Energy concepts with high solar fraction for multi-family houses

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Abstract

In most cases, the heat and power supply of buildings is still planned and realized separately, including the use of renewable energies like photovoltaic and solar thermal. By means of a simulation study, this approach is to be changed and holistic solar-based supply concepts for residential buildings are targeted and developed. As single family houses, multi-family houses offer potentials for the implementation of solar-based energy supply concepts, however they have to be evaluated in terms of the space requirements and the number of stories. Based on various solar energy systems and the boundary conditions from building and construction, energy supply concepts and design specifications for multi-family houses are derived. The results of a simulation study show, that for the building and the measures under investigation a total solar fraction of up to 70 % can be achieved. The most suitable area-ratio of solar thermal to photovoltaic is 20/80 to 50/50.

Keywords: multi-family houses, high solar fraction, simulation, photovoltaic, solar thermal, energy concepts

1. Introduction

More than half of the final-energy demand in Germany is related to heating, cooling and air conditioning of buildings. On the other hand, there is high potential of solar energy that can be gained directly at the buildings, usable to cover major parts of their energy demand. Commonly solar energy concepts for buildings are set-up separately for heat and electricity by different designers, planners and installers. Therefore, the market has developed to concepts focusing either the thermal aspects or the electrical part of the buildings. On the one hand, large solar thermal collector areas and large hot water stores with high thermal capacities are implemented to cover high thermal solar fractions of the heat demand. On the other side, for high electricity gains large PV-systems are integrated aiming to generate as much electricity as possible and/or to realize a surplus in the annual balance of the building demand and production of electricity. Electricity-based concepts increasingly often use PV produced electricity to provide heat. In Germany, depending on the remuneration for feeding PV produced electricity into the public grid and energy costs, a few years ago, PV systems on buildings almost exclusively feed electricity into the grid. By changing in the boundary conditions, gradually PV electricity has been used to cover household and operating electricity requirements of the buildings. Nowadays the use of PV electricity to provide heat - usually in combination with heat pumps - is a growing trend.

Generally, in most cases at best there is a slight interaction of both concepts – although there is high need to achieve cost-effective high solar fractions with acceptance of the investor in both, heat and electricity, to reduce costs for non-renewable energy supply. Solar thermal energy and photovoltaics are by no means mutually contradictory technologies. In order to counteract this widespread opinion and to provide necessary background and recommendations for holistic system solutions aiming for ecologically and economically reasonable solar-based heat and power supplies for residential buildings, as a part of the presented simulation study, corresponding concepts have been developed.

2. Solar Energy Buildings and Key Performance Indicators

A significant reduction of the fossil energy use of buildings can be achieved by utilizing solar thermal (ST) and photovoltaic (PV) energy for their operation. IEA SHC Task 66 focus on the development of economic energy supply concepts with high solar fractions for single-family houses, multi-story residential buildings and

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building blocks or distinguished parts of cities (communities) for both, new buildings and existing buildings after comprehensive refurbishment. The central component to achieve real Solar Energy Buildings (SEB) is the active and passive use of solar energy.

The feasible solar thermal and solar electrical fractions depend significantly on the clime in that the building is located. For central European climate conditions and for households employing e-mobility, according to Task 66 the following solar fractions should be achieved:

- at least 85 % of the heat demand,
- 100 % of the cooling demand and
- at least 60 % of the electricity requirements.

Ahead of achieving these solar fractions by intensive use of solar thermal and solar electric (photovoltaic) energy, the focus must be on reducing the energy demand of the buildings.

To describe, evaluate and/or to compare buildings, so-called Key Performance Indicators (KPIs) are used. They can be applied to

- evaluate and compare different buildings/blocks/communities,
- evaluate and compare different concepts in one building/block/community,
- optimize components of the buildings in terms of energy use/flows, economics, ecology etc.

Note: The aim is to optimize the overall performance of a building. Therefore, all numbers and fractions are evaluated from the view of production and not from consumption. Doing so, also heat losses of stores and other hidden consumer are considered. By this, in some cases, lower rates as expected might result.

