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Rolf-Michael Lüking
Gerd Hauser

Plus Energy Buildings

Technical and Economic Principles

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Rolf-Michael Lüking
Gerd Hauser

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Contact:
Fraunhofer-Institut für Bauphysik IBP
Nobelstrasse 12
70569 Stuttgart
Phone +49 711 970-00
Fax +49 711 970-3395
E-Mail info@ibp.fraunhofer.de
URL www.ibp.fraunhofer.de

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Fraunhofer Information-Centre for Regional Planning and Building Construction IRB
P.O. Box 80 04 69, D-70504 Stuttgart
Nobelstrasse 12, D-70569 Stuttgart
Phone +49 (0) 711 970-2500
Fax +49 (0) 711 970-2508
E-Mail verlag@fraunhofer.de
URL http://verlag.fraunhofer.de

Plus Energy Buildings

Technical and economic principles

A study conducted by

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Prepared by

Dr. Rolf-Michael Lüking, Prof. Dr.-Ing. Gerd Hauser

Rolf-Michael Lüking, Gerd Hauser

PLUS ENERGY BUILDINGS

Technical and economic principles

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1. Introduction

Plus energy houses, i.e. buildings that produce more energy than they consume, will play a key role in the imperative implementation of a future energy supply system which does not depend on fossil (nor nuclear) energy carriers. These buildings offer the opportunity to transfer an energy consumption segment, which at present accounts for nearly 40% of the final energy demand, into a plus segment.

Plus energy buildings are technically feasible; they are certainly not an unrealistic vision of the future but rather a concrete technical option. The developments that were made in construction engineering over the last few decades enable us to reduce building heat losses to a minimum; innovations in the field of plant-engineering allow designing highly efficient supply systems for heating and air-conditioning. On the other hand there are decentralized technologies for generating energy from renewable sources, particularly photovoltaic systems, which are able to directly convert solar energy into electric power. The modules can be attached to the roof or external wall surfaces of the building or, which seems to be preferable, they can be integrated in the building envelope. The technical know-how and the tools for the construction of *plus energy buildings* are already available.

The realization of *plus energy buildings* or even the implementation of a plus energy standard for new buildings through legally binding regulations will, however, need to overcome considerable economic obstacles. For instance, recent calculations with regard to a possible further tightening of energy-related requirements in the forthcoming amendment of the German Energy Savings Directive (EnEV)[1] in 2012 indicate that (already now) there is only a narrow margin for increasing demands on the energy performance of envelope components in the residential sector. As the implementation of EU requirements into national law will only permit new buildings with an energy use of "nearly zero" [2] with effect from 2018/2020, there will be a conflict with the German Energy Conservation Act [3], which subjects energy requirements on buildings to strict cost effectiveness.

In addition, photovoltaic technology, the central element in moving from a low-energy house to a plus energy building, has become more and more discredited in recent years due to the high costs involved. The forthcoming accelerated enhancement of this technology, which is expected to have the greatest potential in the long run, thus often serves to fuel horror scenarios of future price increases in electricity. Also some experts fear that sticking to the expansion of photovoltaic technology, could make electricity to expensive as to be socially unenforceable, thus endangering the entire reconstruction of the energy supply system [4].

The central challenge for the development of *plus energy house* concepts which have the chance of gaining a dominant position on the market is thus an economic one, because the introduction of *plus energy houses* to the market of new constructions can only be successful if they are competitive and there is no need for outsourcing general expenses. It is therefore the essential task of this study to identify an economically profitable combination of building quality and technical equipment in order to be able to realize future residential buildings as *plus energy houses*.

2. Principles of a regenerative energy supply system

2.1 Efficient use of space for regenerative energy production

Though there is need to identify possible solutions to realize *plus energy houses* at the lowest possible cost, this should not cause us to neglect essential boundary conditions of a future regenerative supply system, in which *plus energy houses* will play an active role.

Thus it has to be considered that photovoltaic technology, alongside wind and water power, ranks among the few technologies allowing for direct electricity generation from renewable sources. As will be shown below, the forthcoming transformation of our energy supply system to renewable energy sources is only possible on the basis of direct electricity generation. It makes no sense to stick to a supply approach which is mainly based on the use of chemically bonded energy. It might certainly be assumed that it would be best to retain the existing energy supply system, which is characterized by the use of chemically bound energy carriers, implementing the transformation primarily by substituting fossil fuels with renewable, i.e. biogenic, fuels. A general approach like this is, however, doomed to failure because of the space resources it requires, as the production of biogenic fuels is exceedingly land-intensive (due to the poor energy efficiency of photosynthesis, which is approx. 0.5 %) [5]) (see Table 1).

Table 1: Performance ratio per unit area for different bioenergy products [6]

	Performance ratio per unit area	Performance ratio per unit area, electricity	Manufacturing/ Production costs per kWh energy yield
Rapeseed oil/ biodiesel	0.11 %		> 50 %
Bio gas	0.46 %	0.17 %	25-50 %[1)]
Bio ethanol	0.18 %		80 90 %
Btl-diesel, F-T diesel	0.23 %		> 50 %

[1)] Manufacturing/ production costs depend mainly on the efficiency of heat utilisation.

So even under the most effective process for bioenergy production at present in use - the production of biogas from maize – covering the current primary energy demand in Germany of approximately 46 MWh per person would result in a land requirement of approximately 10,000 m² per person. This would exceed the total agricultural area available for the production of energy crops by a factor of 20 (see Fig. 1) [7].

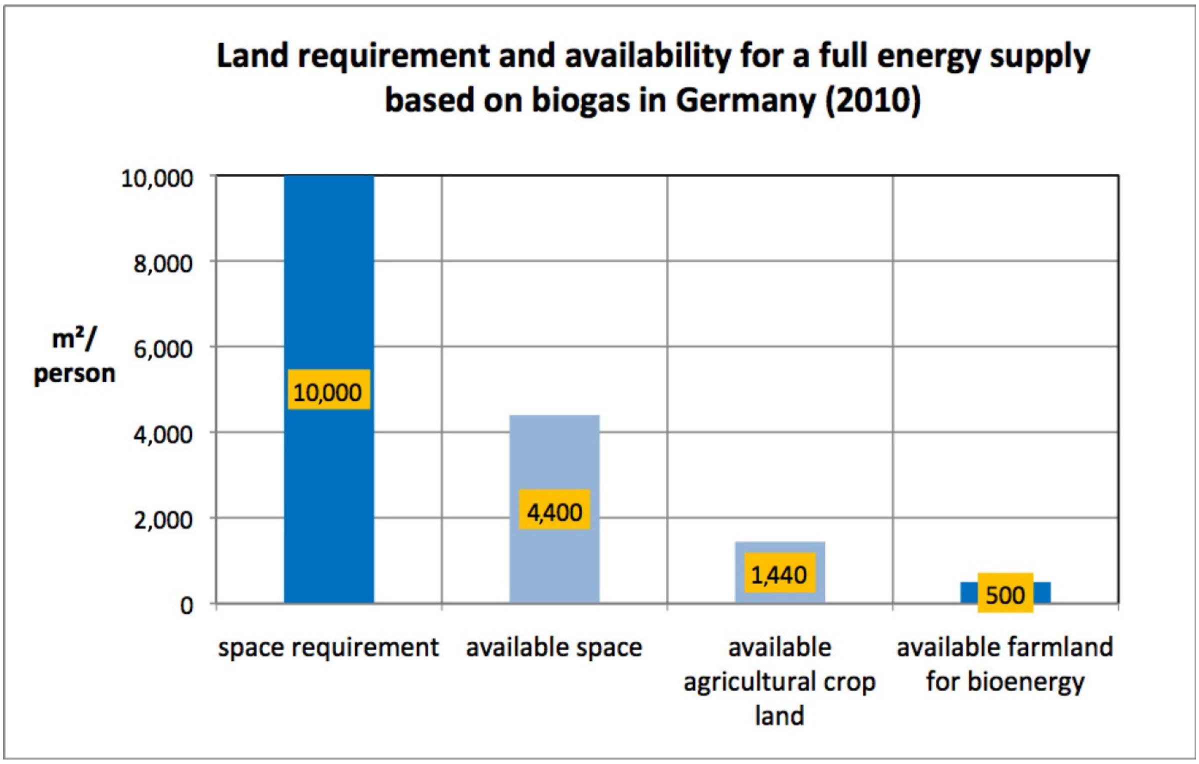


Fig. 1: Space requirement und availability for a fully renewable energy supply based on biogas in Germany (2010)

