The challenge of adapting centralised electricity systems: peak demand and maladaptation in South East Queensland, Australia

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Abstract South East Queensland's (SEQ's) centralised electricity system is under great pressure to adapt. Climate change is converging with socio-economic, demographic and technological changes to create a 'perfect storm' for the region's electricity system. Distribution networks are particularly affected, with these factors contributing to tremendous peak demand growth, about double the rate of growth in average demand in recent years. This paper reviews how Australia's electricity system is adapting to multiple drivers of peak electricity demand. We use socio-technical transitions theory to understand the temporal interconnected social and technical dimensions of adaptation in this setting. Specifically, we present an historical narrative of the emergence of centralisation in Australia and outline the peak demand problem in SEQ and review adaptation options from the international literature. We also analyse the interactions between key social groups and their adaptation responses over the past decade. Our analysis shows that adaptation has become a contested process between supply-chain actors and end-users, each with different economic objectives, adaptation needs and capacities. The resulting adaptation dynamic that is emerging shows worrying signs of maladaptation. Implications for market governance and urban policy and research are discussed.

Keywords Adaptation · Socio-technical transitions · Peak electricity demand · Electricity networks

Introduction

The technology transitions literature has gained prominence in recent years, particularly in addressing complex sustainability issues (Elzen and Wieczorek 2005; Smith et al. 2010). Drawing on the sociology of technology and evolutionary economics, this field deals with the issue of human agency in technological development, and the multi-layered interactions that have led to historically significant technological shifts within societal functions, such as mobility, sanitation and energy supply. This area has yielded valuable insights into the processes and patterns of change of large infrastructural systems, including centralised electricity systems (e.g., van der Vleuten and Raven 2006; Verbong and Geels 2007). Following this tradition, electricity systems are conceptualised as evolving 'socio-technical systems' (STSs); products of a 'seamless web' of interacting social, cultural, physical and institutional elements (Hughes 1987).

Centralised electricity systems around the world face unprecedented challenges: changing climate, shifting settlement patterns and socio-economic and demographic changes and technological developments are posing complex adaptation dilemmas for policy makers and utilities. Climate change-related extreme weather can cause outages (Willbanks et al. 2007; Shahid 2012), reduce system efficiency on hot days and increase demand due to wide use of air-conditioners, most particularly in warmer climates (Miller et al. 2008; Giannakopoulos et al. 2011). Continued urbanisation and economic growth are increasingly associated with energy-intensive lifestyles (Madlener and

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Sunak 2011; Dhakal 2009; Martinez-Zarzoso and Maruotti 2011; Kim and Barles 2012). Globally, these lifestyles are being fed by more affordable mass-produced high electrical demand appliances, such as air-conditioners and flat-screen televisions, forcing governments and utilities to build more infrastructure to keep up with demand. Electric vehicles are poised to add further demand pressure (Higgins et al. 2012).

While directly impacting on security of supply and consumption, the above factors are also driving up electricity demand peaks, which are short periods of elevated electricity use that stem from different seasonal and daily patterns (depending on climate zone). For example, early evening peaks are characteristic in summer afternoons of warm regions. Recent evidence from North America and Australia identifies rapid diffusion and high penetration of residential air-conditioners as the main source of the problem in these regions (e.g., Garnaut 2011; Newsham and Bowker 2010). This paper addresses the question of adapting centralised electricity systems in response to interconnected factors that are driving increased peak demand.

Adaptation often refers to a set of responses to alter, adjust or modify human, technical and economic activities in response to actual or expected climatic stimuli and impacts (Smit et al. 2000). However, as indicated above, adaptation to climate change is situated in a broader landscape of factors (e.g., socio-economic, geographic, demographic and technological trends) that impact on the electricity sector. The problem of peak demand is one such emerging impact. We contextualise this problem within the region of South East Queensland (SEQ), Australia, and draw on socio-technical transitions theory to understand the temporal multi-level, multi-factor and multi-actor dynamics of adaptation in this setting. Specifically, we employ the multi-level perspective (MLP, Geels 2002; Rip and Kemp 1998) as an analytical lens.

