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Cost optimal self-consumption of PV Prosumers with stationary batteries, heat pumps, thermal energy storage and electric vehicles across the world up to 2050

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Abstract

Globally, PV prosumers account for a significant share of the total installed solar PV capacity, which is a growing trend with ever-increasing retail electricity prices. Further propelled by performance improvements of solar PV and innovations that allow for greater consumer choice, with additional benefits such as cost reductions and availability of incentives. PV prosumers may be one of the most important enablers of the energy transition. PV prosumers are set to gain the most by maximising self-consumption, while avoiding large amounts of excess electricity being fed into the grid. Additionally, electricity and heat storage technologies, heat pumps and battery electric vehicles are complementary to achieve the highest possible self-consumption shares for residential PV prosumer systems, which can reach grid-parity within this decade in most regions of the world. This research finds the cost optimal mix of the various complementary technologies such as batteries, electric vehicles, heat pumps and thermal heat storage for PV prosumers across the world by exploring 4 different scenarios. Furthermore, the research presents the threshold for economical maximum battery capacity per installed PV capacity, along with self-consumption ratios, demand cover ratios and heat cover ratios for 145 different regions across the world. This is a first of its kind study to conduct a global analysis of PV prosumers with a range of options to meet their complete energy demand from a future perspective, up to 2050. Maximising self-consumption from solar PV generation to meet all energy needs will be the most economical option in the future, for households across most regions of the world.

Keywords

Photovoltaics, Prosumer, Battery, Electric Vehicle, Heat Pump, Thermal Energy Storage, Vehicle-to-Home

Abbreviations

ATCE	Annual Total Cost of Energy
ATGEC	Annual Total Grid Energy Cost
BEV	Battery Electric Vehicle
COP	Coefficient of Performance
DCR	Demand Cover Ratio
DHW	Domestic Hot Water
DoD	Depth of Discharge
DSC	Direct Self-Consumption
FIT	Feed-in-tariff
GDP	Gross Domestic Product
GSHP	Ground Source Heat Pump
HC	Heating Cartridge

HCR	Heat Cover Ratio
HP	Heat Pump
ICE	Internal Combustion Engine
LUT	Lappeenranta University of Technology
P2P	Peer-to-Peer
pph	people per household
PV	Photovoltaic
RE	Renewable Energy
SCR	Self-Consumption Ratio
SCOP	Seasonal Coefficient of Performance
SH	Space Heating
SoC	State of Charge
TES	Thermal Energy Storage
V2G	Vehicle-to-Grid
V2H	Vehicle-to-Home

1. Introduction

There is growing interest in solar photovoltaics (PV) all over the world, as costs for PV systems are steadily declining and by the end of 2020 are expected to achieve grid-parity in the remaining residential electricity markets (Gerlach et al., 2014; Breyer and Gerlach, 2013). Today, solar PV has become a major actor in the electricity sectors of several countries. Globally, close to 500 TWh of electricity has been produced in 2017 by PV systems (IEA-PVPS, 2018). This represents more than 2% of the global electricity demand, though some countries have rapidly reached significant percentages. Around 500 GW of PV has been installed around the world, which is more than 90 times higher than in 2006 (IEA-PVPS, 2019). Solar PV with options that allow consumers to generate electricity at the point of consumption, and send any excess into the grid, are emerging as an attractive option for households around the world, more so in countries where retail electricity prices are high. Prosumers are end-use consumers of electricity who also produce their own electricity at the point of consumption to meet their own electricity needs and feed excess electricity into “the grid” (the electricity system). In simple terms, prosumers are electricity consumers interacting with the grid by generating some amount of electricity (Martin and Ryor, 2016). The increasing number of prosumers could transform the electricity system and the way in which electricity consumers interact with it. This is happening in a number of countries such as Australia, Germany and many of the EU countries, that are promoting policies for enhanced self-consumption through residential PV installations (IEA-PVPS and CREARA, 2016). While in California, it has become mandatory for new home owners to have solar PV systems that will offset part of their energy bills (Penn, 2018). In addition to the ability of prosumers to self-generate and connect with the grid, prosumers have the potential to help mitigate the growth of energy supply-demand gaps and electricity system losses. These potential benefits are particularly important at the city level, where almost two-thirds of the world’s energy is consumed and is set to rise with rapid rates of urbanisation (IPCC, 2014).

The development of storage technologies, more precisely battery storage (Lithium-based batteries) have enabled prosumers to maximise self-consumption of solar PV generation and further reduce their Annual Total Cost of Energy (ATCE). Germany supports storage through financial incentives for prosumers, which has led to a significant share of new residential PV installations with storage units that reached 100,000 homes in mid-2018, with another 200,000 storage systems expected in the following years (Enkhardt, 2018). In Australia, 20,789 storage units were installed in 2017, mainly in the residential segment (IEA-PVPS, 2018). In countries with high retail electricity prices, rooftop PV-plus-storage systems are increasingly becoming the cost effective option and enabling consumers to turn into prosumers. Some markets have already reached grid-parity for PV systems with battery storage (Werner et al., 2012). Furthermore, driving the demand and contributing to the declining costs of batteries is the increasing adoption of battery electric vehicles (BEVs). The evolution of the

global electric car stock reached nearly 2 million, within six years from 2010 to 2016 (IEA, 2017). The accelerated development of the EV market could be compared to the development of the PV market, with similar penetrations. With more than 1.2 million electric vehicles sold in 2017 (or 1.5% of the global car market), the penetration of this industry could reach the same levels as PV penetration in the power sector in the coming years and possibly evolve even faster (IEA-PVPS, 2018). Cumulative global EV sales has reached 4 million in 2018 and the intervals between each million EVs sold, is shortening (Willuhn, 2018).

Space heating and cooling combined with hot water supply corresponds to nearly half of the energy consumption in buildings (IRENA, 2013). In case of the European Union, there is a target of 20% renewable energy of the final energy consumption by 2020 and is estimated to include 4.9% of final energy from heat pumps as well as 2.9% from PV (IRENA, 2013). Heat pumps (HPs) for domestic heating and hot water supply are currently a niche technology in many EU countries, but they are increasingly expected to play an important role in a low carbon future. This is largely due to a future of rapidly decarbonised electricity supply, in which using electricity via heat pumps is one of the lowest polluting heating options (Fawcett, 2011). Several countries accept HPs as a renewable application sourcing surface geothermal energy and therefore support HP systems to enable a higher share in buildings, replacing conventional heating systems. The cost reduction of HPs is estimated to be about 30 – 40% for heat services by 2050 (IRENA, 2013). Furthermore, these can be coupled with thermal energy storage (TES) technologies, which are relatively inexpensive, reliable and do not require specific maintenance. In particular, residential applications require low temperature energy (i.e. in the range of 50 – 80 °C) and can thus utilise sensible thermal energy storage systems to provide the necessary heating (Facci et al., 2018). Schwarz et al. (2018) and Facci et al. (2018) show that PV integration with TES units in combination with power-to-heat applications (such as HPs) are extremely beneficial. The benefits of PV and HP technologies can be best utilised by combining them in residential energy systems. Past surveys show that PV + HP systems combined with TES can economically challenge conventional solar collector systems (Tjaden et al., 2013).

Finally, a combination of PV, batteries, HPs, TES and BEVs in a residential energy system seems to be a future prospect in order to meet the overall energy demand of households. In this regard, the research explores various settings with 4 different scenarios as constituting the basis for an optimised self-consuming household. However, just the presence of system components are not sufficient to optimise the energy system. Therefore, the aim of this research is to create a PV prosumer model for optimising PV energy usage and the ATCE for average residential households across the different regions of the world. Additionally, the aim is to perform a more comprehensive investigation of the impact of the different system components and the development of the ATCE, self-consumption ratio (SCR), demand cover ratio (DCR) and heat cover ratio (HCR) over the time period from 2015 to 2050. This will also include, finding the least cost PV capacities and the corresponding battery sizes. This is the first study to conduct a global analysis of PV prosumers with a range of complementary solutions to meet their energy demands in the most cost effective manner. The next section 2, presents a literature review of PV prosumer studies conducted nationally and regionally, followed by section 3 with the methods and materials adopted in the research. Section 4, presents the results.. Thereafter, the results are discussed in section 5 and conclusions are drawn in the last section, 6.

