# The impact of climatic, market and regulatory factors on the profitability of shared PV for self-consumption in multi-apartment buildings: A comparison of Australia and Austria

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## Abstract

Although the amount of PV installed in residential buildings is increasing globally, it is largely limited to single-occupancy dwellings and is extremely uneven across jurisdictions. Deployment on apartment buildings remains low, even in Australia with its world-leading residential PV penetration, or in countries subject to specific enabling legislation, such as Austria. We present a comparative study of PV deployment on multi-occupancy residential buildings in these two countries, examining the impact of their distinct climates, financial settings, heating and cooling technologies and regulatory environments. A mixed-integer linear optimisation model is used to compare cost-optimal PV system size and achievable cost savings for a nine-apartment building. We find that Australia's higher insolation and lower investment costs drive higher optimal system size and bill savings, but lower electricity tariffs and regulatory barriers constrain deployment. By contrast, European enabling legislation has not yet achieved success in overcoming Austria's higher investment costs and lower solar exposure, partly due to significant administrative hurdles. Our findings point to possible country-specific policy approaches to increase deployment in this important sector.

*Keywords:*
Photovoltaics; Apartment buildings; PV sharing; Energy communities;

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Residential electricity; Mixed integer linear optimisation; Self-consumption; Austria; Australia

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## 1. Introduction

In order to address the urgent issue of climate change, most countries worldwide have ratified the *Paris Agreement*, with its commitment to keep global temperature rise well below 2 °C [1]. An important and necessary step to achieving this target is the increased diffusion of renewable energy throughout all energy-intensive sectors. Since – along with industry, agriculture and transport – building electricity and heating and cooling are major contributors to global emissions [2], increasing deployment of renewable energy sources, particularly solar photovoltaics (PV) on buildings is making an important contribution towards achieving the global climate goals.

Although residential installations comprise a significant part of this deployment globally, they are very unevenly distributed. In Austria, for example, with a total of 1.4 GW of PV connected to the distribution network [3], only a moderate number of PV systems are to be found on the rooftops of single-family buildings. In contrast, Australia has 8.9 GW of rooftop PV installed on 27 % of stand-alone houses, with residential penetration as high as 50 % in some local government areas [4]. However, in common with many other jurisdictions, both countries see very low levels of PV deployment on multi-occupancy residential buildings. While the disparity in residential PV penetration between these two dissimilar countries might be explained by differences in a range of exogenous factors, including climate, building types, financial and regulatory settings, the reasons for the similarity in their lack of PV deployment on apartment buildings is less clear.

The aim of this study is to examine the country-specific factors that influence the deployment of residential PV and, in particular, the differential impact of these factors on multi-occupancy buildings compared to stand-alone housing. Using the examples of Austria and Australia, we first compare the exogenous factors which might influence residential PV deployment in general. We then investigate the impact of these factors on the cost-optimal design of, and achievable cost savings from, a PV system for a nine-apartment residential building sited in Sydney, Australia or in Vienna, Austria, simulated using different combinations of real, diverse apartment load profiles. The analysis focuses on PV generation for shared self-consumption, an area of increasing interest [5], as current payments for export are low or may be unavailable where commercial tariffs are applied to aggregated building loads.

The novel contribution of this study lies in its consideration of the separate and combined impacts of diverse direct and indirect influencing factors, specifically climate, market conditions, building characteristics and regulatory environments, on residential PV deployment. The contrasting impacts of these factors on the penetration and profitability of rooftop PV for stand-alone housing and for apartment buildings is compared across two geographically remote countries. Additional to this theoretical analysis, an optimisation model is used to quantify the optimal PV installation capacities and achievable cost saving potential of PV on a multi-occupancy building in each country, and their sensitivity to different exogenous factors. In integrating this modelling with the comprehensive comparative study of influencing factors and suggested policy approaches, the article combines theoretical research with practical implementation to fill a gap in the existing literature.

The remainder of this paper is organised as follows. Section 2 provides a brief overview of the existing literature concerning both inter-jurisdictional comparison of factors affecting PV deployment and deployment of PV in multi-occupancy buildings. Section 3 compares the two countries in views of climate, building stock, costs and subsidies, and relevant regulatory arrangements. The optimisation model used in the study is introduced in Section 4, along with the details of the building being modelled and associated data. In Section 5, we present the outputs of the modelling, including cost-optimal PV design and consequent energy bill savings for each location and their dependence on specific influencing factors. In Section 6, we draw some conclusions, make some tentative policy suggestions for increasing PV deployment in this building sector, and identify some potential topics for future research.

## 2. State of the Art and Progress Beyond

In this section, we present a selective review of the literature pertaining to (Section 2.1) the deployment of shared PV in multi-occupancy residential buildings and (Section 2.2) between-country comparison of the conditions (climatic, economic and regulatory) impacting PV deployment. Section 2.3 summarises the context for our research and highlights the novelty of this paper.

### *2.1. PV Sharing in Buildings*

Deployment of shared PV in multi-occupancy buildings is of increasing importance as the twin drivers of reducing carbon emissions and constraining electricity costs favour an increased market share of decentralised renewable electricity generation combined with local self-consumption. While deployment on stand-alone housing was initially supported, in some Australian and European jurisdictions, by subsidised tariffs for export, self-consumption is now likely to be more financially attractive to households [5].

Although some countries have adapted their legislation to support PV sharing concepts, there are still multiple barriers hampering further PV uptake in different countries [6, 7, 8], including Australia [9], where a range of issues specific to apartment buildings have held back deployment in this building sector (which houses 13 % of families [10]) despite a significant opportunity [11]. Even in northern European regions, where PV may not achieve grid parity for individual single-family buildings, shared PV systems can achieve grid-parity when being implemented in energy communities (ECs) and efficiently combined with electrical heating systems [12]. This aligns with broader findings [13] that a PV community approach can be decisive for the profitability of PV. Specifically, PV sharing across ECs is shown to add value [14] at the medium scale and increase the cost-optimal PV potential for larger communities [15].

Shared use of PV enables higher self-consumption through aggregation of diverse household loads [16, 17], giving multi-occupancy buildings a profitability advantage, even without subsidy [18, 19]. Self-consumption can be further enhanced through co-location with battery storage [20], although profitability of battery storage is still hard to achieve [21].

Drivers of residential PV deployment are diverse, however, and include environmental, social and policy influences [22] as well as financial motivations. Besides the issues outlined above, future increased diffusion of PV in general - and PV sharing concepts specifically - will depend on the development of appealing business models [23, 24, 25].

### *2.2. Comparative Literature*

Besides the general literature focusing on PV integration and sharing in buildings and ECs, there is a limited selection of studies comparing drivers and barriers for diverse deployment levels for renewable energy, and especially distributed PV, between different countries.

A number of articles describe the impact of solar irradiation on the profitability of PV in different geographic locations, either within a country [26] or between different European countries [27]. Others focus on financial factors, assessing the profit-optimal PV size for European locations with similar climate but different financial settings [28].

Some authors have made global comparisons, combining climatic and financial considerations. Rodrigues et al. [29] identify economically optimal locations for PV system in countries worldwide, taking into account country specific radiation, subsidies and prices. Similarly, Keiner et al. [30] determine the cost-optimal technology mix for residential PV prosumers across all global regions, though the authors acknowledge that not all jurisdictional differences were accounted for.

Other researchers have compared the impact of different regulatory frameworks on PV deployment. Romero et al. [31] examine the characteristics of sustainable ECs and relevant legal support frameworks to explore the lack of sustainable ECs in Spain, relative to Germany. These factors are explored for European countries [32, 33, 34] and beyond [35]. A broad but compact overview of the global regulatory environment for PV sharing concepts, specifically in apartment buildings, is provided by [5], while [36] present a comprehensive analysis of the legal and regulatory frameworks available for collective ECs in nine EU countries.

### *2.3. Contribution*

The studies discussed above comparing PV implementation and PV sharing in different countries have focused either on the underlying legal regulatory (support) framework or on the techno-economic implications of different climatic conditions. In contrast, this study provides a holistic approach to comparing country-specific factors influencing PV diffusion in the growing multi-occupancy residential building sector. The influencing factors considered in this study are (i) climatic conditions, (ii) costs, tariffs and subsidies, (iii) type of heating and cooling appliances, (iv) residential building stock and (v) governance arrangements and regulatory environment.

Moreover, this study not only provides a theoretical comparison between the influencing factors in two contrasting countries, but also presents the results of a case study for a small multi-apartment building of a type commonly found in the housing stock of both countries (Australia and Austria). The impact of the different exogenous influencing factors on the profitability and the optimal installation capacities of shared PV are quantified. These results are presented in the context of the differences and similarities between the two countries, and the policy implications are discussed.

## 3. Exogenous Influencing Factors to PV Implementation

In this section, we discuss the range of exogenous factors that influence, directly or indirectly, the take-up of PV in the residential building sector. Factors including climate, PV capital costs and electricity tariffs directly influence the financial costs and benefits of PV deployment, while indirect influencing factors include the electricity market structure and regulatory regime, the age, design and construction of the housing stock, and arrangements for governance and ownership of housing.

### *3.1. Climate*

Climatic conditions have a significant impact on both the energy yield from a PV system (and, therefore, the cost of generated energy) and on the size and temporal distribution of energy demand for heating ventilation and cooling (HVAC). The highly dissimilar climates of Australia and Austria are described below and key metrics are compared in Table 1.

Australia's large land mass (approximately 7 690 000 km$^2$) spans over 30 degrees of latitude and over 40 degrees of longitude, while its 34 000 km of coastline is strongly influenced by ocean currents. Consequently, its climate is highly variable and includes large hot arid and semi-arid areas, pockets of Mediterranean and even Alpine climate, and tropical, sub-tropical and oceanic regions that include the main population centres. This study is focused on Sydney, Australia's most populous city (with over 5 million people, 21 % of the national population), which has an average annual global horizontal irradience (GHI) of 1700 kWh/m$^2$, at the midpoint of the national range of 700 kWh/m$^2$ to 2700 kWh/m$^2$.

