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Review

Sustainable Residential Energy Supply: A Literature Review-Based Morphological Analysis

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Abstract: The decarbonization of the energy system will bring substantial changes, from supranational regions to residential sites. This review investigates sustainable energy supply, applying a multi-sectoral approach from a residential site perspective, especially with focus on identifying crucial, plausible factors and their influence on the operation of the system. The traditionally separated mobility, heat, and electricity sectors are examined in more detail with regard to their decarbonization approaches. For every sector, available technologies, demand, and future perspectives are described. Furthermore, the benefits of cross-sectoral integration and technology coupling are examined, besides challenges to the electricity grid due to upcoming technologies, such as electric vehicles and heat pumps. Measures such as transport mode shift and improving building insulation can reduce the demand in their respective sector, although their impact remains uncertain. Moreover, flexibility measures such as Power to X or vehicle to grid couple the electricity sector to other sectors such as the mobility and heat sectors. Based on these findings, a morphological analysis is conducted. A morphological box is presented to summarize the major characteristics of the future residential energy system and investigate mutually incompatible pairs of factors. Lastly, the scenario space is further analyzed in terms of annual energy demand for a district.

Keywords: energy system; morphological analysis; sector coupling; energy system scenario

1. Introduction

The decarbonization of the energy system is promoted in many regions of the world. For example, the EU Energy Roadmap describes a scenario in which 75% of energy is supplied from renewable sources [1]. In research, even more ambitious targets are defined, aiming at an energy system which is 100% based on renewables [2–4]. First ideas for a 100% sustainable energy supply came up in the late 1970s. After 2010, they have become part of public debate [5]. To achieve a sustainable energy system, far-reaching transformations are necessary [6]. Previously, the electricity sector was primarily viewed in isolation. More recent studies also include the transport and heating sector because fossil fuels are the primary energy source in these sectors. Energy systems, comprising of the mobility, heat, and transport sectors, are called integrated [7], multi-energy [8], smart [9], or sector-coupled energy systems [10].

The transformation to a decarbonized energy system is often investigated with complex energy system models. For example, the energy system model renewable energy mix (REMix) optimizes the hourly dispatch and determines the least cost energy system [11]. Integrated assessment models (IAMs), such as the Regional Model of Investments and Development (REMIND), combine knowledge from several domains, for example, climate change, macro-economics, and the energy system with a temporal resolution in the order of years [12]. Energy system models or IAMs are usually based on nation-scale spatial resolution. In some cases, individual regions of nations are analyzed for their decarbonization pathways [13]. One key aspect of all these decarbonization scenarios is energy system technology. The integration of technology to the grid generates costs that can only be estimated in large-scale transformation models and a significant part of these costs arise from the integration at the distribution grid level [14].

The cost of integration of renewable technologies can be decreased by planning of shiftable loads and storage, i.e. load and energy management. These management approaches optimally schedule a device pool, whereby technical restrictions have to be considered [15–18]. To develop future energy management systems, it is necessary to define the expected equipment and its requirements. This work aims to assist the deduction of future energy technologies for districts and projected demand which have to be handled by these technologies.

In the EU, around 25% of final energy (final energy describes the energy consumed by end users and neglects delivery and transformation) is consumed by residents, meaning that this sector represents a significant share of the overall energy demand [19]. Furthermore, decarbonization of the energy system has visible effects on residents and thus influences the acceptance of renewable technologies [20]. Therefore, this contribution analyzes the developments that are relevant at a district system scale.

In this publication, the developments are brought together on the basis of a literature review, followed by a morphological analysis, taking a residential perspective. Reviews for individual technologies are widely available in the literature (e.g., [21–24]). This contribution differs from others in that it focuses on a narrowed part of the energy system (i.e., residential grids) and looks at several sectors whose future shape is highly uncertain. This enables a broader understanding of the energy system from the perspective of residents and the identification of particular challenges. An interdisciplinary approach is pursued. The core of this paper is on technologies which are suitable to be deployed at residential sites. These are placed in the context of their utilization and potential, whereby sociological or techno-economic findings are relevant. This enables a better understanding of the interactions of individual aspects of the energy supply for residents. Due to the wide distribution of this field, this article does not claim to be exhaustive. It conveys the authors findings in relation to the question of: What will future residential energy systems, based on renewable technologies, look like?

This article presents current developments in terms of traditional energy sectors, the mobility (Section 2), heat (Section 3), and electricity sectors (Section 4). Section 5 also examines challenges in integrating these sectors and potential synergy effects. Section 6 shows a morphological analysis of the energy system, based on the findings of the previous sections. Section 7 provides a conclusion.

2. Mobility Sector

The mobility sector represents an essential part of the energy demand, which is currently largely supplied by fossil fuels. Climate-neutral energy supply can, therefore, make a significant contribution to overall decarbonization [25]. The mobility sector is particularly difficult to decarbonize. For example, it is stated that 85% of future transport demand will rely on fossil fuel until 2050 [26].

In Figure 1, it is shown that this is similar to the current situation. Moreover, Figure 1 shows that road transport is currently the prevailing mode.

In this section, the transport sector is described in terms of technologies, demand, and future perspective. An overview of this section can be gained in Figure 2.

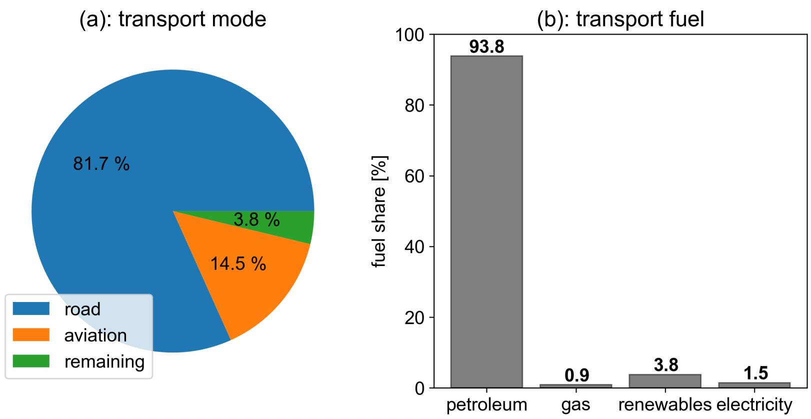

Figure 1. Current status of transport sector in EU countries: (**a**) current energy use for transport by mode; and (**b**) current energy use by fuel. Data used from [19].

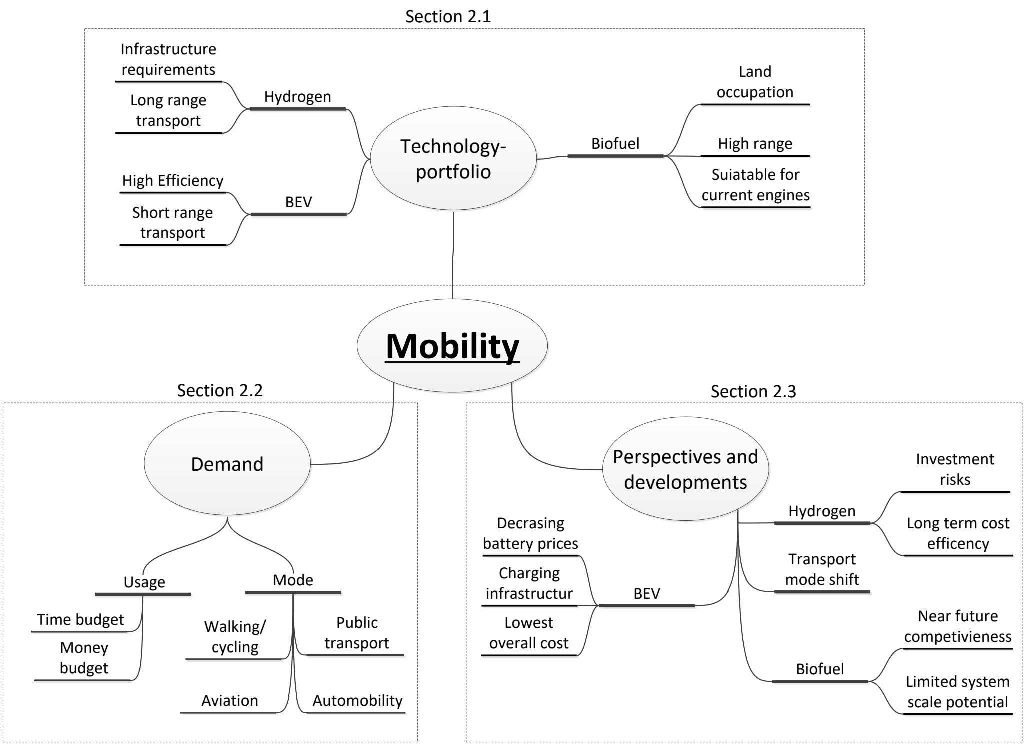

Figure 2. Overview of the mobility section and the respective subsections. Section 2.1 deals with the technology portfolio, Section 2.2 investigates the mobility demand, and Section 2.3 describes perspectives and developments. The branches indicate considered aspects within a subsection.

2.1. Technology Portfolio

For this study, technologies are considered which can be fueled in sustainable manner. Battery electric vehicles (BEV) can be charged by wind or PV power, bio-based fuels are based on the agricultural cycle, and hydrogen can be produced with electricity from renewables. Thus, theses three technologies are considered in this study.

A battery-based electric vehicle (BEV) stores electric energy in a battery to propel an electric engine, thus providing mobility to its passengers. However, a BEV is less suitable for distances longer than 300 miles because the required battery capacity causes significant cost and weight addition, even considering future battery prices [27]. A BEV requires charging infrastructure for operation. This can be provided by home charging or public fast-charging infrastructure. Home charging provides significantly less power than fast-charging infrastructure. However, fast charging can challenge the electricity grid and additional components, such as cooling or buffer batteries, reduce the efficiency [28].

Biofuels are, in principle, suitable fuels for internal combustion engines (ICE) or fuel cells. Challenges for the application of biofuels are the potential requirement of additional processing to enable the usage in current engines [29] and resource constraints due to land use [30]. For example, in the US, 21 gigalitres of ethanol could be produced from marginal land feedstock, which does not compete with food production. This corresponds to around 7% of the expected US liquid fuel demand in 2050 [31]. There is the distinction between first, second, and third generation biofuels [29]. These fuels differ significantly when it comes to feedstock and final chemical structure. First generation biofuels are produced primarily from food crops. Consequently, the competition of fuel and food was attached to first generation biofuel [32]. Second generation biofuel is produced by means of by-products, waste, or dedicated feedstock. The raw material is gained from non-food biomass, although, especially dedicated feedstock, still competes with food production in terms of land use [33]. Third generation biofuel is produced from algal biomass [34]. Algal biomass requires less land for growth but more energy compared to terrestrial biomass [35,36]. Further developments are so-called advanced biofuels, solar fuels, or fourth generation biofuels. These comprise the utilization of synthetic biology to produce biofuel from sunlight and environmental carbon dioxide with a high photon to fuel efficiency, although they are at the research stage [37].

Hydrogen can be produced from fossil resources, biomass, and water [38]. Hydrogen is able to power a vehicle by means of fuel cells and an electric engine. These vehicles are called fuel cell electric vehicle (FCEV). Current FCEVs, such as the Toyota MIRAI, exhibit a cruising range of 500 km, whereas the refilling time is 3 min [39]. Hydrogen can also power combustion engines. These vehicles are called hydrogen-fueled internal combustion engine (H2ICE). However, the advantages of FCEV, such as higher efficiencies and lower operation noise, make this technology more attractive than H2ICE [40]. Hydrogen-based mobility is well suited for more energy-intensive applications such as public transport and light-duty trucks [41]. Furthermore, hydrogen can serve as a fuel for aviation, although hydrogen differs from current aviation fuel in terms of combustion properties, e.g., the linear flame speed. Thus, turbine technology adaptations would be necessary [42].

2.2. Demand

From 1960 to 1990, total worldwide traveling mileage per capita doubled [43]. People spend, on average, 1.1 h per day on traveling and expend 10 to 15% of their income on mobility. These numbers describe the travel time budget and the travel money budget [44]. Combined with economic progression, it is assumed that people will increase their traveled distances and, to keep within the time budget, faster transport technologies are used. Global motorized travel decoupled from economic growth at the beginning of the 21st century. Vehicle ownership stopped increasing at 450–750 vehicles per 1000 persons, depending on the region, whereas air travel increased [45]. In addition, structural differences are visible. The car share is higher in suburbs than in the city core [46].

2.3. Perspectives and Developments

BEV and direct electricity usage are the most cost-effective transportation technology, compared to technologies using synthetic fuels [47]. BEVs exhibit higher efficiencies, compared to hydrogen-based vehicles [48]. However, it is assumed low energy densities of batteries make BEVs not suitable for freight transport or even aviation [49].

Several studies investigate expected future prices of batteries, which are a key component for electric mobility. Learning rates, based on cumulative demand, of 6 to 9% were observed [50]. Battery packs could reach $175/kWh between 2027 and 2040 [51]. Another study even estimates $124/kWh in 2020. Their model takes, besides the cumulative capacity, an innovational aspect into account, which is shown to have a stronger impact than cumulative production [52].

Bio-based fuels rely heavily on feedstock cost to be competitive, especially for first to third generation biofuel [53,54]. As with other technologies, increasing cumulative production is assumed to decrease total cost. However, in the case of biomass, the feedstock prices increase as the production increases. If the installed production capacity is low, the technology learning effect outweighs the increase in feedstock cost. Conversely, at high production volumes, the feedstock price increase can outweigh the learning effect [55]. Biodiesel, a first generation biofuel, is at a mature status, indicating no significant technological improvement potential, whereas some second generation biofuel is at the growth state [56]. Furthermore, second generation biofuels are cost superior to first generation biofuels and some could even compete with fossil fuels in 2020 if the crude oil price reaches €100/barrel [53]. Third generation biofuels require large scale facilities to be effective. These comprise cultivation, pretreatment, and downstream processing [57]. Bio-based-fuels are considered to be cheap during a transition phase to renewable transport [49].

