Solar energy buildings with high degree of independence of energy supply from grids

Elsabet Nielsen and Simon Furbo

Department of Civil and Mechanical Engineering, Technical University of Denmark, Kgs. Lyngby, Denmark

Abstract

A 60 m² solar heating/heat pump/42 m² PV system with a large hot water storage and electric battery can cover about 90% of the total yearly energy demand of 9500 kWh for a typical Danish one family house. If the house is connected to the electrical grid, additional 5500 kWh electricity produced by the system can be sold to the electrical grid during the summer months. The energy demand of the house not covered appear in January and February, which in Denmark are windy months with periods with extremely low electricity costs. The energy storages of the system can be charged during these periods and the total energy demand of the house can in this way be covered 100% by renewables.

Further, the hot water storage and the battery can be operated in a smart way in a good interplay with the electrical grid. The energy storages can be charged in periods with low cost electricity and electricity can be sold to the grid in periods with expensive electricity.

Finally, the hot water storage volume for the solar heating system can be strongly reduced due to the charge periods during the winter with limited solar radiation.

It is recommended to develop optimally designed and sized solar heating/heat pump/PV systems with smart control strategies for different one family houses, so that CO_2 is not emitted by the energy systems of the houses.

Keywords: Solar energy buildings, solar heating/heat pump systems, PV systems, large independent ratios

1. Introduction

Due to the rapid man-made climate change and biodiversity crisis there is a need for urgent conversions from fossil fuel based energy systems to energy systems relying totally on renewables. Today about 80% of the World's energy consumption is covered by fossil fuels. Countries around the World have made commitments on reductions on their coming CO_2 emissions. It is expected that the conversion period from relying on fossil fuels to relying on renewables will be long and costly. Further, the war in Ukraine has shown that democratic countries finance non-democratic countries' vicious activities by importing goods from the non-democratic countries. For that reason, there are urgent needs for democratic countries to stop import of goods inclusive fossil fuels and energy components from non-democratic countries, where the goods often are produced cheap with high CO_2 emissions. This will result in further increase of future energy costs. Consequently, it is foreseen that energy, both electricity and thermal energy, will be expensive in a future only relying on renewables.

Worldwide, operation of buildings accounts for about 40 % of our primary energy consumption and approximately 25 % of our greenhouse gas emissions. In Europe, buildings are responsible for 40 % of our energy consumption and 36 % of our CO_2 emissions.

Based on the above mentioned, it is a great wish that buildings outside district heating areas in the future are equipped with "domestic" energy systems covering almost the total yearly heat demand and a high part of the yearly electricity demand. Further, for buildings in district heating areas it would be great if centralized renewables cover the total yearly heat demand of the buildings and if the electricity demand is covered by "domestic" energy systems with a high degree of independence of energy supply from the electrical grid.

In 1975 the so-called zero energy house was built at the campus of the Technical University of Denmark, Esbensen and Korsgaard (1976). A solar heating system with 42 m² vertical solar collectors and a 30 m^3 hot water tank as heat storage could theoretically cover the yearly heat demand of the house in the Danish climate. However, mainly due to larger heat losses from the heat storage than expected, the system could not completely cover the total

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yearly heat demand of the house, Esbensen and Korsgaard (1977).

In 1978 the first so called plus energy house was built in Denmark, Fischer (1982). The one family house was equipped with its own wind turbine and electric battery and a solar heating system with 40 m² solar collectors and a 5 m^3 hot water rubber tank. The intension was that all heat demands and electricity demands of the house and of an electric vehicle was covered without any energy supply from outside. Unfortunately, the rubber heat storage leaked after a short period, so the ambitious goal was not reached.

The two above mentioned examples on Danish houses with solar heating systems aiming for 100% yearly solar fractions initiated research activities on solar heating systems and heat storage at the Technical University of Denmark. Most research efforts were focused on assistance to solar collector manufacturers in connection with their efforts to develop attractive solar heating systems and components for solar heating systems for the marked. The manufacturers developed competitive solar domestic hot water systems, solar combi systems and solar heating plants for district heating areas. Almost all the systems were economically attractive but had relatively low solar fractions, relying on different types of auxiliary energy supply systems. Systems with high solar fractions were not prioritized due to economically reasons.

PV systems on buildings allow that a part of the electricity demand can be covered by the PV systems. Further, combinations of PV panels and heat pumps allow that the systems can cover a part of both the electricity and heat demand of the buildings. Recently, differently designed, sized and smartly operated PV/heat pump systems have been investigated by Battaglia et al. (2017), Toradmal et al. (2018), Thür et al. (2018) and Heinz and Rieber (2021). Focus has been on how to achieve the highest possible coverage of the electricity and heat demand of the buildings. Also research with the same focus on PVT/heat pump systems have been carried by Dannemand et al.(2019), Sifnaios et al. (2021) and Chhugani et al. (2023),

During the last decades, there has not been much research on how individual solar heating systems can cover almost all heat demand of buildings. However, in Switzerland the first successful one family solar house with a yearly solar fraction of 100% was built in 1989 by the company Jenni Energietechnik AG, Das Sonnenhaus, 2. Auflage 2009, https://docplayer.org/18236832-Unabhaengig-und-umweltbewusst-wohnen-mit-der-sonne-das-sonnenhaus-2-auflage-2009.html (2009). A large solar heating system with several large hot water stores covered the total heat demand of the house during the first year of operation. Jenni Energietechnik AG is one of a kind company focusing on solar energy systems covering the total yearly energy demand with solar energy.