With respect to the different solar fraction used by Task 66, the following Key Performance Indicators (KPIs) are most relevant (nomenclature see chapter 8):

Total solar fraction $f_{sol,tot}$
Fraction of self-generated and self-used PV electricity and useful solar thermal heat referred to the total energy used for household and technical purposes in the form of electricity and heat.
In other words: Energy supplied by the solar part (PV and ST) of a system divided by the total load (electrical and thermal).

$$f_{sol,tot} = \frac{E_{PV,tot} - E_{PV,grid} + Q_{ST,tot} - Q_{ST,grid}}{E_{PV,tot} - E_{PV,grid} + E_{grid} + Q_{ST,tot} - Q_{ST,grid} + Q_{grid} + Q_h - Q_{h,el}} \ [\%] \qquad \text{(eq. 1)}$$

Thermal solar fraction $f_{sol,th}$
Fraction of solar-generated useful heat referred to the total heat consumption. Solar thermal as well as solar electric heat generation (heat pumps based on photovoltaic power) are considered.
In other words: Thermal energy supplied by the solar thermal part of the system and heat supplied by heat pumps using PV produced electricity divided by the total thermal load.

$$f_{sol,th} = \frac{Q_{ST,tot} - Q_{ST,grid} + Q_{sol,PVHG}}{Q_{ST,tot} - Q_{ST,grid} + Q_{grid} + Q_h} \ [\%] \qquad \text{(eq. 2)}$$

Electrical solar fraction $f_{sol,el}$
Fraction of electricity generated by a photovoltaic system referred to the total electricity consumption.
In other words: Energy supplied by the solar electrical part of a system divided by the total electrical load.

Note that also electricity from PV that is used for heat generation, e. g. by heat pumps or resistance heaters, is included.

$$f_{sol,el} = \frac{E_{PV,tot} - E_{PV,grid}}{E_{PV,tot} - E_{PV,grid} + E_{grid}} \ [\%] \qquad \text{(eq. 3)}$$

3. Numerical system simulation - boundary conditions and variants

In front of the simulation study, the building and construction, building physics and boundary conditions for the technical system of the multi-family house and the variants chosen to be examined, are defined. In the case on hand a building, which has been monitored by the corresponding author, is used as reference. For this building with regard to the KPIs variants and changes have been developed and implemented in numerical simulations. The analysis and evaluation of the results focus on the solar fractions and the CO_2 emissions. Representing the major focus and objectives of Task 66, in this paper only solar fractions and energy values are discussed.

In addition to technical aspects, in order to determine a holistic picture of solar-based buildings, also the building requirements will be considered. For heat generation only heat pumps are used. Compared to heat pumps, gas boilers or other heat sources that base on combustion hardly require any electric energy and therefore does not draw notable renewable electricity from a PV system and/or an electrical storage. Thus, for the combustion of fuels, for operation virtually no (renewable) electricity is required - and by this the achievable solar fraction will be low.

3.1. Boundary conditions

In the simulations, only the technologies for producing heat and electricity are varied. The way distributing and transferring the energy for space heating and domestic hot water preparation within the building remain unchanged.

As the reference building has not and German regulations do not provide for cooling in the planning and design of residential building, cooling is not implemented. Furthermore, e-mobility is not taken into account. Self-evident this additional load would significantly reduce the solar fraction related to the building.

Building data (Bockelmann, 2019):

- Multi-family house consisting of two buildings with three floors each, in total 12 apartments. The entire net floor area of both buildings amount to 1,140 m².
- The thermal standard of the entire block is 46.3 kWh/(m²a) (see Figure 2). The buildings have flat roofs and are orientated 24.3° south-east (orientation of the long building side).
- Technology: From the architectural point of view, the PV system and the solar thermal collectors should have the same tilt angle; considering the performance of the solar thermal collector to serve for space heating, the angle is set at 65°. The orientation equals to that of the buildings (24.3° south-east).
- The building is located in Potsdam (Germany), see weather data in Figure 3 (Meteonorm, 2018).

Note: In the following the singular term building always mean and refer to the building data given above.