2. Literature Review

Until recently, across many regions of the world PV systems were mainly installed to feed the generated electricity into the electricity grid, which was remunerated with a feed-in tariff (FIT). However, with decreasing PV FIT and increasing retail prices of grid electricity, utilising the generated PV electricity on-site at the household level is becoming more attractive than feeding it into the grid across many regions of the world. In this context, the literature on PV self-consumption is quite diverse and encompasses a wide range of technologies and systems. The report by IEA PVPS and CREARA (2016) reviews and analyses evolving PV-self consumption policies and business models across key countries and concludes that despite self-consumption

being in an infant stage, most countries are probing regulations to frame its development. Furthermore, the report explores the most essential questions to be considered in order to ensure its smooth development and suggests that the most important one could be to identify whether the optimisation of self-consumption should be considered just locally or from a regional system perspective (IEA PVPS and CREARA, 2016). Weniger et al. (2014) analyse residential PV battery systems by simulations in order to gain insights into their sizing, along with sensitivity analyses with varying sizes of PV battery systems to identify appropriate system configurations. Additionally, Weniger et al. (2016) explore sizing batter converters for residential PV storage systems. Finally, an economic assessment of residential PV battery systems is conducted to derive recommendations for cost optimal sizing (Weniger et al. 2014; 2016). Weniger et al. (2014; 2016), show that the self-consumption rate and the degree of self-sufficiency strongly depend on the PV system and battery size considered, however, the household load profiles were limited to north-east German lowlands. Similarly, Yu (2018) determines the economic attractiveness of the PV self-consumption model combined with lithium-ion batteries in the French residential PV sector in 2030. The study has shown that PV self-consumption with batteries could become profitable for individual investors in France before 2030 (Yu, 2018). However, these studies do not consider the integration of electricity and heat storages, which is an option to optimise self-consumption even further. In this regard, there are studies that have analysed the heating aspect of residential households, such as Brange et al. (2016) wherein, heat prosumers in Sweden were analysed and showed their potential to contribute significant amounts of heat to district heating grids. Furthermore, Delgado et al. (2018) conducts multi-objective optimisations for operational CO₂ emissions and lifecycle costs (LCC) of heat and electricity prosumers in the Netherlands and Finland. The study finds that as energy systems continue to develop, heat export to district grids has potential to become a common practice (Delgado et al., 2018). In addition, Shah et al. (2015) mention the potential of using off-grid residential hybrid energy systems (solar PV, battery, and combined heat and power) to address the energy transition and system integration for the United States of America. The study demonstrates the off-grid residential-scale hybrid energy systems incorporating solar photovoltaic, batteries and a cogeneration unit are able to meet electrical load demands throughout the U.S. using reasonable sized components (Shah et al., 2015). Moreover, these studies are limited to just a region or a specific country and lack a broader global perspective.

Furthermore, there is a lack of holistic prosumer studies that integrated BEVs, heat storage technologies along with solar PV and battery storage. In this context, Bocklisch and Linder (2016) conduct a technical and economic investigation of a decentralised, grid-connected PV, small wind turbine (SWT) – hybrid system with lead-acid battery, lithium-ion battery and heat-storage path. The study finds that configurations with battery storage can achieve even higher self-sufficiencies up to 85% with an economic profit and peak-shaving-/power2heat-concept reduce the maximum grid and battery powers reliably (Bocklisch and Linder, 2016). Another option for enhancing self-consumption along with optimising PV and storage systems further is the integration of BEVs. In this regard, there are studies that have explored the integration of BEVs with prosumer households, such as Gudmunds, (2018), which investigates how the introduction of an EV to residential households, with small scale electricity generation from solar PV and both with and without stationary battery storage, can affect the electricity demand from the grid for these households. The study finds that there are benefits for integrating BEVs with household energy systems, but, it does not include any economic aspects such as investment costs for the components or considered retail electricity prices. Neither are sizes of the different systems in the model optimised. On the other hand, Erdinc et al. (2015) have considered bi-directional flows including the options for vehicle-to-home (V2H), vehicle-to-grid (V2G) and possibilities to use the stationary battery for selling back electricity to the grid. Moreover, different combinations of these options have been investigated together with consumer preferences for charging of the BEV, showing that the costs of electricity could be reduced by up to 65% (Erdinc et al., 2015). As these concepts are evolving and various options for optimising self-generation and consumption are still being explored across different regions of the world, there is a lack of research on prosumer models that combine all the aspects of electricity, heat and electric

mobility integrated into a residential household. Exploring prosumer models across the different regions of the world as well as on a global scale is still lacking and is an issue for future research. In this context, this research explores a PV prosumer model with a combination of PV, batteries, HPs, TES and BEVs in a residential household energy system. Furthermore, it determines a cost optimal combination of the system components in order to minimise the ATCE for the prosumer households. In addition, this research is carried out across 145 regions of the world to provide an overview of prosumer potentials and possible benefits. However, to enable a global overview of prosumers certain broad assumptions and simplifications are inevitable and this is perceived as an acceptable limitation with such analyses. These are further discussed in detail in the following sections.

3. Methods and Materials

The PV prosumer model follows the principles of the LUT Energy System Transition model, which is based on an hourly resolution (Bogdanov and Breyer, 2016; Breyer et al., 2018; Ram et al., 2017a). To determine the cost optimised (least ATCE) PV and stationary battery capacities, simulations were performed on an iterative basis over PV capacities, ranging from 1 – 30 kW_p and stationary battery capacities, ranging from 1 – 50 kWh_{cap}, with intervals of 1 kW_p and 1 kWh_{cap} each for PV and stationary battery capacities respectively. Furthermore, the simulations were carried out on a global scale comprising 145 regions (Breyer et al., 2018; Ram et al., 2017a), in 5-year intervals from 2015 until 2050. A list of all the regions with their abbreviations can be found in the Supplementary Material (Table S1). Simulation programme MATLAB was used in the process of formulating, estimating and visualising the research. Figure 1 provides the schematic representation of the entire PV prosumer system, including all the components in the case of a standard household. Additionally, the black arrows represent electricity flows, while the orange arrows represent the flow of thermal energy in the form of hot water.

Figure 1: Structure of the PV Prosumer model with all system components and the corresponding flow of electricity and heat.

Components of the PV prosumer system from top left to bottom right are enlisted as follows,

- Car 1: BEV with the primary function of daily commutes and occasionally available as tertiary electricity storage. It also plays a role in charge transfers with Car 2 and the stationary battery. External charging (work place charging) is not considered in this model.
- Solar PV electricity generation system: Mostly rooftop PV that generates electricity to meet the energy demands of the entire household and feeds excess electricity into the distribution grid.
- Grid integration: Allows for bidirectional flow of electricity with the local distribution grid and accounts for withdrawal of grid electricity as well as fed-in PV generation.

- d. Electricity storage: Lithium ion batteries that store electricity for utilisation in the household as well as other components (BEVs and HP).
- e. Household electricity demand: This represents all household appliances and equipment that consume electricity.
- f. Car 2: BEV with Vehicle-to-Home (V2H) capability, low usage for commuting and available as secondary electricity storage.
- g. Heating demand: provides the heating requirements of the household, mainly hot water demand and space heating during winters, applicable to the respective regions.
- h. Thermal energy storage: stores thermal energy in the form of hot water in a hot water tank.
- i. Heat Pump/Heating Cartridge: Heat exchange system with the primary function of converting electrical energy to thermal energy.

Sizing of the PV prosumer systems are based on average household energy demands from the different regions considered. Representative average households were considered, as there is substantial variation in household sizes and corresponding energy demands within the regions.

3.1 GDP and Household Size

Household data was adopted from the United Nations database (UNSD, 2017). Additionally, using the Gross Domestic Product (GDP) per capita, a relation between GDP per capita and people per household (pph) was established. The GDP projections were adopted from Toktarova et al. (2019). For the development of pph values until 2050, a linear increase of GDP per capita was assumed. Furthermore, it was assumed that the effect on pph is a quarter of the GDP per capita development, which means a 100% increase in GDP per capita will induce a 25% decrease in pph. This connection portrays a most appropriate development of the pph within the whole transition period and has been derived empirically. For regions with more than one country, the population-weighted average of the countries was considered. For countries that were split into more than one region, the same pph was assumed for all sub-regions. The development of pph through the transition period from 2015 to 2050 for all regions around the world can be found in the Supplementary Material (Figure S1 and Table S2).

