Downscaling – Buildings, rooftop photovoltaics and batteries

19 April 2023

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ISBN 978 0 7340 5704 4

Vecchi, A, Davis, D, Brear, M 2023, ‘Downscaling – Buildings, rooftop photovoltaics and batteries’, *Net Zero Australia*, ISBN 978 0 7340 5704 4, <https://www.netzeroaustralia.net.au/>.

The Net Zero Australia (NZAu) project is a collaborative partnership between the University of Melbourne, The University of Queensland, Princeton University and management consultancy Nous Group. The study examines pathways and detailed infrastructure requirements by which Australia can transition to net zero emissions, and be a major exporter of low emission energy and products.

Net Zero Australia

Downscaling – Buildings, rooftop photovoltaics and batteries

Scenarios considered: E+ and E−

19 April 2023

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Contents

1 Context and scope **1**

1.1 Introduction 1

1.2 Scope of this document 1

2 Background **2**

2.1 Residential and commercial buildings 2

2.2 Rooftop PV 2

3 Outputs of EP and RIO to be downscaled **3**

4 Downscaling task **5**

4.1 Assessment of building energy demand and technology switching 5

4.2 Estimation of rooftop PV surface and capacity 6

4.3 Assignment of behind-the-meter Li-ion batteries to each SA2 region 7

5 Results **8**

5.1 Residential sector energy demand 8

5.2 Commercial sector energy demand 12

5.3 Uptake of rooftop PV and behind-the-meter Li-ion batteries 13

Appendices **19**

Appendix A ..... **Error! Bookmark not defined.**

Appendix B: Validation of the procedure for PV capacity assignment 21

References **22**

1 Context and scope

1.1 Introduction

In 2020, Australian buildings accounted for 18% (754 PJ) of domestic final energy demand and 27% (1426 PJ) of domestic primary energy supply, according to the modelling by the *Net Zero Australia* (NZAu) Project based on the Australian Energy Statistics [1]. In the same year, the final consumption of energy in buildings accounted for direct and supply chain greenhouse gas (GHG) emissions of 115 Mt-CO_2e, i.e. 18.3% of overall domestic emissions. The contribution of residential dwellings and commercial buildings to these emissions and energy demand was approximately equal.

The uptake of demand-side measures, such as fuel switching and energy efficiency improvements is recognised as significant opportunities to reduce GHG emissions from buildings [2]. In addition, the uptake of distributed energy resources, such as rooftop photovoltaics (PV) is progressing at pace and having a significant impact on electricity networks. Small-scale PV installations represent, in aggregate, the largest capacity of renewable generation in Australia, with 3.3 GW installed in 2021, bringing the total installed capacity to 16 GW [3]. Currently, more than 1 in 3 Australian households have rooftop PV installations, and AEMO projects that this will rise to 65% by 2050 [4]. Alongside rooftop PV, small-scale batteries continue to grow steadily in residential and commercial buildings, with a total capacity of about 350 MWh installed by the end of 2021 [3].

This document describes in detail how the net-zero transition unfolds in the Scenarios modelled by the *Net Zero Australia* (NZAu) Project. It looks at which building technologies and appliances will be deployed over time and across different Australian regions, including the siting of rooftop PV and domestic Li-ion batteries.

1.2 Scope of this document

This document describes the background, methodology and outcomes of downscaling the NZAu Project's modelling results concerning buildings. More specifically, this document provides:

- an assessment of the evolution of energy-service demand over time and the associated final energy demand for the residential and commercial buildings sectors;
- a regional breakdown of demand-side appliances for selected residential applications, including space heating and air conditioning, which together represent about 50% of the building final energy demand in 2020; and
- an assessment of rooftop PV and Li-ion battery deployment in individual regions.

In discussing the above, it is worth pointing out the difference between *service* and *energy* demand. The *service demand* refers to the task requested by the user, e.g. the number of washing machine cycles, refrigeration of a given volume or the lighting of a room. *Energy demand* is the energy used to fulfil such a service. Thus, depending on the specific technology chosen, the same service demand may result in different energy demands.

2 Background

2.1 Residential and commercial buildings

Buildings in the NZAu modelling comprise two classes: residential dwellings and commercial facilities. These are both treated as a demand-side sector, where the energy-service demand for each class is projected over the modelling horizon based on historical data, and then the EnergyPATHWAYS (EP) model [5] determines a set of technologies to fulfil such demand.

As detailed in the NZAu Methods, Assumptions, Scenarios & Sensitivities (MASS) document [6], the buildings demand-side transition in EP is represented by tracking:

1. the evolution of energy-service demand with selected drivers, e.g. population, number of households, heating and cooling degree days, etc;
2. the energy efficiency increase for the considered appliances (e.g. 1% yearly improvement for IT & home entertainment, pools, other appliances);
3. the demand-side technology stock evolution; and
4. fuel switching measures with, for instance, all gas and diesel use in commercial buildings switched to electricity by 2045 in the E+ scenario.

More information on how individual end-use subsectors are handled by EP can be found in the MASS document [6].

As an input to EP, the national residential building service demand from the 2015 Residential Energy Baseline Study [2] was disaggregated and assigned to the NZAu 15 domestic regions based on the number of households in each region and the projected heating and cooling degree day drivers. Data from the Residential Energy Baseline Study was decomposed into hourly service demand for 2020 across 15 residential end-use subsectors, which are reported in Table 1, along with the associated energy-service representation for demand projections. For commercial buildings, data from the 2020 Australian Energy Statistics [1] reporting energy use by state and energy vector were used and projected into the future using assumptions of energy efficiency and fuel switching (see Table 1 and/or the MASS document [6]).

2.2 Rooftop PV

The effect of rooftop PV installation and the associated electricity generation was considered as an exogenous input to the Regional Investment and Operations (RIO) optimisation platform [5]. The number of small-scale PV installations by postcode in 2020 was retrieved from the Clean Energy Regulator database [7] and aggregated into NZAu regions. Then, assumptions on state−wise rooftop PV uptake over time were retrieved by averaging the projections from CSIRO and Green Energy Markets, consistently with the approach used by AEMO in its Integrated System Planning (ISP) [4]. Future PV uptake was disaggregated into NZAu regions, assuming a consistent proportional distribution of capacity in each region, while the growth rate in the NT is the average of all the other states. Hourly PV generation availability traces were computed by simulating PV module performance based on solar radiation data for 2018, as located at the centroid of the 10 postcodes with the most installed PV capacity in each region.

3 Outputs of EP and RIO to be downscaled

Figure 1 reports the modelled domestic final energy demand by sector in 2020 and 2050. The breakdown of buildings' final energy demand into more granular end-use subsectors is shown in Figure 2.

Figure 1 | Current and future modelled Australian domestic final energy demand by sector, and respective relative shares, for the two demand-side net-zero Scenarios.