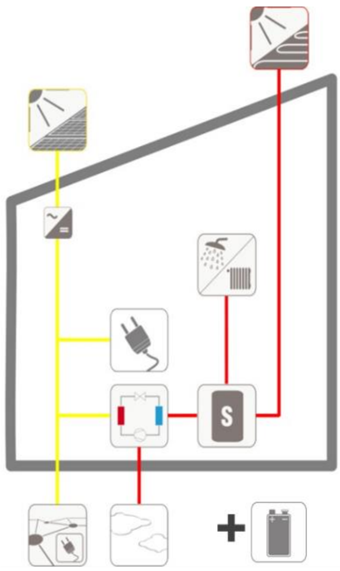

Fig. 1: Energy concept for multi-family house

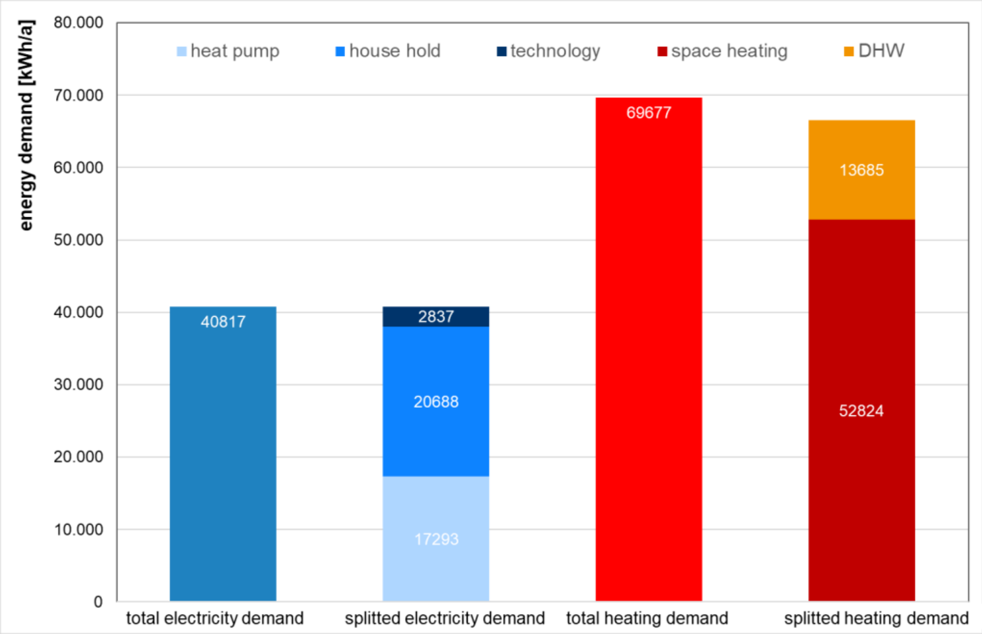

Fig. 2: Electricity demand and demand of thermal energy of the building

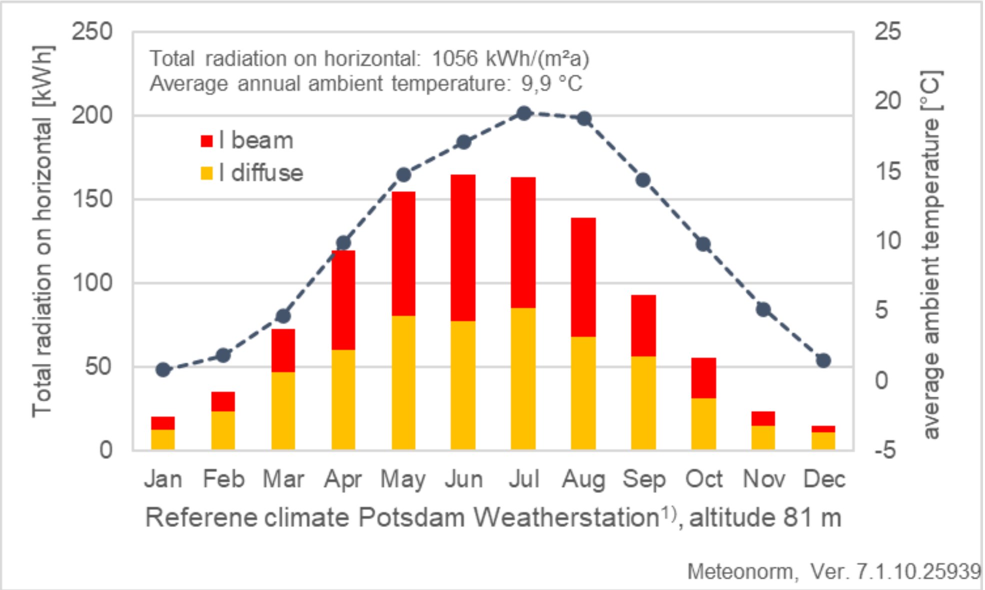

Fig. 3: Weather data Potsdam (Germany), average ambient temperature and solar radiation on horizontal

3.2. Simulation variants

With regard to the regenerative cover factor of the entire energy demand (solar thermal and solar electric), the simulation study determines the variant for which, by a complementary distribution of the shares of solar thermal and photovoltaics on the available roof area, the renewable energy used in the building is maximized. In addition to the varying proportions of solar thermal collectors and PV area, the influences of the different ratios combined with unlike thermal and/or electrical storage have been investigated. Since the influence of selected building physics is also to be evaluated, the thermal insulation of the building, in addition to the technical variants, is altered. (see Table 1)

The key data for the variants examined are summarized in the following table.