The MLP is a process theory that conceptualises STS change as an emergent phenomenon of three interacting levels of the system: *socio-technical regimes* (meso level), *landscapes* (macro level) and *niche innovations* (micro level). Regimes are dominant and stable configurations of physical, social and institutional elements which constitute a socio-technical system (e.g., centralised electricity supply) and are characterised by lock-in dynamics as elements within regimes are ‘aligned and coordinated’ based on legacy infrastructure/technology, policies, guiding principles, user practices, industry rules and regulations and organisational routines that develop over long time periods. Niche innovations refer to small-scale networks of actors, which are distinct from regimes in being loosely coordinated relationships based on trial-and-error experimentation with novel technologies and configurations (Kemp

et al. 1998). The landscape level consists of slowly changing exogenous factors such as climate change, population growth, resource availability and cultural values; influential factors that impact on the interplay between regime and niche levels, but are beyond the control of individual actors.

According to the MLP, incumbent regimes can undergo shifts or *transitions* when *landscape pressures* (e.g., climate change) and technical problems (among others) weaken the alignment between regime elements, thus opening ‘windows of opportunity’ for new configurations or niche innovations to change previously set institutions, physical artefacts, user practices etc. (Geels 2004). These periods of opportunity can catalyse change in regimes, which over multiple decades can bring about change from one STS to another. However, the course of regime change is often a contested process as actors become uncoordinated with differing priorities, goals and visions, which open multiple possible futures for the STS (Brown et al. 2000; Smith et al. 2005).

Steep increases in peak demand is one recent technical problem that has gained widespread attention in Australia. The literature cites a number of adaptation options for managing peak demand (Vine 2012), including building new electricity generation and network infrastructure, direct control of air-conditioners and other electricity ‘hungry’ devices during peak periods (Newsham 2011; Reddy 1991), introducing new time-of-use electricity tariffs (Newsham and Bowker 2010), educating consumers to shift demand and improving housing/household energy efficiency (Vine 2012).

However, adapting effectively requires an understanding of how such options are enacted by different groups of actors in the system, responding to different stimuli, with different adaptation needs and capacities (see Keys et al. 2013); and how these interactions impact on the system as a whole. For example, end-users are more concerned about amenity from electricity (e.g., thermal comfort) than the problem of peak demand. For end-users in Australia, adopting refrigerant air-conditioners may be a valid adaptation response to climate change-related increases in temperature (see Hadley Centre 2011), but a poor response from an electricity network perspective as it increases peak demand, network costs and ultimately electricity prices, which disproportionately impact on low-income consumer groups (Farbotko and Waitt 2011). This is because network operators tend to build grid capacity to cater for the relatively short-lived peak events that are driven by air-conditioner use, and this approach decreases average asset utilisation, placing an upward pressure on electricity prices. Such a scenario increases the vulnerability of low-income groups to fuel poverty and extreme heat events predicted under climate change modelling for Australia (see CSIRO 2007). This interplay and

resulting dynamic between actors illustrates a key adaptation risk—actions carried out by different groups of actors in a complex socio-technical system can lead to *maladaptation* (Barnett and O'Neill 2010; Burton 1997).

This paper adds to the literature by analysing the historical socio-technical factors that bring about maladaptive responses in vast and complex infrastructural systems, like centralised electricity systems. In bringing together STSs perspectives with an evaluation of adaptation actions, we highlight dilemmas and unintended consequences associated with economic policy, electricity industry deregulation, and more recently reform under climate change policy.

Adaptation options and the evolving centralised electricity paradigm

As a process theory, the MLP is concerned with patterns and processes of change over long periods of time. In this section, we are concerned with how adaptation of the centralised electricity system in SEQ is situated within the industry's historical context and the interplay with important landscape factors, and how these play out across scales—national as well as regional. SEQ's peak demand problem, available adaptation options and the system's history therefore constitute the context of our later application of the MLP approach on the past decade of adaptation.