3.2 Solar Data

PV electricity generation profiles were available for every region with full hourly resolution in kWh, according to Bogdanov and Breyer (2016) as shown in Figure 2. These are adopted for the range of PV capacities used in the PV Prosumer model to generate the household PV generation profiles from 2015 until 2050.

Figure 2: Global full load hours of optimally tilted PV systems (Bogdanov and Breyer, 2016).

3.3 Load Profiles

Residential electricity load profiles are available for Brazil, Italy, Japan, Senegal, Thailand, Germany, New Zealand and the United States (Werner et al., 2012). The challenge is in creating load profiles for all regions of the world, which encompasses the local behaviours of residential households. To factor in the local aspects, regions with similar socioeconomic as well as geographical conditions were categorised into ten representative ‘profile regions’. These are NA-US-SWMA (South Western and Middle USA), NA-CA-US-NE (North Eastern USA and Canada), SA (South America), Europe-Nordic-RU (Northern Europe and Russia), Europe-CE-East (Central and Eastern Europe), Europe-South-MENA (Southern Europe and MENA), SSA (Sub-Saharan Africa), Pacific (New Zealand and Australia), SEA (South East Asia) and NEA-Eurasia-CA (Central and Eastern Asia). By combining the load profiles of the various regions, an ‘average human electricity consumption’ load profile was derived, to represent the activities of regular households across the world. Moreover, the variations in load profiles in relation to the average derived load profile helped in categorising the different regions with respect to their profile types. This resulted in regional load profiles containing area specific factors as well as average human behaviours with respect to electricity consumption (comprising the morning and evening peaks). The load profiles for the ten representative ‘profile regions’ are shown in Figure 3. Wherein, it can be noticed that the profiles differ quite substantially during daytimes, which has an impact on Direct Self-Consumption (DSC) of households in those regions. This approach does lead to a more simplified load profile, which is ideal for the case of a representative average household. Whereas, aspects such as the urban and rural household differentiation that is higher in developing countries have not been considered. As it has been observed globally, prosumer proliferation generally begins in urban settings and then expands to the rural segments too.

Figure 3: Weekly load profiles as a share of energy consumption for the ten ‘profile regions’.

Furthermore, the profiles factor in annual variations that occur predominantly due to seasonal changes. Country-wide and regional load profiles were adopted from Toktarova et al. (2019), which have factored in annual variations. These profiles were used to derive the annual mean loads. Further, by combining weekly load profiles with the specific weekly factors using Equation (1) for every week of the year, the profiles for residential electricity loads across households in the different regions of the world were derived.

$$load_{factorised} = load_{raw} \cdot f_{week} \quad (1)$$

In Equation (1), $load_{factorised}$ – real load profile; $load_{raw}$ – raw load profile; f_{week} – factor of the investigated week in comparison to the country-wide or regional annual mean load. This was applied for all weeks of the year and thereby deriving annual residential load profiles across households in the 145 regions. Figure 4 shows the

factorised yearly load profile for the case of Germany. These load profiles are normalised to annual electricity consumption of 1 MWh. Thereafter, the profiles were corrected by the annual electricity consumption per household across the different regions to represent the factorised electricity load profiles of households.

Figure 4: *German yearly factored load profile (normalised to an annual electricity consumption of 1 MWh).*

With the data for pph, total electricity consumption (IEA, 2017) and shares of residential electricity consumption across the different regions (Toktarova et al., 2019), the annual residential electricity consumption per representative average household was estimated for each of the regions. Also, it was assumed that the shares of residential electricity consumption will remain the same for all years until 2050. Indicating that the increase of residential energy consumption is according to the increase in total electricity consumption for each of the regions, respectively. This is a more simplified approach, which presumes the shares of residential electricity consumption to remain the same until 2050. This is based on the presumption that increased electrification across the different sectors will lead to a more stable share of residential electricity consumption.

Load profiles for Space Heating (SH) and Domestic Hot Water (DHW) demand were available on a region-wide scale for all the regions until 2050 (Barbosa et al., 2017). Moreover, SH and DHW factorised load profiles were derived according to the pph and population per region. Electricity consumption, SH and DHW for households in all the regions across the different years can be found in the Supplementary Material (Tables S3 – S5).

3.4 Battery Electric Vehicles

For a standard case of the PV Prosumer model, a residential household with 2 BEVs is envisioned. The capacity of batteries in the BEVs were set to specific values based on recent trends (UBS 2017; ICCT, 2016), with Car 1 having 80 kWh_{cap} and Car 2 having 60 kWh_{cap}. USB (2017) presents detailed analyses of the BEV market with insights into driving ranges and battery packs of upcoming BEVs. Currently, mass-market electric cars with over 350 km range such as the Tesla Model 3 and the Chevy Bolt, along with many more are expected to have similar battery capacities in the near future (Timofeeva, 2017). The Tesla Model 3 offers 50 kWh and 75 kWh packs for ranges of 350 km and 400 km, respectively (UBS, 2017). Whereas, the Chevy Bolt is offered with a 75 kWh pack that provides around 375 km range (Timofeeva, 2017). Nissan Leaf, the highest selling BEV has been upgraded to a 60 kWh battery pack to enable a better range (Lambert, 2018). According to ICCT (2016), the over-40-kWh pack segment increased from nearly zero in 2012 to 12% of overall electric vehicle sales in 2015, and the trend is set to continue toward larger battery packs. From a 2050 perspective, 80 kWh and 60 kWh were assumed as reasonable capacities for BEVs. Based on usability and driving patterns, availability of the BEVs for PV charging is assumed. As Car 1 is usually not at home during daytimes and weekdays, it should be possible to charge as much energy as possible during weekends and evening hours of weekdays. In some cases, Car 1 could satisfy its driving demand from the energy charged in the weekend, for

the entire following week. This could be compared to a filled tank of a conventional internal combustion engine (ICE) vehicle. As Car 2 is mostly stationary, it is available for PV charging and can perform as a vehicle-to-home (V2H) device as well. This enables the possibility to charge as much PV electricity as possible for supplying household demands (electricity and HP). Furthermore, Car 2 is also assumed to provide electricity for charging Car 1. The Depth of Discharge (DoD) for batteries in BEVs is not considered, however, a safety buffer of 25% of the storage capacity was included for emergencies.

From an operational point of view, Car 1 is the primary usage vehicle for daily commuting as well as occasional weekend travels. Whereas, Car 2 is the sparingly used vehicle mainly for secondary activities such as shopping or other domestic purposes. Car 1 being a ‘usually away’ vehicle leaves the household in the morning hours and returns in the late afternoons, representing usual workplace journeys. Additionally, Car 1 is used for free time journeys on weekends. The occurring of the free time journeys was determined by a randomised function built into the simulation. This enables dynamic weekend journeys, independent of solar conditions on weekends. For Car 2, which is a ‘usually at home’ vehicle, the usage time was assumed to be three hours per day based on Marwitz (2012). The occurrence of these journeys were determined randomly, enabling journeys for Car 2 to be independent of solar conditions as well as load demands. Car 2 journeys occur mostly during late mornings. Data pertaining to the usage of Car 1 and Car 2, as well as their driving patterns were adopted from Marwitz (2012). In the case of poor solar conditions, the BEVs are charged by the grid electricity. The BEVs are charged by electricity from the grid during early morning hours, when household electricity demands are usually low (as in Figure 3). In order to minimise grid charging, the State of Charge (SoC) of the BEVs has to be below the safety buffer plus the demand for one daily trip, in order to enable grid charging.