Tab. 1: Simulation variants

Variation	Starting point	Changes/ adaptions
thermal building standard	as build, no changes apart from insulation and heat recovery of air change for the passive house	“average“– 46.3 kWh/(m²a) = as build (GEG) "good“ – 30 kWh/(m²a) "very good” = passive house – 15 kWh/(m²a)
orientation of the building	orientation of PV and ST similar to building	rotation: 0°, 30°, 60° and 90°
varying storage size	as build	50, 100 and 150 l/m² referred to aperture area of the thermal collector 0, 0.5, 1.0 and 2.0 kWh/kW$_p$ (usable capacity of electrical energy storage)
expansion of the area available / solar active area	initial area 108 m² (as build)	add 50 % (new area 162 m²) correspond to approx. 80 % of the roof area
varying the area shares of PV and ST	PV and ST (entire area as build)	0 %/100 % to 100 %/0 % (10 % steps) as shown by the first simulations with the system as build, a high total solar fraction is reached in a range between 20/80 and 80/20 -> used for further simulations
orientation of PV and ST	building orientation south PV and ST tilt angle 65°	orientation PV east / west and ST south
varying the tilt angel of PV	building orientation south	ST – unchanged, tilt angle 65°, orientation south PV –tilt angle 30°, orientation south PV – tilt angle 10°, orientation east/west (tilt angle according to pre-study)
varying efficiency (better components)	initial situation (as build) PV - 16,1 % ST – conventional plate collector	PV – 24 % (very good) (source: technology radar Subtask D, (Task 66, 2024)) ST – high performance CPC-collector

4. Results of the parameter study

The parameter study shows that not one single concept is best. Rather more, depending on the respective evaluation parameter, different variants have advantages and disadvantages.

However, as a goal of the Task 66 the evaluation of the simulations focuses on solar fractions and also on the energy demand, following the question: “How far can fossil energy consumption be reduced?”. It should be noted that the results and conclusions given subsequently refer to the building investigated in this study. However, most results have general character and will apply to other multi-family buildings too.

4.1. Influence of electrical and thermal storage sizes (pre-study)

When considering the capacity of an electrical energy storage, it was found, that the in practice widely used capacity of 0.5 to 1.0 kWh/kW$_p$ has a noticeable influence on the overall system performance and increases the solar-electric fraction. The capacity of 2.0 kWh/kW$_p$ has a significantly higher influence but also the financial outlay increases significantly as well.
As the design value for the simulations on hand a value of 1.0 kWh/kW$_p$ was implemented.

With regard to the specific volume of the hot water store, for the multi-family house under investigation a sensitivity analysis including a flat plate collector results in a reasonable value of 100 l/m², referred to the aperture area of the thermal collector. In that case a specific storage volume of more than 100 l/m² does not lead to a significant increase in the performance of the solar thermal system. On the other hand, a specific volume of 50 l/m² decreases the solar fraction of the system by around 5 percentage points, compared to that with 100 l/m².

4.2. Influence of thermal insulation and orientation of the building

Of course, the better the thermal building standard, the less energy for space heating and by this less electricity for the heat pump is needed. Furthermore, it is clear that the further the house is turned from south orientation to west (or east), due to decreasing passive solar gains, the more energy for space heating is required.

With better thermal insulation of the building (lower energy demand for space heating), the orientation to south results in higher solar fractions. Moreover, the ratio between produced energy and energy demand increases.

By enhancing the thermal insulation of the building and turning the building to the south, a total solar fraction of up to 45 % can be achieved (Figure 4). In this case the maximum thermal solar fraction amount to 45 % (interpolated) and the electrical solar fraction (PV) to 40 % (interpolated) (Figure 5).

<u>Outcome of the variants for reaching SEB:</u> A low energy building (15 kWh/(m²a)) with orientation south is advantageous.

