Renewable and Sustainable Energy Reviews 104 (2019) 95–110

Contents lists available at ScienceDirect

Renewable and Sustainable Energy Reviews

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

Opportunities and barriers for photovoltaics on multi-unit residential buildings: Reviewing the Australian experience

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ARTICLE INFO

Keywords:
Solar energy
Photovoltaics
Apartments
Residential solar
Embedded networks
Australia
Regulatory policy

ABSTRACT

This paper reviews opportunities for, and barriers to, increasing photovoltaic (PV) deployment on apartment buildings, with a particular focus on the Australian experience.

As rapid urbanisation drives increasing housing density, PV penetration in multi-occupancy housing has been limited by comparison with stand-alone housing in many jurisdictions, including in Australia despite its world-leading residential PV penetration. Given the growing commercial attractiveness of residential PV, this also raises equity concerns for apartment households.

PV can potentially be installed to supply electricity to common property, to serve individual apartments, or as a resource shared between multiple apartments through embedded networks, local energy trading or 'behind the meter' deployment models.

Our study undertook a review of the academic literature in this space and of specific Australian regulatory arrangements, as well as conducting a series of semi-structured interviews with a range of relevant stakeholders. Barriers identified include the huge variety amongst existing apartment building stock, demographic factors and knowledge issues. However, the Australian regulatory context - including governance of apartment buildings, regulation of the energy market, and electricity tariff policies - also impacts on the options available to apartment residents.

New business models for deploying PV on apartments are emerging, including initiatives from retailers, developers and community energy organisations. While some issues are specific to the Australian context, or to buildings governed under strata-type arrangements, broader lessons can be taken from the Australian experience, including to inform the design of the regulatory framework required to facilitate widespread PV deployment across all residential housing types.

1. Introduction

The Paris Agreement commits the world to holding average global temperature to "well below 2 °C above pre-industrial levels" and to pursue a 1.5 °C limit, through reducing anthropogenic greenhouse gas emissions to zero [1]. Residential buildings account for almost three quarters of global building energy use and 28% of global electricity use [2,3], while offsetting these loads with rooftop PV has been significant in developing a commercial global PV market and is critical to achieving COP 21 emissions targets. The International Energy Agency (IEA) estimates that achieving the 1.5 °C limit would require "practically all" residential and commercial buildings to reach net-zero emissions by 2040 [4]. Fortunately, the extraordinary technical progress and falling costs of photovoltaics (PV) over the past decade have made

Abbreviations: ACT, Australian Capital Territory; AEMC, Australian Energy Market Commission; AER, Australian Electricity Regulator; AGM, Annual General Meeting; BTM, Behind the Meter; CP, Common Property; CRE, Community Renewable Energy;; EC, Executive Committee; EEU, Energy Efficiency Upgrade; EN, Embedded Network; ENM, Embedded network Manager; ENO, Embedded Network Operator; FiT, Feed-in Tariff; LED, Light Emitting Diode; LET, Local Energy Trading; LGA, Local Government Area; NECF, National Energy Customer Framework; NEM, National Electricity Market; NEO, National Energy Objective; NERL, National Energy Retail Law; NERR, National Energy Retail Rules; NSP, Network Service Provider; NSW, New South Wales; NT, Northern Territory; OC, Owners Corporation (or Body Corporate); PV, Photovoltaic; QLD, Queensland; SA, South Australia; SWIS, Southwest Interconnected System; TAS, Tasmania; VIC, Victoria; WA, Western Australia

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https://doi.org/10.1016/j.rser.2018.12.013
Received 15 August 2017; Received in revised form 8 December 2018; Accepted 9 December 2018

it an increasingly attractive commercial as well as environmental option for such buildings.

With at least 397 GW of PV installed globally by the end of 2017 [5], and around 40% of this being on buildings [5,6], PV deployment on residential buildings is a significant market sector and many countries are adopting policies to support increased residential rooftop PV for self-consumption [7]. Meanwhile, rapid growth in urban population [8] and changing patterns of urban development have led to increasing construction and occupation of multi-unit residential buildings in metropolitan areas. PV penetration on apartment buildings by comparison with standalone housing is extremely uneven across jurisdictions. Certainly, it is much lower in Australia, and this paper seeks first to explore the barriers to PV for such buildings. Given the large and growing market potential for PV on apartment buildings, and even issues of equitable access to the benefits of PV for apartment residents, possible opportunities to address these barriers are then considered.

By the end of 2018, Australia had over 10 GW of (predominantly crystalline Silicon) photovoltaics installed [9], ranking eighth globally, with potential to contribute 5.5% [9] to the national electricity demand. In comparison to other countries, a large proportion of this is connected to the low voltage distribution grid [10] including rooftop installations on some two million households [11], with residential PV penetration averaging 21.6% of dwellings [12] and exceeding 50% in some urban areas [13]. With rising electricity prices, and capital costs of PV continuing to fall, the market for larger PV systems on commercial buildings, including warehouses, is now growing strongly [10]. However, although it represents a valuable market opportunity for the PV industry, and - like community renewable energy (CRE) - has potential to populate the "scale gap" between utility and household renewable energy [14], deployment of PV on Australian apartments has been slow.[1] This is despite the potential economies of scale with larger PV systems and opportunities for apartment owners to aggregate their participation in the retail electricity markets. For the electricity industry, PV is likely more valuable on network feeders supplying apartments as these networks are often also supplying commercial loads which peak earlier in the day than residential loads, hence when PV is performing well in reducing network congestion. The failure of high residential penetration to transfer to multi-occupancy residential buildings despite these advantages suggests there are barriers specific to this sector.

Australia has a number of factors in common with other countries that make its experience relevant in an international context. Growth in medium and high-density housing, particularly apartments, driven by planning policies to cope with increasing urban population, is a phenomenon worldwide, including in Australia. Also, many countries have adopted governance arrangements for multi-occupancy residential buildings similar to Australia's Strata Title (Section 2.2). Finally, the Australian energy market and regulatory environment have a number of features – high levels of retail contestability, moves towards cost-reflective tariffs and declining solar Feed-in Tariffs (FiTs) – that are seen as a future direction for many jurisdictions [15].

This paper therefore reviews the Australian experience with PV on apartment buildings to explore the opportunities and barriers, and identify research priorities for facilitating this market sector, based on a review of relevant literature and legislation, and on a series of interviews with relevant stakeholders. The literature reviewed includes published accounts of apartment PV and sustainability projects and unpublished building energy audits as well as journal articles on apartment PV, energy efficiency and multi-occupancy housing. Relevant legislation pertaining to strata title, energy retailing, embedded networks and PV installation across all Australian jurisdictions is also reviewed.

Semi-structured interviews were undertaken with apartment owners and residents, consultants, engineers and other stakeholders involved with scoping or implementing PV projects on some 30 apartment buildings. The interviews were broad in scope and included discussion of physical and technical aspects of PV and apartment buildings, financial and legal restrictions on sustainability expenditure, interaction with retailers and regulatory bodies, and communication and conflict within resident communities. They were variously augmented by physical observations of the building and infrastructure and by examination of energy bills, usage data and solar potential. Some of the buildings have operational PV installations serving common property and/or apartments whilst others were prevented from installing PV by one or more of the barriers discussed below - as always, some of the most valuable lessons come from deployment failure rather than success.

This paper is part of a broader study of opportunities for PV deployment on apartment buildings, which includes detailed modelling of a range of the technical and financial arrangements for distribution of generated PV between apartments, a techno-economic assessment of the value of PV and of battery storage to different stakeholders under different regulatory and financial settings, and an analysis of the scale and distribution of the opportunity across Australia. This paper therefore focuses on the external factors that have hitherto impeded more extensive PV deployment in this sector in order to help identify possible approaches to overcoming the barriers.

The rest of the paper is structured as follows: Section 2 describes the Australian context, including the legal frameworks for apartment ownership and electricity regulation and an estimate of the scale of the potential opportunity. Different implementation arrangements are presented in Section 3, while Section 4 explores the technical, legal, regulatory and financial barriers to deployment, whether inherent to apartment buildings globally or specific to the Australian regulatory environment. Finally, Section 5 introduces new governance and business models that may help overcome these barriers, and Section 6 identifies some tentative lessons for regulatory design from the Australian experience and suggests further research that could help facilitate the deployment of PV on multi-occupancy buildings.

2. The Australian context

2.1. Apartment demographics and tenure

Australia's large landmass and historically small population led to the development of cities with relatively low population density. Indeed, ownership of a detached house on a 'quarter acre block' has been integral to the Australian Dream [16]. However, while housing density in the cities is still amongst the world's lowest, increasing population pressures in recent years have driven the development of 'compact city' planning strategies in Australia as elsewhere [17]. In 2016, 10% of the Australian population (1.2 million Australian families) lived in apartments [18] (also known as "flats" or "units"[2]) compared to 12% in the USA [19], 14% in the UK and 41% in the European Union [20]. Growth in high-density housing continues, with 33% of new dwelling building approvals in the first quarter of 2018 being apartments [21]. As the spatial distribution of the Australian population is highly uneven, 50% of all apartments are situated in just 24 of the 568 local government areas (see Fig. 1 while in some urban local government areas (notably the City of Sydney, North Sydney and City of Melbourne) over 70% of the population live in multi-unit dwellings [18].

Apartments house a relatively high proportion of overseas born Australians, young single people [22], and households with low gross income [23]. The 2012 Australian Government 'Smart Grid Smart City'

[1] Although figures for residential PV installations by type of dwelling are unavailable, the total number of Australian apartment buildings with PV installed is likely to be less than 100.

[2] "Units" and "apartments" are used interchangeably in this paper.

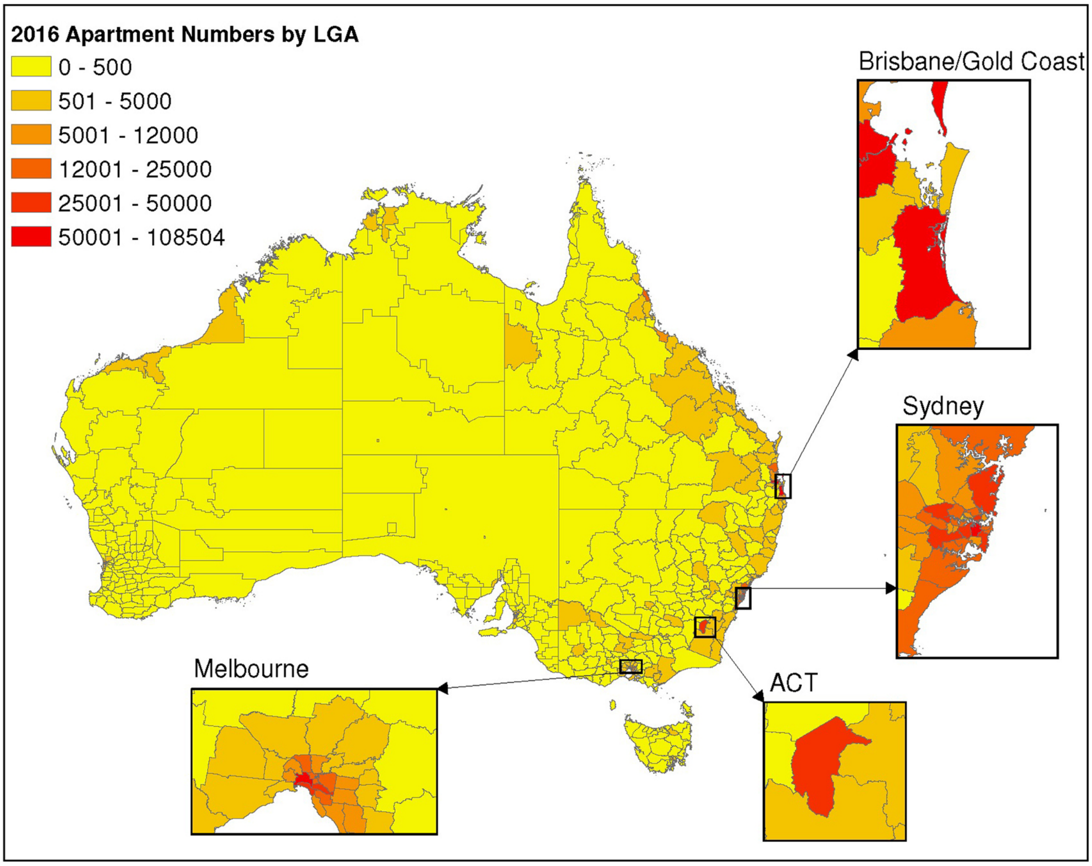

Fig. 1. Spatial distribution of Australian apartments by Local Government Area (LGA) [18].