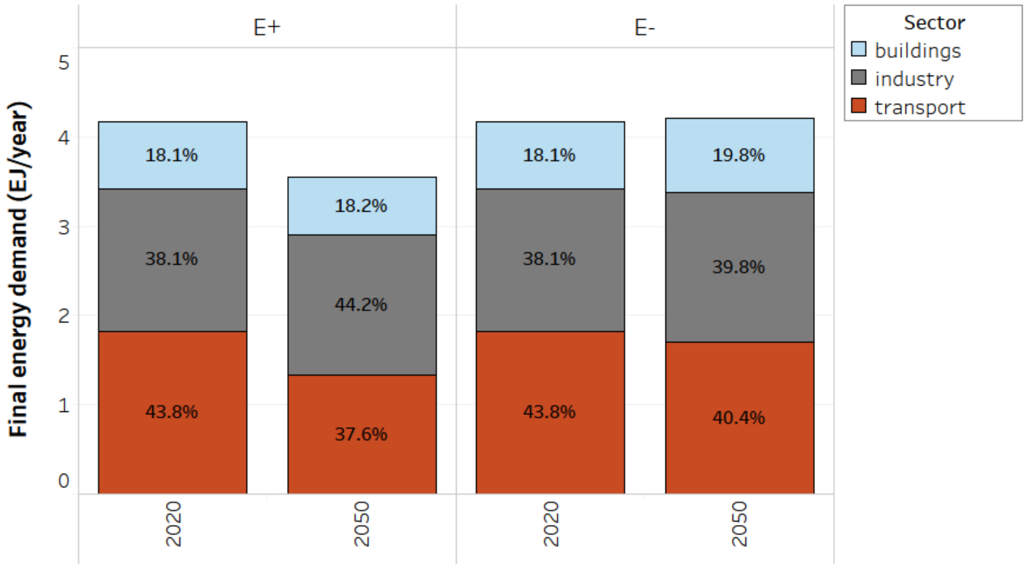
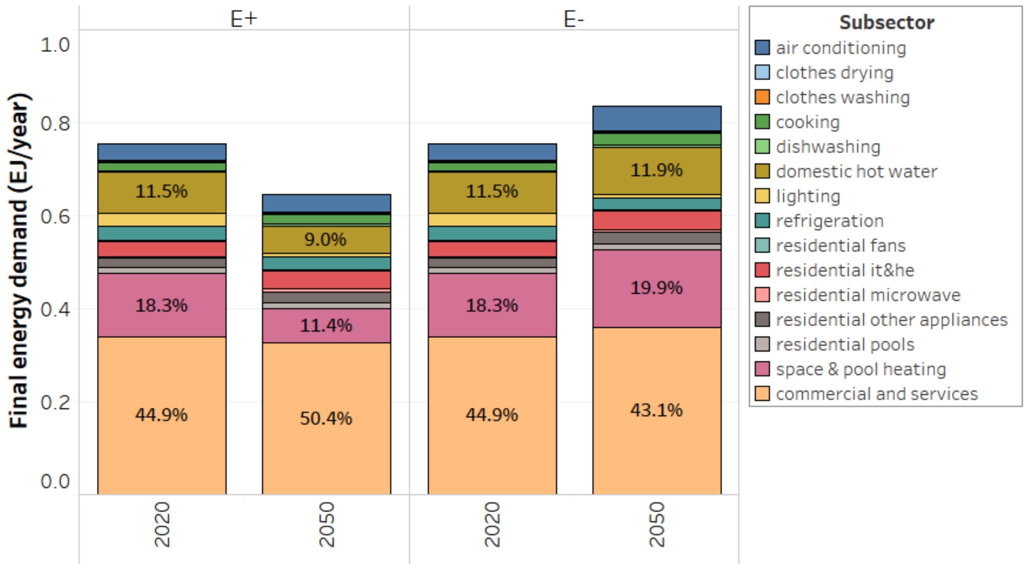


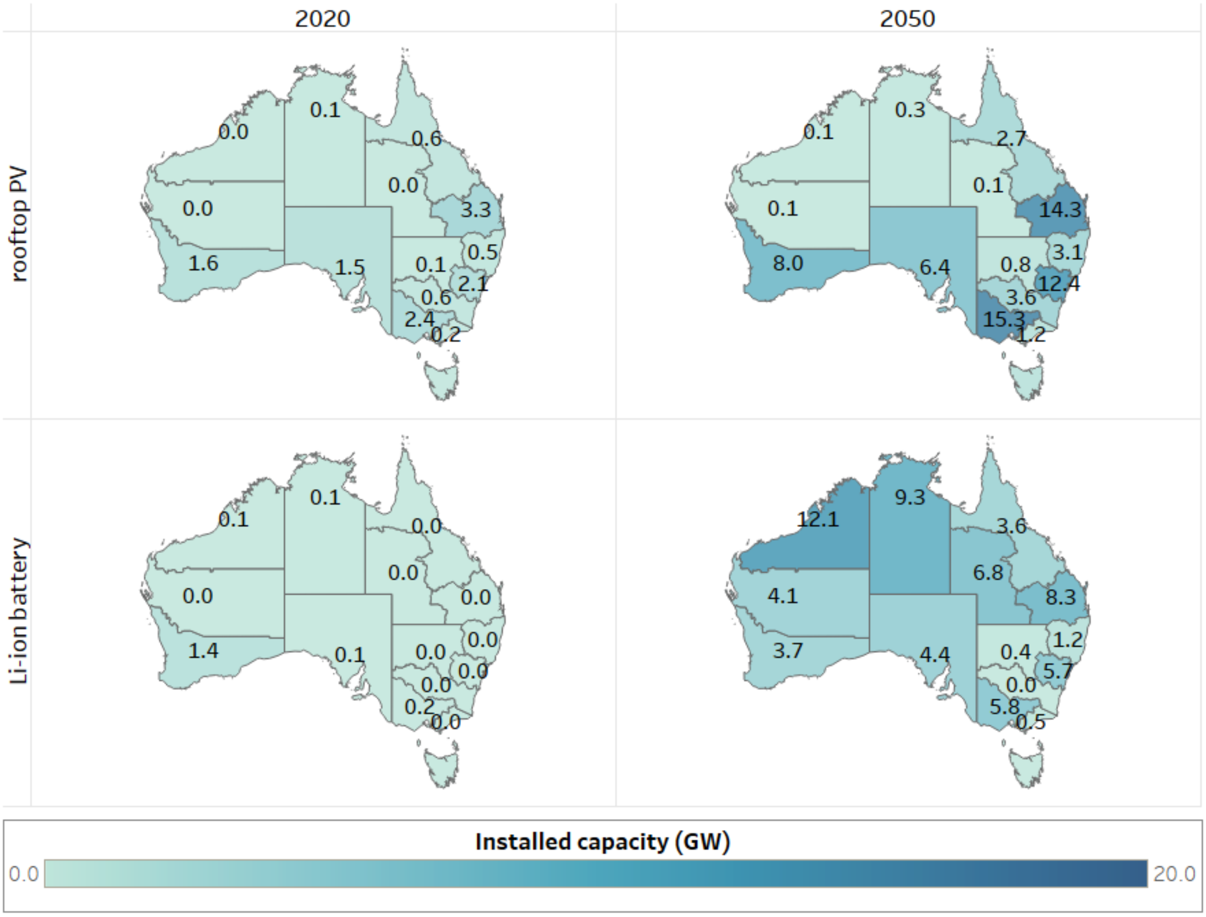
Figure 2 | Current and modelled future buildings' final energy demand by end-use subsector.



Results are reported for both the E+ Rapid Electrification Scenario and the E− Slower Electrification Scenario, which model two alternative demand-side projections with different rates of energy productivity improvement stemming from different assumptions around the speed of electrification and energy efficiency measures [6]. Figure 1 shows that, between 2020 and 2050, both the total domestic final energy demand and the overall share attributed to buildings barely change. However, Figure 2 shows that different contributors to buildings' final demand increase or reduce more significantly, as a result of variations in demand drivers and technology deployment.

As one example, the deployment of rooftop PV and Li-ion batteries by NZAu region is presented in Figure 3, the former being imposed, and the latter being modelled by the NZAu supply-side optimisation. Figure 3 refers to the E+ Scenario, but results for the domestic Li-ion battery rollout are similar for other scenarios too. There is a large uptake of these two technologies across all of Australia. However, we note that the supply-side optimisation determines an aggregate battery capacity and does not distinguish between those which would be deployed behind-the-meter at small-scale, and utility-scale installation. Out of the total modelled Li-ion battery capacity, only a portion would be expected to be installed as residential batteries alongside rooftop PV projects, while the remainder would be deployed as utility-scale batteries connected to either the distribution or transmission networks.

Figure 3 | Installed rooftop PV and domestic Li-ion battery capacity in Australia over time for the E+ Scenario.



4 Downscaling task

The downscaling of building energy demand and technology switching was carried out both for the E+ and the E− Scenarios and follows these steps:

1. the evaluation of the energy-service demand by end-use subsector for residential buildings over time;
2. the aggregation of appliances and building technology uptake by end-use subsector and by region for residential buildings; and
3. the evaluation of the final energy demand by energy vector, for residential and commercial buildings, over time.

The downscaling of rooftop PV is the same across scenarios and was carried out by estimating the capacity and surface covered by rooftop PV projects in each of the SA2 regions defined by the Australian Bureau of Statistics [8] over time. The downscaling of residential, behind the meter Li-ion battery uptake was carried out by assigning an estimated battery capacity to each SA2 region as a proportion of the total modelled installed capacity of batteries, in the E+ Scenario. Further methodology details are presented hereafter.

4.1 Assessment of building energy demand and technology switching

The end-use subsectors that constitute the buildings sector are reported in Table 1. The energy-services demanded of different appliances are projected out to 2060 with the EP model, based on the combination of demand drivers considered (population, GDP, heating and cooling degree days, number of households etc.). Furthermore, the EP model tracks technology stock rollover given assumed technology lifetimes, the final service demand, as well as the assumptions on efficiency gains and sales share by appliance. Hence, the end-use service demand is ultimately converted into an energy demand, across the various energy vectors considered (such as electricity, gas or H_2) given the prevalence of individual appliances in the technology mix. Data postprocessing was carried out to extract useful indicators such as household coverage, installed capacity and fuel switch by region.