Austria is a much smaller country with a surface of a little less than 84 000 km$^2$ located in Central Europe. Outside the mountain regions, therefore, the temperate and humid climate can be considered relative homogeneous, with annual solar exposure in the range of 1000 kWh/m$^2$ to 1300 kWh/m$^2$. Data for the capital city Vienna shows that within the last 40 years, the temperature has never exceeded 40 °C in summer, while in winter temperatures well below $-10\,°\mathrm{C}$ are recorded[2].

Table 1 shows key climate metrics for the two cites while Figure 1 shows the monthly variability of temperature and solar insolation. Note that, although Vienna's climate has much greater annual variability than Sydney, with winter minimum temperatures well below zero, average and maximum summer temperatures only differ by a few degrees between the two cities. However, Sydney enjoys average daily solar exposure almost 50 % higher than Vienna and has twice the average annual precipitation.

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[2] Weather data for Vienna originates from the weather station *Vienna - Hohe Warte* (202 m above sea level). These values deviate from the data of the weather station *Wien-Innere Stadt* in the city centre, which are higher due to the 'heat island effect' of cities.

| Metric | Unit | Sydney | Vienna |
|---|---|---|---|
| Mean annual maximum temperature | °C | $28.9^a$ | $33.6^b$ |
| Mean annual minimum temperature | °C | $8.9^a$ | $-12.4^b$ |
| Mean annual precipitation | mm | $1148^a$ | $643^b$ |
| Mean annual snowfall | cm | 0 | $72^b$ |
| Mean maximum windspeed | km/h | $120^a$ | $107^b$ |
| Mean daily global horizontal irradience | kWh/m$^2$ | $4.55^c$ | $3.10^d$ |

Table 1: Key climate data for Sydney and Vienna

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[a] 29 yr average to 2019[37]
[b] 68 year average to 2018[38, 39]
[c] 29 yr average to 2019[40]
[d] Representative year[41, 42]

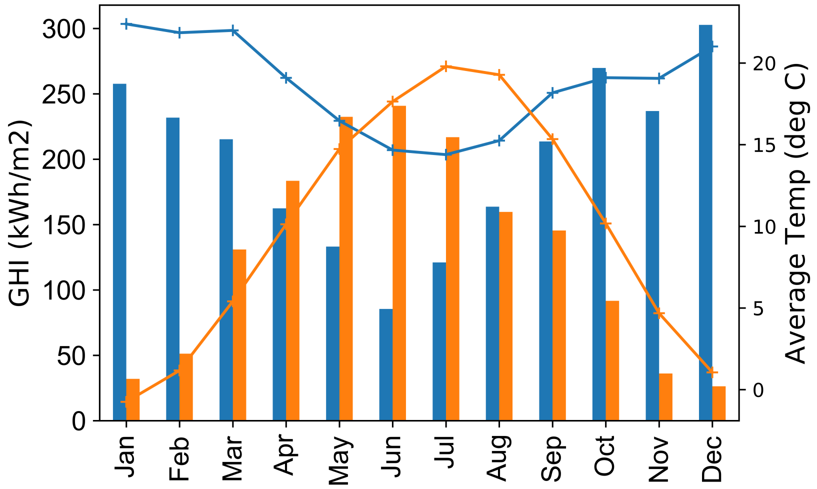

Figure 1: Average monthly Global Horizontal Irradience (GHI) in kWh/m$^2$ and average monthly temperature for a representative year in Vienna and Sydney.

### 3.2. Costs and Tariffs

In this section, the financial parameters likely to affect PV deployment in Australia and Austria are compared, specifically electricity prices, PV system costs and access to finance.

#### 3.2.1. Retail Market and Tariffs

Australia's residential customers are able to choose from a diverse and confusing array of tariffs [43]. These include competitive offers with flat or time of use volumetric rates, as well as a Default Market Offer (DMO) regulated to protect customers unable or unwilling to engage in regular switching between retailers. In 2018, typical flat rate volumetric tariffs were in the range 12 c/kWh[3] to 24 c/kWh [45]. Fixed charges for customers are high, due in part to high network charges which comprise around 44 % of residential electricity bills [46].

Similarly to Australia, Austria also offers a variety of retail electricity tariffs [47]: (i) flat rates with fixed volumetric rates over a specified time horizon, (ii) indexed tariffs based on the market value of electricity (e.g. based on the Austrian electricty price index), (iii) smart tariffs - also called time of use tariffs or (iv) interruptible tariffs. In Austria, flat rate tariffs do not differ significantly to the Australian ones and lie between 19.5 c/kWh [48, 49] and 20.7 c/kWh [50]. However, the fixed component of residential tariffs are significantly lower than in Australia, due to lower network charges comprising only around 25 % of bills.

In the absence of subsidised Feed-In-Tariffs (FiTs) (see Section 3.5), Australian retailers also offer market FiTs, with some states publishing recommended rates. In New South Wales (NSW), FiTs as high as 12 c/kWh are still available to residential customers, although these are likely to be bundled with relatively high volumetric consumption rates and FiTs of 3.2 c/kWh - 7.0 c/kWh are more common. FiTs are generally not available to commercial customers, which include apartment buildings that have aggregated their energy demand through an embedded network to utilise a single grid connection point. In Austria, retailers also offer market FiTs for surplus PV electricity feed-in. These tariffs vary with the retailer, but lie below the price for retail electricity purchase [51], while, for some customers, a fixed-rate, subsidised FiT is also available, as described in Section 3.5.

### *3.2.2. PV System Costs*

Although PV module costs are relatively homogeneous internationally, balance of system and installation costs show some variation. Moreover, installation costs are sensitive to system size and to building-specific factors. In NSW, typical installed cost for residential (5 - 10 kW) PV systems is 1100 EUR/kW, including taxes [52, 45], falling as low as 750 EUR/kW after government subsidies (Section 3.5). By contrast, installed system costs in Austria are significantly higher at around 1570 EUR/kW without subsidies [3, 53], and 1270 EUR/kW with subsidies [54] taken into account (Section 3.5).

For a range of technical and organisational reasons, costs for retrofitting infrastructure to apartment buildings are significantly higher than those for installation on new buildings, with anecdotal evidence of 50 % increases to per-Watt installation costs due to building height, roof types and wiring requirements for apartment buildings [11]. Meanwhile, in many older buildings, PV

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[3] All financial quantities are quoted in Euros and Euro cents, based on an exchange rate of AUD1.00 = EUR0.58 [44]

deployment must compete for investment funding with other sustainability upgrades, including increasing the efficiency of lighting, pumps and other loads or improving building thermal efficiency, which may give higher returns on investment. Even so, only approximately 1 % of the floor area of European buildings undergoes any type of sustainability retrofit each year [55].

#### *3.2.3. Finance*

The availability and cost of finance is dependent on the PV business model [56] and, to some extent, on the ownership and governance arrangements of the building. Where the building has a single owner (more common in Austria than Australia), the owner can make the PV investment and 'provide' electricity to residents. For buildings under multiple ownership, the owners' community or strata body can make the investment, provided split incentives between owner-occupiers and investment owners can be overcome. However, in Australia, finance costs may be higher for strata bodies than for individual owners as they cannot use the building as collateral for a secured loan. In all these cases, the appropriate discount rate to apply to the investment cost is dependent on the specific circumstances of the building owner or owners' community, including availability of reserves and access to loans, as well as on their appetite for risk given uncertain future electricity tariffs. Alternatively, a third party energy retailer or solar company can invest in the PV system and sell the generated electricity to residents (often under a power purchase agreement(PPA)) or (in Austria) lease the system to the building owners or residents.

### *3.3. Housing*

In this section, a comparison of the characteristics of the residential housing stock of Australia and Austria is presented, along with a brief outline of the dominant ownership models.

#### *3.3.1. Building Stock*

The prevalent residential building types in these two countries reflect their different population densities. Although 87% of Austria's nearly 2 million residential *buildings* in 2011 were detached houses, more than half of the *dwellings* were in buildings containing three or more units. In Australia, by contrast, 73 % of *dwellings* are detached houses, and only 14 % are apartments. Nevertheless, while Austria's 2.3 million dwellings in multi-occupancy buildings house 46 % of the population, Australia's 1.4 million apartments house 10 % of the Australian population and this proportion is growing, with less than 60 % of residential building approvals in 2019 being for houses [57].

In both countries, a large proportion of apartments are in smaller, low-rise buildings. In Austria, 71 % of apartment buildings contain ten or less apartments, while in Australia 60 % of apartments were in buildings of less than four storeys in 2016 (although higher-rise buildings are more common in recent construction). This is significant for PV deployment, as low-rise apartment buildings have greater per-dwelling solar rooftop potential [58].

| Dwellings | Australia (2016)[10] | Austria (2011)[59] |
|---|---|---|
| Detached Houses / buildings with one dwelling | 71 % | 47 %[a] |
| Semi-detached houses / buildings with 2 dwellings | 13 % | |
| Apartments / buildings with 3 or more dwellings | 14 % | 53 % |
| Approximate Total Dwellings | 9 705 500 | 4 300 000 |

Table 2: Proportion of dwellings by building type in Australia and Austria

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[a] In Austrian data [60], there is no distinction made between buildings with one or two dwellings.