Trial [24] included interviews of some 3500 households in six urban areas of New South Wales to assess the relationship between demographic and household factors and energy use. Of the detached and semi-detached households surveyed, 12% reported low household incomes (< $800/week), but amongst apartment households this rose to 27% [25]. A 2013 report for the Australian Renewable Energy Authority (ARENA) comparing PV uptake across all postcode areas of Australia, found that average household income in an area has a significant but modest effect on PV uptake, and identified owner occupier status as the factor with the strongest positive impact on PV uptake [26]. It is therefore significant that only 27% of apartment households own their homes (compared to 68% of house residents) [18]. Of those who rent apartments, 87% rent from private landlords or real estate agents. The situation is similar to that in the USA where 88% of dwellings in multi-occupancy buildings are rented compared to only 18% of detached houses [27], there are over 8 million condominium[3] buildings [27], and condominiums are the dominant form of new housing [28]. In contrast, although 71% of UK apartments are rented, the majority of these (59%) belong to local councils or housing associations [29].

2.2. Strata Title

The ownership of apartment buildings in Australia is largely arranged under Strata Title which combines private ownership of individual lots or units with shared ownership of the building structure, common areas, grounds and services. There are an estimated 277,000 strata and community schemes, comprising around 2 million lots across Australia [30], 80% of which are residential. The legal framework for Strata Title in New South Wales (NSW) has been used as the basis for legislation in Singapore, Canada, South Africa (*sectional title*), Indonesia, Malaysia and Brunei [30] while similar governance models for multi-title development are used in many countries including Fiji, Philippines, India, the UAE, the USA (*condominiums)* [31], New Zealand, France (*copropriété*), Germany *Wohnungseigentum*), and the United Kingdom (albeit the rarely used *commonhold* title) [32].

The terminology and legislative detail of strata law varies between Australian jurisdictions but is based on common principles [33], as described in Table 1. The shared spaces and structure of a strata building are called Common Property (CP), which is either owned collectively by the apartment owners, or by the Owners Corporation (OC)[4] (the equivalent of a Homeowners' Association in the US), which acts either as an agent or as a trustee for the owners. In practice, an elected Executive Committee (EC)[5] typically takes on much of the decision making around the upkeep, maintenance and day-to-day management of the building, with some tasks delegated to a Strata Manager – either an individual employee or an external management company. However, decisions relating to the by-laws (or "rules" or "articles") that govern the property, major alterations to common property or large financial expenditure must be taken by a quorate General Meeting or Annual General Meeting (AGM) of the Owners Corporation and may require a Special Resolution [34] supported by two thirds or three quarters of the eligible votes (see Table 1). In these processes,

[3] In the USA, a *condominium* is a building owned under strata-like title, while an *apartment* is leased from a single building owner, corporation or co-operative.

[4] "Owners Corporation" (NSW, VIC, ACT) is also called "Body Corporate" (QLD, TAS, NT), "Strata Corporation" (SA) or "Strata Company" (WA).

[5] Also called "Strata Committee" (NSW), "Management Committee" (SA, TAS), "Council" (WA) or simply "Committee" (VIC, NT).

Table 1
Comparison of strata arrangements across Australia.

	Ownership of common property	Requirement for individual development of CP	Requirement for OC development of CP	Majority needed for special resolution	Quorum/inquorate meeting	OC borrowing limit	Use of sinking fund for new infrastructure
QLD	Owners as tenants in common [51]	Exclusive Use By-law [51]	Ordinary resolution (≤$2000 per lot) or special resolution (> $2000 per lot) [52]	At least 2/3 of cast votes in favour, AND less than 25% of lots and entitlements against. [51]	25% of voters/Adjourn for 1 week. Then meeting is quorate if chair is present. [52]	$250/lot [52]	Includes "spending of a capital or non-recurrent nature" [52]
NSW	Owners as tenants in common [53]	Common Property Rights By-law [35]	Special resolution [35]	Not more than 25% of votes passed are opposed [35]	A quarter of entitled vote/Chair can adjourn for 1 week, or declare meeting quorate [35]	No restriction	Capital works fund uses includes 'other expenses of a capital nature' [35]
VIC	Owners as tenants in common [54]	Special resolution [55]	Special resolution [55]	At least 75% of total lot entitlements or 75% of total votes [55]	50% of total vote/Decisions stand unless members petition for a further meeting [55]	No limit but special resolution if above annual fees [55]	Extraordinary payments require special resolution [55]
SA	OC in trust for the owners [56]	Unanimous resolution [56]	Ordinary resolution	Not more than 25% of all possible votes against [56]	50% of units/Adjourn for 1–2 weeks, then chair can declare meeting quorate [56]	No restriction [56]	Includes "expenditure of a non-recurrent nature" [56]
WA	Owners as tenants in common [57]	Exclusive Use By-law [57]	Resolution without dissent (on limited grounds) [57]	More than 50% of proprietors and units of entitlement for, less than 25% against [57]	50% of total vote/Adjourn for 1 week, then chair can declare meeting quorate [57]	No restriction [57]	Ordinary resolution required above prescribed amount [57]
TAS	OC as trustee for owners [58]	Exclusive Use By-law, (ordinary resolution) [58]	Ordinary resolution [58]	Ordinary resolution only – simple majority [58]	Majority of members [58]		No restrictions. Ordinary resolution needed for Special Levy [58]
NT	OC as trustee for the owners [59]	Exclusive Use By-Law [59]		2/3 of votes cast in favour AND not more than 25% of all entitlements against [59]	50% of total entitlements/Decisions stand unless meeting called within 29 days [60]	Determined by OC [60]	Annual contributions can be used for "other costs reasonably incurred by the body corporate." [60]
ACT	Owners as tenants in common[a] [61]	Special Privilege (unopposed resolution) [61]	Simple majority, for sustainable infrastructure, if conditions met. [61]	Majority of participating members in favour, and less than 1/3 participating members opposed [61]	50% of unit entitlement/Decision stands after 28 days unless petitioned by majority of entitled voters [61]	No limit with special resolution [61]	Can be used for sustainable infrastructure [61]

[a] In ACT, legislation specifically allows OC to acquire sustainability assets as trustee.

apartment tenants have no voting rights (unless given a proxy vote by their landlord who actually owns the apartment), although in NSW they now have the right to attend OC meetings [35]. The effect of apartment ownership models on PV deployment will be discussed in Section 4.1.

2.3. Australian electricity regulation

In common with numerous national energy systems, restructuring of the Australian electricity sector in the 1990s transformed it from a few state-owned, vertically integrated monopoly utilities towards more market-oriented arrangements with a competitive retail market, economically regulated network monopolies, and a competitive wholesale market between large generators and retailers, although recent years have seen increasing vertical re-integration between retail and generation segments. This is overseen by a complex system of state and federal regulation. The National Electricity Market (NEM) supplies electricity to over 85% of Australians (21 million people) through an interconnected network that covers Queensland (QLD), New South Wales (NSW), Victoria (VIC), South Australia (SA), the Australian Capital Territory (ACT) and Tasmania (TAS).[6] The sale and supply of electricity in these jurisdictions is fully contestable and, except in Victoria (where the Victorian Energy Retail Code and Guidelines apply), is regulated by the National Energy Customer Framework (NECF) comprising the National Energy Retail Law (NERL) [36], National Energy Retail Regulations [37], and National Energy Retail Rules (NERR) [38], with the aim outlined in the National Energy Objective (NEO):

> *"to promote efficient investment in, and efficient operation and use of, electricity services for the long-term interests of consumers of electricity with respect to – price, quality, safety, reliability, and security of supply of electricity; and the reliability, safety and security of the national electricity system."*

While there are no explicit environmental objectives in the NEO,[7] its emphasis on the long-term interests of consumers might suggest that NEM arrangements should seek to facilitate renewable energy deployment should consumers wish it. In practice, there are concerns that the present NEO fails to appropriately support such consumers [41].

2.4. Australian electricity tariffs

Given the NEM's arrangements, a household electricity bill has separate energy and network components. The energy component is paid to the retailer and covers their purchases from the wholesale market on the household's behalf, as well as retailer business costs and margin, and retailer obligations associated with a number of environmental schemes. By comparison, network tariffs are regulated. For households, the network tariffs are bundled into a combined retail tariff with the retailer collecting and then passing on the network tariff to the local network business. Network costs typically comprise almost half of total bills. Historically, metering arrangements and objectives of universal electricity access have seen simple tariffs with a fixed ($/day) and volumetric (c/kWh) charge [42].

Like a number of other countries [43,44], Australia is moving towards the use of cost-reflective tariffs as the uptake of particularly peaky loads and distributed generation raise concerns about cross subsidies and lack of efficient price signals in network tariffs. Smart metering is now being rolled out (albeit unevenly) across the NEM State jurisdictions, and demand tariff structures are being increasingly used for small business and residential consumers as a step towards this more cost reflective pricing of the use of network infrastructure. However, application of demand charges to customers' peak demand (rather than demand at the time of network peak) means that many of these tariffs do not reflect the actual cost of network usage [45]. Early experiences with these tariff structures for small consumers in Australia indicate that they are being applied over wide time windows and along with high fixed and low volumetric charges that, in fact, act to limit consumers' ability to reduce their bills via demand side activities such as PV deployment.

Similar to those in 75 countries and 35 states, provinces and territories worldwide [46], generous (US 20c-40c/kWh) premium Feed in Tariffs (FiTs) were implemented in almost all Australian jurisdictions from 2009 to 2012 to incentivise deployment of small-scale PV. Rapid price decreases have now made PV an attractive investment without policy incentives, and the premium tariffs are closed to new customers. Unlike the incremental phase-out of this incentive that has happened in some countries, flat rate FiTs have been reduced very quickly and are now in the region of average wholesale electricity prices (US3–10c/kWh [47,48], compared to retail electricity prices around US17–26c/kWh [10]), although Victoria have introduced time of use FiTs with a peak period rate of US22c/kWh. In most jurisdictions, minimum FiTs are regulated, generally based on the wholesale value of the energy plus transmission losses, with no network or environmental value included. While Victoria's State FiT includes US1.9c/kWh for the social cost of carbon emissions, and 0.4c/kWh for avoided line losses in [47], the network value remains unpriced. Meanwhile, in other states, there is as yet no pricing of carbon, representing a market failure [49] and decreasing the attractiveness of investment in PV. As such, new residential and commercial PV is effectively net metered, with self-consumed PV generation saving consumers the equivalent retail c/kWh tariff, while exports are paid at around one quarter of this tariff. Still, rising NEM electricity prices and falling PV costs have made it an increasingly attractive commercial proposition even under these arrangements and deployment of residential PV has, indeed, now returned to levels seen under the original FiTs [50]. However, as noted earlier, nearly all of this residential deployment is on stand-alone housing.

2.5. Apartment energy and electricity loads

Electricity loads in apartment buildings are made up of individual apartment loads and common property (CP) loads. Due to the diversity of age and design of building stock and the range of climate zones across Australia, there is a high level of variability in the volume of energy consumed and the temporal profile of these loads. A large number of international studies of the factors affecting domestic energy consumption, as reviewed by Jones et al. [62], show an increase in energy consumption with the degree of detachment of the dwelling, suggesting that apartments use less energy than houses.