Table 1 | Residential and commercial building end-use subsectors, associated sector and energy service representation.

End-use subsector	Sector	Service representation
Residential air conditioning	residential	Stock and energy
Residential clothes drying	residential	Stock and energy
Residential clothes washing	residential	Stock and energy
Residential cooktops and ovens	residential	Stock and energy
Residential dishwashing	residential	Stock and energy
Residential fans	residential	Energy only
Residential freezing	residential	Stock and energy
Residential it&he	residential	Energy only
Residential lighting	residential	Stock and energy

Residential microwave	residential	Energy only
Residential other appliances	residential	Energy only
Residential pools	residential	Energy only
Residential refrigeration	residential	Stock and energy
Residential space heating	residential	Stock and energy
Residential water heating	residential	Stock and energy
Commercial and services	commercial	Energy only

Postprocessing of the EP results was finally used to estimate final energy demand by energy vector and sector energy productivity gains that come from technology switching. To do so, the energy productivity improvement of demand-side technologies over time also had to be considered. Results were disaggregated by region for visualisation.

4.2 Estimation of rooftop PV surface and capacity

A regression model was developed to map the rooftop PV capacity to the SA2 regions. This regression model was based on the following data.

- The number of occupied private dwellings and population data from the 2016 census. These were sourced with the Australian Bureau of Statistics' tool TableBuilder [8], at SA2 level.
- Data of small-scale (< 100 kW) solar PV installations by postcode published by the Clean Energy Regulator (CER) for 2020 [7].
- The number of commercial buildings disaggregated into hospitals, hotels, law courts, offices, retail, schools, tertiary, and other public buildings from the commercial buildings baseline study by state [9].
- Global horizontal irradiation data, in units of kWh/m^2, from the global solar atlas [10] sampled by interpolation to SA2 level in the ArcGIS software.

Other parameters, such as the political orientation of occupants and the "neighbourhood effect", that can significantly affect the preference for rooftop PV were not used since they are difficult to quantify [11]. The commercial buildings for each SA2 were assigned from state-based values, proportionally to 2020 population. Then, a PV capacity K_{sr}^{res} was assigned to each subregion through a proportionality factor, $\alpha_{sr,r}^{res}$, that accounts for solar irradiation data (i.e. global horisontal irradiance, GHI_{sr}) and the number of privately owned residential buildings, N_{sr}^{res}, and commercial buildings, N_{sr}^{com}. Thus, once the capacity of PV in a given region K_r was known, the mapping to the selected subregion was computed as follows.

For the residential building sector, for each region r:

$$K_{sr}^{res} = \alpha_{sr,r}^{res} K_r$$

$$\alpha_{sr,r}^{res} = \frac{GHI_{sr} N_{sr}^{res}}{\sum_{sr \in r} GHI_{sr} (N_{sr}^{res} + N_{sr}^{com})}$$

Similarly, for the commercial building sector:

$$\alpha_{sr,r}^{com} = \frac{GHI_{sr} N_{sr}^{com}}{\sum_{sr \in r} GHI_{sr} (N_{sr}^{res} + N_{sr}^{com})}$$

Such an approach conserves the total capacity per NZAu region from the RIO model. Then, an average size of 15 kW was used to estimate the number of PV installations in the commercial sector, while the average installation capacity for residential PV was estimated to minimise the weighted average relative error on the CER data for the number of installations by postcode [7]. This resulted in an average capacity of 5 kW for residential PV, which is reasonable. Results for 2020 were then verified against the installed small-scale PV capacity for those postcodes that matched certain SA2 regions, and the validation is reported in the Appendix. The same approach was repeated using the RIO results for subsequent years, where the population growth and number of buildings, both residential and commercial were scaled based on the regional projections used as energy drivers in the EP model, as reported in the MASS document [6]. The average installation size is assumed to remain constant over time.

4.3 Assignment of behind-the-meter Li-ion batteries to each SA2 region

Two sources ([3] and [7]) report data for the current installed capacity of residential batteries, acknowledging the uncertainty of the data reported. The average value of Li-ion battery installation by state was therefore taken as the average of the figures from each of the two sources. This allowed computation of the percentage of new rooftop solar PV installations in 2020 that also featured a battery, as shown in Table 2. Projections of residential Li-ion battery installations over the modelling horizon to 2060 were then based on the modelled number of rooftop PV installations and the assumption that these state-by-state percentages will increase, so that almost all new rooftop PV installations by 2050 will also incorporate battery storage, as suggested by AEMO's ISP [4]. S-curves were used to represent this transition. Finally, the power capacity for each battery installation is assumed to equal the residential PV (i.e. 5 kW), with a 2 hour discharge time (storage duration).

Table 2 | Estimated proportion of new residential rooftop PV installations in 2020 that incorporated small-scale Li-ion batteries.

State	NSW	NT	Qld	SA	Tas	Vic	WA
% PV projects including battery	3.9	9.8	3.6	8.7	8.9	4.6	1.7

5 Results

5.1 Residential sector energy demand

The major residential energy-service demands by end-use subsector are presented in Table 3, for year 2020 and 2050.

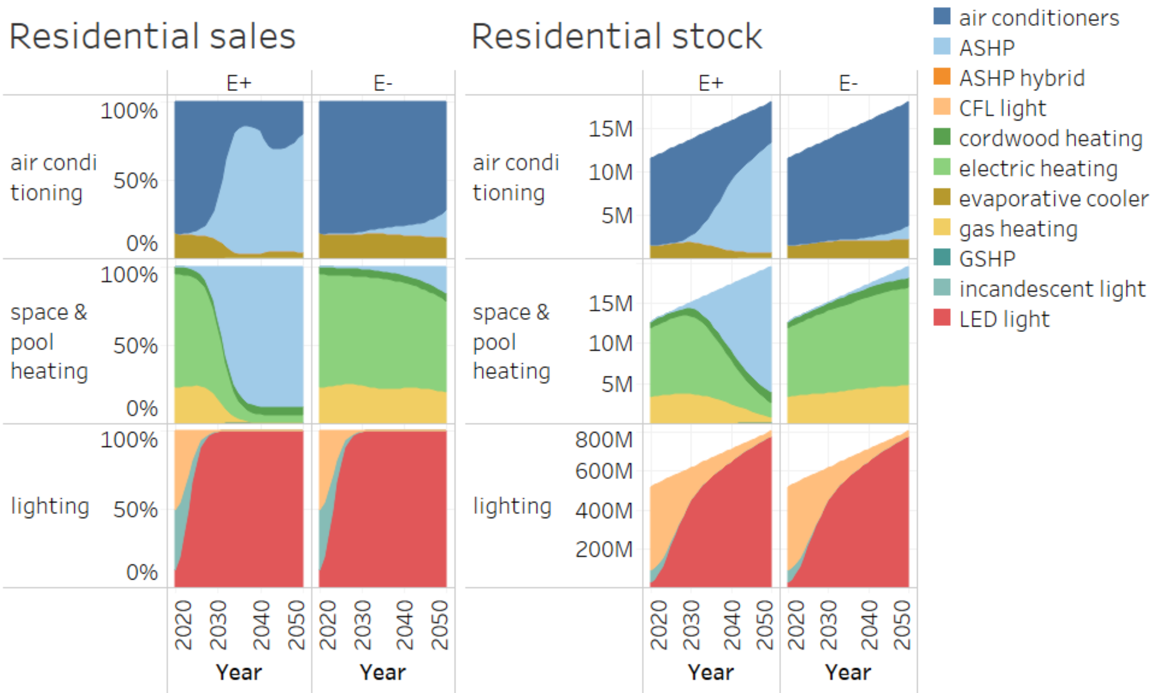
Table 3 | Residential buildings energy-service demand by end-use subsector for the years 2020 and 2050, and for all of Australia.

End-use subsector	2020	2050	Yearly Δ [%/y]
Air conditioning [PJ]	98	201	2.4%
Cooking [PJ]	9	14	1.5%
Refrigeration [Mm^3]	6.2	9.7	1.5%
Clothes drying [kton]	601	802	1.0%
Clothes washing [Mm^3cycle]	534	832	1.5%
Dishwashing [Mcycle]	1,627	2,533	1.5%
Lighting [Tlmh]	241	375	1.5%
Space & pool heating [PJ]	112	157	1.1%
Water heating [PJ]	69	90	0.9%

Overall, energy service demand increases between 2020 and 2050 given the rise of most demand drivers. Space & pool heating exhibits lower growth than other sectors, due to the modelled decrease in heating degree days which similarly affects clothes drying and water heating demand. On the contrary, the highest growth is registered for air conditioning needs, which double by 2050, due to the compounding effects of population growth and an increase in cooling degree days.