Recently an IEA (International Energy Agency) SHC Task 66 project Solar Energy Buildings has started, https://task66.iea-shc.org/. The focus of the project is on development of economic and ecologic feasible solar energy supply concepts with high solar fractions for new and existing single buildings and building blocks or communities. The targeted solar thermal and solar electrical fractions depend significantly on the climate zone. For central European climate conditions solar fractions of at least 85% of the heat demand, 100% of the cooling demand and at least 60% of the electricity requirements for households and e-mobility should be achieved.

In this paper preliminary calculations for a house with differently designed and sized solar energy/heat pump systems with high solar fractions are presented. Both solar heating systems and PV systems are considered.

2. House and energy systems

Calculations are carried out with the POLYSUN program, https://www.velasolaris.com/software/ for a 120 m² one family house located in Denmark outside district heating areas. Three different concepts of the energy system of the house are considered: 1) A heat pump system, 2) a heat pump system and a PV system, 3) a solar heating/heat pump system combined with a PV system. The sizes of the systems inclusive heat storages and electric batteries are varied, allowing determining how the degree of independence of energy supply from the electrical grid is influenced by system size.

The yearly heating and electricity demands assumed are given in Table 1. The energy quantities are typical for relatively new Danish one family houses. Hourly weather data from the Danish design reference year, DRY are used in the calculations.

Tab. 1: Assumed yearly energy demands for one family house

Space heating demand	Domestic hot water consumption	Electrical energy demand	Total energy demand
4707 kWh/year	1749 kWh/year	3000 kWh/year	9456 kWh/year

The heating system of the house is a floor heating system based on hot water flowing through heating coils. The flow temperature is 35°C and the return temperature is 30°C under the dimensioning conditions.

Figure 1 shows a schematically illustration of the heat pump/PV system, and Figure 2 shows a schematically illustration of the solar heating/heat pump/PV system taken in calculation.

The efficiency of the PV panels is 20% at 25°C.

Two different solar collectors are taken in calculation, a standard flat plate collector and an evacuated tubular solar collector from Kingspan, MS30-TMO500.

A 5 kW air-to-water heat pump and electrical batteries of different sizes are assumed.

Two hot water tanks are used for the heat pump system, while one hot water storage is used for the solar heating/heat pump system together with an external DHW unit supplied with heat from the heat storage.

The electricity produced by the PV panels cover the electrical energy demand in the house directly, power the heat pump, charge the electrical battery or is sold to the electric grid.

If the required electricity needed to operate the energy and heating systems and to cover the electrical energy demand in the house can not be covered by the PV panels or the battery, electricity is bought from the electrical grid. The calculations are carried out in such a way, that the total energy demand of the house is meet.

Systems with an electrical battery and heat storages can in the future be operated in a smart way in a good interplay with the electrical grid. This possibility is however not considered in this paper.

To compare the different concepts two energy quantities are used for each investigated system: Electricity bought from the electrical grid and Electricity sold to the electrical grid

Further, an independent ratio, defined as Energy savings/Total energy demand = (Total energy demand – electricity bought from the electrical grid)/Total energy demand, is used.

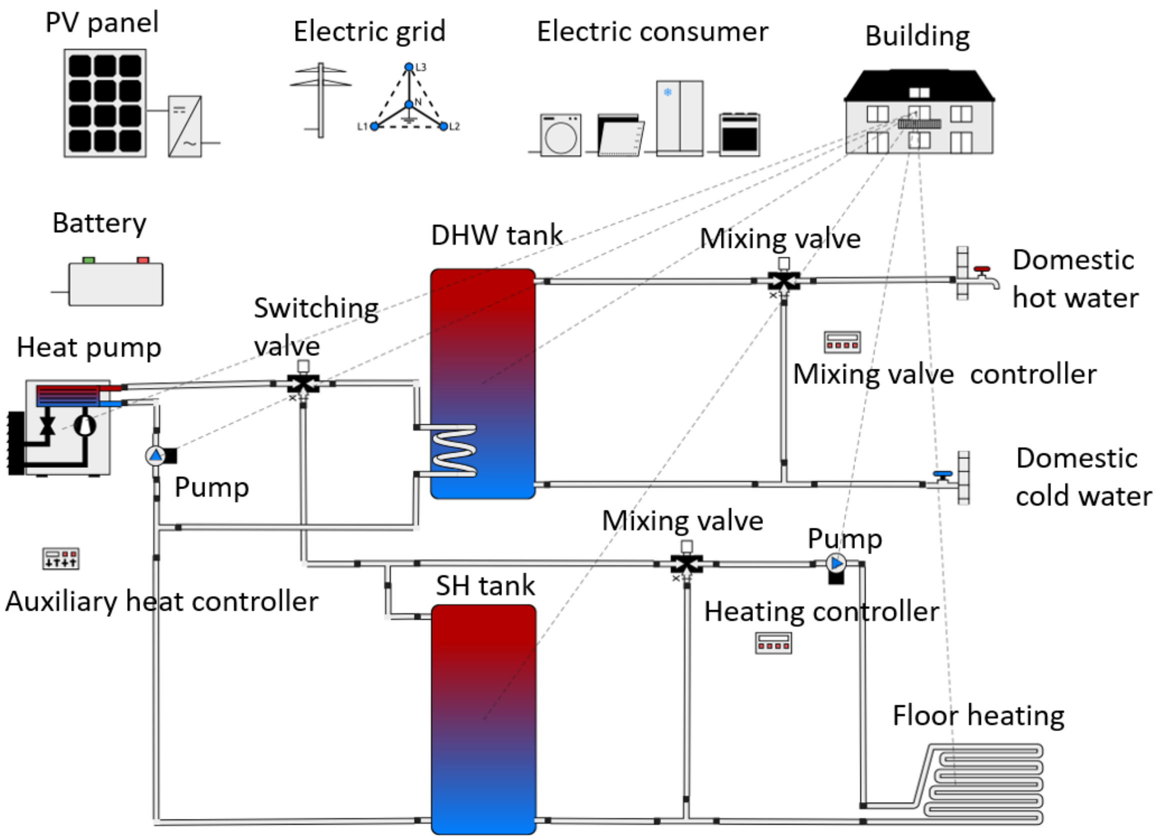

Fig. 1: Schematically illustrations of the heat pump/PV system taken in calculation.

