Techno-Economic Evaluation of Energy Self-Sufficiency for the Energy Supply of Single and Multifamily Buildings

Johannes Bracke[1]

[1] Baumann Consulting, Frankfurt am Main (Germany)

Abstract

Many consumers currently follow the idea of energy self-sufficiency and try to contribute to meet their energy needs to become independent and self-sufficient from the central energy network. In order to achieve load-related energy self-sufficiency, the energy supply must cover the energy demand at any time. Against this background, this study analyzes the costs and potential of load-related energy self-sufficiency of single and multi-family buildings. It is differentiated between electricity-, heat- and energy self-sufficiency. The modelling is carried out with the simulation environment „Polysun Designer" which allows a high temporal, dynamic simulation of the annual energy demand and energy supply.

Keywords: Energy self-sufficiency, Energy supply systems, Whole Building Simulation, Evaluation

Introduction

The realization of extensive reduction targets of greenhouse gas emissions and the associated increased use of renewable energies in Europe and Germany lead to autonomy aspirations of consumers towards becoming more independent from the central energy supply network. As a result, consumers are turning from pure energy consumers to simultaneous energy producers, eventually becoming independent of the central energy supply network (Bardt et al., 2014). Within an interdisciplinary research network, the Institute of Energy Economics and Rational Energy Use (IER) investigated the energy self-sufficiency potential for different system boundaries as well as the required technologies (Tomaschek et al., 2015).

Interestingly, there is no clear definition of the term "energy self-sufficiency" in scientific literature. In this study, a distinction is made between energy self-sufficiency "on balance" and load-related energy self-sufficiency. For energy self-sufficiency on balance, the energy supply for a defined period of time (e.g. twelve months) must be at least equal to the energy demand (Deutschle et al. 2015). The overall balance of the energy exchange between the system and the environment must not be negative. However, energy can be imported from the environment into the system or exported from the system to make up the mismatch between energy supply E_{Supply} and energy demand E_{Demand} (see Fig. 1 a). The impact of energy self-sufficiency "on balance" for private households for different system boundaries is described in McKenna et al. (2016).

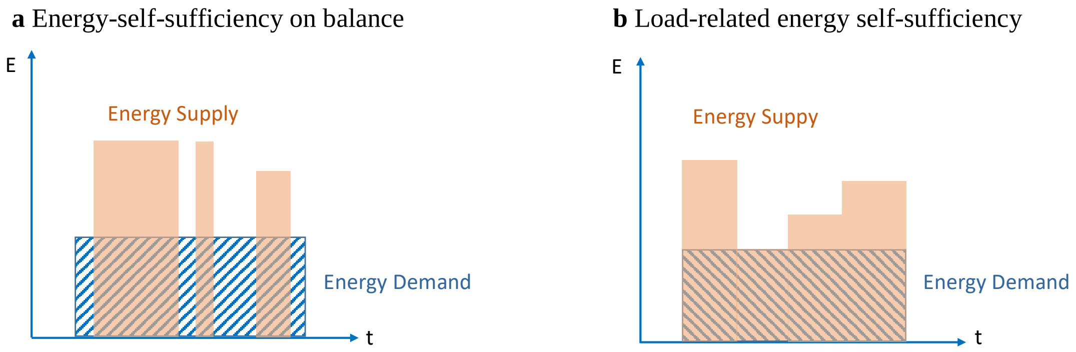
Load-related energy self-sufficiency is the more demanding of the two forms of energy self-sufficiency. It must always be ensured that the energy demand is met by the energy supply (see Fig. 1 b). Energy is never imported into the system at any time. Excluded is the entry of renewable energies such as solar energy, wind energy or hydroelectric power. However, it is allowed to export energy beyond the system boundaries (Deutschle et al., 2015).

$$\int_0^t \dot{E}_{Supply} dt \geq \int_0^t \dot{E}_{Demand} dt \qquad \text{(eq. 1)}$$

$$\dot{E}_{Supply}(t) \geq \dot{E}_{Demand}\,(t) \qquad \text{(eq. 2)}$$

doi:10.18086/eurosun2018.11.16 Available at http://proceedings.ises.org

Against this background, this paper presents the costs and potential of a self-sufficient energy supply, of multi- and single-family buildings, as the smallest system boundary. A distinction is made between electricity, heat and energy self-sufficiency.


a Energy-self-sufficiency on balance

b Load-related energy self-sufficiency

Fig. 1: Distinction between energy self-sufficiency on balance (a) and load-related energy self-sufficiency (b) (Deutschle et al. 2015)

Methodology and Boundary Conditions

The simulation environment “Polysun Designer” is used for the modeling of the energy systems (building model, energy supply system model and energy storage model). The software allows dynamic simulations of the annual energy demand and energy supply with a high temporal resolution. “Polysun Designer” is a software for the simulation of building energy systems developed and distributed by Vela Solaris. Polysun carries out dynamic annual simulations with a temporal resolution of up to one minute. The output parameters are, for example, the yield of the PV (Photovoltaic) system, the PV self- consumption factor or the annual performance factor of a heat pump.

Fig. 2 shows the basic process of a simulation with Polysun Designer. First, the input parameters are defined. These include the climate data, the building data (U-values, g-values, building dimensions) and the load profiles of the energy consumers (hot water, household electricity). The energy system is built on individual components (e.g. heat pump, PV system, battery storage system, building). The dimensioning of the system components is based on recommendations of the component manufacturers.