The daily trip demands were calculated using Equation (2), as follows:

$$E_{Car,trip} = \frac{\text{Yearly driving distance}}{\Sigma \text{journeys}} \cdot E_{cons}. \quad (2)$$

Wherein, $E_{car,trip}$ – electricity demand per car trip and E_{cons} – specific electricity consumption of BEVs. The specific electricity consumption of the BEVs was set to 20 kWh/ 100 km (Marwitz, 2012), including energy losses and discharging efficiencies. The discharging efficiency of Car 2 to supply household demands and Car 1 charging was assumed at 96.8% (Luo et al., 2015), which represents the charging and discharging efficiency of Li-Ion batteries in the LUT Energy System Transition model (Breyer et al., 2018). Driving distances per year were assumed as 14,000 km and 10,000 km per year for Car 1 and Car 2 respectively, these were adopted from Khalili et al., (2019) that was based on a database from the ICCT (2012). Moreover, the global annual average of all cars were in the range of the average mileage of passenger car drivers in Germany at 12,800 km (Khalili et al., 2019). In addition, the study Eurostat (2007) showed that the global daily driving distances are more or less in the range of European mean values, which are 30-40 km per day.

3.5 Stationary Battery

A stationary battery is part of the standard PV prosumer household and the model based on various factors, in achieving the least ATCEoption, determines its capacity. A combination of installed capacities of PV and stationary batteries are determined by an iterative process to achieve the ATCE for the different prosumer households across the various regions of the world. As shown in Figure 1, the stationary battery satisfies the electricity demand of the household and the HP, as well as charges Car 1 occasionally. The model prioritises charging of the stationary battery after DSC. Its primarily role is to deliver electricity to meet demands during evening and night hours, but also covering peak demands during daytimes when PV generation falls short, provided that the stationary battery is sufficiently charged. In order to minimise utilisation of grid electricity, charge transfers between the stationary battery and Car 1 are prioritised over charging Car 2 with grid electricity. This does not impact the household demand and provides for the possibility of maximising the utilisation of PV electricity within the system. A Li-ion battery is set as the standard for the PV Prosumer household, as they are

increasingly common in residential applications. The DoD was assumed at 95%, while the charging and discharging efficiency was 96.8%, similar to BEVs (Luo et al., 2015). Along with charge transfers, the stationary battery is complemented by Car 2 that can cover demands during insufficiencies. Moreover, Car 2 has the provision to transfer excess charge to Car 1.

3.6 Heating System (Heat Pump, Heating Cartridge)

Currently, there is no technology to rival heat pumps for efficiently using electricity to deliver residential and commercial space heating (Fawcett et al., 2015). Ground source heat pumps (GSHP), which absorb energy from the ground using a dedicated borehole or network of buried pipes was chosen to be part of the standard PV prosumer household. As, the efficiencies compared to air source HPs are much better, the operational costs are lower and availability in comparison to water source HPs is higher. Another advantage of GSHPs is the stable Coefficient of Performance (COP) over the whole year caused by the stored solar energy in the ground, even during the winters with very low temperatures. The choice of GSHP as part of the representative prosumer household was based on the resulting lower annual costs as compared to other HPs, as the end objective of the research is to attain a cost optimal setting for PV prosumers. However, it could be the case that other HPs could be better in terms of performance for specific weather conditions. The HP specifications are based on a commercially available HP with the possibility of heating water up to 90°C. Whereas, the rated power is 7 kW_{el}. The COP was set to a permanent value of 3.8 for operation at nominal value. For additional filling of the TES by PV generation, the COP is set at 3 and this is further discussed below along with the TES.

Heating requirements across the different regions of the world vary significantly, primarily due to climatic and geographic conditions. Therefore, for regions with a SH demand of less than 2 MWh_{th} per capita annually, application of HPs with TES of 800 litres capacity is not the most appropriate solution. As investment costs for the system components are not reasonable for lower heat demands. For regions with a SH demand under the above-mentioned limit, heating cartridges were adopted with 7 kW_{th} output power. Figure 5 maps the regions across the world according to the heating systems utilised. Only two regions change their system types during the energy transition period. Ecuador, which switches from a cartridge system to a HP system in 2045. Whereas, South Africa and Lesotho changes from a HP system to a cartridge system in 2050.

Another aspect to be considered is the minimum potable water temperature to be maintained. In this regard, the European standards DIN EN 806-2 (DIN, 2005) and DIN EN 1717 (DIN, 2000) recommend a temperature of minimum 60°C for the avoidance of legionella development in potable water. Hence, operations at a nominal temperature of 65°C was adopted to be well within the limits. This consideration seems as an optimal combination of the minimum temperature necessary for potable water quality as well as for the most efficient operation of HPs.

Figure 5: A global map representing heating systems of the various regions.

3.7 Thermal Energy Storage

The TES assumed is a tank-in-tank storage with a water capacity of 800 litres for HP systems and 200 litres for heating cartridge systems. This includes storage capacities for SH and DHW in one device, as they are usually used for solar thermal applications (Stadler and Sterner, 2017). A standby of 25% was set for the TES as shown in Figure 6, which guarantees coverage of SH and DHW demands during refilling. Thereby ensuring, household occupants to carry out domestic activities such as taking a bath or shower, even when TES SOC is quite low without any refilling. Refilling is triggered when SOC of the TES falls below the 25% standby. The demand is covered either by DSC from PV generation or by the stationary battery depending on the time of day and availability of generation. Alternatively, the BEVs can also be utilised for satisfying the demand depending on the availability of charge in them and if none of the energy storage options are able to cover the demand, the refilling demand is covered by grid electricity. The TES gets filled by the HP with a COP of 3.8, as mentioned earlier. The maximum TES capacity is therefore 800 litres at 65°C. Equation (3) describes the estimation of storable capacity of thermal energy in the TES.

$$E_{th,cap} = c_{p,water} \cdot V_{TES} \cdot \Delta T \quad (3)$$

Wherein, E_{th} – thermal energy; $c_{p,water}$ – specific heat capacity of water (0.0016 kWh_{th}/(kg·K), derived from 4.19 kJ/(kg·K)); V_{TES} – storage volume of the TES; ΔT – temperature difference (45 K for nominal operation, 70 K for PV additional filling).

Situations in which the stationary battery is fully charged, both BEVs are fully charged or not available and the TES is completely filled with 800 litres at 65°C, the generated PV electricity surplus is normally fed into the grid. But, this would hinder SCR optimisation, since capacity in the TES is still available. Generally, the TES as well as HPs are designed for 90°C. Therefore, the system has the possibility to fill the TES up to 89.6 kWh_{th}, which means 800 litres at 90°C. Although COP of 3 for PV additional filling is lower than for nominal operation, the possibility of utilising more low cost energy compensates the lower efficiency. In order to maximise SCR optimisation, an added storage capacity of 32 kWh_{th,cap} is factored into the PV Prosumer model. Figure 6 visualises the TES filling conditions. PV additional filling is also considered for the heating cartridge systems with 200 litres TES. In this case, efficiency for the heating cartridge remains the same. The nominal capacity for a 200 litres TES is 14.4 kWh_{th}, while the full thermal capacity is 22.4 kWh_{th}.

Figure 6: Thermal capacities of TES filling for the operational modes of HP and Heating Cartridge.

The losses of thermal energy storage systems are between 1.6 kWh_{th} and 2.5 kWh_{th} per day (24 hrs) according to Viessmann Werke GmbH (Viessmann, 2017). Considering the 800 litres TES, thermal energy losses of about 0.15% per hour could be expected. This value was considered independently of the SOC and TES size. The efficiency assumptions for all relevant system components are listed in the Appendix (Table A.2).

3.8 Financial Target Function

The ATCE is estimated according to Equation (4), which is minimised over the year.

$$ATCE = \sum_i^{technology} (Capex_i \cdot crf_i + opex_{fix,i} + opex_{var,i} \cdot E_{throughput}) + cost_{grid} - income_{feed-in} \quad (4)$$

Wherein, $ATCE$ – annual total cost of energy, $Capex$ – investment cost for technology, crf – annuity factor, $opex_{fix}$ – fixed operational expenditures, $opex_{var}$ – variable operational expenditures, $E_{throughput}$ – energy handling of component (e.g. discharged energy of the battery), $cost_{grid}$ – cost of remaining electricity supplied by the grid, $income_{feed-in}$ – income from PV electricity fed-in to the grid.