Given the energy-service demand of each appliance type, the amount and type of energy required is then a function of the types of technologies adopted to deliver each service. To this end, outcomes from the tracked technology stock evolution over time are based on sales share and unit replacement. The sales share and technology stock evolution for selected residential end-use subsectors are shown in Figure 4 with the grouping of demand-side technologies reported in Table A.1.

Figure 4 | Residential technology sales share (left) and resulting technology stock evolution (right) for selected end-use subsectors and the demand-side Scenarios.



Air Source Heat Pumps (ASHP) dominate the market for space heating and air conditioning by 2030 in the E+ Scenario, saturating at 90% of overall sales by 2040. This results in close-to-complete electrification of these two end-use subsectors by 2050. However, the heat pump uptake is slower in the E− Scenario, with gas heating playing still a significant contributor in 2050. In both scenarios, LED uptake reaches 100% of sales by 2030. A similarly rapid switching is observed in other end-use subsectors. For instance, induction stoves cover 94% of new sales by 2040 and almost completely phase out gas cooktop sales by 2050 in the E+ Scenario. The effect of technological learning is reflected in performance improvements over time, as shown in Table 4.

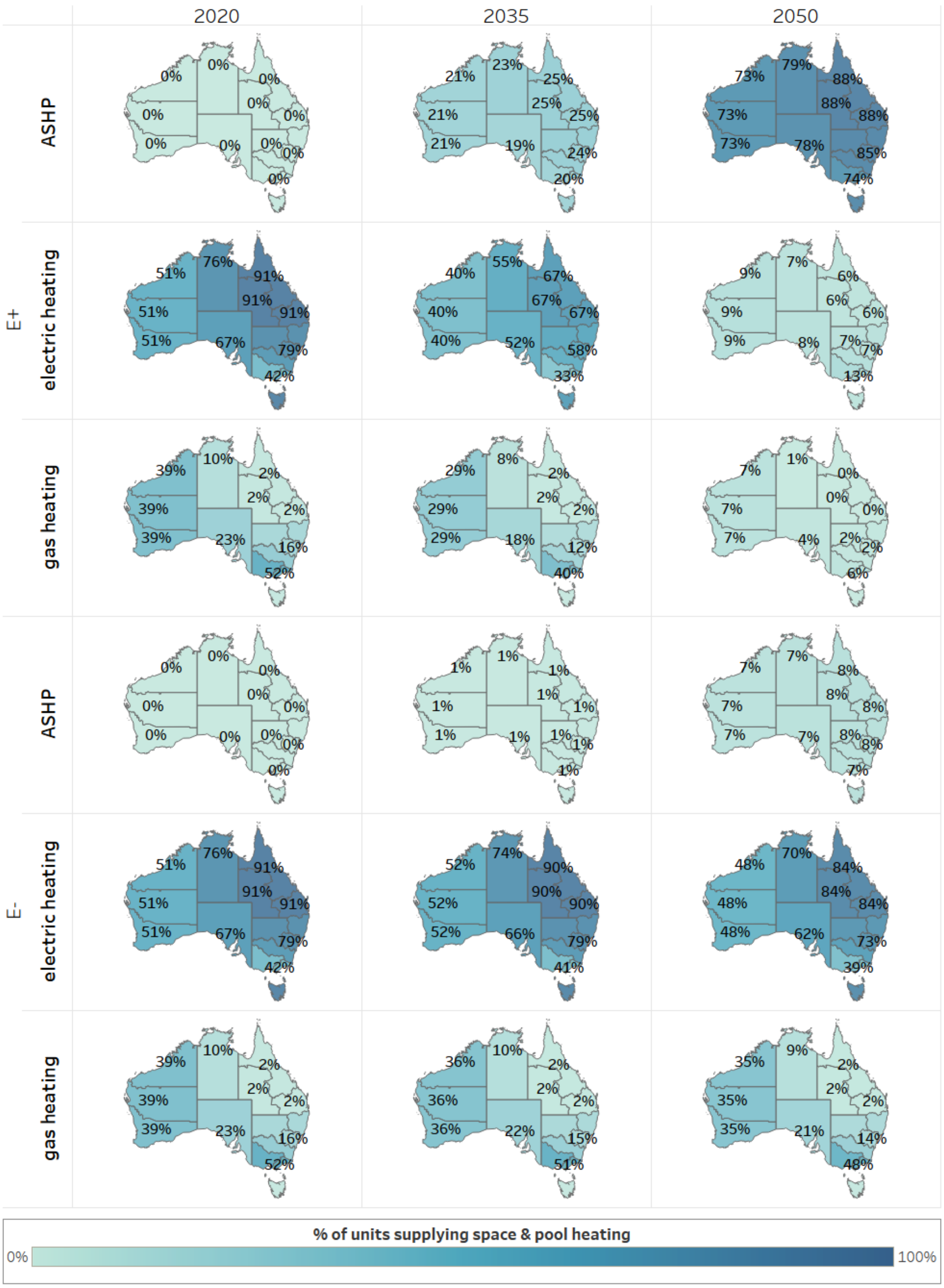
Table 4 | Performance improvement over time for selected technology groups.

Technology group	2020	2050	Units	Yearly Δ [%/y]
ASHP* hybrid	3.9	5.7	W_{th}/W_e	1.3%
ASHP*	3.9	4.9	W_{th}/W_e	0.8%
GSHP*	4.1	4.1	W_{th}/W_e	0.0%
HVAC*	3.3	3.8	W_{th}/W_e	0.4%
Cordwood stoves	0.8	0.8	W_{th}/W_{th}	0.0%
Evaporative Cooler	12.0	12.0	W_{th}/W_e	0.0%
Gas heating	0.8	0.9	W_{th}/W_{th}	0.4%
Resistive heating	0.9	0.9	W_{th}/W_e	0.00%
Incandescent light	16.8	16.8	lmh/Wh	0.00%
CFL* light	52.0	55.2	lmh/Wh	0.2%
LED* light	157.0	202.0	lmh/Wh	0.8%

* Air Source Heat Pumps (ASHP), Ground Source Heat Pumps (GSHP), Heating, Ventilation and Air Conditioning (HVAC), Compact Fluorescent Lamps (CFL), Light Emitting Diodes (LED).

ASHP and LED lights are newer technologies and therefore exhibit the highest performance improvement. Technology learning and stock replacement with progressively more productive technologies counterbalance the increase in energy service-demand across buildings, as discussed earlier.

Figure 5 | Percentage of different technologies supplying space heating over time.



As an example, Figure 5 shows the spatial and temporal evolution of the technologies supplying the space and pool heating. Over time, a transition from electric heating to more productive ASHPs can be observed for both scenarios. In the E+ Scenario, ASHP supply around 80% of the total energy required for space heating in 2050, while the majority of the total energy demand is provided by electric heating and gas heating technologies (with the potential use of synthetic methane and biogas) in the E− Scenario. Across the NZAu regions, states that currently rely on gas for heating preserve a larger proportion of gas heating appliances up to 2050.

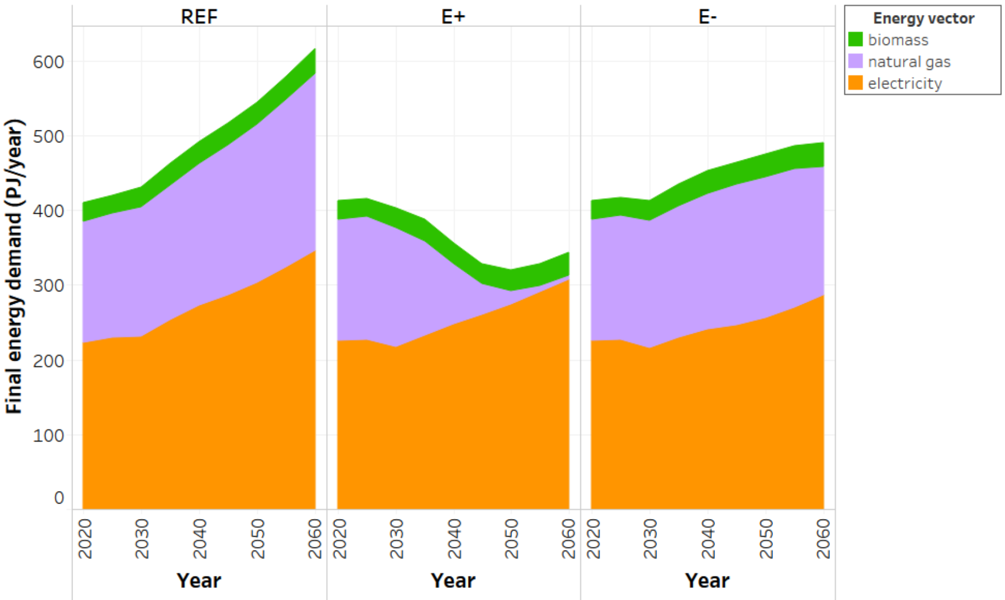
The major residential final energy demand by end-use subsector is presented in Table 5, for year 2020 and 2050, for the E+ Scenario. Space heating accounts for the largest share of energy demand from 2020 to 2050. Yet, space heating demand decreases over time despite population growth and the associated rise in the residential heated area. This is due to energy efficiency increases and electrification via ASHP observed in Figure 5. Because of an increase in both the cooling degree days and the population, air conditioning demand also grows. However, energy productivity gains maintain this increase below that observed for cooking. Similarly, productivity gains coming from the uptake of LED lighting reduces demand by almost 4% each year, despite service demand growth.