The peak demand problem in South East Queensland and possible management strategies

SEQ is a relatively small sub-tropical region within the Queensland state government jurisdiction, mainly located between 26° S and 28° S latitude. It spans an area of 22,890 square kilometres and is highly urbanised with most of its 3 million inhabitants located in the major centres of Brisbane (Queensland's capital), Gold Coast, Sunshine Coast, Ipswich and Toowoomba (ABS 2011). As a fast growing region in Australia, SEQ has a well-documented peak demand problem (Queensland Government 2008). According to the region's distributor (www.energex.com.au), 13 % of capacity is only used for a few hours, a few times a year. One recent study on peak demand in the region was undertaken as part of the SEQ Climate Adaptation Research Initiative (Wang et al. 2012). In summary, this study gathered and analysed demand data for a period of 10 years (2002–2011) based on half-hour time series data obtained from Energex. Peak annual demand growth was estimated at 4.1 %, about double the rate of overall annual demand growth (2.2 %) (see Fig. 1). Rising use of air-conditioners coinciding with other residential loads (in the early evening) has been identified as a major driver of peak demand growth. Based on historical and simulated projections, Wang et al. (2012) suggested that

Fig. 1 Annual peak and average electricity demands in the region of SEQ, Australia

annual peak electricity demand will continue to grow independently from average demand.

Various strategies for managing peak demand are cited in the literature. Newsham and Bowker (2010) reviewed several pilot projects for direct load control in North America and concluded that reductions between 0.3 and 1.2 kW per air-conditioning unit could be achieved. A number of North American studies have also examined the impact of dynamic tariffs structures on peak electricity reductions (Newsham and Bowker 2010; Faruqui and Sergici 2010). Based on reviews of previous studies, Newsham and Bowker (2010) found that critical peak pricing (applied on a small number of *event* days advertised by the utility company a day in advance) is the most effective strategy from this class, achieving 30 % load reduction compared to 5 % for time-of-use tariffs. A less direct approach to shaping customer usage patterns is through education and feedback (Vine 2012), though no research has evaluated the impact on peak demand. Building energy efficiency has received widespread attention as a cost-effective strategy for energy (and emissions) reduction (Miller et al. 2012) that can also reduce demand peaks (Steinfeld et al. 2011). This option incorporates passive solar design, cross ventilation, shading and building orientation, and also appropriate building materials, facades and colours. Steinfeld et al. (2011) analysed peak load characteristics of Sydney office buildings and found that peak loads for office buildings with best practice energy performance were 26 % lower than for buildings with average energy performance, while the total annual energy consumption was 57 % lower.

Historical review: regional and national-scale analysis, major landscape developments and the emerging centralised electricity regime

The development of a centralised electricity system in Australia and the SEQ region emerged from the interplay

of major social, economic, political and technological changes that occurred throughout the OECD during the twentieth century. The electricity industry was established in the late nineteenth century with many small utilities based in colonial town centres, and evolved and developed into a national-scale and nationally regulated sector over a period of more than 100 years (Booth 2003). The colonial centres became capital cities within six states and two territories (referred to in this paper as states for simplicity) after federation in 1901. Early electricity utilities were niche innovations in the context of a broader regime for stationery energy, typically dominated by wood fuel for heating and cooking, and kerosene, gas and candles for lighting. Electricity suppliers were vertically integrated companies owned privately or by local government municipalities, typically supplying electricity to nearby customers, street lighting and tramways (Sharma 2003). One of SEQ's first utilities was the Brisbane Tramway Company, which supplied electricity to Brisbane's inner city commercial and industrial customers and the railways; later the company was the first to supply electricity to suburban customers in SEQ, following the adoption of more efficient alternating current generators (Simmers 2004).