For comparing annual energy costs, Equation (5) representing a 100% grid supply based energy system without PV and stationary battery is considered. This is minimised over an entire year. In the case of 100% grid supply, Car 2 is assumed as a normal BEV, as V2H application may not be beneficial. The HP operates nominally with grid supply, to minimise annual total grid energy cost (ATGEC) according to Equation (5). $ATGEC = \sum_i^{HP, TES} (Capex_i \cdot crf_i + opex_{fix,i} + opex_{var,i} \cdot E_{throughput}) + \left(\frac{E_{th,DHW} + E_{th,SH}}{COP_{nom}} + E_{el,house} + E_{el,car1} + E_{el,car2} \right) \cdot price_{grid}$ (5)

Wherein, $ATGEC$ – Annual Total Grid Energy Cost, $E_{th,DHW}$ – annual thermal energy for hot water demand; $E_{th,SH}$ – annual thermal energy for space heating; COP_{nom} – Coefficient of Performance of HP for operation at nominal value; $E_{el,house}$ – annual electricity consumption of household; $E_{el,car}$ – annual electricity demand for driving.

Financial assumptions for system components and grid electricity prices across the different regions are based on the LUT Energy System Transition model (Breyer et al., 2018; Ram et al., 2017a; ETIP-PV, 2017) and available in the Appendix (Table A.1) and Supplementary Material (Table S6) respectively. The costs of PV systems and battery storage systems vary quite significantly across the different regions (IRENA, 2018) and have been converging towards regional standards (Schachinger, 2018; ETIP-PV, 2017). Standard capex and opex costs are considered for all technologies across the different regions of the world, as costs of these technologies are assumed to converge towards a global standard from a long-term perspective. Moreover, the retail electricity tariffs (grid electricity prices) are from various sources that are collated in Gerlach et al., (2014) and in Breyer and Gerlach, (2013). The further regional categorisation of the retail electricity tariffs is based on averages across individual regions according to the electricity consumption of the respective regions. In the case of BEVs, no storage costs are considered as it is assumed batteries are paid for along with the car (whose primary function is commuting). For all regions of the world, a standard feed-in reimbursement of 0.02 €/kWh was assumed. Despite the presence of a significantly varying FIT across the different regions of the world, a low FIT is assumed from a 2050 perspective. Furthermore, the research is aimed at exploring options for residential households to optimise their self-consumption and minimise their energy costs without the aid of fiscal benefits in the form of taxes, subsidies, fees or others. Alternatively, the applied fixed reimbursement could be perceived as a form of revenue generation or a long-term agreement with electricity service providers on an average price for the excess electricity supplied by households. From a long-term perspective, FITs across the different regions of the world are expected to decline close to conventional grid costs, with rapidly declining PV and storage costs. Moreover, the feed-in reimbursement is assumed to be available only for up to 50% of generated electricity from the installed PV systems at households.

3.9 Operation and scenarios

Operation of the PV Prosumer model is considered to occur sequentially as represented by the flow diagrams in Figure 7. Adopting this process ensures maximising self-consumption and minimising the ATCE.

Figure 7: Flow charts indicating the sequential operation of the components of a PV Prosumer household. PV electricity utilisation (left) and charge transfer between the BEVs (right).

As shown in Figure 7 (left), the stationary battery has first priority in the sequential order for utilisation of surplus PV electricity (available after meeting the household demand). Once the stationary battery is charged completely, TES at 60°C is second in the sequential order. After TES is filled completely at 60°C, Car 2 with V2H capability (if at the household) is considered in the sequential order. After Car 2 is charged completely, Car 1 (if at the household) is taken up in the sequential order for charging. Since, the primary role of Car 1 is daily commuting, the availability during PV generation hours is much lesser compared to Car 2. Charge transfers between the stationary battery, Car 2 and Car 1 ensures adequate levels of storage required for most efficient usage of generated PV electricity. In cases where Car 1 and Car 2 are unavailable at the household or are fully charged, TES is next in the sequential order. Additionally, TES is heated up to 90°C (to store maximum heat). Finally, if there is still surplus PV electricity, it is fed into the grid for a FIT of 0.02 €/kWh as the final step in the sequential order. In addition, a further optimisation of the batteries (stationary and BEVs) occurs in the early morning hours, as shown in Figure 7 (right), to ensure sufficient charge availability in both BEVs as well as optimal utilisation of all 3 electricity storage options. At 5 am, charge transfer from the stationary battery to Car 1 occurs (if SOC of stationay battery is more than the minimum), alternatively charge transfer from Car 2 to Car 1 occurs (if SOC of stationay battery is below minimum as well as for Car 1). In case Car 2 as well as Car 1 along with the stationary battery have SOC below minimum, electricity from the grid is drawn to charge both Car 1 and Car 2 to meet their daily requirements (commuting demands). From a sequential point of view, Car 1 would be charged first as the utilisation is earlier as compared to Car 2, which is utilised later in the day and has the opportunity to be charged by PV generation during the late morning hours.

Furthermore, the PV Prosumer model is considered to operate in 4 different scenarios to better capture the wide range of household compositions across the various regions of the world. Table 1 shows the different scenarios, which are

- ‘Two Cars’ scenario: in this case, both the BEVs are in operation.
- ‘Only Car 1’ scenario: in this case, just the BEV that is primarily used for commuting is in operation.
- ‘Only Car 2’ scenario: in this case, just the BEV used primarily for V2H as secondary storage is in operation.
- ‘No Cars’ scenario: in this case, both the BEVs are not in operation.

Table 1: *Scenarios based on the usage of BEVs.*

Scenarios	Car 1	Car 2 (V2H)
‘Two Cars’	✓	✓
‘Only Car 1’	✓	
‘Only Car 2’		✓
‘No Cars’		

Results are presented according to the 4 different scenarios.

4. Results

Eight representative regions across the world were selected to display the results in a broader context. The regions are, FI (Finland), DE (Germany), JP-E (Japan East), AU-W (Australia West), ID-KL-SW (Indonesia East), KENUG (Kenya and Uganda), BR-SP (Brazil – Sao Paulo) and US-MW (United States – Midwest).

4.1 Total Cost of Energy and Grid-Parity

The resulting ATCE for all scenarios in households across the 8 regions are shown in Figure 8. ATCE is reduced from about 900 – 6000 €/a in 100% grid supply scenarios to approximately 550 – 5500 €/a in minimum cost development scenarios for households across the 8 regions. Despite the fact that annual electricity demand is increased with the adoption of BEVs, the SCR can also be increased with BEV charging from low cost PV electricity. Hence, compensating for the expected additional costs of increased electricity consumption. The additional costs are observed in Figure 8, highlighting 100% grid supply costs. The development of ATCE for PV systems decrease linearly, following the decreasing investment costs for the system components until 2050. Stagnating or slightly decreasing energy costs for 100% grid supply in some regions result from the decline of HP and TES costs, which compensate the increasing grid electricity prices. Figure 9 shows the annual cost saving potential for households across all regions and scenarios in 2030, using a PV system as compared to 100% grid supply. Furthermore, results for 2050 are shown in the Supplementary Material (Figure S2). Moreover, utilising SCR optimised residential PV systems is already profitable for households in many regions with high grid electricity prices in 2015. On the contrary, for households in regions with low grid electricity prices it is not yet profitable to optimise self-consumption, due to significantly high investment costs mainly for stationary batteries for these conditions.

Figure 8: ATCE for the least cost system (left) and full grid supply (right) in households across the 8 regions, for the ‘Two Cars Scenario’ (top), ‘Only Car 1 Scenario’ (center top), ‘Only Car 2 Scenario’ (center bottom) and ‘No Cars Scenario’ (bottom).

Figure 9: ATCE saving potential for households in all regions in 2030, for the ‘Two Cars Scenario’ (top left), ‘Only Car 1 Scenario’ (top right), ‘Only Car 2 Scenario’ (bottom left) and ‘No Cars Scenario’ (bottom right). Regions with no cost saving potential are marked grey.