### *3.3.2. Building Age and Energy Use*

In general, the heat load of dwellings in multi-occupancy buildings is significantly lower than for single-family buildings, due to smaller external wall (and ceiling and floor) areas resulting in lower heat losses. However, the apartment building stock in both countries is diverse in age, design and construction and, while some data is available for Austria, there is little quantitative information available about the Australian building stock. Many of Australia's older apartment buildings are two- or three-storey 'walkups', often brick-built, while recent years have seen an increase in medium- and high-rise buildings of more modern construction. However, many of these newer buildings have been found to have construction and safety defects, with one study finding that 97 % of apartment buildings constructed in NSW between 2003 and 2018 have at least one defect, predominantly related to waterproofing and fire safety systems [61]. These findings have impacted demand for new apartments and, along with reduced population growth and the impact of the COVID-19 pandemic, have resulted in a (likely temporary) decrease in the rate of apartment construction [62]

In Australia, all new residential buildings are subject to minimum country-wide energy efficiency requirements, detailed in the National Construction Code, as well as state-level performance standards. These are commonly verified through the Nationwide House Energy Rating Scheme (NatHERS) which rates thermal comfort on a scale of 0 to 10 stars. The average star rating of apartment buildings constructed in NSW increased from 5.7 to 6.4 between 2016 and 2020, while houses built in the year to May 2020 average 6.0. These newer apartment buildings have an average annual cooling load of 6.2 $\text{kWh/m}^2$ and heating load of 8.8 $\text{kWh/m}^2$, but this average figure masks high variability with 20 % of new apartment buildings rated 5.0 or less [63]. There is little empirical data available for older buildings, but anecdotal evidence suggests star ratings of 3.0 are not uncommon, with an equivalent annual heating and cooling load in Sydney of $27.0\,\mathrm{kWh/m^2}$.

Because of Austria's cooler climate, specific heating load for newer buildings in Vienna are around seven times the average heating loads for Australia, as shown in Table 3, which also demonstrates how the specific heating load of Austrian apartments and houses varies with the construction period [64].

| | Specific heat load in $\mathrm{kWh/m^2/yr}$ | |
|---|---|---|
| Construction period | Multi-apartment buildings | Single-family buildings |
| before 1919 | 145 | 245 |
| 1919-1944 | 160 | 270 |
| 1945-1960 | 145 | 265 |
| 1961-1970 | 125 | 235 |
| 1971-1980 | 115 | 225 |
| 1981-1990 | 80 | 180 |
| after 1990 | 60 | 160 |

Table 3: Austrian building standard for specific heat load in apartments and houses, by construction period [64].

### *3.3.3. Heating and Cooling*

Since HVAC can account for a significant proportion of residential loads, consideration of the energy sources and technologies used in each country is necessary. In Austria, space heating in multi-apartment buildings is predominantly supplied by gas [65], while electric cooling is rarely deployed. While gas heating also exists in some older Australian apartment buildings, and many households still have no heating provision, split system electric air-conditioning now predominates, in part because of its ability to provide cooling in addition to heating services.

### *3.3.4. Building Ownership*

The ownership and governance arrangements for multi-occupancy buildings affect the availability of finance and the decision-making process for building upgrades, including installation of sustainability infrastructure such as rooftop PV. In particular, investment decision making can be more challenging when multiple owners are involved and can be further complicated by split incentives between owners and residents. Similar ownership arrangements exist in both these countries, but the proportion of apartments governed under each structure diverge.

Common types of sole ownership include:

- Private entity: Owned by private individual or company.

- Social housing: Owned by government housing authority.
- Cooperative or community housing: Owned by not-for-profit housing co-operative or community group.

Under sole ownership, the owner is able to develop the property, but may lack commercial incentive to invest in a PV system or other sustainability infrastructure where the benefit rather flows to tenants. Conversely, for social or community housing, sustainable investment can create benefit for (sometimes vulnerable) tenants.

Although there are a number of possible arrangements to facilitate ownership of an apartment building by multiple owners, the majority of shared properties in both these countries are owned under Strata Title or Condominium Ownership, which entails joint ownership of the building structure and grounds, so that development of or changes to the building structure require agreement between owners. In Austria, this requires a majority of owners to agree, while, in Australia, the details of governance arrangements (including the type of majority needed) vary between states and the type of proposed development [11]. New apartment buildings are usually owned and built by a single developer who has the opportunity to invest in solar prior to establishing the strata body or selling individual apartments, without the complexity of collective decision making. PV deployment is therefore likely to be easier to achieve for new buildings than for brownfield sites.

In both countries, approximately two thirds of apartments are rented[4]. However, looking at rentals across all housing types, in Austria, 17 % of tenants are in social housing, 39 % in cooperative housing and only the remaining 44 % pay rent to a private landlord [67]. In contrast, 82 % of Australian tenants pay rent to a private landlord or real estate agent, while only 12 % live in social housing and 2 % rent from a co-operative or community organisation [10].

### *3.4. Regulation relating to shared PV*

This section compares regulatory and legislative environments in the two countries that affect PV implementation in apartment buildings. While Austria has enacted specific legislation to enable PV sharing in residential buildings, in Australia, PV sharing is allowed by omission but faces a range of regulatory barriers.

Different technical arrangements are possible to facilitate deployment of PV to meet apartment energy loads [17]:

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[4] In Australia, 32 % of apartments are owner-occupied and 66 % are rented (excluding ’Not stated’ and ’Not applicable’ categories) [10] while, in Austria, 26 % of dwellings in buildings of three or more dwellings are owner-occupied and 67 % are rented [66].

(1) Individual PV systems for each apartment: Applying PV generation to the energy used in a single apartment is analogous to the arrangement in houses, and has been implemented for some new build and retrofitted buildings in Australia, but is relatively rare - though theoretically permitted - in Austria. Where the building is under multiple ownership, however, there is administrative complexity around the equitable allocation of shared roof resources to individual apartment owners and, regardless of ownership arrangements, the use of multiple small systems incurs higher investment costs and results in lower self-consumption than a shared system. In Australian strata buildings, this type of deployment requires a 'strata bylaw' to be passed by the building owners.

(2) Shared PV system distributed 'behind the meter': In Austria, amendments to the *Electricity Industry and Organization Act* [68], which came into force in 2017, specifically allow the implementation of behind-the-meter shared PV systems in buildings with more than one apartment. In this arrangement, residents continue to buy grid electricity from a retailer through their usual meter and purchase solar generation through a secondary distribution and metering system (which increases the investment cost). In Australia, this arrangement is allowed provided the sale of the solar energy is by an authorised energy retailer or arranged under a PPA.

(3) Shared PV system connected through an embedded network (EN): If a shared PV system is connected within an EN or microgrid, the generated energy can be bundled with grid electricity (purchased at commercial tariffs[5] through the main grid connection point, leveraging the aggregated building demand) and sold to apartment residents. If the EN is owned and operated by the building owners, the dual benefits of lower grid electricity cost and cheap PV generation can be passed on to apartment owners and, potentially, residents. However, changes to Australian retail energy law, focused on extending competitive electricity market access to apartment residents, set a high administrative barrier to establishing an EN. Although allowed under the 2017 legislation, the authors are not aware of any existing embedded networks in Austrian apartment buildings.

(4) Peer-to-peer (P2P) energy trading: Where apartments have their own individual PV system (as in (1) above) or an allocated portion of a shared system, they may be able to trade their generated energy with other apartment residents. This trading will either utilise the distribution grid infrastructure (which, in Australia, incurs high Distribution Use of Service charges) or requires an embedded network (with the difficulties outlined in (3)), which has been trialled in one Western Australian apartment building [69]. In Austria, P2P trading is allowed within buildings, while trading be-

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[5] Commercial tariffs generally have lower volumetric rates than residential, although they may be combined with peak demand charges.

tween multiple buildings is currently the subject of pilot projects and the legislative framework to enable P2P trading between multiple buildings is under development[6].

### *3.5. Government Incentives for PV Deployment*

In both Australia and Austria, policy measures used to support PV deployment on residential buildings, have included sudsidised Feed-In-Tariffs (FiTs) and capital subsidies [3, 45]. However, in Australia, the high FiTs (around 35 c/kWh) funded by state governments to stimulate widespread deployment of residential PV have now been closed, bar some legacy arrangements, although market FiTs are still available for solar households (see 3.2.1).

In Austria, ’tariff subsides’ (FiTs) are mandated annually, valid nationwide and applied for 13 years [54, 72]. The relevant body, *Oemag*, buys exported rooftop PV generation with a 2020 tariff of 7.67 c/kWh[54, 72]. The FiT is only available for PV systems between 5 kW and 200 kW [73] and up to a total annual subsidy budget of 8 000 000 EUR, allocated according to the proportion of self-supply and the time of application [73, 72]. For owners dissatisfied with *Oemag's* tariff offer, or having PV systems below 5 kW or above 200 kW, or if the *Oemag* budget is fully utilised, there is the option of selling surplus PV to the retailer[7] as described in Section 3.2.1. The low FiT rates in both countries act as an incentive for PV systems designed to maximise self-consumption, which includes shared PV systems in apartment buildings.

Both countries also provide investment subsidies towards the purchase and installation costs of a residential PV system. In Australia, these take the form of Small-scale Technology Certificates (STCs) [74]. One STC is generated for each MWh of renewable energy assumed to be generated by the PV system and can be traded at a market rate, around 23 EUR [75], which is equivalent to a discount of approximately 35 c/W on the installation price of a 10 kW PV system in Sydney. In Austria, the federal government provides a grant of 27.5 c/W for rooftop systems up to 5 kW or 25 c/W for systems under 100 kW, up to a maximum 30 % of the total investment cost [3].

Australian state and territory governments also operate a number of incentive schemes for residential PV (and battery) deployment, but these are generally short-term and often exclude multi-occupancy dwellings. In Austria, besides the nationwide valid subvention schemes, it is possible for federal states to apply individual incentive schemes for PV and/or battery storage [76][8]. Such individual incentives are provided for business as well as residential buildings.