Table 5 | Residential buildings final energy demand by end-use subsector for year 2020 and 2050 (E+ Scenario).

End-use subsector	2020 [PJ]	2050 [PJ]	Subsector share	Yearly Δ [%/y]
Air conditioning [PJ]	35.9	37.5	12%	0.15%
Cooking [PJ]	17.3	20.7	6%	0.60%
Refrigeration [PJ]	29.4	25.5	8%	-0.47%
Clothes washing [PJ]	1.2	1.2	0%	-0.11%
Clothes drying [PJ]	3.2	4.0	1%	0.72%
Dishwashing [PJ]	3.7	5.9	2%	1.58%
Lighting [PJ]	29.0	8.7	3%	-3.95%
Other electric appliances [PJ]	59.1	72.7	23%	0.69%
Space heating [PJ]	150.3	86.5	27%	-1.82%
Water heating [PJ]	86.4	57.9	18%	-1.33%

The effect of technology and energy service evolution on the final energy demand for the residential sector is represented in Figure 6. The residential sector in the E+ Scenario is almost fully electrified by 2050. However, in the E− Scenario, this transition is slower, and gas is used to supply about 35% of the energy demand in 2050. As a consequence of energy efficiency improvements and electrification, the residential final energy demand can even be lower in 2050 than currently. Whilst no change in the use of biomass for buildings space heating has been modelled, it is unlikely that some of this biomass use would not also undergo electrification. However, this trend would only have minor impact on the need for final electricity shown in Figure 6 and Figure 7.

Figure 6 | Evolution of final energy demand by energy vector for the residential sector.



5.2 Commercial sector energy demand

Commercial building data is more fragmented and did not allow a break down of energy-service demand into end-use subsectors. The final energy demand data for 2020 from the Australian Energy Statistics [1] were therefore projected based on population growth and scenario-specific assumptions on fuel switching as shown in Figure 7 and reported in the NZAu MASS document [6].

Figure 7 | Evolution over time of final energy demand by energy vector for the commercial sector.

The commercial building sector is fully electrified by 2045 in the E+ Scenario, while electrification is delayed by 60 years in the E− Scenario. A more rapid electrification allows a reduction in the overall final energy consumption for the commercial building sector, despite an increase in service demand.

5.3 Uptake of rooftop PV and behind-the-meter Li-ion batteries

The cumulative rooftop PV installed capacity by region, as informed by exogenous projections described in Section 4.3 is presented in Figure 8. Rooftop PV capacity grows from 13 GW in 2020 to 69 GW in 2050. Figure 8 also shows that, based on the methodology described in Section 4.1.2, less than 1% of rooftop PV capacity could be expected to be installed on commercial buildings.

Figure 8 | Installed rooftop PV capacity (GW) by NZAu region over time.

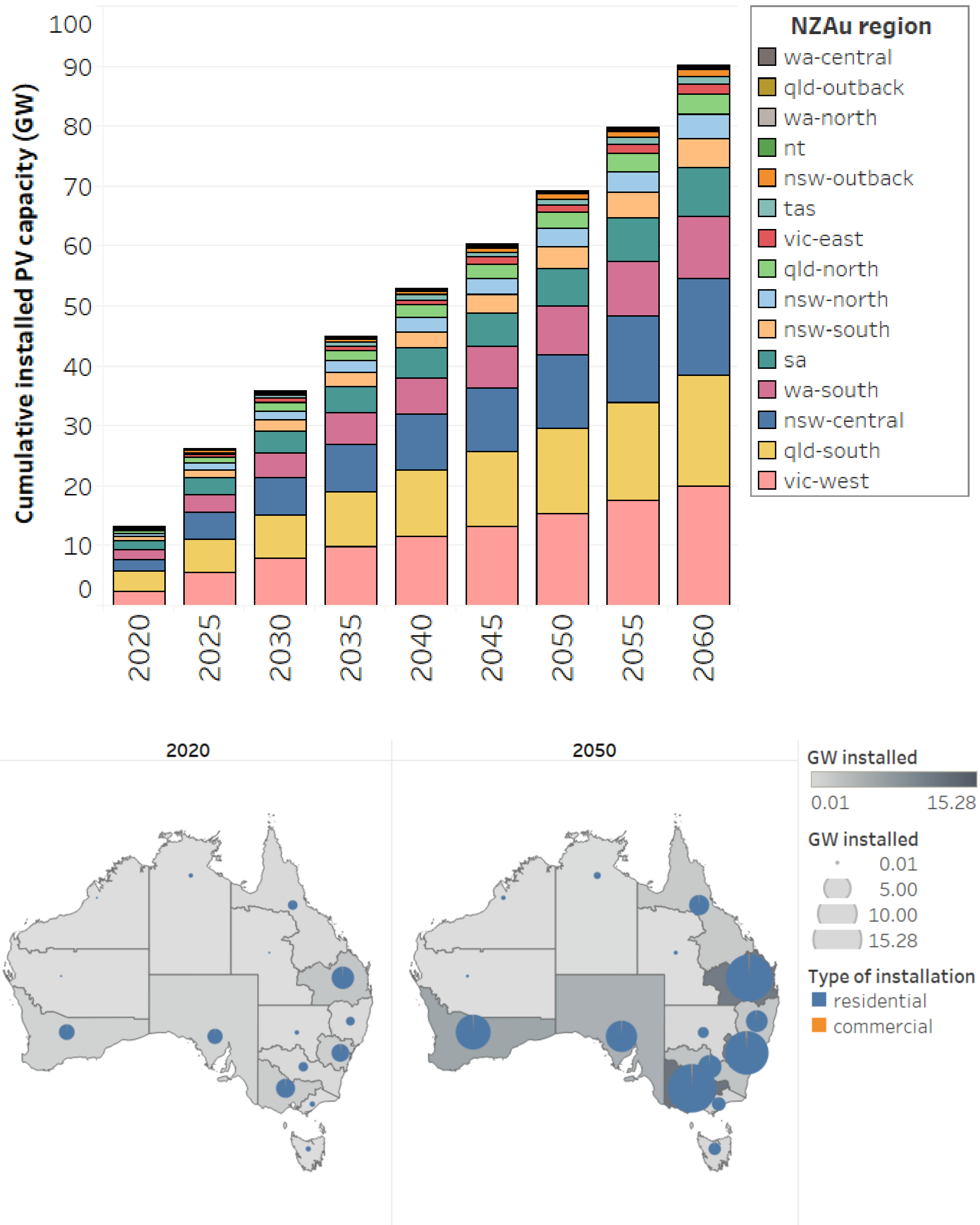
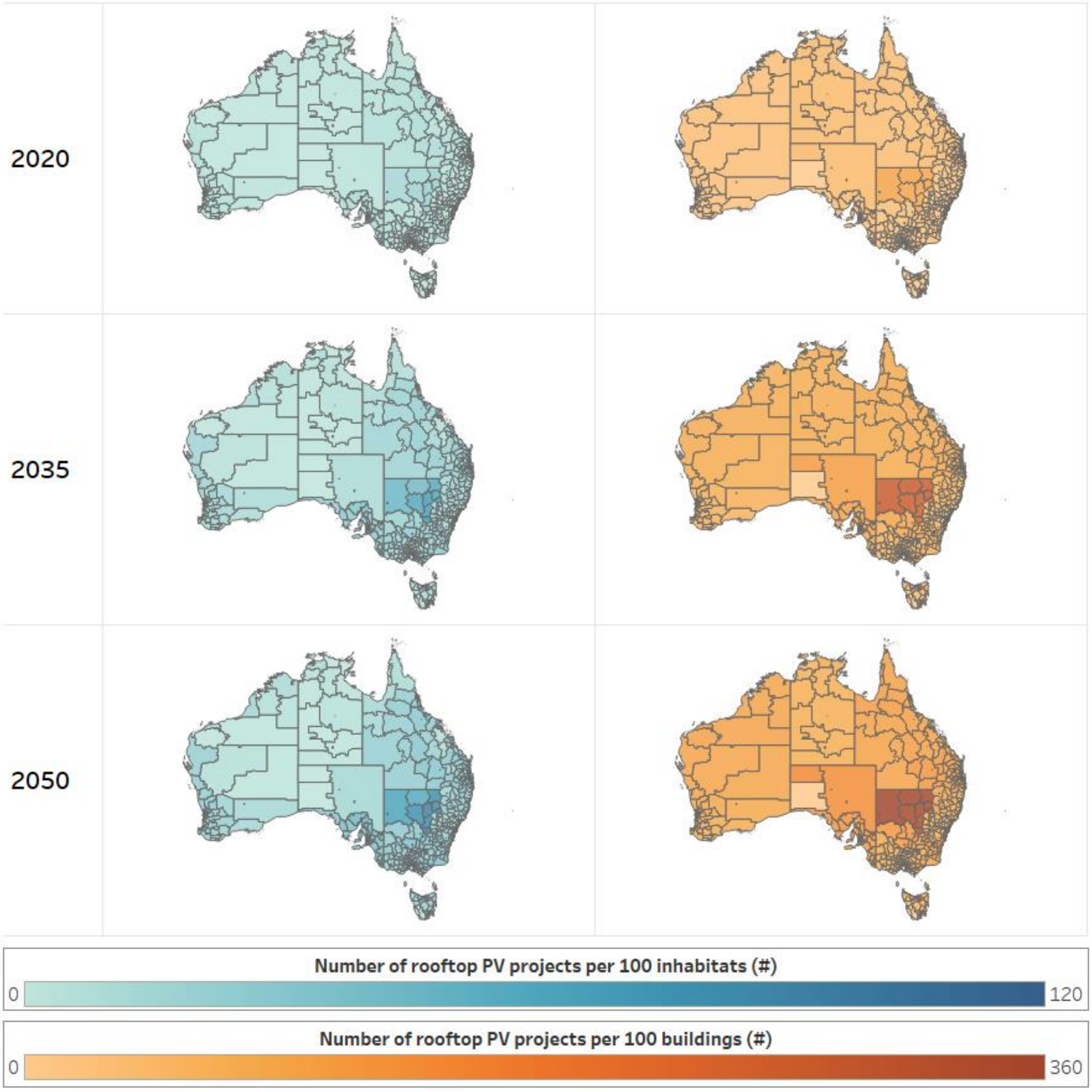