In Figure 10 the ATCEratios of PV to grid supply, or rather respective system profitability for all regions in relation to the GDP per capita, are plotted for 2030. The stage of development of the regions, expressed by GDP per capita, has a minor impact on the level of profitability. As, higher energy consumption of households in developed countries make a SCR optimisation more useful. Compared to full grid supply, SCR optimised PV systems are able to reduce ATCE up to 80% within the next decade. Until 2050, it is possible to save up to 90% of energy expenditures across all the scenarios. The use of BEVs has a marginal impact on the time required to achieve regional grid-parity. For the ‘Two Cars Scenario’, the last region (Tajikistan and Kyrgyzstan) attains grid-parity between 2025 and 2030. For the ‘Only Car 1 Scenario’ and ‘No Cars Scenario’, the last region (Tajikistan and Kyrgyzstan) will get beyond grid-parity between 2035 and 2040. Whereas, for the ‘Only Car 2 Scenario’, the last two regions (Tajikistan and Kyrgyzstan as well as Kazakhstan) attain grid-parity by 2035. However, the heating system (HP and TES) is not optimised for every region. As, the break-even point is very close to the grid-parity limit of the PV system cost to 100% grid supply cost ratio of 1. A marginally optimised TES capacity would be sufficient to shift the year for the last region to attain grid-parity across all scenarios by five years earlier, at a minimum. Nevertheless, some regions are able to reduce their ATCE up to 90%, as compared to 100% grid supply.

Figure 10: System profitability (ratio of ATCE of PV to grid supply) over GDP per capita for the different regions of the world in 2030, for the ‘Two Cars Scenario’ (top left), ‘Only Car 1 Scenario’ (top right), ‘Only Car 2 Scenario’ (bottom left) and ‘No Cars Scenario’ (bottom right).

4.2 Self-Consumption Ratio

Optimisation of SCR can be achieved partially, as the substantial decline of PV system costs lead to an effect that makes large feed-in quantities economically attractive. The SCR levels off between 30% - 60% until 2050 for all scenarios, for households in most regions of the world as shown in Figure 11. The difference between the scenarios is not very significant, but noticeable. By using both the BEVs (Car 1 and Car 2), the SCR can be improved by about 10 percentage points for households in some regions. The charging of Car 1 via the stationary battery results in a higher SCR than using only one V2H BEV (Car 2). There are several reasons for the difference between ‘Only Car 1 Scenario’ and ‘Only Car 2 Scenario’, for a higher SCR, the stationary battery transfers as much energy as possible to Car 1 in the morning hours. Therefore, SOC of the stationary battery is quite low when PV electricity is available again. This enables charging the stationary battery to a high level, almost on a daily basis. This effect is lacking in the ‘Only Car 2 Scenario’, as the stationary battery is deprioritised by Car 2 as a low cost storage option. The availability of Car 2 during daytimes and as a V2H option keeps recharging demand low, which leads to prevailing high SOC of Car 2. Furthermore, the lack of additional driving demand of Car 1 reduces the need for transfer of electricity from Car 2 to Car 1.

The regional variation of SCR as shown in Figure 11, which is influenced by the corresponding regional grid electricity prices. Households in regions that have low grid electricity prices (such as Russia) tend to have a high SCR, as the installed capacities of PV and battery are much lower in comparison to households in other regions with higher grid electricity prices. The impact of the grid electricity prices varies through the transition period as the costs of PV and battery systems decline substantially, while grid electricity prices in most regions increase through the transition period until 2050. High levels of SCR are prevalent in the early periods of the transition as most regions still do not achieve grid parity. Whereas, in the later periods of the transition lower SCR is observed as most regions have achieved grid parity. This trend is highlighted in the Supplementary Material (Figure S7).

Figure 11: Comparison of self-consumption ratio (SCR) for households in all regions in 2050, for the ‘Two Cars Scenario’ (top left), ‘Only Car 1 Scenario’ (top right), ‘Only Car 2 Scenario’ (bottom left) and ‘No Cars Scenario’ (bottom right).

Optimisation of the capacity of stationary battery has varying effects based on the difference between regions with excellent to moderate solar conditions. In case of the ‘Two Cars Scenario’, difference between households in Finland and Australia is quite low, at about 15%_{abs}. While, in the ‘Only Car 1 Scenario’ a spread of about 20%_{abs} is expected between 2025 and 2045. In 2050, the SCRs will begin to match up. For the ‘Only Car 2 Scenario’ a difference of up to 15%_{abs} until 2025 is noticed, with similar SCRs in 2050. The impact on SCR of using both cars or either of them, compared to the ‘No Cars Scenario’ across the various regions in 2050 can be seen in Figure 11. Moreover, SCR is observed to be higher in the initial periods as compared to the later periods in most regions during the transition, across all the scenarios. The development of the SCR for the different scenarios across the 8 regions through the transition period from 2015 to 2050 can be seen in Figure 12.

Figure 12: Development of the Self-Consumption Ratio in households across the 8 regions, for the ‘Two Cars Scenario’ (top left), ‘Only Car 1 Scenario’ (top right), ‘Only Car 2 Scenario’ (bottom left) and ‘No Cars Scenario’ (bottom right).

On comparing Figures 13 and 14, it can be observed that SCR develops in contrast to ATCE. Furthermore, results show that the SCR is mostly dependent on the installed PV capacity in the ‘Two Cars Scenario’ and the

‘Only Car 2 Scenario’. While, for the ‘Only Car 1 Scenario’ and the ‘No Cars Scenario’, the SCR increases with higher battery capacities (for small to mid-sized batteries). This indicates that an optimal sizing of PV capacity and storage capacity (BEVs + stationary battery) is necessary for higher SCRs. For the case of households in Germany (Figure 14), a halving of the installed PV capacity, causes additional energy costs of under 200 €/a, which results in a SCR increase of approximately 25% (refer Figure 13, bottom left and Figure 14).

Figure 13: ATCE for households in Germany for the ‘Only Car 2 Scenario’ in 2015 (top left), 2020 (top right), 2030 (bottom left) and 2050 (bottom right).

Figure 14: Self-consumption ratio in households across Germany for the ‘Only Car 2 Scenario’ in 2030.

4.3 Demand and Heat Cover Ratios

DCR and HCR vary significantly across the different scenarios as shown in Figure 15. Households in regions with excellent solar conditions are able to cover, theoretically up to 100% of their demands for electricity and heat in 2050 with self-produced PV electricity. While, households in regions with seasonal solar variation (good solar conditions during summers, but moderate conditions in winter), such as in the United States or in Central Europe, are able to cover 90% - 95% of their electricity demand and 85% - 95% of their heat demand until 2050 on their own, across all scenarios. On the other hand, households in regions with relatively lower solar potential and higher heat demands, such as Canada or Northern Europe, can cover about 60% - 75% of their electricity demand and around 60% - 70% of their heat demand through self-generation. Higher DCR and HCR are achieved for the 'Two Cars Scenario', while they are much lower for the 'No Cars Scenario' as indicated by Figure 15. Therefore, it can be concluded that widespread affordable electricity storage technologies are indispensable to effectively meet power and heat demands. The development of DCR and HCR through the years witness large changes in the early years and near stagnation from 2030 onwards for most regions across the world. As, the added value for DCR and HCR of cost optimised systems are not very significant beyond a certain point.

The extent for DCR can be noticed from scenarios without Car 2 at a range of smaller capacities of stationary battery. For a majority of the regions, increments in PV and stationary battery capacities have to coincide during the early years, resulting in significantly higher ATCE. Whereas for later years, as PV systems and batteries become more affordable and large PV capacities are part of the least cost system, larger battery capacities can make a significant difference. For the case of households in Australia in the 'No Cars Scenario', the DCR for PV capacities from 7 kW_p – 30 kW_p remains the same. However, as stationary battery capacities increase from 1 kWh_{cap} – 13 kWh_{cap} the DCR rises up to 40%_{abs} by 2050. In the case of households in Indonesia, this impact is even more significant. An increase in battery capacity from 1 kWh_{cap} to 4 kWh_{cap} results in a DCR improvement of around 30%_{abs}. The development of HCR is contradictory to the development of SCR through the years. This implies that a low SCR results in a high HCR, as additional capacities of PV are required for filling the TES. Nevertheless, the amount of energy necessary to fill the TES is comparably smaller to the amount of energy generated.