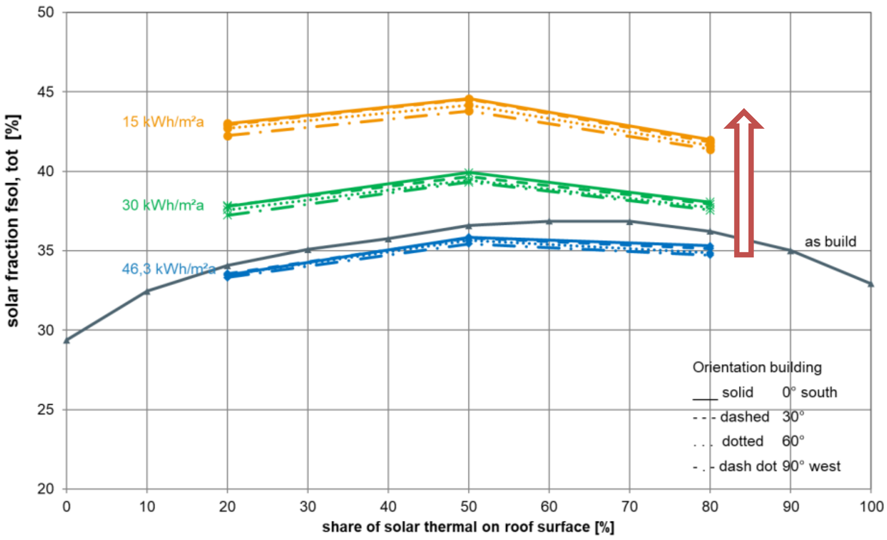

Fig. 4: Total solar fraction – thermal insulation and orientation of building

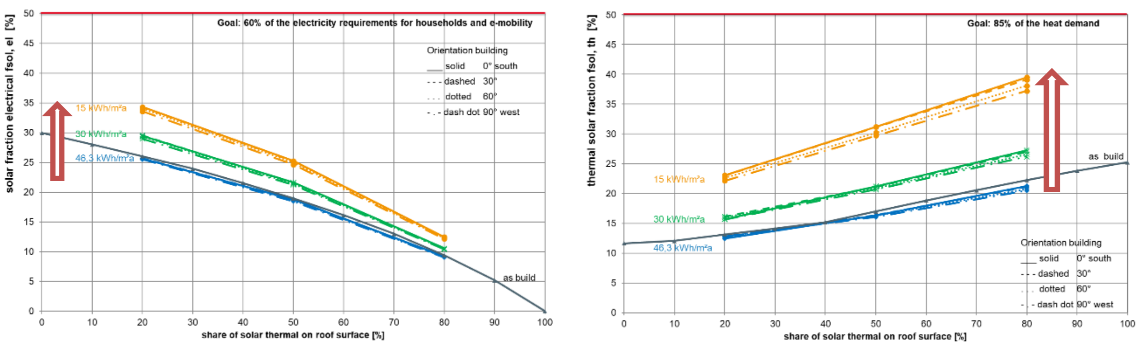

Fig. 5: Electrical solar fraction (left) and thermal solar fraction (right) – thermal insulation and orientation of building

4.3. Influence of orientation und tilt angle on the system performance (PV and ST)

An orientation to south provides the highest solar irradiation and therefore, at first glance, the highest yield. If the tilt angle of a south oriented PV module and a thermal solar collector is adapted to archive the highest yield, of course the highest solar fraction will be reached.

By orienting the systems to south and modify the tilt angle (starting point see Table 1), a total solar fraction of up to 45 % can be achieved (Figure 6). The maximum thermal solar fraction amount to 45 % (interpolated) and the electrical solar fraction to 42 % (interpolated) (Figure 7).

<u>Outcome of the variants for reaching SEB:</u> PV modules and solar thermal collectors should be oriented to south. PV should have a tilt angle of 30°, while the tilt angle of solar thermal collectors should be 65°.