For hydrogen-based mobility, additional infrastructure is required for production, storage, delivery, and filling [58]. The most cost-efficient infrastructure depends on the distance between production and consumption site and demand. Distances below 200 km favor road transport, bigger distances and high demand favor pipeline infrastructure [59]. Hydrogen is more cost-effective than biofuels in 2050 if the additional infrastructure requirements are disregarded. However, the necessary investments in new infrastructure for hydrogen utilization are expensive, and renewably produced hydrogen is estimated to cost $9.7/kg ($0.29/kWh, considering the lower heating value) in 2030 [38]. For around ten years, permissible hydrogen prices will not cover the infrastructure cost, resulting in negative cash flow. Amortization is expected after 15 years, thus making investments in hydrogen infrastructure risky [41].

Besides carbon-free fuels, lifestyle changes could also contribute to emission reduction and energy efficiency improvement [44]. Some bigger cities have started to shift the primary transportation mode. These concepts comprise reducing mobility demand and changing its structure by shifting car-based mobility to public transport-, bicycle-, and footpath-based mobility [46]. Another concept combines bicycles with electric mobility by assisting the propulsion with an electric engine. Thus, application scenarios of bicycles are extended to light cargo duties. The assisted propulsion also enables the usage of bicycles on more demanding routes and makes them more attractive for people who are worried about their physical constitution [60]. Different transport modes can also be combined within a single journey, which is called intermodal transport [61]. A shift of transport mode is difficult for rural areas because of lower population densities and bigger distances, compared to urban areas [62]. In rural areas, dial-a-ride services can offer mobility and bundle demands [63].

Energy systems scenarios show a broad variety of possible feature developments [64]. In [62], a drastically changed structure is assumed. Urban mobility is based on cycling and walking. Freight transport utilizes cargo bikes. In [3], BEVs are assumed to cover 50% of the private car transport demand. On the other hand, high estimates assume bio-based fuels to supply 50% of countries transport energy demand [2]. Even significant technological advancement is assumed in future scenarios. For example, in [4], batteries are assumed to be capable of powering air travel for distances up to 1500 km.

3. Heating Sector

The room temperature is an important aspect to achieve the desired comfort level of residents inside buildings. Heating and cooling is required for temperature control, although the energy demand for heating is significantly higher than for cooling [65]. This section only deals with heating, which is currently primarily based on oil and gas heaters. The possibilities for sustainable heat supply, heat demand, and perspectives are investigated. Figure 3 shows the contents of this section.

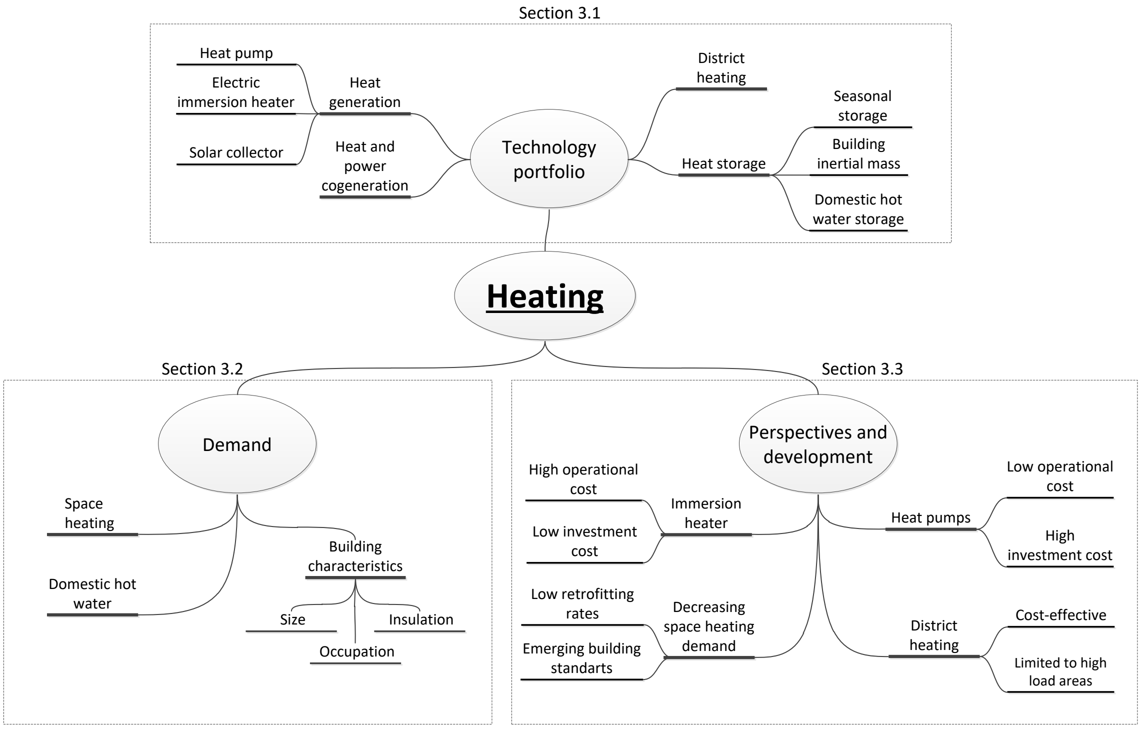

Figure 3. Overview of the heating section and the respective subsections. Section 3.1 deals with the technologies capable for heating application, Section 3.2 investigates the heating demand, and Section 3.3 describes perspectives and developments. The branches indicate considered aspects within a subsection.

3.1. Technology Portfolio

Considered technologies are solar collectors, combined heat and power (CHP) plants, electrical immersion heaters, and heat pumps. Solar collectors convert radiation directly to heat, CHP plants exploit waste heat of a thermodynamic cycle or a electrochemical process, electrical immersion heaters convert electricity directly to heat, and heat pumps convert electricity to heat but additionally draw energy from the environment [3,66,67].

Flat and evacuated tube solar collectors convert solar radiation directly to heat. These collectors are suitable to provide thermal energy for low-temperature applications, such as domestic hot water and space heating [68]. Improved insulation enables the solar collector to provide higher temperature heat by preventing convective heat losses [21,69]. Transparent faced elements, so-called transpired solar collectors, are suitable for preheating environmental air before entering a building [70]. Heat pumps gain a major fraction of their heat output from the environment; thus, they convert electricity to heat more efficiently than immersion heaters [71]. From a climate change mitigation perspective, heat pumps are the most suitable technology to make use of excess electricity [72]. Heat pumps with flexible electricity demand, and thus a flexible heat output, can improve power quality [22]. However, immersion heaters have better grid supporting capabilities, due to the lack of startup time and no ramping constraints [71].

District heating systems are another potent heating technology because they can directly utilize industrial waste heat. This heat usually has a sufficient temperature level for space heating and domestic hot water [73,74]. Beside waste heat, required heat can be supplied by biomass or a central, large scale heat pump. Large scale heat pumps draw energy from sources such as sewage or ambient water, e.g., from a lake or river [75]. Waste heat provides the lowest cost, whereas a central heat pump emits significantly less CO_2 (given electricity with low CO_2 emissions is used) [76].

Combined heat and power (CHP) technologies are suitable to provide heat and, furthermore, electricity. For residential application, these are called micro-CHP and generate up to 50 kW of electrical power. Different technologies provide heat and power cogeneration capabilities, which are internal combustion engines, micro-gas turbines, Stirling-engines, organic Rankine-cycles, and fuel cells [77]. In the past, CHP units were primarily powered by fossil fuels. Other possible energy carriers are synthetic or biological natural gas, methanol, and hydrogen [78]. Another energy carrier is biomass, which can be burned directly in CHP systems [66]. A challenge for the operation of CHP units is the dual dependency of heat and power. This means heat and power cannot be generated in arbitrary ratios. The scheduling of CHP units in an optimal manner is called CHP economic dispatch problem [79,80].

Heat storage allows the flexibilization of heat supply, especially if an intermittent source, such as a solar collector, is installed. Heat can be stored using different principles: sensible, latent, or thermochemical heat storage [81]. Sensible heat storage is based on the heat capacity of a material. The storage media is heated up or cooled down, depending on the desired process direction. Latent heat storage relies on the phase change enthalpy of materials, such as organic material, salt hydrates, eutectic materials (eutectic means the lowest possible melting temperature of mixtures; at the eutectic temperature, the liquid can change completely to the solid phase and vice versa), and ice [81,82]. Thermochemical heat storage is based on reaction enthalpy. An endothermic reaction charges the storage and an exothermic reaction discharges the storage [83]. In domestic application, sensible heat storage by hot water tanks is common [69]. For well-insulated buildings, the building inertial mass can act as sufficient heat storage, thus avoiding the necessity of other technologies [22]. Using this passive heat storage is more cost-effective than storage by dedicated accumulation tanks [84]. Heat storage can also work in seasonal timescales. It stores energy in big water reservoirs (hot water or aquifer thermal energy storage), the soil (borehole thermal energy storage), or combination of soil and water (gravel water thermal energy storage) [85].

3.2. Demand

Energy consumption of buildings accounts for a significant share of total energy usage. Key factors for the energy consumption of buildings are the location and size [86]. Furthermore, the number of inhabitants in a household, floor space, specific energy consumption, and economic situation affect the heating demand [65]. Considering building location, the living space per inhabitant is bigger in rural areas than in urban areas [87]. The major technical parameter for determining the heat demand is the building envelope (foundation, roof doors, and windows). Other parameter are shape, orientation, and remaining solar passive heating due to a shading system [23]. Specific building heat demand, also called heating energy intensity, has decreased significantly in the last decades. Around 1975, residential buildings built in Germany required 200 kWh/(m^2a). Due to building codes, single-family residential buildings heating demand has declined to 50 kWh/(m^2 a) for German houses built in 2015. The voluntary passive house standard even reaches heating energy demands below 15 kWh/(m^2 a) [88]. To reach the low heating demand, the passive house standard requires a ventilation system that includes additional heat recovery, especially for low-temperature countries, such as Germany [89]. The refurbishment of buildings and construction of new buildings with improved insolation can decrease future heating demand [1]. The demolition and replacement rate of buildings is below 1% [88] and buildings have a lifetime of 40 to 120 a [90]. Refurbishing of existing dwelling facades and windows reduce the heating demand [91]. However, low refurbishing rates were found in the past, for example around 1% /a in Germany from 2005 to 2008 [92].

Besides space heating demand, domestic hot water, used for showering, dish washing, etc., requires energy to ensure an adequate temperature level. For example, in Finland, the average domestic hot water temperature is 55 to 65 °C and the drawing per person is 43 L/d [93]. Moreover, domestic hot water profiles exhibit significant peaks in the morning and in the evening due to occupant behavior [94].

3.3. Perspectives and Developments

Immersion boilers are a mature technology, for which no future cost reduction is expected. Contrarily, heat pumps are assumed to decrease in cost by economies of scale and technological improvement [95]. However, immersion heaters are identified to enable the biggest renewable energy integration, despite heat pumps and district heating being more efficient [66]. CHP that utilize biomass is a well-established technology, although fuel cost can seldom be settled by electricity revenues [96] and biomass is more valuable in the transport sector [66]. Due to increasing numbers of deployed units, fuel cells exhibited a learning rate of 13% from 2010 to 2013 [78]. Another study found a similar learning rate of 16%. Moreover, a significant fraction of the system components is already mature, thus major further cost reduction would require system simplifications [97]. Current research deals with new electrolyzer technology, which provides fuel cell and electrolyzer functionality, thus extending the functionality to hydrogen storage [98].

From a cost perspective, district heating outperforms decentralized technologies, such as heat pumps, electrical immersion heaters, and gas boilers, in areas with high heating demand, such as urban areas [14]. The lower the heat demand per area is, the higher the investment cost in district heating becomes [73]. Current development describes a so-called fourth generation district heating system, replacing older generations which used steam and relatively hot water as heat carriers. The utilization of water at around 50 °C as a heat carrier reduces system losses and increases heat generation efficiency [74].

If only minor specific heat demand reduction is assumed, heating demand in western countries is supposed to stagnate. Moreover, domestic hot water demand consumption is assumed to remain almost constant from 2000 to 2050 [65]. Other studies assume that due to insulation the specific heat demand of building will decrease. For example, building heating demand could be estimated to be 63 kWh/(m^2 a), which requires retrofitting of nearly the entire building stock [99].

4. Electricity Sector

This section deals with the electricity sector. It describes sustainable electricity generation technologies and implications for the residential electricity supply. Moreover, the electricity demand is characterized, whereas the description is based on current electricity consuming devices. The section concludes by discussing future perspectives. In Figure 4, the content of the section is shown.

4.1. Technology Portfolio

A broad range of technologies is considered for future energy generation, such as solar energy systems, wind energy converters, fossil fuel based power plants, nuclear power, CHP, hydro, tidal, and run on the river plants. Solar and wind energy systems have the greatest energetic potential amongst the renewable technologies [96]. On the low voltage distribution grid, PV-systems, small-scale CHP, and small wind energy converters are already viable [100–102].

For a residential application, a PV system is especially attractive. This has been supported by financial incentives [103,104]. In Germany, PV-systems are primarily mounted in the open field or on rooftops [105]. Besides that, a vertically mounted system configuration is attractive for high-rise buildings [106]. Crystalline, silicon-based PV-generators are predominant on the market. Thin film PV-generators are available on the market, although their market-share lags behind crystalline silicon generators. Multi-junction PV-systems exhibit improved efficiencies, compared to crystalline or thin film technology; however, they are mostly at the R&D stage [24].