The variation of DCR and HCR across households in the different regions and the impact of BEVs in 2025 are shown in Figure 15. Using both the BEVs ('Two Cars Scenario'), the DCR is marginally higher for households in most of the regions, compared to the 'No Cars Scenario'. The variation in HCR of the 'Two Cars Scenario' and 'No Cars Scenario' is very evident for households in the African and Asian regions, which do not have significant heating demands. In addition, lack of chargeable BEVs allows for PV additional filling of the TES, which is attributed to stable solar conditions throughout the year. As observed from Figure 15, retail grid electricity prices have an impact on the DCR and HCR, as households in countries and regions with low electricity prices (mainly due to subsidies) tend to have lower DCR and HCR. On the contrary, households in countries and regions with higher retail grid electricity prices have much higher DCR and HCR.

Figure 15: Demand cover ratio (DCR) in households across all regions in 2025, for the ‘Two Cars Scenario’ (top left) and ‘No Cars Scenario’ (top right) and heat cover ratio (HCR) in households across all regions in 2025, for the ‘Two Cars Scenario’ (bottom left) and ‘No Cars Scenario’ (bottom right).

4.4 Least ATCE System Design

The range of least ATCE system designs vary significantly across the regions in the simulated scenarios. Figure 16 shows the least ATCE system designs for the year 2030 with one or more regions that do not reach grid-parity. The impact of Car 2 on the capacity of the stationary battery can be observed here as well. In the ‘Two Cars Scenario’, some regions that already have large PV capacities also have battery capacities up to 15 kWh_{cap}, as part of their least cost system configuration. Majority of the regions have a resulting battery capacity of just 1 kWh_{cap}, due to the presence of Car 2. The relevance of stationary batteries is a lot higher for the ‘Only Car 1 Scenario’ and the ‘No Cars Scenario’. Until 2050, majority of the regions will have stationary battery capacities greater than 1 kWh_{cap} for a least cost system design. For the two scenarios ‘Only Car 1 Scenario’ and ‘No Cars Scenario’, a dependence of battery capacities on PV capacities is quite evident. For high PV capacities, relatively high battery capacities are necessary. Furthermore, the use of Car 1 with energy supply via the stationary battery has an impact on the least ATCE system design, which increases corresponding system capacities. The least cost system designs for 2015, 2020, 2030 and 2050 for the different scenarios can be found in the Supplementary Material (Figures S3-S6).

Figure 16: Least cost system designs in 2030 for the ‘Two Cars Scenario’ (top left), ‘Only Car 1 Scenario’ (top right), ‘Only Car 2 Scenario’ (bottom left) and ‘No Cars Scenario’ (bottom right). The 8 regions are marked green. The $2 \text{ kWh}_{\text{cap}}/\text{kW}_p$ line represents a projected cost efficiency limit.

For all the scenarios, development of least ATCE systems seems to have a cost efficiency limit of battery / PV capacity ratio of $2 \text{ kWh}_{\text{cap}}/\text{kW}_p$ (Figure 16). With a few exceptions, most of the systems are below this limit. Across all the scenarios, it is observed that very high battery capacities do not occur in residential PV systems for households in most regions. In the absence of V2H, small and mid-sized battery capacities are the most optimal. Whereas, with BEVs and V2H, only smaller battery capacities are necessary. PV capacities will vary depending on solar conditions as well as energy demand for electricity and heat, across households in the various regions and years.

5. Discussion

The emergence of demand side technologies along with PV, energy storage options and energy management systems are continuing to change the way electricity is sourced and consumed. Despite a growing number of global energy scenario analyses, many of them lack comprehensive analyses of even energy storage systems as shown by Koskinen and Breyer (2016). Therefore, analyses on the role of PV prosumers in global energy systems is extremely scarce, Ram et al. (2017a) and Breyer et al. (2018) have analysed PV prosumers from a

global power sector perspective. It is shown that residential PV prosumers can contribute up to 5.5% of the total power generation by 2050, with a global installed capacity of around 2 TW (Ram et al., 2017a; Breyer et al., 2018). Regional variation of the installed capacities as well as generation shares of residential PV prosumers is shown in Figure 17. Furthermore, the global residential battery capacity in 2050 is around 4107 GWh_{cap}, as the prosumer aspect of the model is limited to just a combination of solar PV and Li-ion batteries (Ram et al., 2017a; Breyer et al., 2018). In regard, this research highlights that value addition of PV prosumers can reach beyond just the power sector and can integrate heating as well as mobility aspects of residential households. Furthermore, this research is an effort to better understand the synergies of various complementary technologies such as Li-ion batteries, BEVs, HPs and TES that will most likely play a role in future energy systems, in the context of residential PV prosumers. As many studies have already pointed out the benefits of integrating different components, such as absorption of surplus electricity by power-to-heat systems can offer flexibility to PV prosumers as well as the electricity system (Oluleye et al., 2018). Oluleye et al. (2018) also point out the benefits of coupling HPs with TES in a PV prosumer context. Additionally, Schwarz et al. (2018) analyse PV prosumer systems with various components and the effects of residential electricity tariffs on their design and sizing. It is quite evident that optimising the right system design and size is crucial to get maximum benefits for PV prosumers, as showcased in the results of this research. Moreover, demand patterns for both electricity and heat can vary significantly across the various regions of the world and sometimes within the regions themselves. Therefore localising PV prosumer models is extremely important to determine the most optimal solution in an accurate manner. On that note, the major benefit of this model is its ability to be modified according to different regional conditions and utilised to generate results with greater local significance, as showcased for the case of Germany (Keiner, 2018) and India (Ram et al., 2017b).

Figure 17: Installed capacities (left) and electricity generation shares (right) of residential PV prosumers across the different regions of the world in 2050 (Ram et al., 2017a; Breyer et al., 2018).

In general, from the results it is observed that PV prosumer systems are economically advantageous for residential households in all the different compositions of BEVs (the 4 scenarios). These results are realised without the consideration of substantial incentive mechanisms that are present in many countries, which can have a significant impact on the overall ATCE. High feed-in compensation rates could guarantee a secure financial return for the installation of the PV system and maximise generation fed into the grid. Furthermore, these can also influence the SCR coupled with HCR and DCR. Additionally, dynamic retail electricity pricing that is not considered in this research can influence the results, mostly in favour of PV prosumer systems. Another factor that was not considered in this research is the requirement of rooftop area (or other suitable area within the residential premises), which primarily varies with the size of the PV system. As the results indicate, the optimal size does not reach the maximum possible expansion of PV systems and corresponding roof areas, which should not be a major limiting aspect. Nevertheless, PV systems remain attractive in the residential household sector with the current compensation and electricity prices in many regions of the world.

They become more attractive through the transition period as retail electricity prices increase coupled with increasing consumption. In order to optimise their ATCE, PV prosumers are expected to utilise maximum roof area (or other suitable areas within the residential premises). The option of not being a PV prosumer results in higher costs for electricity at the retail level on average and, hence, translates into a higher value of PV systems for residential households in the future. In this context, Weniger et al., (2014) and Weniger et al., (2016) identified that the optimal PV system size will shrink to small-scale systems with higher self-consumption rates, as the incomes from the feed-in payments will play a minor role in future. Additionally, Weniger et al., (2014; 2016) show that in the long-term a conjunction of PV systems with batteries will be not only profitable, but also the most economical solution. Results of this study show that the role of multi-objective optimisations have an important role in determining system configurations, which offer the best performance based on costs and other system parameters (Delgado et al., 2017). Delgado et al. (2017) conclude that GSHPs offer the best combinations of cost-optimality, operational equivalent CO₂ emissions, and exergy among the main heat supply systems investigated, and that they are generally best complemented with PV, which is similar to the findings of this study. Furthermore, Delgado et al. (2018) conclude that heat pumps represent the optimal main heat supply component in the Netherlands and Finland, and PV systems are the most attractive supplementary onsite generation components. Delgado et al. (2018) give valuable insights into the potential of prosumers in central and northern Europe, yet acknowledge that significant differences might arise in other geographical locations, indicating the need for separate case study assessments. This study has shown the presence of this variation across households in the different regions of the world. However, it also shows the immense potential for PV prosumers and makes an attempt at estimating the financial benefits for households across the different regions.