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[6] based on the European document *Clean Energy for all Europeans Package* and more specifically the *Renewable Energy Directive* [70] and the *Electricity Market Directive* [71].

[7] End-users can access a FiT either from their retailer or from *Oemag*, not both.

[8] For example, in Lower Austria there is the possibility of subsidising a photovoltaic system in combination with thorough building renovation.

### 3.6. *Observed effects of direct and indirect influencing factors*

In 2018, Austria had deployed less than 1.5 GW of PV in total, almost all of it connected to the distribution network [3]. In 2016[9] 88.3 % of PV was deployed on the roof or the facade of buildings [77]. Although it is not known what proportion of this is on residential buildings, the total amount of residential PV is likely significantly below 1.3 GW. By contrast, 51 % of Australia's 17.6 GW of installed PV is on residential buildings [4]. This discrepancy is likely the result of multiple factors, including Australia's higher solar resource and consequent PV yield and lower PV investment costs. However, a significant factor in Australia's high residential solar deployment is the country's proportion of stand-alone or semi-detached dwellings, driven by low population density compared to Austria and many other countries, and comparatively low proportion of rental properties.

Whilst, for houses (whether detached, semi-detached or terraced), there is a clear correspondence between a roof area and the dwelling below (which are often both owned by a single household), apartment buildings entail more complexity, in both the physical and governance relationships, which make PV deployment more challenging. Austria has legislated to support shared PV systems in these buildings, though without, to date, substantive changes to the deployment rates, in part because of organisational and bureaucratic barriers and remaining regulatory uncertainty. Meanwhile, Australia's reliance on a regulatory structure that favours individual market participation over co-ordinated engagement has also failed to deliver deployment in this sector.

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[9] Prior to the amendment of the *Electricity Industry and Organization Act* which allowed PV sharing concepts in multi-apartment buildings.

## 4. Model and Method

The previous section highlighted both differences and similarities between the climatic conditions, building stock (building standards), costs and tariffs and regulatory contexts of these two countries. The combined influence of these factors results in high residential PV penetration in Australia compared to Austria, but low PV deployment on apartments in both countries. The aim of the following analysis is to identify the impact of these exogenous factors on cost-optimal PV installation capacities and on residents' financial benefits, expressed as net present value (NPV). The optimisation model used to conduct this analysis, with the objective of maximising the residents' NPV, is introduced in Section 4.1. In Section 4.2, the building under investigation is presented and parameters for the case studies are defined. Section 4.3 describes the load and PV generation data used for the study, Section 4.4 describes the heating and cooling loads and Section 4.5 sets out the financial settings for the analysis.

### *4.1. Optimisation Model*

An optimisation model is set up to maximise the building residents' NPV over a specified time horizon. In the course of the NPV maximisation it is determined whether installing a PV system has a positive impact on the residents' or building owners' finances. Where PV system installation is profitable, the cost-optimal PV system capacity is determined. This analysis concerns the aggregated financial outcomes for all apartment residents; details of how costs and benefits are distributed between different stakeholders are beyond the scope of this article.

The NPV calculation in its original form (Equation 1) juxtaposes upfront investment costs $I_0$ (e.g. for installation of PV systems) with the sum of properly discounted future cash-flow streams. A cash flow stream is defined as annual revenues $R(y)$[10] minus annual costs $C(y)$ (for heat, electricity and cooling as well as technology maintenance costs).

$$NPV = -I_0 + \sum_{y=1}^{Y} \frac{(R(y) - C(y))}{(1+z)^y} \tag{1}$$

Significant factors for the NPV calculation include the different cost terms, the discount rate $z$ and the time horizon of investigation $Y$.

The optimisation model is subject to a variety of constraints, of which the most important are the necessity to supply the electricity load, heating and cooling demand at all times:

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[10] In this specific implementation, $R(y)$ is always zero as the model assumes a FiT of zero (Section 4.5).

- The underlying electricity load (excluding HVAC) can be supplied by PV generation (where a PV system is determined to be profitable and has therefore been installed) or by grid-purchased electricity.
- For a building with electric heating, the conventional electricity load is enlarged by the heating demand; for gas heating the cost of gas energy demand is calculated separately.
- For a building with cooling demand, the conventional electricity load is enlarged by the cooling demand.

The PV system is modelled (Equation 2) such that the PV generation, which is determined by the installed PV capacity (optimisation variable) and the location-specific climate data, is applied to the electricity load $e_{pv2eload}(t, y)$ (which may include HVAC load), with any surplus PV generation fed into the grid $e_{pv2grid}(t, y)$.

$$\sum_{d} P_{pv}(d) \cdot IRR_{solar}(d, t, y) = e_{pv2eload}(t, y) + e_{pv2grid}(t, y) \tag{2}$$

The model determines the cost-optimal energy flows as well as the cost-optimal PV capacity. Where a PV system is found not to be profitable, the optimisation model would determine the optimal PV capacity to be zero. Specific variable/parameter definitions are to be found in Table 4.

| Abbreviation | Explanation | Classification |
|---|---|---|
| $C(y)$ | Annual costs | Variable |
| $I_0$ | Upfront investment costs | Variable |
| $IRR_{solar}(d, t, y)$ | Solar irradiation per direction, year and timestep | Input data |
| $NPV$ | Net present value | Optimisation objective |
| $P_{pv}$ | Cost-optimal PV capacity | Optimisation variable |
| $R(y)$ | Annual revenues | Variable |
| $Y$ | Time horizon in years | Input data |
| $d$ | Direction (North/South/East/West) | - |
| $e_{pv2eload}(t, y)$ | PV electricity for electricity load coverage | Optimisation variable |
| $e_{pv2grid}(t, y)$ | Surplus PV electricity feed into the grid | Optimisation variable |
| $t$ | Timestep (35040 quarter-hours per year) | Control variable |
| $y$ | Year | Control variable |
| $z$ | Interest rate | Input data |

Table 4: Nomenclature

### *4.2. Building Set-Up and Case Study Definition*

In order to quantify the impact of a variety of factors on the profitability of residential PV sharing and according optimal PV system sizes, a simulated three-storey multi-apartment building with nine residential units (typical of the building stock in both Sydney and Vienna) is chosen for investigation. The building specifications (Table 5), including dimensions, building quality and roof slope (as described in Appendix B) are assumed equal in both locations, while variable characteristics, including the type of heating system implemented and jurisdictional-specific electricity tariffs and PV installation costs are applied as appropriate. The model parameters are illustrated in Figure 2.

| **Metric** | **Vienna** | **Sydney** |
|---|---|---|
| Basic electricity load[a] | Nine real-measured apartment profiles | |
| HVAC | Gas heating only | Electric heating and cooling |
| Specific heat load | $145\,\text{kWh/m}^2\text{/yr}$ | N/A |
| Array tilt | 30 °C | 30 °C |
| Array orientation | South | North |

Table 5: Characteristics of Sydney and Vienna buildings used in the optimisation model

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[a] excluding HVAC

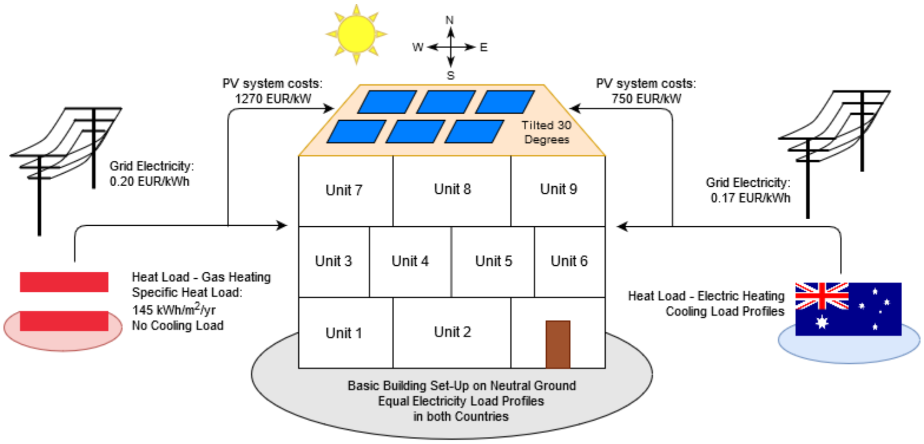

Figure 2: Case study illustration

### *4.3. Load and Generation Data*

The nine residential units in the building are allocated real measured apartment household load profiles at a 15-minute resolution. Excluding HVAC loads, the likely difference between household demand of apartments situated in Vienna and Sydney is considered to be insignificant compared to the impact of other household and apartment characteristics. The same data has therefore been used for both locations, sourced from a datset of 30-minute interval load data for 13 700 NSW households [78]. Load profiles were filtered for apartments (as opposed to houses) and for households without air-conditioning (heating or cooling) infrastructure, as indicated by the associated survey data. Moreover, to ensure the analysis remains robust to the diversity of apartment load profiles within the dataset [79], three selections of nine buildings (identified below as buildings *b1*, *b2* and *b3*) are used independently as inputs to the model. Common property loads for this type of apartment building are usually very low, often comprising only a few light fittings [17], and have been disregarded for this analysis. The average daily load profiles for each building are shown in Appendix A and annual electricity demand for each building is shown in Table 6.

| **Abbreviation** | **Description** | **Annual electricity load** |
|---|---|---|
| *b1* | Multi-apartment building 1 | 27 289 kWh/yr |
| *b2* | Multi-apartment building 2 | 23 771 kWh/yr |
| *b3* | Multi-apartment building 3 | 28 310 kWh/yr |

Table 6: Abbreviations and total annual load for the three buildings modelled

The solar PV generation for each location is calculated per kW-peak, using the PVWatts Model in NREL's open-source software tool SAM [80]. For Sydney, a weather file (solar irradiation, temperature and wind speed) derived from Bureau of Meteorology data for a 'Reference Meteorological Year' was used [81], while the weather file for Vienna used data for a representative year from the database of the Energy Economics Group, TU Wien [41] and ZAMG (Austrian metereological institute) [42]. The PV array modelled[11] is orientated at 180 ° and 0 ° for Vienna and Sydney, respectively, with modules tilted at 30 ° (which is approximately the optimum array tilt to maximise annual energy generation for both cities, despite their different latitudes).