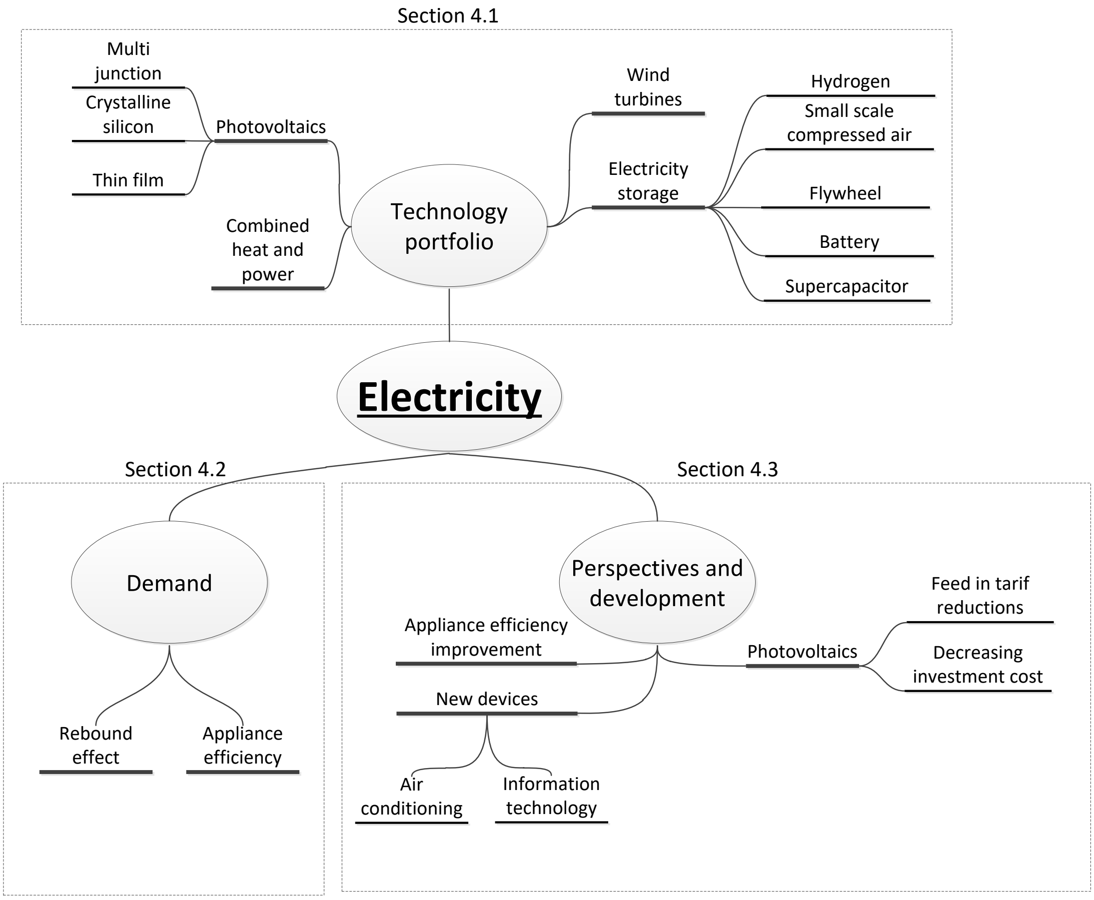

Figure 4. Overview of the electricity section and the respective subsections. Section 4.1 deals with the technology portfolio, Section 4.2 electricity discusses demand dependencies, and Section 4.3 describes perspectives and developments. The branches indicate considered aspects within a subsection.

Small-scale wind turbines have a rotor diameter of 3 to 10 m and a rated power of 1.4 to 16 kW [107]. These wind turbines can supply a household with sufficient electrical energy [100]. Drawbacks, such as high initial investment cost and aeroacoustic noise, hinder the emergence of smalls scale wind turbines [108]. Moreover, the bigger is the wind turbine, the better is the economic potential, considering equal wind resources [109]. However, large wind turbines emit noise, which is audible several hundred meters away from the turbine. Thus, they have to be built several hundred meters away from residential areas [110,111]. For this paper, due to the economic disadvantage of small-scale wind energy systems and restrictions to build larger ones close to a residential site, wind energy technology is assumed not to be built at a residential site.

Previously mentioned CHP units are also capable of producing electrical energy at a residential level. A more detailed description can be found in the previous heating section. Renewable energy systems, especially based on PV and wind energy, are weather dependent and thus exhibit an intermittent electricity generation profile, which does not match the load at all points in time. The temporal difference between load and generation can be compensated by storage devices. Battery storage, flywheels, supercapacitors, and small-scale compressed air energy storage is applicable in sub-MW applications [112]. Moreover, the term hydrogen storage is often found. It describes a system composed of an electrolyzer, a fuel cell stack, and a hydrogen storage device [113]. However, it has to be noted that the overall efficiency is quite low. Even though electrolyzers reach efficiencies up to 90%, the reverse process, by means of a polymer electrolyte membrane fuel cell, only reach 40% [48]. Application wise, battery storage is well suited for PV-systems. For example, battery storage can increase self-sufficiency and own consumption of a commercial building [114] or a household [102] by storing energy on a diurnal scale. The combination hydrogen storage and battery storage can decrease energy cost and CO_2 emissions if installed at a district-level [115].

4.2. Demand

The future total electricity demand is highly uncertain. Some models assume a decreasing electricity demand due to efficiency improvements of appliances while other models show increasing electricity demand due to further electrification [116]. In general, electricity demand depends on income, dwelling area and employment status [117,118]. According to data from [119], the electricity demand of an EU citizen for lighting and appliances lies at 1135 kWh/a.

Reducing electricity demand is identified as one of the key challenges for the future energy system [120]. Technology, such as efficient light bulbs, can reduce electricity demand. However, other appliances consume significantly more energy, as can be seen in Figure 5. Furthermore, it is shown that devices with high power consumption do not necessarily result in high annual energy consumption. Efficiency standards indicate the energy consumption of devices, assisting the consumer to purchase more efficient devices. It is found that these efficiency standards do not increase the purchase price. Moreover, the lifecycle cost show an accelerated decrease after efficiency standards were introduced, which have increased consumer benefit [121].

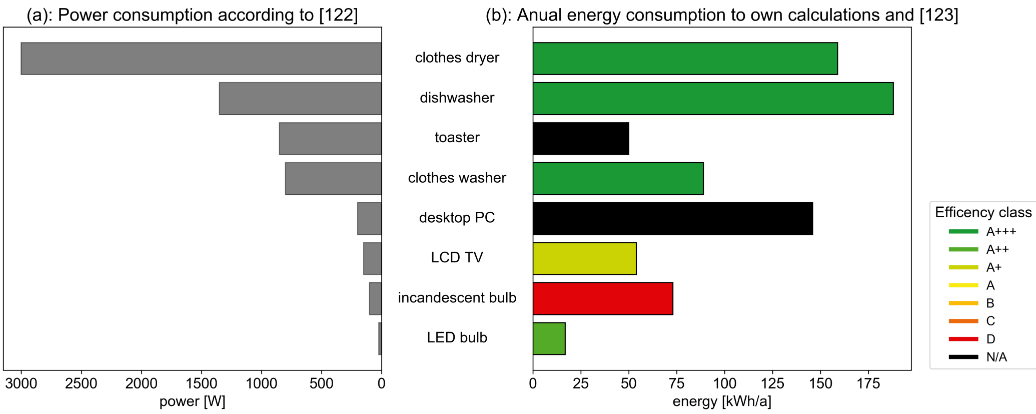

Figure 5. (**a**) Electrical power consumption of typical household appliances. Power data are gained from [122]. (**b**) Electrical energy consumption of typical household appliances. The data assume two hours per day of utilization time for a light bulb and a PC. The LED bulb emits 3000 lumen, the incandescent bulb 1500 lumen. Remaining data are gained from [123].

Energy savings can cause a rebound effect. This means that, due to saved money, households can afford additional appliances, which induce additional energy demand for operation. The rebound effect can be estimated to be 11 to 16%, which means that this percentage of the originally saved energy is consumed by other activities that become possible due to the energy savings [124,125].

4.3. Perspectives and Developments

From an ecological point of view, PV and wind supplied energy systems can mitigate greenhouse gas emissions [66,116,126,127]. For Europe, wind-dominated electricity systems result in lower generation cost than PV-dominated systems. However, the impact of the supply technology on the overall cost is small [127]. From a district point of view, these two technologies result in either significant local energy generation for solar dominated systems or a centralized/external energy generation for wind dominated systems.

In the past, a high learning rate and thus a cost reduction were observed for PV-systems. According to a projection from 2008, PV-systems were assumed to reach a learning rate of 20%. In 2018, PV-systems exhibited a learning rate of 25% [128]. These values show that high learning rates are realistic for renewable energy systems. A characteristic of high share renewable, solar dominated systems is the requirement of additional battery storage [116,126]. A PV-battery system can become cost-competitive in 2020 [52]. They could become increasingly important because countries have been decreasing their feed-in tariff. Therefore, own consumption of electricity becomes more beneficial. In general, the effectiveness of feed-in subsidies is part of the public debate, especially if the cost of PV-electricity reaches grid parity [129].

Most demand forecasts refer to total electricity demand. The demand depends on technological, economic, behavioral, and regional aspects [4,130]. In [131], it is expected that energy demand in Germany will decrease and in the UK energy demand will increase, although, on a per capita basis, both counties increase their total electricity demand by around 0.5%. This shows that, from an overall perspective, the demographic development is significant. Appliance efficiency improvement can decrease the energy consumption of a household by 13% in 2020, compared to 2005 [132]. It is assumed that further reduction is difficult to achieve because major electricity consumption is caused by water heating, which shows little improvement potential [132,133]. Increasing appliance efficiency requires the exchange of the existing stock by newly produced apparatus with improved technology. However, this leads to additional energy required for production. This energy has to be saved during operation time; otherwise, reusing a product might be preferable [134]. The introduction of information and communication technology (ICT) enables advanced energy efficiency measures. However, these devices consume energy during operation, partially counteracting the efficiency improvement measures [130]. Another source of additional future electricity demand is caused by the requirement of cooling due to building insulation [135,136]. In [137], energy efficiency measures are assumed to decrease electricity consumption by 5 to 10%. For a region in northern Germany, electricity demand for devices is reduced by around 6% to account for improved efficiency [13].

5. Integration

The integration of the heat, mobility, and electricity sector into a combined energy system significantly decrease the overall system cost [14]. On the bigger scale, these are often described as Power to X or vehicle to grid. On a smaller scale, the combination of technologies offers new conversion paths or synergies. Moreover, many upcoming technologies rely on electricity to operate, such as BEVs and heat pumps. Therefore, reliable electricity supply is crucial for the integration of these technologies.

5.1. Technology Coupling

Different integrated energy approaches are currently under investigation. Most of them are based on the electricity sector. Combinations of the electricity sector and any other sector are called Power to X. In this case, X represents the desired form of energy. Power to X substantially improves the system flexibility by adding nonelectrical storage possibilities.

Power to heat describes the utilization of electricity to generate heat. This leads to an integration of the electricity sector into the heat sector. Furthermore, heat can be easily stored, thus providing additional flexibility to the system [138]. Power to gas describes the usage of electricity to produce either hydrogen or synthetic natural gas. The first step comprises electrolysis, which requires electricity. The produced hydrogen can be further processed to synthetic natural gas, which requires an additional carbon source. If catalytic methanation is performed, the reaction is highly exothermic, which means heat has to be removed and can be utilized by another process [139]. Power to liquid is similar to power to gas, i.e., a chemical energy carrier is produced by means of electricity-based hydrogen production and a carbon source. The carbon source can be CO_2 or biomass. Produced products are suitable fuels for the transport sector, for example methanol [49]. Hydrocarbon products from power to gas or power to liquid processes are called electrofuels [66]. Power to heat has potential benefits at residential levels, such as lower operational cost due to fuel substitution [140]. Power to heat can convert PV generated electricity for heating applications by means of immersion heaters, thus reducing fossil fuel consumption [141]. Furthermore, power to heat is cheaper than power to gas if it serves only energy storage purposes [142]. Power to gas is not cost-effective, especially due to electrolyzer capital cost [139]. However, power to gas could become cost competitive if a high share of volatile renewable energy is installed and investment cost decline [143].

Contrary to Power to X, vehicle to grid can feed electricity back into the grid. It connects the electricity sector directly to the mobility sector. Fuel cell-based electric vehicles can supply neighboring houses, thus reducing the power imported from the utility grid. However, to be economically beneficial, the hydrogen price needs to decrease [144]. BEVs are capable of primary frequency control. They improve the system frequency response and reduce the required primary control reserves of conventional power plants [145].

Furthermore, technologies can be combined to achieve synergistic effects. A combination of a PV generator and a solar collector is called hybrid photovoltaic thermal (PV/T) system. This system removes heat from a PV generator by a working fluid. Thus, the efficiency of the PV generator is improved. The overall system efficiency can surpass 90% [146]. A heat pump can be combined with a solar collector. The solar collector evaporates the refrigerant of the heat pump at increased temperature, compared to ground or air-based heat pump. The system shows payback times of about two years under optimal configuration and Singaporean weather conditions [147]. A heat pump can also be combined with a PV system, for increased electricity self-consumption. However, for Germany, it is found that PV-generation is high when the heat demand is low and vice versa, leading to a moderate increase in self-sufficiency [148]. The combination of solar collectors, domestic heat storage, and an organic Rankine-cycle provides domestic hot water and electricity, taking advantage of low-cost thermal energy storage [149]. Furthermore, a solar collector can be coupled with a heat pump and a seasonal heat storage. The solar collector heats up the storage if excess heat is available for storage. Thus, the efficiency of the heat pump improves, due to higher operation temperature [150].

5.2. Grid Structure and Operational Aspects

Future energy supply, based on renewables, will cast additional challenges to the electricity grid. The emerging deployment of electricity-based mobility and heating technologies complicates grid operation, i.e., frequency stabilization and voltage control.

The electricity grid structure is characterized by its primary voltage, the network length, the number of loads or nodes and the peak load [151]. The grid cannot store energy; demand and supply must be balanced at all times. Moreover, the electricity grid is a complex system. Even local problems can cascade and become uncontrollable [152].

The challenges of grids in urban areas differ from rural areas. The reason is a high load density, which motivates the usage of heavily meshed systems. In general, these are resilient to single component failure [153]. In rural areas with low load densities, radial grids are preferred. These electricity grids ensure operation either by backup generation capacities or with connections to neighboring grids [154].

The integration of renewable energy introduces new challenges to the distribution grid. In the past, power was distributed from high voltage levels to the consumers. However, the installation of PV-Systems can cause a reverse power flow, leading to voltage limit violations [155]. Moreover, voltage band violations can also be caused by the addition of EVs, especially if they are charged in an uncontrolled manner [156]. Voltage band violations can be mitigated by local voltage controllers. The controllers are able to reduce the charging power of the EV, thus increasing the local voltage [157]. Another approach uses game-theoretic approaches to adjust the charging power of EVs in a distribution grid, also aiming to mitigate voltage band violations [158]. If heat pumps and PV-systems are added to a residential grid, voltage band requirements are barely followed and, moreover, quick voltage variations, due to volatile PV-generation, are observed [159].