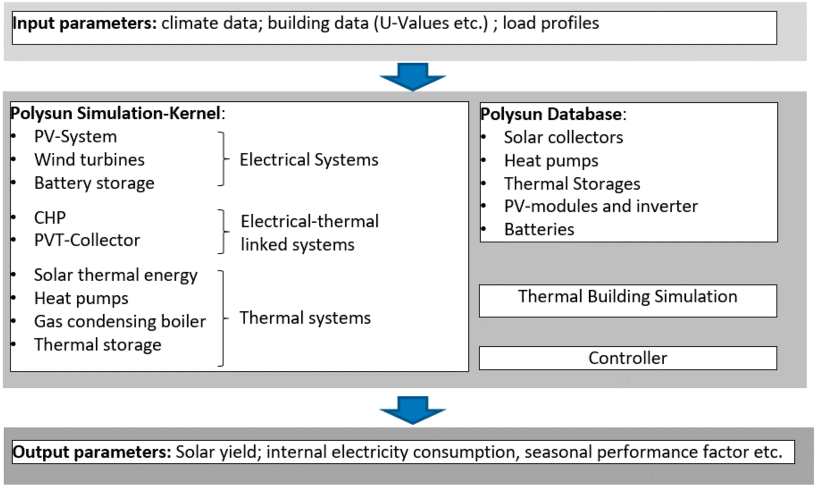


Fig. 2: Simulation process with “Polysun Designer”

To be able to assess the energy self-sufficiency potential for residential buildings, the definition of energy evaluation parameters is necessary. According to McKenna et al (2015b), the level of load-related energy self-sufficiency a and the PV self-consumption factor e can be used for this. The load-related energy self-sufficiency is defined as the ratio between energy production E_E and energy consumption V_G McKenna et al. (2015b).

$$a = \frac{\mathrm{E_E}}{\mathrm{V_G}} = \frac{\int_0^t \dot{E}_E \cdot dt}{\int_0^t \dot{V}_G \cdot dt} \qquad \text{(eq. 3)}$$

The PV self-consumption factor *e* is the share of electricity (i.e. considering storage losses) that is used in the building itself. $\mathrm{E_{ES}}$ describes the amount of energy used for own electricity consumption:

$$e = \frac{\mathrm{E_{ES}}}{E_E} = \frac{\int_0^t \dot{\mathrm{E}}_{\mathrm{ES}} \cdot dt}{\int_0^t \dot{E}_E \cdot dt} \qquad \text{(eq. 4)}$$

The paper considers two building energy standards to determine the influence of the heat demand on the energy self-sufficiency potential. For this purpose, a new building and an existing building are examined (cf. Table 1). The building energy standard of the new building is oriented towards the requirements of the passive house standard. The building energy standard of the existing is based on data of the German building stock and meets the requirements of the German Building Insulation Ordinance of 1995 (WSVO 95) (BUND 1994). The single-family building has a heated living area of 163 m^2. The multifamily building has five apartment units with a total heated living area of 258 m^2 (cf. Table 1).

The temporal resolution for this simulation is 15 minutes. The minimum level of energy self-sufficiency and the personal power consumption is determined for a one-year period. The investigated forms of self-sufficiency are load-related electricity self-sufficiency ($a_{electricity}$), load-related heat self-sufficiency ($\mathrm{a_{heat}}$) and load-related energy self-sufficiency (a_{energy}) which is the total of electricity and heat. In addition, the PV self-consumption factor ($e_{Electricity}$) is calculated. The energy demand for mobility (fuels) and the energy use of raw materials / technologies (grey energy) are not included in the following analysis.

The "future" test reference year of region 6 (Germany) is the basis for the heat demand calculation as well as the yield calculation of the PV and the solar thermal systems. The climate data of the test reference years (TRY) of the German Weather Service (DWD) contain measurement data, such as the outdoor temperature and solar radiation, in hourly resolution for 15 representative regions in Germany (DWD 2011).

Tab. 1: Summary of the system parameters for the single-family building (SFB) and multi-family building (MFB)

		SFB		MFB	
	Unit	Existing Building	New Construction	Existing Building	New Construction
Specific heating demand	kWh/m^2	100	17	98	16
Specific domestic hot water demand	kWh/m^2	9.8		20.5	
Household electricity demand	kWh/a	3500		15000	
Air handling unit electricity demand	kWh/a	-	627		1331
Solar thermal storage volume	l/m^2 (Solar thermal module area)	90		90	
Number of residents	-	3		10	
Gross floor area ($A_{(Gross)}$)	m^2	263		419	
Living space ($A_{(living)}$)	m^2	203		323	
Heated living space ($A_{(living,heated)}$)	m^2	163		258	
Households / living units	-	1		5	
Residents per unit	-	3		2	
Building floor area	m^2	88		105	
Roof slope	°	50		35	
Roof orientation	-	North-South		North-South	
Surface-area to volume ratio	m^2/m^3	0.84		0.7	

The temporal structure of the energy demand is determined using load profiles. The load profiles for electricity and hot water, with a temporal resolution of up to 1 minute, are taken from the VDI 4655 (VDI 4655 2008). The energy consumption of the building heating system is calculated for each hour of the year using Polysun Designer and consists of the power consumption of the heat distribution pumps and the power consumption of the heat pumps. The load profile for the building heat demand is calculated with the dynamic building energy model for each time step of the simulation. Transmission heat losses, heat losses through ventilation and infiltration, passive heat gains through solar radiation and internal gains are calculated. Thus, the influence of the effective heat storage capacity of the building is considered (Vela Solaris 2014).