Despite an effort to capture the regional variations, conducting a global analysis in the context of residential PV prosumers involves a fair number of limitations. The assumptions regarding the PV prosumer model have been described extensively in the earlier sections. However, these assumptions entail a broader view of residential prosumers in the different regions of the world and limit an in-depth analysis. Electricity demand growth across the different regions is assumed according to standard growth assumptions, which do not factor in a higher rate of electrification that could have an overall impact on residential electricity demand in the different regions of the world. Similarly, load profiles across the different regions of the world are based on average household presumptions. Whereas, in reality household sizes and demand profiles vary substantially with income levels and regional factors. An attempt has been made to factor in the regional variations as far as possible. Additionally, with recent trends and practices households are varying their demands in response to retail electricity prices. This is another limitation, as far as differential pricing of electricity is considered. The current research assumes static retail electricity tariffs in the long-term, which could apply to many regions but with increased digitisation differential electricity tariffs could be a future prospect. Similarly, a standard feed-in tariff is assumed in the current research. Whereas, solar PV feed-in tariffs vary significantly across the different regions of the world. In addition, standard global costs are assumed for all the components of a PV prosumer household. While in reality, costs may vary substantially across the different regions of the world with varying tax structures and labour costs.

Regardless of the limitations, optimisation of energy system components presents valuable insights across all the regions, but further components could add value, e.g. by including seasonal storage technologies in an intelligent residential energy system. This involves conversion of surplus electricity during summer times into hydrogen and storing it. In winter times, the hydrogen can be re-converted via fuel cells back into useable electricity and heat. Therefore, increasing the SCR and HCR. Residential seasonal storage solutions are already available (HPS, 2017). Additionally, smart home and home automation technologies with a variety of integrated energy management components are also becoming more widespread. There is a growing synergy with energy and communication technology transitions, which also entails societal changes as further explored by Ruotsalainen et al. (2017). These technologies enable consumers to optimise their energy use, match it with

their needs, and when applicable, with their energy generation and storage, while saving money or energy in simple ways (Parag et al., 2016). Peer-to-peer (P2P) energy sharing is gaining a lot of attention, it involves technologies and models at the demand side of power systems, which are able to manage the increasing connections of prosumers and provide platforms for energy transactions. In P2P energy sharing, prosumers directly trade energy with each other to achieve a win-win outcome. From the perspectives of power systems, P2P energy sharing has the potential to facilitate local energy balance and increase self-sufficiency. P2P energy sharing is an emerging phenomenon that has the potential to reshape the paradigm of power systems and bring various benefits for both prosumers as well as power systems (Zhou et al., 2018). Furthermore, the role of prosumers in co-creating flexibility is a promising area to be further explored, offering greater potential for optimising energy utilisation as well as minimising overall ATCE across a substantial number of prosumers (Kubli et al., 2018). These aspects of the rapidly evolving prosumer segment need to be integrated in future research.

6. Conclusions

Combining PV generation systems with various energy storage technologies for electricity and heat have proven to be highly beneficial for PV prosumers, particularly for reducing ATCE, as shown earlier. Optimising ATCE and SCR is a challenge and depends on various external factors, such as electricity prices, solar conditions, policy support for PV prosumers and so on. Nevertheless, as indicated earlier a balance can be reached. Although the sensitivity of ATCE is not high for most of the cases, a balance is easy to find, at least for later years wherein PV capacities do not have a significant impact on ATCE.

A large amount of energy fed into the grid could pose problems (Hollinger et al., 2013). Substantial PV prosumer installations may result in challenges for distribution grid management, but it can also be a source of sustainable and affordable energy supply for society, while playing a vital role in climate change mitigation (Jäger-Waldau, 2018). From the results, it can be concluded that there is no standard least cost system design across all regions. Therefore, an optimisation of the system across different component configurations is a very beneficial exercise to enable informed decision making on appropriate system design and sizing. In the case of some regions, it may be beneficial to determine an optimal size for the TES and HP. For regions with moderate solar conditions, a TES of 800 litres and a HP of 7 kW_{el} seem to be good choices, as indicated by the results. Whereas, for regions with good solar conditions and warm temperatures with lower heating demands (which is mostly hot water demand and some space heating for a few days in a year), lower system sizes will be ideal. As shown by Enkhardt (2018), having large number of PV prosumers can also have collective benefits such as, stabilising the local distribution grids, reducing grid infrastructure refurbishments and more flexible EV charging. Additionally, clusters of connected storage systems could take on the role of traditional grids (Enkhardt, 2018).

Integrating BEVs into residential PV systems is extremely beneficial for optimising energy usage as well as ATCE, as indicated by the results. Furthermore, energy demand for driving can also be covered by PV generation. With increasing fuel costs, BEVs charged with low cost PV could provide not only an affordable transport option, but also a sustainable one. In addition, application of V2H enables higher SCR and lower ATCE, as indicated by the results. However, optimal usage of stationary batteries along with V2H vehicles needs further examining.

In comparison to 100% grid supply, optimised residential PV systems will be able to reduce ATCE by up to 50%_{abs}, as indicated by the results. This could amount to several thousand euros per annum in household savings, which could be the most economical energy designs in the coming years. Moreover, in some regions further savings could be realised with optimal seasonal storage. Summarising the results, residential PV

Prosumer systems will be a very cost effective solution of generating and consuming energy in households and pursuing higher levels of energy self-sufficiency.

In this context, energy markets have to be redesigned for the prosumer era that could maximise residential and commercial energy sufficiency, democratise energy systems, and prepare society for ubiquitous, distributed, smart and integral energy activities. Thus, further investigation into the role of residential households as heat and electricity prosumers might provide constructive outcomes in the pursuit of sustainability and energy transitions regionally as well as globally.

Supplementary Material

The supplementary data associated with this article can be found in the online version at (link to be added)

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Appendix

Table A.1: Financial assumptions for the various PV Prosumer system components (Ram et al., 2017; Schmidt et al., 2017 and Knitter et al., 2017), for all regions and modelled years.

Financial Assumptions

	Unit	2015	2020	2025	2030	2035	2040	2045	2050
PV Rooftop									
Capex	[€/kW _p]	1360	1090	890	760	680	610	550	500
Opex fix	[€/(kW _p ·a)]	20	16	13	11	10	9	8	8
Lifetime	[a]	30	30	35	35	35	40	40	40
Stationary Battery									
Capex	[€/kWh _{cap}]	600	300	200	150	120	100	85	75
Opex fix	[€/(kWh _{cap} ·a)]	24	9	5	3.75	3	2.5	2.125	1.875
Opex var	[€/(kWh _{through} ·a)]	0.0002	0.0002	0.0002	0.0002	0.0002	0.0002	0.0002	0.0002
Lifetime	[a]	15	20	20	20	20	20	20	20
Heat Pump									
Capex	[€/kW _{el}]	1600	1500	1500	1400	1400	1300	1300	1200
Opex fix	[€/(kW _{el} ·a)]	20.6	19.5	19.5	17.9	17.9	17.4	17.4	16.9
Lifetime	[a]	20	20	20	20	20	20	20	20
Heating Cartridge									
Capex	[€/kW _{el}]	570	570	570	570	570	570	570	570
Opex fix	[€/(kW _{el} ·a)]	10	10	10	10	10	10	10	10
Lifetime	[a]	30	30	30	30	30	30	30	30
Thermal Energy Storage									
Capex	[€/kWh _{cap}]	50	40	30	30	20	20	20	20
Opex fix	[€/(kWh _{cap} ·a)]	0.75	0.6	0.45	0.45	0.3	0.3	0.3	0.3
Lifetime	[a]	25	25	25	25	30	30	30	30

Table A.2: Efficiency assumptions for storage and energy conversion technologies, for all regions and modelled years.

Efficiency Assumptions							
	Unit	Stationary Battery	TES	Car 1	Car 2	HP	Heating Cartridge
Charging	[%]	96.8	100	96.8	96.8	-	-
Discharging	[%]	96.8	100	-	96.8	-	-
Standby losses	[%/h]	0	0.15	0	0	-	-
Electricity-to-Heat conversion nominal COP	-	-	-	-	-	3.8	1
Electricity-to-Heat conversion PV additional filling COP	-	-	-	-	-	3.0	1