The energy demand for planting and yielding biogenic energy has not even been taken into account here - it can amount to 50 % of the energy yield in the case of biogas production from maize. The increasing additional competition for land, which will arise in future from the growing demand for regenerative raw materials, has not been considered, either.

Even taking into account a reduction in the primary energy demand of up to 50% as foreseen in the energy concept of the Federal Government [8] and assuming a decline of population to 65 million by 2050, there is still a striking lack of space.

Compensating for the lack of land which is noticeable even today by importing bio energy is not an acceptable option, either. Without having to discuss the numerous possible effects of such an approach, its disastrous nature can be anticipated from the fact that globally even less agricultural area will be available per head of the world population than in Germany today (about 1.4 billion ha of agricultural land is confronted by a world population of 7 billion people, which will probably increase to 10 billion by 2050) [9].

It cannot be denied that the use of bio energy as well as the utilization of waste is ecologically worthwhile and reasonable. On the contrary, chemically bonded energy from regenerative production will maintain a qualitatively outstanding position as it can be stored without any problems. The widespread perception of renewables providing inexhaustible sources of energy cannot be sustained with regard to fossil fuels. That is why the assessment of fuels from a primary energy point of view (as done within the framework of the EnEV and its underlying standards [10; 11; 12], where only the non-renewable shares of energy are taken into account) is highly questionable: this will lead to an increased demand for biogenic fuels and thereby directly into a sustainability trap.

If one compares this disillusioning diagnosis with the efficient use of space made by wind and solar power plants, which for simplicity are here (conservatively) assumed to have an annual yield of 100 kWh/m² (including the average distance spaces required for wind energy power plants) a much more favourable proportion results. The land requirement is reduced to 300 m² per person in relation to current values of energy consumption and a population of 81.5 billion. In this regard it must be considered that the yield is immediately available as universally usable delivered electric energy, which is why it can be measured against the current (!) final energy requirement amounting to approximately 30 MWh per person and year (Fig. 2).

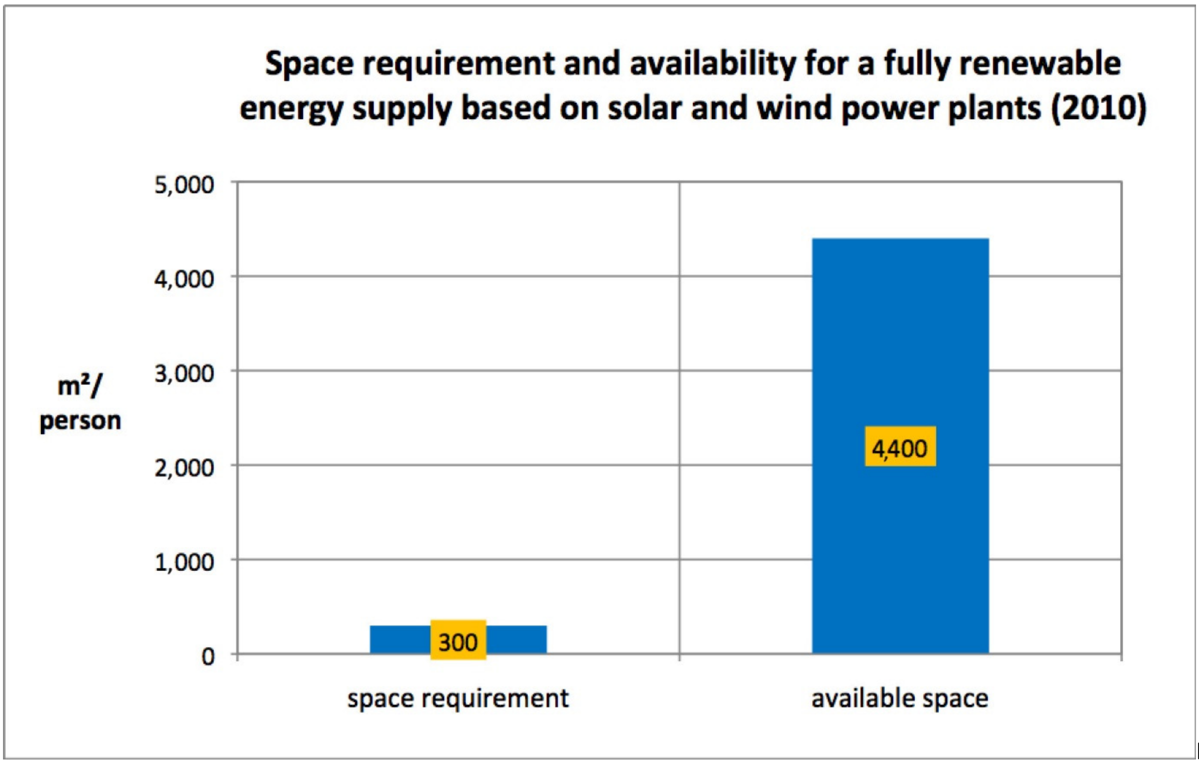


Fig. 2: Space requirement and space availability for a fully renewable energy supply based on solar and wind power plants (2010)

In fact, wind and solar power plants have a much greater potential to contribute to a fully renewable energy supply based on regenerative sources only. Whereas the production of electricity from biomass by combustion involves heat loss, wind and solar power plants directly supply electric energy, which can be transformed at (virtually) no loss into all required forms of energy and be used to considerably reduce the final energy demand. For instance, electrically driven heat pumps with a seasonal performance factor of 4 only need a quarter of the delivered energy required by a condensing boiler to perform the same thermal services. Regarding mobility, the final energy demand can be similarly reduced through direct use of electricity in electric motors. The land requirement for energy generation is thus considerably reduced. Photovoltaic technology, which was often discredited as being “inefficient”, moreover provides a great advantage: PV modules can be installed in urbanized areas, particularly on buildings, thereby reducing the pressure to use unsealed areas, and agricultural areas, in particular.

Considering the current and forthcoming technical options for the regenerative production of energy, the intended transformation of our energy supply system will only succeed if it follows the principle of minimizing the use of fuel while focusing (preferably exclusively) on the use of electric power, using solar and wind power plants as its supporting pillars (even if not the only ones).

In view of this situation, only secondary importance can be attached to the various types of bioenergy. With regard to the limited potential of renewable energy sources, “secondary” must be interpreted in the strict sense of being exclusively reserved to consumer segments where fuels cannot be substituted by electricity (air traffic, for instance). In the first place, however, bioenergy sources should be used to compensate for the technical problems resulting from an energy-supply concept that is dominated by solar and wind power plants.