For the economic evaluation, all costs related to the building energy supply are considered. The costs include the investment costs of the system components as well as the gas and electricity procurement costs. Revenue from feeding PV electricity into the public grid leads to a reduction in costs (feed-in tariff). Other funding programs in addition to the EEG (German Renewable Energy Law) are not considered for this study. The overall annual costs (annuity) are calculated from the expenditure and revenue according to VDI 2067. The assumptions listed in Table 2 are used for the economic valuation.

Tab. 2: Summary of the assumptions for the economic evaluation

	Unit	Assumption
Reporting period	a	20
Imputed interest rate	%	4
Energy price alteration	%	4
Maintenance price alteration	%	2.5
Energy price / feed-in remuneration		
Electricity price (incl. value added tax)	€/kWh	0.26
Feed in remuneration	€/kWh	0.12
Gas price (incl. value added tax) depending on annual gas consumption	€/kWh	0.066-0.1
Solar systems (incl. assembly without electrical/thermal energy storage)		
Price PV-System (incl. value added tax)	€/kWp	1650
Price PV-System (incl. value added tax)	€/m^2	302
Price solar-thermal system (incl. value added tax)	€/m^2	750-1030
Electrical/thermal energy storage		
Battery storage price (incl. value added tax)	€/kWh	1675
Thermal storage price (incl. value added tax)	€/l	1.1
Gas-fired condensing boiler	€	4168

Energy Supply Systems

The energy supply systems are selected to cover the highest possible share of the buildings' energy demand with renewable energies. For the single-family building, the electricity- and heat supply are entirely based on electricity. The electricity supply is provided by a PV system and an AC-coupled battery storage system as well as a connection to the public grid. An electric heat pump is used for the heat supply of the building. The electric heat pump is connected to a vertical geothermal tubing system (see Fig. 4). The external energy source of the heat pump is either supplied by PV electricity, electricity from the battery storage, or electricity from the public grid. The heat pump is also connected to thermal storage. PU rigid foam with an insulation thickness of 150 mm is used as insulation material for the thermal storage. The HVAC control strategy is designed to achieve the highest possible degree of energy self-sufficiency. Priority is given to the energy supply of electricity consumers (household appliances + heat pump) with PV electricity. If excess PV electricity is available, the battery storage is charged. If the battery storage is fully charged and there is still excess electricity available from the PV system, the PV energy is thermally stored by extended heat pump operation (excess control). The requirement for this control is that the current PV output exceeds the required electrical load of the heat pump. The excess temperature control of the heat pump increases the temperature setpoint of the thermal storage from 50 to 60 °C. Furthermore, the night-time room-temperature setback of three Kelvin leads to a shift of the heat pump operation into the hours of the day. This makes frequent operation of the heat pump with PV electricity possible. Another advantage of the night-time temperature-setback is that the heat pump won't discharge the battery storage overnight. As a result, the household electricity consumers can use the temporarily stored PV electricity. An air handling unit is available for the new construction building to ensure an adequate ventilation.

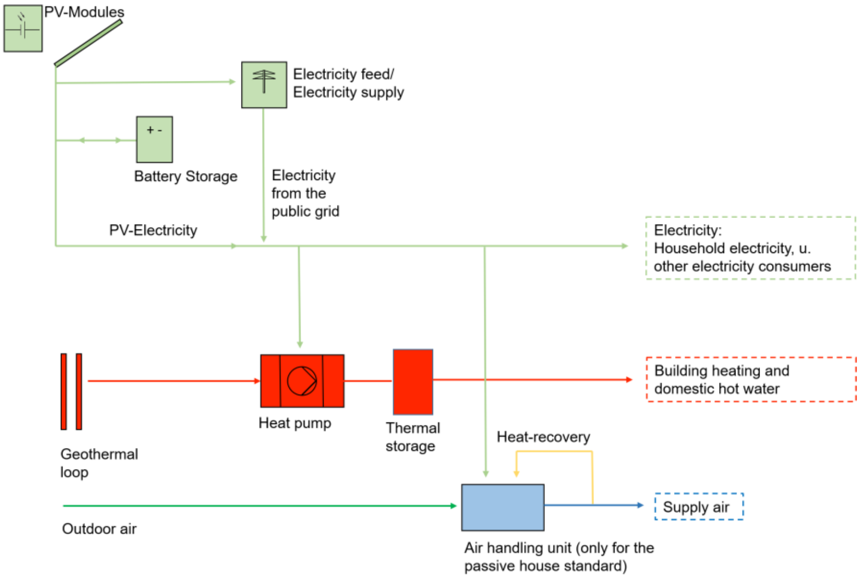


Fig. 4: Schematic of the heat and electricity supply of the single-family building

The electrical energy supply of the multi-family building is provided by a PV system, which is coupled to battery storage (see Fig. 5). In addition, a connection to the public power grid is available. According to the operating strategy, PV energy is first used for the direct supply of the electricity consumers. If excess PV electricity is available, it is used to charge the battery storage. Battery charging by the public grid electricity is not possible. Further excess electricity production of PV electricity is fed into the public grid. If the PV system is not able to meet the electricity loads, the battery will be discharged. If the battery is completely discharged, electricity is obtained form the public grid. The heating demand is met by a gas condensing boiler and a solar-thermal heating system. Both heat sources are connected to thermal storage, which is divided into two zones. The upper third of the thermal storage is used for DHW heating and has temperatures of 50-60 °C. With a fresh water station, the cold water is heated to the set-point temperature using an external heat exchanger. The lower 2/3 of the thermal storage are available for room heating purposes. A heat exchanger is integrated in the lower storage section, which enables the solar collectors to be integrated.