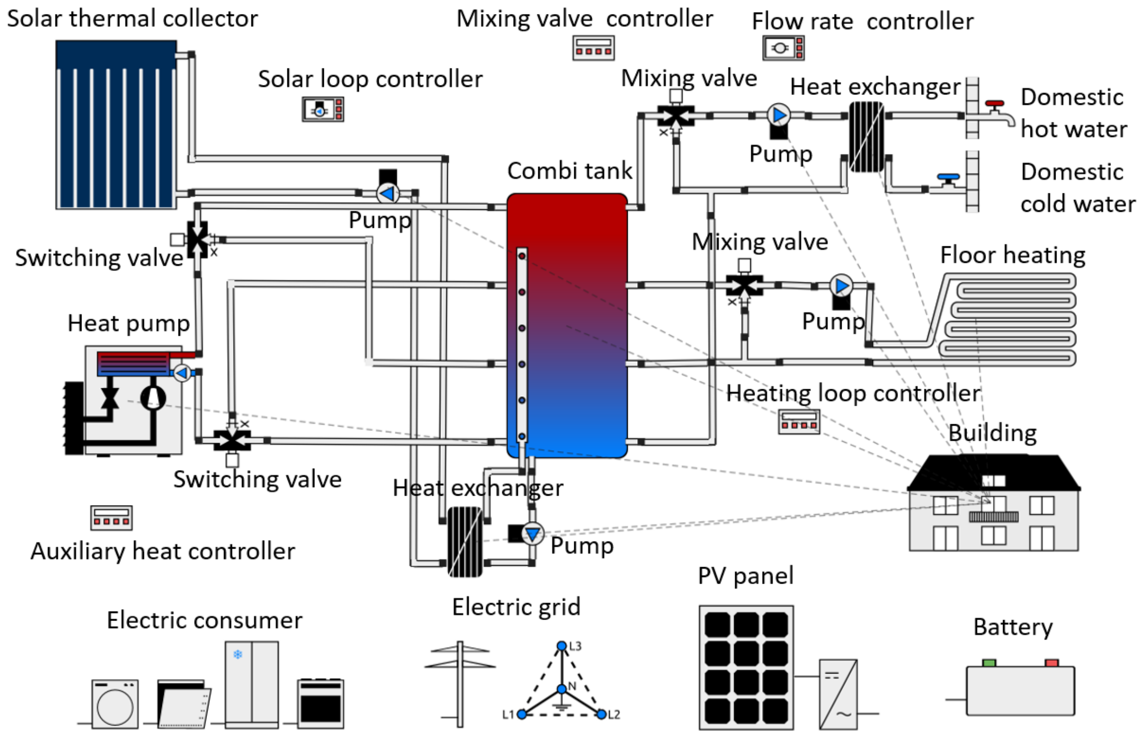

Fig. 2: Schematically illustrations of the solar heating/heat pump/PV system taken in calculation.

3. Calculation results

Calculated results for the heat pump system without PV panels, electrical battery and solar collectors are shown in Figure 3 and Figure 4 for different domestic hot water tank volumes. The hot water tank volume for space heating is 600 L in all the calculations. A small domestic hot water tank results in the highest yearly independent ratio of about 45%, because a reduced tank volume results in a reduced tank heat loss. Additional calculations show that the volume of the hot water tank for space heating not significantly influence the independent ratio of the system.

Calculation results for the heat pump system with PV panels without electrical battery and solar collectors are shown in Figure 5, Figure 6 and Figure 7 for different south facing PV panel tilts. The PV area is 53 m², the domestic hot water tank volume is 300 L and the hot water tank volume for space heating is 600 L. The yearly electricity sold to the grid and the yearly independent ratio peaks, and the electricity bought from the grid is lowest for a PV panel tilt of 40°. The highest yearly independent ratio for the heat pump/PV system is about 69%. Calculations with the same system with PV areas of 28 m² and 14 m² showed that the yearly independent ratio decreased to about 64% and 58%, respectively, see figure 8 and Figure 9. Also for the heat pump/PV system a small domestic hot water tank results in the highest yearly independent ratio, while the volume of the hot water tank for space heating not significantly influence the independent ratio of the system.

Calculations with the heat pump system combined with PV panels with an area of 53 m² and a 30 kWh electrical battery showed that the yearly independent ratio increased to 81%.

