# SOLAR ENERGY FOR ZERO ENERGY BUILDINGS – A COMPARISON BETWEEN SOLAR THERMAL, PV AND PHOTOVOLTAIC-THERMAL (PV/T) SYSTEMS

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**ABSTRACT**

In a net zero energy building, the energy needed to operate the building is met by renewable energy generated on site. Buildings require energy both in the form of heat and electricity, and hybrid photovoltaic-thermal (PV/T) modules are therefore an interesting technology for building applications. This paper describes a comparative simulation study of solar thermal, photovoltaic (PV) and PV/T systems on a Norwegian residential building model, with the objective to reach net zero energy balance. The results show that PV/T systems can reach a higher energy output than separate solar thermal and PV installations, but the building with only state-of-the-art PV modules and no thermal collectors gets closest to meeting the nZEB requirements.

*Keywords: net zero energy building, PV/T, PV, solar thermal, import/export balance*

## INTRODUCTION

Buildings account for around a third of the global energy use. Making buildings more energy efficient is therefore an important tool in the effort to reduce global greenhouse gas emissions. In a net zero energy building (nZEB), the amount of energy required to operate the building is generated by renewable energy sources on or near the building [1]. During a specified period of time, typically a year, the building reaches a net zero energy balance.

Utilization of solar energy is one of the main strategies used for on-site renewable energy generation. Buildings require energy both in the form of heat and electricity during operation, which can be provided by solar thermal collectors and photovoltaic (PV) modules. In projects with ambitious energy targets or limited available area for installations, solar thermal collectors and PV modules may be competing for the available space on the buildings' roof and facades.

### PV/T modules

In a hybrid photovoltaic-thermal (PV/T) module, electricity and heat are generated simultaneously. This can lead to a high total efficiency per module area and possibly a reduced use of space compared to separate systems. PV/T technology has so far not had a commercial breakthrough comparable to that of PV or solar thermal, but the interest in the technology is increasing, especially in connection to low or zero energy buildings [2].

PV modules convert only around 10-20 % of the radiation to electricity, while the rest is reflected or dissipated as heat in the module. The basic idea behind PV/T technology is to utilize more of the incoming solar radiation by also harvesting the waste heat from PV modules. Since PV cell efficiency typically decreases with increased cell temperature, removing the waste heat can also lead to an increased electricity output.

A number of PV/T technologies are available. For flat plate PV/T modules, a basic distinction can be made between covered and uncovered modules. Simply put, an uncovered PV/T module is a PV module with cooling. It produces an equal or larger amount of electricity than a regular PV module, and in addition some low-temperature heat. A covered PV/T module is similar to a solar thermal collector with added PV cells. Since the extra cover prevents heat loss from convection, this type of module has a higher heat output than an uncovered one. A recent market study from Germany found 41 producers of PV/T modules, out of which 30 were marketing uncovered modules [3].

This paper describes a comparative simulation study of solar thermal, PV and PV/T systems, applied to the case of a Norwegian low energy residential building. The goal is to achieve a zero energy balance. The energy yield of the different systems are analysed and compared, and the building energy balance is calculated.

## The building model

The building model used in the simulations is based on a concept building model developed at the Research Centre on Zero Emission Buildings (the ZEB Centre, www.zeb.no) in Trondheim, Norway. The model represents a state of the art Norwegian building, and is designed to meet the requirements of the Norwegian passive house standard [4]. The material use, embodied energy and emissions, HVAC, technical details and energy performance of the concept building model is well documented and is presented in [5].

The ZEB concept building model is a two-storey residential building with 160 $m^2$ heated floor area, located in Oslo in Southern Norway (59.53° N, 10.41° E). It has a simple rectangular design with a flat roof, and a footprint of 8 x 10 m (the longer sides facing north and south). Meteonorm [6] data is used in the simulation. The annual solar irradiation on an optimally inclined surface (45° south-facing) in Oslo is around 1150 $kWh/m^2$, and the average ambient temperature 6.3°C. The largest fraction of the solar radiation is available in the summer, when the heating demand is low, but during spring and autumn significant irradiance levels and heating demand occurs at the same time.