The annual solar PV generation determined by SAM is 780 $\mathrm{kWh/kW_{dc}}$ and 1409 $\mathrm{kWh/kW_{dc}}$ in Vienna and Sydney, respectively (equivalent to 936 $\mathrm{kWh/kW_{ac}}$ and 1691 $\mathrm{kWh/kW_{ac}}$). Note that the system generates 81 % more energy in Sydney than in Vienna, due to the combined effect of higher solar exposure and higher solar elevation at lower latitude.

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[11] SAM default system settings were used for the study, i.e. DC to AC ratio of 1.2, inverter efficiency of 96 % and total losses of 14 %.

### *4.4. HVAC Energy Demand*

As described in Section 3.3.3, HVAC requirements are very different between these two cities. In order to explore the impact of this, two scenarios have been modeled. In the first scenario (Section 5.1) the same energy requirements are assumed in both countries, with no HVAC load included (pure conventional electricity load only). In the second scenario (Section 5.1), a gas-fuelled heating load is considered in the Austrian context, while the Sydney apartment load profiles are increased to allow heating and cooling using split-system air-conditioning. This additional HVAC load profile is derived using the SGSC dataset (Section 4.3) as the difference between the average load profile for apartments with split system air-conditioning and the average load profile for apartments with no air-conditioning. The resultant profile (Figures A.13 and A.14), shows both summer and winter HVAC load, with higher morning and evening peaks in winter. This average HVAC load has been added to each apartment load for the second scenario.

### *4.5. Financial Parameters*

Table 7 shows the location-specific cost parameters used as inputs to the model. Note that PV investment costs include currently available subsidies in each country (Section 3.5); although these subsidies are expected to be phased out over time, customer investment costs are unlikely to increase substantially as capital costs are also expected to decline. Sensitivity to removal of investment subsidies (without the benefit of reduced capital costs) is shown in Section 5.5. Although modest residential feed-in tariffs are currently available in both countries, policies to support self-consumption and low (or negative) wholesale costs as PV penetration increases may see them phased out over time. Since the focus of this analysis is on shared PV for self-consumption, zero payment for export has been assumed.

By using identical building characteristics (size, thermal properties, roof form, basic electricity load) for both locations, the impact of different exogenous country-specific factors on the profitability of PV systems and optimal installation capacities can be quantified.

| **Description** | **Costs** | |
|---|---|---|
| | Vienna | Sydney |
| PV System | | |
| PV investment costs | 1270 EUR/kW | 750 EUR/kW |
| PV maintenance costs | 60 EUR/yr | 60 EUR/yr |
| PV cleaning costs | 2.5 EUR/m$^2$/yr | 2.5 EUR/m$^2$/yr |
| Electricity Tariff | | |
| Volumetric charge | 0.20 EUR/kWh | 0.17 EUR/kWh |
| Fixed retail charge | 110 EUR/yr | 183 EUR/yr |
| Feed-in tariff | 0.00 EUR/kWh | 0.00 EUR/kWh |
| Gas Tariff | | |
| Volumetric charge | 0.05 EUR/kWh | no gas heating |
| Maintenance gas heating | 150 EUR/yr | no gas heating |
| Other | | |
| Discount rate[a] | 6 % | 6 % |
| Time horizon | 20 years | 20 years |

Table 7: Financial settings for Vienna and Sydney used in the model

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[a] A discount rate of 6 % is assumed, to allow for inflation and a level of investment risk.

## 5. Results - Profitability and Optimal Sizing of PV

This section shows the impact of different exogenous influencing factors on the profitability and optimal capacities of implementing PV systems by comparing results for Sydney, Australia (SYD) and Vienna, Austria (VIE).

The impact of exogenous influencing factors is quantified by first determining the cost-optimal PV system capacities for the individual case studies, along with the assessment of the achievable reductions in the energy bills, without heating or cooling loads ('noHVAC') in Section 5.1. The impact of including appropriate heating and cooling ('HVAC') loads is then shown in Section 5.2. The impacts of differential solar exposure and retail electricity tariffs are explored in Sections 5.3 and 5.4 respectively, and sensitivity to removal of investment subsidies is examined in 5.5.

The cost reduction $C_{red}$ is calculated as described in Equation 3.

$$C_{red} = \frac{NPV_{noPV} - NPV_{withPV}}{NPV_{noPV}} \tag{3}$$

### 5.1. Base case: no HVAC

Figure 3 shows the results for cost-optimal PV system implementation in Vienna and Sydney if heating and cooling loads are not taken into account. Optimal system size is in the range 4.0 kW to 5.5 kW for Vienna and 6.0 kW to 7.0 kW in Sydney. This low optimal size, compared to typical system sizes installed on Australian houses, is due in part to the lower household load of apartments [79], but is also a consequence of modelling a zero-FiT scenario, which results in self-consumption of 89 % of PV generation in Vienna and 66 % in Sydney. Although the Sydney system has lower investment cost, higher annual generation and, therefore, lower energy cost, it is offsetting cheaper grid electricity than in Vienna, which has the effect of moderating the increase in cost-optimal system capacity. However, the achievable cost reduction in Sydney is up to five times that of Vienna. The results show little variation between the three buildings, suggesting that aggregation of the diverse load profiles within each buildings largely eliminates random variability between the selected load profiles.

### 5.2. Impact of HVAC loads

If heating and cooling loads for each location are considered, the difference in optimal PV capacity and cost reductions become more obvious, as shown in Figure 4. For Vienna, it is evident that consideration of HVAC has no impact on the cost-optimal PV capacities (compared to Figure 3), since the building is gas heated in this location. However, consideration of (gas) heating costs as well as electricity costs significantly reduces NPV and, therefore, cost savings due to PV are significantly reduced as a proportion of total energy costs (Equation 3).

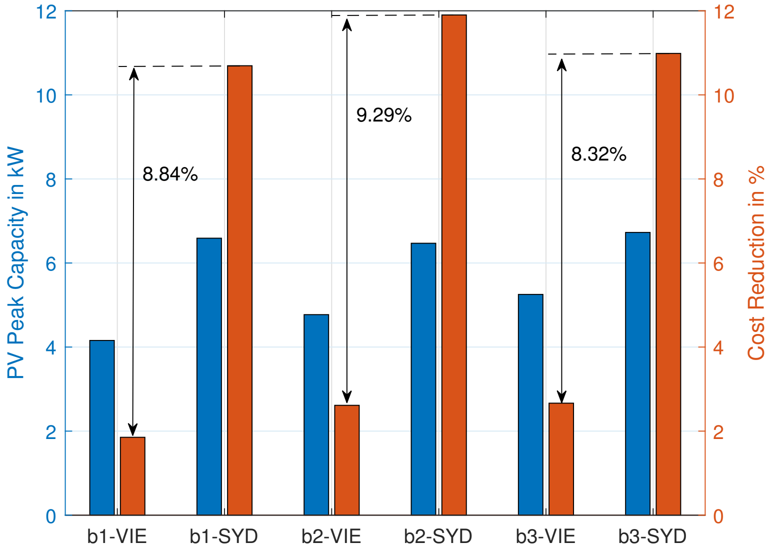

Figure 3: Cost-optimal PV system size and cost reduction, without consideration of HVAC

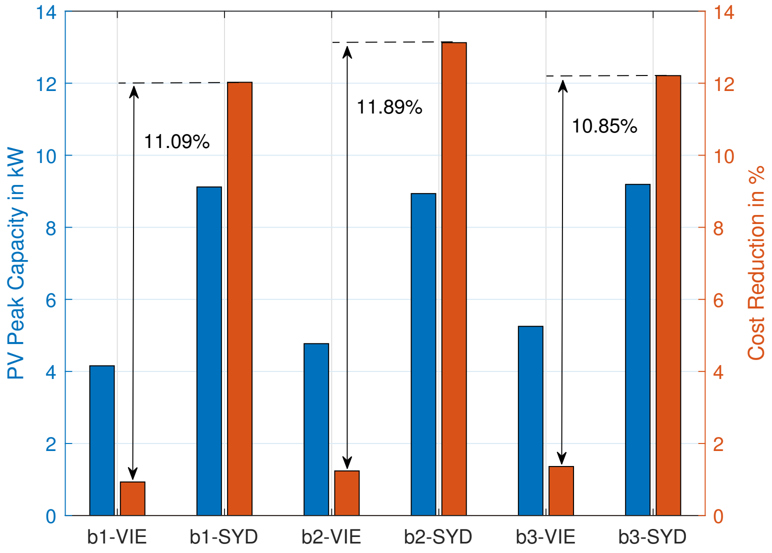

Figure 4: Cost-optimal PV system size and cost reduction, HVAC considered

For Sydney, however, addition of HVAC increases the cost-optimal PV capacity to meet the increased electrical load. As the increased PV generation is applied to the total (base plus HVAC) load, the proportional cost reductions are also increased. As shown in Figure 5, addition of HVAC loads increases the cost optimal PV system size by approximately 2.5 kW or 36 % - 38 % of the optimal size without HVAC, due to the high proportional increase in load (Table 8). The increase in proportional cost reduction when applying PV generation to aggregated Base + HVAC load can be understood with reference to Figures A.14 and A.16 which show summer cooling loads having a relatively high daytime component, thereby aligning with peak summer PV generation.

| Building | HVAC as % of total electricity load | Increase in optimal PV capacities[a] |
|---|---|---|
| *b1* | 25.9 % | 38.4 % |
| *b2* | 28.6 % | 38.1 % |
| *b3* | 25.2 % | 36.7 % |

Table 8: Contribution of HVAC to total load and its impact on cost-optimal PV system size in Sydney

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[a] Difference between PV capacities (with and without HVAC considered) divided by the base case optimal PV capacity.