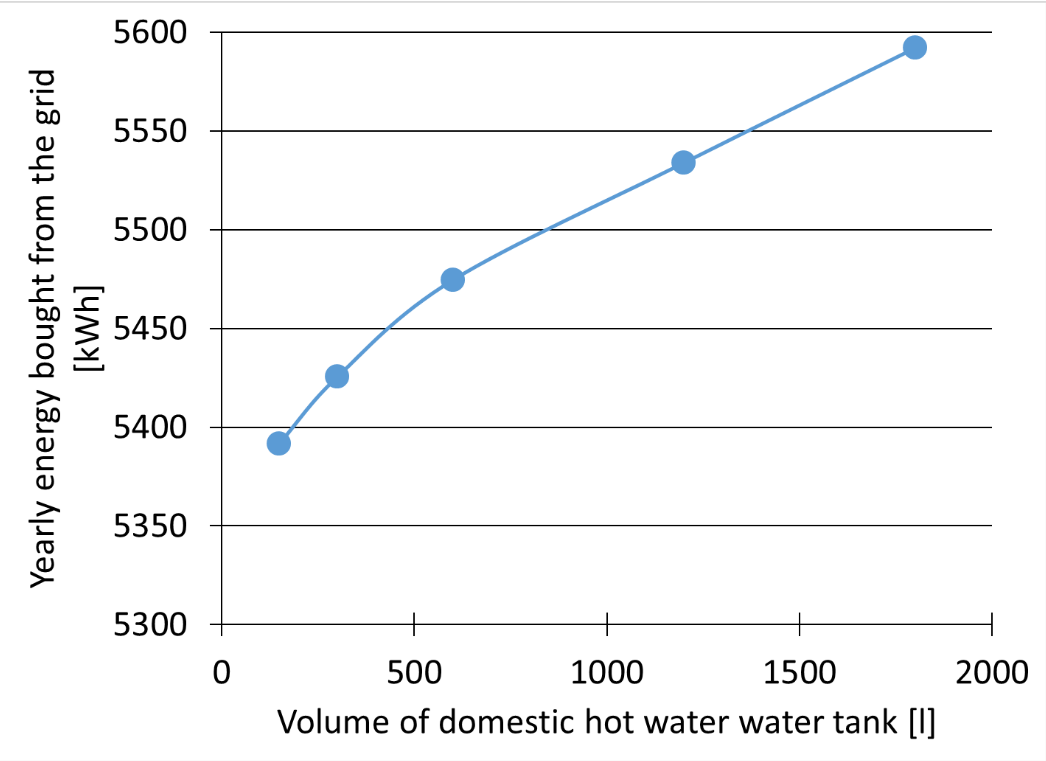

Fig. 3: Yearly electricity bought from the grid as function of the domestic hot water tank volume for the heat pump system.

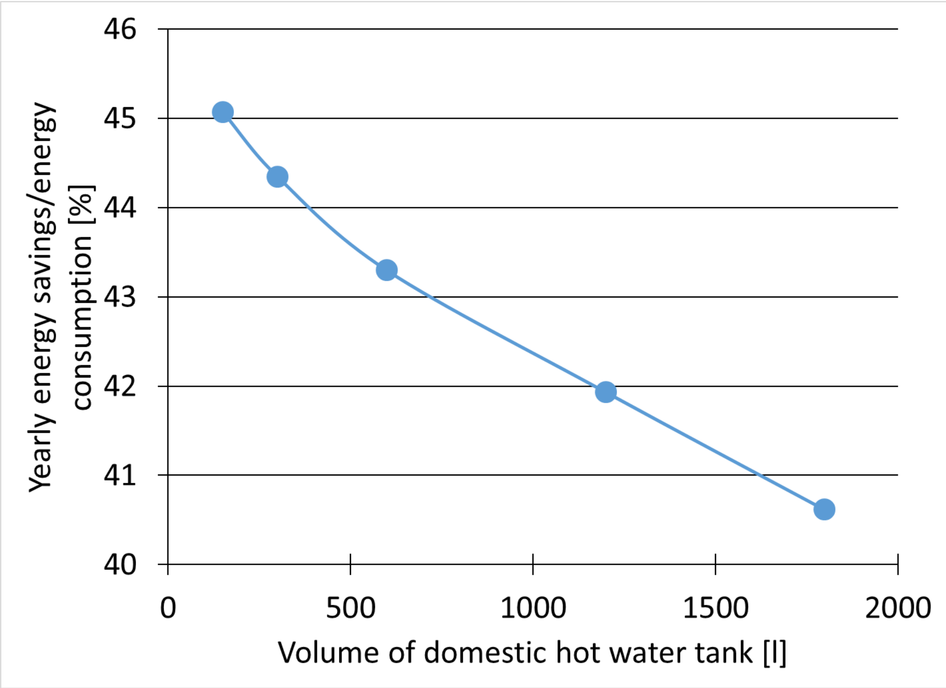

Fig. 4: Yearly independent ratio as function of the domestic hot water tank volume for the heat pump system.