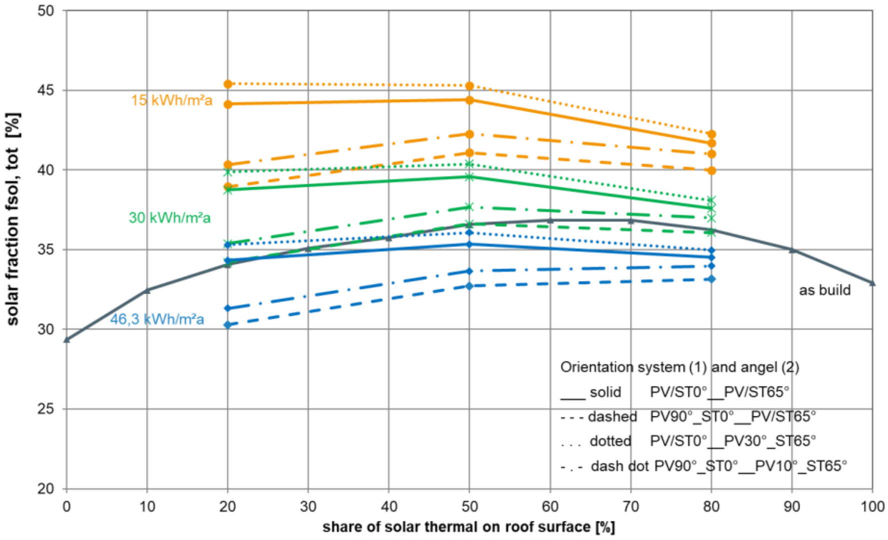

Fig. 6: Total solar fraction – orientation and tilt angle of solar appliances

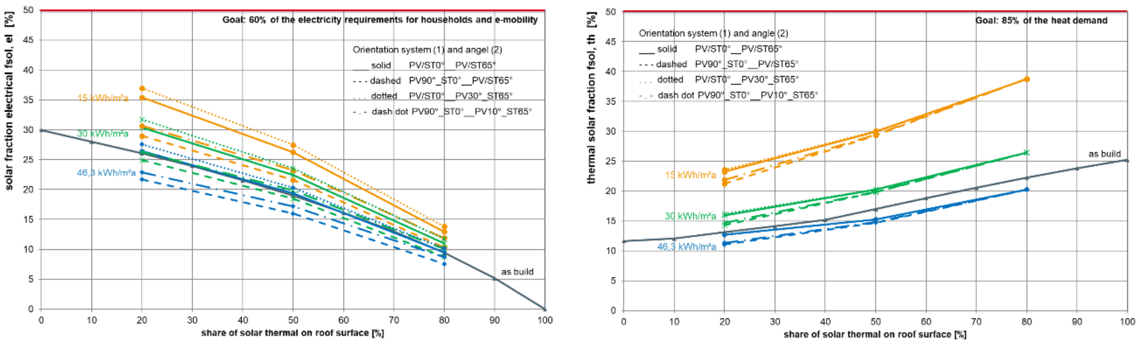

Fig. 7: Electrical solar fraction (left) and thermal solar fraction (right)– orientation and tilt angle of solar appliances

4.4. Influence of efficiency and area of solar applications (PV and ST)

Self-evident the higher the efficiency and the area of solar applications, the more energy can be generated and the higher the solar fraction will be.

By altering the efficiency and the area of solar applications in a range that is feasible for the given building (starting point see Table 1), a total solar fraction of up to 70 % can be achieved (Figure 8). The maximum thermal solar fraction amount to 70 % and the electrical solar fraction to 72 % (Figure 9).

<u>Outcome of the variants for reaching SEB:</u> The efficiency and area of PV and ST should be as high as possible. To approach and reach the goals stated in Task 66 for the given building (see Figure 8 and 9), the ratio of the net floor area to the area of solar applications (PV and ST) for the 15 kWh/(m²a) building must not be larger than 7. The 30 kWh/(m²a) building is approaching the Task 66 target, while the 46.3 kWh/(m²a) building needs much more solar area.