Integrated energy systems can provide grid services, in order to maintain operation specification. In [160], it is shown that batteries can provide frequency regulation (primary control). Combined with power to heat technologies, such as electric immersion boilers, the overall self-consumption of a household increases. Grid-connected PV and wind systems rely on power electronics to feed electric energy into the grid. These power electronics can provide auxiliary services such as voltage control by variable reactive power output. Additionally, storage can improve the power quality further [161]. Adding battery storage to a residential grid smoothens the power characteristics by reducing the peak to average ratio. However, in [162], it is found that voltage quality is not significantly affected.

6. Morphological Analysis

In the following, a scenario is defined as a future system state. To investigate scenarios for future residential energy supply, a morphology analysis is performed. The morphological analysis is a systematic, analytical technique [163]. It is based on scientific fundamentals, i.e., analysis and synthesis and especially useful for multi-dimensional, non-quantifiable problems. The morphological analysis identifies the most important dimensions of a problem and examines the internal relationships to reduce the scenario space [164].

6.1. Scenario Space

The characteristics and factors are derived from the previous literature review. Comparing the technology portfolio of the mobility, heating, and electricity sectors, some differences are indicated. In the mobility sector, some technologies that can provide sustainable mobility are available, but it is difficult to estimate which will prevail in the future or whether there will be an application-specific design, at present. In addition, there are efforts to reduce the use of these technologies, for example by changing mobility habits. In the heating sector, on the other hand, there are many technologies available, and their use, unlike in the mobility sector, depends to a certain extent on local conditions. Furthermore, the heating sector can be considered rather slow in its adaptability (long building lifetimes compared to shorter lifetimes of cars). These can also cause fragmentation, for example by building a new district with modern technologies close to an old district. In the electricity sector especially PV systems are common for residential energy systems. These systems are field-tested and economically viable applications causing less uncertainty regarding the future development compared with the other sectors.

The aim is to construct a morphological box, also known as Zwicky box [165]. The factors follow the structure of the literature review. Each sector, i.e., mobility, heat, or electricity, is divided into technology and demand, which are considered as a factor. All scenarios aim to show the load on the residential electricity grid of a decarbonized energy system to identify future challenges. In the following, the considered factor-parameters and underlying hypotheses are described.

Factor 1: Individual mobility

M1 (BEV): Current individual mobility is completely replaced by electric mobility. Due to research and economics of scale, the battery prices decrease and BEVs become affordable to everyone.

M2 (Hydrogen (local)): Hydrogen mobility is one of the much-researched technologies. Currently, vehicles are already available. Further development improves hydrogen production technology. Infrastructural development results in on-site production at residential sites to reduce transport infrastructure cost.

M3 (Hydrogen (central): Hydrogen mobility is predominant. To achieve scaling effects, hydrogen will be produced in centralized, large-scale plants outside the district, resulting in no local electricity consumption for hydrogen production at the residential site. Utilizing biofuels would have the same effect due to external fuel production. They could be provided by large scale production of third generation biofuel.

Factor 2: Mode shift/Mobility demand

MD1 (Significant): In the urban environment, local public transport and bicycle traffic is pushed severely through the conversion of the urban infrastructure. This way, automobiles are no longe used for short distance traveling.

MD2 (Minor): In the urban environment, local public transport and bicycle traffic is promoted by infrastructure improvement. However, automobiles are still frequently used for short distance traveling.

MD3 (None): The local infrastructure is not adjusted at all. The automobile remains the primary mode of travel.

Factor 3: Heating technology

H1 (Heat pump): Heat pumps are the primary technology for heat generation. They are considered to be the most effective technology for using electricity to provide heat and cost are reduced by scaling effects and technological improvement.

H2 (Immersion heater): Advanced building insulation allows the use of fast heating elements. This enables the integration of large scale renewables by providing flexibility to the system.

H3 (CHP): Mikro-CHP plants generate heat and power with high overall efficiency. In this scenario, they are widely installed. The required fuel originates from biomass, externally produced hydrogen, or synthetic natural gas. It is assumed that the CHP unit is operated in heat guided mode.

H4 (No electrical heating): District heating systems, which utilize waste heat, provide cost-effective heat supply. Furthermore, they do not require significant energy, thus they are considered as no electrical heating technology. Another renewable, non-electric heating approach (from a residential grid perspective) is via power to gas utilization and gas heaters at the residential site.

Factor 4: Building insulation

HD1 (Passive house): Thermal building isolation is severely pushed. The passive house standard is applied to every building of the considered district.

HD2 (Current building code): Thermal building isolation is improved. Every building complies with the current building code. Older buildings are refurbished.

HD3 (Partial refurbishment): Refurbishment significantly reduces the heat demand, due to buildings according to current building code. However, many buildings with old insulation are still inhabited.

HD4 (Old building): Thermal insulation is not improved. Older houses are still in use without refurbishment.

Factor 5: Local electricity generation

E1 (High PV-generation): PV systems are the primary technology for generating electricity. Their installation is strongly supported. Even non-south-orientated rooftop areas and facades are used for PV-system installation.

E2 (Medium PV-generation): PV-systems are common in districts. They are installed at rooftop areas with optimal properties regarding orientation and inclination.

E3 (External generation): Electricity is not generated locally. Due to our focus on residential aspects, the specific energy source is out of scope for this hypothesis; for example large scale wind energy could be the primary generation technology.

Factor 6: Device consumption

ED1 (Reduced): Electric appliances continue to decrease in energy consumption. New devices will not consume significant amounts of electricity, thus the overall electricity demand decreases.

ED2 (Steady): Appliances efficiency increases, although savings are invested into additional devices which mitigate the savings and, moreover, new technologies are added to the household which consume additional electricity. Overall, the electricity consumption of devices remains constant.

ED3 (Increasing): Appliances efficiency improvements are minor because conversion from electricity to heat is already very efficient and many devices rely on electricity. Moreover, additional appliances are added, such as air conditioning and smart home technology.

Table 1 shows the overall scenario space by means of the morphological box. Every factor is represented by one column. A scenario is created by the combination of one value for every factor. Overall, the morphological box describes 1296 possible scenarios.

Table 1. Morphological box of the residential energy system.

	Factor 1: Individual Mobility	Factor 2: Mode Shift	Factor 3: Heating	Factor 4: Heating Demand	Factor 5: Electricity	Factor 6: Appliance Demand
hypotheses	M1: BEV	MD1: Significant	H1: Heat pump	HD1: Passive house	E1: High PV-generation	ED1: Reduced
	M2: Hydrogen (local)	MD2: Minor	H2: Immersion heater	HD2: Current building code	E2: Medium PV-generation	ED2: Steady
	M3: Hydrogen (central)	MD3: None	H3: CHP	HD3: Partial refurbishment	E3: External generation	ED3: Increasing
			H4: No el. heating	HD4: Old buildings		

6.2. Scenario Space Pruning

The scenario space pruning is based on the literature review. However, it has to be noted that excluded combinations are still based on the authors' interpretation and current state of the art. Unlikely combinations are analyzed by means of a cross-consistency assessment. This procedure investigates the possible occurrence of binary combinations. Impossible or inconsistent combination are marked. The following combinations are disregarded:

- The immersion heater technology is assumed to be feasible only with low heat demand buildings to compensate for the low efficiency of immersion heaters. For this investigation, it is assumed that only the passive house is feasible to be combined with immersion heaters.
- The pair of device consumption improvement and passive house is not considered because additional air conditioning and ventilation due to building insulation require significant electrical energy.
- Local hydrogen production requires electricity for operation. Thus, if no generation is installed at a residential site, hydrogen production would be more effective closer to electricity producing facilities. Consequently, the combination of locally produced hydrogen for mobility and no local electricity generation is disregarded.

Without these pairs, the scenario space is reduced to 840 scenarios. Figure 6 shows the cross-consistency matrix. The disregarded pairs are marked with a cross.

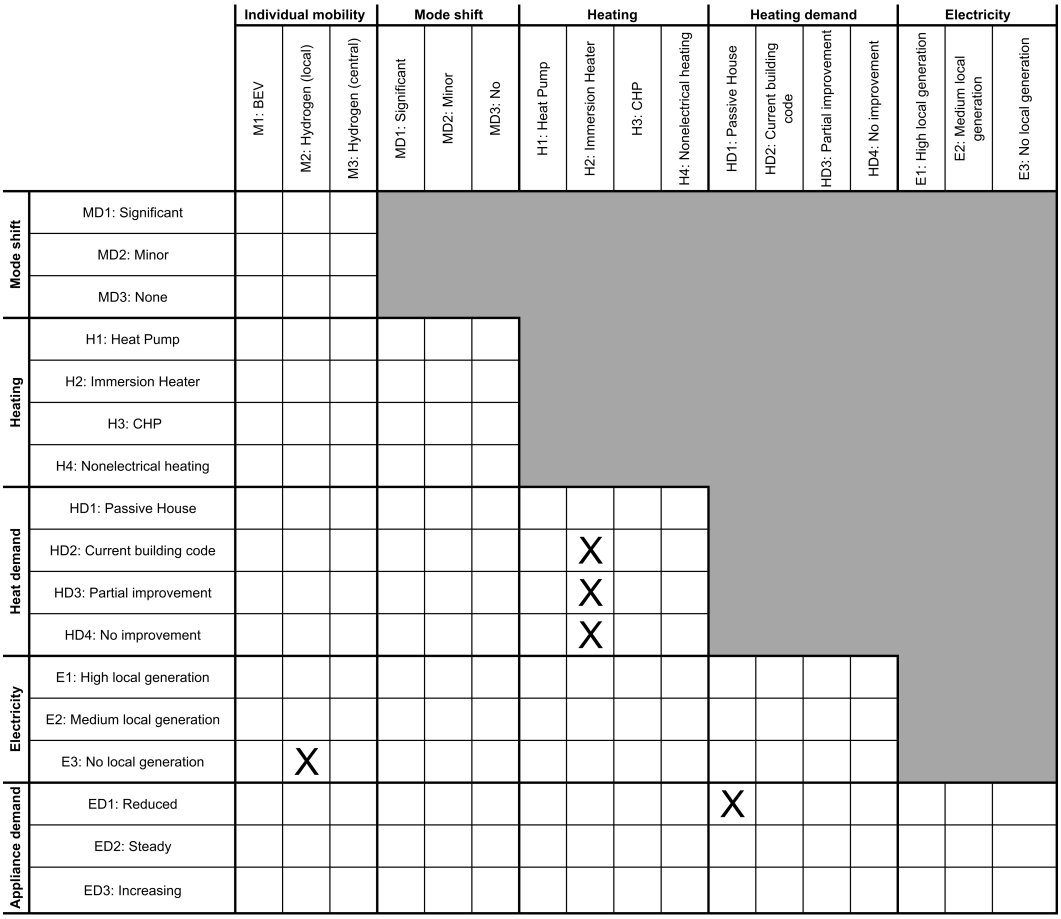

Figure 6. Cross-consistency matrix of the morphological box for the residential energy system.

6.3. Scenario Space Evaluation

The scenario space is investigated by associating parameters for every factor. From that, the annual net electricity demand for a residential district is calculated. The problem is inherently complex. Especially factors such as mode shift and device efficiency are difficult to quantify. To be able to describe the scenario space, assumptions for the effect of the individual factor values are made. Table 2 shows basic demographic and technical parameters. To put less weight on unique, individual behavior of inhabitants, one hundred households are chosen to represent a district.

Table 2. Parameters for calculation.

Variable	Symbol	Value
Number households	N_h	100
Persons per household	n	1.9 [166]
Living space per person	A_N	46.5 m^2 [167]
Optimal PV rooftop area per person	$A_{roof,N}$	13.1 m^2 [168]
PV-generation	$E_{PV,A}$	180 kWh/(m^2 a) [105]
Device electricity consumption per person	E_{dev}	1135 kWh/a [119]
Vehicle ownership per person	$ve_{ownership}$	0.5 [45]
Vehicle usage	ve_{usage}	11370 km/a [46]
Domestic hot water demand per person	DHW_{demand}	42 L/day [93]
Domestic hot water temperature	θ_{DHW}	60 °C [94]
Local hydrogen production efficiency	$\eta_{H_2,prod.}$	0.85
Cold water supply temperature	$\theta_{coldwater}$	12 °C
Heat capacity water	cp_{water}	1.16 Wh/(kg K)
Density water	ρ_{water}	1.0 kg/m^3

In Table 3, parameter assumptions are shown, following the structure of the morphological box. The energy consumption of a BEV is assumed to be 17 kWh/100 km (tank-to-wheel) [169] with a charging efficiency of 95% (round trip efficiency of 90 % [48], assuming the charging efficiency to be equal to the discharging efficiency). The energy consumption of a hydrogen fueled vehicle is calculated with a hydrogen demand of 0.76 kg/100 km [59] (specific energy hydrogen: 33 kWh/kg), taking an electrolyzer efficiency of 90% [48] and filling efficiency of 92% (energy for compression: 2.7 kWh/kg_{H_2} [59]) into account. The mode shift ratio describes how much of the current car based demand is shifted to alternative concepts. From the authors' perspective, this is a major uncertainty which is reflected by the broad value distribution.

Table 3. Morphological box, supplemented with numerical assumptions (input variables).

	Factor 1: Individual Mobility	Factor 2: Mode Shift	Factor 3: Heating	Factor 4: Heating Demand	Factor 5: Electricity	Factor 6: Appliance Demand
Symbol:	e_{ve}	r_{shift}	COP_h	I_{heat}	f_{PV}	r_{dev}
hypotheses	18.9 kWh/100	90	4.5	15 kWh/(m^2 a)	2	−30
	30.3 kWh/100	50	1	50 kWh/(m^2 a)	1	0
	0	0	−0.8	125 kWh/(m^2 a)	0	+30
			0	200 kWh/(m^2 a)		

The heating technology is described by the COP, which expresses the ratio of gained heat divided by spent electricity. The heat pump value describes a high-efficiency air-source heat pump [22]. The immersion boiler is assumed to transform heat to electricity without any losses and the CHP scenario is implemented by fuel cells. The heat demand values are taking from the reviewed values for Germany.

