delta\beta\sigma}$	Supplies ancillary services and enables short term load shifting.
	Capacity payments*	Incentivises generation in appropriate locations and of a type that is suited to future load profiles. Mitigating impacts of the "missing money" problem.
	Intra-day storage$^{*\phi\delta\sigma}$	Flattens load/energy arbitrage, provides ancillary services. Supports transmission and distribution networks.
	Seasonal storage $^{\sigma}$	Reduces variation in loads between summer/winter and shoulder periods.
Flattening load profile	Transmission$^{*\sigma}$ and distribution level storage$^{*\delta\sigma}$	Flattens load/energy arbitrage, provides ancillary services. Supports distribution network.
	Time and load varying tariffs$^{*\phi\delta\beta\sigma}$	Provides incentives for load flattening – reducing the peak and raising mid-day minimums.
	Domestic storage incentives	Incentivise load flattening and potentially voltage regulation.
	Smart loads/automation $^{\phi\delta}$	Provides ancillary services and maximises benefits achievable via tariff reform.
	DR or VPPs$^{*\phi\delta\sigma}$	Provides ancillary services and allows for load flattening.
	P2P trading $^{\phi\sigma}$	May incentivise behaviour change around energy use and reduce the rates of rooftop PV installation.

(MW) of rooftop PV installed, the wholesale energy price has a downward pressure between 0.02 and 0.03 AU$/MWh. The cumulative impact of this continued uptake is significant and is supported by reports from the ISO (AEMO, 2019b) of increasing numbers of negative price intervals. In 2019–2020, the wholesale energy prices during mid-day trading intervals in the WEM were typically in the order of AU$30-$50/MWh across spring and autumn with more than 1300 MW of installed rooftop PV. As detailed in Section 1.1, the ISO expects another 1300 MW of PV to connect to the system by 2029–30 (AEMO, 2020b). The longer-term effect on the wholesale energy price is complex (shown in the historical price variations in Appendix B). However, it is clear the uptake of rooftop PV will continue to put downward pressure on the WEM wholesale energy price under the current market design. This price impact is supported by AEMO, which has estimated that over 40% of October trading intervals in the WEM will be negative by as soon as 2021 (AEMO, 2019b).

Fig. 5 shows the noon wholesale energy price and the output of the predictive model. As expected from the model selection, the model describes the broader relationship but poorly identifies price spikes. The mean downward sloping trajectory of the wholesale energy price is reflected in the downward pressure of rooftop PV in the model (Table 4). The later years show increased price volatility.

3.2. WEM no longer fit for purpose

Interviewees considered that the current WEM design is not adequate to address the challenges associated with the projected uptake of rooftop PV systems and that, if left unchanged, would result in "a complete market failure" (P1 from Table 2). Several interviewees considered that this could start with increasing incidences of zero and negative daytime prices pushing baseload generators out of the market.[13] Over-generation in the distribution system from rooftop PV systems would create operational and safety constraints associated with voltage and reactive power management. These findings have been supported by recent ISO reports (AEMO, 2019b, 2020g). Interviewees stressed that removing the baseload generators from the market would compromise the grid's stability through loss of inertia and system strength issues (the reduced ability of protection systems to see faults). The capacity market was seen as no longer fit for purpose because it rewards generation in the wrong locations and of the wrong type to redress current and future system constraints.

The failings of current ancillary services markets to reward the required services (e.g. inertia, ramping, and rate of change of frequency) and that excludes alternative technologies (e.g. batteries) and market approaches (e.g. DR, VPPs, and P2P) from playing a role in maintaining system security during the transition was widely identified by interviewees. The limited visibility and control of rooftop PV systems by the ISO will also make it harder to maintain frequency within safe operating bounds. The limited visibility reduces the capacity for DR, VPPs, and P2P market approaches to connect prosumers with markets. In addition, current retail tariff structures were identified as not sending signals to customers that could incentivise different energy use behaviours required to stop the duck's belly from growing and its pond from drying up.

[13] Australia's newest coal fired power station, commissioned in 2009, is located on the SWIS. Owners of this power station wrote off the facility's value in November 2020, with media reporting this being due to the impact of rooftop PV - Parkinson, 2020. Rooftop solar claims its biggest victim yet – Australia's newest coal generator, Renew Economy.

3.3. Changes required for the ongoing functioning of the SWIS

Many interviewees identified that curtailing rooftop PV output would almost inevitably be needed to avoid system collapse as the duck pond dries. While the necessity for some curtailment was acknowledged, it was almost unanimously seen as non-desirable, both politically and in the likelihood that it could further encourage grid defection. Curtailment could occur either via disconnection of bulk households at the distribution feeder level or by implementing capabilities to control household inverter interactions with the distribution system. The ISO has estimated that if the latter approach is unsuccessful and the former is required, then each curtailment event would require approximately 60,000 households to be disconnected by 2022 during the increasing number of minimum demand intervals, rising to 300,000 by 2026 to maintain system security (AEMO, 2019b). Respondents were focussed on measures that could control the interaction of rooftop PV with the electric power system, together with measures to flatten the network's load profile, while incentivising approaches (on both the supply- and demand-side) that would better correlate with underlying demand. The predominant incentives mentioned by respondents to achieve this included market and tariff reforms, technical standards, and control systems. The change mechanisms mentioned by interviewees and how these mechanisms help address the issues stemming from high rooftop PV installation rates are summarised in Table 4. The issues identified by stakeholders were cross-checked against findings in related industry reports that outlined a transition pathway for electricity systems and/or markets to integrate large quantities of DERs generally or rooftop PV specifically (Table 4).

3.3.1. Technical requirements

The introduction of new connection standards was viewed as the quickest and relatively simplest means to manage the integration of rooftop PV into the power system as they could be implemented without new regulation or legislation. Improved inverters could allow households to support distribution level voltages and reactive power, thereby helping to resolve rather than create network constraints (AEMO, 2019b; Austin, 2020; Giraldez et al., 2018; Prabakar et al., 2019; Teng and Strbac, 2016; Yazdani et al., 2017). Installation of smart meters with remote communications (Standards Australia, 2015) would allow third parties to access both the loads and rooftop PV outputs for active participation in system management. This access could be direct via the ISO for system balancing or through an aggregator for inclusion in DR programs or VPPs that could bid capacity into energy and/or ancillary services markets (AEMO, 2019b; Department of Energy and Climate Change (DECC), 2014; Enbala, 2018; Energy Networks Australia and CSIRO, 2017; FERC, 2020; Glass et al., 2019; Knieps, 2016; Mengelkamp et al., 2017).

These measures, aimed at addressing the increasing incidence of bidirectional power flows and variability introduced to the system by rooftop PV, would not address the fundamental problems associated with the mismatch between the existing generation fleet and system demand. To address these issues, respondents recommended introducing new tariffs, additional storage capacity, and the creation of new markets. These measures could reduce or slow the growth of the duck's belly and delay the drying of the pond, thereby allowing more time for other system stabilising mechanisms to be put in place.

3.3.2. Markets

Interviewees considered that new markets must be created to support the introduction and retention of mechanisms to supply network support services such as inertia, fast frequency response, and ramping capability. Specific mention was made of the need for rule changes to allow battery storage and synchronous condensers to participate in markets. Regular mention was made of the need for services such as inertia and system strength, which have historically been a by-product of normal operation, to be priced for supply within the market. These markets would need to incentivise or reward security during minimum generation periods when it is noneconomic and/or not technically possible for traditional thermal generators to run. Respondents considered that these markets should also allow prosumers to participate directly through a VPP or via DR aggregators. These mechanisms are also being investigated to address similar issues unfolding in Australia's NEM and WEM (ESB, 2019) and California (FERC, 2020).

As for ESB (2020), our study's respondents were keenest on technology-agnostic market solutions that provide system services. Two of the respondents mentioned that the State could provide these services as a public good. Some jurisdictions have already placed a requirement to purchase system security services on retailers, assuming that this would be the most economically efficient mechanism to do so (ESB, 2019; Finkel et al., 2017; Woodhouse, 2016). There may be limited benefit to this approach in the SWIS, given there is only a single retailer for retail customers, removing the potential for market competition to drive innovation and lower prices. The WA State Government could consider underwriting the provision of system support services, which can be considered a public good, given that their provision may otherwise run at an economic loss during the transition. This approach could establish the foundation for a stable power system that integrates high levels of rooftop PV into the future. Some interviewees considered that this strategy would come at some risk, as the State is the owner of some existing thermal peaking plants, and they may seek to extend their operating life rather than investing in alternative technologies. Some commentators, such as Liebreich (2017), have cautioned on any policy decisions that could lock in long-life traditional thermal generators if this were to preclude future options for low carbon solutions. Capacity payments are one measure that could affect this outcome. Other risks include the potential to exclude cheaper, cleaner and more flexible technologies; and may require measures to curtail solar PV output, which could accelerate grid defection and increase retail costs to all customers.

Another more controlled means of guaranteeing a match between the system load profile and the generation mix noted by interviewees was to amend the existing reserve capacity mechanism. This approach could be used to reward different types of capacity, not just during peak demand intervals, but locational and functional capacity, such as inertia, load rejection, or ramping. The value of capacity mechanisms in maintaining system security during the transition is reported by researchers such as Kraan et al. (2019) and the International Energy Agency (2016).

3.3.3. Flattening the load profile

Most interviewees from within the WEM considered that tariff reform could flatten loads and address impacts described by the drying duck pond. These views were tempered by acknowledging that political realities and the existing market structure would make implementing tariff reform very challenging. The Energy Transformation Taskforce (2020)'s DER Roadmap identifies this as an issue and seeks to address it through a combination of measures, including early and ongoing customer engagement together with tariff pilot trials. The expectation that variable tariffs could assist in flattening the load curve was also reported in the reviewed industry reports (CAISO, 2020a, b; Distributed

Energy Integration Program, 2020; Energy Transformation Taskforce, 2020; ESB, 2019, 2020). However, as reported in Section 1.2, evidence demonstrating the effectiveness of variable tariffs to influence the load curve is inconsistent.

In order to maximise the potential benefits of variable tariffs, energy users should be encouraged to adopt home automation systems to allow devices to respond to changing price signals on their behalf (Lo et al., 2019). With automation, the price variance need not be so large as to create social equity issues. These price signals can also be used by new market-based approaches such as DR, VPPs and P2P trading schemes (Enbala, 2018; Parag and Sovacool, 2016; Say et al., 2019), to trigger demand and supply changes. The usefulness of this approach was noted by a Californian interviewee and was supported by industry reports (CEC, 2020b; ESB, 2019), who favoured the use of energy productivity schemes and using time-varying tariffs to communicate with devices as an automated response rather than requiring behaviour changes.

An innovative approach to dealing with excess mid-day generation was suggested by one policy executive, who suggested providing energy free to hospitals, schools, and vulnerable customers who are coupled with community batteries. This approach could help alleviate energy equity concerns (Athawale and Felder, 2016) and may be beneficial in Australia, which has a history of political reluctance to make changes that could negatively impact voters (Wilkinson et al., 2020a). The need to manage voter backlash associated with perceived inequitable impacts from tariff reforms was noted by most Australian and Californian interviewees and reported by the Distributed Energy Integration Program (2020).

The opportunity to use a combination of emerging and established storage technologies to shift loads was identified as a key requirement for load flattening by interviewees and industry reports (Energy Transformation Taskforce, 2020). Pumped hydro was identified as the lowest-cost storage technology. However, the lack of both water and elevation would limit its adoption in the SWIS. Chemical storage batteries were seen as the most likely to be deployed, with a preference for centralised batteries to be placed in the distribution sub-stations where they could help address power quality issues (Energy Transformation Taskforce, 2020).

Batteries can supply the full suite of system support services required under a high rooftop PV scenario (Das et al., 2018, 2019); however, they are currently precluded from doing so under existing market rules. Changing these rules raised many questions from interviewees around their integration into markets and control systems. For instance, if a battery is allocated payment under a capacity reserve mechanism and paid to supply spinning reserve or black start capability, questions were raised whether it could also participate in the energy market and do so concurrently or must capacity be reserved for each market offering individually? This situation becomes further complicated when aggregators are introduced. Interviewees raised questions on how much control aggregators should have over residential loads and generation and how they or customers could interface with wholesale markets and have their market offerings verified. These issues, along with those associated with governance, have been recognised by Australian regulatory and policy agencies and the ISO in the WEM and NEM (Energy Security Board, 2019; Energy Transformation Taskforce, 2020; ESB, 2020).

While centralised batteries were viewed as easier for the ISO to control and the most economically efficient to implement, behind-the-meter household storage was also seen as providing significant system advantages. This approach was predicated on household storage being connected using standards that required them to help maintain the security of the distribution system. Interviewees also regularly cited the need for tariffs to incentivise battery charging at times of peak PV output to maximise the potential to flatten the duck's belly by lifting daytime electricity consumption. Tariffs could also incentivise behaviours that would manage voltage and reactive power issues within the distribution network.

4. Discussion on required policy changes in the WEM

There is a statistical relationship showing that the increasing uptake of rooftop PV is suppressing the mid-day wholesale energy prices, which is supported by reports from the ISO. While the relationships are complex, a continuation of this trend will increasingly put financial pressures on traditional thermal generators, which can expect to increasingly be priced out of the market during periods of high irradiation. Combined with the need to technically manage minimum load periods, these changes will have implications for the operability of the electricity system during these trading intervals and will impact the ability to meet the afternoon ramping and evening peaks periods.

The bulk curtailment of distribution feeders to maintain system operability during periods of peak solar output is politically and socially unacceptable, making it less likely to occur. However, other forms of curtailment will be required during the transition as the ISO must maintain the electric power system within safe operating conditions. Methods of control focus on the interaction between rooftop PV and the distribution system and the consequent impacts on the transmission system.

Policy decisions should be made, along with the supporting regulatory mechanisms and technical rules to allow for integrating rooftop PV systems into the wholesale energy market to support system operation via the provision of load shifting and ancillary services. This framework will enable resources located within the distribution system to help alleviate the voltage, reactive power, and frequency-related problems to which they are increasingly contributing. To manage the interactions of rooftop PV within both the physical system and the trading market, advanced metering infrastructure and inverters complying with updated standards, together with new distributed energy control systems, will need to be adopted. These technologies will collectively allow for rooftop PV to be controllable and included in DR, VPP and P2P programs for participation within the wholesale energy and ancillary services markets.

The potential to flatten the demand curve and avoid the drying duck pond through tariff reform may be insufficient on its own to significantly delay the MOE's impacts on baseload thermal generators. The introduction of new in-home automation that maximises load shifting in response to even small retail tariff changes should be supported. While this may not flatten the load curve, it may buy additional time during which additional policy and technical changes can be made. The objective of these actions is not to protect existing thermal generators from exiting the market but rather to ensure system stability is maintained throughout the transition.