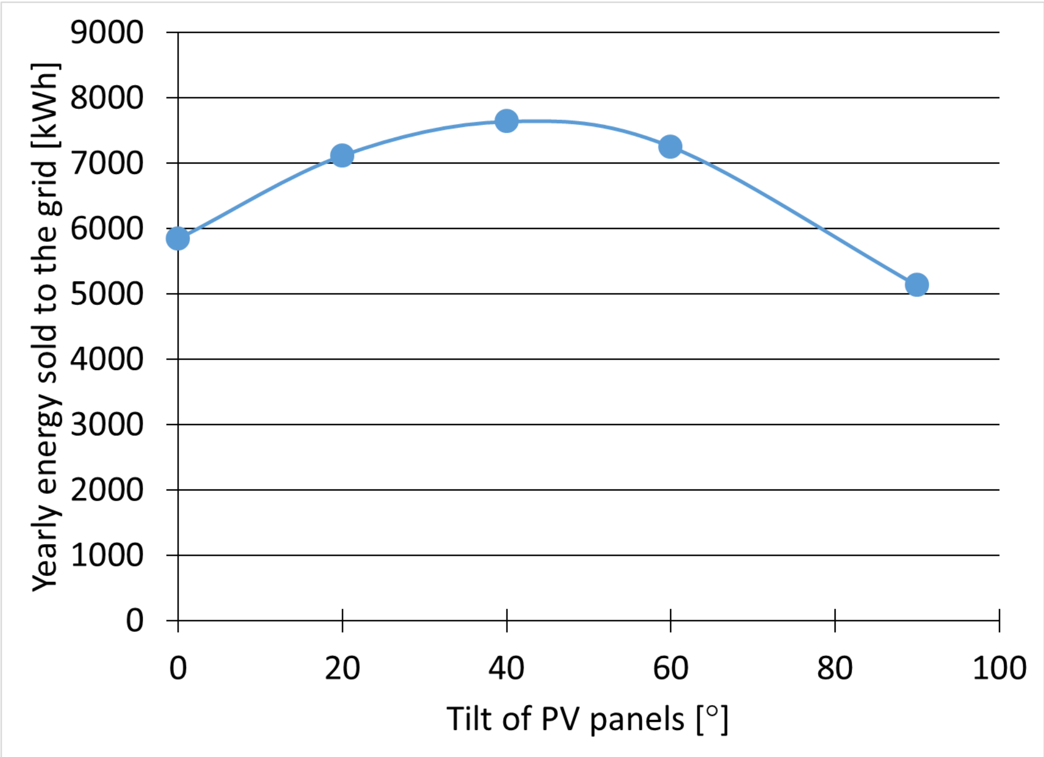

Fig. 5: Yearly electricity sold to the grid as a function of the PV panel tilt for the heat pump/PV system

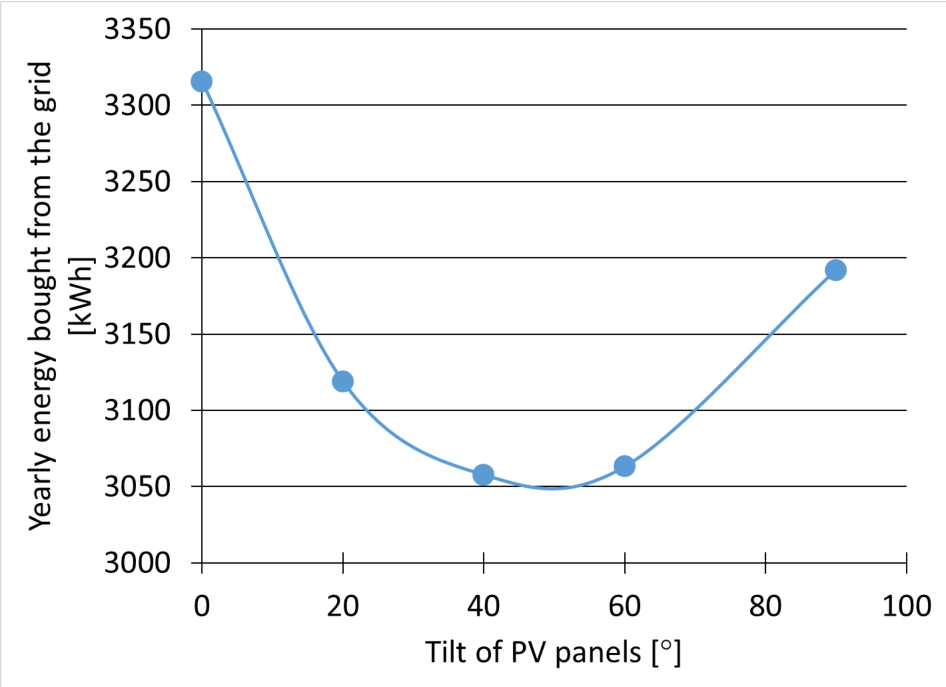

Fig. 6: Yearly electricity bought from the grid as a function of the PV panel tilt for the heat pump/PV system

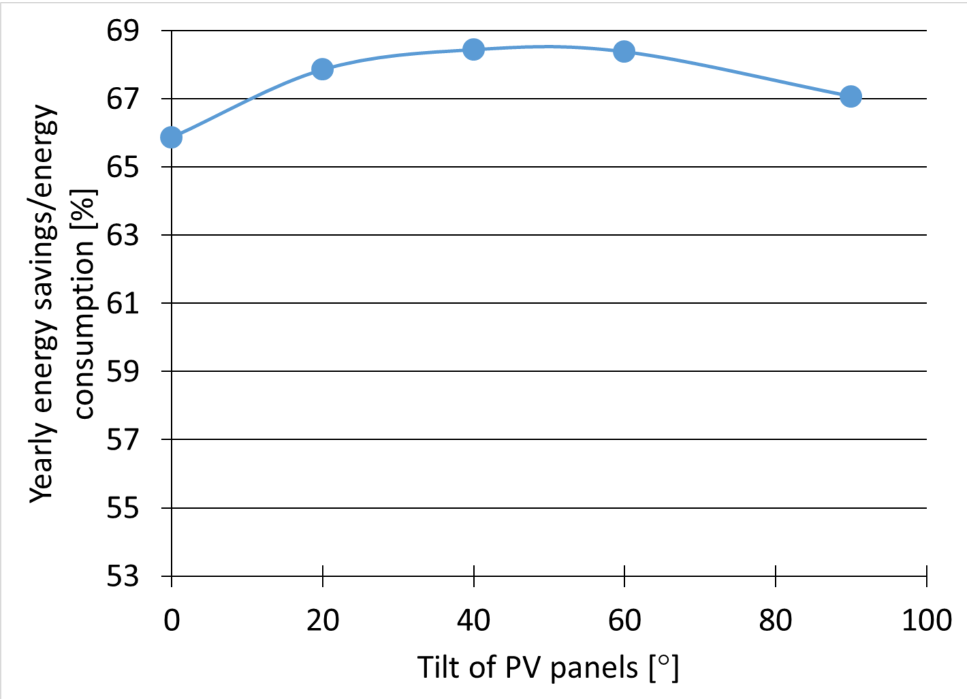

Fig. 7: Yearly independent ratio as a function of the PV panel tilt for the heat pump/PV system. PV area is 53 m²