The electricity generation is based on optimal rooftop areas for PV installation and scaled according to the assumed factor. Device consumption is also a major uncertainty and, thus, the values describe a broad scenario space for the respective factor. The (hydrogen (central) hypothesis assumes external hydrogen generation. The centralized fuel production does not affect the local grid. This means, mobility does not contribute to local electricity demand, which is expressed by zero energy demand. For CHP, the description via COP is uncommon. It is used to be consistent with the other technologies. A thermal to electrical power ratio of 0.8 is assumed, representing a fuel cell operating at max. efficiency [80]. Because this device does not consume, but rather produces, electricity, the COP gets a negative sign.

Equations (1)–(3) describe the modeling approach for the individual sectors (parameters and input variables are listed in Tables 2 and 3, respectively). For the mobility sector, we model the demand for electrical energy as

$$E_{mobility} := N \cdot ve_{ownership} \cdot ve_{usage} \cdot \left(1 - r_{shift}\right) \cdot e_{av}, \tag{1}$$

where

$$N := N_h \cdot n.$$

The heat demand is modeled by

$$Q_{heat,demand} := N \cdot A_N \cdot I_{heat} + DHW_{demand} \cdot N \cdot 365\,\mathrm{d/a} \cdot \rho_{water} \cdot (\theta_{DHW} - \theta_{coldwater}) \cdot cp_{water}$$

and thus the demand for electrical energy in this sector is modeled as

$$E_{heat} := Q_{heat,demand} \cdot COP_h. \tag{2}$$

We model the energy demand in the electricity sector as

$$E_{electricity} := -N \cdot A_{roof,N} \cdot E_{PV,A} \cdot f_{PV} + E_{dev} \cdot N \cdot (1 - r_{dev}). \tag{3}$$

Equations (4)–(6) model the synergy between local hydrogen production for mobility and CHP (again, parameters and input variables are listed in Table 2 and Table 3, respectively). Excess PV-production, after considering demand of mobility and devices (see Equations (1) and (3)), is modeled as

$$E_{ex.PV} := \begin{cases} E_{mobility} + E_{electricity} & \text{if} E_{mobility} + E_{electricity} < 0 \\ 0 & \text{otherwise} \end{cases} . \tag{4}$$

Note that the variables are defined such that generated energy is indicated by a negative sign.

The amount of heat that can be produced from excess PV-production by producing hydrogen via an electrolyzer and utilizing that hydrogen by CHP-technology is modeled as

$$Q_{H_2,poss} := \frac{|E_{ex.PV}| \cdot \eta_{H_2,prod.}}{1 + \frac{1}{|COP_h|}}. \tag{5}$$

It is assumed that electrolyzers are primarily built to produce hydrogen for mobility. Thus, for this investigation, the hypotheses local hydrogen production and CHP are required to locally produce hydrogen for heating. The amount of local electricity for heating via hydrogen, when no excess hydrogen is produced, is modeled as

$$E_{el,H_2,heat} := \begin{cases} E_{ex.PV} \cdot \frac{Q_{H_2,poss}}{Q_{heat,demand}} & \text{if} Q_{H_2,poss} > Q_{heat,demand} \wedge COP_h = -0.8 \wedge e_{av} = 30.3 \\ E_{ex.PV} & \text{if} Q_{H_2,poss} \leq Q_{heat,demand} \wedge COP_h = -0.8 \wedge e_{av} = 30.3 \\ 0 & \text{otherwise} \end{cases} . \tag{6}$$

Finally, Equation (7) models the overall net energy demand, using Equations (1)–(4), for a scenario as

$$E_{total} := E_{mobility} + E_{heat} + E_{electricity} - E_{el,H_2,heat}. \tag{7}$$

Figure 7 shows the net electrical energy demand of the scenario space. Negative values indicate net feeding behavior throughout the year. The majority of the scenarios result in net feeding (69%). Maximum demand for the considered districts is 914 MWh/a and the minimum demand is −2229 MWh/a, indicating the maximum amount of energy fed back.

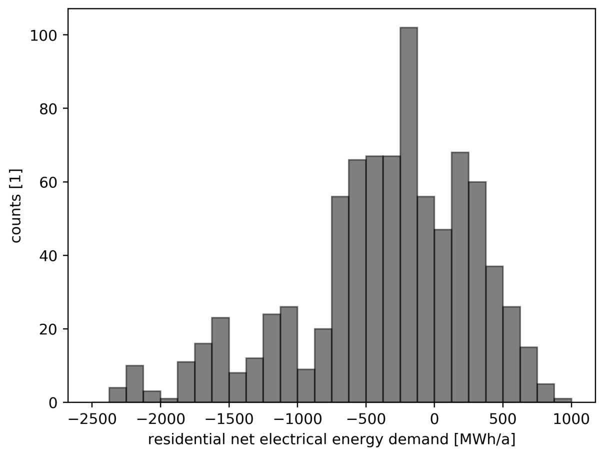

Figure 7. Annual electrical energy demand of the morphological analysis scenario space.

Figures 8–10 investigate the scenario space in more detail, by indicating the influence of every hypothesis, according to technology and demand factors within the scenario space.

Figure 8 shows the mobility sector related factors, mobility technology, and mode shift, in terms of their respective hypotheses. It indicates that every hypothesis can be found across the scenario space. Note that, for the mobility technology, the local hydrogen hypotheses does not result in exceptionally high demanding scenarios because the combination of no local generation and local hydrogen production is disregarded by the cross-consistency assessment.

Figure 9 indicates a clear localization of the heating technology within the scenario space. CHP-technology scenarios are predominantly found on the feeding side. High demand scenarios utilize heat pumps or immersion heaters. Overall, immersion heater scenarios are low in numbers within the scenario space because it is assumed that only passive house heat isolation may be combined with immersion heaters to compensate for the high energy demand during operation. No electrical heating scenarios are centered relatively narrowly around zero energy demand, indicating a dependency on other factors. In terms of demand, it is shown that high feeding scenarios consist of old buildings or partial refurbishment insulation hypotheses. Better insulated scenarios are more closely centered around zero energy demand.

Figure 10 shows a distinct assignment of local generation scenarios. High PV generation tends to feed more energy over the course of the year, while lower generation scenarios are shifted to the demanding side. In terms of appliance efficiency, no clear mapping is shown; every hypothesis occurs throughout the scenario space.

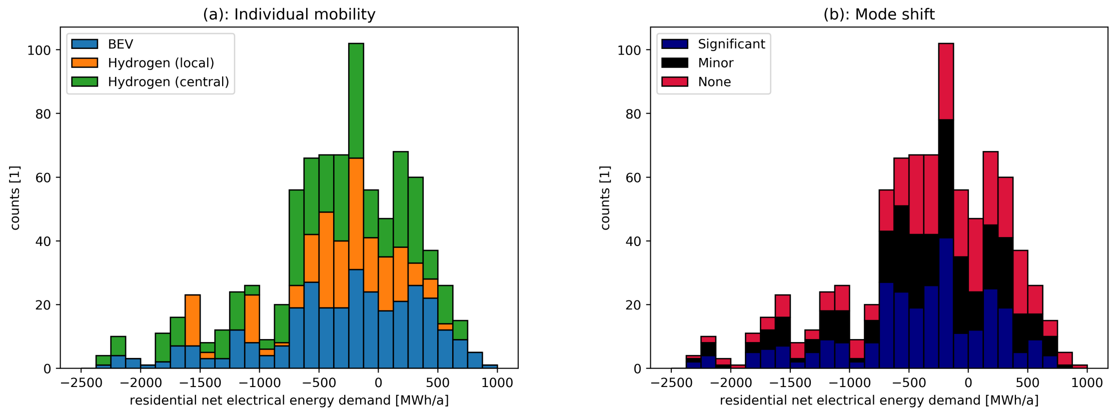

Figure 8. Mobility sector related factors within the scenario space: (**a**) mobility technology; and (**b**) mode shift, which decreases usage of a mobility technology.

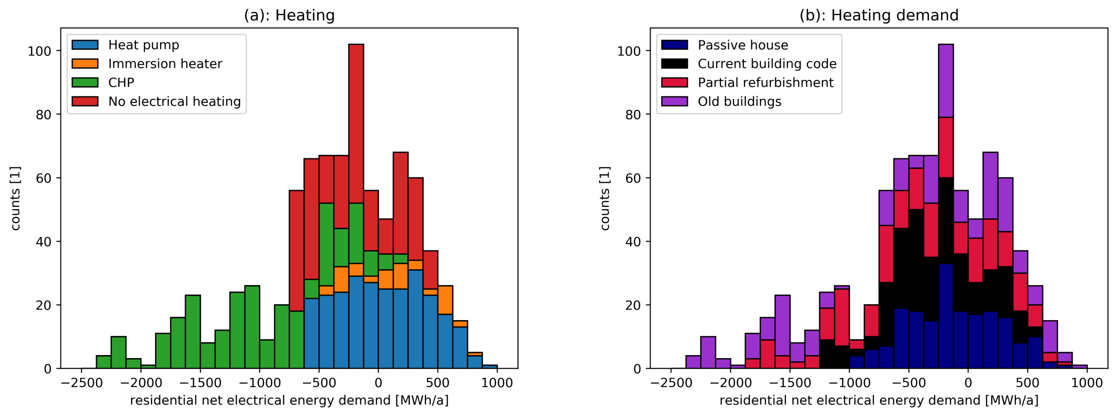

Figure 9. Heating sector related factors within the scenario space: (**a**) heating technology; and (**b**) heat demand due to space heating.

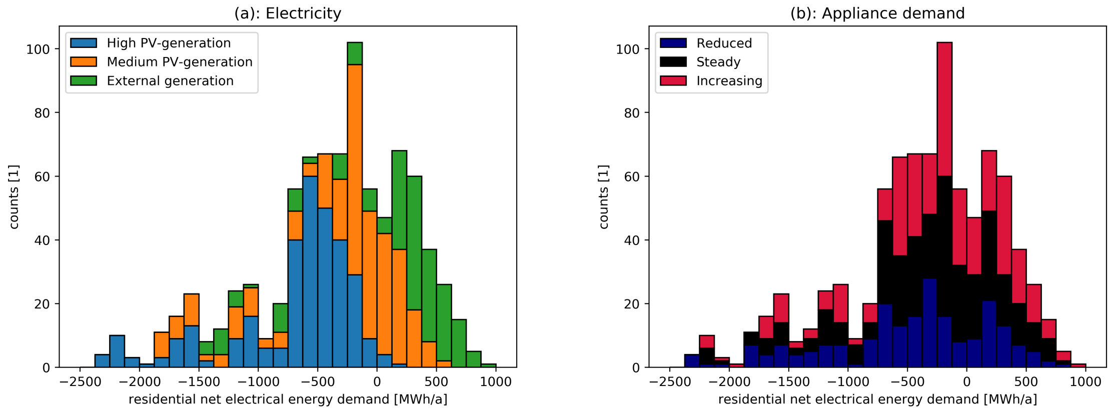

Figure 10. Electricity sector related factors within the scenario space: (**a**) local generation; and (**b**) appliance demand.

7. Conclusions

This review has dealt with technology and perspectives of future energy supply for residents and integrated the results into a morphological analysis. The traditionally separated sectors mobility, heat, and electricity have been examined in detail, as have been the challenges of integration into the electricity grid and possible technological synergy potentials. Based on the investigated literature, these are the authors conclusions:

BEVs are the most mature technology for renewable transport today, which is reflected in high learning rates and, thus, cost-reduction. They would increase the local residential energy demand due to home charging. High-density energy carriers, such as hydrogen or bio-based fuels are pivotal for applications beyond BEV range, such as cargo duties and aviation. Currently, infrastructure and cost are the major hindrances of hydrogen, whereas land-use constrains bio-based fuel utilization. Hydrogen and bio-based fuels could be produced externally, thus not affecting the local electricity grid directly. However, hydrogen could also be produced locally. Overall, also taking the uncertainty due to mode shift into account, the effect of the transport sector on the local grid strongly depends on the decarbonization pathway.

At the moment, heat pumps are the most energy efficient heating technology. Immersion boilers require additional electricity for the same heating output, albeit they offer better grid integration capabilities and lower investment cost than heat pumps. Building heating demand decreases because of building code, refurbishment, and reconstruction. However, the modernization of the entire building stock requires generations due to the low refurbishment rates and long building lifetimes. Thus, the energy demand could vary significantly, depending on the building structure of a respective district.

Renewable energy supply, locally on residential sites, is expected to be predominantly based on PV-generators. Future appliance energy demand remains uncertain. Efficiency measures reduce the energy consumption of devices. However, not every device shows significant optimization potential. New devices will most likely be added to households in the future, such as information and communication technology.

Interconnections between the electricity sector and heat, power, or gas sector increase the system flexibility. Especially power to heat affects the residential system because it can be implemented by heat pumps or immersion heaters. It is widely assumed, but far from certain, that residential energy supply will rely primarily on electricity. Therefore, the electricity grid could be of central importance. Current research investigates measures to ensure the electricity grid stability during operation, e.g. by local voltage controllers.

The scenario space of this paper represents possible configurations of the future residential energy system, i.e., future system states. It provides a basis for future work to evaluate technical applications for the residential sector such as grid expansion, energy management systems, or local control systems.

The scenarios offer a broad diversification of the energy demand, as indicated by the morphological analysis, primarily influenced by heating technology, heat insulation, and local generation.The results of this study provide researchers and practitioners with a basis for further parameterization and an estimation of the parameter impact, especially for investigations on lower temporal resolutions. Furthermore, it can serve as an overview of influencing factors for residential energy systems or as a starting point for a deeper literature investigation regarding certain subtopics.