New markets will be needed to support the installation and retention of technologies and approaches that can supply system support services such as frequency regulation, inertia, ramping, voltage regulation and new load creation, where they are not currently cost-competitive. Multiple technologies and approaches will be required, including battery storage and DR programs, which can act as both load and demand on the system. The design of the capacity payments scheme should also be revisited with an expanded focus on the availability of system support services during low load and shoulder periods rather than solely on the supply of energy during peak demand periods. These markets and/or capacity payments will be essential for bankable investments in new technologies to be made. Care should be taken to avoid such capacity payments from unnecessarily locking in traditional thermal generators for longer than required for supporting a transition.

In large electric power systems with sophisticated trading markets, targeted forward markets could be implemented to reduce the price differentials and incentivise zero-carbon alternatives to traditional thermal generators. Markets with limited competition and shallow forward markets such as the WEM may need to consider whether navigating the transition is more efficiently managed as a public rather than private good.

A combination of behind the meter battery storage and distribution level storage will be required to allow for intraday load shifting. Distribution level storage has been identified as more economically efficient than behind the meter storage while also allowing for additional distribution network support services to be provided and to reduce the likelihood of bulk curtailment events (Energy Transformation Taskforce, 2020). Energy productivity, such as improved building design and products designed for participation in DR, will also help manage the integration of more rooftop PV systems. Transmission level storage will also be required to manage diurnal and seasonal energy arbitrage.

Finally, system control methodology will require a fundamental redesign as the electric power system transitions from one reliant on tens of generators on the transmission network to a system consisting of millions of generators increasingly located within the distribution network. A greater reliance on artificial intelligence to control the distributed energy systems with diminishing reliance on human system controllers will be required (Tayal, 2017). The transition towards inverter connected energy sources will also require progressive changes to the way faults are detected and cleared on transmission and distribution networks.

5. Conclusion

Electric power systems globally are undergoing transitions towards a system heavily influenced by inverter controlled DERs. This trend is evident in the SWIS, which has some of the highest installation rates of rooftop PV resources anywhere in the world. The statistical analysis supports the intuitive concept that increasing rates of rooftop PV will suppress wholesale energy prices during the day. The natural outcome of this will be the progressive removal of much of the traditional thermal generation from daytime trading intervals, starting with those that provide baseload power or are not well-matched to future underlying demand requirements as the duck pond dries and ultimately leading to their early retirement from operation. These findings are supported by the ISO's assessments (AEMO, 2020f).

This paper is focused on an islanded electricity system in Australia. However, with rooftop PV system penetration rates continuing to increase globally on both economic and environmental grounds, the challenges and solutions identified by this research will become increasingly pertinent to electric power systems and markets elsewhere. Interviews with industry experts within WA, California and Europe have identified that significant market and technological changes will be required to manage the impacts of a transition to high rates of rooftop PV within electric power systems. No single solution is available, but rather a broad range of changes will be needed. Immediate revisions to connection standards are required to enable rooftop PV systems to strengthen the distribution system while providing greater visibility to system managers and distributed markets. Regulatory changes enabling these markets are required, including for ancillary services (such as frequency response, voltage regulation, inertia, ramping, rate of change of frequency and system strength), and to allow participation of DR, P2P and VPPs aggregators in these markets. These changes will need to account for the varied roles that energy storage technologies can play in markets. Renewed consideration of the role of markets versus governments is required during the transition, particularly in smaller systems that lack sufficient competition for effective market function. Finally, as the electric power system moves from one with tens of generators to one with millions of power sources, the dispatch and control systems must become exponentially more sophisticated and automated.

5.1. Future research

Implementation of new markets, such as DR, P2P and VPP, will require the support and involvement of prosumers. Research is required on the role of prosumers in shaping these new markets and taking them from niche business models into the mainstream market to achieve the desired system supporting objectives.

Each of the individual measures identified in this paper can help address some aspects of the drying duck pond and fattening duck's belly. However, quantitative modelling will be required to determine the extent of their contribution so that policymakers can prioritise enabling regulatory reforms required for their introduction. These studies will be unique to each electric power system in supporting the market's transition.

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.

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Appendix A. Ordinary Least Squares Regression Analysis of Noon[14] Trading Intervals – Summary analysis

Mid-day Spot Analysis

Publicly available data from AEMO and the Bureau of Meteorology (BoM) weather data was used as an input to determine the following approach

[14] OLS results shown in Fig. 5 have included comparison analysis of the associated noon point system load. The functional form and analysis undertaken was otherwise identical to provide a comparison model.

and functional form.

Following a parsimonious model approach, data was sourced from daily Perth metropolitan readings for temperature, solar irradiance and rainfall (Bureau of Meteorology, 2018). Although all data were clean with minimum missing data points, they were extracted and merged into a single dataset to be used in the analysis undertaken in this paper. Perth Metro station 9225 was used as the reference point for analysis as it is in a central location in the Perth metropolitan region. Future work could consider using a model that includes all locational environmental data in the SWIS weighted to the location of rooftop PV generation (AEMO, 2017). Correlation analysis was conducted on the data set, and while minor correlation of data was found, relationships were as expected[15] or considered insignificant for the purposes of this research.

Wholesale energy data were available from July 1, 2012 (Government of Western Australia, 2004) when the WEM commenced in Western Australia (Independent Market Operator, 2012). This data was sourced from the AEMO website (AEMO, 2020e) and was found to be clean, though outlying data points in the later years were identified during residual analysis.[16] Aggregated monthly PV capacity for the SWIS was sourced from AEMO (AEMO, 2020c) with the last data point, February 29, 2020, used as the endpoint for analysis. The terminology is applied from the duck curve naming convention using the noon demand point as a reference (Maticka, 2019).

The wholesale energy price value relationship proposed[17] was specified as follows for each trading interval:

$$B_0 = f(PV, T, S, R) + \varepsilon_i \qquad \text{(Equation 1)}$$

The estimate equation developed was as follows:

$$B_n = \beta_0 + \beta_p PV_d + \beta_p T_d + \beta_p S_d + \beta_p R_d + \beta_j SUmmer + \beta_f Winter + \beta_m Spring + \beta_{my} WeekendPH + \varepsilon_n \qquad \text{(Equation 2)}$$

Analysis has found that the following factors help explain the monthly relationship for the wholesale energy price and DPV in the SWIS as:

β_0 :A constant term.

$n-$ Selection of the noonTrading Interval. A trading interval is the 30-min period commencing on the hour or the half-hour. Noon trading interval 12:00:00–12:30:00.

$d-$ Calendar date. Calendar date was restricted from WEM start to last available Rooftop PV installation data available at time of analysis, 2012–July to 2020–Feb.

B_n- Wholesale Energy Price (time of trading interval n) AU$/MWh.

PV_d: The amount of installed rooftop PV capacity in the SWIS area based on post-codes and was sourced from AEMO (2020c). Monthly data was linearly smoothed to daily capacity in the SWIS at d. The sign was expected to be negative because as more rooftop PV generation is installed, the wholesale energy price should fall for all generation (MW).

T: Maximum temperature (Degree C), day. Perth Metro station (9225) reading.

S: Daily aggregated global solar exposure (MJ/m*m). Used as a proxy for PV generation and reduces sessional variations. Perth Metro station (9225) reading.

R: Daily rainfall at the Perth metro station. Used as a proxy for cloud cover that affects rooftop PV generation in the Perth metropolitan area that contains the majority of rooftop PV in the SWIS. Perth Metro station (9225) reading.

ε_n: Error term.

The following dummy variables were used to account for seasonal and weekend/Public holiday effects:

Summer, *Winter*, *Spring*. *with Weekend and Public holidays combined to a single variable*: These variables have been selected to account for the seasonal and weekend/Public holiday variation.[18] The lowest demand season of autumn dummy variable was omitted in the OLS analysis as the base demand season and the expected result in all seasonal dummy variables being positive.

The resulting estimate equation was generated using the regression function in R for each point of the dataset. Modelling showed the relationship with the weather in that on sunny days, which are periods of higher PV generation, downward pressure on the wholesale energy price occurs. As more rooftop PV is installed, this effect is increased. On hot days corresponding with high demand, there is upward pressure on the wholesale energy price. Rainfall was not found to be a significant variable but was retained for completeness of the model. This match expected results and follows basic economic principles, as more of a product is produced, the lower the price.

The overall fit of the equation could be considered low with $\overline{R}^2$ value of 0.156 compared to the fit of the System Load regression results of 0.666. This finding is unsurprising, considering the variation of how prices are determined and the high amount of variability due to bidder and consumer behaviour, but what is more important is that the PV uptake relationship to the noon wholesale energy price is a significant contributor. The model did not show signs of omitted variable bias, which was a concern as the electricity demand is an implied product (that is, electricity is not directly useable).

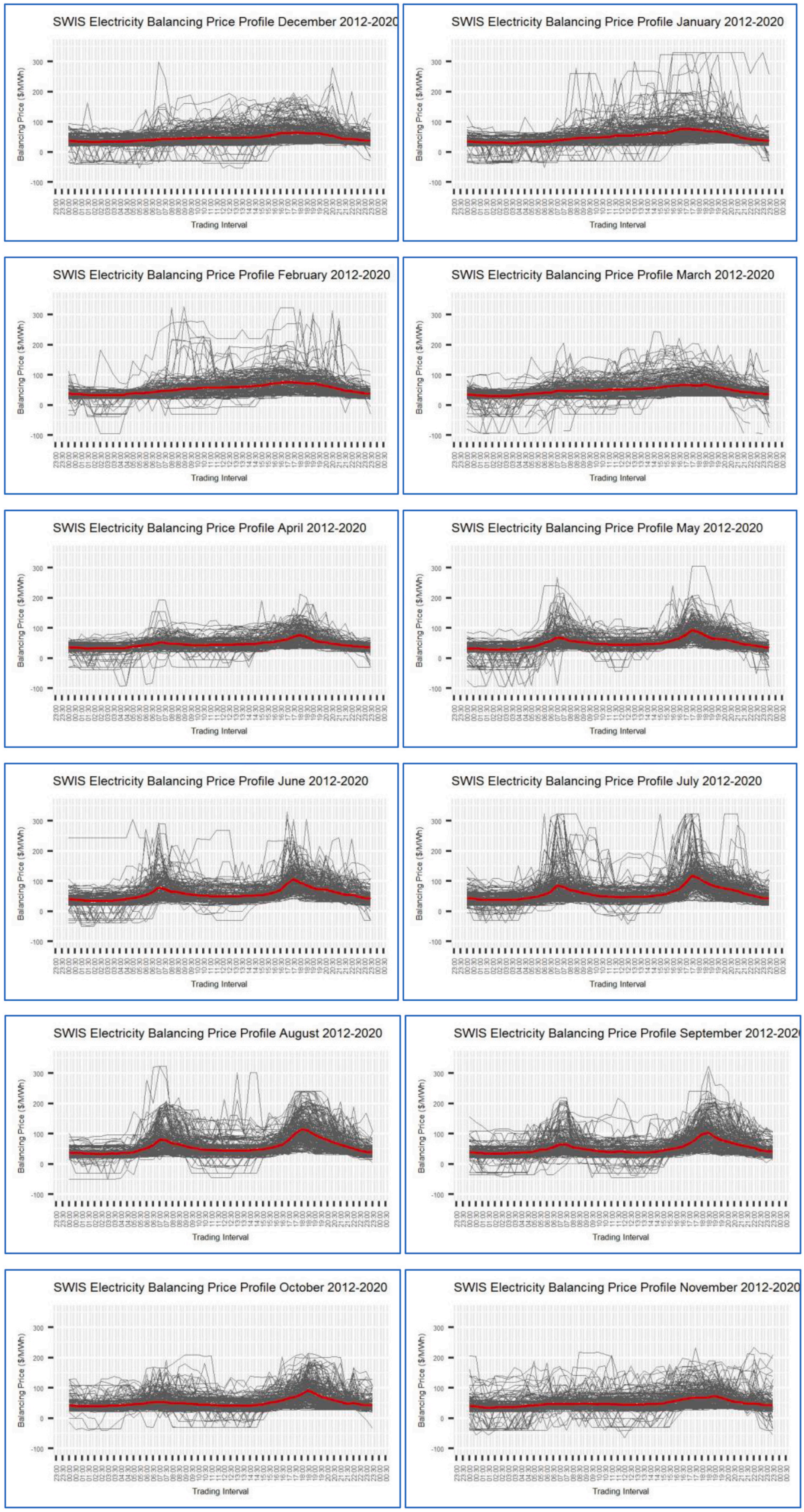
Appendix B. Thumbnail traces of monthly price traces

[15] Temperature and solar irradiation showed an expected relationship as long summer days drive high summer temperature conditions in Western Australia.

[16] White tests were undertaken and a weighted regression using a bisquare method was explored to test the effect of outlining data points. This did not notable alter the statistical terms though as expected the predicted error range increased when using this method.

[17] While the daily rainfall amount (millimetres) was not a significant variable it was included in the model as the correlation of solar radiance may be considered as a suitable substitute this would further complicate the seasonal relationship of the environmental variables if excluded.

[18] Prior models considered for the paper included monthly dummy variables but found a seasonal approach provide more significant results and is aligned to how the market operator (AEMO) discuss variations in various formal publications such as the WA Electricity Statement of Opportunities. Log-log models and lagged explanatory variables were explored as well as weighted linear regression to address relatively minor heteroscedasticity in the error terms. Another model used outage data as a predictor variable. As expected, system load did not show a significant relationship and the balancing price significance band was narrowed. As the approach taken in the analysis was to construct the simplest model to support the interviews this model was not used. Investigated models produced minor improvements in $\overline{R}^2$ and the additional complexity to elucidate the results with the qualitative interviews out weighted the relatively minor improvements in the models.


SWIS Electricity Balancing Price Profile December 2012-2020
SWIS Electricity Balancing Price Profile January 2012-2020
SWIS Electricity Balancing Price Profile February 2012-2020
SWIS Electricity Balancing Price Profile March 2012-2020
SWIS Electricity Balancing Price Profile April 2012-2020
SWIS Electricity Balancing Price Profile May 2012-2020
SWIS Electricity Balancing Price Profile June 2012-2020
SWIS Electricity Balancing Price Profile July 2012-2020
SWIS Electricity Balancing Price Profile August 2012-2020
SWIS Electricity Balancing Price Profile September 2012-2020
SWIS Electricity Balancing Price Profile October 2012-2020
SWIS Electricity Balancing Price Profile November 2012-2020
Balancing Price ($/MWh)
Trading Interval

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Is peer-to-peer electricity trading empowering users? Evidence on motivations and roles in a prosumer business model trial in Australia

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Original research article

Is peer-to-peer electricity trading empowering users? Evidence on motivations and roles in a prosumer business model trial in Australia

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ABSTRACT

Peer-to-peer (P2P) electricity markets have attracted significant attention as a promising model enabling the integration of distributed energy sources by creating consumer-based electricity markets. Despite the significance of users in this model, knowledge is still lacking as to who the users interested in P2P electricity markets are and what role they can play in building them. We aim to fill this knowledge gap by providing evidence from the first real-world trial of a P2P electricity market facilitated by blockchain technology across a regulated electricity network. We apply sustainability transition and innovation thinking to analyse the trial participants as users shaping the P2P-related innovation process. Supported by our empirical results, we found that users joined the P2P market trial to learn and co-create the future of prosumer-centred electricity markets. We also found that if P2P is to enter the mainstream market, the assistance of other actors (e.g., intermediaries and activists) is important in order to cross the chasm to reach the majority of users and move from a learning and probing phase to breakthrough and wide diffusion.