The energy need of the building is shown in Table 1, as determined in [5]. During the winter months, the space heating dominates, while no space heating is needed during t May to August. The DHW energy need is relatively constant during the year, as are the electricity needs. The energy needed for domestic hot water (DHW) and electricity are specified in accordance with standard values from the Norwegian standard NS 3031 [7], as are the internal heat gains from people and equipment.

*Table 1: The energy need of the building as determined in [5]*

| Energy need | kWh/year | kWh/m2 year |
|---|---|---|
| Space heating | 3349 | 20.9 |
| Domestic hot water | 3811 | 23.8 |
| Electricity | 4074 | 25.5 |
| Total | 11234 | 70.2 |

The storage tank is the centre of the buildings heating system. The solar thermal system (or thermal part of the PV/T system) is connected to the lower part of the tank with an internal heat exchanger. An air-to-water heat pump provides the auxiliary energy by feeding the upper or middle part of the tank directly, based on the required temperature. The building has a low temperature hydronic heating system with floor heating and radiators, with feed/return temperatures are 25/35°C and 30/40°C respectively. The required volume for DHW is heated in a tank-in-tank system. The delivery temperature is 45°C at the tap, with a 55°C set point temperature in the tank. Legionella growth is prevented by heating the tank to 70°C weekly.

## METHOD

### Comparative study

Three versions of the building (A, B and C) are simulated to study the performance of different solar energy systems for zero energy buildings. The simulations are based on a model of the building and HVAC system which is further described in [5]. Building A has a system with a combination of solar thermal collectors and PV modules, and represents the original design of the building model. Building B has a system of PV/T and PV modules, and building C has only PV modules installed. The hydronic heating system is the same in all versions of the building, except for the dimensions of the tank and piping.

The boundary condition used in this study is the area of the roof (80 $m^2$) and the design objective of the installation is to reach a net zero energy balance over on year. Installing solar energy systems on flat roofs, especially in northern regions, requires that row-to-row shading is considered. It was calculated that only two rows of modules could be installed on the roof at a close to optimal tilt angle of 45°. Performance data and dimensions from modules available on the market have been used in the study. It is assumed to be are no restrictions (in time or power) on the electricity exchange with the grid. In the case of thermal energy, the generated energy from the solar collectors is only useful if it can be used directly or stored; in the latter case given that the storage is not fully loaded. The usefulness of the solar thermal output also depends on the temperature of the energy carrier.

*Table 2: The characteristics of the solar modules used in the simulations.*

| Module | Technology | Gross area [m2] | Electric efficiency at STC* [%] | Optical efficiency η0 [%] |
|---|---|---|---|---|
| ST | Flat plate | 2.0 | - | 80.0 |
| PV | Poly-Si | 1.65 | 15.8 | - |
| PV/Ta | Mono-Si, uncovered, uninsulated | 1.64 | 17.4 | 61.4 |
| PV/Tb | Poly-Si, covered, insulated | 2.26 | 12.0 | 71.5 |

**Standard test conditions: 1000 W/$m^2$, spectrum AM 1.5, 25°C cell temperature*

The solar thermal collectors and PV modules used in the simulation are selected to represent the average of products that are available on the market in terms of performance. The market for PV/T modules is still relatively small, and the quality of a PV module depends both on the thermal and electric performance it is difficult to find a module that represents the market average. In an attempt to account for these differences, two different PV/T modules were used in the simulations: a PV/T module with good electric performance (PV/Ta), and a covered PV/T module with good thermal performance (PV/Tb). An overview of the module characteristics is given in Table 2.