Figure 9 shows the projected installation of rooftop PV projects; both the number of PV projects per 100 inhabitants and per 100 privately owned buildings have been reported as suitable metrics to highlight rooftop PV penetration. Although results for some of the SA2 regions predict more than 1 rooftop PV installation per building, two considerations should be kept in mind when interpreting these results. First, shared residential buildings other than privately-owned, such as tower blocks and multi-family complexes may be also covered by PV installations, particularly in big city centres, and these have not been incorporated in the present estimations. Second, while the PV capacity is apportioned to each NZAu region based on its solar resource, as described by its capacity factor [6], the allocation of the capacity to SA2 regions is performed using the population and number of privately owned buildings (see Section 4.2). In regional areas with high solar irradiation but low population, this leads to overpredictions in the number of rooftop PV projects per building. The zoom-in of Figure 9 into an area including greater Melbourne and Sydney regions, as well as some of the NSW-outback regions, shown in Figure 10, illustrates these considerations.

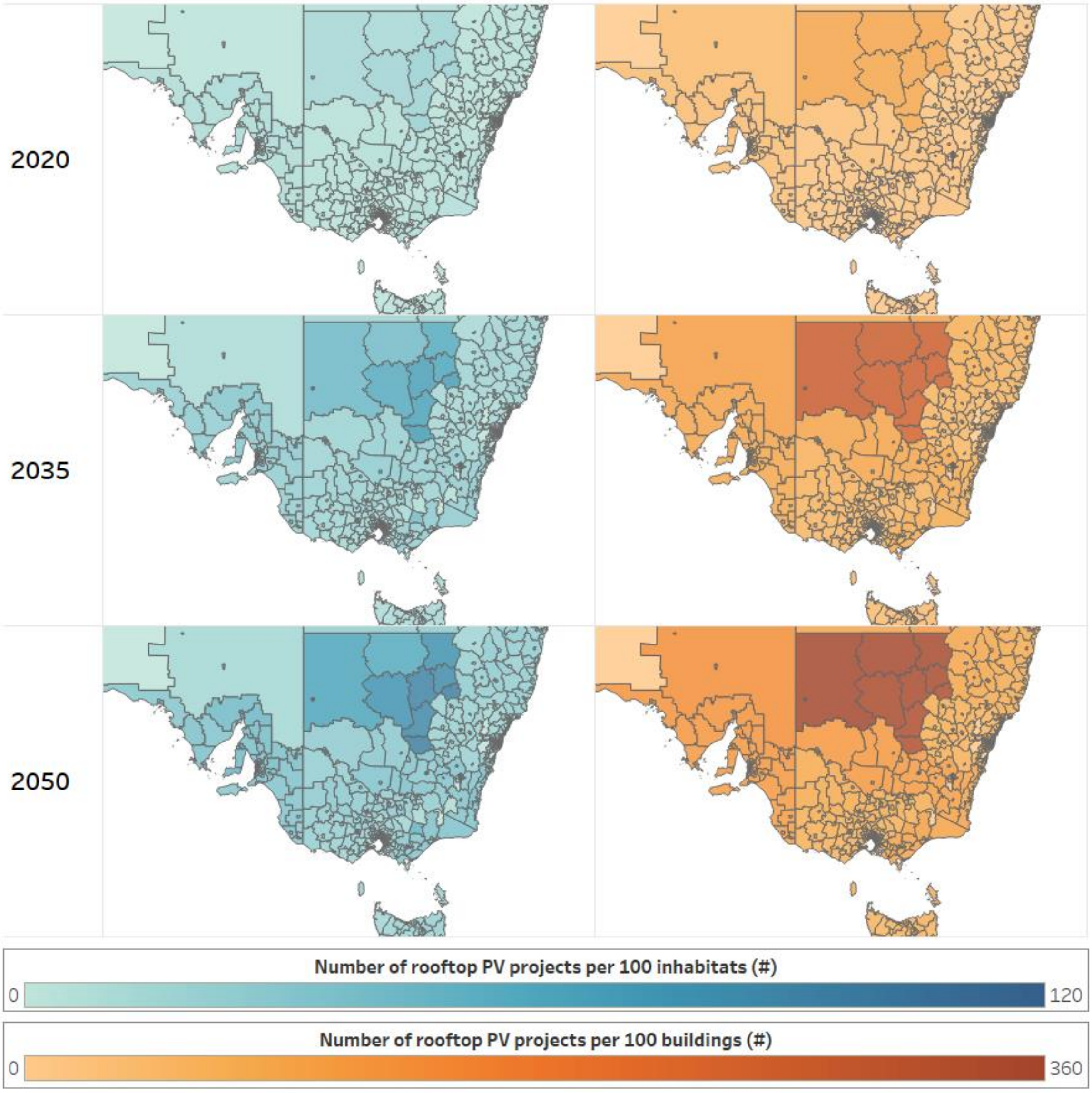
Figure 9 | PV installation over time at the SA2 level.



On average, the number of PV installations was found to be 5.6 for every 100 inhabitants in 2020, which increases to 20.4 in 2050. The average number of projects for every 100 privately-owned buildings increases from 24 to 80 over this same time period. This is comparable to but greater than AEMO's projection of a rise from about 30% to 65% of the buildings in the National Electricity Market (NEM) region to be covered by PV installations over the same 30-year period [4]. The Clean Energy Council reported about 33% coverage for 2021 [3].