1. Introduction

In traditional electricity systems, end users act only as passive consumers and receivers of electricity supplied from centralised generation *via* transmission and distribution grids [1]. This traditional model is being challenged as falling prices of small-scale solar photovoltaic (PV) systems and batteries motivate households and commercial properties to install their own on-site generation capacity. This is transforming traditional end users into active parts of the electricity system [1-3], earning them the title of prosumers – actors who both produce and consume electricity [4-6].

In countries such as Australia, nearly one quarter of households have installed PV systems [7] and prosumers are remunerated for excess energy production through government-sponsored feed-in-tariff (FiT) or buy-back schemes *via* existing electricity retailers. Here, the high level of PV penetration is affecting the technical and economic stability of the centralised electricity system [8], making subsidies and retailers' default purchase of self-generated energy exported to central grids unsustainable [9]. However, as subsidies decline and eventually expire, prosumers are left in a post-subsidy era with no alternative revenue model for their excess electricity [4]. There is increasing interest in post-subsidy market models that could create new value streams for prosumers [1,4,5,10], better reflecting the bidirectional nature of the new electricity system [11] and facilitating the transition to a distributed and clean electricity system [12,13]. One such business model innovation is the peer-to-peer (P2P) market model [5,10,14-18], which in principle allows prosumers and consumers to trade with each other without needing an electricity supplier or retailer as middleman. The middleman is replaced with a third-party digital platform, such as a blockchain-based platform, that allows prosumers and consumers to interact directly and negotiate better prices for their electricity, in contrast to relying on the offer from a licensed supplier [5,14]. It is believed that P2P markets will create future electricity markets with users at their heart, democratising local energy provision [15]. In addition, the P2P model could improve access to affordable clean electricity for those users who do not own renewable energy technologies. This concept has been described as energy and flexibility justice [19-23].

While the concept of P2P electricity trading has recently attracted increasing research interest [18,24-27], it has only existed in the form of conceptual models and experiments in closed environments such as embedded networks [15], university campuses [17,28], and organised energy communities in islanded micro-grids [5,16,26] where P2P sharing and trading occurs in the form of a computational simulation, or behind the utility meter in environments shielded from incumbents and regulations [29]. The P2P case study described here provides

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evidence from the first real-world P2P electricity trading trial facilitated by blockchain technology, which allows consumers and prosumers to trade electricity over the regulated electricity network, directly affecting their electricity bills.

Existing research into the P2P model is limited by its concentration on the technological and pricing aspects of P2P electricity trading. Much less attention has been paid to real-world prosumers and consumers (here collectively referred to as electricity users), i.e., individuals or groups that use electricity as well as associated technologies (e.g., solar panels) to consume, produce, and distribute energy.[1] The users in the P2P model are no longer passive consumers of the output (as in traditional business models), instead being directly involved in the P2P value exchange and thus central to its successful development [31]. Ahl et al. [24] reported that the relationship between electricity users and blockchain-based P2P business models (and vice versa) has yet to be empirically studied. Furthermore, they also found no published research into why and how consumers would want to participate in P2P market innovation. This paper aims to fill these research gaps and provide knowledge of how users can contribute to P2P model-related innovation processes that go beyond merely consuming [10,24,30]. By doing so, we hope to assist the research community, policy-makers, and industry actors to grasp the potential implications of this business model [24].

We have looked beyond the techno-economic literature to better understand and conceptualise the relationship between users (here, trial participants) and the development of a business model innovation (i.e., the P2P market trial). We engage with the sustainability transition and innovation diffusion literatures, which provide us with a conceptualisation of users that goes beyond the one-dimensional view of users as playing a role only in consuming innovations [30]. In this body of literature, scholars emphasise that users are important change agents, enacting agency throughout the innovation process, from the development of niche market ideas to adopting the niche innovations in everyday practice [32]. However, earlier studies have largely emphasised the role of users in supporting product innovation, while user contributions to new business model development remain under-explored in the transition literature [12]. Existing business model innovation research is still mainly concerned with the roles of firms, managers, entrepreneurs, and advocacy organisations in the process of business model implementation [13,33]. This paper attempts to fill this research gap by conceptualising P2P electricity trading as a niche business model innovation within a broader transition to sustainable energy systems [4,32,35] and by placing users at the centre of our analysis.

The aim of this study is to investigate the motivations and roles of users in developing P2P electricity markets. We provide evidence from the first real-world example of P2P electricity trading *via* a blockchain platform, located in Fremantle, Western Australia (WA). This aim is fulfilled by addressing the following research questions:

1 Who are the electricity users who are willing to experiment with P2P electricity trading and what motivates them?
2 What roles do electricity users play in shaping P2P electricity trading-related innovation?

The paper is structured as follows: In Section 2, we introduce the background to the P2P market model and its potential to support the renewable energy transition. In Section 3, we look more closely at how users are conceptualised in the transition and innovation literatures, before synthesising these literatures into a conceptual framework for analysing the empirical case. Section 4 introduces the research design, methodology, and case study, followed by the empirical results in Section 5. The results are analysed and discussed using the conceptual framework in Section 6, while the conclusions are presented in Section 7.

2. Peer-to-peer electricity trading models

Environmental concerns, technological innovation, and the impacts of prosumers on markets and system operability have led to increasing interest in distributed renewable electricity systems as alternatives to the dominant centralised model of electricity production and consumption [34,35]. Growing numbers of scholars and industry actors are emphasising that new distributed grids will require marketplace innovation to reflect the decentralised infrastructure and the changing character of users who, by adopting distributed energy technologies, have become active market participants who can produce, sell, and buy electricity as well as reap benefits from their demand flexibility [4,11,15,19,20]. Yet many challenges remain, including finding business models that can fairly distribute costs and benefits among a large number of self-interested market participants [24] and facilitate energy and flexibility justice [19,20]. Several prosumer-focused solutions are being proposed, with different levels of interaction and levels of dependence on the existing energy system [4,5]. This paper examines an autonomous P2P model,[2] defined by Parag and Sovacool [5], that in theory allows prosumers and consumers to interconnect and trade directly with each other. This model is perhaps the farthest from today's electricity market design [4], serving as a starting point for establishing the P2P trial that is our case study.

The research literature defines the P2P electricity market as an autonomous P2P network of prosumers and consumers, often compared to an Uber or Airbnb model for the electricity sector [5]. Influenced by ideas of the “sharing economy”, a software-enabled P2P market model allows consumers and prosumers to buy and sell self-generated electricity and other services, such as flexibility or demand response, in an open electricity market across the regulated distribution network [10,18,24,36]. Blockchain technology is the software platform considered to enable the P2P marketplace [14,24,27,36]. Blockchain is a decentralised Internet protocol that could, in theory, enable transactions of monetary and non-monetary digital assets[3] directly between peers without the necessary involvement of a middleman, such as a licensed energy retailer [14,36]. Due to its ability to create smart contracts and ledgers, blockchain algorithms could replace the need for a licensed retailer to overlook and verify contractual agreements between peers [27].

Like other new technologies and business models, the P2P model is still unsupported by existing regulatory structures, financial institutions and lacks societal awareness or acceptance [24]. Ruotsalainen et al. [29] identify the importance of considering that the P2P market model currently only exists as a vision of a desirable future without accounting for existing electricity sector actors and infrastructure. Embedding the P2P model in real-world settings across the public grid infrastructure entails significant caveats and complexities that must be resolved if the theoretical benefits are to be realised [4,5].

An increasing number of scholars and industry actors believe that the P2P model is unlikely to result in the complete collapse of the incumbent electricity sector; instead, utilities and public authorities may continue to exist alongside prosumer networks. However, the future

[1] Definition inspired by Schot et al. [30].

[2] The P2P model is the most radical prosumer-based business model innovation, in which prosumers and consumers trade directly with one another in a seamless network without a need for the large grid market. Other prosumer-based models are “prosumer-to-interconnected or islanded microgrids” and “organised prosumer groups market”, both including different levels of interaction between prosumer networks and the large grid market [5].

[3] Digital assets that can be traded on a blockchain are not limited to financial transactions (e.g., payments for electricity). In the energy sector, other non-monetary assets that could be traded are, for example, demand-side and flexibility services, energy certificates, carbon offsets, and/or storage services [37].

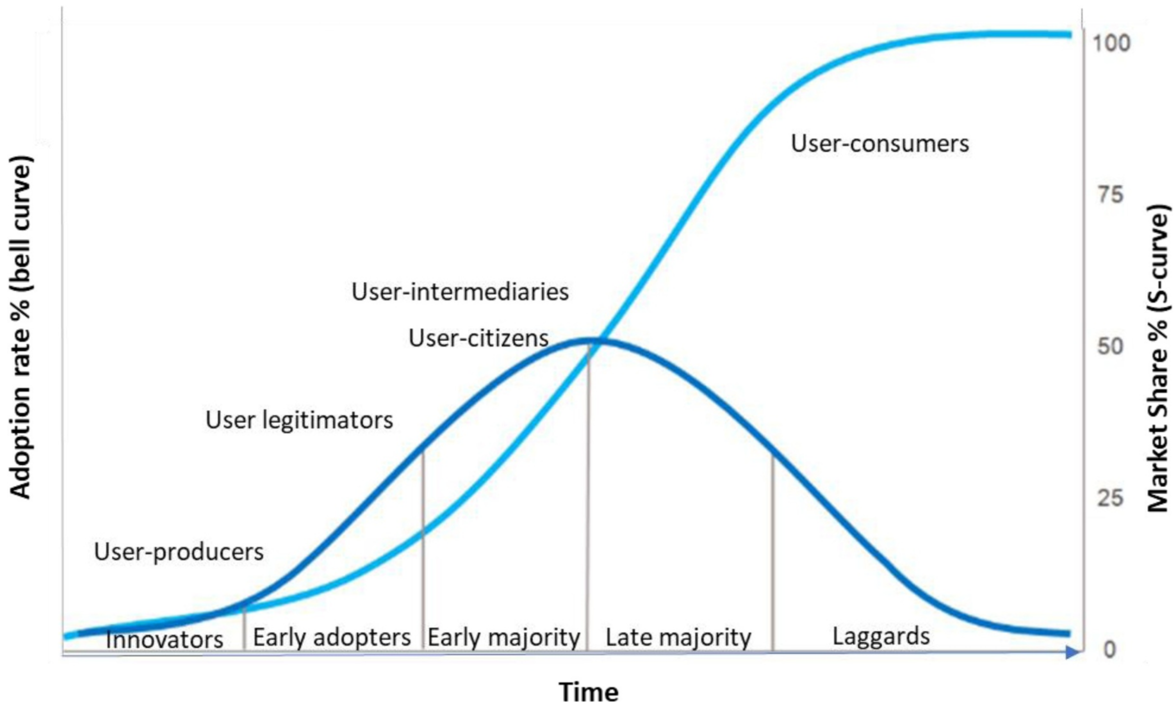

Fig. 1. Categorisation of users along the innovation adoption bell curve [50] (*x*-axis labels) and typology of user at different points of the innovation S-curve [30] (S-curve labels).

roles of various actors in a P2P trading model are not yet known [10,29]. We do not wish to study actor roles in the future P2P market (assumed to be a mature and established system design). Instead, we examine the transition and innovation processes leading to this market, and the specific roles prosumers and consumers can play in developing P2P markets by studying their motivations, expectations, and conduct in a real-world P2P trial. Specific technical details and critique of the blockchain-enabled P2P transaction model lie outside the scope of this study.

3. Achieving transition through business model innovation

As described in the previous section, the P2P model offers several potential social and technical benefits for the future of distributed energy systems [5]. Yet the challenge remains to understand how this niche business model innovation can break through and challenge the dominant electricity market model, and to identify the roles users can play in this process. The sustainability transition and innovation literatures offer useful frameworks with which to study the role of niche innovations in systemic sectoral transitions. The multi-level perspective (MLP) [38] has been one of the most prominent frameworks in this field, treating technological change as an interaction between three analytical levels: the niche, regime, and landscape. The socio-technical regime consists of actors, institutions, and infrastructure aligned around a dominant design. The regime can be challenged from the niche level, a protected space in which radical technological innovations emerge and grow. Regime change can also be affected by external landscape forces, emerging from the broader socioeconomic system (e.g., political agenda). A regime transition is a complex co-evolutionary process that involves fundamental reordering of the social and technical components of a socio-technical system. The MLP is described in more detail in seminal papers by Geels and Schot [39], Rip and Kemp [40], Geels [38], and Smith et al. [41].

While MLP emphasises building new regimes, which takes decades, we argue that this perspective can be useful in understanding more recent innovations within the context of long-term systemic change. The ability to see the "context of a transition" can be useful when analysing specific technological novelties. This is evident in most single-case studies using MLP, for example, examining the struggle of plant-based "milk" against entrenched dairy milk [42] or the niche-regime interaction of solar PV technology in the Netherlands [43]. However, existing transition research has concentrated on novel technological products within niches as drivers of change. Scholars have stressed that new technologies alone will not suffice to achieve systemic change, noting the importance of business model innovations because they connect multiple actors, mediate between the production and consumption sides, and support the introduction of novel technologies in the market. [12,13,31,33].

Business model-oriented transition research became established with the analysis of energy service companies in the UK [13,44], new business models for whole-house retrofitting in the Netherlands [12], and distributed business models under the Energiewende in Germany [31]. Similarly, we consider business models to be niche innovations in their own right. We therefore use MLP to position our case study in the broader electricity sector transition, in which the centralised energy market is challenged by innovative electricity market models emerging as niche innovations. While this study focuses on the P2P model, we understand that different business model innovations are competing, interacting, and complementing one another in gradually developing the future market model for a decarbonised electricity sector [13,45,46].

3.1. Users in niche business model innovation

Transition thinking has recently been refined by integrating business model innovation ideas [12,13]. Existing transition studies have focused on the roles of firms, entrepreneurs, managers, and advocacy organisations when implementing new business models in the context of a sector in transition [4,12,13,31,33]. In the transition literature, business models are traditionally regarded as integral to firms, as a means to deliver customer value, with customers seen as passive business model adopters. If the dominant business model logic in the electricity sector is to be broken, more knowledge is needed of the role users can play in business model innovation as they evolve from being mere consumers to being key actors in the electricity market.

Although not specifically emphasised in research into business model innovation, the system-building role of users in the energy system transition has been highlighted by Schot et al. [30], who, using the MLP framework, defined a typology of users who support new technologies in different innovation phases along the innovation S-curve [30,47-49]. In their conceptualisation, users can act as producers, legitimators, intermediaries, citizens, and consumers (see Fig. 1). While Schot et al. [30] claim that this user typology matters in long-term systemic transition, they also cite examples of its application to relatively specific and recent niche developments related to small-scale consumer-side renewables. We accordingly argue that this user typology can be applied in studying early-stage innovations as well.