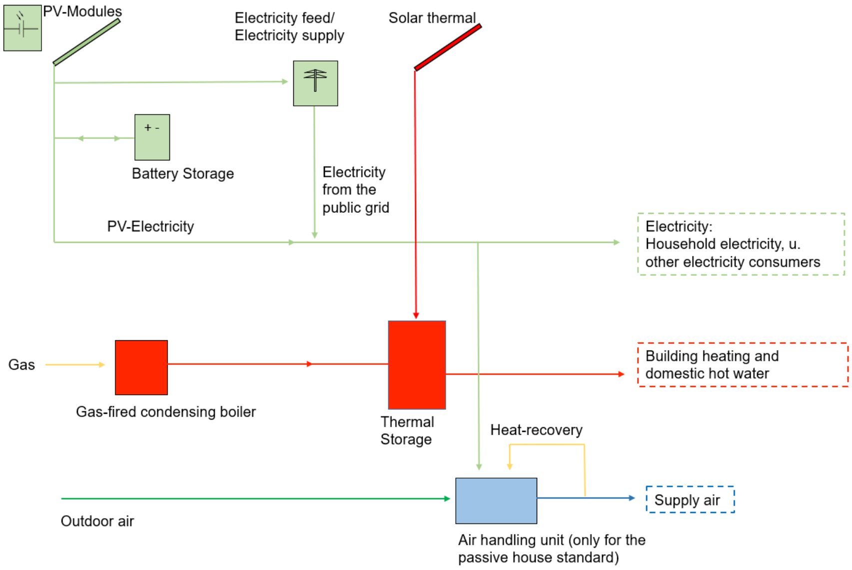
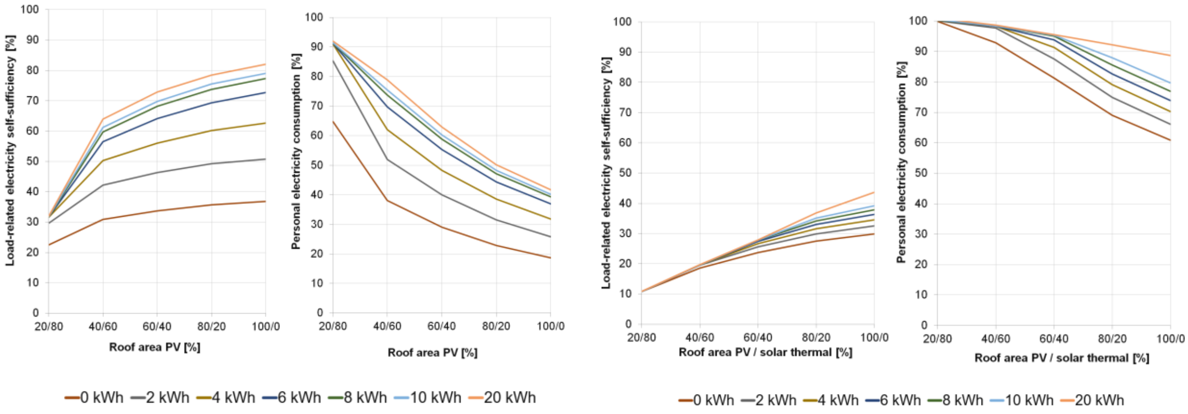


Fig. 5: Schematic of the heat and electricity supply of the multi-family building

Sensitivity analyses vary the roof area for PV and solar thermal systems from 0 to 100 %. The battery storage capacity varies between 0 and 20 kWh. The available roof area for energetic use is used completely for regenerative energy generation by PV modules or solar thermal collectors. Deductions due to roof installations etc. are considered.

Results for Energy Self Sufficiency

To show the main influences on the load-related electricity self-sufficiency, the results for the single-family building (passive house standard) are presented first. The analysis of the load-related electricity self-sufficiency shows that a PV system with 20 kWh battery storage can cover up to 82 % of the household electricity demand (see Fig. 6a). With an increase in battery storage capacity, the largest increase in load-related electricity self-sufficiency and PV self-consumption can be achieved. Without a battery storage, the increase of PV roof area from 0 to 100% only leads to a slight increase of the load-related electricity self-sufficiency from 22 to 37 % and also leads to a sharp reduction of the self-consumption factor from 65 to 19 %. The results for the new construction building shown in Fig. 6a can also be transferred to the existing building. For the existing building, the load-related electricity self-sufficiency levels are between 1-2 % above those of the new construction building, as the electricity consumption of the ventilation system is eliminated. For the multifamily building, 44 % of the consumer electricity consumption can be covered if the entire roof is utilized for PV modules and a 20-kWh battery storage is used (see Fig. 6b). Without a battery storage, the maximum load-related electricity factor is 30 %. Compared to the single-family building, the multi-family building has significantly higher electricity self-consumption factors (cf. Fig. 6b). Due to the higher electricity demand compared to the single-family building, consumer electricity uses a significantly higher proportion of PV energy.



a Single-family building

b Multi-family building

Fig 6: Influence of the PV roof area share and the battery capacity on electricity self-consumption and load-related electricity self-sufficiency for the single-family building (a) and multi-family building (b) both for new construction.