2.2 Balancing requirement for power supply fluctuations

The problems arising from a supply approach which is dominated by solar electricity and wind power plants are serious. Above all, electricity gained from wind and sun is not continuously available but only intermittently and subject to considerable power fluctuations. To ensure the required synchronicity of electricity demand and supply is one of the key challenges of the transformation process. As solar electricity plants, wind power and hydroelectric (run-of-river) power stations are only partially controllable or can only have their output reduced, renewable energy in the form of stored solar energy will be of vital importance in future situations where the intermittent energy supply falls below the power demand. Any other use, either in the mobility sector or to supply heat to buildings (even when using energy generated by combined heat and power stations, which have the reputation of being highly efficient), is counterproductive as far as the maximum possible conversion to a regenerative supply system is concerned. This applies all the more as the dependency of individual consumers such as air and shipping traffic on fossil fuels additionally reduces the quantities available. Actually, the resources for the production of renewable fuels appear to be absolutely insufficient - even taking into account energy recovery from bio-waste, and even allowing exclusively subsidiary use. Consequently, there is an additional or even a priority requirement for secondary fuels such as hydrogen or renewable methane, which can be gained (though with high energy losses) from surplus electricity [13]. As the main problem of the transformation process in energy supply is the difficulty of storing electricity, the systematic discharge of existing storage units (for instance, in the form of fossil fuels) to supply services which can also be supplied by electricity, is detrimental in principle. That is why it is absolutely necessary to avoid the use of fuels for the thermal conditioning of buildings, all the more so as no efficiency gains through decentralized fuel utilization could be discovered, not even in the context of the existing energy supply system [14].

The task of integrating fluctuating energy supplies and building-energy supply concepts implies yet another aspect. Increasing inputs from wind and solar power plants not only involve the problem of a temporary shortage in the electricity supply, but also the necessity to integrate temporary over supplies. In fact, situations have already occurred where excess wind energy had to be buffered via Europe's interconnected power grid and/or offered free of charge at the Energy Exchange. Due to the required, accelerated expansion of power generation plants on the basis of renewable energy sources it is unavoidable that excess electricity supplies will increase considerably in both frequency and volume. In particular, it cannot be expected that the capacities of electricity buffer stores will be expanded in the same order of magnitude (for obvious technical and economic reasons). Here, buildings with their given heating and cooling requirements could provide a load balance, namely by using the excess electricity supply for heating purposes [14; 15]. This option not only implies a huge potential in terms of quantity - also, the technical and financial effort for thermal energy storage is minimal compared to the intermediate storage of electricity in accumulators or the operation of thermal balance power plants for grid stabilization [15]. Basically, all buildings supplied with electricity are suitable to support load balancing. The easiest and most cost-effective technical implementation is, however, given in the new building sector, thus making it perfectly sensible not to limit the active role of a *plus energy house* in the power supply system to energy generation, but to accept the development of load balancing potentials as an additional challenge - at least in the medium term.

2.3 The role of *plus energy houses* within a regenerative energy supply system

Regarding the development of concepts for sustainable plus-energy buildings according to the boundary conditions of a supply system based on renewables as outlined above, the following consequences result:

Besides the characteristic feature of a positive overall energy balance (being referred to in the designation '*plus energy house*'), the avoidance of any fuel use is an essential component. Particularly with regard to the active contribution expected to be made by *plus energy houses* in the transition period towards a new energy system and its permanent performance, the use of limited external resources is almost a contradiction. This applies all the more so as the space reserve provided by the building surfaces would not be used for energy generation, which is associated with both ecological and economic disadvantages.

Concepts of *plus energy buildings* should also ensure the technical option to cover the residual energy demand exclusively from fluctuating electricity oversupplies, because - even if the *plus energy house* produces more electricity than the building actually needs (in the annual balance, that is) - still major volumes of electricity will have to be purchased from the power supply grid during the core months of the heating period. It will therefore be conducive to combine good thermal insulation and building components of high heat-storage capacity (and possibly to integrate thermal buffer stores) to achieve greater temporal flexibility as regards the use of this supply service. This would allow to minimize the indirect use of fuel from thermal power plants, thus contributing to balance the asynchronicity of supply/demand situations and, hence, to stabilise the power grid.

3. Clarifying the notion of *plus energy buildings*

The above-described requirements for a future energy supply system allow to formulate six concrete attributes regarding the concept of a *plus energy house* with the prospect of becoming a new building standard on the market:

1. A *plus energy house* is highly efficient, i.e. it is distinguished by a high energy performance of the building envelope in connection with efficient heat recovery.
2. A *plus energy house* is characterized by a mono-energy supply concept on the basis of the energy carrier electricity.
3. Energy requirements are largely covered by the energy that is generated directly in the house or its immediate vicinity, by photovoltaic or small wind power plants.
4. A *plus energy house* is connected to the electric supply grid, which meets the energy recovery demand that cannot be covered through its own power production.
5. In the annual balance, the volume of electricity that was imported from the grid will be at least compensated for by the amount of plus energy that was fed into the grid.
6. A *plus energy house* should, moreover, be designed in such a way that it can use overcapacities of electricity in the power grid for heating.

The active role, which *plus energy houses* by definition play in the energy supply system distinguishes them fundamentally from energy-independent buildings that neither require the energy services of the supply system nor have any plus power to offer in return. From a technical point of view, energy-independent buildings can easily be realized, as has already been shown in a number of research projects. However, the required technical and economic efforts exceed by far the efforts for implementing *plus energy houses*, without creating any added value as regards a guaranteed energy supply. On the contrary, energy-independent buildings fall behind the *plus energy house*, which can contribute to the energy supply beyond its own needs, not only economically but also ecologically. Over-optimistic expectations and the often used image of *plus energy houses* as 'power stations' are yet inappropriate; though they illustrate the upcoming turnaround, they exaggerate the existing possibilities. In particular, technical limits are imposed by the size of suitable areas for the solar yield so that, judging by the efficiency of their PV systems, buildings can merely be presented as mini-power-plants. Above all, the prime aim of future building planning should not be to give priority to designs with huge 30° pent roofs in place of familiar and well-tried architectural solutions. Neither the necessity nor the charm of an energy-induced 'new architecture' is put in question here. However, the sensible integration of self-generated electricity into the energy supply concept must be given priority over plus maximization.

The development of less optimal areas in the building envelope for solar power generation is indeed an important technical challenge, all the more so as it includes the possibility to achieve a better middle-term diversification of solar energy gains during sun-up hours. Due to the resulting higher production costs, such areas will however not be considered in the process of approaching an economically sustainable concept for *plus energy buildings*. In this context, these surfaces are negligible as no maximization of excess energy is involved, which would have been counterproductive for a wide and rapid market penetration by *plus energy houses*. In fact, a rather careful approach to the plus-energy building standard is taken: in the following part, the programmatic “plus” is only related to the shares of energy that were previously considered in the energy balance of residential buildings (the energy requirements for heating and cooling), before introducing domestic electricity to the building energy balance. More specifically: The limiting value “zero”, which results from the inclusion of domestic electricity in the annual balance, will be examined more closely. This integral consideration is to provide more information on the economic consequences to be expected for a building that is designed and constructed as a *plus energy house*.