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References

1. Energy Roadmap 2050. Available online: https://ec.europa.eu/energy/sites/ener/files/documents/2012_energy_roadmap_2050_en_0.pdf (accessed on 2 May 2019).
2. Lund, H.; Mathiesen, B.V. Energy system analysis of 100% renewable energy systems—The case of Denmark in years 2030 and 2050. *Energy* **2009**, *34*, 524–531. [CrossRef]
3. Mathiesen, B.V.; Lund, H.; Connolly, D.; Wenzel, H.; Østergaard, P.A.; Möller, B.; Nielsen, S.; Ridjan, I.; Karnøe, P.; Sperling, K.; et al. Smart Energy Systems for coherent 100% renewable energy and transport solutions. *Appl. Energy* **2015**, *145*, 139–154. [CrossRef]
4. Jacobson, M.Z.; Delucchi, M.A.; Bauer, Z.A.; Goodman, S.C.; Chapman, W.E.; Cameron, M.A.; Bozonnat, C.; Chobadi, L.; Clonts, H.A.; Enevoldsen, P.; et al. 100% Clean and Renewable Wind, Water, and Sunlight All-Sector Energy Roadmaps for 139 Countries of the World. *Joule* **2017**, *1*, 108–121. [CrossRef]
5. Hohmeyer, O.H.; Bohm, S. Trends toward 100% renewable electricity supply in Germany and Europe: A paradigm shift in energy policies. *Wiley Interdiscip. Rev. Energy Environ.* **2015**, *4*, 74–97. [CrossRef]
6. Hoffert, M.I.; Caldeira, K.; Jain, A.K.; Haites, E.F.; Harvey, L.D.D.; Potter, S.D.; Schlesinger, M.E.; Schneider, S.H.; Watts, R.G.; Wigley, T.M.L.; et al. Energy implications of future stabilization of atmospheric CO_2 content. *Nature* **1998**, *395*, 881. [CrossRef]
7. Girardin, L.; Marechal, F.; Dubuis, M.; Calame-Darbellay, N.; Favrat, D. EnerGis: A geographical information based system for the evaluation of integrated energy conversion systems in urban areas. *Energy* **2010**, *35*, 830–840. [CrossRef]
8. Mancarella, P.; Andersson, G.; Peças-Lopes, J.A.; Bell, K.R.W. Modelling of integrated multi-energy systems: Drivers, requirements, and opportunities. In Proceedings of the 2016 Power Systems Computation Conference (PSCC), Genoa, Italy, 20–24 June 2016; pp. 1–22. [CrossRef]
9. Lund, H.; Østergaard, P.A.; Connolly, D.; Mathiesen, B.V. Smart energy and smart energy systems. *Energy* **2017**, *137*, 556–565. [CrossRef]
10. Robinius, M.; Otto, A.; Heuser, P.; Welder, L.; Syranidis, K.; Ryberg, S.D.; Grube, T.; Markewitz, P.; Peters, R.; Stolten, D. Linking the Power and Transport Sectors—Part 1: The Principle of Sector Coupling. *Energies* **2017**, *10*, 956. [CrossRef]
11. Scholz, Y.; Gils, H.C.; Pietzcker, R.C. Application of a high-detail energy system model to derive power sector characteristics at high wind and solar shares. *Energy Econ.* **2017**, *64*, 568–582. [CrossRef]
12. Ueckerdt, F.; Pietzcker, R.; Scholz, Y.; Stetter, D.; Giannousakis, A.; Luderer, G. Decarbonizing global power supply under region-specific consideration of challenges and options of integrating variable renewables in the REMIND model. *Energy Econ.* **2017**, *64*, 665–684. [CrossRef]
13. Beck, H.P.; von Haaren, C.; Kuck, J.; Rode, M.; Ahmels, J.; Dossola, F.; Hingst, J.; Kaiser, F.; Kruse, A.; Palmas, C.; et al. *Szenarien zur Energieversorgung in Niedersachsen im Jahr 2050: Gutachten*; Niedersachsisches Ministerium fur Umwelt, Energie und Klimaschutz: Hannover, Germany, 2016.

14. Brown, T.; Bischof-Niemz, T.; Blok, K.; Breyer, C.; Lund, H.; Mathiesen, B. Response to 'Burden of proof: A comprehensive review of the feasibility of 100 renewable-electricity systems'. *Renew. Sustain. Energy Rev.* **2018**, *92*, 834–847. [CrossRef]
15. Bui, V.; Hussain, A.; Kim, H. A Multiagent-Based Hierarchical Energy Management Strategy for Multi-Microgrids Considering Adjustable Power and Demand Response. *IEEE Trans. Smart Grid* **2018**, *9*, 1323–1333. [CrossRef]
16. Kok, J.K.; Warmer, C.J.; Kamphuis, I.G. PowerMatcher: multiagent control in the electricity infrastructure. In Proceedings of the 4th International Conference on Autonomous Agents and Multiagent Systems (AAMAS 2005), Utrecht, The Netherlands, 25–29 July 2005. [CrossRef]
17. Arcos-Aviles, D.; Pascual, J.; Marroyo, L.; Sanchis, P.; Guinjoan, F. Fuzzy Logic-Based Energy Management System Design for Residential Grid-Connected Microgrids. *IEEE Trans. Smart Grid* **2018**, *9*, 530–543. [CrossRef]
18. Talha, M.; Saeed, M.S.; Mohiuddin, G.; Ahmad, M.; Nazar, M.J.; Javaid, N. Energy Optimization in Home Energy Management System Using Artificial Fish Swarm Algorithm and Genetic Algorithm. In *Advances in Intelligent Networking and Collaborative Systems*; Barolli, L., Woungang, I., Hussain, O.K., Eds.; Springer International Publishing: Berlin/Heidelberg, Germany, 2017; pp. 203–213.
19. Eurostat. *Energy Balance Sheets 2016 Data-2018 Edition*; Publications Office of the European Union: Luxembourg, 2018.
20. Wüstenhagen, R.; Wolsink, M.; Bürer, M.J. Social acceptance of renewable energy innovation: An introduction to the concept. *Energy Policy* **2007**, *35*, 2683–2691. [CrossRef]
21. Colangelo, G.; Favale, E.; Miglietta, P.; de Risi, A. Innovation in flat solar thermal collectors: A review of the last ten years experimental results. *Renew. Sustain. Energy Rev.* **2016**, *57*, 1141–1159. [CrossRef]
22. Fischer, D.; Madani, H. On heat pumps in smart grids: A review. *Renew. Sustain. Energy Rev.* **2017**, *70*, 342–357. [CrossRef]
23. Pacheco, R.; Ordóñez, J.; Martínez, G. Energy efficient design of building: A review. *Renew. Sustain. Energy Rev.* **2012**, *16*, 3559–3573. [CrossRef]
24. Khan, J.; Arsalan, M.H. Solar power technologies for sustainable electricity generation—A review. *Renew. Sustain. Energy Rev.* **2016**, *55*, 414–425. [CrossRef]
25. Henning, H.M.; Umbach, E.; Drake, F.D.; Fischedick, M.; Haucap, J.; Hübner, G.; Münch, W.; Pittel, K.; Rehtanz, C.; Sauer, J.; et al. *Sektorkopplung–Optionen fur die nächste Phase der Energiewende*; acatech–Deutsche Akademie der Technikwissenschaften: Munich, Germany, 2017.
26. Pietzcker, R.C.; Longden, T.; Chen, W.; Fu, S.; Kriegler, E.; Kyle, P.; Luderer, G. Long-term transport energy demand and climate policy: Alternative visions on transport decarbonization in energy-economy models. *Energy* **2014**, *64*, 95–108. [CrossRef]
27. Gröger, O.; Gasteiger, H.A.; Suchsland, J.P. Review—Electromobility: Batteries or Fuel Cells? *J. Electrochem. Soc.* **2015**, *162*, A2605–A2622. [CrossRef]
28. Ligen, Y.; Vrubel, H.; Girault, H.H. Mobility from Renewable Electricity: Infrastructure Comparison for Battery and Hydrogen Fuel Cell Vehicles. *World Electr. Veh. J.* **2018**, *9*, 3. [CrossRef]
29. Bergthorson, J.M.; Thomson, M.J. A review of the combustion and emissions properties of advanced transportation biofuels and their impact on existing and future engines. *Renew. Sustain. Energy Rev.* **2015**, *42*, 1393–1417. [CrossRef]
30. Bentsen, N.S.; Jack, M.W.; Felby, C.; Thorsen, B.J. Allocation of biomass resources for minimising energy system greenhouse gas emissions. *Energy* **2014**, *69*, 506–515. [CrossRef]
31. Gelfand, I.; Sahajpal, R.; Zhang, X.; Izaurralde, R.C.; Gross, K.L.; Robertson, G.P. Sustainable bioenergy production from marginal lands in the US Midwest. *Nature* **2013**, *493*, 514. [CrossRef]
32. Mohr, A.; Raman, S. Lessons from first generation biofuels and implications for the sustainability appraisal of second generation biofuels. *Energy Policy* **2013**, *63*, 114–122. [CrossRef]
33. Sims, R.E.H.; Mabee, W.; Saddler, J.N.; Taylor, M. An overview of second generation biofuel technologies. *Bioresour. Technol.* **2010**, *101*, 1570–1580. [CrossRef]
34. Lee, R.A.; Lavoie, J.M. From first- to third-generation biofuels: Challenges of producing a commodity from a biomass of increasing complexity. *Anim. Front.* **2013**, *3*, 6–11. [CrossRef]
35. Moody, J.W.; McGinty, C.M.; Quinn, J.C. Global evaluation of biofuel potential from microalgae. *Proc. Natl. Acad. Sci. USA* **2014**, *111*, 8691–8696. [CrossRef]

36. Clarens, A.F.; Resurreccion, E.P.; White, M.A.; Colosi, L.M. Environmental Life Cycle Comparison of Algae to Other Bioenergy Feedstocks. *Environ. Sci. Technol.* **2010**, *44*, 1813–1819. [CrossRef]
37. Aro, E.M. From first generation biofuels to advanced solar biofuels. *Ambio* **2016**, *45*, 24–31. [CrossRef]
38. Ochoa Bique, A.; Zondervan, E. An outlook towards hydrogen supply chain networks in 2050—Design of novel fuel infrastructures in Germany. *Chem. Eng. Res. Des.* **2018**, *134*, 90–103. [CrossRef]
39. Yoshida, T.; Kojima, K. Toyota MIRAI Fuel Cell Vehicle and Progress Toward a Future Hydrogen Society. *Interface Mag.* **2015**, *24*, 45–49. [CrossRef]
40. Gurz, M.; Baltacioglu, E.; Hames, Y.; Kaya, K. The meeting of hydrogen and automotive: A review. *Int. J. Hydrog. Energy* **2017**, *42*, 23334–23346. [CrossRef]
41. Ball, M.; Weeda, M. The hydrogen economy—Vision or reality? *Int. J. Hydrog. Energy* **2015**, *40*, 7903–7919. [CrossRef]
42. Goldmann, A.; Sauter, W.; Oettinger, M.; Kluge, T.; Schröder, U.; Seume, R.J.; Friedrichs, J.; Dinkelacker, F. A Study on Electrofuels in Aviation. *Energies* **2018**, *11*, 392. [CrossRef]
43. Schafer, A. The global demand for motorized mobility. *Transp. Res. Part A Policy Pract.* **1998**, *32*, 455–477. [CrossRef]
44. Schafer, A.; Victor, D.G. Global passenger travel: implications for carbon dioxide emissions. *Energy* **1999**, *24*, 657–679. [CrossRef]
45. Millard-Ball, A.; Schipper, L. Are We Reaching Peak Travel? Trends in Passenger Transport in Eight Industrialized Countries. *Transp. Rev.* **2011**, *31*, 357–378. [CrossRef]
46. Buehler, R.; Pucher, J.; Gerike, R.; Götschi, T. Reducing car dependence in the heart of Europe: lessons from Germany, Austria, and Switzerland. *Transp. Rev.* **2017**, *37*, 4–28. [CrossRef]
47. Brown, T.; Schlachtberger, D.; Kies, A.; Schramm, S.; Greiner, M. Synergies of sector coupling and transmission reinforcement in a cost-optimised, highly renewable European energy system. *Energy* **2018**, *160*, 720–739. [CrossRef]
48. Stamenkovic, V.R.; Strmcnik, D.; Lopes, P.P.; Markovic, N.M. Energy and fuels from electrochemical interfaces. *Nat. Mater.* **2016**, *16*, 57. [CrossRef] [PubMed]
49. Connolly, D.; Mathiesen, B.V.; Ridjan, I. A comparison between renewable transport fuels that can supplement or replace biofuels in a 100% renewable energy system. *Energy* **2014**, *73*, 110–125. [CrossRef]
50. Nykvist, B.; Nilsson, M. Rapidly falling costs of battery packs for electric vehicles. *Nat. Clim. Chang.* **2015**, *5*, 329. [CrossRef]
51. Schmidt, O.; Hawkes, A.; Gambhir, A.; Staffell, I. The future cost of electrical energy storage based on experience rates. *Nat. Energy* **2017**, *2*, 17110. [CrossRef]
52. Kittner, N.; Lill, F.; Kammen, D.M. Energy storage deployment and innovation for the clean energy transition. *Nat. Energy* **2017**, *2*, 17125. [CrossRef]
53. Festel, G.; Würmseher, M.; Rammer, C.; Boles, E.; Bellof, M. Modelling production cost scenarios for biofuels and fossil fuels in Europe. *J. Clean. Prod.* **2014**, *66*, 242–253. [CrossRef]
54. Elliott, D.C.; Biller, P.; Ross, A.B.; Schmidt, A.J.; Jones, S.B. Hydrothermal liquefaction of biomass: Developments from batch to continuous process. *Bioresour. Technol.* **2015**, *178*, 147–156. [CrossRef]
55. Mustapha, W.F.; Bolkesjø, T.F.; Martinsen, T.; Trømborg, E. Techno-economic comparison of promising biofuel conversion pathways in a Nordic context—Effects of feedstock costs and technology learning. *Energy Convers. Manag.* **2017**, *149*, 368–380. [CrossRef]
56. Dehghani Madvar, M.; Aslani, A.; Ahmadi, M.H.; Karbalaie Ghomi, N.S. Current status and future forecasting of biofuels technology development. *Int. J. Energy Res.* **2019**, *43*, 1142–1160. [CrossRef]
57. Khan, M.I.; Shin, J.H.; Kim, J.D. The promising future of microalgae: current status, challenges, and optimization of a sustainable and renewable industry for biofuels, feed, and other products. *Microb. Cell Factories* **2018**, *17*, 36. [CrossRef]
58. Sinigaglia, T.; Lewiski, F.; Santos Martins, M.E.; Mairesse Siluk, J.C. Production, storage, fuel stations of hydrogen and its utilization in automotive applications-a review. *Int. J. Hydrog. Energy* **2017**, *42*, 24597–24611. [CrossRef]
59. Reuß, M.; Grube, T.; Robinius, M.; Preuster, P.; Wasserscheid, P.; Stolten, D. Seasonal storage and alternative carriers: A flexible hydrogen supply chain model. *Appl. Energy* **2017**, *200*, 290–302. [CrossRef]
60. Behrendt, F. Why cycling matters for electric mobility: towards diverse, active and sustainable e-mobilities. *Mobilities* **2018**, *13*, 64–80. [CrossRef]