From a market perspective, the early decades of the twentieth century were a highly contested period for Brisbane's burgeoning electricity industry, characterised by competition for customers and between private and public (local government) interests (Simmers 2004). The industry was loosely regulated by the state government, which held powers to grant permission for electricity companies to build network infrastructure to new customers. Electricity was expensive, but demand for electric lighting was substantial due to perceived superiority (convenience, safety, reduced heat) over traditional lighting. This demand prompted investment in progressively larger coal-fired generator sets (Simmers 2004), enabling local electricity systems to emerge as a new regime for lighting. Demand continued to grow with the diffusion of electrical appliances and industrial machinery, while technical improvements and economies-of-scale in the electricity supply-chain reduced retail prices. In time, electricity became symbolised as a basic need. State governments soon recognised the political appeal of supplying electricity and began enacting legislation to own electricity supply assets (Sharma 2003).

State ownership was all but complete by the late 1940s (Sharma 2003). Each state jurisdiction operated vertically integrated monopolies with centralised planning and operation (Moran 2008; Sharma and Bartels 1997). States concerned themselves with problem agendas regarding urban air quality, electricity prices and service reliability and established regulated standards, which guided utility

planners towards a hub-and-spoke infrastructure model. As dominant actors, states also pursued their own economic objectives (jobs, use of state resources) and ensured independence from other states (Sharma 2003). In time fewer, larger and more remote generators were linked to customers, irrespective of load size, distance from a generator and network infrastructure costs. Queensland's network in particular became more dispersed than any other state as demand grew with rising living standards (Wadley 1981).

In the 1950s, Australia (along with much of the world) entered a prolonged economic boom lasting until the early 1970s. Growth was brought about by a combination of landscape factors stemming from widespread acceptance of Keynesian economic policy, immigration policy and population growth, shifting employment from agriculture to manufacturing and services, and urban policy that promoted home ownership and low density suburban development of outer metropolitan areas (Berry 1999). During this time, city-regions began competing for investment and accommodated the needs of both labour markets and capital through highway enabled suburban sprawl (Harvey 1989; McCarty 1970). Urban expansionist policy in the second half of the century became particularly evident along SEQ's coastal strip, as the region became the fastest growing in Australia, and small towns in the Gold Coast and Sunshine Coast merged with Brisbane through an apparent sea of housing estates (Spearritt 2009).

Growth in the electricity network necessarily followed and increases in supply capacity accelerated to accommodate the proliferation and diffusion of electrical appliances and growing consumer desire for greater comfort (Shove 2003; Schipper 1987); electricity now provided for wants as well as needs. Seasonal and daily electricity demand peaks emerged as heating and cooling appliances became more common, while pronounced daily peaks can be traced to a combination of spatial segregation of residential areas (dormitory suburbs) from other uses (e.g., commercial and industrial) (Schnore 1957) and increasing participation of women in the workforce (Evans and Kelley 2008), shifting most household electricity consumption outside of normal working hours.

Towards the latter part of the century, the global economic policy landscape shifted to less government involvement and more open, competitive and deregulated markets. Concerns about the efficiency and international competitiveness of the sector were evident at the federal level during the 80s and early 90s (Moran 2008; Sharma 2003). Political momentum continued to build leading to the eventual establishment the National Electricity Market—a wholesale spot market facilitated by a single grid linking all eastern Australian states, including Queensland. A federal competition agenda was also pursued leading to progressive disaggregation of the electricity supply-chain

and privatisation of both electricity generation and retail businesses. This reform was intended to bring about a competitive market, delivering long-term benefits to consumers with respect to price, quality and reliability as codified in the National Electricity Law. Today, national institutions govern the system, overseeing investment in centralised infrastructure (Australian Energy Regulator) and managing market access, operation and market planning (Australian Energy Market Operator).

Application of the MLP to adaptation of centralised electricity systems

Thus far, we have shown how landscape developments related to population and economic growth, rising affluence (and consumer values) and urban sprawl produced an electricity regime based on fewer large coal-fired generators and vast transmission and distribution networks. The evolution of centralisation was also linked to the changing dominance of regime actors and formalisation of rules and regulations; from small private and local government companies loosely governed by states, to state owned and governed monopolies, through to a federally governed industry of private and state owned companies. Lock-in effects became evident with increasing investment and formalisation of rules and processes. On the demand side, changing social practices and urbanisation patterns drove up electricity consumption, particularly of a peaky nature. The response adopted by regime actors to this problem has been largely directed towards augmenting and reinforcing the network, increasing system costs. However, in recent years, evidence has grown regarding the adaptation value of demand-side management options, underscoring a growing awareness within the regime for the need to change investment rules and practices in the electricity sector.