This framework offers a user-to-system perspective in which users are one of the system builders, breaking down the structures of dominant regimes. For example, user-legitimators focus on convincing regulators, while user–citizens focus on opposing incumbents. The users in this framework are important in aligning system components for successful systemic innovation. Though it provides important insights, this perspective pays insufficient attention to micro-dynamics and agency among the users themselves, which are important when studying small-scale local innovations. The diffusion of innovation literature highlights the importance of the user-to-user influence on innovation [50]. In this body of literature, the most widely applied user categorisation was developed by Rogers [50], who divided users into ideal types of adopters ranged along a bell curve based on innovativeness, i.e., the different time points when particular users adopt an innovation give them different influences on its development and diffusion. Here, users range from the most innovative innovators, through early adopters, early-majority adopters, and late-majority adopters, to sceptical laggards (see Fig. 1).

As Roger's bell curve is a derivative of the S-curve, we propose that these typologies can be synthesised into the categorisation of user roles in niche development processes depicted in Fig. 1. Both these categorisations support the view that users are not a homogenous group with a single role but are heterogeneous actors who play different roles in supporting innovations. By combining these perspectives, we emphasise that users can play a role in both system- and micro-level (i.e., user-to-user) dynamics. Both these categorisations can be plotted over time, creating the foundation for our analytical framework (see Fig. 2).

As indicated earlier, sustainability transitions and innovation occur over time, conceptualised as the phases of system innovation. Various authors have described the technological innovation phases; for our framework, we apply the four-phase model developed by Geels [51] (described in Table 1), because it includes the probing and learning phase as a separate category (Section 3.2).

3.2. Analytical framework

While the work of Schot et al. [30] and Rogers [50] emphasises user contributions to all innovation phases, other scholars emphasise the user role in specific phases of the innovation process. Through a literature review, we strengthen our initial analytical framework, shown in Fig. 1, broadening our view of how users are conceptualised in specific innovation phases; the end result is depicted in Fig. 2 and summarised in Table 2.

In the first phase of innovation, when the novelty is emerging, researchers have noted the importance of users in inventing and creating novel solutions and routines [30]. These users can either be self-motivated, or can be identified by other actors, such as private firms, in order to customise the new technology and improve its quality, performance, and user-acceptance before introduction in the mainstream market [52]. These users are often cosmopolitan, connected internationally to a small group of innovators with whom they share interest in and enthusiasm for novel ideas and technologies [50]. They can understand and apply complex technical knowledge and cope with a high degree of uncertainty. To afford potential losses resulting from supporting an innovation, they usually have substantial financial

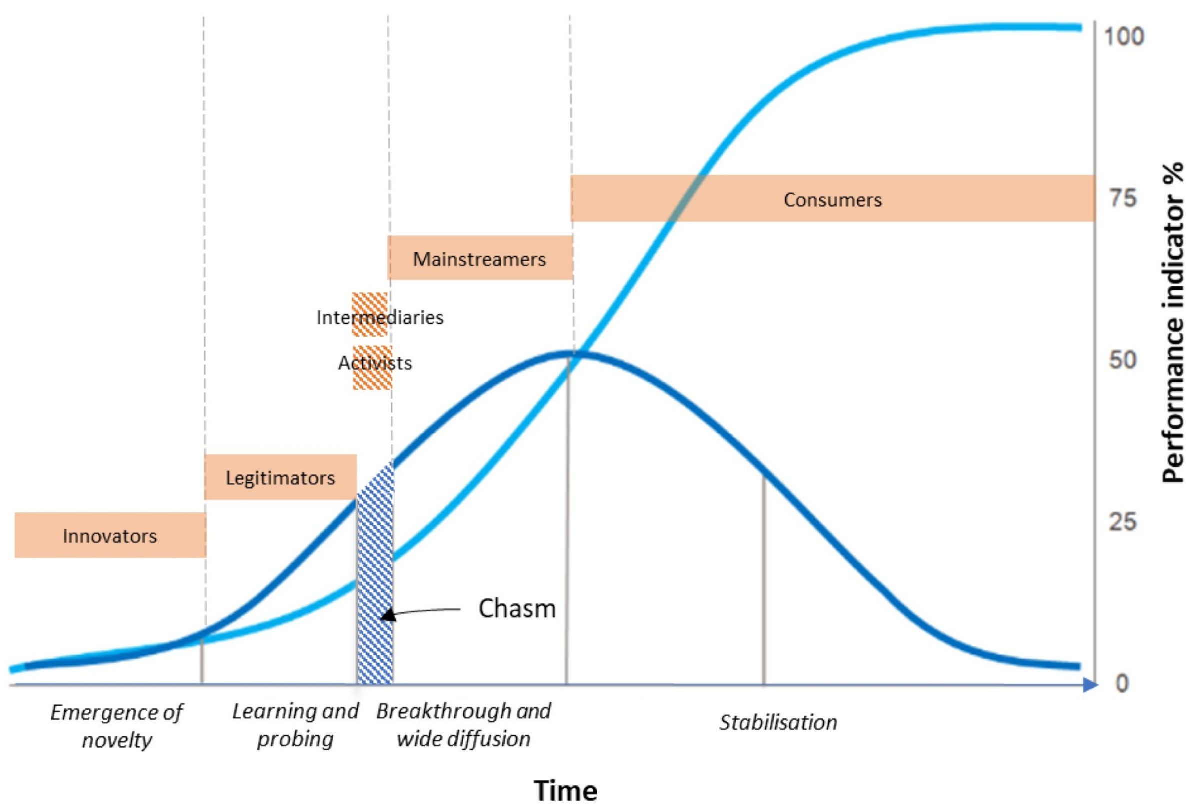

Fig. 2. User roles (graph labels) across four phases of innovation (*x*-axis labels), showing the innovation phase in which each user type is most active. This schema includes the chasm to be crossed to move from learning and probing to breakthrough and wide diffusion with the assistance of user–intermediaries and activists.

Table 1
Four phases of system innovation, adapted from Geels [51].

Phase	Characteristic
Phase 1. Emergence of novelty	An innovation emerges to solve a problem or offer a new alternative to the dominant regime, i.e., sector. It is nurtured by a small actor network (of technology pioneers and innovators) sharing expectations of the future performance of the innovation. To improve the innovation's price and performance, they experiment to improve the design and accommodate user preferences.
Phase 2. Probing and learning	The supporting network evolves into an established group or community of specialists, producers, and consumers. These actors work together to improve the innovation through learning about market preferences and understanding the necessary legislative change.
Phase 3. Breakthrough and wide diffusion	With the help of external pressures and internal momentum, the innovation gains more actor and legislative support, which improves the price/performance ratio and achieves economies of scale and learning. The linkages and co-development of new system elements increase, building new infrastructures, new governmental agencies, and professional organisations.
Phase 4. Stabilisation of the new regime	A new socio-technical regime is created around the innovation with new infrastructure and new widely adopted user practices, policies, and regulations.

resources [50]. Alternatively, these users seek and utilise new supportive institutions such as tax reductions and subsidies to support an innovation [30]. Extensive research has long acknowledged users' co-creation role in how both systems and technologies are developed, adopted, and appropriated by society [53-60]. Existing literature refers to these users as user-innovators [50], producers [30], enthusiasts, or product designers [56,59,61-64]; in our framework, we refer to them as *innovators* (Fig. 2).

In the second innovation phase, users are important in supporting the application of the innovation in a local context, legitimising it. Compared with users in the first phase, these users are locally integrated and have more influence on their proximate environment. They adopt the innovation soon after launch because they see a compelling reason to use it and are willing to accept the related uncertainties and costs in exchange for future benefits [50]. They embed the innovation locally, reducing the innovation-related uncertainty by learning about and probing the innovation, making errors and improving innovation-related knowledge [30]. With their local influence, they can convince people and increase expectations of the relevance and significance of the innovation. They create narratives to align opinions about the innovation among their peers and other system actors [30,50,65,66]. These users try to stimulate acceptance of the innovation in their peer networks by encouraging imitation and competitive reactions among most users, playing a crucial role in creating conditions for the wide diffusion of the innovation [66-70]. Existing literature calls them early adopters [50], user-legitimators [30], entrepreneurial users, and lead users [57,71,72]; we call them *legitimators* (Fig. 2).

By considering how the existing literature identifies the way in which users contribute to development in different innovation phases,

Table 2.
Summary of the user roles across the transition phases with descriptions of how these users contribute to the innovation and transition process.

Transition phase	User role	User role defined in the existing literature	Contribution to the innovation and transition process
Emergence of novelty	**Innovators**	• User–producers [30] • Innovators [50] • Product designers [50, 56, 59, 61-63] • Energy enthusiasts [64]	• Invent and create new technical and organisational solutions and routines • Use supporting institutions (e.g., tax reductions and subsidies) • Enthusiasm for new ideas; understand and apply complex technical knowledge • Look for ideas outside of the local context • Can cope with high uncertainty • Have substantial financial resources
Probing and learning	**Legitimators**	• User–legitimators [30] • Early adopters [50] • User–entrepreneurs, entrepreneurial lead users [57,71,72] • Opinion leaders [65,66]	• Embed innovation in the local context • Reduce uncertainty by making errors and learning • Convince and increase expectations of the relevance and significance of the innovation • Stimulate acceptance of the innovation among their peer networks
Breakthrough and wide diffusion	**Intermediaries**	• User–intermediaries [30] • Energy user communities [76-79]	• Create space for alignment of new actors, institutions, and technologies • Voice expectations, interpretations, and uses of new technologies to the regime actors • Enrol new actors, creating networks between them • Cooperate with other actors such as firms and (non) governmental organisations
	Activists	• User–citizens [30] • Grassroots movements [76,81-84] • Activist groups [30,80]	• Involved in transition politics • Mobilise social movement for reform • Actively try to overcome resistance of incumbent actors • Dissatisfied with current regime
	Mainstreamers	• Early-majority users [50]	• Important in creating network effects among users • Adopt just before the average member of a system • Seldom hold an opinion-leadership position • They have great willingness to adopt but seldom lead
Stabilisation of the new regime	**Consumers**	• User–consumers [30] • Late-majority users [73] • Market product consumers [86,87] • Market participants [25] • End-users [88-91] • Consumers with preferences, needs, behaviours, and practices [92]	• Buy products and embed them in their daily practices • Adopt just after the average user, after innovation-related uncertainty is reduced • Use the innovation due to peer pressure or because it has become the dominant choice

we can see how existing categorisations and descriptions overlap. We can also identify disagreement regarding what it takes to move from one phase to the next. While Rogers' [50] categorisation suggests that early adopters can take an innovation from niche to wide diffusion by acting as influential opinion leaders, evidence shows that the diffusion process is not always as linear as this theory predicts [73]. A relevant criticism comes from Moore [73], who has claimed that, in some cases, an innovation that is well received by early adopters will not necessarily succeed among most users due to significant differences between their motivations for adopting the innovation, creating a chasm (see Fig. 2) between these two user groups [73]. Moore [73] theory explains the issue of bridging the chasm between early adopters and early-majority users, noting that an early adopter looks to other early adopters for validation, whereas members of the traditional user group look to other traditional users for validation that the business model is worth adopting and/or promoting. It is also important to note that Rogers' [50] perspective assumes that early adopters have a good position from which to access the rest of their social network of peers within a firm or industry.

The users' importance in bridging the chasm by enabling the breakthrough to pass from experimentation to wide diffusion has been emphasised by Schot et al. [30]. They label these users *intermediaries*[4] and *activists*, terms we decided to adopt in our framework. Intermediaries represent those users who not only attempt to communicate with other more sceptical users, but also create space or serve as a bridge for alignment between different actor groups, institutions, and technologies to support the wide diffusion of the niche innovation. They are active in communicating innovation-related preferences and expectations with existing regime actors to appropriate and align existing regulations and standards, thereby promoting the innovation [30]. Another example of user-intermediaries cited in the literature is that of energy user communities [76-79]. Activists play a crucial role in enabling the niche innovation breakthrough by being involved in transition politics. These users are generally dissatisfied with the existing regime, actively lobbying for reform to overcome the regime resistance and weaken the position of incumbents. These users have previously also been called activist groups [30,80] and grassroots movements [17,76,81-85].

After a successful breakthrough is achieved, users start playing an important role in the wider diffusion process by adopting the innovation in their everyday practices. This category was emphasised by Rogers [50], who called these users early-majority users, seeing them as crucial for creating a network effect to mainstream the innovation. Based on their role, we therefore call these users *mainstreamers* (Fig. 2). While they have great willingness to adopt an innovation, they seldom hold strong opinions or leadership positions and take longer to decide to adopt an innovation. These users wait until other users develop and experiment with an innovation to improve its price and performance before they adopt it [50].

After the innovation has achieved wide diffusion, the stabilisation phase follows. In this phase, users play the most important role by buying products and embedding them in their daily practices. In this phase, *consumers*, as they are called in our framework, adopt the innovation just after the average user, once innovation-related uncertainty is reduced. They do so because it has become the dominant choice or because of peer pressure. Existing literature describes these users as late-majority users and laggards [50], consumers [30,50,86,87], market participants [26], and end-users [88-91].

[4] The role of an innovation intermediary is not limited to users. Extensive literature on intermediary actors in sustainability transitions identifies the intermediary roles of specialised private and public organisations, government-funded agencies, consultancy firms, as well as individuals such as managers and academics [74,75].

4. Methodology

4.1. Case study: Western Australia and the case of the RENeW Nexus project

The Renewable Energy and Water Nexus (RENeW Nexus) project was implemented in Fremantle, WA. It consisted of an early trial of a blockchain-based P2P trading model in real-world conditions, operating across the regulated electricity network and affecting participants' electricity bills. The aim of RENeW Nexus was to test both the technical and social aspects of P2P trading. Considering the social aspects, which are the focus of this paper, the project aimed to understand why and how participants engaged in P2P trading as well as how the P2P model itself affected participants' engagement with the novel trading option.

The project consortium comprised a city council, a land developer, two universities, a blockchain start-up, as well as an electricity network operator, retailer, and generator. While the retailer is also the largest generator in the state's electricity market, constituting a combined retail and generation organisation, for the purposes of this trial, it is treated as a retailer alone and is referred to as such. Existing regulations require that residential users must purchase their electricity from the public retailer. The retailer's involvement in the trial was therefore essential to allow payment of the half-hourly P2P trades, which were settled in the end-of-month retail electricity bills.

The retailer provided secondary meters to display real-time data to the participants and to manage the customer relationship and billing. It also acted as a buyer of last resort for unsold solar exports, a seller of any shortfall electricity that could not be supplied by peers at any time, and an enforcer of consumer protection rules. While the active P2P trading component of the RENeW Nexus project is outside the scope of this paper (Fig. 3), this information is provided to explain the relevance of the middleman to a trial of an autonomous concept.

The trial was run in the City of Fremantle, which offers a suitable context for sustainability-oriented innovation, given its history of political and civil sustainability leadership. The city's higher number of prosumers and lower energy grid electricity consumption than state averages [93] strengthens its suitability for trialling the P2P electricity trading model.