61. Gebhardt, L.; Krajzewicz, D.; Oostendorp, R.; Goletz, M.; Greger, K.; Klötzke, M.; Wagner, P.; Heinrichs, D. Intermodal Urban Mobility: Users, Uses, and Use Cases. *Transp. Res. Procedia* **2016**, *14*, 1183–1192. [CrossRef]
62. Kammerlander, M.; Schanes, K.; Hartwig, F.; Jäger, J.; Omann, I.; O'Keeffe, M. A resource-efficient and sufficient future mobility system for improved well-being in Europe. *Eur. J. Futur. Res.* **2015**, *3*, 8. [CrossRef]
63. König, A.; Grippenkoven, J. From public mobility on demand to autonomous public mobility on demand -Learning from dial-a-ride services in Germany. In *Logistik und Supply Chain Management*; University of Bamberg Press: Bamberg, Germany, 2017; pp. 295–305.
64. Edelenbosch, O.Y.; McCollum, D.L.; van Vuuren, D.P.; Bertram, C.; Carrara, S.; Daly, H.; Fujimori, S.; Kitous, A.; Kyle, P.; Ó Broin, E.; et al. Decomposing passenger transport futures: Comparing results of global integrated assessment models. *Transp. Res. Part D Transp. Environ.* **2017**, *55*, 281–293. [CrossRef]
65. Ürge Vorsatz, D.; Cabeza, L.F.; Serrano, S.; Barreneche, C.; Petrichenko, K. Heating and cooling energy trends and drivers in buildings. *Renew. Sustain. Energy Rev.* **2015**, *41*, 85–98. [CrossRef]
66. Connolly, D.; Lund, H.; Mathiesen, B. Smart Energy Europe: The technical and economic impact of one potential 100% renewable energy scenario for the European Union. *Renew. Sustain. Energy Rev.* **2016**, *60*, 1634–1653. [CrossRef]
67. Sabiha, M.A.; Saidur, R.; Mekhilef, S.; Mahian, O. Progress and latest developments of evacuated tube solar collectors. *Renew. Sustain. Energy Rev.* **2015**, *51*, 1038–1054. [CrossRef]
68. Kalogirou, S.A. Solar thermal collectors and applications. *Prog. Energy Combust. Sci.* **2004**, *30*, 231–295. [CrossRef]
69. Rodríguez-Hidalgo, M.C.; Rodríguez-Aumente, P.A.; Lecuona, A.; Legrand, M.; Ventas, R. Domestic hot water consumption vs. solar thermal energy storage: The optimum size of the storage tank. *Appl. Energy* **2012**, *97*, 897–906. [CrossRef]
70. Wang, Y.; Shukla, A.; Liu, S. A state of art review on methodologies for heat transfer and energy flow characteristics of the active building envelopes. *Renew. Sustain. Energy Rev.* **2017**, *78*, 1102–1116. [CrossRef]
71. Nielsen, M.G.; Morales, J.M.; Zugno, M.; Pedersen, T.E.; Madsen, H. Economic valuation of heat pumps and electric boilers in the Danish energy system. *Appl. Energy* **2016**, *167*, 189–200. [CrossRef]
72. Sternberg, A.; Bardow, A. Power-to-What?—Environmental assessment of energy storage systems. *Energy Environ. Sci.* **2015**, *8*, 389–400. [CrossRef]
73. Gudmundsson, O.; Thorsen, J.E.; Zhang, L. Cost analysis of district heating compared to its competing technologies. *Wit Trans. Ecol. Environ.* **2013**, *1*, 3–13. [CrossRef]
74. Lund, H.; Østergaard, P.A.; Chang, M.; Werner, S.; Svendsen, S.; Sorknæs, P.; Thorsen, J.E.; Hvelplund, F.; Mortensen, B.O.G.; Mathiesen, B.V.; et al. The status of 4th generation district heating: Research and results. *Energy* **2018**, *164*, 147–159. [CrossRef]
75. David, A.; Mathiesen, B.V.; Averfalk, H.; Werner, S.; Lund, H. Heat Roadmap Europe: Large-Scale Electric Heat Pumps in District Heating Systems. *Energies* **2017**, *10*, 578. [CrossRef]
76. Arnaudo, M.; Zaalouk, O.A.; Topel, M.; Laumert, B. Techno-economic Analysis Of Integrated Energy Systems At Urban District Level—A Swedish Case Study. *Energy Procedia* **2018**, *149*, 286–296. [CrossRef]
77. Martinez, S.; Michaux, G.; Salagnac, P.; Bouvier, J.L. Micro-combined heat and power systems (micro-CHP) based on renewable energy sources. *Energy Convers. Manag.* **2017**, *154*, 262–285. [CrossRef]
78. Dodds, P.E.; Staffell, I.; Hawkes, A.D.; Li, F.; Grünewald, P.; McDowall, W.; Ekins, P. Hydrogen and fuel cell technologies for heating: A review. *Int. J. Hydrog. Energy* **2015**, *40*, 2065–2083. [CrossRef]
79. Alipour, M.; Zare, K.; Mohammadi-Ivatloo, B. Short-term scheduling of combined heat and power generation units in the presence of demand response programs. *Energy* **2014**, *71*, 289–301. [CrossRef]
80. Nazari-Heris, M.; Abapour, S.; Mohammadi-Ivatloo, B. Optimal economic dispatch of FC-CHP based heat and power micro-grids. *Appl. Therm. Eng.* **2017**, *114*, 756–769. [CrossRef]
81. Pereira da Cunha, J.; Eames, P. Thermal energy storage for low and medium temperature applications using phase change materials—A review. *Appl. Energy* **2016**, *177*, 227–238. [CrossRef]
82. Ibrahim, N.I.; Khan, M.M.A.; Mahbubul, I.M.; Saidur, R.; Al-Sulaiman, F.A. Experimental testing of the performance of a solar absorption cooling system assisted with ice-storage for an office space. *Energy Convers. Manag.* **2017**, *148*, 1399–1408. [CrossRef]
83. Pardo, P.; Deydier, A.; Anxionnaz-Minvielle, Z.; Rougé, S.; Cabassud, M.; Cognet, P. A review on high temperature thermochemical heat energy storage. *Renew. Sustain. Energy Rev.* **2014**, *32*, 591–610. [CrossRef]

84. Hedegaard, K.; Mathiesen, B.V.; Lund, H.; Heiselberg, P. Wind power integration using individual heat pumps—Analysis of different heat storage options. *Energy* **2012**, *47*, 284–293. [CrossRef]
85. Lanahan, M.; Tabares-Velasco, C.P. Seasonal Thermal-Energy Storage: A Critical Review on BTES Systems, Modeling, and System Design for Higher System Efficiency. *Energies* **2017**, *10*, 743. [CrossRef]
86. Pérez-Lombard, L.; Ortiz, J.; Pout, C. A review on buildings energy consumption information. *Energy Build.* **2008**, *40*, 394–398. [CrossRef]
87. Rüttenauer, T. Neighbours matter: A nation-wide small-area assessment of environmental inequality in Germany. *Soc. Sci. Res.* **2018**, *70*, 198–211. [CrossRef]
88. Harvey, L.D.D. Recent Advances in Sustainable Buildings: Review of the Energy and Cost Performance of the State-of-the-Art Best Practices from Around the World. *Annu. Rev. Environ. Resour.* **2013**, *38*, 281–309. [CrossRef]
89. Guillén-Lambea, S.; Rodríguez-Soria, B.; Marín, J.M. Review of European ventilation strategies to meet the cooling and heating demands of nearly zero energy buildings (nZEB)/Passivhaus. Comparison with the USA. *Renew. Sustain. Energy Rev.* **2016**, *62*, 561–574. [CrossRef]
90. Jennings, M.; Hirst, N.; Gambhir, A. *Reduction of Carbon Dioxide Emissions in the Global Building Sector to 2050*; Grantham Institute for Climate Change: London, UK, 2011.
91. Weiss, J.; Dunkelberg, E.; Vogelpohl, T. Improving policy instruments to better tap into homeowner refurbishment potential: Lessons learned from a case study in Germany. *Energy Policy* **2012**, *44*, 406–415. [CrossRef]
92. Diefenbach, N.; Cischinsky, H.; Rodenfels, M.; Clausnitzer, K.D. *Datenbasis Gebäudebestand Datenerhebung zur energetischen Qualität und zu den Modernisierungstrends im deutschen Wohngebäudebestand*; Institut für Wohnen und Umwelt GmbH: Darmstadt, Germany, 2010.
93. Ahmed, K.; Pylsy, P.; Kurnitski, J. Monthly domestic hot water profiles for energy calculation in Finnish apartment buildings. *Energy Build.* **2015**, *97*, 77–85. [CrossRef]
94. Ahmed, K.; Pylsy, P.; Kurnitski, J. Hourly consumption profiles of domestic hot water for different occupant groups in dwellings. *Sol. Energy* **2016**, *137*, 516–530. [CrossRef]
95. Hofmeister, M. *Technology Data for Energy Plants for Electricity and District Heating Generation, Chapter 40 and 41*; Danish Energy Agency: Copenhagen, Denmark, 2016.
96. Ellabban, O.; Abu-Rub, H.; Blaabjerg, F. Renewable energy resources: Current status, future prospects and their enabling technology. *Renew. Sustain. Energy Rev.* **2014**, *39*, 748–764. [CrossRef]
97. Staffell, I.; Green, R. The cost of domestic fuel cell micro-CHP systems. *Int. J. Hydrog. Energy* **2013**, *38*, 1088–1102. [CrossRef]
98. Buttler, A.; Spliethoff, H. Current status of water electrolysis for energy storage, grid balancing and sector coupling via power-to-gas and power-to-liquids: A review. *Renew. Sustain. Energy Rev.* **2018**, *82*, 2440–2454. [CrossRef]
99. Nitsch, J.; Pregger, T.; Naegler, T.; Heide, D.; de Tena, D.L.; Trieb, F.; Scholz, Y.; Nienhaus, K.; Gerhardt, N.; Sterner, M.; et al. *Langfristszenarien und Strategien für den Ausbau der erneuerbaren Energien in Deutschland bei Berücksichtigung der Entwicklung in Europa und global (Leitstudie 2011—Schlussbericht an das BMU)*; Deutsches Zentrum für Luft- und Raumfahrt, Fraunhofer-Institut für Windenergie und Energiesystemtechnik, Ingenieurbüro für neue Energien: Stuttgart, Germany, 2012.
100. Ahshan, R.; Al-Badi, A.; Hosseinzadeh, N.; Shafiq, M. Small Wind Turbine Systems for Application in Oman. In Proceedings of the 2018 5th International Conference on Electric Power and Energy Conversion Systems (EPECS), Kitakyushu, Japan, 23–25 April 2018; pp. 1–6. [CrossRef]
101. Kolanowski, B.R. *Small-Scale Cogeneration Handbook*, 2nd ed.; Fairmont Press: Lilburn, Georgia, 2003.
102. Weniger, J.; Tjaden, T.; Quaschning, V. Sizing of Residential PV Battery Systems. *Energy Procedia* **2014**, *46*, 78–87. [CrossRef]
103. Borenstein, S. Private Net Benefits of Residential Solar PV: The Role of Electricity Tariffs, Tax Incentives, and Rebates. *J. Assoc. Environ. Resour.* **2017**, *4*, S85–S122. [CrossRef]
104. Chapman, A.J.; McLellan, B.; Tezuka, T. Residential solar PV policy: An analysis of impacts, successes and failures in the Australian case. *Renew. Energy* **2016**, *86*, 1265–1279. [CrossRef]
105. Wirth, H. *Recent Facts about Photovoltaics in Germany*; Fraunhofer ISE: Freiburg im Breisgau, Germany, 2018.
106. Ghazali, A.; Salleh, E.I.; Haw, L.C.; Mat, S.; Sopian, K. Feasibility of vertical photovoltaic system on high-rise building in Malaysia: performance evaluation. *Int. J. Low-Carbon Technol.* **2017**, *12*, 263–271. [CrossRef]