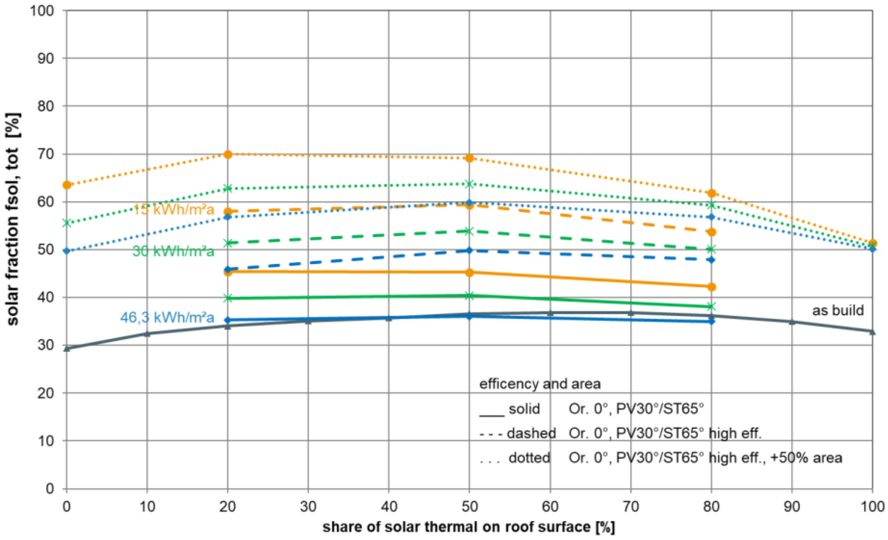

Fig. 8: Total solar fraction – efficiency and area of solar appliances

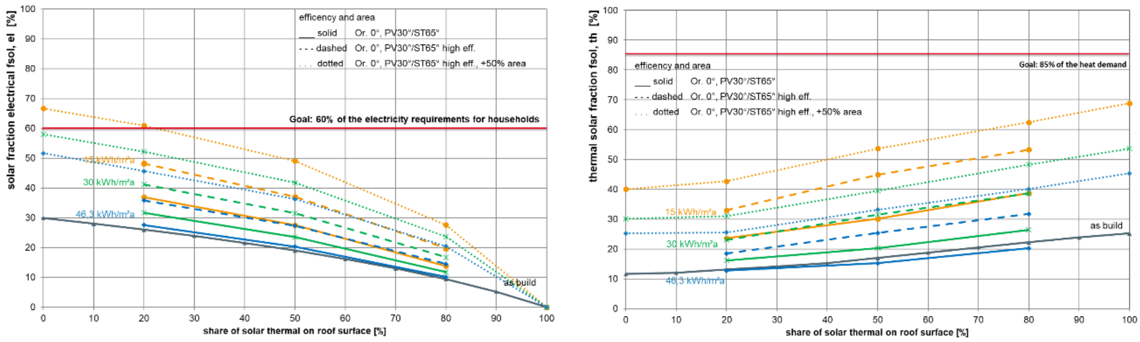

Fig. 9: Electrical solar fraction (left) and thermal solar fraction (right) – efficiency and area of solar appliances

4.5. Energy production, feed-in and electricity purchase from the local grid

The adaptations of the supply concept and system components mostly result in different energy productions in terms of electricity and heat. By improving the system, the yields generally increase (Figure 10). If the concepts are adapted according to the mentioned outcomes, the electricity production increases by 144 % that of heat by 48 %.

Since the reduction of the use of fossil fuels was a goal underlying the strive to reach high solar fractions, the results show that some adjustments in parallel lead to reduced electricity purchase from the grid. Electricity purchase from grid can be reduced by up to 30 %, depending on the measures implemented. At the same time, the feed-in of surplus electricity into the public grid increases by 267 %. This can support increasing the share of renewable energy in the grid and might in addition have network-friendly effects. (Figure 11)

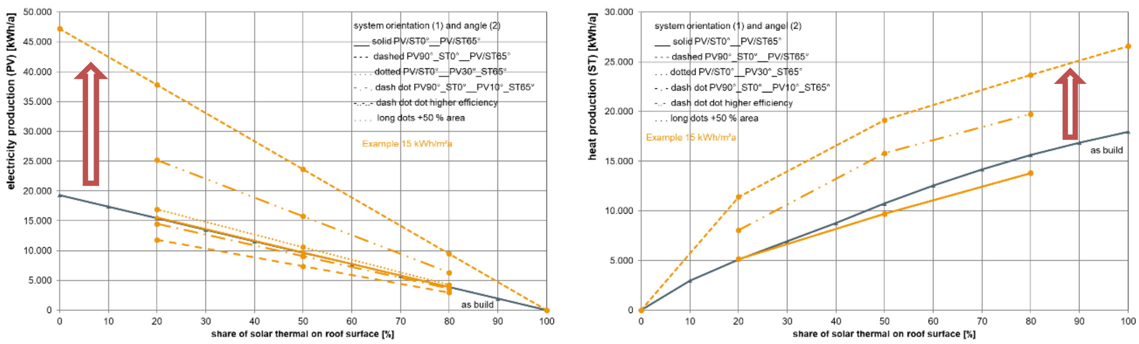

Fig. 10: Electricity production (PV) (left) and heat production (ST) (right)

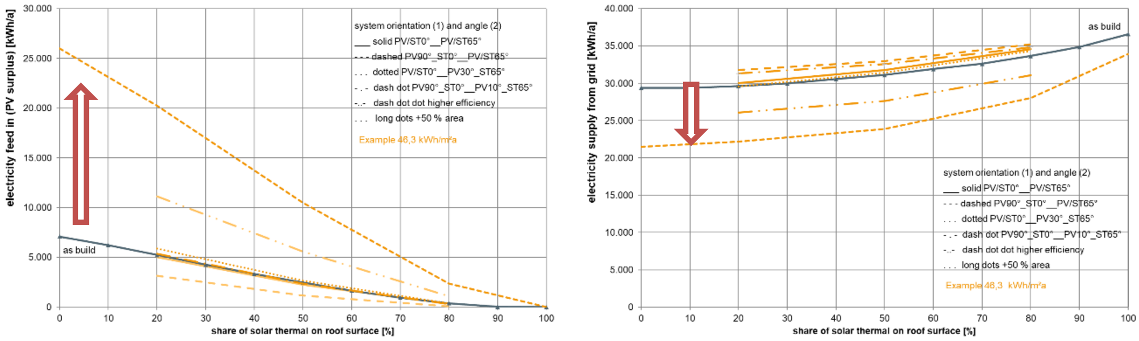

Fig. 11: Electricity feed in the grid (left) and grid supply (right)

5. Conclusions

Using an existing example of a multi-family house in Germany, by means of system simulation solar energy supply concepts have been investigated systematically. With focus on technical and energy efficiency, various building designs and technical systems have been analyzed and compared with each other. The aim was to show which concepts and approaches for integrating solar thermal and photovoltaic systems can be used to achieve high solar fractions and thus most climate-neutral energy concepts.