4.2. Participants in the P2P trial

Voluntary participants in the P2P trial in Fremantle were sought *via* announcements on social media and the city council's website as well as through word of mouth. Fifty participants in total – forty prosumers and ten consumers – self-nominated for inclusion in the trial. A participant represents a household rather than an individual; the choice of the household level for analysis was influenced by the context of the electricity sector, in which the household remains the main unit of analysis. The prosumer participants were home owners, which was necessary to allow for the installation of updated metering infrastructure and was typically a prerequisite for having a solar PV system. As shown in Fig. 3, the numbers of trial participants declined to twelve prosumers and six consumers following presentation of the P2P trading tariff structures. Readers are referred to Section 5.4 for reasons why participants chose to withdraw and to Appendix A for details on the specific P2P trading approach and associated pricing structures used in the trial.

4.3. Research design

This paper presents a single-case study analysis based on a mixed-method research design [94-96]. One benefit of single-case studies is that they can be particularly useful in exploratory work and in generating new hypotheses [97]. While we are aware that the generalisability of single-case study findings can be limited, the case chosen is exemplary, reflecting a real-life phenomenon not studied in the past [94], i.e., the world's first P2P model of electricity trading across the public electricity

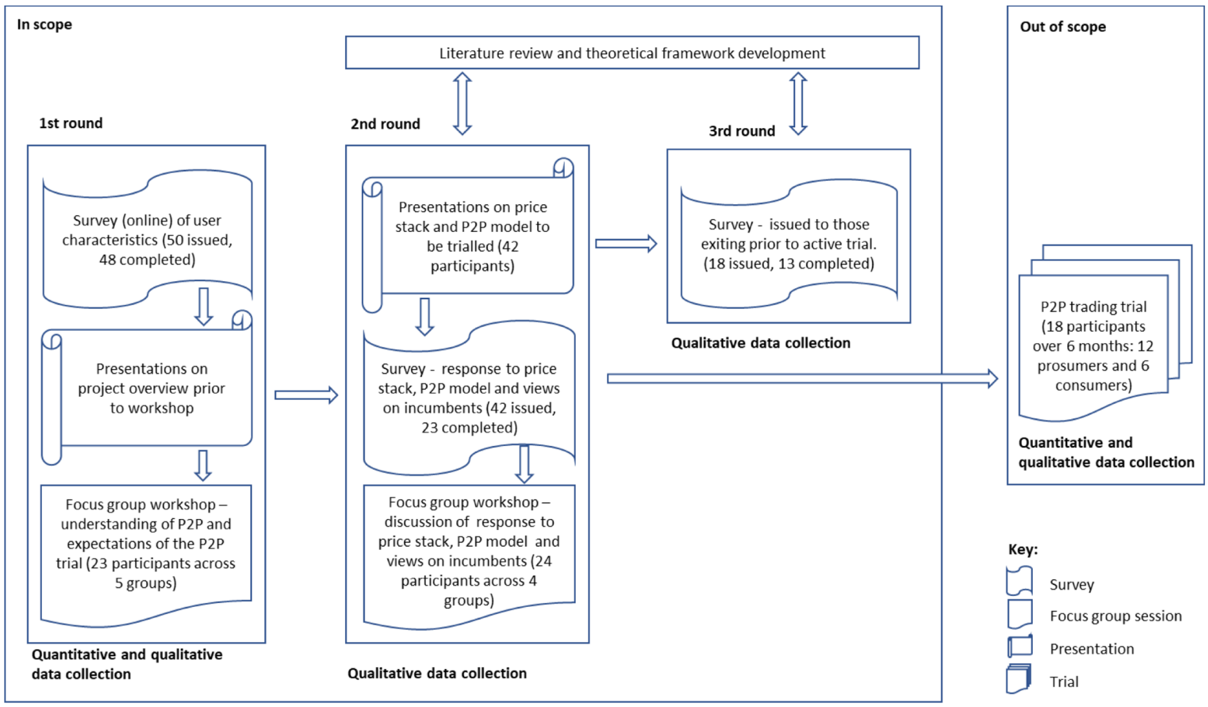

Fig. 3. Stages of qualitative and quantitative data collection up to the commencement of the live P2P trial. This paper focuses on research findings stemming from the data collected in the "In scope" box. The P2P trading trial results are out of the scope of this paper.

grid. While the sample is small, at the time of writing, it represented the only participants globally who were actively P2P trading across a regulated electricity network using blockchain technology. The absence of other comparable real-world case studies precluded employing a comparative case study methodology. Considering these weaknesses, scholars seeking to apply the present findings should consider the nature of the community in which the trial was undertaken [98] (see Section 4.1).

An inductive research approach was selected, starting with exploratory data collection that would guide us to suitable conceptual perspectives, serving as a foundation for our analytical framework [99]. Data were collected in three separate rounds using mixed methods to gain a broader perspective on our research object [100]. These rounds included three surveys and two focus group discussions with the self-nominated participants, as detailed in Fig. 3. Questions in the first survey and first focus group session (Appendix B) were exploratory and designed to suit a diverse range of research aims for the broader RENeW Nexus project. The successive survey instruments (Appendices C and D) and focus groups were designed to test emergent theories and our evolving analytical framework. The benefit of having used different data collection methods is that they allow triangulation of our primary sources [96], especially given that secondary sources relating to users of P2P electricity trading models are still lacking [100]. Fig. 3 summarises both the focus of each data collection activity and the numbers of participants in each activity.

While surveys were conducted with individuals each representing a household, the focus group sessions were conducted with individuals in groups of four or five with an independent facilitator allocated to each table. At the first focus group workshop, each participant provided independent written responses to the two questions (regarding participants' understanding of P2P and their motivations for participating) on Post-it notes. Each note was then discussed at each table to identify common themes and areas for extrapolation. All written notes were later themed and coded using NVivo 12 qualitative analysis software. At both focus group workshops, audio recordings of the discussions at each table were transcribed verbatim into NVivo 12. The same coding categories used for the written responses were then applied to each transcript. Coded themes from the written responses can be considered more representative of individual thoughts, whereas those mentioned during the focus group discussion drew out issues more important to the groups.

5. Results

5.1. The first P2P electricity trading users

According to the survey, the participants had a median household income of over AUD 156,000 per year. This is 48% greater than the median household income for Fremantle residents [101], indicating that the users involved in the trial were from relatively financially secure households.

Eight prosumers had acquired their PV systems in 2009 or earlier, while over 50% of all prosumers had installed rooftop PV systems between 2016 and 2018 (Fig. 4).

The survey revealed that the participating prosumers perceived themselves as having a good understanding of PV technology and of how to make the most of their self-generated electricity. In fact, 67% of prosumer households revealed that they often or very often adjusted their consumption patterns to use more electricity during the daytime; 55% claimed to set their appliances on a timer to increase the consumption of self-generated electricity.

5.2. Motives for trialling P2P electricity trading

The initial survey asked participants about their attitudes towards the incumbent electricity sector in WA in order to explore whether these had affected their motivations for joining the trial. The results indicate that 58% of participants were dissatisfied with the existing electricity retailer, prosumers generally being less satisfied than consumers (Fig. 5). The most common reason for dissatisfaction was financial, related to high grid electricity prices (AUD 0.28/kWh) and low financial compensation for the renewable energy generation (the FiT is AUD 0.07/kWh). For a full breakdown of the tariffs relevant to the P2P trial in the local electricity market, see Appendix A.

A significant number of respondents also mentioned dissatisfaction with the network grid operator's supply charges. Concerns were raised that the supply charges were passing through transmission costs that

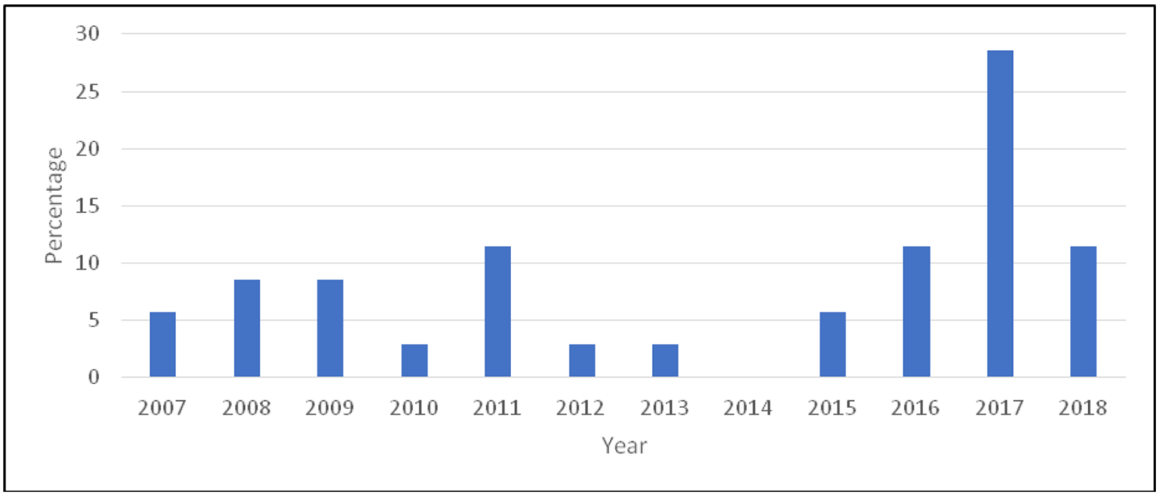

Fig. 4. PV installation year for the prosumer households.

participants perceived to be unnecessary in the context of the high levels of local renewable energy generation.

Other less frequent reasons for dissatisfaction with the electricity retailer concerned the lack of detailed electricity usage information in electricity bills, lack of incentives to save electricity, and perception that the retailer/generator does not invest enough in renewable energy production (Fig. 6).

The results of the first focus group workshop revealed that the largest single motivation for joining the trial was participant interest in knowledge acquisition, including the opportunity to learn about: personal electricity use and the electricity system in general; what will happen after the FiTs expire; and the potential solution offered by P2P trading (see Fig. 7). The second strongest motivation was the chance to be "ahead of the curve" and trial a cutting-edge technology. Interactions between participants during focus group discussions reflected a sense of excitement at being part of a cutting-edge innovation. There was also a collegial tone, as many participants were early adopters of rooftop solar technology and shared enthusiasm for renewable energy and sustainability, with the P2P trial seen as embodying these principles. This is shown from the following quotations recorded from each workshop table:

> Light a fire that could go global quickly … and have a rapid transition to a clean energy future.

> I feel good that Fremantle is starting this and we can say, you know, that you are proud of this.

> In 30 years' time when it is common practice – knowing that you were at the beginning.

> Sends a very clear message to the government that people are interested in sustainability and they want better policy.

> Love being involved in stimulating renewable uptake.

The participants were motivated by the potential to steer the sustainability transition towards a more socially equitable and clean energy system by demonstrating the successful application of a P2P trading model. Around half of the participants were motivated by efficiency improvements, described both in terms of financial efficiency, which might be achieved by eliminating the retailer/middlemen, and in terms of energy transfer efficiency, with more local solutions and less need for long-distance transmission. Notably, during the focus group discussion, only 25% of respondents stated that they were motivated to join the trial to save money or by the expectation of being financially better off, and this was mentioned apologetically:

> This is going to sound really terrible, but one of my motivations was to get cheaper power.

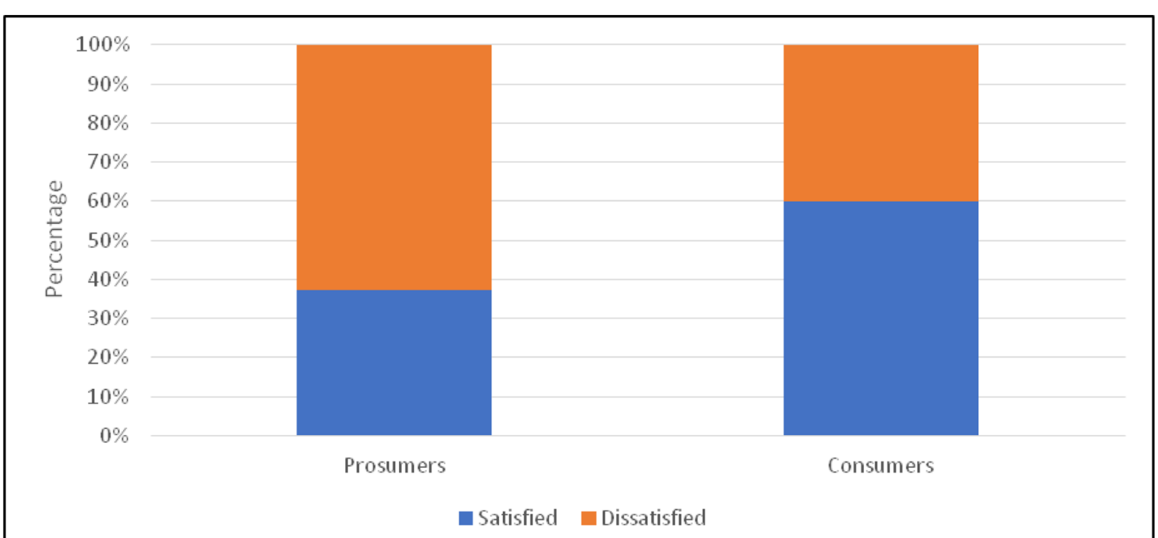

Fig. 5. Participant satisfaction with the current electricity retailer.

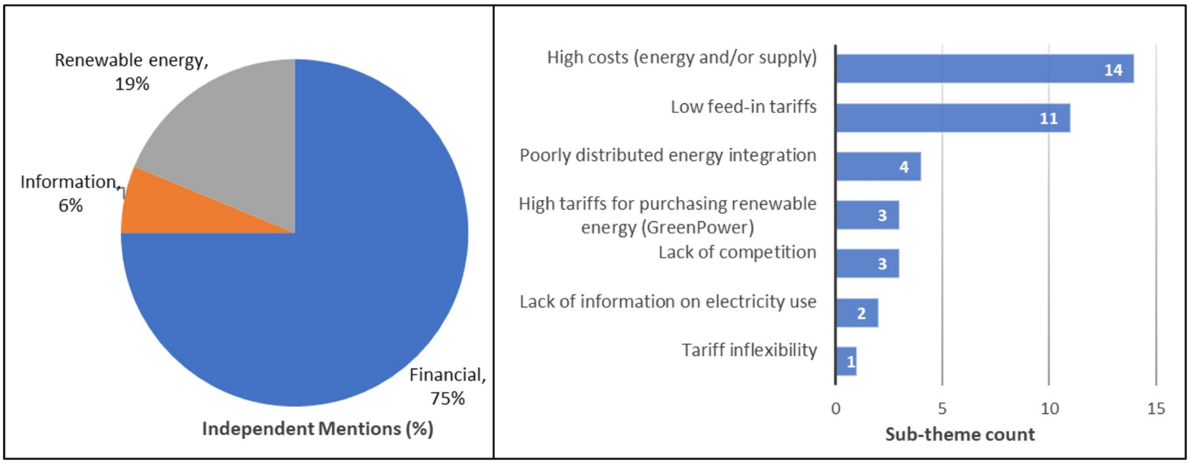

Fig. 6. Reasons for participant dissatisfaction with the electricity retailer: key themes (left pie chart) and broken down into sub-themes (right bar chart).