107. Becerra, M.; Morán, J.; Jerez, A.; Cepeda, F.; Valenzuela, M. Wind energy potential in Chile: Assessment of a small scale wind farm for residential clients. *Energy Convers. Manag.* **2017**, *140*, 71–90. [CrossRef]
108. Tummala, A.; Velamati, R.K.; Sinha, D.K.; Indraja, V.; Krishna, V.H. A review on small scale wind turbines. *Renew. Sustain. Energy Rev.* **2016**, *56*, 1351–1371. [CrossRef]
109. Eckel, H.; Hartmann, S.; Eggersglüß, W. *Wirtschaftlichkeit von kleinen Windenergieanlagen*; Kuratorium für Technik und Bauwesen in der Landwirtschaft e. V. (KTBL): Darmstadt, Germany, 2012.
110. Karl, B.; Gösta, B.; Gabriella, E.; Mats, E.N. Infrasound and low frequency noise from wind turbines: Exposure and health effects. *Environ. Res. Lett.* **2011**, *6*, 035103.
111. Berger, R.G.; Ashtiani, P.; Ollson, C.A.; Whitfield Aslund, M.; McCallum, L.C.; Leventhall, G.; Knopper, L.D. Health-Based Audible Noise Guidelines Account for Infrasound and Low-Frequency Noise Produced by Wind Turbines. *Front. Public Health* **2015**, *3*, 31. [CrossRef] [PubMed]
112. Nikolaidis, P.; Poullikkas, A. A comparative review of electrical energy storage systems for better sustainability. *J. Power Technol.* **2017**, *97*, 220–245.
113. Ould Amrouche, S.; Rekioua, D.; Rekioua, T.; Bacha, S. Overview of energy storage in renewable energy systems. *Int. J. Hydrog. Energy* **2016**, *41*, 20914–20927. [CrossRef]
114. Merei, G.; Moshövel, J.; Magnor, D.; Sauer, D.U. Optimization of self-consumption and techno-economic analysis of PV-battery systems in commercial applications. *Appl. Energy* **2016**, *168*, 171–178. [CrossRef]
115. Prasanna, A.; Dorer, V. Feasibility of renewable hydrogen based energy supply for a district. *Energy Procedia* **2017**, *122*, 373–378. [CrossRef]
116. Luderer, G.; Pietzcker, R.C.; Carrara, S.; de Boer, H.S.; Fujimori, S.; Johnson, N.; Mima, S.; Arent, D. Assessment of wind and solar power in global low-carbon energy scenarios: An introduction. *Energy Econ.* **2017**, *64*, 542–551. [CrossRef]
117. Anderson, B.; Lin, S.; Newing, A.; Bahaj, A.; James, P. Electricity consumption and household characteristics: Implications for census-taking in a smart metered future. *Comput. Environ. Urban Syst.* **2017**, *63*, 58–67. [CrossRef]
118. Kavousian, A.; Rajagopal, R.; Fischer, M. Ranking appliance energy efficiency in households: Utilizing smart meter data and energy efficiency frontiers to estimate and identify the determinants of appliance energy efficiency in residential buildings. *Energy Build.* **2015**, *99*, 220–230. [CrossRef]
119. Belaïd, F. Understanding the spectrum of domestic energy consumption: Empirical evidence from France. *Energy Policy* **2016**, *92*, 220–233. [CrossRef]
120. Rogelj, J.; Luderer, G.; Pietzcker, R.C.; Kriegler, E.; Schaeffer, M.; Krey, V.; Riahi, K. Energy system transformations for limiting end-of-century warming to below 1.5 °C. *Nat. Clim. Chang.* **2015**, *5*, 519. [CrossRef]
121. Buskirk, R.D.V.; Kantner, C.L.S.; Gerke, B.F.; Chu, S. A retrospective investigation of energy efficiency standards: policies may have accelerated long term declines in appliance costs. *Environ. Res. Lett.* **2014**, *9*, 114010. [CrossRef]
122. Wholesale Solar Home Page. Available online: https://www.wholesalesolar.com/solar-information/how-to-save-energy/power-table (accessed on 17 January 2019).
123. EcoTopTen Home Page-Energy Consumption of Different Devices. Available online: www.ecotopten.de (accessed on 21 February 2019).
124. Antal, M.; van den Bergh, J.C.J.M. Re-spending rebound: A macro-level assessment for OECD countries and emerging economies. *Energy Policy* **2014**, *68*, 585–590. [CrossRef]
125. Nässén, J.; Holmberg, J. Quantifying the rebound effects of energy efficiency improvements and energy conserving behaviour in Sweden. *Energy Effic.* **2009**, *2*, 221–231. [CrossRef]
126. Berrill, P.; Arvesen, A.; Scholz, Y.; Gils, H.C.; Hertwich, E.G. Environmental impacts of high penetration renewable energy scenarios for Europe. *Environ. Res. Lett.* **2016**, *11*, 014012. [CrossRef]
127. Gils, H.C.; Scholz, Y.; Pregger, T.; Luca de Tena, D.; Heide, D. Integrated modelling of variable renewable energy-based power supply in Europe. *Energy* **2017**, *123*, 173–188. [CrossRef]
128. Burger, B.; Kiefer, K.; Kost, C.; Nold, S.; Philipps, S.; Preu, R.; Rentsch, J.; Schlegl, T.; Stryi-Hipp, G.; Willenke, G.; et al. *Photovoltaics Report*; Fraunhofer Institute for Solar Energy Systems, ISE: Freiburg im Breisgau, Germany, 2018.
129. Karneyeva, Y.; Wüstenhagen, R. Solar feed-in tariffs in a post-grid parity world: The role of risk, investor diversity and business models. *Energy Policy* **2017**, *106*, 445–456. [CrossRef]

130. Papachristos, G. Household electricity consumption and CO2 emissions in the Netherlands: A model-based analysis. *Energy Build.* **2015**, *86*, 403–414. [CrossRef]
131. Boßmann, T.; Staffell, I. The shape of future electricity demand: Exploring load curves in 2050s Germany and Britain. *Energy* **2015**, *90*, 1317–1333. [CrossRef]
132. Laicane, I.; Blumberga, D.; Blumberga, A.; Rosa, M. Evaluation of Household Electricity Savings. Analysis of Household Electricity Demand Profile and User Activities. *Energy Procedia* **2015**, *72*, 285–292. [CrossRef]
133. Borg, S.P.; Kelly, N.J. The effect of appliance energy efficiency improvements on domestic electric loads in European households. *Energy Build.* **2011**, *43*, 2240–2250. [CrossRef]
134. Cooper, D.R.; Gutowski, T.G. The Environmental Impacts of Reuse: A Review. *J. Ind. Ecol.* **2015**, *21*, 38–56. [CrossRef]
135. Jylhä, K.; Jokisalo, J.; Ruosteenoja, K.; Pilli-Sihvola, K.; Kalamees, T.; Seitola, T.; Mäkelä, H.M.; Hyvönen, R.; Laapas, M.; Drebs, A. Energy demand for the heating and cooling of residential houses in Finland in a changing climate. *Energy Build.* **2015**, *99*, 104–116. [CrossRef]
136. Aebischer, B.; Catenazzi, G.; Jakob, M. Impact of Climate Change on Thermal Comfort, Heating and Cooling Energy Demand in Europe. 2007. Available online: http://www.verozo.be/sites/verozo/files/files/ImpactClimateChange_ETHSwitzerland.pdf (accessed on 10 January 2020).
137. Knopf, B.; Nahmmacher, P.; Schmid, E. The European renewable energy target for 2030—An impact assessment of the electricity sector. *Energy Policy* **2015**, *85*, 50–60. [CrossRef]
138. Nepustil, U.; Laing-Nepustil, D.; Lodemann, D.; Sivabalan, R.; Hausmann, V. High Temperature Latent Heat Storage with Direct Electrical Charging – Second Generation Design. *Energy Procedia* **2016**, *99*, 314–320. [CrossRef]
139. Götz, M.; Lefebvre, J.; Mörs, F.; McDaniel Koch, A.; Graf, F.; Bajohr, S.; Reimert, R.; Kolb, T. Renewable Power-to-Gas: A technological and economic review. *Renew. Energy* **2016**, *85*, 1371–1390. [CrossRef]
140. Bloess, A.; Schill, W.P.; Zerrahn, A. Power-to-heat for renewable energy integration: A review of technologies, modeling approaches, and flexibility potentials. *Appl. Energy* **2018**, *212*, 1611–1626. [CrossRef]
141. Klement, P.; Thomsen, T.; Lammers, F.; Zobel, M.; Hanke, B.; Maydell, K.V. Photovoltaic-Energy-Profiles used in Power to Heat Time-Lapse Tests. *Environ. Sci.* **2014**. [CrossRef]
142. Blanco, H.; Faaij, A. A review at the role of storage in energy systems with a focus on Power to Gas and long-term storage. *Renew. Sustain. Energy Rev.* **2018**, *81*, 1049–1086. [CrossRef]
143. Jentsch, M.; Trost, T.; Sterner, M. Optimal Use of Power-to-Gas Energy Storage Systems in an 85Renewable Energy Scenario. *Energy Procedia* **2014**, *46*, 254–261. [CrossRef]
144. Robledo, C.B.; Oldenbroek, V.; Abbruzzese, F.; van Wijk, A.J.M. Integrating a hydrogen fuel cell electric vehicle with vehicle-to-grid technology, photovoltaic power and a residential building. *Appl. Energy* **2018**, *215*, 615–629. [CrossRef]
145. Izadkhast, S.; Garcia-Gonzalez, P.; Frías, P. An Aggregate Model of Plug-In Electric Vehicles for Primary Frequency Control. *IEEE Trans. Power Syst.* **2015**, *30*, 1475–1482. [CrossRef]
146. Besheer, A.H.; Smyth, M.; Zacharopoulos, A.; Mondol, J.; Pugsley, A. Review on recent approaches for hybrid PV/T solar technology. *Int. J. Energy Res.* **2016**, *40*, 2038–2053. [CrossRef]
147. Hawlader, M.N.A.; Chou, S.K.; Ullah, M.Z. The performance of a solar assisted heat pump water heating system. *Appl. Therm. Eng.* **2001**, *21*, 1049–1065. [CrossRef]
148. Fischer, D.; Rautenberg, F.; Wirtz, T.; Wille-Haussmann, B.; Madani, H. Smart Meter Enabled Control for Variable Speed Heat Pumps to Increase PV Self-Consumption. In Proceedings of the 24th IIR International Congress of Refrigeration, Yokohama, Japan, 22–16 August 2015. [CrossRef]
149. Ramos, A.; Chatzopoulou, M.A.; Freeman, J.; Markides, C.N. Optimisation of a high-efficiency solar-driven organic Rankine cycle for applications in the built environment. *Appl. Energy* **2018**, *228*, 755–765. [CrossRef]
150. Nam, J.Y.; Gao, Y.X.; Yoon, H.S.; Lee, H.K. Study on the Performance of a Ground Source Heat Pump System Assisted by Solar Thermal Storage. *Energies* **2015**, *8*, 365. [CrossRef]
151. Postigo Marcos, E.F.; Mateo Domingo, C.; Gómez San Román, T.; Palmintier, B.; Hodge, B.M.; Krishnan, V.; de Cuadra García, F.; Mather, B. A Review of Power Distribution Test Feeders in the United States and the Need for Synthetic Representative Networks. *Energies* **2017**, *10*, 896. [CrossRef]
152. Armaroli, N.; Balzani, V. Towards an electricity-powered world. *Energy Environ. Sci.* **2011**, *4*, 3193–3222. [CrossRef]

153. Schneider, K.; Phanivong, P.; Lacroix, J. IEEE 342-node low voltage networked test system. In Proceedings of the 2014 IEEE PES General Meeting | Conference & Exposition, National Harbor, MD, USA, 27–31 July 2014; pp. 1–5. [CrossRef]
154. Heuck, K.; Dettmann, K.D.; Schulz, D. *Elektrische Energieversorgung*; Springer: Berlin/Heidelberg, Germany, 2010. [CrossRef]
155. Kenneth, A.P.; Folly, K. Voltage Rise Issue with High Penetration of Grid Connected PV. *IFAC Proc. Vol.* **2014**, *47*, 4959–4966. [CrossRef]
156. Clement-Nyns, K.; Haesen, E.; Driesen, J. The Impact of Charging Plug-In Hybrid Electric Vehicles on a Residential Distribution Grid. *IEEE Trans. Power Syst.* **2010**, *25*, 371–380. [CrossRef]
157. Deconinck, G.; Craemer, K.D.; Claessens, B. Combining Market-Based Control with Distribution Grid Constraints when Coordinating Electric Vehicle Charging. *Engineering* **2015**, *1*, 453–465. [CrossRef]
158. Beaude, O.; He, Y.; Hennebel, M. Introducing decentralized EV charging coordination for the voltage regulation. In Proceedings of the IEEE PES ISGT Europe 2013, Lyngby, Denmark, 6–9 October 2013; pp. 1–5. [CrossRef]
159. Marszal-Pomianowska, A.; de Cerio Mendaza, I.D.; Bak-Jensen, B.; Heiselberg, P. A performance evaluation of future low voltage grids in presence of prosumers modelled in high temporal resolution. *Sustain. Cities Soc.* **2019**, *44*, 702–714. [CrossRef]
160. Feron, B.; Monti, A. Domestic Battery and Power-to-Heat Storage for Self-Consumption and Provision of Primary Control Reserve. In Proceedings of the 2018 Power Systems Computation Conference (PSCC), Dublin, Ireland, 11–15 June 2018; pp. 1–6. [CrossRef]
161. Carrasco, J.M.; Franquelo, L.G.; Bialasiewicz, J.T.; Galvan, E.; PortilloGuisado, R.C.; Prats, M.A.M.; Leon, J.I.; Moreno-Alfonso, N. Power-Electronic Systems for the Grid Integration of Renewable Energy Sources: A Survey. *IEEE Trans. Ind. Electron.* **2006**, *53*, 1002–1016. [CrossRef]
162. Faessler, B.; Schuler, M.; Preißinger, M.; Kepplinger, P. Battery Storage Systems as Grid-Balancing Measure in Low-Voltage Distribution Grids with Distributed Generation. *Energies* **2017**, *10*, 2161. [CrossRef]
163. Kosow, H.; Robert, G. *Methoden der Zukunfts- und Szenarioanalyse Überblick, Bewertung und Auswahlkriterien*; Institute for Futures Studies and Technology Assessment: Berlin, Germany, 2008.
164. Ritchey, T. Modeling Alternative Futures with General Morphological Analysis. *World Futur. Rev.* **2011**, *3*, 83–94. [CrossRef]
165. Ritchey, T. General Morphological Analysis-A General Method for Non Quantified Modelling. Available online: http://swemorph.com/pdf/gma.pdf (accessed on 30 April 2019).
166. Destatis. *Entwicklung der Privathaushalte bis 2035-Ergebnisse der Haushaltsvorausberechnung*; Statistisches Bundesamt: Wiesbaden, Germany, 2017.
167. Destatis. *Gebäude und Wohnungen-Bestand an Wohnungen und Wohngebäuden Bauabgang von Wohnungen und Wohngebäuden Lange Reihen ab 1969–2017*; Statistisches Bundesamt: Wiesbaden, Germany, 2018.
168. Wiginton, L.K.; Nguyen, H.T.; Pearce, J.M. Quantifying rooftop solar photovoltaic potential for regional renewable energy policy. *Comput. Environ. Urban Syst.* **2010**, *34*, 345–357. [CrossRef]
169. Canals Casals, L.; Martinez-Laserna, E.; Amante García, B.; Nieto, N. Sustainability analysis of the electric vehicle use in Europe for CO2 emissions reduction. *J. Clean. Prod.* **2016**, *127*, 425–437. [CrossRef]