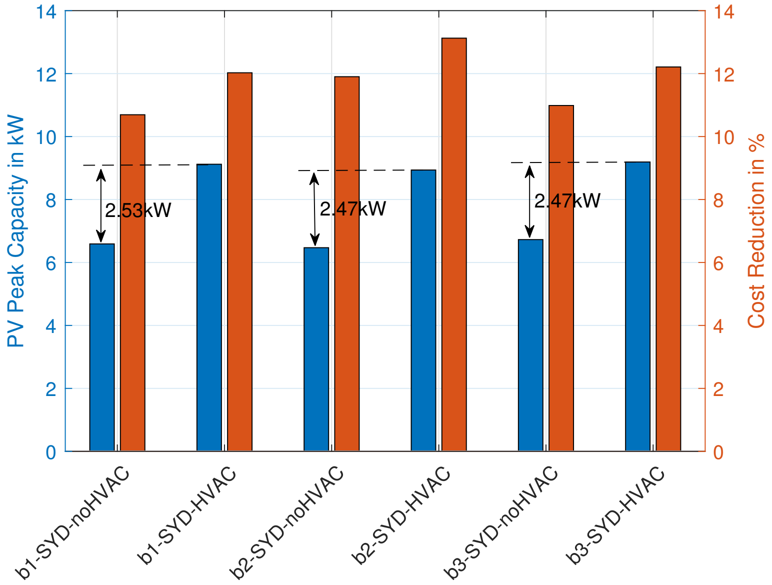

Figure 5: Cost-optimal PV system size and cost reduction for Sydney, with and without HVAC

### *5.3. Impact of Solar Irradiation*

As discussed in Section 5.1 the relatively small difference in cost-optimal PV installation capacities in Sydney and Vienna for the default setting is due, in part, to the higher solar exposure and therefore PV output in Sydney. However, this result is also affected by differential retail tariffs and PV installation costs. Therefore, to be able to isolate the influence of the solar irradiation, the retail electricity prices and PV system investment costs are levelled for Vienna and Sydney (to the average of the respective costs in both locations). The results given in Table 9 are calculated with the following levelised costs/prices for both locations:

- Volumetric electricity charge: 0.185 EUR/kWh
- Fixed electricity charge: 146.5 EUR/yr
- PV system installation costs: 1010 EUR/kW

| | | Cost Reduction (%) | | Cost-optimal PV capacity(kW ) | |
|---|---|---|---|---|---|
| | | HVAC | No HVAC | HVAC | No HVAC |
| *b1* | VIE | 1.31 | 2.61 | 4.85 | 4.85 |
| | SYD | 11.12 | 10.03 | 8.09 | 5.85 |
| *b2* | VIE | 1.68 | 3.56 | 5.52 | 5.52 |
| | SYD | 12.25 | 11.29 | 7.94 | 5.81 |
| *b3* | VIE | 1.82 | 3.58 | 6.00 | 6.00 |
| | SYD | 11.33 | 10.33 | 8.17 | 5.96 |
| Average | VIE | 1.60 | 3.25 | 5.46 | 5.46 |
| | SYD | 11.57 | 10.55 | 8.07 | 5.87 |

Table 9: Comparison of cost-optimal PV capacity and achievable cost reduction, with and without HVAC, using levelised electricity price and PV investment costs

Table 9 shows a comparison of the cost-optimal PV system size and proportional cost reductions achievable (with and without consideration of HVAC) with these levelised costs. Without HVAC, the average optimal PV system size in Sydney is only 7 % higher than in Vienna, but the average cost reduction is 10.55 %, compared to only 3.25 % for Vienna. With consideration of HVAC loads, the average optimal PV system size for Sydney increases to 8.07 kW and the average cost reduction increases to 11.57 % while, for Vienna (with no change in system size), the average cost reduction falls to 1.6 % of total energy costs.

### *5.4. Impact of Electricity Prices*

To understand the impact of the volumetric electricity price on achievable cost savings, the analysis is repeated with the volumetric tariff components interchanged, so that the cost in Sydney is raised from 0.17 EUR/kWh to Viennese levels of 0.20 EUR/kWh while the Viennese price is lowered to 0.17 EUR/kWh. The results for the base scenario are summarised in Figure 6 and those with consideration of HVAC are shown in Figure 7. Table 10 gives an overview of cost reduction and PV system sizes for both scenarios.

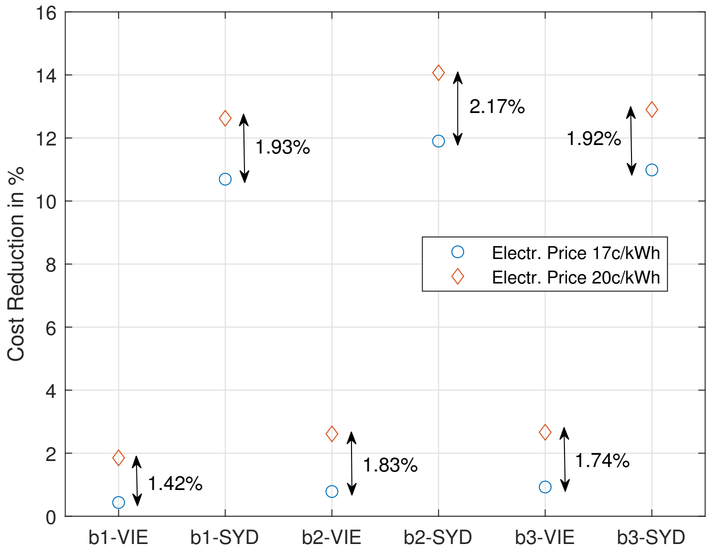

Figure 6: Impact of varying retail electricity prices on the overall energy cost reduction, without consideration of HVAC

Figure 6, where no HVAC load is considered, shows the 3 c/kWh cost difference in retail electricity prices results in an overall energy cost reduction difference between one 1 % and 2 % in most cases. However, it should be noted that those small cost differences are more significant in Vienna, where achievable cost reductions are in the range 0.5 % - 3 %, than in Sydney where 10.5 % - 14 % savings are achievable. Thus, the impact of a change in volumetric retail electricity prices has a greater impact in jurisdictions with limited profitability of PV than where high cost savings are already achievable due to other factors such as high solar irradiation.

With HVAC loads considered, the impact of the 3 c/kWh tariff change on achievable cost savings as a proportion of total energy costs remains at around 2 % in Sydney (Figure 7), although it should be noted that this represents a smaller impact on absolute savings than for the base scenario. In Vienna, by contrast, the proportional impact of the 3 c/kWh tariff change is approximately

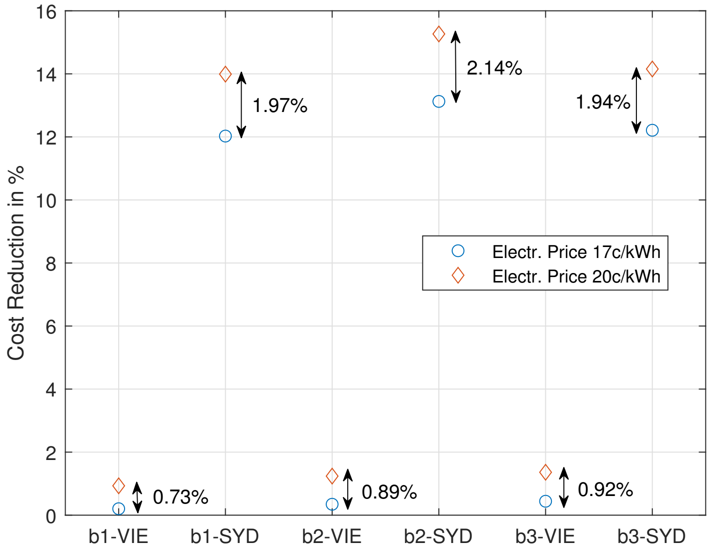

Figure 7: Impact of varying retail electricity prices on the overall energy cost reduction, with HVAC considered

halved if HVAC is considered, as it has no impact on the cost of the HVAC gas bill.

| | | Electricity Price in EUR/kWh | Cost Reduction in % | | Cost-optimal PV Capacity in kW | |
|---|---|---|---|---|---|---|
| | | | HVAC | No HVAC | HVAC | No HVAC |
| *b1* | VIE | 0.2 | 0.93 | 1.85 | 4.16 | 4.16 |
| | | 0.17 | 0.20 | 0.44 | 3.22 | 3.22 |
| | SYD | 0.2 | 13.99 | 12.63 | 10.10 | 7.36 |
| | | 0.17 | 12.03 | 10.69 | 9.12 | 6.59 |
| *b2* | VIE | 0.2 | 1.24 | 2.61 | 4.77 | 4.77 |
| | | 0.17 | 0.35 | 0.78 | 3.79 | 3.79 |
| | SYD | 0.2 | 15.27 | 14.07 | 9.90 | 7.16 |
| | | 0.17 | 13.13 | 11.90 | 8.94 | 6.47 |
| *b3* | VIE | 0.2 | 1.36 | 2.66 | 5.25 | 5.25 |
| | | 0.17 | 0.44 | 0.93 | 4.26 | 4.26 |
| | SYD | 0.2 | 14.15 | 12.90 | 10.22 | 7.46 |
| | | 0.17 | 12.21 | 10.99 | 9.19 | 6.73 |

Table 10: Impact of varying the volumetric component of the retail tariff on cost-optimal PV size and achievable cost reductions

### *5.5. Impact of Higher PV System Costs*

Since the PV system investment costs shown in Table 7 include subsidies per kW of installed PV capacity, this Section examines the differences in optimally installed PV system capacities if PV system costs are considered without subsidies. This means that in Sydney the PV installation costs are increased from 750 EUR/kW to 1100 EUR/kW, and in Vienna from 1270 EUR/kW to 1570 EUR/kW.