However, there is a limited amount of published data regarding energy loads, and some apartment building energy studies [63,64] omit CP loads and/or use typical household loads without consideration of dwelling type. In Australia, discussion of apartment energy loads draws heavily on two sources. A 2005 Energy Australia report [65] is often cited in comparisons of energy use in different types of housing as evidence that per-capita energy emissions are highest in high-rise apartment buildings and higher in mid- and low rise apartment buildings than in detached houses, although it is unclear whether these emissions calculations are based solely on total energy use or consider the energy sources utilised. Conversely, a 2010 IPART study [66] suggests that apartment loads (excluding CP) are lower than those for

[6] In Western Australia (WA), electricity is supplied through the South West interconnected System (SWIS), the North West interconnected System and over 30 smaller networks. Currently the state-owned retailer Synergy holds a regulated monopoly for customers consuming less than 50MWh per annum. The Northern Territory is in the process of adopting the NERL for the separate Interim Northern Territory Electricity Network, which serves the Darwin-Katherine region.

[7] Unlike the NEO, the Wholesale Electricity Market objectives that govern the SWIS specify the avoidance of discrimination against sustainable and renewable energy options. However, a recent comprehensive energy review [39] recommended moving to full contestability and adoption of the NERL and NERR, but the future of these reforms are now unclear [40].

detached dwellings, and this is supported by Fan et al.'s statistical analysis [67] of around 3400 NSW households from the Smart Grid Smart Cities dataset [25], which shows average daily demands of 22.3kWh for detached houses and 11.2 kWh for apartments. This result can be partially explained by the smaller average floor area and occupancy of apartments; the same dataset reveals average daily loads *per occupant* of 6.7 kWh for apartments (excluding CP) and 7.7 kWh for houses.

This apartment estimate doesn't, however, include CP demand which may include lighting for common areas, stairwells and carparks; lifts; water heating and pumping for centralised hot water and/or pools; heating, air conditioning and ventilation for common areas and sometimes for all apartments. Although CP energy demand can be relatively low in low-rise walk-up apartments, it can account for a large proportion of the total building energy usage in high and medium rise buildings [65]. A 2015 study by the authors [68] found that, in common with other residential building loads, CP demand is likely to have morning and evening peaks, but some buildings can have continuous CP loads that result in relatively flat average daily demand profiles. The same study showed that this average load often masks large spikes in instantaneous load, due to high power equipment (lifts, extraction fans, pumps) sometimes coupled with poor control strategies (e.g. faulty or incorrectly set timers).

There is much work to be done in examining the relationship between apartment building load profiles and potential drivers including building type and characteristics, household demographics and appliance use. Certainly, effective PV system design for apartment buildings requires detailed information about the building load characteristics given the far greater value of self-consumed PV generation versus that exported to the grid.

In conclusion, Australia's changing residential context includes a move towards greater apartment living, while the NEM regulatory and market arrangements have facilitated significant residential PV deployment, but almost all has been on stand-alone housing.

2.6. Apartment rooftop potential

PV deployment on building roofs and facades can be applied to the building (BAPV) or integrated into the building (BIPV). Although prototyping and testing of BIPV materials and façade deployment of PV is ongoing, its current market share is very small in Australia [10] as elsewhere [13]. This study therefore focusses on the application of BAPV to building roofs, being the most likely solution in the short-term, particularly for retrofitting to existing buildings.

Although the ABS Census collects information on the number of people living in apartments (Section 2.1), the absence of comprehensive data on the number of apartment *buildings*, as well as the diversity of the building stock, present challenges in assessing the area available for PV deployment in this sector. A detailed analysis, utilising 3D building models, constructed from photogrammetry and LiDAR surveys of Australian urban centres, combined with building census data is underway. The study combines methodologies from NREL [69] and others [70] to exclude small roof planes and areas with low insolation, and correlates the potential PV arrays with the number of dwellings in the building. Initial results for the City of Melbourne LGA suggest that, on average, 48% of roof space is usable for PV installation on low-rise (one to three storey) apartment buildings and 38% on, medium- and high-rise, compared to 35% and 40% on detached and attached houses respectively [71], although further work is required to account for obstructions and shading sources below the resolution of the 3D map used for the analysis, which will likely reduce these figures. For Melbourne, this gives an estimate of mean potential PV system size of 2.3–5.3 kWp/unit for low-rise and 1.1–1.6 kWp/unit for high-rise buildings. The total potential on City of Melbourne apartment buildings is estimated at 38–53 MWp, ten times the estimated installed capacity on all commercial, industrial and residential rooftops in the LGA [72]. Scaled by the number of dwellings in appropriate categories across Australia [18], this suggests between 2.9GWp and 4.0GWp of potential capacity on apartment buildings nationally [71].

The estimated 44–63 GWh that could be generated annually by PV deployment on apartment buildings in the City of Melbourne represents 1.0–1.5% of the estimated LGA energy demand [72]. The potential for distributed PV generation to reduce peak demand in the NEM has been shown to vary significantly between zone substations [73]. However, as outlined in Section 2.1, Australian apartment buildings are located predominantly in the major urban centres where zone substations are likely to experience significant daytime demand, so may be more likely to have favourable network impacts than PV on stand-alone dwellings. Full utilisation of the apartment PV potential across the city would also allow approximately 108,000 residents [18] access to the benefits of distributed renewable energy, and reduce annual greenhouse gas emissions by an estimated 66 kilotonnes.[8] Installation of PV on the suitable roofspace of all Australian apartment rooftops could generate an estimated 4.2–5.8 TWh[9] annually, supplying 1.6–2.2% of national energy demand and avoiding 3.2–4.4 Megatonnes of greenhouse gas emissions.

3. Possible PV implementation models

Typically, rooftop PV is deployed as multiple modules (of typical dimension approximately 1.6 m × 1.0 m and peak power capacity 250–280 W per module), rack mounted to allow for cooling air movement behind the panel. On pitched roofs, these are often mounted flush to the roof slope, while on flat roofs they may be installed orientated to north with an angle of tilt similar to the latitude inorder to maximise specific energy yield. However, in this implementation, avoidance of self-shading caused by proximate rows of tilted modules requires significant spacing between rows, and the high tilt angles can cause vulnerability to high winds. Installation with minimal (10–15°) tilt and closely packed rows reduces the energy generation of each module but increases utilisation of the roof space and may be financially preferable due to the low marginal cost of additional modules.

Where there is potential to install rooftop PV on apartment buildings, it can be used to supply CP and/or individual apartment loads, with a variety of possible implementation arrangements as shown in Table 2 and described below.

3.1. Individual PV for apartments

The only installation model that does not involve shared governance of the PV system, and so superficially the simplest arrangement, is for an owner-occupier to purchase and install a PV system 'behind the meter' (BTM) and use it to offset their own household electricity load. This is the arrangement for 2 million Australian solar households, which thus far include only a small number of apartments. Where the roof is owned by the apartment owner (as is the case for a small proportion of top-floor apartments in some low-rise buildings), this arrangement is relatively simple, but complications arise in the majority of strata-titled buildings where the roof space is part of the CP so installation of PV for a single apartment entails inequitable utilisation of a shared resource for the sole benefit of an individual household. Because of the issues this causes (Section 4.1.1), take-up of retrofitted PV for individual apartment use will likely remain infrequent and ad hoc.

However, a number of new residential developments are installing or facilitating individual BTM apartment PV systems. Examples include the Riverdale "Flo" Project, with 2 kW arrays installed for each of the

[8] Emissions reduction based on the emissions factor for Victoria of 1.08 kg CO_2-e/kWh [74] reduced by 0.045 kg CO_2-e/kWh to account for embodied emissions from manufacture, operation and decommissioning [75].

[9] Assuming the same average yield as existing PV installations [9].

Table 2
Implementation Models for PV in Apartments.

		Distribution arrangement		
		Behind the meter	**Embedded network**	**Local distribution network**
Demand Met By PV	Individual units	Individual PV for apartments **(3.1)**		
	Common property	Shared PV to supply CP **(3.2)**		
	Units and CP	Shared PV distributed behind the meter **(3.5)**	Shared PV distributed via embedded network **(3.3)**	Shared or individual PV, local energy trading **(3.4)**

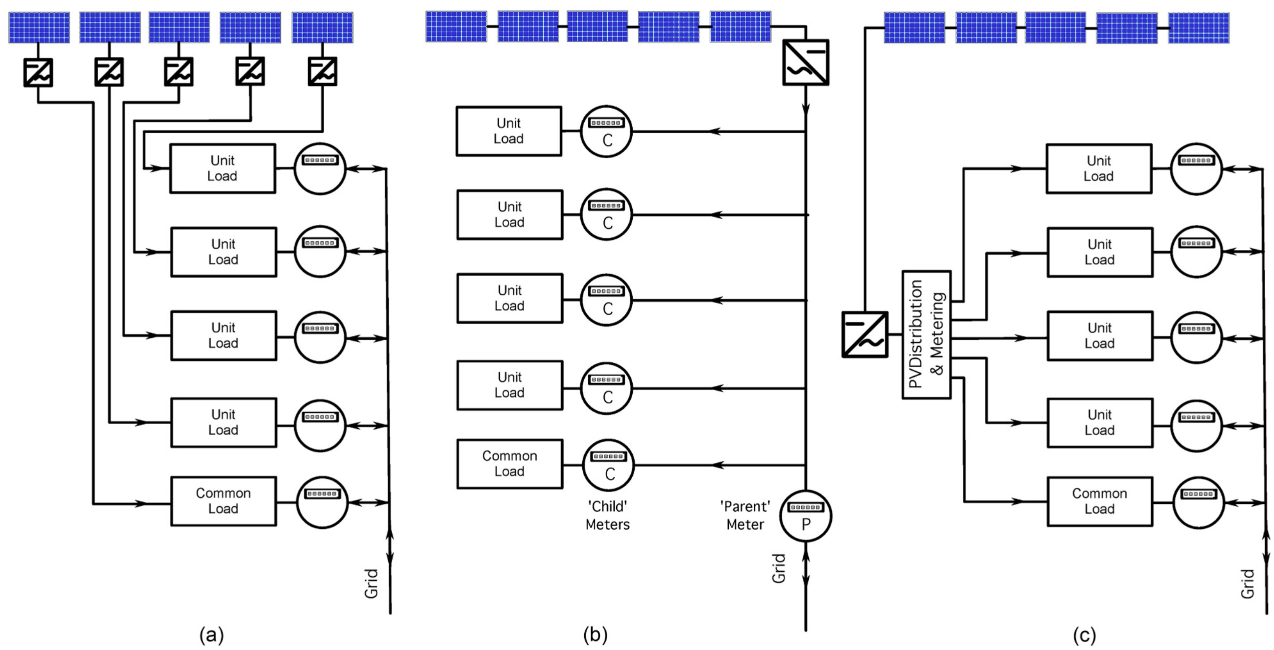

Fig. 2. PV system configurations. (a) Individual PV systems behind the meter (Sections 3.1 and 3.2). (b) embedded network (Section 3.3). (c) shared PV system behind the meter (Section 3.5).

86 apartments [76,77], and Square One Apartments [78] built with mounting rails, cabling, meters and conduit pre-installed to allow each apartment to install a 1.08 kW system with minimum cost and disruption. These arrangements overcome equity issues by apportioning use of the commonly-owned roof space equally between all owners. A similar arrangement, albeit on a smaller scale, has been retrofitted to one of the case-studies, a 5-apartment building in NSW with 20 kW shared between residents through the use of panel-mounted microinverters, effectively giving each apartment its own 4 kW system (Fig. 2(a)). However, since apartments with low daytime loads will export much of their generation to the grid, individual BTM PV for apartments may not be as commercially favourable as other possible arrangements.

3.2. Shared PV for common property

The most common electrical arrangement for PV on apartments is to use a shared generation resource on shared roof space to supply shared CP demand behind the meter. Installation is relatively straightforward as CP demand is connected via a small number of meters (often just one), with cabling through the building minimised. Because the benefit of reduced energy bills flows to the OC (and can be passed on to apartment owners as reduced strata fees), split incentive issues (Section 4.1.2) are less significant than when dealing with apartment demand.