The study was based on the definitions and objectives of IEA SHC Task 66. The aims defined in Task 66 announce thermal solar fraction larger than 85 % and electric solar fraction above 65 %.

The evaluation of the results of the simulations show that there is not one best concept. Depending on the respective parameter different system designs and variants have advantages and disadvantages.

The results documented in this paper are valid for the specified building including the defined insulation standards and a thermal store of 100 l per square meter aperture area of a thermal collector. With respect to the photovoltaic system an electrical storage with a useful capacity of 1 kWh/kW_p has been implemented.

The following findings have been derived:

- For the building under investigation and the mentioned measures, the goal for renewable electricity production, given by Task 66, can be achieved - for thermal energy it cannot.
- Measures to achieve a high solar fraction in a multi-family house are
  - Building insulation standard and orientation: Reduce the energy demand as much as possible -> very good thermal building standard -> 15 kWh/(m²a) is needed.
  - Orientation and tilt angle of solar applications: All systems should be orientated south. PV should have a tilt angle of 30°, solar thermal collectors should have a tilt angle of 65°.
  - Efficiency of the systems: Very good component and system efficiency are needed.
  - Area of system: Ratio between net floor area and area of solar applications (PV and ST) for the 15 kWh/(m²a) building should not be greater than 7. The 30 kWh/(m²a) building is approaching the Task 66 target, while the 46.3 kWh/(m²a) building needs much more solar area.
- The feed-in of surplus PV electricity into the public grid decreases with an increase in the size of the solar thermal system because less PV electricity is produced.
- Enhancing the system might lead to a reduction of electricity supply from the grid. The electricity supply for the building can be reduced by up to 30 %.
- At the same time the feed-in of surplus electricity into the public grid increases by more than 250 %. This can support increasing the share of renewable energy in the grid and might in addition have network-friendly effects.

With regard to the solar fractions (with all measures included) the following results can be presented:

- Total solar fraction: → up to 70 %
  Variants with high total solar fraction range from a ratio between ST and PV of around 20/80 to 50/50. The total solar fraction increases with the size of the solar thermal collector, but in order to be able to cover household electricity, a minimum proportion of photovoltaics should be available.
- Thermal solar fraction: → up to 70 %
  It is evident that electricity-oriented heat generation benefits from PV systems. As the PV system becomes smaller, this fact of an electricity-oriented concepts is reduced. On the other hand, due to its greater area efficiency, a solar thermal application may overcompensate this effect. Of course, the maximum thermal solar fraction is generated by a ratio of ST to PV of 100/0.
- Electrical solar fraction: → up to 65 %
  The smaller the PV area, the lower the share of solar electricity coverage. Self-evident the maximum electrical solar fraction is generated by a ratio of ST to PV of 0/100. To reach the target for the 15 kWh/(m²a) building the ratio between net floor area and PV area should around 7. For building with higher energy demand ratio lower than 7 are mandatory.

6. Acknowledgments

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As well as we would like to thank IEA Solar Heating and Cooling Technology Collaboration Program (SHC TCP) for developing and disseminating the project and the results of Task 66.

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8. Nomenclature

Symbol	Definition	Unit
E_{grid}	energy (electric), electricity from grid	kWh
$E_{PV,grid}$	energy (electric), generated by photovoltaics, feed into grid	kWh
$E_{PV,tot}$	energy (electric), generated by photovoltaics on site, total (AC)	kWh
GEG	Gebäudeenergiegesetz Act on Energy Conservation and the Use of Renewable Energies for Heating and Cooling in Buildings (Germany)	
KPI	Key Performance Indicator	
PV	Photovoltaic	
Q_{grid}	energy (thermal), delivered from a thermal grid, e.g. a district heating system	kWh
$Q_{h/c}$	energy (thermal), generated from a heating/cooling system; space heating as well as domestic hot water	kWh

Symbol	Definition	Unit
$Q_{h,el}$	energy (thermal), generated through electrical energy e.g. heat from a heat pump or a heating element	kWh
$Q_{sol,PVHG}$	energy (thermal) based on solar-electric heat generation powered by photovoltaics in combination with e.g. electrical heating elements or heat pumps	kWh
$Q_{ST,grid}$	energy (thermal), generated by a solar thermal collector, feed into a thermal grid / District Heating System	kWh
$Q_{ST,tot}$	energy (thermal), generated by solar thermal collector/systems in total	kWh
SEB	Solar Energy Building	
ST	Solar thermal	