The maximum degrees of load-related heat self-sufficiency for the single-family building are between 55 % (passive house standard) and 30 % (existing building). The highest rates of load-related heat self-sufficiency are achieved if the entire roof surface of is covered with PV modules. For the multi-family building, the maximum load-related heat self-sufficiency is 57 % for the new construction building and up to 24 % for the existing building. The maximum degrees of heat self-sufficiency are achieved when the entire roof area is covered with solar thermal collectors.

A total load-related energy self-sufficiency is neither possible for the single-family building nor for the multi-family building. For the single-family building, a maximum of 45 % (existing building) to 71 % (new construction building) of the building's energy demand can be covered with renewable energies. The maximum load-related energy self-sufficiency levels are achieved with 100 % PV roof area and a battery capacity of 20 kWh. For both building standards, an increase in the degree of energy self-sufficiency can be seen for both building types with an increasing proportion of PV roof area and increasing battery storage capacity (see Fig. 7).

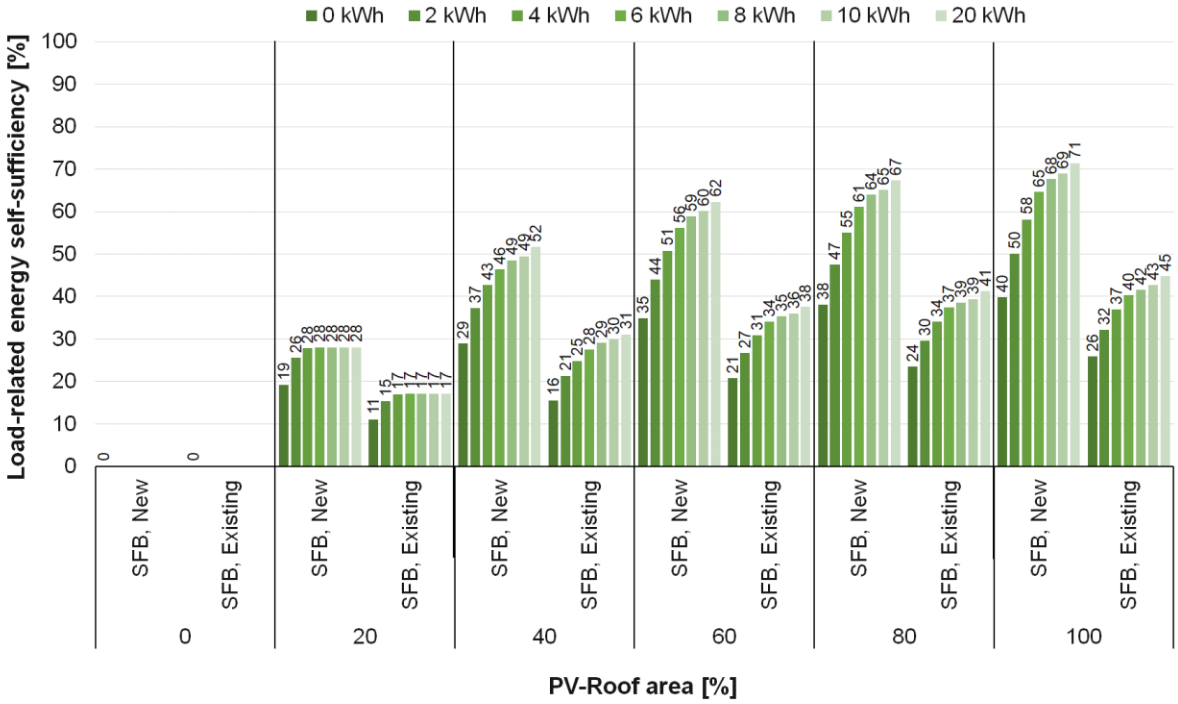


Fig. 7: Influence of PV roof area and battery capacity on the load-related energy self-sufficiency for the single-family building (SFB)

For the multi-family building the maximum load-related energy self-sufficiency is 20 % for the existing building and 36 % for the new construction. For both building types, an increase in load-oriented energy self-sufficiency up to a PV/Solar-thermal roof area of 60 %/40 % and a battery capacity of 6 kWh can be seen. A further increase in the PV area with a simultaneous reduction of solar thermal roof area leads to lower load-oriented energy self-sufficiency factors. This is due to the fact that the additional PV yield can only be stored to a limited extent in the battery and thus the grid feed-in increases.