4. Structural and technical equipment of *plus energy buildings*

4.1 PV plants as an integral part of *plus energy buildings*

In principle, buildings of widely divergent constructions and designs, equipped with different types of technical systems, come into consideration as *plus energy houses*. Even when excluding all theoretically possible concepts of using fuels in *plus energy houses*, such buildings (which do not necessarily need thermal insulation and use a direct electric heating system to control indoor temperatures, for instance) are feasible, namely in privileged places (e.g. areas that are close to water courses or large wind turbines). The characteristic "Plus" can also be achieved through the export of heat generated in large-scale solar thermal plants. This option, however, raises the question of how this plus could be offset against the volume of domestic electricity purchased. Concepts of this kind will not be considered further here. Although these concepts cannot be discarded a priori and (in individual cases) may prove to be sensible approaches for on-site use of natural resources, they do not work as standard- or reference solutions for the required establishment of *plus energy houses* as a generally available building standard. Moreover, excess supply of renewable energy (which would make a lower standard of insulation and less efficient technical building systems appear tolerable) is available only in exceptional cases. Rather, the technical instruments for achieving a positive overall balance that are available to the producers of renewable energy are confined to photovoltaic systems and small wind-power plants, with small wind plants playing only a minor role (not only because of their flexibility regarding location but also due to the restrictive approval procedures). In standard cases, a *plus energy house* depends on photovoltaic technology as energy source. The higher costs involved with covering the energy demand by photovoltaic electricity imply the necessity of energy optimization on the demand side, requiring building constructions that ensure a low demand for delivered energy.

4.2 Ventilation systems using heat recovery and heat pumps as indispensable components of *plus energy houses*

The identification of *plus energy houses* as buildings which combine a low delivered energy requirement, based on the exclusive use of electric energy, suggests considering so-called “passive houses” as the technically suitable basis for their realization. Passive houses are also characterized by a low delivered energy requirement, which can be achieved by combining an energy-optimized building envelope and a ventilation system with heat recovery. Moreover, passive houses normally use electricity as the energy source for heating. This concept has a (mainly economically interesting) advantage: the heating load may be reduced (due to the high-quality design of the building envelope) such that the residual required heat can be supplied to the rooms through the ventilation system, thus avoiding the need for a water-based heating system. The high importance of a favourable building orientation is also a common element of both concepts; notably, the orientation of a *plus energy house* should not only aim to realize high passive heat gains but primarily to obtain a high electricity yield from solar radiation through photovoltaic technology. This is not necessarily synonymous with a strict southward alignment of the photovoltaic modules, which is currently to be favoured for economic reasons. With decreasing production costs for solar electricity, even roof surfaces with an east/west orientation could become more attractive in the medium term, as this will allow to obtain higher total volumes of electricity; also, the prolongation of daily yield times in the summer months can improve a building's degree of self-sufficiency.

These considerations might lead to the conclusion that a *plus energy house* is a passive house which has been enhanced by a self-sufficiency component in the form of solar electricity from photovoltaic systems. However self-evident this conclusion seems to be, it neglects the fact that the objectives of passive-house and plus-energy concepts definitely show incongruities. Whereas the passive house has to be optimized with regard to its energy needs (net energy demand) in order to achieve a heating load of < 10 W/m² of usable floor area, the challenge for a plus-energy concept is to achieve the economic optimum of a low delivered energy use (final energy demand). In this regard the passive house competes with buildings that are thermally conditioned by electric heat pumps, which use ambient heat to supply many times more net thermal energy from the electricity that drives the heat pump system. Despite having a significantly poorer constructional standard, a building that is heated in this way can yet perform like a passive house (or even better) in terms of the electricity requirement. The example given below illustrates the difference:

Under German climate conditions, the heating load of < 10 W/m² will result in a heating energy demand of up to 15 kWh/(m²a) for a passive house. This can be met by the ventilation system via direct electrical heating of the supply air as needed. The amount of electricity required for this purpose, which is equal to about 15 kWh/(m²a) (excluding the auxiliary energy requirement) appears economically acceptable in view of the extremely low investment cost for the technical equipment. From the final (delivered) energy point of view it is, however, possible to run a building that has a greater heating energy demand but consumes significantly less power due to the use of a heat pump. For instance, a building that is characterized by an energy need for heating of 30 kWh/(m²) will require a power input of only 7.5 kWh/(m²a) for space heating (auxiliary energy excluded) if being supplied by a heat pump with a seasonal performance factor of 4 (in relation to the overall system). In relation to the objective of a *plus energy house*, i.e. to satisfy its energy needs from PV power, this deficit is quite substantial, especially as this supply approach also provides the opportunity of highly efficient DHW heating. Of course there is the possibility of using a heat pump also for heating a passive house. In practice, this is generally done by using "compact units" for ventilation, space and DHW heating. These devices extract the residual heat from the exhaust air piping by means of a miniature heat pump. Also, the input of electricity for heating passive houses can thus be considerably reduced to values of around 10 kWh/(m²a). This example, however, demonstrates that optimizing the heat supply technology is the key measure to reduce the need for delivered energy, whereas from the constructional perspective – even though on a high level – ample scope exists for engineering design.

Reducing the delivered energy need for heating by technical measures is clearly preferable to taking structural optimization measures, also as regards the interaction of buildings with the electrical power supply grid. Both, a low energy requirement and a low power requirement are favourable in order to have to make as little use as possible of external resources, especially grid capacities and backup power from thermal power plants.

A (directly) electrically operated passive house has a heating load of < 10 W/m², which approximately corresponds to the maximum electrical power demand per square meter floor space. By contrast, a building with a heating load of 20 W/m², which is conditioned by means of a heat pump with performance factor 4, merely needs 5 W/m² of electrical power, i.e. only half as much. Correspondingly, less backup power will be required for the building, both on the supply side and with regard to grid capacities.

Compared to structural measures, plant engineering measures will more efficiently improve the correlation between energy supply and demand, by raising the self-consumption rate of building-generated solar power for heating purposes. Figure 3 illustrates the different supply/demand correlations for a building based on two scenarios: (1) building standard complies with the reference values specified in EnEV 2009, heat supplied by a heat pump (seasonal performance factor SPF = 4.3), (2) passive house standard, heat supplied by a compact device with a seasonal performance factor of 1.5 (averaged from the performance factor of the extract-air heat pump and the direct electricity supply to handle peak loads). In the annual balance, the solar electricity supply assumed in this example corresponds to the power demand of 1,300 kWh for space heating.