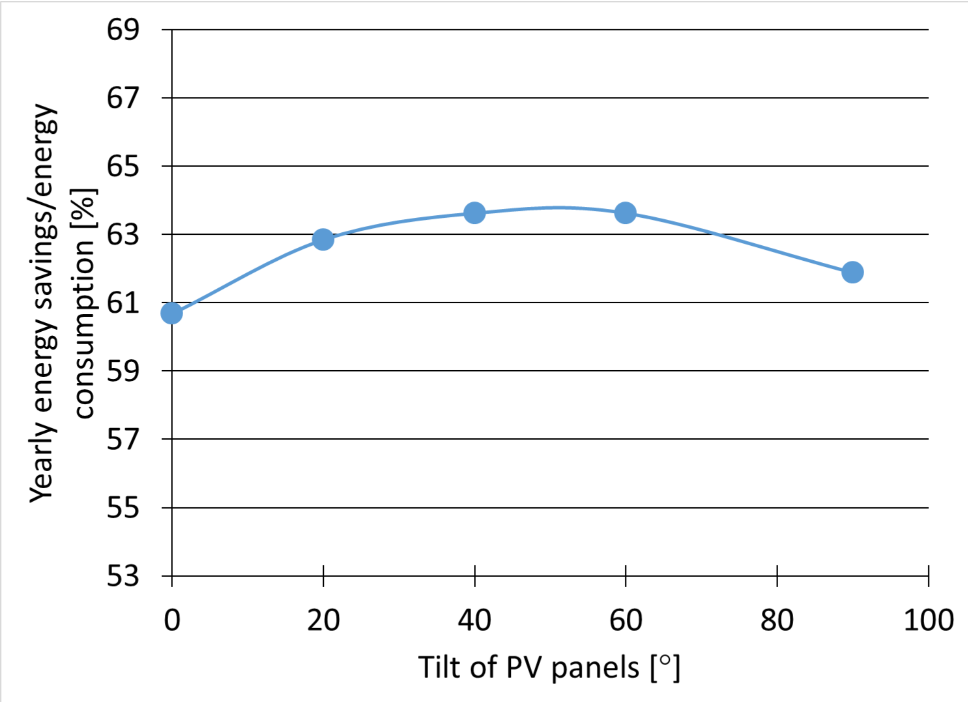

Fig. 8: Yearly independent ratio as a function of the PV panel tilt for the heat pump/PV system. PV area is 27 m^2

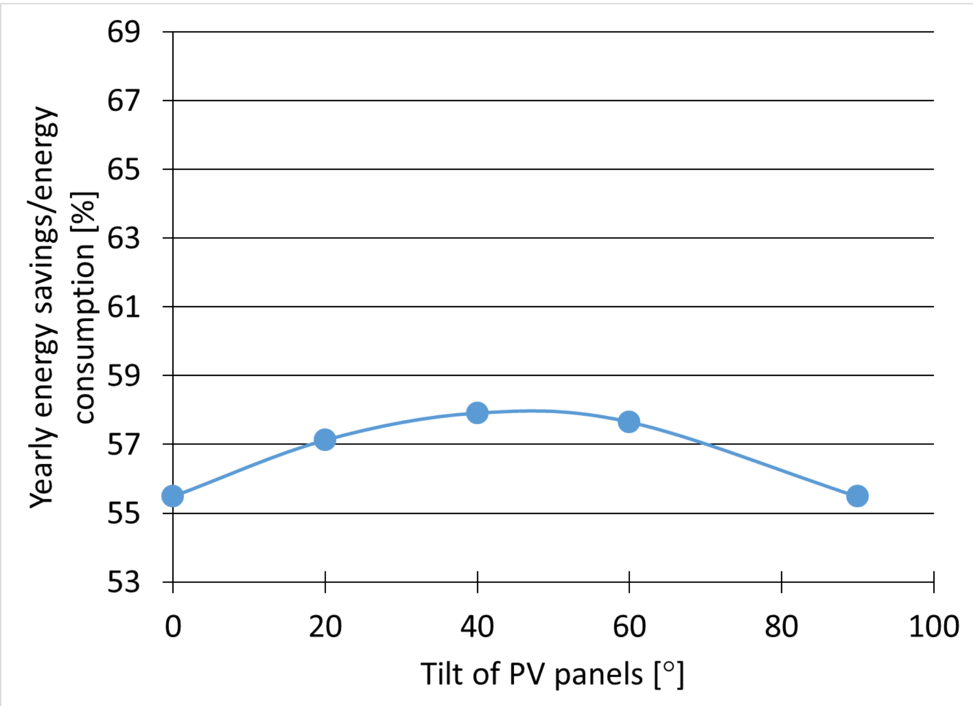

Fig. 9: Yearly independent ratio as a function of the PV panel tilt for the heat pump/PV system. PV area is 14 m²

Calculations show that the yearly independent ratio for the solar heating/heat pump system without PV panels and with 60 m² flat plate solar collectors and a 2500 L heat storage with the upper 208 L reserved for heat supply to the DHW unit is about 57%. The best solar collector tilt is about 75°.

Figure 10, Figure 11 and Figure 12 show the yearly electricity sold to the electrical grid, bought from the electrical grid and the independent ratio for the 60 m² solar heating/heat pump system combined with south facing 40° tilted PV panels as function of the PV panel area. Introduction of PV panels increase the independent ratio. With a PV panel area of 42 m² the independent ratio reach about 67% for the combined solar heating/heat pump/PV system. By adding an electrical battery of 30 kWh, the yearly independent ratio is further increased to about 72%, 79% and 81% for 14 m², 28 m² and 42 m² PV panels, respectively.