**Zero energy balance**

There are several ways of calculating the energy balance of a nZEB, depending among other things on the system boundary and weighting factors for different energy sources that are used. A proposal for a consistent definition was presented by Sartori et al [8].The annual import/export balance is used in the present case. That is, the balance is calculated between energy delivered, or imported, to the building ($E_{delivered}$) and the energy exported from the building ($E_{exported}$). The energy balance is then calculated according to equation ( 1 ).

$$E_{net} = |E_{exported}| - |E_{delivered}| \quad (1)$$

The balance in this case is calculated with total annaul values. A net zero energy balance is reached if $E_{net}$ (kWh) is zero or positive. Since the auxiliary energy to the heating system of the building is provided by a heat pump the only form of delivered energy is electricity. No weighting factor is therefore necessary in this case.

The solar fraction (SF), i.e. the fraction of the thermal energy demand of the building that can be covered by the solar thermal and PV/T systems can be calculated according equation ( 2 ), where $Q_{sol}$ (kWh) is the thermal energy from the solar energy system, $Q_{dem}$ (kWh) is the thermal energy needed for space heating and DHW.

$$SF = \frac{Q_{sol}}{Q_{dem}} \quad (2)$$

**RESULTS**

The simulations are performed in the program Polysun from Vela Solaris, which is a dynamic simulation tool for solar energy solutions[9]. The main parameters used in the simulations for buildings A, B and C are shown in Table 3. In addition to the modules described above, two systems with state-of-the-art solar thermal collectors and PV modules were added (A* and C*). The differences in total installed areas are due to the use of real module dimensions are been used.

*Table 3: The main parameters of the simulated system variants.*

| System | Description | Installed area ST/PVT/PV [$m^2$] | Rated electric power [kWp] | Tank volume [l] |
|---|---|---|---|---|
| A | ST and PV | 10/0/21 | 3.4 | 1200 |
| B1 | Only PV/Ta | 0/30/0 | 5.1 | 1800 |
| B2 | PV/Tc and PV | 0/21/11 | 4.6 | 600 |
| C | Only PV | 0/11/18 | 4.7 | 0 |
| A* | State-of-the-art (ST and PV) | 0/8/23 | 4.7 | 1200 |
| C* | State-of-the-art (only PV) | 0/0/30 | 6.0 | 0 |

The annual thermal and electricity output in of the systems are shown in Figure 1, measured in kilowatt hours. The systems with highest thermal energy output (A, B3 and A*) are also the system with the highest total output with this way of calculating. The solar fraction (SF) of the thermal energy demand is shown in Table 4, together with the import/export energy balance calculations. None of the system reaches net zero energy balance ($E_{net} > 0$). The system that is closest to reaching a balance is system C*, with only state-of-the-art PV modules and no thermal collectors. This system meets 87% of the delivered electricity with exported solar electricity.

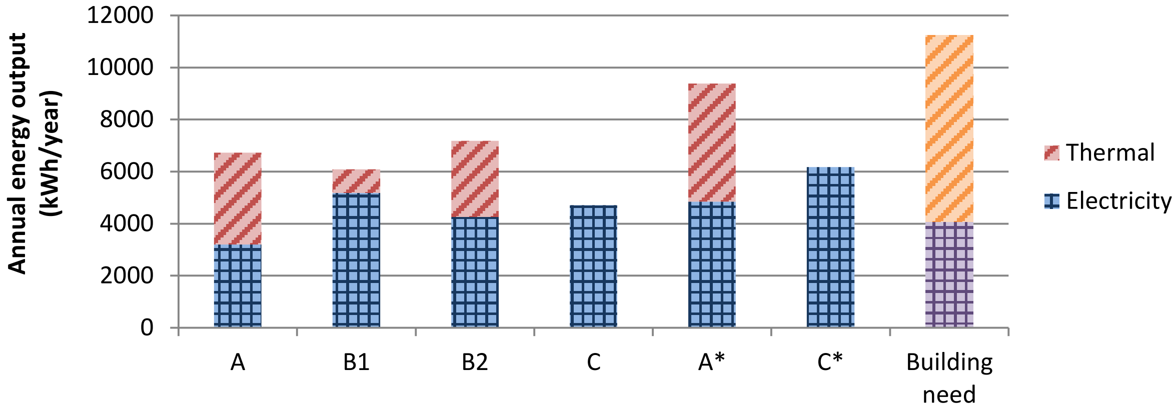


*Figure 1: The annual thermal and electricity output of the different systems. The rightmost column shows the thermal and electric energy need of the building.*