All the successful PV projects investigated for this study had also undergone energy efficiency upgrades (EEUs) to CP facilities. These included installation of efficient devices (LED lighting, low torque lift motors, efficient extraction fans) and improving demand management through motion sensors, carbon monoxide sensors and time switches. In some cases, EC members who started to plan for a PV system realised that relatively low cost and short payback times (e.g. typical payback of 2–3 years for LED lighting upgrades compared to 8–10 years for PV) made EEUs an “easier sell” to OC members. In many cases, EEUs were used as a starter project, a first step for the OC to take on a path to sustainability and an opportunity to convince doubters with economic outcomes. Conversely, however, one strata combined EEUs and PV installation in a single project (with a payback of four years) in order to make the PV more economically attractive to the OC.

For high-rise buildings, where CP loads are likely to be sufficient to utilise the maximum possible generation from rooftop PV [68], this is often the most practical model for PV deployment unless the vertical façade can also be used for PV generation [79,80]. As discussed in the following sections, distribution of PV to apartment loads is a significantly more challenging alternative.

3.3. Shared PV distributed to apartments via embedded network

Significantly, over 60% of Australian apartment dwellers live in low-rise buildings of three storeys or less (though this proportion is decreasing) [18], where the potential rooftop generation is likely to exceed the daytime CP load [68] and so can either be exported to the grid, or used to contribute to apartment loads. A study of an Italian apartment building [81] found that applying PV to the aggregated building load was the most beneficial arrangement for householders, though it did not consider the capital costs of the PV system. Certainly, decreasing FiTs (Section 2.4) make self-consumption more attractive, and electricity can be distributed to coincident household loads through an embedded network (EN) where the network is configured with a 'parent and child' smart-metering arrangement. Here, only a single connection with the grid is established for the whole EN via the 'parent' or 'gate' meter, and individual apartments are supplied via 'child' meters (Fig. 2(b)). A shared PV system on the shared roof space can be owned and operated by the OC, the building developer or owner, or by another commercial entity or community organisation. Energy from the grid and from the PV is distributed via the EN to individual apartments (termed 'off market customers'). Although the costs of retrofitting the network can be significant and there is an administrative burden associated with retailing energy to residents (Section 4.5.2), the balancing of PV and load amongst the CP and apartments, and the removal of multiple grid connections and associated fixed network charges may generate significant cost savings for households. Only one of the projects studied had installed an embedded network, although two others were actively exploring this model.

3.4. Shared PV distributed to apartments via local energy trading

An alternative method of distributing PV energy from the roof of an apartment building to individual units is to use Local Energy Trading (LET), also known as Virtual Net Metering, a form of peer-to-peer trading. LET involves the use of the local distribution network to move energy between distributed generators and consumers by netting PV generation exported to the grid against energy imported from the grid by a participating load, on a time-of-use basis [82]. In its simplest form, the netting is only applied to the energy and retail portion of electricity bills, with the customer still paying the full network charges for all the energy consumed.

However, where the generator and consumer are geographically close, only a small part of the network is utilised, so it can be argued that the cost to the network is lower than the transmission and distribution charges included in retail bills. Arrangements in several US states allow some customers to pay a reduced network charge (or 'wheeling charge') for locally generated energy, or to avoid network charges completely [83]. Alternatively, a payment for exporting generation close to the load, known as a Local Generator Network Credit has been proposed [84].

Apartment buildings with PV present suitable participants for LET, with a large number of energy consumers in very close proximity to the rooftop generation, so using only a very small part of the low voltage network (within the building) to distribute energy. LET could be used to distribute generation from a shared PV system to multiple building occupants (one to many) – as implemented in the Netherlands [7] - or to allow energy from individual PV systems (Section 3.1) to be traded between neighbouring apartments.

The impact of Local Energy Trading in facilitating PV on apartment buildings has been demonstrated in California, where the California Solar Initiative mandated energy companies to offer LET tariffs to developers of multi-occupancy residential buildings. These were initially targeted at low-income households [85], coupled with capacity-based incentives for PV installation, which favoured the larger schemes required to supply apartments as well as CP loads, but have now been extended to all multi-occupancy buildings [86].

3.5. Shared PV distributed to apartments 'behind the meter'

An alternative to using an EN or LET for distributing PV to apartments and common property is to keep the PV system 'behind the meter' (BTM), as it is for individual apartment systems (Section 3.1). In this arrangement (Fig. 2(c)), a shared PV system is connected behind the meter of all participating apartments. Households retain access to the retail market and purchase electricity from their choice of energy retailer, but supplement this with electricity generated by a shared PV system, which is netted off their load. In the simplest technical implementation, the instantaneous PV electricity is allowed to flow in proportion to household loads, with excess generation exported to the grid via the household meters, and devices installed to prevent grid energy transferring between households when there is no PV generation. More complex arrangements could optimise PV utilisation to minimise aggregate household energy costs across the building [87].

4. Barriers to apartment PV deployment

The City of Melbourne's Higher Density Residential Efficiency Solutions (HI-RES) project [88] identified four categories of barriers to sustainable improvements in multi-unit residential buildings: governance, physical limitations of existing building stock, lack of finance and lack of knowledge. What follows is an exploration of the barriers to PV deployment on apartment buildings, drawing on the series of semi-structured interviews conducted for this study, with reference to the literature and relevant legislation, structured around the HI-RES categories with the addition of a category relating to regulatory and network issues specific to PV.

4.1. Governance Issues

4.1.1. Issues related to Strata Title

A 2012 report by the City Futures Research Centre [89] found that although 75% of NSW strata owners surveyed reported that there was some level of co-operation between owners in the management of their buildings, a minority reported issues ranging from apathy and lack of engagement to bullying, intimidation and deliberate exclusion, with decision making (particularly around major expenditure) sometimes hampered by divergent priorities (between owner-occupiers and investment owners or between different household types) and personality clashes. Certainly, our interviews revealed instances of difficulty around collective decision making in the strata context which impacted on the ability of residents and OCs to invest in PV.

An individual who wants to install PV on a strata building for their own use will need a general meeting of the OC to give them time-limited exclusive use of the common property roof space, usually through a new by-law which may require a special or unanimous resolution (see Table 1). Because there are risks that must be borne by the OC (e.g. potential damage to roof structure, disruption of common areas for cabling, etc.), this can be hard to achieve, particularly as there is no direct benefit to other owners.

Although there is a valid issue of equitable use of CP roof space, this can also be seen as an example of how the "tragedy of the anticommons" [90] prevents appropriate utilisation of CP [30,91]. In Queensland, the so-called "ban the banners" legislation [92] sought to reduce the ability of OCs to prevent sustainable improvements (including PV installation) to strata buildings by amending the Building Act [93] to prohibit obstruction of PV or solar hot water installation on the grounds of preserving the external appearance of a building. However, the revised act does still allow prohibition of PV or solar hot water installation if it "interferes with a person's use … of any part of the building" [[93], Section 246T]. Similarly, in ACT, strata rules are deemed to have no validity if their enactment would restrict sustainability infrastructure [61].

For the OC to install PV to meet common property loads or to supply all the apartments, a bylaw is generally not required, but in some jurisdictions a special resolution is needed (see Table 1) and it can be hard to secure the necessary majority vote at an AGM. A large proportion of the interviewees in this study reported lack of engagement or owner apathy as key issues and potential barriers to sustainable improvements, although one saw low AGM attendance as a positive sign (demonstrating a lack of problems). Proxy votes, held by managing agents or other owners on behalf of multiple non-resident owners, were cited by two interviewees as acting as a block to capital expenditure.

In most projects, PV (and other sustainability) retrofits were driven by a committed individual or small group, but a single individual (with either an aversion to OC expenditure or a strong anti-sustainability agenda) could also act as an effective opposition.

4.1.2. Split incentive

'Split incentive' (or 'principal-agent') issues between property owners and their tenants have been much discussed with reference to energy efficiency investments [94–97]. Owners of rental properties are less likely to invest in energy efficiency measures than owner-occupiers, as the benefits (reduced energy costs) are enjoyed by their tenants. Additionally, renters are unlikely to invest, particularly in "immobile" technologies such as PV [98], as they cannot recoup the full value of their investment if they move, even if they were permitted to install the infrastructure. A study by ACU [99] found that owners who did not live in their apartments were far less likely than owner-occupiers to support spending on sustainable retrofits, as well as being less confident about contributing to OC financial decisions. The 2012 Household Energy Consumption survey showed that only 3.9% of rental households had solar PV or hot water compared to 20.2% of owner-occupied households [23]. However, a 2015 survey of 12,200 households across 11 OECD countries [100] found that, although a large divide between owners and renters is evident in some energy efficiency technologies, the split for PV is less significant internationally (with 9.8% of owner occupiers and 7.3% of renters having access to PV systems), whether because of the relatively low penetration of PV in the countries surveyed, or unusually high renter access to the technology, is unclear. Consistent with the literature, some of the EC members interviewed for this study suggested that non-resident landlords are either less engaged or more resistant to expenditure than owner-occupiers, but one suggested that, being more commercially minded, landlords are more open to an economic argument for PV deployment to meet CP loads where the financial benefit can be demonstrated to flow to OC members.

As well as split incentives between apartment owners and tenants, strata schemes are also subject to principal-agent issues between apartment purchasers and the "original owner" of the scheme, usually a property developer [101]. The strata scheme is set up when the building is sub-divided into apartment 'lots' which are initially all owned by the developer. The developer (acting as the Owners Corporation) is therefore responsible for establishing the by-laws and the financial and management structure of the scheme, as well as for the design and construction of the building itself. Moreover, developers may commit the OC to long-term arrangements with third party strata managers and utility providers [32] or install embedded networks in new apartment buildings with embedded network operators (ENOs) appointed to operate the network and sell electricity to the residents [102]. The interests of the developer in negotiating these arrangements do not necessarily align with the interests of the subsequent apartment owners or residents.

4.1.3. Turnover

High turnover in apartment ownership, compared to standalone houses, is also an issue as property owners are less likely to install PV if they envisage selling the property in the near future [103]. The 2016 Australian Census [18] found that apartment owner-occupier households were twice as likely as owner-occupiers of other dwellings (13% compared to 6%) to have moved in the previous year, whilst almost half of them (45%) had moved in the previous 5 years, compared to only 25% for other dwellings. Coupled with high levels of investment ownership, this is likely to support a short-term approach to building improvements generally and sustainability retrofits in particular. The high mobility of tenants (30% had moved in the previous year; 71% in the previous 5 years) may also create a disincentive to long-term energy supply arrangements such as Power Purchase Agreements that might otherwise help fund PV installation to meet apartment loads.

4.2. Physical limitations of building stock

There are a number of physical barriers to retrofitting PV to apartment buildings that can apply regardless of the implementation or ownership models adopted. Shortage of total roof space relative to total energy demand is likely to be most problematic in high-rise buildings, but competition for roof space (e.g. as shared open space) can be an issue in all building types. Within the small sample of projects drawn on for this study, a wide range of roof fixtures – including solar hot water, air conditioning units, aerials, phone masts (an income stream for some OCs), housings for lift motors and safety harness fixing points - were found to reduce available space and, in some cases, create shading issues.

The fixing points for the racks used for the installation of PV on the flat roofs found commonly on apartment buildings may penetrate waterproof coatings and can make access difficult for scheduled resurfacing. Non-penetrating, ballast mounting systems are available, but their greater weight may necessitate engineering assessment and/or structural improvements, and can therefore increase capital costs. In addition, cabling may compromise fire separation barriers within the building. For large systems, an engineering assessment of the building will be required and reinforcement of the structure may be necessary. Liability for damage caused by installers was a concern for many OCs.

The height of many apartment buildings often necessitates a crane for installation and may require extra provisions to ensure safe working access, further increasing capital costs for PV.

4.3. Financial issues

4.3.1. Capital raising

Regardless of the profitability of PV investment, capital constraints can make it unfeasible to install PV. Like any major common property development, PV installation in a strata block can be funded either by using the existing sinking fund, by imposing a special levy (usually requiring a special resolution), or by borrowing. Arkcoll and Guilding [104] suggest that using a sinking fund is a preferable option in terms of greater cost efficiency, equity between past, present and future owners, minimisation of financial distress and promotion of community harmony. However, OCs may either have inadequate sinking funds or prefer to reserve them for more urgent repairs [88]. A special resolution may also be needed to allow the OC to make significant investment in the property that is outside the established maintenance plan, or to borrow money (Table 2). Because OCs do not own the CP but manage it on behalf of the owners, any borrowing by the OC is unsecured and therefore may come at a higher cost than it would for a property owner.