By replacing the flat plate solar collector with the evacuated tubular solar collector the yearly independent ratio is increased to 85% for the 60 m² solar heating/heat pump/42 m² PV system with 30 kWh electrical battery. By using a 90 kWh or a 200 kWh electrical battery, the independent ratio is increased to 86% and 87%, respectively.

For the 60 m² solar heating/heat pump/42 m² PV system with evacuated solar collectors, a 30 kWh electrical battery and a 30 m^3 hot water tank the yearly independent ratio is 87%. For the 60 m² solar heating/heat pump/42 m² PV system with evacuated solar collectors, a 200 kWh electrical battery and a 30 m^3 hot water tank the yearly independent ratio is 91%. 5540 kWh produced by the system can on a yearly basis be sold to the electrical grid. The electricity is sold in the summer months.

The calculations shows that it is not possible without extremely large heat storages and electrical batteries for the solar energy systems to cover the energy demand completely in the house in Denmark. However, the only period of the year where the large systems with large energy storages can not cover the energy demand completely is in January and February. In this period, windy days with extremely cheap electricity are available in Denmark due to the high number of wind turbines. Consequently, during these days the heat storage and the electrical battery can be charged with renewable energy in a cheap way. In this way the energy demand of the house can be completely covered by renewables.

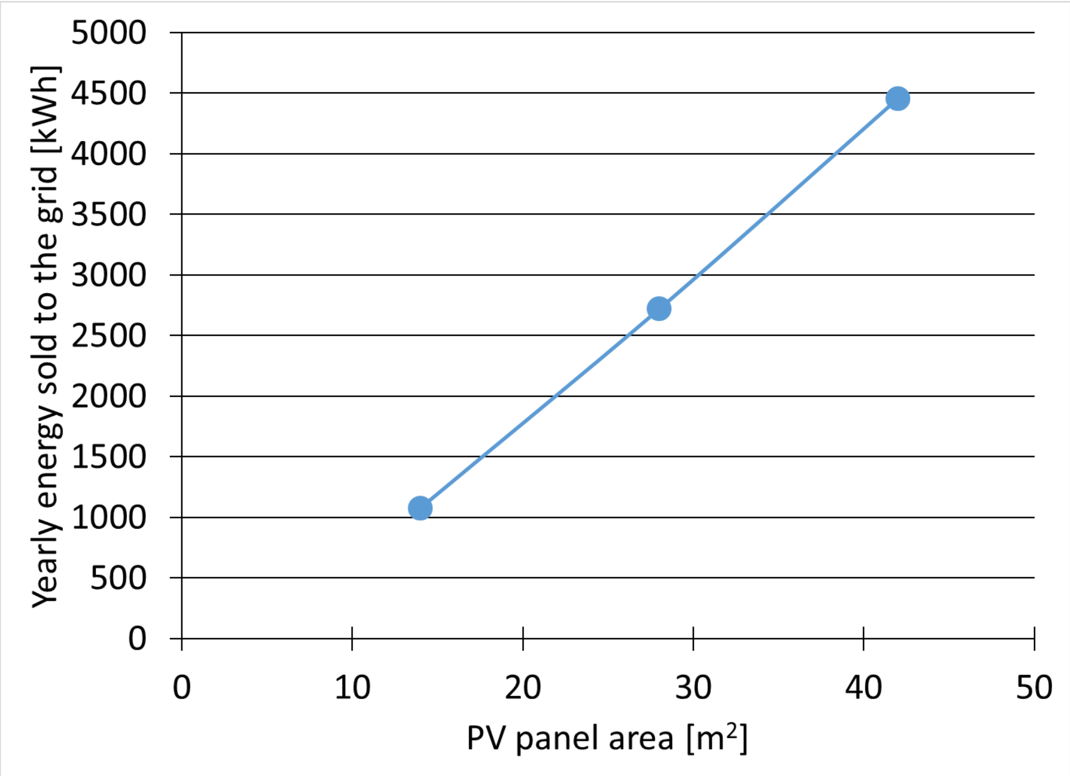

Fig. 10: Yearly electricity sold to the grid for a 60 m² solar heating/heat pump system combined with PV panels with different areas.