Despite this apparent irreverence to the financial implications of the P2P model, many follow-up questions at the end of the session were related to potential financial implications of the trial.

5.3. User expectations of P2P electricity trading

Asking participants about their expectations revealed that they had good knowledge of P2P trading and clear expectations about the future potential and performance of this new trading model. The most frequently voiced expectations concerned local community trading, flexible and lower prices, and improved system efficiency. Eight participants independently noted that they expected the P2P scheme would reduce the need for involvement of the existing retailer. This view was then generally agreed on during the focus group discussions, with the following quotation being indicative of the expectations raised during discussion:

> So you're providing your neighbours with some of the electricity you acquire through your PV panels, and not necessarily going through the retailer and the main energy companies. So I don't understand the software involved with it, but I understand it is about sending power from your PV panels to your neighbours and cutting out the middleman.

Seven participants independently noted expectations related to decentralising and localising the market, improving use of the local distribution network, and the possibility of local electricity sharing:

> This way of working means that you're not beholden to the big picture of power. It's really very local.

Six participants related P2P trading to the specific use of blockchain technology and crypto currencies (Fig. 8). Fewer expectations concerned the potential of P2P trading, for example, to increase the use of the distribution grid infrastructure, increase adoption of renewable energy production and batteries, and ensure a secure trading platform.

5.4. User reaction to the design of the P2P electricity trading model

Following the first focus group workshop, the design of the P2P electricity trading system was negotiated and developed by the project consortium and later introduced to the participants during the second workshop. A notable shift in user willingness to participate occurred when they received detailed information about the final design of the P2P trading model. Appendix A details the pre-existing tariff structure and a comparison with the P2P pricing design that was trialled.

The consortium-developed tariff design adopted in the trial evoked concerns among the trial participants, particularly in terms of the impact this would have on any remaining FiTs they were entitled to. This was mostly the case for small electricity users and those receiving the legacy AUD 0.4/kWh FiT, which they would have to forfeit if they joined the trial. A price forecast model presented at the workshop showed that, with the new fixed daily charges, participants who were large electricity users would benefit, whereas households that currently purchased and sold small amounts of electricity, and thus used the grid less, would be disadvantaged by participating in the trial.

Responses to the survey administered immediately after the presentation demonstrated that attendees understood the justification for the new daily charges embedded in the P2P model, i.e., that they were important for maintaining the distribution system and ensuring

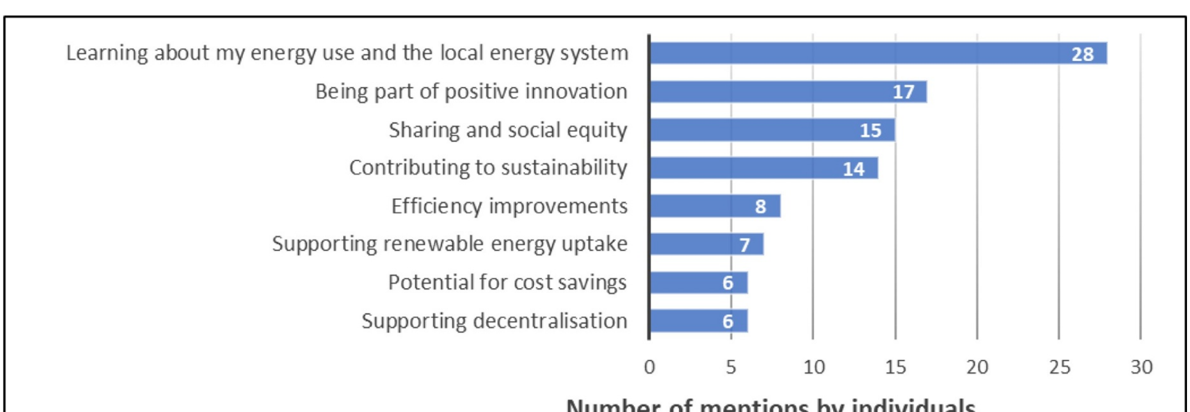

Fig. 7. Motivations for participating in the P2P trial, showing the number of times individual participants mentioned the themes during independent note-taking in the first focus group workshop.

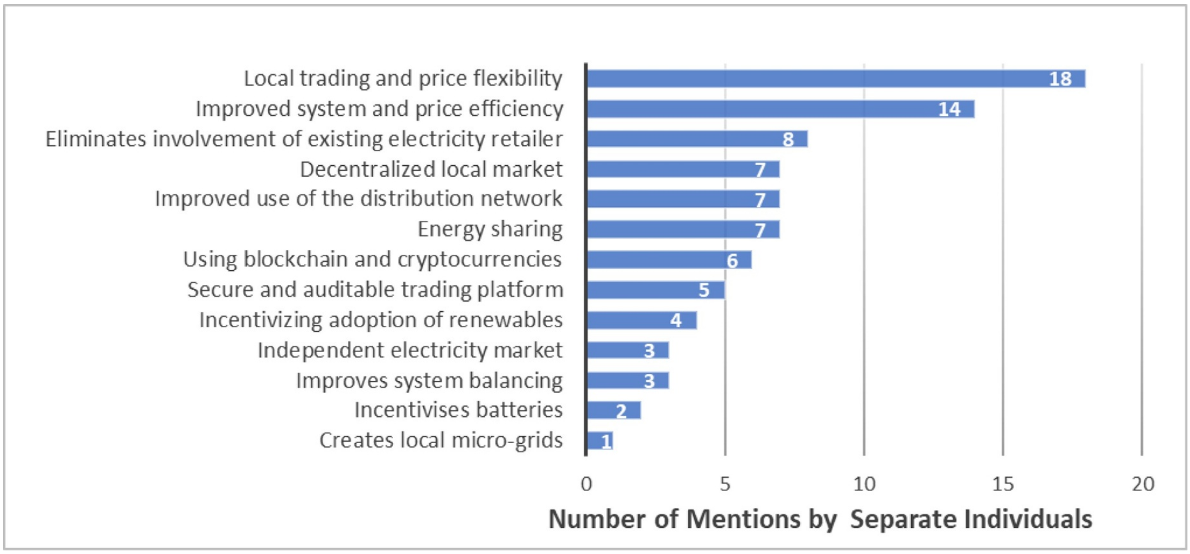

Fig. 8. Participant expectations of P2P electricity trading based on the number of times individual participants mentioned the themes during independent note-taking in the focus group workshop.

adequate generation capacity. The general acceptance of the P2P trading charges to support the broader electricity system was matched by nearly unanimous agreement that electricity should be made available to everyone in the community at reasonable prices.

Despite understanding the basis for higher prices, the participants expressed concern that the trial would reward big electricity users and penalise small ones. Many of these participants said that the design benefited the incumbents and lacked appropriate compensation for small residential electricity producers and consumers. Many of them thought that P2P trading should be subsidised to encourage uptake, as had occurred previously with solar PV.

The mood of participants was less positive in the second focus group workshop than in the first. This was expressed during the focus groups in terms of the final P2P model not aligning with participants' initial expectations. This misalignment is evident in Table 3, which contains contrasting quotations from the first and second workshops. Discussion in the focus groups indicated ongoing enthusiasm for P2P trading as a concept, but people were unsure of its benefits for themselves. Many stated that they would need time to review the information before committing to participate in the active trial.

Many participants joined based on a desire to support local community trading and positive societal change. However, there was a mismatch between the trading design and participants' expectations. The trading was considered overly market driven, based purely on demand and supply but with no ability to selectively support and sell to selected individuals within the community. Other concerns related to a design that was inappropriate for the actual participants, not reflecting the local movement of electricity and presenting a high financial risk for the prosumers involved in the trial. Concerns about the design are summarised into themes in Table 4.

After the P2P trial design was presented, almost half of the initial participants decided to leave the trial. An exit survey was completed by 13 of the original participants who elected to leave. Ten said they would have stayed in the trial if it did not make them financially worse off than continuing with their existing tariffs. Of those who decided to proceed with the P2P trading trial, 10 were estimated to be approximately AUD 200 per year worse off, two were expected to break even, and the remainder was expected to benefit. Only the households with large PV systems were expected to benefit financially from the P2P trading model.

Table 3.
Quotations from the first and second focus group workshops showing the divergence between initial expectations (first workshop) and the realities of the P2P market model to be trialled (as understood by participants in the second workshop).

First focus group session	Second focus group session
I feel strongly about the sharing economy, and this is another way of sharing.	We're looking at something that's competitive with one another. And it – to me, it just doesn't actually sit right to have that, the spirit of it doesn't gel.
I love the idea of hooking into the shared community battery … and just the actual value of sharing for a common cause. Yeah, we all have these systems. If we can share our energy, it makes so much more sense than having all these individual unique systems that we've got to pay for, look after, so it's a common cause.	It is very market-driven.
	It's a lot like … stock trading.
So, people who want to buy electricity can trade online, and ideally get slightly below the wholesale price, and ideally we get paid more than what the retailer, the monopoly, offers.	
	Because for all my good intentions, I'm working full-time, I've got two children to look after and there's a lot of things to do in the day – I don't, can't guarantee I'm going to get the time to sit down, look at, open the platform and compare the platform with the current buy and sell prices for what I'm producing and change the price.

Table 4.
Key themes emerging from the workshop in which the P2P trading model and associated tariff structure were revealed to trial participants.

Theme	Summary
Financial incentives matter	*Worse Off:* If people are going to be worse off financially, then they would be less likely to participate. Fixed charges were understood but discouraged participation. *Subsidies Required:* All groups thought that P2P trading should be subsidised to encourage uptake, as occurred with solar PV.
Alignment with community values	*Design is too market driven or not community oriented enough:* Many participants joined on the basis of supporting the local community and broader social equity issues. The design is too market driven with no ability to trade with individuals of one's choice. *Social equity:* The design is similar to the stock market; the uneducated or disadvantaged will be less able to trade effectively and therefore will be further disadvantaged. *Need to support community trading:* Participants were willing to accept the small additional costs of P2P in the trial to demonstrate the benefits of P2P for the community sharing of electricity, in the expectation that it would lead to lower costs in the longer term should the P2P network be scaled up.
The P2P market design	*Different design required:* Participants liked the concept of P2P but thought it would be better suited to either closed networks, such as trading within apartment blocks, or to those who have batteries and can sell their excess electricity during peak times. *Reflect local movement of electricity:* Some wanted the design to reflect cost savings from reduced electricity transmission, and others wanted the fixed capacity charge to be increased to encourage energy-efficiency outcomes. *Risk too high for prosumers*: Some felt that prosumers were taking on too much risk by offering their own electricity production and selling into an unknown market with a limited number of consumers, which could lead to reduced returns on their investment.

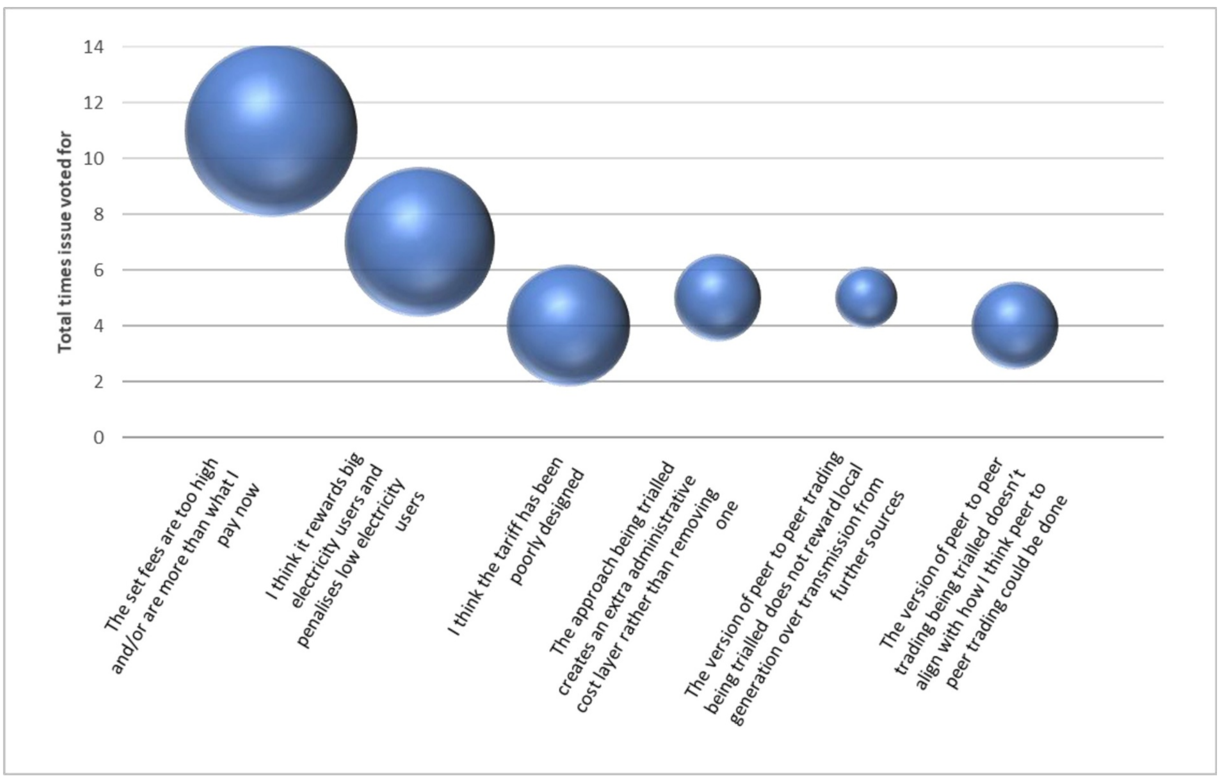

Fig. 9. Survey results concerning reasons why people dropped out of the trial. Respondents could select multiple reasons and then rate them in order of importance. The position of the bubble on the *y*-axis indicates the number of times the reason was selected, whereas the bubble size represents how often the reason featured as one of the top four reasons for each respondent withdrawing from the trial.

The various opinions about the pricing design of the trial expressed by focus groups during the second workshop were mirrored by responses obtained in the exit surveys. The strongest reason why participants withdrew from the trial was that the P2P trading design was too expensive and/or unaligned with the participants' initial expectations about the future potential of the innovation (see Fig. 9 for a summary).

6. Analysis and discussion

In the following section, we analyse the results and discuss them within the context of our analytical framework (Fig. 2).

6.1. Roles of P2P trial participants in innovation processes

Our findings indicate that the users in the P2P trading trial are financially secure households with a high interest in social equity and transitioning to decarbonised energy systems. They have good knowledge of their local context and the issues that they would like to help resolve. An important attribute of the trial participants is their good understanding of renewable energy technologies and their consumption and production patterns. They are also strongly motivated to learn about their own electricity use and broader innovations in the electricity sector, without being discouraged by initial complexities and financial losses. They also want to be "ahead of the curve" and have first-hand experience of a cutting-edge technology. These findings indicate that they aspire to be *innovators* (Fig. 2).