Environmental Upgrade Agreements - specific loans to cover capital costs of sustainability improvements to residential and commercial buildings, which are repaid via local councils as increased rates charges – are designed to reduce the cost of borrowing, and to help overcome the split-incentive issue, as the rate liability is passed on to the new owners when the property is sold. However, there are issues with the legal requirements on strata OCs that mean they may require approval by 100% of the owners (and in Victoria, 100% of tenants) [105], making Environmental Upgrade Agreements in their existing form hard to utilise for residential strata property.

Whether PV is funded from a loan, sinking fund or special levy, an economic argument is usually needed to gain OC approval for the investment. Typically, behind the meter PV installations between 5 kW and 10 kW in Australia involve payback periods of 4–8 years [106], but this can be considerably longer. Because some other sustainability retrofits have much shorter paybacks (e.g. 2–3 years for upgrading to LED lighting for one of the projects studied), PV may be seen as low priority, to be considered only after other improvements have been completed. Even then, because of the high turnover of ownership in apartments, the payback period may be too long. Altmann [107] notes that the costs of environmental improvements retrofitted to properties must be recouped within a few years to be financially viable for owners if there is a high turnover of ownership.

Recent initiatives by some Australian city councils [108,109] providing grant subsidies to OCs for installation of PV (as well as for energy assessments and other retrofitted sustainability improvements) have been instrumental in overcoming some of the barriers discussed here and assisting some of the case studies to deploy PV.

4.3.2. Tariff structures

Due to the large difference between import and export tariffs (Section 2.4), PV systems installed to meet common property loads (Section 3.2) are likely to be sized to minimise exports, often resulting in under-utilisation of the rooftop solar potential. Systems installed for individual apartments (Section 3.1) may result in high levels of grid export (from apartments with low daytime loads) and consequent low self-consumption, even where there is energy simultaneously imported from the grid to meet high daytime loads elsewhere in the building. Because retail tariffs don't properly value PV exports or include the cost of carbon emissions, the full value of PV may not accrue to either apartment owners or residents.

Further diluting any energy price signal, for many apartment buildings the CP energy demand is sufficient to trigger high-usage commercial tariff structures with a high ratio of capacity to volumetric charges. Volumetric tariffs reduced to US9c – US16c/kWh [10] with high demand charges based on evening peaks were a significant factor, for several of the projects reviewed in this study, in decisions not to deploy PV to meet common property loads. Under a demand tariff, if PV generation does not impact on peak demand, reductions in bills may be relatively modest per kW installed, with far greater uncertainty, and payback periods can be substantially longer than for residential buildings or apartments on more volumetric tariffs. Poor or non-existent management of common property load spikes [68] can also result in high demand charges which outweigh economic savings from reduced or offset volumetric charges.

Although distributed energy generation could help reduce the need for network investment by reducing peak demand, a virtual study of Local Energy Trading within the NEM [82] has shown that the lack of cost-reflectivity in network charges for local generation disincentivises deployment of distributed generation and in some circumstances creates perverse incentives to duplicate existing network infrastructure. So far, implementation of Local Energy Trading in Australia has been restricted to isolated arrangements between a single generator and a single user paying full network tariffs [83,110] A rule change request to the Australian Energy Market Commission (AEMC) to allow Local Generation Network Credits has been rejected [84] effectively limiting opportunities for LET within the NEM (or in other jurisdictions adopting the NECF) to where NSPs pay network support payments to address identified network constraints.

4.4. Knowledge issues

4.4.1. Access to information

The importance of improving knowledge quality and management in increasing PV deployment on apartment buildings has been noted elsewhere [111]. Similarly, in Australia, a Swinburne University survey [112] commissioned by the HI-RES project [88] identified a lack of information and guidance for sustainability retrofits in apartments. In response, a group of councils created the Smart Blocks website [113] which, along with non-profits such as *Green Strata* [114] and other local councils [115], provides information about PV deployment and other sustainability upgrades, as well as practical advice on negotiating the barriers. Networking initiatives such as City of Melbourne's *Hi-Life Expo* and City of Sydney's *Solar Apartments Roundtable* bring stakeholders together for information-sharing and mutual support, and go some way towards addressing the knowledge problem. However, interviewees identified specific issues related to installation expertise and discount rates, described below.

4.4.2. PV installers

The experience of some EC members suggests that many solar installers lack experience and understanding of apartment buildings and may be reluctant to engage with OCs. Reported failures include not responding to enquiries, quoting without visiting the building, reluctance or failure to quote, bad communication, and failure to deliver. For some OCs, these failures resulted in delay or cancellation of PV projects. This can be seen as an example of the so-called "energy-efficiency gap" (discussed in detail by Ameli and Brandt [116]), whereby factors including lack of information reduce the uptake of energy efficiency measures below an economically rational level.

Conversely, a number of the projects in this study had been given quotes for PV installation that appeared to overestimate potential savings (either by ignoring shading or by modelling PV generation with panel tilt or orientation angles that would be impracticable on the sites) or that excluded a range of installation costs (e.g. plant hire for roof access, moving existing roof fixings, roof x-rays or structural engineering assessment, switchboard upgrades, inverter protection or ventilation, or waterproofing roof fixing points). It is unclear whether this is due to overenthusiastic salesmanship or is an information failure (overestimation of savings or underestimation of costs) which could serve to reduce the energy-efficiency gap [117].

4.4.3. Energy costs and discount rates

Modelling the financial costs and benefits of PV deployment on a building is subject to a number of unknown variables - particularly interest rates, inflation rates and changes to energy tariffs. OCs in our interview sample had received solar proposals based on predicted energy inflation rates ranging from 1% to 6%pa. This can create great uncertainty for owners over the lifetime of the project, although the effect of this uncertainty on behaviour varies. For one of the case studies, the risk of uncertain returns meant a very high 'hurdle rate' was used in the financial forecasts. This supports the theory of Hassett and Metcalf [118] that 'rational' consumer risk aversion drives high discount rates and so slows roll out of energy-saving technologies. However, the EC in another case study cited uncertainty in energy costs (coupled to price increases in recent years) as their reason *for* investing in PV despite relatively pessimistic financial modelling.

Implicit Discount Rates have been shown to be dependent on multiple factors: preferences (including risk preferences and environmental preferences), predictably (ir)rational behaviour and external factors [119]. When calculating the economic costs and benefits of PV installation, participants in this study utilised *explicit* discount rates varying from 0% to 10%, with corresponding payback periods ranging from 6 years to 19 years. This suggests that the risk preferences of key EC members can be at least as important as economic realities in this decision-making.

4.5. Regulatory issues

In addition to the barriers that affect sustainability improvements generally, PV is also subject to some specific issues related to planning regulations, network rules and energy retail law. A recent study comparing outcomes for deployment of PV and storage in multi-occupancy residential building buildings in Austria and Germany [63] found profitability to be highly dependent on the jurisdictional regulatory environment. An exploration of the impact of the Australian regulatory environment, as outlined in Section 2, on the deployment of PV on apartment buildings follows.

4.5.1. Development consent

In Australia, residential development is controlled by local council rules which are based on state legislation. In many jurisdictions, small residential PV installations are permitted without requiring an application for development approval, provided they comply with maximum allowable protrusions from rooftops. There are greater restrictions, however, in heritage areas, for heritage listed buildings, in planned homogeneous estates, in cyclonic regions, and for larger residential systems in some jurisdictions.[10]

As zoning arrangements mean that apartment blocks tend to be clustered, solar access issues can arise, with potential shading caused by existing or future buildings. Despite some discussion around protecting rights to solar access through easements, restrictive covenants or planning law [124,125], there has been little progress in developing legal protections, and where planning rules protect solar access it is generally for amenity, not solar generation.

4.5.2. Embedded networks and retail regulation

The establishment of an embedded network in an apartment building, e.g. to share PV and/or otherwise collectively optimise energy bills, raises additional regulatory challenges. Where an embedded network is installed in an apartment building, the OC (or other organisation) acts as an Embedded Network Operator (ENO) and, within the NEM, is therefore subject to regulatory obligations, and must either register as a Network Service Provider (NSP) or be granted exemption by the Australian Energy Regulator (AER) [126]. The ENO also acts as an energy seller, purchasing electricity from the network and on-selling (along with PV generated energy) to residents (often through a Power Purchase Agreement). The ENO must therefore either be registered as an energy retailer or apply for a retail exemption under the Energy Retail Law [36]. Conditions attached to network and retail exemptions may include restrictions on recouping the capital and operating costs of the embedded network [127,128], gaining the informed consent of 100% of residents, extended periods of consultation, appointment of an Embedded Network Manager (ENM), and maintaining residents' access to a choice of alternative retailer within the National Energy Market [128].

This right of all customers to participate fully in the energy market, enshrined in the National Energy Retail Law and reinforced by the AEMC's "*Power of Choice*" review [129], has been strongly emphasised in recent rule determinations and guidelines [127,130], partly in order to enable large commercial customers within ENs, which have potentially been subject to monopoly rents extracted by ENOs, to negotiate directly with retailers. The AER considers retrofitting an EN to be a retrograde step [126,129] and sees market access as a first principal to be upheld, even for residential customers who have explicitly chosen the EN package over the market offer, for reasons which may include accessing the non-financial benefits of cheap and clean self-generated energy, community engagement and potentially a degree of energy independence, and even where EN tariffs are constrained to minimum market rates.[11] [12]

This emphasis on market access creates a significant barrier to retrofitting a residential EN. Two of our case studies rejected the option of an EN because of the difficulty of achieving NSP and retail exemptions, whilst another - a student co-operative comprising 8 apartments – required an estimated AU$130,000 of pro-bono legal work, including constructing a Power Purchase Agreement with tariffs pegged to the lowest available market offer and automatic cancellation if even a single occupant from a household wished to exercise their right of access to the retail market. Importantly, the administrative hurdle to establishing an EN looks set to increase, with a recent review of EN regulation [131] recommending discarding the exemption framework in favour of restricting EN operation to registered electricity retailers only.

In WA, in the absence of retail contestability for residential customers, the arrangements for embedded networks within the SWIS are considerably simpler: Retail exemptions are managed by the Public Utilities Office, there is no requirement for an ENM, and a price-cap is utilised to protect customers. It is unclear whether this situation will continue or if the regulations will be aligned with those for the NEM [40].

The recent AEMC review of EN regulation [131] continues to focus on individual customers' access to the retail market at the expense of co-ordinated approaches to sharing distributed resources through embedded networks. This presumption that ENs are inherently anti-competitive may do more to protect the interests of NSPs than consumers [132].

4.5.3. Network connection

Domestic PV systems are governed by Australian Standard AS4777 [133–135] which sets out standards for installation, inverter specifications and grid protection for PV systems up to 10 kVA (single phase) or 30 kVA (three phase) capacity. For larger systems, there is no national standard and network operators may impose additional protection requirements for safety reasons and to protect the network. For many apartment buildings, PV systems sized to meet building loads are likely to exceed 30 kVA, which increases the technical complexity and costs of installation (e.g. requirements for inverters above 30 kW are described in [136]). For some OCs, this acts as an effective upper limit on the size of the PV system, although the array may be oversized to maximise generation, e.g. a 40kWp array with a 30 kW inverter.

Retrofitting an embedded network involves installation of a new 'gateway' meter and NSPs may impose additional conditions to meet current network and safety standards, including requirements to upgrade switchboards or add additional doors and ventilation to meter

[10] In general, the same rules apply to apartment buildings as to individual houses, although in the ACT, PV installations on detached houses are exempt and do not require building approval, while those on other buildings do [120]. In Victoria, a planning permit is only required if the building is in a heritage zone and the PV panels will be visible from the street. In SA, rooftop PV installations either are not considered development or do not require development plan consent [121]. In WA, planning approval is generally not required, apart from in specific heritage areas or homogeneous estates. In the Northern Territory, a building permit is required in cyclonic regions only [122]. In New South Wales, installations above 10 kW but below 100 kW (which would include most apartment installations) are 'complying developments' which require council certification, while those below 10 kW are 'exempt developments' which do not [123].