Australia's electricity regime entered a new era at the turn of this century, with the roll-out of various climate change policy measures supporting demand-side management and renewable energy. These policies arose in the context of additional landscape pressures, allowing windows of opportunity for niche innovations based on decentralised (small-scale) electricity technologies and supply configurations, and causing previously coordinated and aligned regime actors to pursue divergent adaptation strategies. In this section, we present a narrative of these adaptation dynamics, drawing on the MLP and illustrating the indications of maladaptation and the prospect for two emerging and contested futures for the centralised grid.

The latter part of the twentieth century and early years of the twenty-first century saw historic droughts, floods, heat waves and fires across Australia, which impacted on the political mood towards environmental issues (Gascoigne

2008). Global shifts in political mood regarding anthropogenic climate change also impacted on Australian politics. These landscape changes resulted in new energy policies to promote renewable energy, energy efficiency and demand management. Diffusion of refrigerant air-conditioners also reached the take-off phase at this time, surging from 35 % in 2000 to an estimated 70 % today (EES 2006) and placing significant strain on residential distribution systems. The dramatic penetration of residential air-conditioners was arguably an adaptation response to historically high summer temperatures in Australia (see Hadley Centre 2011), and a combination of more affordable air-conditioners with relatively poor thermal performance of Australian housing (see Horne and Hayles 2008). Distributors responded by making significant investments in additional network infrastructure (AEMC 2010; Garnaut 2011). For example, about AUD\$45 billion is scheduled for network investment across Australia for the current planning period (July 2010–June 2015), with about one-third of that investment for peak demand growth alone (Dunstan et al. 2011). In SEQ, Energex received approval from the energy regulator to invest AUD\$6.4 billion for the current period, a 58 % increase from the previous 5-year period. Previous increases in network spending resulted in dramatic electricity price rises, in the order of 30 % in the 2007–2010 period; a result that is expected to be replicated as locked-in network investments for the current determination period flow through to future retail pricing determinations (AEMC 2010). Queensland's economic regulator recently approved electricity price rises, which will effectively raise electricity bills for the average residential customer in 2013–2014 by more than 20 % compared to the preceding year (QCA 2013).

To counter increasing electricity costs, some end-users took advantage of recent photovoltaic (PV) technology developments and favourable climate change policies. Specifically, more affordable mass-produced PV systems from China and government incentives for PV enabled typically middle–high-income households (Bruce et al. 2009) to effectively hedge against electricity price rises. A federal PV rebate was established in 2000 to encourage small end-users (typically households, small businesses and community groups) to invest in grid-connected renewable energy. Federal and state governments introduced rebates for solar hot water and heat pump systems as well. This was followed by a raft of further incentives, including a federal renewable energy target underpinned by a renewable energy certificates market, and notably, state-based feed-in tariffs (FiTs) for small grid-connected PV systems (typically <5 kW). Queensland's net FiT was among the highest in the country at 44 cents/kWh, or about double the retail electricity price in SEQ, which allowed some PV owners to generate an income from the excess electricity they produced.

These conditions drove meteoric growth in the PV market, with over 500,000 systems installed across Australia, or over 1,031 MW capacity by 2011 (up from 0.4 MW in 2000 and 111.9 MW in 2009; CEC 2011). The growth reduced the economic cost of PV to grid parity for residential systems in 2012 (APVA 2011). Regime actors became concerned about the impact of high PV penetration on grid stability and social equity, and the influence of generous FiTs on electricity prices (e.g., Nelson et al. 2012). This prompted most state governments to remove or vastly reduce FiTs in the last couple of years. In July 2012, Queensland's FiT was reduced to 8 c/kWh as part of a suite of policy changes to address factors driving up electricity prices.