However, while they are interested in supporting the emergence of the niche P2P market and are self-motivated to do so, they are neither independent inventors nor creators. Instead, they show great interest in learning about the innovation and in embedding it in the local context.

This points to the trial participants being *legitimators* (Fig. 2), as described in Table 2. They strongly believe their participation could increase outside expectations and therefore support the transition to more socially equitable and local renewable energy systems through demonstrating the P2P model.

According to the results, most of the trial participants share a degree of dissatisfaction with the incumbent electricity companies, whom they perceive as controlling and undervaluing the price of self-generated renewable electricity. Although this finding recalls the role of *activists* (Fig. 2), i.e., users actively speaking out against the *status quo* and incumbents, the dissatisfaction is strongest among prosumers and mostly concerns the low financial reward for self-generated electricity. These users differ from grassroots movements and activist groups in that they are not a self-organised group of consumers defining their identity through fighting the establishment to allow for the future of P2P trading. These participants are not stubbornly acting against the incumbents; instead, they prefer acting with the incumbents *via* the project consortium to improve the quality, performance, and user-acceptance of the model before its potential introduction in the mainstream market. However, the initial design of the P2P trading model was developed with little consideration of user input and the co-production process was weak, resulting in user criticism of poor system design with inappropriate pricing. These factors contributed to a high number of dropouts from the project. This result supports existing literature that identifies the importance of collaborating with users to help co-create the innovation design and improve user acceptance [56,59,64].

Although all trial participants initially appeared to be *legitimators* of P2P trading, fewer than half of them remained in the trial after the introduction of the P2P tariff structure that indicated likely financial losses. Those who exited were unprepared to adopt the new approach until financial uncertainties and risks declined. While these users did not wish to legitimise the innovation, they could still play an important role in a later stage of innovation as *mainstreamers* (Fig. 2), i.e., users contributing to wider diffusion, after the price–performance ratio has improved.

Our analysis uncovers important findings in relation to the hypothesis of the chasm (see Fig. 2), i.e., a gap between the experimentation and wide diffusion phases [73]. We found that the two groups of trial participants seemed to have different motivations for adopting the innovation, being on the opposite sides of the chasm. However, none of the trial participants expressed interest in helping to bridge the chasm by aligning other actors or recruiting other users in the community. This bridging role needs to be filled by another/external actor, an *intermediary actor* [12,102], which in our case could be the project consortium, primarily the retailer and network operator, due to their direct access to most customers. They could bridge the chasm by taking the lessons from the *innovators* and *legitimators* to the *mainstreamers* and *consumers*.

However, the chasm will not be bridged until the project consortium acknowledges the roles the trial participants wish to play. Our findings point to a misalignment between how consortium members perceive the participants' involvement and how the participants want to be involved. Our results indicate that most trial participants viewed themselves as an active part of the trial, contributing to learning and locally implementing the new business model as *innovators* and *legitimators*; in contrast, the project consortium viewed the participants merely as *consumers*, playing a role in consuming the new market product. Incumbents, such as the utilities in the consortium, often strive to induce the users to conform to their view of the niche market solution rather than working with them in a co-creation process [103]. This discrepancy in the perception of the user's role was likely a main reason for the high dropout rate and the perception of a weak trial design. While at first glance, high prices seemed to have been the main reason for losing almost half the initial trial participants, our analytical framework helped us understand that the high drop-out rate could also have been a consequence of the consortium side failing to consider the user role.

Regarding our conceptual starting point in transition thinking, our analysis confirms the importance of viewing electricity users as agents shaping the sustainability transition process, as proposed by Schot et al. [30]. However, our empirical results indicate that their conception of the user role entails several limitations. First, they assume that users involved in innovation always seek to have specific system-level influence as an organised group with a clear identity related to the innovation [30,50,63]. Our results instead indicate that users can advance transition efforts without necessarily being the instigators or drivers of a transition. Instead, users can support the transition by adopting the innovation and collaborating with other project actors, provided the innovation appears to align with their idealised vision of the future and/or is financially beneficial to them. They need not be part of a collective movement, but rather can be organised and assisted by another intermediary actor in the system [48,102,104]. Second, their conception places users in idealised categories that are exhaustive and often mutually exclusive. Our results suggest that the participants in the P2P trading trial do not belong to a certain group or conform to a user category with a single role, but instead assume multiple key roles in the innovation process, often as individuals [32]. Our findings support the recent conclusion of Sopjani *et al.* [32] that users can assume multiple roles simultaneously within transition processes.

In addition, the user typology developed by Schot et al. [30] is useful for analysing the user-to-system dynamics, though it ignores the micro-level agency and user-to-user interaction through the different innovation phases (see Section 3.2). Complementing the transition perspective on users with innovation diffusion research and with additional user-related literature (see Table 2) has been helpful in emphasising that trial participants can both shape the wider socio-technical system change as well as influence their peers in the innovation process.

Perhaps our biggest contribution to the user-focused transition literature is the application of our analytical framework to a case of business model innovation. While an increasing number of studies analyse the role of managers, private firms, and entrepreneurs in business model innovation processes, we have shown that successful business model innovation requires attention to users as explicit transition-shaping agents.

6.2. Policy implications and areas for further research

The present findings have several policy- and industry-related implications. First, our theoretical framework suggests that in innovation trials, it is important to consider the innovation phase when designing a project and recruiting trial participants. Very-early-stage projects may be best served by targeting users wishing to co-create and legitimise an innovation and who are specifically interested in learning about and probing it. It is also essential for recruiters to understand the important roles of these users, namely, to facilitate learning processes, embed the innovation locally, and raise expectations directly related to local issues. The actor consortium could have involved participants in the initial design processes to increase the trial success, which directly depends on the consumer's image of what a P2P market design should be like. For the Fremantle trial community, this included aspects of social equity and sharing energy within the community, aspects that the eventual market design failed to deliver.

As the high rate of drop-outs from the project demonstrated, finding users who are interested in supporting early innovation processes is not easy, as most users tend to get discouraged by high uncertainty and/or lack of alignment with their underlying values and expectations. While this is not surprising, it emphasises the need to involve trial participants in the tariff design process to minimise their disappointment and reduce the number of drop-outs.

Furthermore, early efforts should be made to target the recruitment of local opinion leaders, i.e., those whose views future customers will value and listen to. In addition, effort should be made to recruit users who wish to intermediate and lobby for the innovation. These represent the users essential for taking the innovation to the breakthrough and wide diffusion phases. This could include the recruitment of institutionalised user communities already committed to the transition, such as the energy communities recognised in the UK [82,105], the

Netherlands, and Germany [106]. More effort could have been made to include a public participant as a prosumer, such as the City of Fremantle and its facilities, given that they have local influence, could have acted as an intermediary, and would have balanced the residential participants with complementary load profiles.

When it comes to areas of future research, future trials of P2P market models should strive to accommodate a range of users and load profiles, thereby demonstrating marketplace structures closer to real-world conditions. The fact that this was not done in the present trial was partly due to the inherent inflexibility of the regulatory environment, but was also a by-product of the tight project timelines. The tight timelines precluded the resolution of constraints, collaborative design, and the strategic recruitment of participants. Future projects should allow sufficient time to work through and resolve these issues. Another area that should be analysed is the choice of technology employed – in this case blockchain – and its ability to fulfil the specific needs of P2P market participants. We believe a more careful study should be made of whether the blockchain ledger is well suited to users' intentions to create a local community electricity market with local benefits. This is important to consider, as blockchain technologies have evolved to suit adversarial contexts in which trading is verified by computer code rather than by social agreement, making it potentially at odds with the underlying values of trial participants.

Future studies could also address aspects outside of the scope of this study. Analysing users involved in prosumer-based electricity markets elsewhere in the world, in both local and broader regional electricity markets across different geographical regions, could strengthen the present findings. Positioning these studies within the analytical framework outlined here could improve our understanding of user interest in and adoption of the P2P model and allow for further testing of the relationships between user roles and transition phases.

While this study has provided important insights into the roles of first users in transition processes, it has not been possible to demonstrate the potential systemic effects or broader benefits of scaling up P2P electricity markets. Empirical studies of these matters must wait until there has been greater uptake of P2P electricity markets. Conclusive results will require substantially longer time horizons that are more consistent with broader transitions.

7. Conclusions

This paper provides new insights into the role that electricity users can play in innovation, paving the way to a fossil-fuel-free electricity system. Using the empirical case of a P2P electricity trading innovation trial in Western Australia, we present new findings about what motivated users to participate in this novel trading model and about their role in its development and diffusion. This adds to our limited knowledge of the users interested in P2P electricity trading, a knowledge gap identified by Ahl et al. [24]. Our findings indicate that the users who joined the P2P trial were typically financially secure households with great interest in social equity and transitioning to environmentally cleaner energy systems. They have good knowledge of their local context and of the issues that they would like to help resolve.

In addition, by synthesizing existing concepts from the transition and innovation literatures, we constructed an analytical framework that allows for a more comprehensive understanding of the roles users can play in different innovation phases: from idea creation, through crossing the chasm, to integrating a novelty into everyday practices. We found that the users who joined the P2P trial wished to learn about a cutting-edge technology, locally validate and implement a new community-based electricity market model, and actively challenge the incumbent sector, with which they were dissatisfied. These participants remained dedicated, despite the innovation-related complexities of price and performance. While such users are crucial for the learning phase of innovation, our analytical framework indicates that they are unlikely to cross the chasm and reach the more hesitant mainstream users. Here, we suggest that the project consortium could potentially act as intermediaries where users cannot. The consortium could bridge the chasm between different users, helping take new innovations into the mainstream. However, the chasm can only be bridged if the consortium acknowledges the diverse roles users can play, instead of viewing them solely as passive consumers.

The conceptual contribution of this paper stems from a synthesis of the sustainability transition and innovation diffusion literatures that allows for both systemic [30] and micro-level understandings [50] of user roles in all stages of the sustainability transition process. This study has demonstrated that users are important not only in developing and adopting sustainable product innovation, but also in related business model innovation, through which value is created from new sustainability-oriented technologies [12,13].

Acknowledgements and Conflicts of Interest

The RENeW Nexus project is funded by the Australian Government through the Smart Cities and Suburbs Program. There are no conflicts of interest between the funding source and the outcomes presented in this paper. Partners involved in the project were the City of Fremantle, LandCorp, Curtin and Murdoch universities, Power Ledger, Western Power, and Synergy.

Appendix A. P2P Tariffs

Pre-existing tariffs comprised a subsidised renewable energy buy-back rate, a daily supply charge, and a charge based on the kilowatt hours of usage. The daily supply charge comprised a state government-subsidised network supply fee, while the electricity charge comprised a bundle of both energy- and non-energy-related expenses. The largest non-energy expense was related to recovering costs associated with capacity payments made to all generators in the network. These are part of the local capacity market designed to ensure sufficient generation capacity in the market to meet the demand during peak periods that last for only a few hours each year, typically on the very hottest summer days.

Table A1
Pre-existing and trialled peer-to-peer tariffs (AUD).

Existing tariff items	Rate (AUD)	P2P trial tariff item	Rate (AUD)
Supply charge	1.015/day	Network supply charge	2.20/day
		Capacity charge	1.10/day
Electricity charge	0.2833/kWh	Peak (3–9 pm)	0.0909/kWh
		Off-peak	0.0572/kWh
Renewable energy buy-back rate (no feed-in tariff)	0.07135/kWh	Renewable energy buy-back rate	0.04/kWh
Renewable energy buy-back rate (with feed-in tariff)	0.4/kWh		
		P2P trading platform operator's charge (paid by buyer)	0.005/kWh
		P2P sale price	Set by participants

As summarised in Table A1, the trial introduced time-of-use tariffs (9.09 cents/kWh peak and 5.72 cents/kWh off-peak), which had substantially lower per-unit costs than were payable by non-trial electricity users (28.33 cents/kWh). This was balanced by fixed daily charges (AUD 3.30/day) introduced during the trial to separate the real energy-related costs from the service- and capacity-related costs of energy supply. This tariff design allowed for trading of the energy-only component. The daily network and capacity charges were also designed to reflect the pricing model that both the network and retailer considered likely to be introduced before any P2P trading schemes were enabled within the jurisdiction. Notwithstanding, it is acknowledged as a potential limitation of the study that trial participants were required to pay an AUD 3.30 daily fee, versus those not in the trial, who paid AUD 1.015 per day. This tariff structure rewards the participants using more energy and would have resulted in cost increases for the households using less energy. Many of the initial trial participants were at the lower energy-use end of the Western Australian spectrum, as would be expected in a conservation-minded community.

Participants could set their own rates for the energy they intended to buy or sell on the P2P trading platform. Any excess energy not sold on the platform was bought by the retailer at a buy-back rate of 4 cents/kWh. The buy-back rate was set low to incentivise P2P trades. Participants could amend their buy and sell rates at any point for current and/or future half-hour trading periods.

Prosumers with the lowest sell prices had first priority in trading. When there was more supply than demand in the trading environment, electricity offered at the lowest sell prices was sold and that offered at higher sell prices was left over, to be bought by the retailer, which was the buyer of last resort. Consumers offering higher buy prices had the first priority in buying energy. When there was more demand than supply in the trading environment, the highest buy prices were accepted first and the lower buy prices were left over, to be accepted by the retailer. Sellers were charged a transaction cost of 0.5 cents/kWh by the P2P platform operator.

Appendix B. Initial User Characteristics Survey Instrument

Implied consent

☐ I have received information regarding this research and had an opportunity to ask questions. I believe I understand the purpose, extent and possible risks of my involvement in this project and I voluntarily consent to take part.

Introduction

As part of the RENeW Nexus project, we are interested in getting a better understanding of your house design and daily energy and water consumption. Please help us by completing this 10 minutes survey.