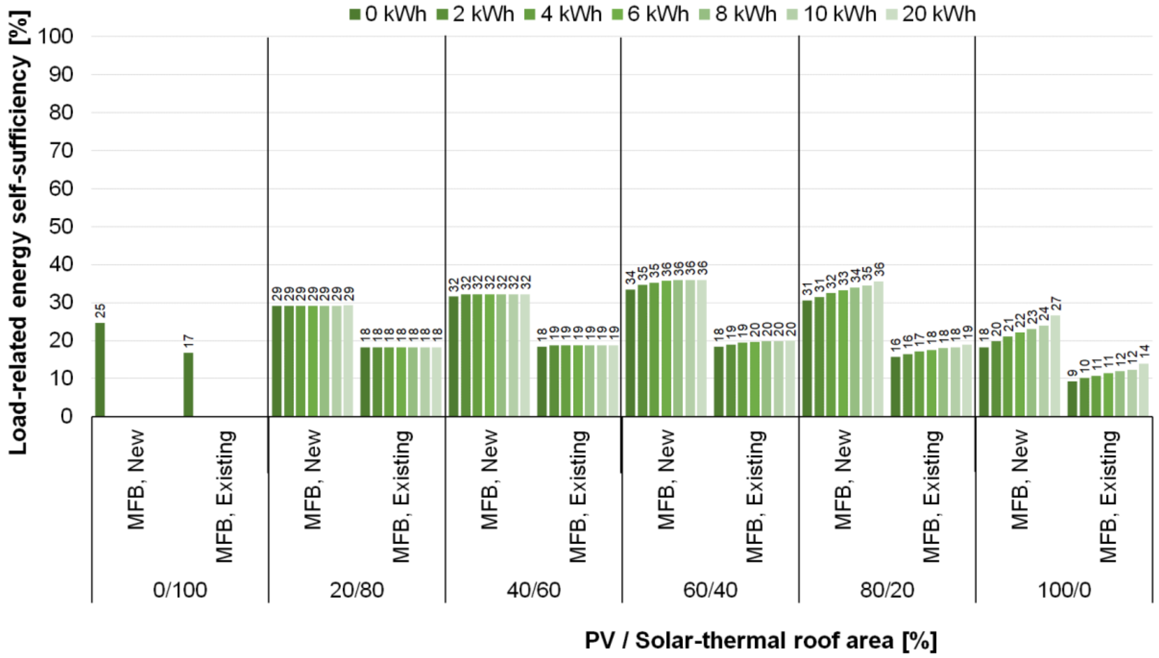


Fig. 8: Influence of PV/solar thermal roof area and battery capacity on the load-related energy self-sufficiency for the multi-family building (MFB)

Results for Cost-Effectiveness

The economic evaluation consists of a cost comparison of the selected energy systems with a conventional energy supply system as a base case. The base case consists of a gas condensing boiler and an electricity connection to the public grid. The reference costs for the single-family building are 2,679 €/a for the new construction and 3,890 €/a for the existing building. For the multifamily building the costs amount to 7,760 €/a for the new construction and 9,250 €/a for the existing building.

The combination of a heat pump with a PV system is not economical under current conditions compared to a conventional energy supply for the single-family building, since the annuities without battery storage are 32 to 59 % above those of the base case. With a battery storage, the annuities are even up to 163 % higher than the base case (see Fig. 8). The annual payments for the maximum degree of load-related energy self-sufficiency are 140 % (existing building) respectively 163 % (new construction) above the base case. This shows that the advantage of the higher PV self-consumption due to the additional investment in a battery storage does not outweigh the cost disadvantage.

The selected energy system of the multi-family building is not economical compared to the base case for the maximum of load-related energy self-sufficiency (60/40 % PV/Solar-thermal roof area). For this PV/Solar-thermal combination the annuities are 23 % (new construction) and 21 % (existing building) above the base case (see Fig. 9). With the maximum of battery storage capacity, the annuities are up to 31 % higher compared to the base case. However, there are also economic advantages for certain system combinations. If the available roof area is fully utilized with PV modules in combination with 4 kWh battery storage, the annuities are between 7,113 €/a and 7,657 €/a for the new building and 8,710 €/a and 9,250 €/a for the existing building. Thus, the annuities are below the base case. The reason for the lower annuities compared to the base case is the high PV electricity self-consumption of the multi-family building. Due to the electricity price of 0.26 €/kWh, the savings in electricity costs have a greater impact on the annuity than the possible increase in income from the feed-in tariff of 0.12 €/kWh.

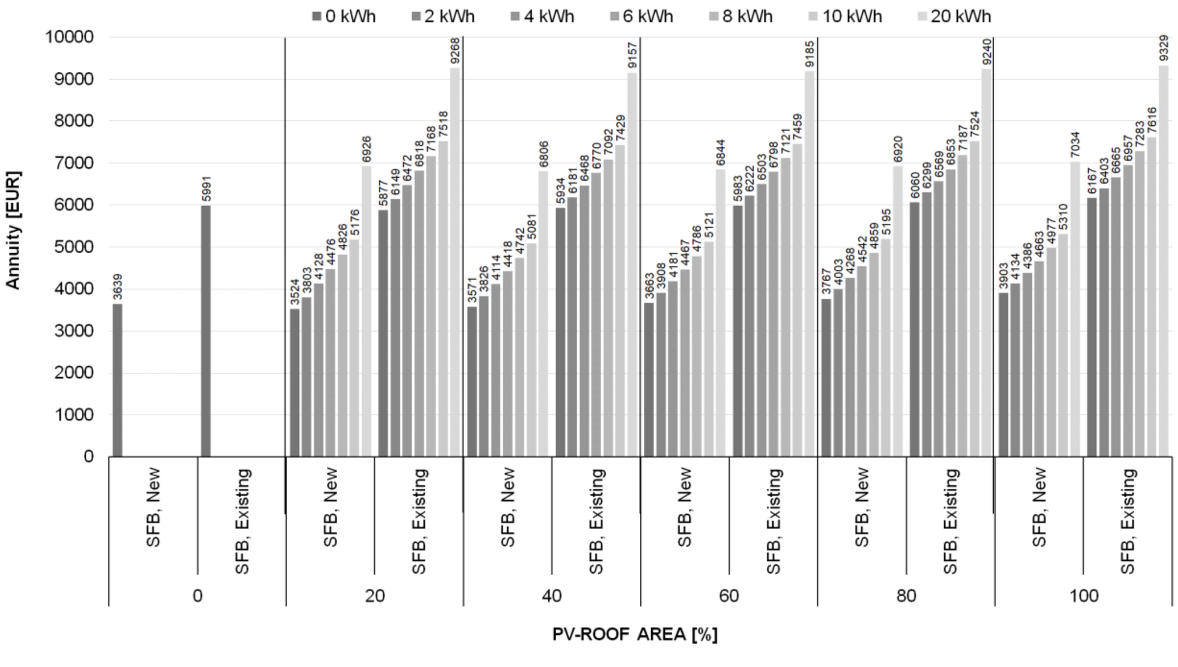


Fig. 8: Influence of PV/solar thermal roof area and battery capacity on annuity for the single-family building (SFB)