[11] *Power of Choice* notwithstanding, market access is currently subject to jurisdictional restrictions. In Queensland, ACT and Tasmania, state regulation does not allow on-market customers within an embedded network, so customers opting out from an EN arrangement must have their meter connected directly to the network, bypassing the parent meter.

[12] One engineer interviewed has installed and operated over 100 ENs in Queensland apartment buildings without having to facilitate a single on-market customer, highlighting the potential economic benefits to residents of ENs. Queensland adopted the NECF from July 2015, but future arrangements for on-market customers within ENs are unclear.

rooms. As the existing household meters are the property of the local NSP, if they are suitable for EN use, the ENO must either purchase or lease them from the NSP, but some networks will not facilitate this, obliging the ENO to replace all the household meters, even in buildings where smart meters have recently been installed (at the customers' cost). It is not yet clear how contestability of metering supply (introduced from December 2017) is impacting on the transfer of meters to retrofitted ENs [137].

The expense and administrative burden of the changes discussed above can act as a disincentive to retrofitting ENs, and may serve to protect the network income of incumbent NSPs. From the perspective of the NSP, establishment of an EN will reduce revenue, as income is collected for energy delivered at one connection point under a commercial tariff, rather than multiple residential consumers under higher residential tariffs. The inclusion of distributed generation and other demand side resources can further reduce NSP revenue as energy is shared locally, rather than imported via the network connection. There is therefore little incentive for NSPs to facilitate ENs. Similar to requirements introduced to require NSPs to publish costs and times associated with processing applications for grid connection of PV systems [138], regulation could reasonably be adopted to prevent network service providers from obstructing EN retrofits through imposing unnecessary conditions.

4.5.4. *Financial rules*

Apart from the complexity of strata laws and energy regulation, another difficulty for PV on apartment buildings is the inconsistency of other regulations in their treatment of strata bodies. One example is the taxable status of OC income, which creates an additional financial obstacle to investment in PV by Owners Corporations.

Taxation ruling TR 2015/3 [139] (replacing TR IT2505 [140]) considers OCs as businesses but treats income to the OC from the use of common property as "proprietors' assessable income", meaning that it should be divided amongst the individual owners and declared (along with a share of operating expenses) on each individual's tax return. Although PV installed to meet CP loads may result in minimal daytime export and most FiTs are now reduced to a few cents per kilowatt so the taxable amounts are likely to be small, the administrative complexity can still be a disincentive for apartment owners. Furthermore, if an OC installs PV and an embedded network and so becomes an exempt seller of electricity to apartment owners and tenants, each proprietor may need to declare their share of the income and expenses relating to the energy selling.[13] This ruling is regardless of the jurisdictional strata legislation in South Australia and Northern Territory stating that CP is owned by the OC as a trustee for the proprietors, rather than the proprietors themselves (Table 2). However, in the ACT, in order to overcome this barrier, OCs have been permitted to hold "sustainability infrastructure" in trust for the proprietors [61], so that income derived from it only generates a single tax liability to the OC.

Conversely, the National Credit Code [141] considers an OC to be a consumer, rather than a business, and treats it in the same way as a natural person, so that any party supplying credit or leasing goods to an OC must be a licenced lender, governed by the code. While this does afford protection to the OC, it also restricts the ability of (for example) a Community Renewable Energy Organisation (Section 5.2) to lease a PV system to the OC in the way they would to a business.

5. Governance models

Despite the wide range of barriers to deploying PV on Australian apartment buildings, the opportunities are significant. A range of ownership and governance arrangements are possible which may help to overcome some of the key challenges.

5.1. *Strata ownership*

The obvious vehicle for investment in and management of a PV system on a strata-titled apartment building is the Owners Corporation. A new development in WA is trailing this approach, with a PV and storage system installed in a 3-apartment building owned by the strata body and managed by a strata management company [142]. The scheme benefits from the particularly regulatory environment in WA where there is currently no retail contestability for residential customers, with energy reselling regulated under housing regulation [57,143], and so avoids some of the issues outlined in Section 4.5.2 above.

5.2. *Community energy*

One alternative model is ownership through a Community Renewable Energy (CRE) organisation. In Australia, community energy is relatively new and a number of different legal and financial models are emerging [144,145]. One of the potential projects reviewed has explored the possibility of a partnership with *Pingala*, a Sydney-based CRE organisation [146], whereby the OC agrees to allow use of the roof by the CRE organisation, and enters into an agreement to buy the generated energy to meet CP load for the lifetime of the project through a Power Purchase Agreement. (An alternative model, whereby the CRE organisation would lease the PV system to the OC was rejected due to the NCC issue outlined in Section 4.5.4.) Crucially, because it would not need to commit the capital for the investment, OC agreement may be easier to secure. Capital could be raised through a share offer available to owners and tenants (and to the wider community if necessary), and repaid with a return over the life of the project. This helps to overcome the split incentive issue by allowing all building occupants to benefit from the installation if they wish. If an owner or tenant leaves the strata, they could keep their shares or sell them, so this arrangement may also help counter short-termism and make longer payback periods more acceptable.

This approach would go some way towards 'closing the loop' between community investors and energy users, which is an aspiration of CRE policy [147]. It could also bring other benefits of CRE: community engagement & motivation, local sustainability & self-reliance, energy efficiency & RE education.

Different CRE arrangements have been used successfully to deploy PV on apartment buildings in other countries. Repower London [65] installs community-owned PV on council-owned apartment buildings, selling energy to the landlord to meet common property demand and exporting excess generation.

5.3. *Commercial*

Commercial models of governance are also possible, where a third party installs PV on apartments and sells energy either to the OC to meet CP demand or (via an embedded network or LET) to residents. The commercial organisation might be the building developer, an energy retailer or a solar installer. Overseas examples include Toshiba in Germany [148] and Pietra Apartments in New York [149]. In Australia, a number of companies are involved in retrofitting and operating ENs in apartment buildings, utilising reduced network connection charges and bulk energy purchase arrangements to offer competitive tariffs for residents [150–152]. However, as margins are reduced by rising wholesale energy prices, some of these companies are raising the energy thresholds they require for retrofitting ENs to buildings. The experience of some of our interviewees suggests that financial arrangements between the EN company and strata body can be opaque, with the strata body carrying much of the risk with little of the benefit.

[13] A provisional 2017 private tax ruling in response to an application by Green Strata Network may exempt export payments from tax liability where they are used only to offset the cost of CP consumption.

A number of companies have developed products aimed at facilitating landlords in selling PV generated energy behind the meter to their tenants [153–155] but these are aimed at houses and so far fail to address issues for apartment tenants. However, one Victorian retailer [155] is trialling a BTM system (Section 3.5) designed for apartment buildings. The retailer installs a PV system (sized according to the number of apartment owners opting into the scheme) on the roof space, which is leased from the OC at no cost. Owner-occupiers and tenants buy power through a solar power purchase agreement with differential tariffs for self-consumed and exported energy. A similar arrangement, proposed in Queensland [156], involves creation of a Trust to install and operate a PV system, with energy sold to the OC to supply CP load, and excess generation 'donated' by the OC to apartment residents in return for a 'solar levy', although details of the legal framework are unclear.

5.4. Peer to peer energy trading and solar gardens

An energy trading platform that allows customers to sell excess PV generation directly to other householders through a local microgrid, using blockchain technology to provide customer security, is being trialled in a new WA development that includes apartments [157,158]. This platform could enable apartment owners to purchase solar energy from PV systems attached to neighbouring apartments, houses or other buildings (so would have benefits for multi-system buildings outlined in Section 3.1) and enable OCs to sell excess generation to apartments and other customers.

Another Australian retailer [159] has trialled a type of peer-to-peer energy trading in Victoria, that enables residential customers to purchase solar exported to the grid by their other customers, through a premium tariff that provides an augmented FiT. This type of scheme could be used by apartment residents to access solar energy, albeit without direct correspondence between the generation and the load.

Similar to the previous peer to peer example, community solar gardens are an approach to providing PV to apartment residents while avoiding the barriers to deployment of PV on apartment buildings. Residents purchase or lease a share in a community-owned solar farm, situated close to the load on the distribution network, with a proportion of the electricity generated being netted off their bill. Popular in the US, where 734 MW of PV have been installed under this arrangement [160], solar gardens are now being trialled in Australia [161–163].

However, the recent Australian Local Generation Network Credit ruling outlined in Section 4.3.2 [84] means that purchases of 'local' energy – whether from a neighbour's rooftop or a solar garden - would still be subject to the full network charges, while energy exported into the distribution network will not receive any credit for network benefits. This restricts the ability of these platforms to enable households to realise the full benefits of distributed generation in physical proximity to load.

6. Discussion and conclusions

This study has identified a significant and under-exploited opportunity for deployment of PV on apartment buildings in Australia, as elsewhere, although the physical limitations of building stock may restrict PV deployment on some existing buildings. Potential benefits include a significant contribution to electricity generation, possible deferment of network augmentation, emissions reduction and more equitable access to renewable energy. Despite barriers related to governance, finance, knowledge and regulation, implementation models exist that are technically and financially viable in the right circumstances, while information dissemination and sharing can help residents navigate the technical complexities and identify appropriate opportunities.

The dearth of publicly available data regarding energy usage in apartment buildings is currently an impediment to a complete understanding of the value of PV deployment in this sector, and therefore to decision making on the part of OCs and other third-party energy service providers. Hence, there is potentially valuable research to be done in modelling the distribution of PV generated energy to meet apartment loads using a range of tariff structures and under different financial and ownership arrangements.

Although discrepancies between different areas of regulation, tensions between government at federal, state and local levels, and legislative variations across jurisdictions have added complexity and confusion, opportunities are also present for positive regulatory innovation – as in the provisions to support OCs investing in sustainability improvements incorporated into QLD and ACT strata law. Such innovations are relevant to other jurisdictions with similar governance systems. But beyond strata law, increasing deployment of renewable energy and other sustainable technologies in this sector requires greater recognition across multiple areas of housing and energy policy of the increasing importance of multi-occupancy buildings in our cities.

Deployment of PV on apartment buildings requires a significant degree of co-ordination between residents and other players to appropriately share the costs and benefits of PV, whether behind the meter or through an embedded network. The complexity of collective decision-making within communities is inevitable, but regulatory policy should focus on avoiding additional obstacles to this co-ordinated action. Currently, Australian energy retail and embedded network regulation acts as a significant obstacle to OCs installing embedded networks to distribute PV-generated energy. Recognition of ENs as a valid energy option for communities such as apartment occupants brings into question the apparent regulatory assumption that full retail market access is always in the best interests of all consumers. Local Energy Trading could also be facilitated, either through Local Generation Network Credits, or other tariff arrangements that recognise the network benefits of distributed energy resources. Reform of the NEO to include a sustainable energy system as a regulatory objective would allow the NEM governance institutions to explicitly consider environment in rule making processes such as these.

More broadly, an energy market that is overly reliant on consumers acting as autonomous players may, paradoxically, reduce consumer choice by restricting opportunities for co-ordination of the growing range of distributed resources available to energy users. This has policy implications internationally for distributed storage and demand management as well as PV and embedded networks, with application beyond apartment buildings including micro-grids and grid-based resources.

Acknowledgements

The authors would like to thank Chris Byrne, Dr Bjorn Stürmberg, Louis Janse van Rensberg and all the study participants for the information they provided.

Funding

The preparation of this paper was supported by Energy Consumers Australia (Grant AP841), a studentship from the Co-operative Research Council for Low Carbon Living and an Australian Government Research Training Program Scholarship.

Declaration of interests

None.

References

[1] United Nations. Framework Convention on Climate Change (UN FCCC). FCCC/CP/2015/L.9/Rev.1 - Adoption of the Paris Agreement; 2015.
[2] US Energy Information Administration. International Energy Outlook. 2016.