Demographics

1. What is your property address? _______

2. How many people live in your house?
    - Adults _______
    - Children (under 15 years old) _______
    - Children (15 and above) _______

3. What is your total annual household income (before tax)? *(drop down list)*
    - I prefer not to say
    - Up to $10,399
    - $10,400-$15,599
    - $15,600-$20,799
    - $20,800-$31,199
    - $31,200-$41,599
    - $41,600-$51,999
    - $52,000-$64,999
    - $65,000-$77,999
    - $78,000-$103,999
    - $104,000-$129,999
    - $130,000-$155,999
    - $156,000-$181,999
    - $182,000-$207,999
    - $208,000 or more

House design

4. Please select your dwelling type *(drop down list)*
    - Separate house
    - Semi-detached, terrace house or townhouse
    - Apartment → Q6

5. How many storeys is your dwelling? *(drop down list)*
   - One storey
   - Two or more storeys

6. How many bedrooms, bathrooms and living areas do you have?
   - Bedrooms _______
   - Bathrooms _______
   - Living areas _______

7. In which year was your house built or last renovated?
   - _______
   - I don't know

8. What is the NatHERS Star rating of your house?
   - _______
   - I don't know

9. Does your house have insulation in the following locations:

	Yes	No	I don't know
Ceiling	☐	☐	☐
Roof	☐	☐	☐
Walls	☐	☐	☐
Floor	☐	☐	☐

10. What is the size (kW) of your PV system?
    - _______ → Q12
    - I don't know
    - I don't have one → Q13

11. Which year were you solar panels installed? _______

12. How often do you maintain your solar panels?
    - Never
    - Every few months
    - Every few years
    - My solar panels are new
    - Other: please specify

13. What is the volume (L) of your rainwater system?
    - _______
    - I don't have one → Q14

14. What is the approximate area (m^2) of your roof?
    - _______
    - I don't know

15. What is the approximate area (m^2) of your outdoor irrigated garden?
    - _______
    - I don't know

Fixtures and appliances

16. How many of these electric heating and cooling devices are present on your property?

Electric heating and cooling devices	0	1	2	3	4	5
Reverse cycle air conditioner (split system)	☐	☐	☐	☐	☐	☐
Ducted reverse cycle air conditioner	☐	☐	☐	☐	☐	☐
Ducted evaporative air conditioner	☐	☐	☐	☐	☐	☐
Ceiling and/or pedestal fans	☐	☐	☐	☐	☐	☐
Portable air conditioner	☐	☐	☐	☐	☐	☐
Portable electric heater	☐	☐	☐	☐	☐	☐
Portable oil heater	☐	☐	☐	☐	☐	☐
Floor heater	☐	☐	☐	☐	☐	☐
Other (please specify)	☐	☐	☐	☐	☐	☐

17. How many of these electric appliances are present on your property?

Appliances	0	1	2	3	4	5
Fridge/freezer	☐	☐	☐	☐	☐	☐
Electric oven	☐	☐	☐	☐	☐	☐
Microwave	☐	☐	☐	☐	☐	☐
TV	☐	☐	☐	☐	☐	☐
Home entertainment system	☐	☐	☐	☐	☐	☐
Computers	☐	☐	☐	☐	☐	☐
Clothes dryer	☐	☐	☐	☐	☐	☐
Washing machine	☐	☐	☐	☐	☐	☐
Dishwasher	☐	☐	☐	☐	☐	☐
Pool pump	☐	☐	☐	☐	☐	☐

18. How many of these fixtures are present on your property?

Fixtures	0	1	2	3	4	5
Pool	☐	☐	☐	☐	☐	☐
Spa	☐	☐	☐	☐	☐	☐
Toilet	☐	☐	☐	☐	☐	☐
Shower	☐	☐	☐	☐	☐	☐
Bathtub	☐	☐	☐	☐	☐	☐
Sink/basin	☐	☐	☐	☐	☐	☐

19. What is your water heating system? *(drop-down menu)*

- Gas – instantaneous or storage
- Electric storage
- Instantaneous electric
- Solar, electric boosted
- Heat pump

20. What type of lighting do you have in your house? Please select all that apply

- LED
- Halogen
- Fluorescent
- Incandescent

Routines and lifestyle

21. What does a normal weekday look like for you and other members of your household? Please check the boxes that apply for you and each of your household members.

	Off-site full-time worker	Off-site part-time worker	Work from home	Shift worker	I work varying hours	At home	Pre-schooler at home	Full-time student/day care	Part-time at day care
You	☐	☐	☐	☐	☐	☐	☐	☐	☐
Member 1	☐	☐	☐	☐	☐	☐	☐	☐	☐
Member 2	☐	☐	☐	☐	☐	☐	☐	☐	☐
Member 3	☐	☐	☐	☐	☐	☐	☐	☐	☐
Member 4	☐	☐	☐	☐	☐	☐	☐	☐	☐
Member 5	☐	☐	☐	☐	☐	☐	☐	☐	☐

22. How strongly do you agree with the following statements?

	Strongly disagree	Disagree	Neutral	Agree	Strongly agree
Comfort at home in summer is important to me even if it means spending more on energy	☐	☐	☐	☐	☐
Comfort at home in winter is important to me even if it means spending more on energy	☐	☐	☐	☐	☐
I value money over comfort	☐	☐	☐	☐	☐
It is important for me to reduce my energy costs	☐	☐	☐	☐	☐
It is important for me to reduce my water costs	☐	☐	☐	☐	☐

Electricity practices

23. How do you and your household keep warm in winter? Please rank from what you do with more frequency to what you do the least

- We put warm clothes on
- We cover ourselves with blankets
- We close the windows and curtains
- We take advantage of the sun to heat the house during the day
- We take a warm shower or bath
- We turn the heater on
- We use a fireplace
- We have hot drinks/food
- Other: please specify

24. How do you and your household keep cool in summer? Please rank from what you do with more frequency to what you do the least

- We put lighter clothes on
- We open the windows at night for natural ventilation
- We shade our house during the summer
- We spray ourselves with water
- We turn on the fans
- We turn on the air conditioner
- We have a cold shower
- Other: please specify

25. How often do you/your household use the air conditioner in summer?

Very often	Often	Sometimes	Rarely	Very rarely
☐	☐	☐	☐	☐

26. When you use your air conditioner, what time of the day do you usually do it? Please select all that apply

- Mornings
- Afternoons
- Evenings
- Night
- All day

27. How often do you/your household use the heater in winter?

Very often	Often	Sometimes	Rarely	Very rarely
☐	☐	☐	☐	☐

28. When you use your heater, what time of the day do you usually do it? Please select all that apply

- Mornings
- Afternoons
- Evenings
- Night
- All day

29. [for prosumers] Are any of your appliances programmed to work on a timer? If so, please select which ones

- I don't have any appliances set on a timer
- Irrigation
- Pool pump
- Dishwasher
- Washing machine
- Heater or air conditioner
- Standby power
- Other: please specify

30. [for prosumers] Are you familiar with the solar panel technology and how it works?

- Yes
- No

31. [for prosumers] How often do you try to use appliances during the day when your solar panels are generating electricity?

Very often	Often	Sometime s	Rarely	Very rarely
☐	☐	☐	☐	☐

Water practices

32. On average, how many showers are taken in your house per day? _______

33. On average, how many washing loads do you do per week? _______

34. On average, how many times per week do you turn on the dishwasher? _______

Energy App

35. Would you be interested to see your electricity consumption in real-time?
    - Yes
    - No → Q39
    - I don't know → Q39

36. Assuming you had the energy usage app on a mobile device, please order the following features in order of priority, from most important to least important.
    - Energy usage/consumption today
    - Energy traded this week
    - Energy traded this week versus last week
    - Savings this week/month OR season
    - My current balance ($$)
    - "How am I doing today?" (in terms of my energy usage goals)
    - "How am I tracking?" (against similar households)
    - Alerts/Notifications

37. How would you use the information about your electricity consumption if you could access it in real-time? Please select all that apply
    - I would keep an eye on it out of curiosity
    - I would change the way I use certain appliances to reduce my bills
    - I would try to identify where the electricity is coming from
    - I don't think I would use it, I'm too busy
    - I don't know
    - Other: please specify

Service providers

38. Are you satisfied with the current electricity services provided by Synergy (e.g. tariffs, service, model)?
    - Yes
    - No → Why not? _______

39. Are you satisfied with the current water services provided by WaterCorp (e.g. tariffs, service, model)?
    - Yes
    - No → Why not? _______

Appendix C. Second Survey Instrument – Testing how the P2P pricing design aligned with expectations and values and how this influenced perception of the incumbent utilities

Please circle the relevant options for questions 1 to 3:

1) I am currently registered as a:

   A. Prosumer
   B. Consumer: or
   C. Not yet registered in the trial.

2) I attended the August RENew Nexus trial workshop: **Yes / No**

3) Would you be prepared to pay more for energy if you knew it was produced within your local community from renewable sources? **Yes / No**

4) If you answered yes to question 3, then please indicate how much more you would be prepared to pay for renewable energy produced within your local community:
   $____________

On a scale from 1 to 5, please circle the number that best corresponds to your thoughts in response to the following questions.

5) I think that peer to peer energy trading will result in more solar PV being installed on domestic rooftops than if peer to peer trading wasn't available.

Strongly agree **Strongly disagree**

1	2	3	4	5

Can you briefly describe your reasons?

6) I think the Western Power grid charge* proposed for the RENew Nexus trial is fair and reasonable.
   (*The grid charge is to cover Western Power's costs in providing and maintaining the poles and wires that transport electricity to each dwelling/business).

Strongly agree **Strongly disagree**

1	2	3	4	5

Can you briefly describe why you gave it this rating?

7) I think the capacity charge* proposed for the RENew Nexus trial is fair and reasonable.
   (*The Government makes a capacity payment to all electricity generators on the grid to ensure that there is enough generation capacity to meet the peak grid demand (usually on very hot summer days). This payment is to ensure the financial viability of some generators that may only be required on a few very hot days every year or two. Synergy's purchase costs of renewable energy certificates is also being covered by the Capacity Charge. In the trial's electricity bill, these costs are being spread across all electricity users and recovered on an equitable basis).

Strongly agree **Strongly disagree**

1	2	3	4	5

Can you briefly describe why you gave it this rating?

8) I think the Synergy Everyday off peak and Everyday peak tariffs* proposed for the RENew Nexus trial are fair and reasonable.
   (*The Synergy Everyday tariffs relates to what you pay Synergy for the actual kilowatts of electricity that you consume that are in addition to those supplied by trial participants. These kilowatts are produced by the mixture of all generators on the grid. Energy will be charged at 9.9 cents per kilowatt hour during peak times and 5.72 cents during off peak hours.)

Strongly agree **Strongly disagree**

1	2	3	4	5

Can you briefly describe why you gave it this rating?

9) I think the default Synergy Buyback Rate* proposed for the RENew Nexus trial is fair and reasonable.
(*The default buyback rate is the price that Synergy will pay you for the excess solar PV from your system if you don't find a buyer from within the trial at your preferred sale price. This is expected to be 4 cents per kilowatt hour).

Strongly agree **Strongly disagree**

1	2	3	4	5

Can you briefly describe why you gave it this rating?

10) I think the transaction charge* as proposed for the trial is fair and reasonable.
(*This is the fee that Power Ledger will charge for hosting the trading platform that allows you to trade energy with your community peers).

Strongly agree **Strongly disagree**

1	2	3	4	5

Can you briefly describe why you gave it this rating?

11) I think that we shouldn't be charged the capacity charge* as part of our electricity bill if we're doing peer to peer trading.
(*As for question 7, above, the Government makes a capacity payment to all electricity generators on the grid to ensure that there is enough generation capacity to meet the peak grid demand (usually on very hot summer days). This payment is to ensure the financial viability of some generators that may only be required on a few very hot days every year or two. Synergy's purchase costs of renewable energy certificates is also being covered by the Capacity Charge. In the trial's electricity bill, these costs are being spread across all electricity users and recovered on an equitable basis).

Strongly agree **Strongly disagree**

1	2	3	4	5

Can you briefly describe why you gave it this rating?

12) I think that we shouldn't have to pay Western Power grid charges as part of our electricity bill if we're doing peer to peer trading.
(*As for Question 6, above, the grid charges is to cover Western Power's costs in providing and maintaining the poles and wires that transport electricity to each dwelling/business).

Strongly agree **Strongly disagree**

1	2	3	4	5

13) I think that electricity should be charged based on the time of use (such as cheaper in the middle of the night but more expensive at peak times) rather than a flat energy charge.

Strongly agree **Strongly disagree**

1	2	3	4	5

14) I think it's important that energy can be provided at a reasonable price to everyone in our community, including the poor and disadvantaged.

Strongly agree **Strongly disagree**

1	2	3	4	5

Can you briefly describe why you gave it this rating?

15) I think that the billing approach proposed in the RenewNexus trial closely aligns with my expectations of peer to peer trading.

Strongly agree **Strongly disagree**

1	2	3	4	5

Can you briefly describe your response?

16) I think it's important that I can go to my retailer or biller when I've got a problem with my bill to have my issue investigated/resolved (e.g. when I feel I've been charged too much; I haven't been paid enough for my PV exports; or I can't afford to pay my bill just now).

Strongly agree **Strongly disagree**

1	2	3	4	5

Can you briefly describe why you gave it this rating?

Appendix D. Third Survey Instrument – Testing reasons for households exiting the trial

Consent tick box

As part of the RENeW Nexus project, we are interested in gaining a better understanding of why householders have decided not to participate in the RENeW Nexus Plan peer to peer energy trading trial. If you would like to participate in the RENeW Nexus Plan trial but have not yet registered please do so via the Synergy link that was sent to you on the 31st October.

Thank you for your participation in the trial up to this point. If you maintain your decision not to participate in the RENeW Nexus Plan peer to peer energy trading trial, we encourage you to remain engaged with the project as it progresses. You are still able to monitor your generation and usage via the energyOS platform.

Property address (so we can match their results from the first survey)

Did you fill out the Survey Monkey questionnaire in August?

- If so, skip
- If not, do you have solar PV system? Y/N

I attended the August RENeW Nexus trial workshop and information session/s on 3rd August and/or 19th October (tick attendance)

Are you satisfied with the service provided by Synergy (e.g. tariffs, service, model)? - Y/N, open ended response

Are you satisfied with the service provided by Western Power- Y/N, (open ended response)

I would have participated in the RENeW Nexus Plan trial if: (open ended response)

Why are you choosing to not participate in the RENeW Nexus Plan trial (choose as many options as apply to you and then number your top 5 from 1 (biggest reason) to 5):

- I do not produce enough excess solar PV energy to trade
- I do not require additional energy than what I currently generate
- I do not wish to virtually purchase energy from other participants
- It looks like too much extra work for the potential savings
- The version of peer to peer trading being trialled doesn't align with how I think peer to peer trading could be done
- I thought peer to peer trading would be more community oriented, but this is very impersonal and "free-market", kind of like the stock exchange
- The approach being trialled creates an extra administrative cost layer rather than removing one
- Using the peer to peer trading platform looks too difficult
- The peer to peer trading platform does not show me what I want to see
- The version of peer to peer trading being trialled does not reward local generation over transmission from further sources
- It doesn't allow me to trade with the person/people of my choice
- I think it rewards big energy users and penalises low energy users
- I think the tariff has been poorly designed
- I think the set fees are too high
- The set fees are more than what I pay now
- The set fees are outside of my household budget
- There isn't scope for me to change my energy use patterns, so I wouldn't get much value out of the peer to peer trading
- I cannot see how this will help the transition to a cleaner energy future

Answer strongly agree, agree, neutral, disagree or strongly disagree to the following:

- Comfort at home in summer is important to me even if it means spending more on energy
- Comfort at home in winter is important to me even if it means spending more on energy
- I value monetary savings over comfort
- It is important for me to reduce my energy costs
- It is important for me to reduce my water costs

Have you looked at the energyOS platform to view your energy usage patterns over the past couple of months? Yes/No
If yes, did using the energyOS platform influence your energy use at home? (open ended response)

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