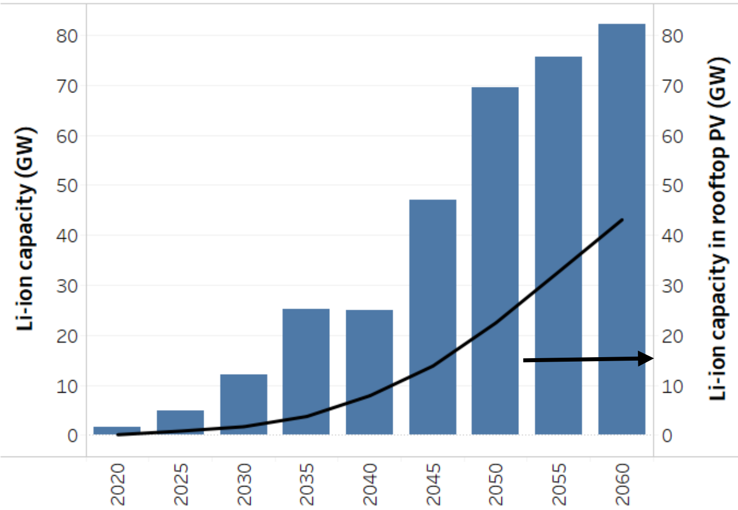
It should be noted that Figure 10 shows almost all buildings in rural areas are modelled to install rooftop PV. Furthermore, as the number of privately owned buildings may not be sufficient to accommodate the required PV capacity, there may be a need to promote policy frameworks and incentives that subsidise the PV uptake on rented houses. As an alternative or complementary to the above measures, deployment of small-scale PV installations on surfaces other than building roofs (such as over crops and other plantations) may also be prospective as means of achieving the projected levels of distributed solar generation.

Figure 10 | Zoom in of rooftop PV projects at SA2 level.



Energy storage will also play an important role in the net-zero transition. Currently between 1 and 11% of the new PV projects, depending on the state, incorporate Li-ion battery installations. Under the assumption that almost all new projects will be equipped with batteries by 2050, out of the 70 GW of Li-ion batteries in 2050 that are modelled by NZAu’s supply-side optimisation, 22.5 GW will sit behind-the-meter, installed alongside PV projects, with an average duration of 2 hours. This is illustrated in Figure 11. The remaining 68% of the Li-ion battery capacity (47.5 GW) would therefore be deployed as utility-scale projects. The estimated behind-the-meter Li-ion capacity corresponds to about 26% of the national peak demand electricity that distribution networks are predicted to face in 2050, according to the NZAu modelling results. This peak values were estimated from the aggregated commercial, residential, transport and industrial energy demand, which in NZAu are independently tracked with 1 h time resolution. The dedicated companion downscaling report *Downscaling - Electricity and gas distribution systems* discusses the operation and costing of electricity and gas distribution networks. This high proportion of distributed batteries underscores the important role of this behind-the-meter technology could play in mitigating the need for distribution infrastructure augmentation: having behind-the-meter batteries supply up to 26% of the electricity demand at peak times means a significant reduction in electricity distribution network investment.

Figure 11 | Total capacity of battery storage installed (left-hand axis) and capacity of 2h batteries used in rooftop PV projects.



The predictions of residential and utility-scale Li-ion battery deployment are consistent with the AEMO ISP2022 results, where by 2050 31 GW of flexible controllable loads and 16 GW of utility-scale storage have been modelled in their 'Step Change' Scenario. Here, 19 GW are assigned to residential batteries in the NEM (to be considered as controllable loads) and 30 GW to utility-scale storage. When considering the aggregate 245 GWh of battery storage predicted by this study for the NEM, having the estimated amount of 2h behind-the-meter batteries deployed results in the remaining utility-scale batteries being 10h duration, on average. Notably, this value is larger than the most common practice in Li-ion applications in operation worldwide [12] and, under these circumstances, other energy storage solutions have been proposed as more financially viable [13]. However, the 2h duration assumed in for this downscaling task is notional and arbitrary, and the RIO platform currently does not consider a distinction between behind-the-meter and utility-scale batteries. Being able to distinguish between those two is likely to result in lower aggregated amounts of battery projects to be deployed (in energy terms), with durations independently optimised for different use requirements.

To conclude, Figure 13 reports the installed number capacity of rooftop PV and domestic behind-the-meter Li-ion batteries alongside each other, by NZAu region. It can be appreciated how the assumed S-shaped uptake of installation with associated battery manifests itself in a faster growth of Li-ion capacity in later years, as opposed to an uptake of rooftop PV which is projected to be steadier over time. These different trends result in the number of total rooftop PV projects integrating Li-ion batteries by 2050 to significantly increase from the current values in Table 2 to an average of about 1 in 3 by 2050, as presented in Figure 13 at SA2 granularity.

Figure 12 | Time evolution of installed rooftop PV and behind-the-meter Li-ion battery capacity by NZAu region.

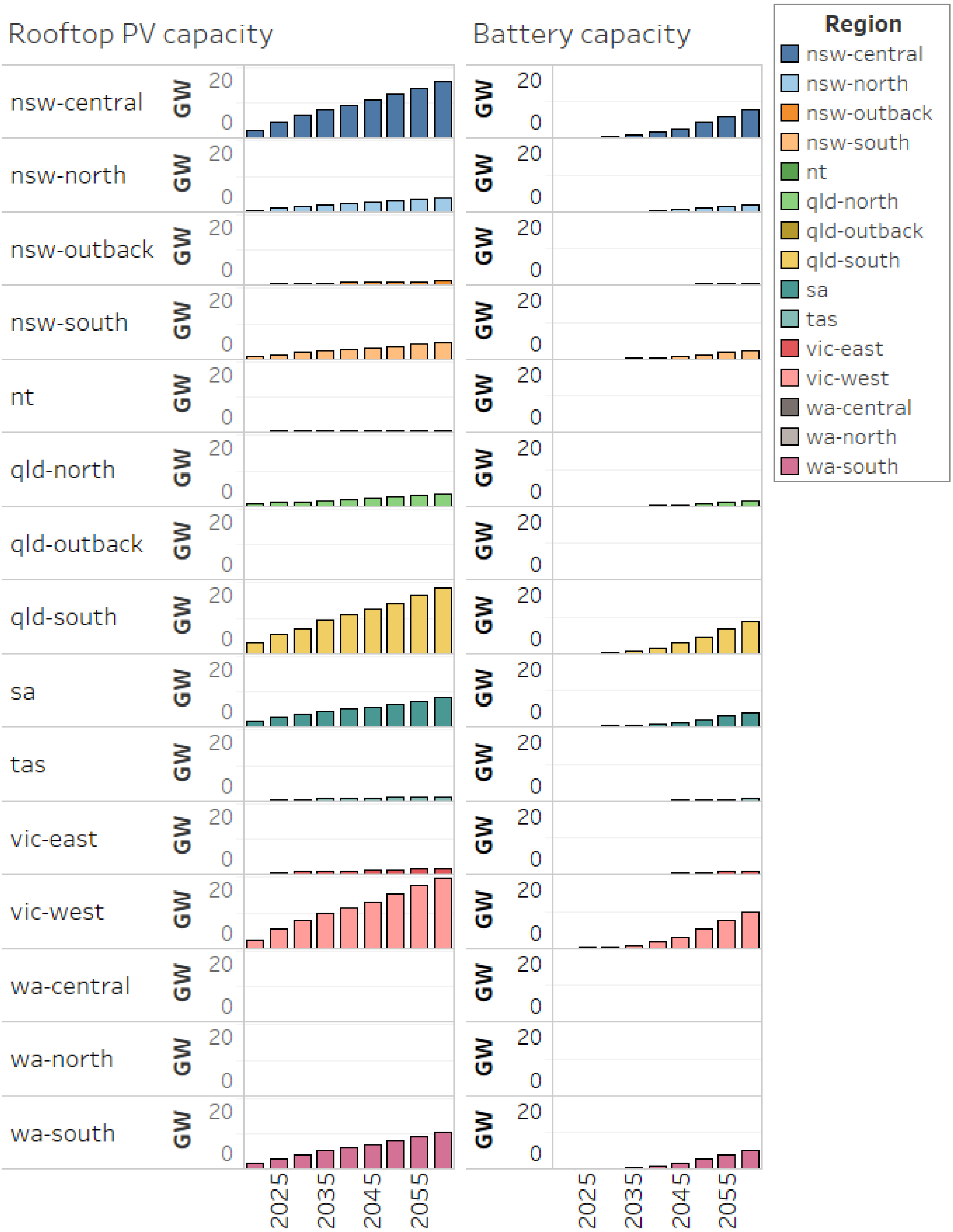
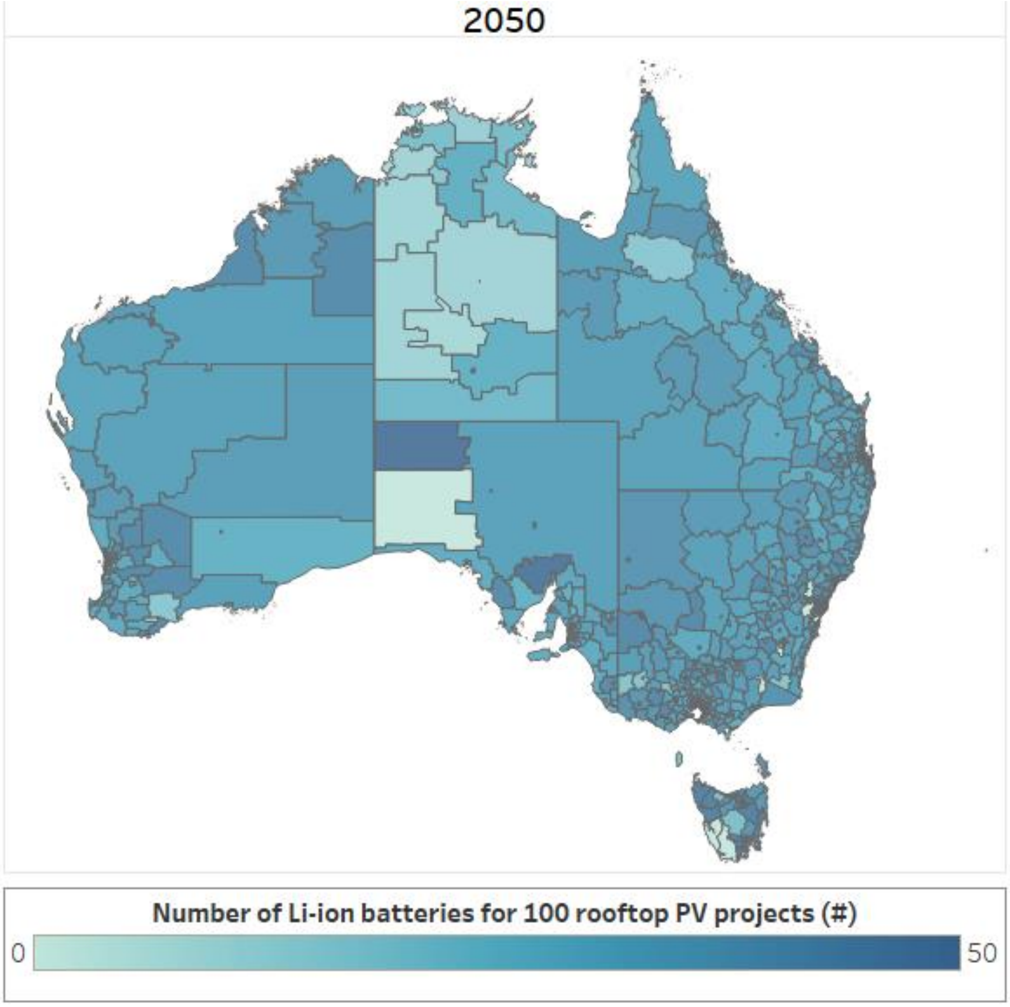