⟨https://www.eia.gov/outlooks/aeo/data/browser/#/?Id=15-IEO2016&region=4-0&cases=Reference&start=2010&end=2040&f=A&linechart=Reference-d021916a.2-15-IEO2016.4-0~~~~~~~~~Reference-d021916a.34-15-IEO2016.4-0~Reference-d021916a.35-15-IEO2016.4-0~Reference-d021916a.36-15-IEO2016.4-0~Reference-d021916a.37-15-IEO2016.4-0~Reference-d021916a.38-15-IEO2016.4-0~Reference-d021916a.39-15-IEO2016.4-0~Reference-d021916a.40-15-IEO2016.4-0~Reference-d021916a.41-15-IEO2016.4-0&map=&sourcekey=0⟩ [Accessed 18 November 2018].
[3] IEA. Key World Energy Statistics. International Energy Agency; 2017.
[4] IEA. World Energy Outlook. International Energy Agency; 2016.
[5] International Energy Authority. IEA-PVPS A Snapshot of Global Photovoltaic Markets 1992–2017; 2017.
[6] IEA-PVPS. Trends in photovoltaic applications. International Energy Authority; 2016.
[7] IEA-PVPS. Review and analysis of PV self-consumption policies. International Energy Authority; 2016.
[8] World Bank. World Bank - Urban Population. ⟨http://data.worldbank.org/indicator/SP.URB.TOTL?Start=1968&end=2015&view=chart⟩ [Accessed 15 May 2017].
[9] APVI. Press Release; 2018.
[10] Johnston W, Egan R. APVI National Survey Report of PV Power Applications in Australia 2016. Australian PV Institute; 2017.
[11] Clean Energy Regulator. Postcode data for small-scale installations; 2018. ⟨http://www.cleanenergyregulator.gov.au/RET/Forms-and-resources/Postcode-data-for-small-scale-installations⟩ [Accessed 7 December 2018].
[12] Roberts MB, Copper J, Bruce A, Barton T, Haghdadi N, Hu R. APVI/Solar Citizens Solar Trends Report; 2018.
[13] International. Energy Agency. IEA-PVPS Annual Report 2017. (IEA); 2018.
[14] C4CE. National Community Energy Strategy. Coalition for Community Energy; 2015.
[15] Pérez-Arriaga IJ, Knittel C, Miller R, Tabors R. Utility of the future: an MIT Energy Initiative response to an industry in transition. MIT Energy Initiative, Massachusetts Institute of Technology; 2016.
[16] Kellett J. The Australian quarter acre block: the death of a dream? TPR: Town Plan Rev 2011;82:263–84.
[17] Bunker R. How is the compact city faring in Australia? Plan Pract Res 2014;29:449–60.
[18] ABS. Census of Population and Housing. Australian Bureau of Statistics; 2016.
[19] US Census Bureau. American community survey, 1-year estimates; 2014. ⟨http://www.nmhc.org/Content.aspx?Id=4708#Res_Demo⟩ [Accessed 17 May 2017].
[20] European Commission. Distribution of population by degree of urbanisation, dwelling type and income group - EU-SILC survey; 2011. ⟨http://ec.europa.eu/eurostat/web/income-and-living-conditions/data/database⟩ [Accessed 13 October 2016].
[21] ABS. Building approvals March 2018. Australian Bureau of Statistics; 2018.
[22] Randolph B, Easthope H. 'Governing the compact city': the governance of strata title developments in Sydney. In: Proceedings of the international conference of sustainable urban areas. Rotterdam; 2007.
[23] ABS. Household energy consumption. Australian Bureau of Statistics; 2012.
[24] AusGrid. ARUP, Energeia, Frontier Economics, Institute for Sustainable Futures, University of Technology Sydney. Smart Grid, Smart City: Shaping Australia's Energy Future - Executive Report; 2014.
[25] Department of Industry. Innovation and Science. Smart grid, smart city - customer trial data; 2015. ⟨https://data.gov.au/dataset/smart-grid-smart-city-customer-trial-data⟩ [Accessed 10/2016].
[26] Acil Allen Consulting. Drivers of domestic PV uptake - Characteristics of households with solar photovoltaic systems; 2013.
[27] United States Census Bureau. American Housing Survey for the United States - National Summary Tables; 2013.
[28] Dredge D, Coiacetto E. Strata title: towards a research agenda for informed planning practice. Plan Pract Res 2011;26:417–33.
[29] Office for National Statistics. General lifestyle survey overview: Chapter 4 - Housing and consumer durables; 2011.
[30] Easthope H, Randolph B. Governing the compact city: the challenges of apartment living in Sydney. Aust Hous Stud 2009;24:243–59.
[31] Rosenberry K. The application of the federal and state constitutions to condominiums, cooperatives and planned developments. Real Prop Probate Trust J 1984;19:1–31.
[32] Easthope H, Warnken J, Sherry C, Coiacetto E, Dredge D, Guilding C, et al. How property title impacts urban consolidation: a life cycle examination of multi-title developments. Urban Policy Res 2014;32:289–304.
[33] Sherry C. The New South Wales strata and community titles acts. Int J Law Built Environ 2009;1:130–42.
[34] Sherry C. The legal fundamentals of high rise buildings and master planned estates. Aust Prop Law J 2008;16:1–23.
[35] Government of New South Wales. Strata Schemes Management Bill 2015; 2015.
[36] National Energy Retail Law (South Australia) Act. 2011.
[37] National Energy Retail Regulations. 2012.
[38] National Energy Retail Rules Version 1. 2012.
[39] Government of Western Australia. Information paper: Transitioning to the National Electricity Regulatory Framework. Department of Finance, Public Utilities Office; 2016.
[40] Gifford J. Full retail contestability plans for WA on hold (PV Magazine Australia); 2018. [Accessed 21 May 2018].
[41] MacGill I, Healy Stephen. Chapter 20 - Is Electricity Industry Reform the Right Answer to the Wrong Question? Lessons from Australian Restructuring and Climate Policy. In: Sioshansi Fereidoon P, editor. Evolution of Global Electricity Markets Academic Press; 2013. p. 615–44. https://doi.org/10.1016/B978-0-12-397891-2.00020-1.
[42] Australian Energy Market Commission. Residential Electricity Price Trends Report; 2015.
[43] MacGill I, Smith R. Consumers or prosumers, customers or competitors? - Some Australian perspectives on possible energy users of the future. Econ Energy Environ Policy 2017:6.
[44] Pérez-Arriaga IJ, Jenkins JD, Batlle C. A regulatory framework for an evolving electricity sector: highlights of the MIT Utility of the Future study. Econ Energy Environ Policy 2017:6.
[45] Australian Photovoltaic Institute. APVI submission to Ergon Energy's consultation paper: The case for demand-based tariffs; 2015.
[46] REN21. Renewables Global Status Report. Renewable Energy Policy Network for the 21st Century; 2016.
[47] Essential Services Commission. Minimum Electricity Feed in Tariffs to Apply From 1 July 2018 Final Decision 27 February; 2018.
[48] IPART. Solar feed-in-tariffs: The value of electricity from small-scale solar panels in 2018-19. Draft report. NSW Independent Pricing and regulatory Tribunal; 2018.
[49] Gillingham K, Newell RG, Palmer K. Energy efficiency economics and policy. National Bureau of Economic Research; 2009.
[50] Edis T. Rooftop solar enjoys second boom as fossil fuel scare campaign. Renew Economy; 2017. ⟨http://reneweconomy.com.au/rooftop-solar-enjoys-second-boom-as-fossil-fuel-scare-campaign-backfires-97399/⟩ [Accessed 12 April 2018].
[51] Queensland Government. Body Corporate and Community Management Act; 1997.
[52] Queensland Government. Body Corporate and Community Management (Accommodation Module) Regulation; 2008.
[53] Government of New South Wales. Strata Schemes Development Act; 2015.
[54] Victorian Government. Subdivision Act 1988; 2008.
[55] Victorian Government. Owners Corporations Act; 2006.
[56] Government of South Australia. Strata Titles Act; 1988.
[57] Government of Western Australia. Strata Titles Act; 1985.
[58] Government of Tasmania. Strata Titles Act; 1988.
[59] Northern Territory of Australia. Unit Title Schemes Act; 2009.
[60] Northern Territory of Australia. Unit Title Schemes (Management Modules) Regulations; 2009.
[61] Australian Capital Territory. Unit Titles (Management) Act; 2011.
[62] Jones RV, Fuertes A, Lomas KJ. The socio-economic, dwelling and appliance related factors affecting electricity consumption in domestic buildings. Renew Sustain Energy Rev 2015;43:901–17.
[63] Fina B, Fleischhacker A, Auer H, Lettner G. Economic assessment and business models of rooftop photovoltaic systems in multiapartment buildings: case studies for Austria and Germany. J Renew Energy 2018;2018:1–16.
[64] Musolino V, Alet P, Regamey Y, Hutter A, Perret-Aebi L, Ballif C. Multi-occupancy buildings as micro-grids: an asset for integrating photovoltaics in power systems. In: Proceedings of the renewable power generation Conference; 2014.
[65] Myors P, O'Leary R, Helstroom R. Multi unit residential buildings energy and peak demand study. Energy Australia/NSW Dept of Infrastructure, Planning & Natural Resources; 2005.
[66] IPART. Residential energy and water use in Sydney, the Blue Mountains and Illawarra: Results from the 2010 household survey. Independent Pricing and Regulatory Tribunal; 2010.
[67] Fan H, MacGill IF, Sproul AB. Statistical analysis of driving factors of residential energy demand in the greater Sydney region, Australia. Energy Build 2015;105:9–25.
[68] Roberts MB, Huxham G, Bruce A, MacGill I. Using PV to help meet common property energy demand in residential apartment buildings. Australian Summer Study in Energy Productivity. Sydney; 2016.
[69] Gagnon P, Margolis R, Melius J, Phillips C, Elmore R. Rooftop Solar Photovoltaic Technical Potential in the United States: A Detailed Assessment. (NREL); 2016.
[70] Copper JK, Sproul AB, Bruce AG. A method to calculate array spacing and potential system size of photovoltaic arrays in the urban environment using vector analysis. Appl Energy 2016:161.
[71] Roberts M, Copper J, Bruce A. An analysis of Australian rooftop solar potential on residential buildings. In: Proceedings of the Asia Pacific Solar Research Conference. Sydney; 2018.
[72] Copper J, Roberts M, Bruce A. Spatial Analysis of Solar Potential in Melbourne. (APVI); 2017.
[73] Haghdadi N, Bruce A, MacGill I, Passey R. Impact of distributed photovoltaic systems on zone substation peak demand. IEEE Trans Sustain Energy 2017:1.
[74] Department of Environment and Energy. National Greenhouse Accounts Factors July. 2017. Commonwealth of Australia; 2017.
[75] Hsu DD, O'Donoughue P, Fthenakis V, Heath GA, Kim HC, Sawyer P, et al. Life cycle greenhouse gas emissions of crystalline silicon photovoltaic electricity generation. J Ind Ecol 2012;16:S122–35.
[76] Psaros. Flo Apartments. 2014. ⟨http://www.psaros.com.au/project/flo-by-psaros/⟩ [Accessed 19 October 2015].
[77] Vorrath S. WA residential complex installs 2 kW of solar for each apartment. Renew Economy; 2015. ⟨http://reneweconomy.com.au/wa-residential-complex-installs-2kw-of-solar-for-each-apartment-24669/⟩ [Accessed 18 May 2017].
[78] Colgan Industries. Square One Apartments. 2015. ⟨http://www.squareoneliving.com/sustain.htm⟩ [Accessed 11 October 2015].
[79] Annonymous. Australia's first off-the-grid solar-powered high-rise planned in Melbourne. Architecture and Design; 2016. ⟨http://www.architectureanddesign.com.au/news/off-grid-building-gets-a-boost-with-new-solar-powe⟩ [Accessed 18 May 2017].

[80] Jewell C. We can get net zero high-rise resi – with the right support. The Fifth Estate; 2016. ⟨http://www.thefifthestate.com.au/innovation/building-construction/we-can-get-net-zero-high-rise-resi-with-the-right-support/83908⟩ [Accessed 4 August 2017].