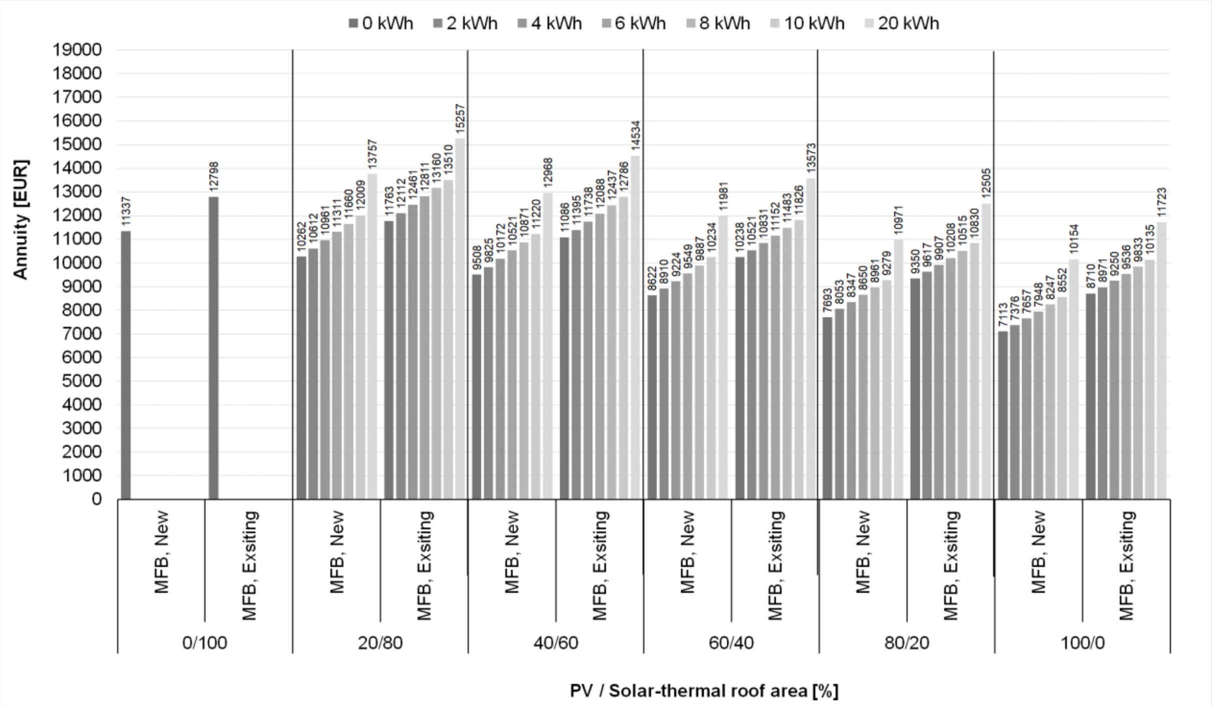


Fig. 9: Influence of PV/Solar-thermal roof area and battery capacity on annuity for the multi-family building (MFB)

Conclusion

Based on the reduction of greenhouse gas emissions and the associated increased use of renewable energies, this paper analyses the technical and economical potential of load-related energy self-sufficiency for the energy supply of single-family and multi-family buildings. To evaluate the effect of different heating requirements, the analysis distinguishes between a new construction and an existing building. The modeling of the energy systems (building model, heat supply systems, PV and battery storage technologies) was carried out with the simulation environment "Polysun-Designer", which enables a high-resolution and dynamic annual simulation of energy demand and energy supply.

The analysis of the load-related electricity self-sufficiency has shown that a PV system can cover up to 37 % of the household electricity demand of a single-family building. By using a battery storage, the load-related electricity self-sufficiency can be increased up to 82 %. For the multi-family building, the maximum degree of load-related electricity self-sufficiency with a PV system is 30 % and can be increased to 43 % with a 20-kWh battery storage. A full load-related electricity self-sufficiency is not possible and a connection to the public utility is necessary for all the analyzed buildings. The results of the load-related heat self-sufficiency indicate that, depending on the building energy standard, the maximum values are 30 % (existing building) and 55 % (new construction) for the single-family building and 24 % (existing building) and 57 % (new construction).

A full load-related energy self-sufficiency is not possible for any of the analyzed building types and energy standards. The highest degree of load-related energy self-sufficiency can be achieved with a PV system in combination with a heat pump and a battery storage. Depending on the building energy standard, a maximum of 45 % (existing building) to 71 % (new building) of the building energy demand can be covered by renewable energies for the single-family building. The highest degree of load-related energy self-sufficiency for the multi-family building can be achieved with a utilization of the roof area with 60 % PV-modules and 40 % solar thermal modules. The values range between 20 % (existing building) and 36 % (new construction) for the multi-family building.