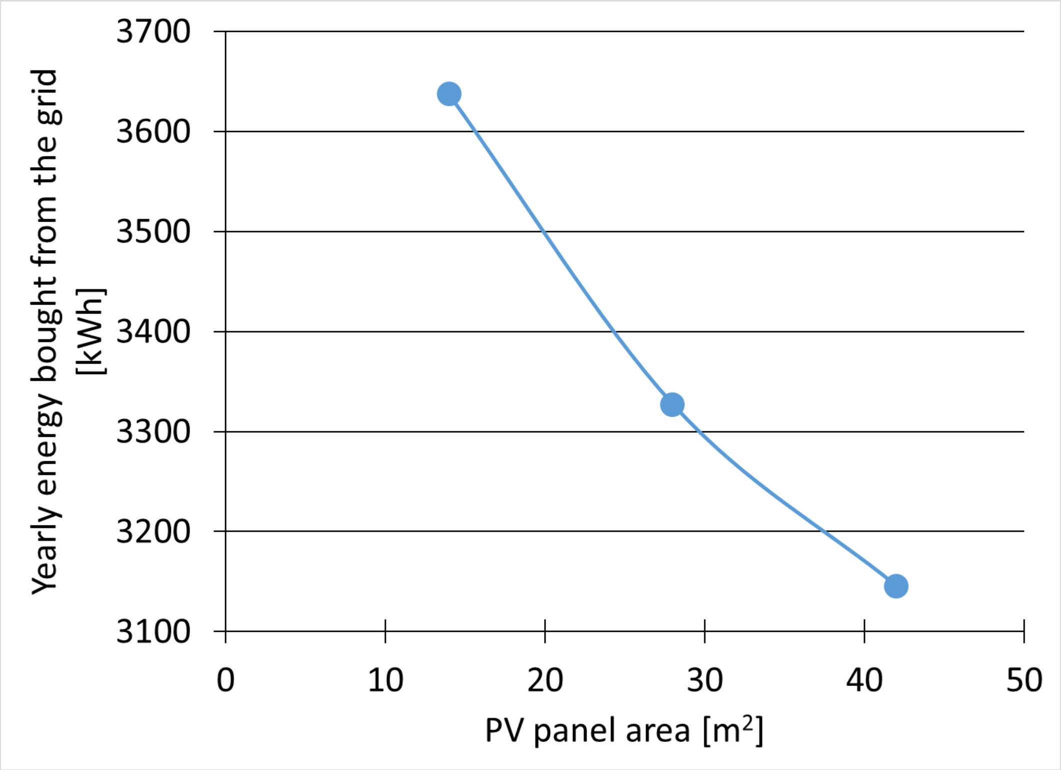

Fig. 11: Yearly electricity bought from the grid for a 60 m² solar heating/heat pump system combined with PV panels with different areas.

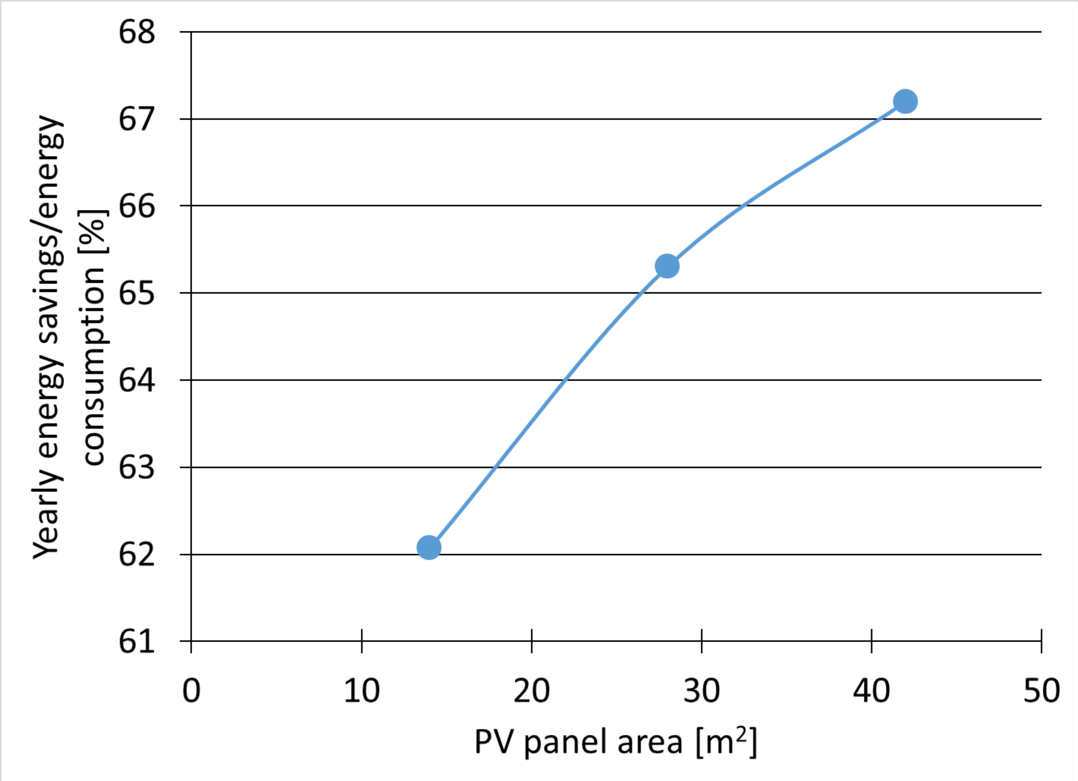

Fig. 12: Yearly independent ratio for a 60 m² solar heating/heat pump system combined with PV panels with different areas.

4. Conclusions

A 60 m² solar heating/heat pump/42 m² PV system with a large hot water storage and battery can cover about 90% of the total yearly energy demand of 9500 kWh for a typical Danish one family house. If the house is connected to the electrical grid, 5500 kWh electricity produced by the system can furthermore be sold to the electrical grid during the summer months. The energy demand of the house not covered appear in January and February, which in Denmark are windy months with periods with extremely low electricity costs. The energy storages of the system can be charged from the electrical grid during these periods and the total energy demand of the house can in this way be covered 100% by renewables.

The optimal tilts for the south facing solar collectors and PV panels are about 75° and 40°, respectively.

Further, the hot water storage and the battery can be operated in a smart way in a good interplay with the electrical grid. The energy storages can be charged in periods with low cost electricity and electricity can be sold to the grid in periods with expensive electricity.

Finally, the hot water storage volume for the solar heating system can be strongly reduced due to the charge periods during the winter with limited solar radiation.

It is recommended to develop optimally designed and sized solar heating/heat pump/PV systems with smart control strategies for different one family houses, so that CO_2 is not emitted by the energy systems of the houses.

5. Acknowledgments

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IEA (International Energy Agency) SHC Task 66 project Solar Energy Buildings, https://task66.iea-shc.org/.

Use of units and symbols: For the use of units and symbols, please see the appendix below.