Climate change politics also shifted investment practices in the large-scale generation sector, as financiers factored in carbon pricing and a carbon constrained future. Climate change policy and pricing carbon dioxide emissions were debated during the 2007 federal election. This and other environmental issues arguably resulted in the ousting of the incumbent conservative government, and election of Kevin Rudd's pro-carbon pricing Labour government (Gascoigne 2008). Prime Minister Rudd signed the Kyoto Protocol soon after the election signalling the government's intent to set emission reduction targets for Australia. Consequently, more investment flowed to more expensive but lower emission gas generators for peaking and base-load power, particularly in Queensland, where significant coal seam gas resources were identified (Simshauser et al. 2011a). Towards the end of 2011, the Australian Government passed laws to price carbon, commencing in July 2012 with a carbon tax set at \$23/tonne.

In terms of demand management and energy efficiency, regime actors at both the federal and state government level were active in delivering programmes to reduce emissions, address peak demand and the burden of mounting electricity prices. The Australian Government implemented minimum energy performance standards for major appliances. In 2008, an insulation rebate was rolled out as part of the government's stimulus package during the global financial crisis. (However, this programme was discontinued amid concerns regarding the programme's implementation.) Other federal programmes included smart grid trials, and financing mechanisms and agencies to fund renewable energy and energy efficiency. In SEQ, Energex initiated remote demand management trials, while the Queensland Government established an energy audit programme for households and businesses, which provided education and advice on how to reduce electricity costs.

Early signs of policy success emerged in 2010, with the National Electricity Market registering a modest fall in consumption of 212 MWh (0.1 %), the first in its history, followed by a further fall of 1,836 GWh (1.0 %)

in 2011, and a sharp fall of 4,660 GWh (2.4 %) in 2012 (AEMO 2012). These falls were brought about by a combination of economic factors (declining manufacturing activity due to high Australian dollar, and lower than expected domestic economic growth) and notably, significant penetration of small-scale PV and demand-side curtailment (AEMO 2012). AEMO's latest forecast is for modest annual demand growth of 1.7 % for the 2010–2020 period.

Early signs of maladaptation: combining the multi-level perspective with an adaptation evaluation framework

Historical analysis of the emergence of electricity centralisation in Australia shows that electricity demand and peak demand are products of complex multi-level interactions. At the landscape level, government policy trends related to population and economic growth and urban expansionism shaped a supply-oriented electricity sector. An electricity regime based on large generators and vast transmission and distribution systems developed with the aim of achieving economies-of-scale in a market growth context. State governments became attracted to the notion of supplying essential services through infrastructure ownership, and end-users progressively aligned with this regime by enacting practices that became increasingly energy intensive. Aspirations shifted towards greater levels of comfort in response to economic/urban growth and consumer-capitalist policies; a process enabled by an increasingly abundant supply of cheap mass-produced electrical goods and growing household income.

Amidst this historical interplay between the landscape and regime levels, recent natural disasters and the introduction of climate change policy disrupted and weakened the alignment between regime actors. Resulting adaptation patterns across Australia's electricity system reveal a tension between supply-chain actors and end-users (see Fig. 2). Supply-chain actors have typically employed an adaptation strategy within the dominant centralisation *paradigm* (Dosi 1982), whereby innovation (e.g., direct demand management and smart grids/redundancy etc.) is aimed at preserving profitability and viability of legacy assets and organisational competencies, as well as meeting regulated standards for safety, reliability and security of supply. Many end-users or consumers, used to meeting needs and wants with increasingly affordable electrical gadgets, have chosen to adapt to elevated summer temperatures by actively managing thermal comfort with high demand refrigerant air-conditioners, and some have responded to electricity cost consequences through energy independence measures (e.g., installing small-scale PV systems). Clean energy and energy efficiency policy measures are reducing demand as well, which illustrates how

Fig. 2 Signs of maladaptation emerging from different economic objectives and divergent adaptation strategies between electricity supply-chain actors and end-users

momentum for climate change mitigation is placing pressure on the regime to fundamentally change.