[81] Sajjad IA, Manganelli M, Martirano L, Roberto Napoli, Chicco G, Parise G. Net metering benefits for residential buildings: a case study in Italy. In: Proceedings of the IEEE 15th international conference on environment and electrical engineering (EEEIC); 2015.

[82] Rutovitz J, Langham E, Teske S, Atherton A, McIntosh L. Virtual trials of local network charges and local electricity trading: summary report. Institute for Sustainable Futures, UTS; 2016.

[83] Langham E, Cooper C, Ison N. Virtual Net Metering in Australia: opportunities and barriers. (Report prepared for Total Environment Centre); 2013.

[84] Australian Energy Market Commission. Draft Rule Determination: National Electricity Amendment (Local Generation Network Credits Rule); 2016.

[85] CSI/CCSE. Multifamily Affordable Solar Housing (MASH) Progress Report; February 2011.

[86] Bichkoff L, Curran E, Loewen J, O'Rourke S, Seybert E, Kamins S. California solar initiative annual program assessment. CPUC; 2015.

[87] Roache-Wilson H, Hale M, Sheldon F, Hagger I. CSIRO Solar Hackathon - AirPV; 2016. ⟨http://devpost.com/software/airpv-vatkdx⟩ [Accessed 13 August 2017].

[88] City of Melbourne. Delivering sustainable solutions for apartments: final report for the higher density residential efficiency solutions (Hi-RES) project. City of Melbourne; 2012.

[89] Easthope H, Randolph B, Judd S. Governing the compact city: the role and effectiveness of strata management. Sydney: City Futures Research Centre; 2012.

[90] Heller MA. The tragedy of the anticommons: property in the transition from Marx to markets. Harv Law Rev 1998;111:621–88.

[91] Hastings EM, Wong SK, Walters M. Governance in a co-ownership environment: the management of multiple-ownership property in Hong Kong. Prop Manag 2006;24:293–308.

[92] Queensland Government. Queensland Building and Other Legislation Amendment Bill 2009; 2009.

[93] Queensland Government. Queensland Building Act 1975; 1975.

[94] Schleich J, Gruber E. Beyond case studies: barriers to energy efficiency in commerce and the services sector. Energy Econ 2008;30:449–64.

[95] Brechling V, Smith S. Household efficiency in the UK. Fisc Stud 1994;15:44.

[96] Jaffe AB, Stavins RN. The energy efficiency gap - what does it mean? Energy Policy 1994;22:804–10.

[97] Gillingham K, Harding M, Rapson D. Split incentives in residential energy consumption. Energy J 2012;33:37–62.

[98] Ameli N, Brandt N. Determinants of households' investment in energy efficiency and renewables: evidence from the OECD survey on household environmental behaviour and attitudes. Environ Res Lett 2015;10:044015.

[99] Rex J, Leshinsky R. Sustainable retrofits of apartment buildings: developing a process to address the barriers to adoption. In: Campbell C, Ma JJ, editors. Looking forward, looking back: Drawing on the past to shape the future of marketing: Proceedings of the 2013 World Marketing Congress. Cham: Springer International Publishing; 2016. p. 284–91.

[100] Krishnamurthy CKB, Kriström B. How large is the owner-renter divide in energy efficient technology? Evidence from an OECD cross-section. Energy J 2015;36:1.

[101] Easthope H, Randolph B. Principal-agent problems in multi-unit developments: the impact of developer actions on the on-going management of strata titled properties. Environ Plan A 2016;48:1829–47.

[102] Victoria State Government. General Exemption Order - Draft Position Paper; 2016.

[103] Ma C, Polyakov M, Pandit R. Capitalisation of residential solar photovoltaic systems in Western Australia. Aust J Agric Resour Econ 2015;60:366–85.

[104] Arkcoll K, Guilding C, Lamminamki D, McManus L, Warnken J. Funding common property expenditure in multi-owned housing schemes. Prop Manag 2013;31:282–96.

[105] Everett S, Bateman B. Innovative funding for sustainable retrofitting. Carbon Insights; 2010. ⟨http://bit.ly/1LnHXZQ⟩ [Accessed 1 October 2015].

[106] Martin J. 5kW solar power systems: price, power output, and returns; 2017. ⟨https://www.solarchoice.net.au/blog/5kw-solar-system-price-output-return/⟩ [Accessed 19 May 2017].

[107] Altmann E. Apartments, Co-ownership and sustainability: implementation barriers for retrofitting the built environment. J Environ Policy Plan 2013;16:437–57.

[108] City of Melbourne. Smart Blocks Rebates; 2015.

[109] City of Sydney. Environmental Grants; 2015. ⟨http://bit.ly/1Kji2pd⟩ [accessed 18 May 2017].

[110] UTS. UTS takes the lead in customer-led renewables; 2015. ⟨http://newsroom.uts.edu.au/news/2015/09/uts-takes-lead-customer-led-renewables⟩ [Accessed 6 October 2016].

[111] Muyingo H. Organizational challenges in the adoption of building applied photovoltaics in the Swedish tenant-owner housing sector. Sustainability 2015;7:3637–64.

[112] Rex DJ, Leshinsky DR. Understanding the knowledge and information requirements for sustainable retrofits: a two stage study of apartment owners in Melbourne, Australia. Swinburne University of Technology; 2012.

[113] Smart Blocks. Smart Blocks. ⟨http://smartblocks.com.au⟩ [Accessed 18 May 2017].

[114] Green Strata. Solar Photovoltaic (PV) Energy Production, ⟨http://greenstrata.com.au/topic/solar-photovoltaic-energy-production⟩ [Accessed 19 May 2017].

[115] Randwick Waverley and Woollahra Councils, Green Strata. Go Solar; 2010. ⟨http://reduceyourfootprint.com.au/media/uploads/projects/attachments/Go_Solar_Apartments_SP_FAQ_28_Oct_2010-0.pdf⟩ [Accessed 22 May 2018].

[116] Ameli N, Brandt N. What impedes household investment in energy efficiency and renewable energy? OECD economics department working paper; 2015.

[117] Nadel SM, Keating KM. Engineering estimates vs. impact evaluation results: how do they compare and why? American Council for an Energy-Efficient Economy; 1991.

[118] Hassett KA, Metcalf GE. Energy conservation investment: do consumers discount the future correctly? Energy Policy 1993;21:710–6.

[119] Schleich J, Gassmann X. CorinneFaure, ThomasMeissner. Making the implicit explicit: a look inside the implicit discount rate. Energy Policy 2016;97:321–31.

[120] Australian Capital Territory. Planning and Development Regulation. 2008.

[121] South Australia. Development Regulations. 2008.

[122] Northern Territory Government. Building note 83: solar photovoltaic installations non-cyclonic regions; 2011.

[123] Government of New South Wales. State Environmental Planning Policy Infrastructure; 2007.

[124] Bradbrook AJ. The legal right to solar access. Environ Des Guide 2011:68.

[125] Bradbrook AJ. Solar access law: 30 years on. Environ Plan Law J 2010;27:5–22.

[126] AER. AER Electricity NSP Registration Exemption Guideline - Version 5 - 1 December 2016. Australian Energy Regulator; 2016.

[127] AEMC. National Electricity Amendment (Embedded Networks) Rule 2015 - Final Determination No. 15; 2015.

[128] AEMC. National Electricity Amendment (Embedded Networks) Rule 2015 No. 15. Commission AEM; 2015.

[129] AER. Notice of Final Instrument - Revised AER Retail Exempt Selling Guideline - March 2016. Australian Energy Regulator; 2016.

[130] Australian Energy Market Commission. Power of Choice review - giving consumers options in the way they use electricity; 2012.

[131] AEMC. Review of regulatory arrangements for embedded networks - final report. Australian Energy Market Commission; 2017.

[132] Roberts MB, Passey R, Bruce A, MAcGill I. APVI/CEEM Submission to AEMC draft report on embedded networks; 2017.

[133] AS 4777. 2 Grid connection of energy systems via inverters. Standards Australia; 2015.

[134] AS 4777. 3 Grid connection of energy systems via inverters. Standards Australia; 2005.

[135] AS 4777. 1 Grid connection of energy systems via inverters. Standards Australia; 2005.

[136] Ausgrid. NS 194 protection requirements of embedded generators > 30 kW; 2013.

[137] AEMC. Final rule determination. Expanding competition in metering and related services. Commission AEM; 2015.

[138] AEMC. Final rule determination: National Electricity Amendment (Connecting Embedded Generators) Rule 2014. Commission AEM; 2014.

[139] Australian Tax Office. TR 2015/3: Income tax: matters relating to strata title bodies constituted under strata title legislation; 2015.

[140] Australian Tax Office. Taxation Ruling No. IT 2505.

[141] Australian Government. National credit code. Schedule to National Consumer Credit Protection Act; 2009.

[142] Green J, Newman P. Planning and governance for decentralised energy assets in medium-density housing: the WGV gen Y case study. Urban Policy Res 2017:1–14.

[143] Government of Western Australia. Residential Tenancies Act; 1987.

[144] Mey F, Hicks J. Community renewable energy in Australia: Exploring its character & emergence in the context of climate change action. In: Proceedings of the 5th EMES international research conference on social enterprise. Helsinki; 2015.

[145] Coalition for Community Energy. National Community Energy Strategy - Appendix E: Behind the Meter Community Solar Models; 2015.

[146] Pingala Community Renewables for Sydney Inc Pingala; 2017. ⟨http://pingala.org.au/⟩ [Accessed 19 May 2017].

[147] Ison N, Byrne M, Gilding j, Hicks J, Memery C. Community energy advocacy strategy - final. (C4CE); 2014.

[148] Meza E. Toshiba to install and operate PV systems on German apartment buildings (PV Magazine); 2013. ⟨http://bit.ly/1MGjvHk⟩ [Accessed 16 October 2015].

[149] Mark-Taylor Residential. Powering up at Pietra Apartments (PR Newswire); 2011. ⟨http://prn.to/1MGjbsb⟩ [Accessed 18 May 2017].

[150] Navari. Navari. ⟨http://navari.com.au/⟩ [Accessed 18 May 2017].

[151] Befficient by GSI Pty Ltd. Benergy; 2015. ⟨http://www.benergy.com.au/⟩ [Accessed 19 October 2016].

[152] ERC. Energy Resources Corporation. ⟨http://www.energyresourcescorporation.com.au/body-corporate.html⟩ [Accessed 18 May 2017].

[153] SunTenants. *We make solar work for rentals. Fair and simple*; 2018. https://www.suntenants.com/ [accessed: 14 December 2018].

[154] Green Initiatives Group Pty Ltd. Solar Investor; 2016. ⟨http://solarinvestor.com.au/⟩ [Accessed 17 May 2017].

[155] Allume. Allume Energy; 2016. ⟨http://www.allumeenergy.com.au/⟩ [accessed 17 October 2016].

[156] Prideaux A. Digital solar and strata: a feasibility analysis for South East Queensland. University of Queenland, Wattblock; 2017.

[157] Jewell C. Power Ledger sticks it to low solar feed-in tariffs; 2016. ⟨http://www.thefifthestate.com.au/energy-lead/power-ledger-sticks-it-to-low-solar-feed-in-

tariffs/84075〉 [Accessed 6 October 2016].
[158] Western Power. White Gum Valley energy sharing trial; 2018. https://westernpower.com.au/energy-solutions/projects-and-trials/white-gum-valley-energy-sharing/ [Accessed 21 May 2018].
[159] Powershop. Your Neighbourhood Solar, 2016. 〈https://blog.powershop.com.au/your-neighbourhood-solar/〉 [Accessed 18 May 2017].
[160] SEPA. Community solar program design models. Smart Electric Power Alliance; 2018.
[161] Ison N. Renewables for All: Briefing paper Solar Gardens. Community Power Agency; 2018.
[162] ARENA. Solar gardens to bring rooftop solar to all Australians; 2018. 〈https://arena.gov.au/news/solar-gardens-bring-rooftop-solar-australians/〉 [Accessed 22 May 2018].
[163] Solar Share. Share in Canberra's sustainable future; 2018. 〈https://solarshare.com.au/〉 [Accessed 22 May 2018].