As expected, the higher the PV system installation costs, the less profitable PV system installation becomes. As a result, the cost-optimal PV system installation capacities shrink in this scenario along with the cost saving potential, in comparison to the default setting with lower, subsidised investment costs. Figures 8 and 9 show a comparison of optimal PV installation capacities and consequent cost savings for the scenarios with and without HVAC taken into consideration. Note that the removal of subsidies significantly reduces optimal system size and cost savings in both countries, with and without consideration of HVAC, and that, in Vienna, this results in cost savings below 1%.

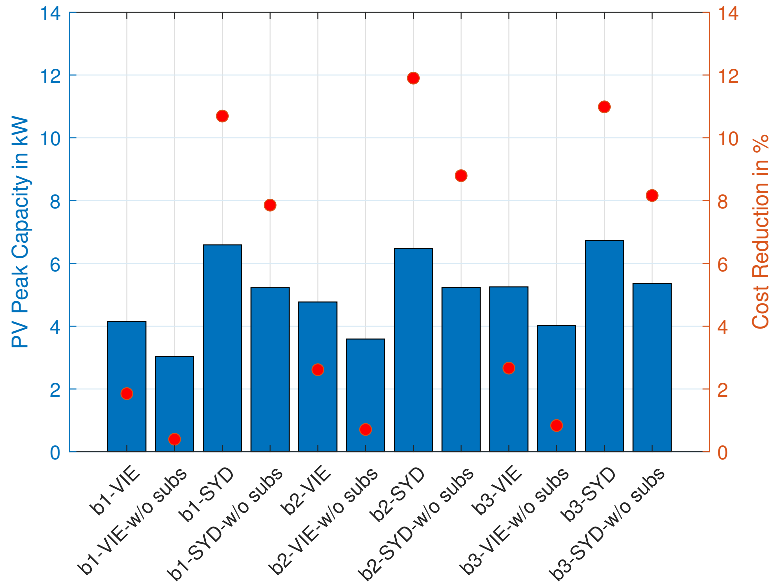

Figure 8: Comparison of optimal PV capacities and cost savings for PV prices with and without subsidies, without consideration of HVAC

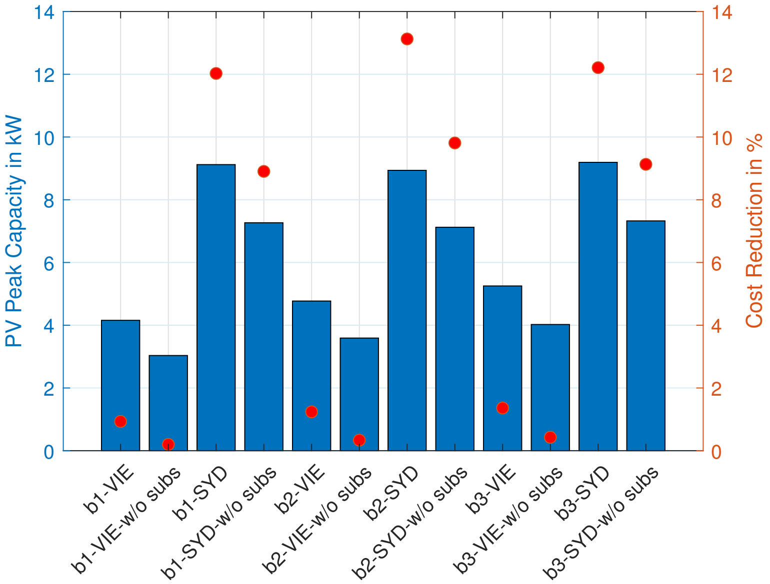

Figure 9: Comparison of optimal PV capacities and cost savings for PV prices with and without subsidies, with HVAC considered

## 6. Discussion and Conclusion

The quantitative analysis presented above examines the impact of a range of exogenous factors on the optimum PV system size and the achievable cost savings for apartment buildings in Australia and Austria.

*Climate* - perhaps the most obvious difference between these two locations - has a dual impact. Firstly, the greater solar exposure in Australia increases the PV energy yield and, combined with lower *investment costs* in Australia's mature PV market, increases the cost-competitiveness of PV generated electricity. Although, on average, this results in only a 23 % increase in the cost-optimal PV system size (for the scenarios without HVAC) in Sydney relative to Vienna, the achievable cost-savings are more than four times higher. Secondly, Sydney's associated higher temperatures also create a cooling demand that has some alignment with PV generation and contributes to cost-optimal system sizes approximately 50 % larger in Sydney than in Vienna (for the scenarios with HVAC). This result also highlights the significance of the use of split-system air-conditioning in many Sydney apartments, to provide both heating and cooling, in increasing year-round electricity demand, though it should be noted that different outcomes would be obtained in other Australian jurisdictions where either heating or cooling loads dominate.

The influence of Australia's lower retail *electricity tariffs* reduces both the achievable savings and the cost-optimal PV system size (Table 10). The results suggest that lowering Austrian tariffs to Australian levels (so from 20 c/kWh to 17 c/kWh) would have a much greater negative impact (proportionally) on PV cost savings in that country and would therefore likely impede Austrian PV deployment. Removal of government investment subsidies, without equivalent market-led capital cost reductions, would significantly reduce PV deployment in either country and, in Austria, would almost eliminate potential bill savings. Note also that availability of FiTs for solar export from apartment buildings would increase the optimal system size and achievable savings.

The impacts of climate, HVAC technology, PV costs, investment subsidies and electricity tariffs apply to single dwelling buildings as well as to apartments and, therefore, contribute to the high levels of PV deployment on Australian houses (which comprise 85 % of residential dwellings) compared to Austria. However, in Australia, PV deployment on apartment buildings remains very low. This is due, in part, to investment barriers relating to shared building ownership (under Strata Title), combined with split incentives between private landlords and tenants. These barriers might be reduced by changes to tax laws that currently incentivise short-term property investment over owner-occupation, and by forthcoming NSW legislatory changes to streamline the approval process for sustainability retrofits in apartment buildings [82]. Nevertheless, an emphasis on energy users' individual participation in the energy market means that targetted regulatory support is lacking, both for shared PV ownership and for households acting co-operatively in aggregating their loads to leverage lower energy costs [11].

In Austria, the investment decision-making barriers are less significant in the higher proportion of social and co-operative housing. Additionally, there is explicit regulatory support for ECs within apartment buildings, which allows shared PV systems, although legislative loopholes and a significant administrative burden discourage potential EC participants. However, PV deployment remains low in Austrian apartment buildings, as across the whole residential sector. It is likely that this can largely be explained by lower PV energy yields and high investment costs.

Deployment of solar PV for self-consumption in apartment buildings to generate low-cost, low-emission electricity in close proximity to residential loads could reduce energy bills for households, ease grid constraints and help reduce upward pressure on global temperatures. Moreover, in both countries apartment residents are less able to access the benefits of self-generated renewable energy than occupants of stand-alone housing, which presents an issue of social inequity. There is therefore a case for policy support to facilitate greater deployment. Our study suggests that the low penetration of PV in the multi-occupancy housing sectors of Austria and Australia have different causes and highlights that, while financial incentives can assist, there are broader regulatory barriers to be addressed. Further research, focused on comparative analyis of policy outcomes across multiple jurisdictions, would create greater understanding of the potential solutions.

## Author Declaration

We wish to confirm that there are no conflicts of interest associated with this publication and that there has been no financial support for this work that could have influenced its outcome.
Declarations of interest: None.

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## Appendix A. Load Profiles

### *Appendix A.1. Base Apartment Load Profiles (no HVAC)*

The load profiles of the three buildings investigated are illustrated as the mean values for each hour over one year.

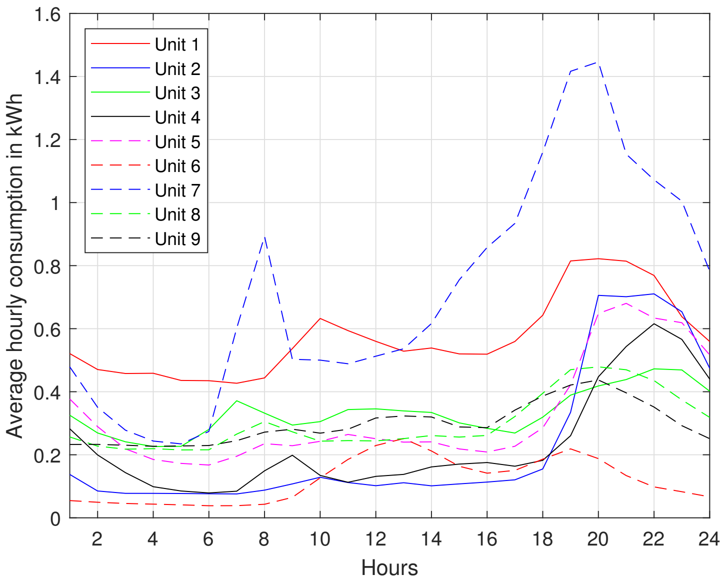

Figure A.10: Apartment load profiles of building b1

### *Appendix A.2. HVAC load profiles (Sydney)*

Figures A.13 and A.14 show average winter and summer HVAC loads derived from average load profiles for apartments with and without split-system air conditioning. This profile has been added to each apartment profile to simulate electrical HVAC loads in Sydney, with the resultant total building loads, with and without HVAC, shown in Appendix A.3.