Unfortunately, this dynamic is leading to early signs of maladaptation. Barnett and O'Neill (2010) defined 5 types of maladaptation based on observed water infrastructure adaptation in a large urban region of Australia that was responding to severe drought. The responses they cite led to the following: increased greenhouse gas emissions, disproportionate burden on the most vulnerable, high opportunity costs and reduced incentive to adapt and path dependency. In the case of Australia's electricity system, vulnerable groups such as low-income households are beginning to experience fuel poverty as system-wide costs escalate (Simshauser et al. 2011b), and path dependency appears likely to continue as further investments flow to centralised assets to solve problems related to peak demand and high penetration of PV.

Furthermore, the roll-out of PV and energy conservation strategies in response to rising electricity prices could develop into a technological substitution transition pathway (Geels and Schot 2007), where niche innovations (and networks) in energy services and small-scale electricity

generation gain momentum and progressively replace the centralised electricity regime, resulting in stranded assets, power struggles and regime defence strategies (aka. sailing ship effects: see supply-chain adaptation strategies in Fig. 2). Social inequity risks becoming more severe over time as the vicious cycle of electricity price rises to pay for centralised assets in a declining market fuel further market development for small-scale local energy solutions. Such a scenario will drive *niche-accumulation* (Geels and Schot 2007), or improvements in price/performance ratios of small-scale generators relative to central grid electricity, which is likely to further erode market share from the National Electricity Market. For example, the cost of solar electricity systems is expected to continue declining (APVA 2011), and the emerging market for electric vehicles is projected to dramatically reduce the cost of battery storage over the next decade (Narula et al. 2011; Hensley et al. 2012). Such developments will improve cost/performance ratios of off-grid systems, perhaps to a point where these systems are more cost-effective than grid electricity for more and more end-users, particularly at the grid's fringe (SKM 2011).

Discussion

The aim of this paper was to address the question of adapting centralised electricity systems to climate change and other exogenous factors pushing up peak demand. We contextualised our analysis within SEQ and Australia and used the MLP (Geels 2002; Rip and Kemp 1998) as an analytical lens to understand how centralisation evolved and how adaptation has proceeded in this setting. This analysis indicated some early signs of maladaptation of the system, as outlined by Barnett and O'Neill (2010). While not detailing the reasons why maladaptation occurs, Barnett and O'Neill (2010) cite the time-lag between climate change and institutional change as a key factor. In this paper, we add that maladaptation arises in a complex socio-technical system where different groups of actors behave in economically rational ways and employ divergent adaptation strategies in response to multi-factor and multi-level interplay.

Applying the MLP helped situate recent adaptation by regime actors in terms of historical (landscape) factors and processes that shaped lock-in effects and triggered windows of opportunity. Early development of the electricity industry saw state governments seize control of electricity supply and become dominant actors to drive state-centric economic development. Investment and engineering practices favoured centralisation under guiding principles of economic growth and social equity. User practices initially reflected the view of electricity as a basic need, but then shifted to 'wants' as government sponsored economic and urban growth made housing, electricity and electrical appliances more available. Increasing scale of infrastructure (and investment) coupled with demand growth produced a lock-in spiral, which accelerated with a move to national-level governance, integration of state systems into a larger network (and market), disaggregation of the supply-chain and further formalisation of rules and regulations. Windows of opportunity have opened recently for niche innovations in distributed energy systems and strategies (i.e., micro-renewables, energy efficiency and demand management), in response to two emerging landscape pressures: (1) peak demand-investment coupling producing steep rises in electricity prices, and (2) climate change and related policy incentives for renewable energy and energy efficiency.

Consequently, electricity supply in Australia appears set to transition, albeit with tension in the foreseeable future between divergent technological paradigms and trajectories. One trajectory, led by supply-chain actors, follows continual improvement and reinforcement of the legacy centralised system, with augmentation focussed on addressing problems associated with peak demand and grid-connected micro-generators (a *super grid*); and another involves end-users,

typically affluent, reducing reliance on the central grid as relative price/performance ratios for micro-generators and off-grid systems improve (an *off-grid revolution*), thus reducing market demand and revenue for the super grid.