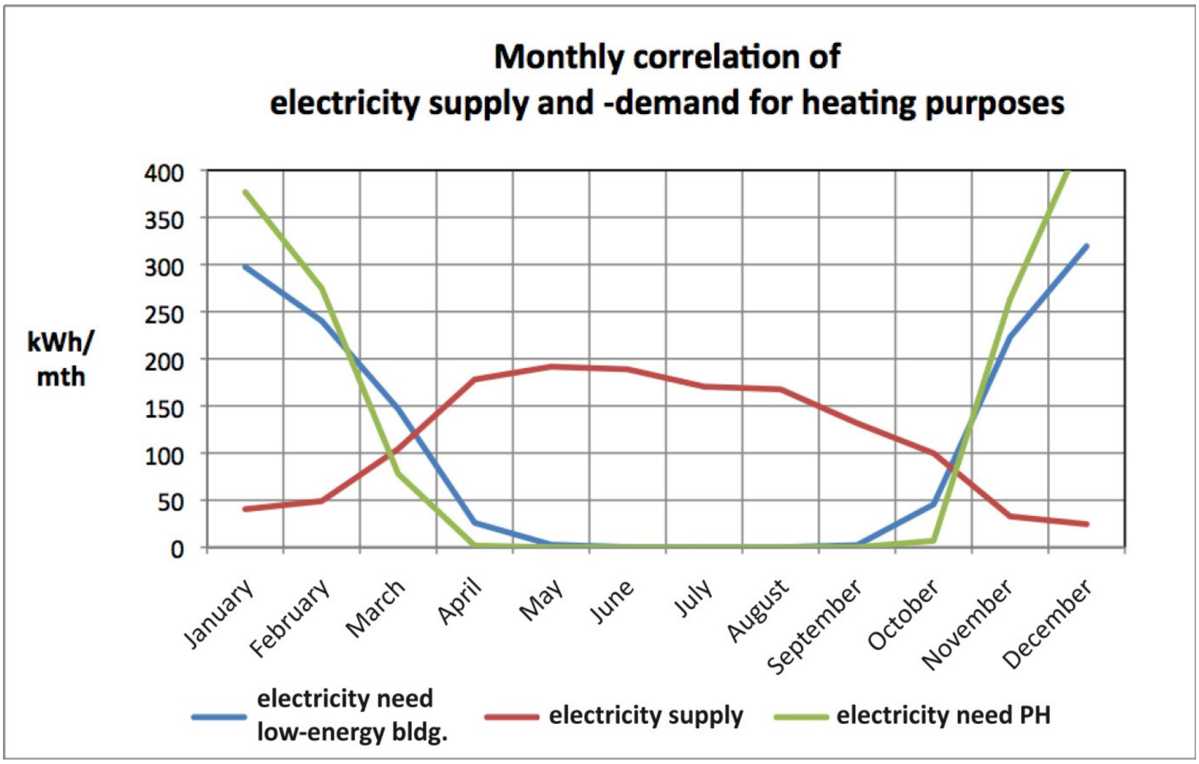


Fig. 3: Monthly correlation of power supply and demand for heating, calculated for different concepts of *plus energy buildings* (see Annex for calculation principles)

Evidently, the passive house not only has a higher peak demand of electric power for heating; also, there are major discrepancies between energy supply and demand in the core months of the heating period. The 'heat-pump house', by comparison, requires greater shares of energy in the transitional periods when higher solar power yields are available. If the output of the PV system is raised in order to increase the energy surplus in the annual balance, this advantage of the low-energy building version will still be reinforced. With regard to the possible use of fluctuating energy supplies from the grid, another advantage can be derived from the profile of the heating period - which is prolonged but dampened in terms of (demand) amplitude - as this implies the opportunity to discharge excess capacity over an extended period of time.

These considerations in no way disqualify the passive house as a basis for *plus energy buildings* - however, this concept (which focuses on structural optimization) does not offer a preferential option, let alone the exclusive one. It is, however, indispensable to focus on plant-engineering measures in order to activate the exergy quality of electricity as the future lead energy for an added value in use.

Besides electrically driven heat pumps also ventilation systems with heat recovery (a must for passive houses in any case) fulfill this requirement. Compared to heat pumps, these systems are distinguished by an even better ratio of power input and heat output; this is however true only for a certain share of the energy demand. Furthermore, they make a considerable contribution to minimize the use of electric power from the grid for heat supply.

The use of ventilation systems with heat recovery and electric heat pumps can hence be identified as a characteristic feature of an economically favourable plus energy building. In conjunction with photovoltaic systems or – in exceptional cases – with small wind power turbines they are the main pillars of a stringent plus-energy house concept.

Any other components designed to improve the energy performance of buildings are generally up for discussion, however. This applies mainly to plant components such as solar thermal systems, but there is also a certain flexibility concerning the energy efficiency of the building envelope (although at a high level) because the "Golden Rule", namely that every energy demand avoided is preferable to its coverage from renewable sources, reaches its limits in the case of *plus energy houses*, its application being subject to economic efficiency. In the context of a *plus energy house*, the two options of investing in the avoidance of energy use or in renewable energy generation (which are approximately equivalent from an ecological point of view) are in economic competition.

5. Integrating PV systems into the energy supply of buildings- Economic principles

With regard to the requirements of a renewable energy supply system it is absolutely essential to establish a close link between two elements, namely generating electricity in *plus energy buildings* and covering the heating/cooling demand by electricity. This combination is equally indispensable for the economic operation of *plus energy buildings*. Currently, generating electricity in photovoltaic plants is still associated with high costs - yet this element needs to be integrated in the building concept, too. From the investor's point of view this aspect is, however, not yet relevant as the payment tariffs specified in the German Renewable Energy Sources Act (EEG) [16] guarantee the cost-effective operation of a PV plant, provided the photovoltaic generator has a suitable orientation and is not exposed to shade. At present (2012), building-generated solar power that is fed into the grid is being reimbursed with 24.43 ct (net) per kWh for a period of 20 years. The Renewable Energy Sources Act (EEG) grants payments of 8.05 ct (net) for electricity used on-site and 12.43 ct (net) per kWh for the energy shares that exceed a 30 %-rate of self-consumption. In view of the fact that no procurement costs will occur for self-consumed electricity, this regulation enhances the economic attractiveness of the investment and is an incentive to increase the self-consumption rate.

The favourable conditions currently granted by the Renewable Energy Sources Act (EEG) do not, however, provide a suitable basis for establishing future-proof concepts of *plus energy buildings*, as this basis is being considered extremely fragile. This statement refers less to EEG regulations concerning the annual degression of the reimbursement for newly installed PV systems; rather, it relates to the fact that funding photovoltaic technology is called into question over and over again for economic reasons, as the remuneration paid is re-allocated to the total purchase price for electricity via the so-called 'EEG surcharge'. The resulting price increase for electricity customers is more and more denounced as socially intolerable or as harmful for the economic competitiveness of German industry [4].

The calculation method for the EEG surcharge, which is under very controversial discussion, will not be addressed here in greater detail. It is actually much more important to point out how unbelievably short-sighted it is to fundamentally criticize the Renewable Energy Sources Act (EEG), with repeated criticism mainly relating to high EEG funding rates of photovoltaic electricity. Firstly, this Act has been substantially more successful than predicted (not only by its critics, but even by its initiators), both as regards the expansion rate of renewable power generation and concerning the realized learning curves of the respective technologies. Secondly, we even now owe to the EEG a cost level for the generation of wind- and solar power (being the two most important future technologies for energy generation) that has the potential to conclude the era of electricity price increases that has been continuing for decades.

Thus an approximate upper limit for future electricity price increases can be derived from the current EEG payments for electricity generated by photovoltaic systems and wind power plants: this limit results from the difference between the electricity production costs in conventional power plants, which has to be added to the present purchase price of electricity. Including a blanket allowance for expenditures on the forthcoming grid and storage expansion (which have been roughly projected by the EU Energy Commissioner not to exceed 1.5 ct/kWh) and assuming the energy demand to be covered by 50 % from wind and by 50 % from solar power, EEG payments will result in a net limit price below 35 ct/kWh (provided that constant, legally regulated fees are charged on the electricity production costs):

0.5 * 24.43 ct/kWh	(EEG feed-in tariff for solar electricity as from January 1, 2012)
+ 0.5 * 8.8 ct/kWh	(average payment for electricity generated by onshore wind turbines)
- 7 ct/kWh	(electricity production costs in conventional power stations)
+ 21.24 ct/kWh	(net electricity price for residential customers in the first half of 2011 [17])
+ 1.5 ct/kWh	(supplemental surcharge for grid and storage expansion)
= 32.36 ct/kWh	(net).

The perspective of an increase in net electricity prices of more than 52 % for private households appears to be worrying. Based on the envisaged period of time until the year 2050 stipulated in the energy concept of the Federal Government for the complete transformation to electricity generation from renewable sources, this would correspond, however, to an average price increase rate of less than 1% and would thus be significantly lower than the average rate of inflation over many years, which is actually just one-third of the yearly energy price increase rates of the past years and decades (1998-2011: 2.9 % [17]). The foreseeability of a limitation of the electricity price development is all the more remarkable because for other sources of energy there is no likelihood of a fundamental reversal of the economic trend towards rising energy prices, neither in parallel with the general inflation rate nor even below. On the contrary, because of the increasing global energy consumption, an accelerated energy price increase has to be anticipated for fossil and also for renewable fuels.