### *Appendix A.3. Total Building Load Profiles*

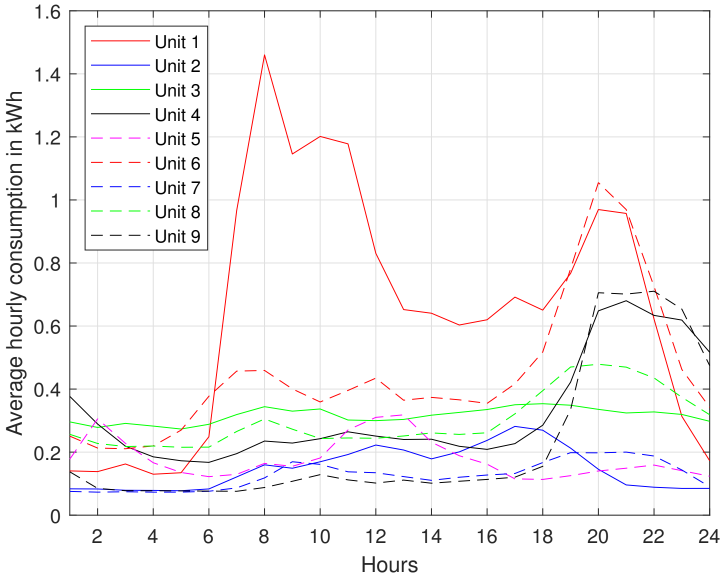

Figure A.11: Apartment load profiles of building b2

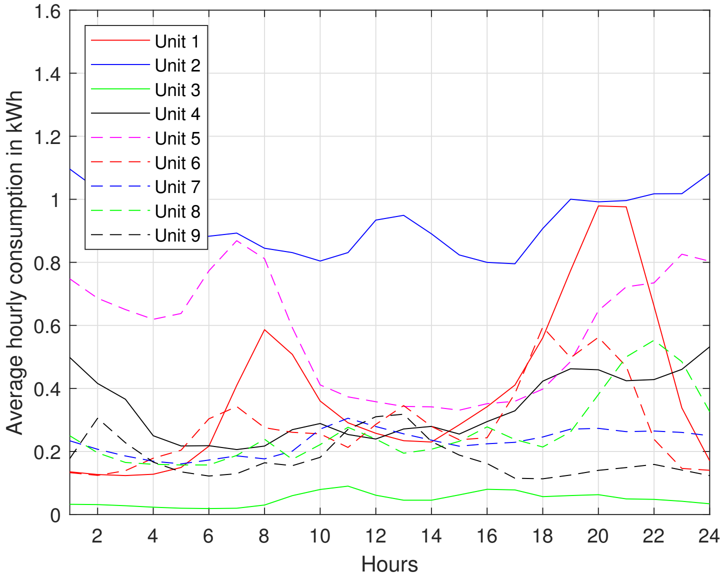

Figure A.12: Apartment load profiles of building b3

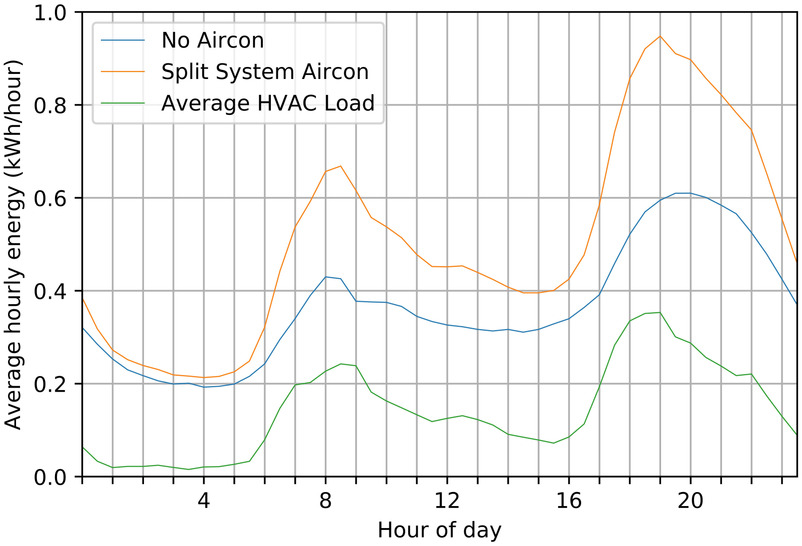

Figure A.13: Winter HVAC Load

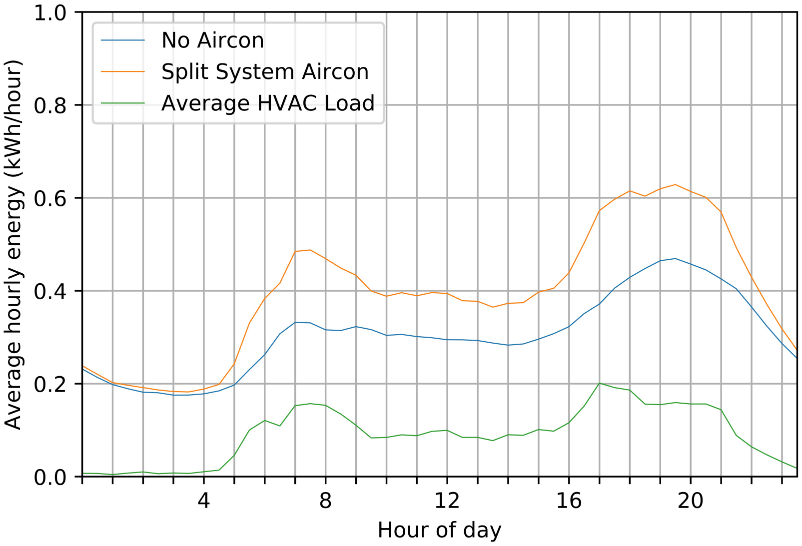

Figure A.14: Summer HVAC Load

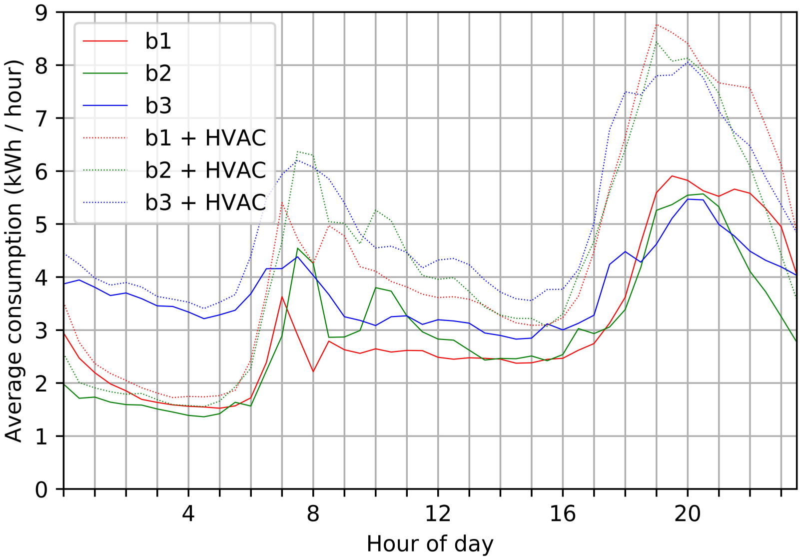

Figure A.15: Total winter load of buildings b1, b2 and b3 with and without HVAC

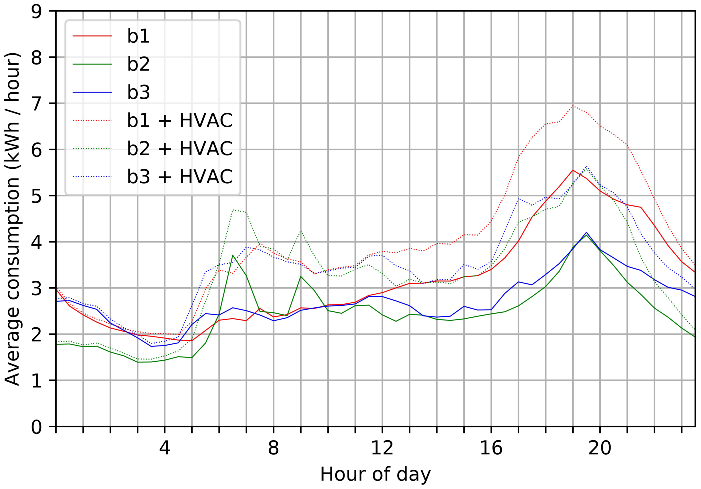

Figure A.16: Total summer load of buildings b1, b2 and b3 with and without HVAC

## Appendix B. Building Specifications

The object of investigation is an exemplary multi-apartment building with nine residential units. The building dimensions are assumed realistically with an average apartment size of $70\,\mathrm{m}^2$. The living area per floor therefore can be assumed as $210\,\mathrm{m}^2$. Approximately 20 %-30 % of the total floor space is reserved for general areas (staircase, aisle), leading to a building with a total floor area of $266\,\mathrm{m}^2$ ($14\,\mathrm{m}$ x $19\,\mathrm{m}$). Based on that, the rooftop area (assuming a roof tilted with $30\,^{\circ}$) can be calculated to be approximately $154\,\mathrm{m}^2$ in the directions of North and South, respectively. The total rooftop area is therefore $308\,\mathrm{m}^2$.