Policy makers in Australia face the complex task of managing the transition from fossil fuel-based centralisation in a growing electricity market to partial decentralisation in a stabilising or declining market with a growing proportion of electricity from renewable sources. Such a transition has been envisioned and discussed by others in relation to severe landscape pressures, such as disruption in fuel supply or supply-chain vulnerability to climate change impacts (Blokhuis et al. 2011; Bouffard and Kirschen 2008; Verbong and Geels 2010). Our analysis also highlights the central role of climate change policy in driving greater decentralisation and lower demand.

We suggest the multi-level dynamics of maladaptation outlined above hold important implications for market governance and economic policy. The first implication is pragmatic and concerns the process for signalling investment in new generation and network infrastructure. The second relates to broader issues of addressing long-term economic and urban policy.

Firstly, despite three consecutive years of market falls, Australia's market operator persists with forecasting market growth, albeit modest in their 'low scenario', which will continue to drive investment in new infrastructure. This infrastructure will face high risks of becoming stranded or underutilised, contributing to the linked problems of steep rising retail electricity prices and energy poverty. The current investment process is insensitive to market disruptions due to new technology and climate change policy. Policy makers, regulators and industry need to consider new investment protocols that evaluate grid versus non-grid investments on the basis of adaptation effectiveness, which includes emission reduction objectives, but goes beyond to consider social equity concerns and the risk of exacerbating path dependency in the sector. Further research is needed to explore new market designs and develop modelling tools and methods to underpin such investment protocols.

The second implication suggests that addressing the risk of maladaptation will require situating climate change policy in the context of historical momentum for economic growth and urban expansionism and related social transformation (i.e., rising affluent lifestyles). Recent economic reform agendas have focussed on notions of decoupling economic growth from consumption of resources, in this case shifting the energy market based on profit from electricity throughput towards an energy services paradigm (Steinberger et al. 2009). Recent attempts to decouple utility incentives appear to be partial and inadequate (Kihm 2009), and some authors express concern about the

prospect of rebound effects associated with technological and market design improvements, particularly given the prevailing consumer-capitalist society (Herring and Roy 2007; Trainer 2011). While wholesale changes to economic policy are unlikely, the urban policy realm may hold some promise for addressing these concerns.

Much has been written about the potential role of eco-developments and cities in seeding new configurations for production and consumption systems (e.g., Bulkeley et al. 2010; Romero-Lankao and Dodman 2011; Swilling 2011). Szatow et al. (2012) recently discussed the central role of property sector actors in driving cleaner and more efficient energy supply configurations. As outlined in this paper, urban development patterns in Australia have been a key contributor to driving energy demand and peak demand issues emerge from segregated land uses. Addressing peak demand and related electricity prices rises effectively involves moving away from segregating land uses towards mixed-uses, thus improving network utilisation. In terms of addressing consumption, some also point to the value of urban consolidation—a form of rationing—which involves reducing dwelling and lot size (Clune et al. 2012). Urban consolidation and densification appears to be a logical response and offers benefits in terms of using existing infrastructure more efficiently. However, the energy transition described in this paper is one of energy quality—from high quality (coal) to low (renewable) in terms of energy return. Some authors raise questions about urban densification in the context of an energy system based on low-gain renewable energy (Hagan 2012; Hui 2001; Tainter et al. 2003). Research is needed to examine the relationship between urban density and renewable energy supply and to identify optimal urban planning models that would harmonise with more renewable and decentralised electricity supply configurations.

From a governance perspective, undertaking this urban research will require unique institutional arrangements across land use and infrastructure regimes. For example, the Queensland Government has land use and infrastructure planning powers for certain state designated urban development areas, including new satellite cities in SEQ. This sort of institutional innovation offers substantial opportunities to explore new energy supply regimes that can effectively and equitably address climate change mitigation and adaptation policy objectives. We consider this research endeavour urgent given the long timeframes involved in transitioning urban areas and associated infrastructural systems.

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