Regarding the influence that a wider use of renewable energy will have on the electricity price development, two essential aspects - which apply especially to photovoltaic technology - have not yet been considered within this unquestionably rough estimate of marginal values:

1. Further decreasing production costs for electricity from renewable sources may be expected. A 2010 forecast of the cost development for electricity from renewable sources compared to electricity generated in conventional power stations shows that

even small photovoltaic installations may be fully competitive as early as 2030 (Figure 4). Even though this prediction was only made in 2010, it is already considered to be almost out of date.

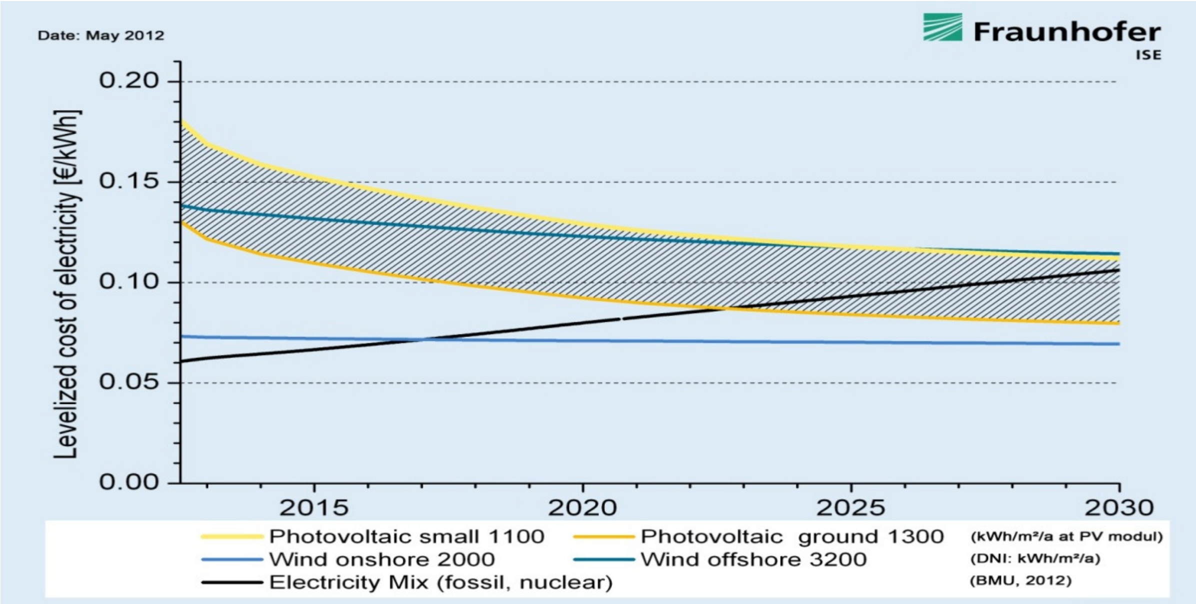


Fig. 4: Predicted electricity generating costs of renewable energy up to 2030 (based on learning curves) [18]

2. The direct use of PV-generated electricity at the place of production involves considerable economic advantages, as production costs for self-consumed solar electricity need not be compared with the electricity generating costs of conventional thermal power plants but with the purchase price of electricity, which is higher by factor 3.

Despite these fundamentally positive perspectives of photovoltaic electricity the (presently still) high costs still cannot be denied. A *plus energy house* concept which ignores this fact and is dazzled by the EEG payments for solar electricity is in danger of experiencing reality at short notice when subsidies for photovoltaic electricity are further reduced (depending on market developments, these may decrease by up to 24 % annually), radically capped or given up completely. The development of a *plus energy house* concept should include the challenge to limit the need for allocating costs to the community to a minimum. In this way an active contribution would be made to ensuring the further development of this indispensable technology, particularly from the economic point of view. In the following economic analyses of possible *plus energy house* concepts, the EEG payment regulations are left out of consideration.

The above mentioned advantage of photovoltaics installed directly on the building provides the decisive approach: because when it comes to the supply of buildings with heating / cooling and with both domestic and auxiliary electricity, it is not so much the difference between solar power plants and conventional power plants which is relevant to production costs, but the difference between costs for electricity generated from photovoltaic facilities and the price for domestic electricity. In other words, with regard to the economic feasibility of requirements, the production costs of electricity generated from photovoltaic facilities must be treated as savings in the cost of energy supplied from the grid, similar to the costs for insulation measures of external building components.

On the basis of this approach, it is not relevant to calculate possible returns on investments when determining the current production costs for solar electricity. Instead, a procedure is used which has been established in similar form to determine the price of saved energy, for cases in which the energy performance of building components has been improved. The calculated production costs are considered as prices for saved energy, by analogy with the determination of prices for avoided energy purchase. This procedure implies a double advantage: in this way it is possible to directly compare the self-consumption rate of generated electricity with the purchase price of electricity and to weigh up PV installation investments against competitive investments required for structural or plant engineering measures. This procedure (which will also be applied to other investments in the further course) is shown in Figure 5.

The production costs for 1 kWh power in photovoltaic facilities (K in € / kWh) result from the required annual expenses, which comprise the annual cost of maintenance z*I and the cost of capital, i.e. the product of the annuity factor a and the investment costs I. $K = (a+z)*I$ The annuity factor a depends on the real interest rate p and the service life n of the investment according to the formula given below: $a = p/(1-(1+p)^{-n})$ The real interest rate p results from the effective interest rate of the loan for the investment p_D and the inflation rate i: $p = (1+ p_D)/(1 + i) - 1))$ The interest rate for a mortgage loan is assumed to be 4.5 %; given an inflation rate of 1.6 % and a time period (n) of 25 years, a real interest rate of 2.85 % results. The factor z for determining the annual cost of maintenance is assumed to be 1.5 %.

Fig. 5: Methods and assumptions used for determining the cost-effectiveness of photovoltaic facilities

In the fourth quarter of 2011, the net investment costs for photovoltaic facilities < 100 kWh (including installation, but without value added tax) amounted to 2,082 €/kWp (see Fig. 6).