Figure 13 | Overall share of rooftop PV projects with a Li-ion battery in 2050.



Appendices

Table A.1 | Grouping of individual demand-side technologies.

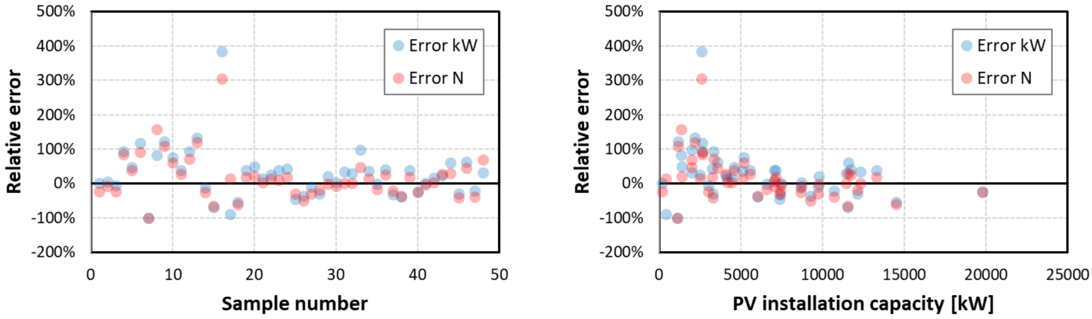
Demand-side technology	Technology group
ASHP Hybrid w Natural Gas Boiler/Radiator - Cooling	ASHP hybrid
ASHP Hybrid w Distillate Furnace - Cooling	ASHP hybrid
ASHP Hybrid w Kerosene Furnace - Cooling	ASHP hybrid
ASHP Hybrid w LPG Furnace - Cooling	ASHP hybrid
ASHP Hybrid w Natural Gas Boiler/Radiator - Cooling	ASHP hybrid
ASHP Hybrid w Natural Gas Furnace - Cooling	ASHP hybrid
CFL Exterior	CFL light
CFL GSL	CFL light
CFL Reflector	CFL light
Halogen Reflector	CFL light
T-8 Linear Fluorescent	CFL light
High Efficiency Air Source Heat Pump - Cooling	ASHP
Reference Air Source Heat Pump - Cooling	ASHP
Reference Air Source Heat Pump - Heating	ASHP
Reference Electric Heat Pump Water Heater	ASHP
High Efficiency Bottom Mount Refrigerator	refrigerators
High Efficiency Chest Freezer	refrigerators
High Efficiency Side Mount Refrigerator	refrigerators
High Efficiency Top Mount Refrigerator	refrigerators
High Efficiency Upright Freezer	refrigerators
Reference Side Mount Refrigerator	refrigerators
Reference Upright Freezer	refrigerators
High Efficiency Clothes Washer - Front Loading	other electric appliances
High Efficiency Clothes Washer - Top Loading	other electric appliances
High Efficiency Dishwasher	other electric appliances
High Efficiency Electric Clothes Dryer	other electric appliances
Reference Clothes Washer - Front Loading	other electric appliances
Reference Dishwasher	other electric appliances
Reference Electric Clothes Dryer	other electric appliances

High Efficiency Central Air Conditioner	air conditioners
High Efficiency Room Air Conditioner	air conditioners
Reference Central Air Conditioner	air conditioners
Reference Room Air Conditioner	air conditioners
High Efficiency Geothermal Heat Pump - Cooling	GSHP
Reference Geothermal Heat Pump - Cooling	GSHP
Reference Geothermal Heat Pump - Heating	GSHP
Incandescent GSL	incandescent light
LED Exterior	LED light
LED GSL	LED light
LED Linear Fluorescent	LED light
LED Reflector	LED light
Reference Electric Furnace	electric heating
Reference Electric Resistance Water Heater	electric heating
Reference Electric Unit Heaters	electric heating
Reference Gas Cooktop/Stove	gas appliances
Reference LPG Cooktop/Stove	gas appliances
Reference LPG Furnace	gas heating
Reference Natural Gas Furnace	gas heating
Reference Natural Gas Heat Pump - Cooling	gas heating
Reference Gas Water Heater	gas heating
Reference Instantaneous Gas Water Heater	gas heating
Reference Instantaneous LPG Water Heater	gas heating
Reference LPG Water Heater	gas heating
Reference Natural Gas Boiler/Radiator	gas heating
Solar Water Heater with Electric Backup	STC + electric backup
Solar Water Heater with Gas Backup	STC + gas backup
Cordwood Stoves	cordwood heating
Cordwood Water Heater	cordwood heating
Evaporative Cooler	evaporative coolers

Validation of the procedure for PV capacity assignment

The rooftop PV capacity predicted is compared to the values from the Clean Energy Regulator in Figure A.1. Besides large errors in only a few cases, relative discrepancies remain largely within the ± 100%. Values may seem large, but it is worth mentioning, first, how even complex models do include gaussian noise in the prediction, as the uptake of PV has a high level of stochasticity [11]. Secondly, small scales project can result in large percentage errors.

Figure A.1 | Relative error on the size and number of PV installations against values from the CER.



When the samples are scaled on the basis of the PV installation, errors are notably lower for larger cumulative projects. Above 5000 kW, maximum and minimum error is, respectively 75.5% and -69% based on power and -64.2 to 60% based on number of installations. Standard deviations are 38% and 29.7% respectively. Values seem to be appropriate for the analysis to be carried out. Additionally, they display a link between the error on number of projects and installed capacity, which is expected, with the deviations on the number of projects being consistently lower, as that is the chosen criterion for determining the sample residential project size.

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