The economic evaluation for the single-family building has shown that none of the investigated technologies can compete with a conventional energy supply (connection to the public grid + gas condensing boiler). For the multi-family building, some of the investigated energy system combinations show a cost benefit compared to a conventional energy supply. However, the maximum degrees of load-related energy self-sufficiency are not beneficial from an economic point of view.

The paper has shown how partially load-related energy self-sufficiency for single-family and multi-family buildings can be achieved both for new and existing building energy standards. Therefore, the utilization of PV-modules and solar thermal systems, as well as thermal and battery storage technologies are necessary. The attainable degree of energy self-sufficiency depends to a large extent on the building heat demand. A partially load-related energy self-sufficiency can be realized for residential buildings but at very high costs for most of the cases.

This conclusion can only apply to the investigated buildings and the assumed economic conditions. Future price developments in the energy sector (e.g. feed-in rate, energy prices, battery storage and equipment costs, costs for CO_2 emissions) may lead to a reassessment of the results.

The influence on the energy distribution network is negligible for this analysis. However, the increased use of renewable energies can lead to burdens on the energy system that need to be investigated in more detail. In addition, mobility and grey energy can be included in the evaluation of energy self-sufficiency in further studies.

References

Bardt H, Chrischilles E, Growitsch C, Hagspiel S, Schaupp L (2014) Eigenerzeugung und Selbstverbrauch von Strom – Stand, Potentiale und Trends. Z Energiewirtsch 38:83–99

Bundesregierung (1994) Verordnung über einen energiesparenden Wärmeschutz bei Gebäuden (Wärmeschutzverordnung - WärmeschutzV) vom 16. August 1994

Deutscher Wetterdienst (2011) Aktualisierte und erweiterte Testreferenzjahre von Deutschland für mittlere, extreme und zukünftige Witterungsverhältnisse. http://www.bbsr.bund.de/EnEVPortal/

DE/Regelungen/Testreferenzjahre/Testreferenzjahre/03_ergebnisse. html?nn=437706. Zugegriffen: 21. September 2015

Deutschle J, Hauser W, Sonnberger M, Tomaschek J, Brodecki L, Fahl U (2015) Energie-Autarkie und Energie-Autonomie in Theorie und Praxis. Z Energiewirtsch 39:151–162

McKenna R, Herbes C, FichtnerW(2015a) Energieautarkie: Vorschlag einer Arbeitsdefinition als Grundlage für die Bewertung konkreter Projekte. Z Energiewirtsch 39:235–252

McKenna R, Herbes C, FichtnerW(2015b) Energieautarkie: Definitionen, Für- bzw. Gegenargumente, und entstehende Forschungsbedarfe. KiT working paper series in production and energy, Karlsruhe

McKenna R, Merkel E, Fichtner W (2016) Energy autonomy in residential building: A techno-economic model-based analysis of the scale effects. Appl Energy. doi:10.1016/j.apenergy.2016.03.062

Tomaschek J, Fahl U, Brodecki L (2015) Analyse des Energie-Autarkiegrades unterschiedlich großer Bilanzräume mittels integrierter Energiesystemmodellierung. http://fachdokumente.lubw.baden-wuerttemberg.de/servlet/is/122354/bwe13033_bwe13034_final.pdf?command=downloadContent&filename=bwe13033_bwe13034_final.pdf&FIS=203 Zugegriffen: 5. November 2015

VDI 4655 (2008) Referenzlastprofile von Ein- und Mehrfamilienhäusern für den Einsatz von KWK-Anlagen, Verein Deutscher Ingenieure (VDI), Beuth Verlag, Düsseldorf

Vela Solaris (2014) Polysun Simulation Software. Benutzerdokumentation

Appendix:

Table 1: Photovoltaic System Performance Figures

Manufacturer	BenQ Solar
Typ	GreenTriplex PM060M02
Rated Output	290 W
Module Efficiency	18 %
Dimensions (L x W x H)	1,639 m x 0,983 m x 0,04 m
Gross Area	1,61 m^2
Temperature coefficient	-0,42 %/K

	Unit	Value
Reduction of PV yield due to contamination	%	2
Degradation per year	%	0,2
Wind Share	%	50
Rear Ventilation	-	medium
Cable Losses	%	2

Table 2: Battery Performance Figures

	Unit	Technical Details
Nominal Capacity	kWh	2 kWh (expandable in 2 kWh steps)
Battery Technology	-	lithium iron phosphate
Battery Coupling	-	AC-Coupling
Max. Battery Efficiency	%	98
Max. Efficiency Battery Inverter	%	96
Battery Life	a	20
Charging Cycles	-	10000
Max. Discharge Depth	%	100
Warranty on the battery cells	a	10

Table 3: Solar Thermal System Performance Figures

	Unit	Technical Details
Gross Surface	m^2	2,36
Absorber Area	m^2	1,6
η_0	-	0,756
α_1	-	1,362
α_2	-	0,002
c_{eff}	kJ/K	19,6

Table 4: Heat Pump Performance Figures

	Heat Pump New Construction	Heat Pump Existing Building
Manufacturer	Viessmann	Viessmann
Typ	Vitocal 300-G BWC.06	Vitocal 300-G BWC.10
Heating Capacity	5,69	10,36
COP	4,6	5,01
Refrigerant	R410A	R410A
Max. Supply Water Temperature	65 °C	65 °C