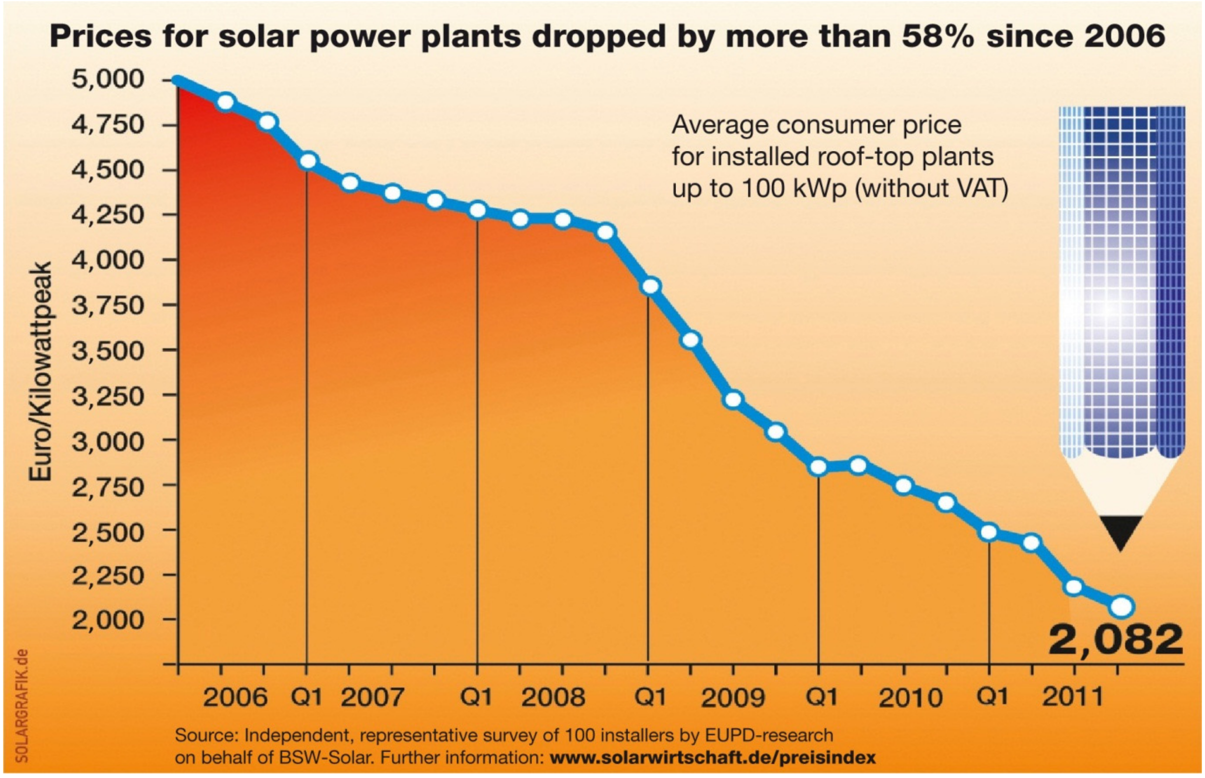


Fig. 6: Price development of solar power plants since 2006 [19]

Based on the above mentioned assumptions for an economic efficiency calculation (Figure 5) annual costs amounting to 148.9 €/kWp result. If one compares these costs to the average net purchase price of domestic electricity of 21.24 ct (net) [17] it becomes obvious that - even starting with an annual yield of 701 kWh/kWp - self-generated energy is less expensive than external energy procurement (148.9 €/kWp / 0.2124 €/kWh = 701 kWh/kWp). At almost any location in Germany, an annual yield of 701 kWh/kWp can be taken for granted for the average photovoltaic installation, provided the installations have a south orientation and are not shaded by obstructions. Annual yields between 800 and 1000 kWh may normally be calculated for south-oriented areas. Even considering minor power losses that are liable to occur in the course of an expected operating time of 25 years, it can hence be stated that the so-called 'grid-parity' has already been achieved due to the strong price decreases for solar power plants in 2011, which went along with a considerable increase of electricity prices for domestic customers.

Achieving grid parity does not, however, imply that operating a *plus energy house* will immediately result in equal or even lower energy costs compared to a similar house without its own electricity being generated from photovoltaic facilities. The price for the electricity generated is not sufficient as a calculation basis, since continuous simultaneity of electricity generation and power requirement is not given. Even in the case of an (at least) consolidated annual balance between electricity generation and power requirement, a share of the electric energy demand still has to be drawn from the grid, whereas electricity generated from photovoltaic facilities is fed into the grid proportionally - and this at prices below cost, if one disregards current subsidies according to the EEG (the German Renewable Energy Resources Act).

For the case considered here, namely the photovoltaic facility annually producing the same amount of electricity that is required for the building's thermal conditioning and for household purposes, the effective electricity price results as follows:

Operative electricity price = cost-price of solar energy + (1 – self consumption rate) * (purchase price of electricity – feed-in price)

The current solar electricity production costs have already been mentioned. In the following, a final retail price of 2,200 €/kWp (net price, including installation) is assumed. Under this assumption (which lies somewhat above the plant investment price determined by the German Solar Industry Federation for plants up to 100 kWp) the higher specific prices of small-scale plants with performances of 4 – 8 kWp as they are discussed here are taken into account. In view of anticipated further price reductions, this presumption might be considered as sustainable even having regard to forthcoming market reassessment effects. On the basis of the calculation approaches illustrated in Figure 5, annual costs of 156.20 €/kWp will result.

The assumptions regarding future price trends for photovoltaic facilities, i.e. the further course of the "learning curve", basically follow the scenarios provided by Fraunhofer Institute for Solar Energy [18]. Compared to the average annual price decline of almost 14 % between 2006 and 2011, a significantly slowed-down development is presumed. For 2013, a further decline in prices by 8 % is assumed, which is subsequently expected to decrease by half a percentage point annually, and eventually to follow the general price development from 2028 onwards.

Apart from the production costs, another three parameters have to be identified or assumed when determining the annual energy costs of a *plus energy house*:

1. The purchase price of electricity

2. The feed-in tariff (price for the power fed into the grid)

3. The self-consumption rate of the electricity produced on site

Ad 1: On average, the purchase price of electricity for domestic customers amounts to 21.24 ct net or 25.3 ct per kWh including the legal value added tax [17]. This price, which has been determined for the first half of the year 2011 for end customers with an annual energy consumption of 2500 to 5000 kWh, is included in the following calculations. Special electricity tariffs for operating heat pumps are not taken into account here for two reasons:

a) Special tariffs for electric heating systems diverge greatly in their amounts and will not be available throughout the country; anyway, they are only available in cases where net operator and energy supplier are identical.

b) These special tariffs are irrelevant when it comes to investigating economic effects of building energy supply with or without integration of PV generated power (all other system technology being identical), as they can be used in both cases (at least roughly) to the same extent.

Ad 2: At present the payment for feed-in solar electricity is legally regulated via the EEG (Renewable Energy Sources Act). This payment is subsidized through the EEG surcharge which aims at introducing this - currently still expensive - technology to the market and hence is no indication of the real market value of feed-in energy. The attempt of an economic localization of *plus energy houses* excluding EEG subsidies is faced with the problem of making a statement as regards conformity with normal market remuneration for solar electricity. As an appropriate, clear physical allocation to conventional electricity products is almost impossible, we are left with a large number of comparison figures which can be used here, including average wholesale prices for electricity, stock exchange prices for base-load and peak-load power, conventional electricity production costs in base-load or peak-load power plants, avoided or additional net utilization charges may be included or excluded etc. As far as any data at all is available on these comparison figures, it is subject to major uncertainties and a high variability, which is why it is superfluous to discuss the effects of individual options in detail. Instead, with reference to the already cited study [18] a price of 7 ct/kWh was made up according to the electricity production costs identified for 2012 as a basis for a possible level for feed-in payments, whereby certainly no overestimation of the market value is involved.

Ad 3: The self-consumption rate, i.e. the ratio of solar electricity used in the building in comparison to the overall production, has to be distinguished from the amount of self supply (degree of self-sufficiency), which measures the share of self-consumed energy against the total energy need. The lower the energy yield in relation to the energy demand, the greater the self-consumption rate. In the opposite case, the self-supply rate (degree of self-sufficiency) increases. In the case of equal annual amounts of electricity production and electricity consumption, the amounts of self-consumption and self-supply are identical, which is not, however, the case in the monthly balance.

When evaluating the EEG, which provides for a differentiated compensation arrangement for self-consumed solar electricity, some investigations followed up the question which amount of self-consumption is actually being (or can be) achieved in residential buildings. The results agree that only a moderately good synchronicity between production and consumption can be achieved without additional expenditure (self-consumption rate of about 20 % to 30% in the photovoltaic power range relevant for *plus energy houses* [20]).

The rate is highly dependent on the ratio of produced energy/ consumed energy, on the technical equipment and on user behaviour.