The state-of-the-art system with solar thermal and PV (A*) has the highest solar fraction, and is the second closest to reach a balance with 82% of the delivered energy met by on-site electricity. Of the studied systems with PV/T, the uncovered PV/T system in B1 is the closest to a balance, with 71% of the delivered electricity met by solar generated electricity. Due to the use of a heat pump for auxiliary energy, the systems with high electricity output are favoured in this calculation.

*Table 4: The thermal solar fraction and annual energy balance calculations of the systems. A negative value of $E_{net}$ means that the building has not reached a zero energy balance.*

| System | SF [%] | $E_{net}$ [kWh] | $E_{exported}$/ $E_{delivered}$ [%] |
|---|---|---|---|
| A | 42 | -3 044 | 51 |
| B1 | 10 | -2 112 | 71 |
| B2 | 37 | -2 022 | 68 |
| C | 0 | -2 414 | 66 |
| A* | 53 | -1 047 | 82 |
| C* | 0 | -945 | 87 |

**DISCUSSION**

The idea that hybrid PV/T modules would be able to perform better than a side by side installation of PV modules and solar thermal collectors is supported by the results of this study. However, the system with state-of-the art PV modules only comes closest to reaching a net zero energy balance. The number of different modules studied here is small, as is the number of available PV/T modules on the market. No far-reaching conclusions on PV/T technology can therefore be drawn from these results.

The system with uncovered and uninsulated PV/T modules (B1) has a higher electric yield than the one with average quality PV modules (C). However, it should be noted that the efficiency of the PV modules used here is slightly lower than that of the PV/Ta modules. The thermal output of system B1 is small and of low temperature, which means that an auxiliary heat source is necessary also during summer. Built examples from suggest that uncovered PV/T modules perform well in systems with ground source heat pumps, where the low temperature output can be used to recharge the ground storage, or as direct input to the heat pump when the temperature level is sufficient.

System B2, with a combination of PV and covered PV/T performs slightly better than system A with average solar thermal and PV, suggesting that covered PV/T modules could be suitable for smaller residential systems, like the one studied here. However, as Adam et al. [3] found in their market survey,  the number of market-available covered PV/T modules is very small. The validity of the performance data for PV/Tb module is therefore quite uncertain. A limiting factor for this technology is the high demands on module materials, which has to endure significant changes in temperature without degradation or damage.

In this study the import/export balance was calculated on a yearly basis, which means that self-consumption is not taken into account. Further work will be to include electricity use profiles in the calculation to evaluate the load match. Since an air-to-water heat pump was used as auxiliary energy source, the import/export balance included only electricity. Further work will be to consider other heat sources, such as bio energy, which requires use of weighing factors in the energy balance calculations. In addition, further work will focus on the greenhouse gas emission balance of the systems, which includes the embodied emissions of the different solar energy technologies. Alternative module layouts, e.g. a larger number of modules but at a at lower tilt angle, will also be considered in further studies.

## CONCLUSION

A comparative simulation of solar energy systems on a Norwegian building model has been performed, with the objective to reach a net zero energy balance over one year. The building model is a Norwegian passive house, located in Oslo. The study looked at different combinations of solar thermal collectors, PV modules and hybrid PV/T modules in different, installed at 45° on the flat roof of the building. The annual import/export energy balance was used to calculate the zero energy balance. Since the auxiliary energy was provided by an air-to water heat pump, only electricity was considered in this balance. In this study, none of the solar energy systems managed to meet the energy demand, and a net zero energy balance was not reached in any of the versions of the building. The system that was closest to reach a balance included only state-of-the-art PV modules and no thermal collectors. Of the PV/T systems, the uncovered, uninsulated system came closest to the zero energy balance in this example, although the total energy output measured in kWh was highest from the covered PV/T system.

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