In order to achieve a high self-consumption rate, basically three strategic approaches should be considered:

1. The reduction of the ratio between energy production and consumption. This possibility is excluded for a building design for which this ratio has been determined to be at least 1.
2. The use of electric storage systems, especially accumulators, which can store temporary excess energy for use in low-radiation phases. Depending on the initial situation, the potential for raising the self-consumption rate through integration of accumulators differs considerably, especially with regard to the ratio of electricity production and power requirement. Even with small storage units which accumulate e.g. half of the average daily consumption, the self-consumption rate can be substantially increased and more than doubled in some cases – relating to domestic electricity consumption. Compared with this, the installation of greater storage capacities has relatively smaller effects on self-consumption [20]. Currently, the market for the required storage technology is being characterized by high dynamism, not least because of the EEG regulations. The starting level is, however, low, so that economically sustainable storage technologies for an increase in the self consumption rate can only be expected in a few years.
3. A cost-effective way to improve the amount of self-consumption is provided by the use of control technology to synchronize supply and consumption. For instance, loads can be shifted into favourable supply periods with the aid of simple automatic timers. This applies especially to major consumers of electricity as dishwashers, washing machines and dryers. To a certain extent, modern temperature-stable cooling units can also be used for load-shifts by cutting-off of the electricity supply in the early morning hours (e.g. 6-10 a.m. [20]). As a result, the self-consumption rate can be increased by up to 10 %. These minimally invasive optimization measures require, nevertheless, a certain planning effort. Thus it is not recommended to synchronize all flexible consumers at noontime when solar radiation is at its peak, because the advantage of load-shift is reversed on days with low solar radiation. An attractive field is opened up here for appropriate control equipment.

In the following considerations it is assumed that possibilities for the synchronization of supply and demand as specified under (3) will be mobilized in new *plus energy houses*. Moreover, the *plus energy house* which not only provides its own auxiliary and domestic electricity but also satisfies its electricity need for heating (in the annual balance) by generating its own electricity, offers another share of consumption with a high potential for load-shifting: the need for domestic hot water. This applies particularly to *plus energy houses* where the heat pump primarily uses heat sources outside the building (i.e. not exhaust air from the building). In this case, the supply of electricity for DHW heating can be separated from the DHW demand (with the aid of a water storage tank that covers the daily requirement or double), to be shifted almost completely to daytime periods with high solar radiation. Incidentally, controlling the heating of domestic hot water while at the same time reducing electricity use and electrical power consumption can thus indirectly open up an essential share of the load-shift potential, which is offered by connecting washing and dishwashing machines to the hot water storage.

6. Energy balances and energy costs of different *plus energy building* concepts

In the following section, the economic impact of integrating photovoltaic facilities into the energy supply of residential buildings will be demonstrated using the example of a single-family home.

The building is situated in an unshaded position at Potsdam, which is the EnEV (2012) reference location. The photovoltaic plant is installed at the pitched roof, which has a 30° inclination to the south. The plant performance ratio, i.e. the relation between the actual yield and the target yield of a plant, is moderately – in relation to the efficiency of modern plants – assumed to be 77 %. The annual transmission losses of 0.25 % (related to the output capacity) are accounted for by reducing the performance ratio. Assuming a life span of 25 years, an average effective performance ratio of 74.6 % results.

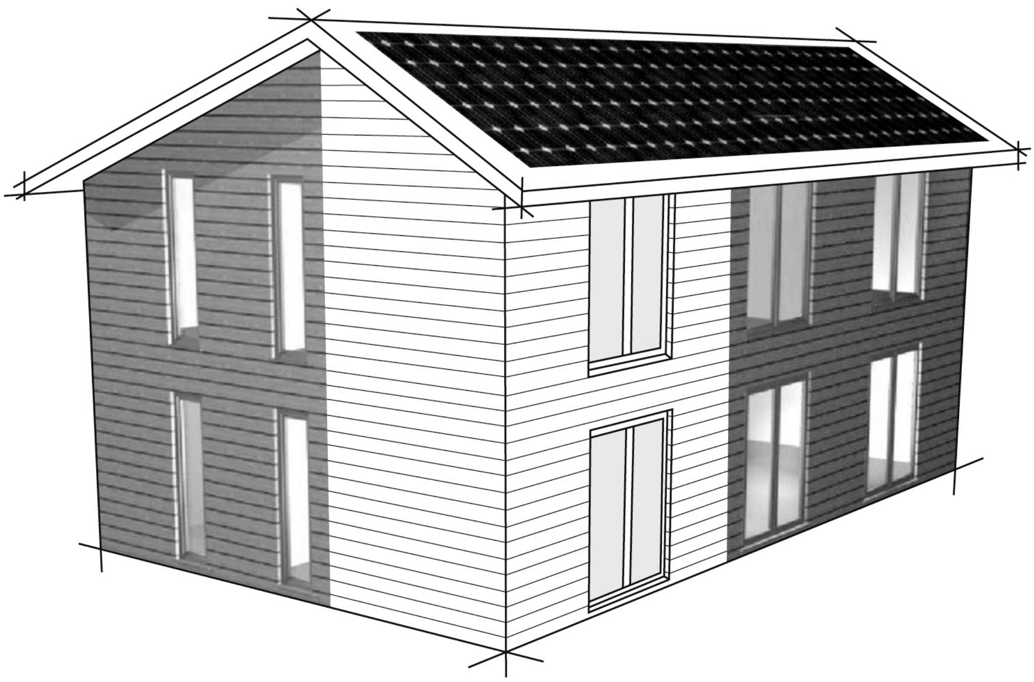


Fig. 7: Single-family house, 30° pitched roof, south orientation

Three variants will be investigated:

a) Heat supply via a brine-to-water heat pump (B/W_HP), energy quality of the external building components slightly better than the reference values for residential buildings stipulated in EnEV [1],
b) Heat supply via an air-to-water heat pump (A/W_HP), energy quality of the external building components slightly better than the reference values for residential buildings stipulated in EnEV [1],
c) Plus energy building constructed as a passive house (PH).

Table 2 lists the key parameters that are determined on the basis of the methods and assumptions specified in the annex.

Table 2: Parameters of the single-family home under investigation

Location:	Potsdam	Volume		540.0	[m^3]
Building:	SFH, no basement	A/V_e		0.76	[m^{-1}]
		A_N		172.8	[m^2]
		Living space		153.4	[m^2]
Construction		U-values			
Components	m^2	B/W_HP	A/W_HP	PH	
External wall	182.0	0.24	0.24	0.12	[W/(m^2K)]
Roof	100.0	0.20	0.20	0.10	[W/(m^2K)]
Windows	35.0	1.0	1.0	0.80	[W/(m^2K)]
Ground slab	89.0	0.25	0.25	0.20	[W/(m^2K)]
Main door	2.2	1	1	1	[W/(m^2K)]
Loss coefficient of the thermal bridge ΔU_{WB}		0.01	0.01	0	[W/(m^2K)]
n_{50}-value		1.0	1.0	0.5	[h^{-1}]
Technical building installations					
Heat recovery, ventilation system		80	80	85	%
Power consumption, ventilation		20	20	40	[W]
Power consumption, circulation pump		20	20	0	[W]
Heat pump SPF		4.8	3.7	2.6	[]

Proceeding on this basis, the required rated output of the photovoltaic plant is calculated as follows, namely: required rated output = annual power requirement /(total annual solar irradation, incident on the roof surface covered by 1 kWp PV systems * Performance Ratio)

For the passive house construction (PH), the calculated energy need for heating is 13.0 kWh/(m^2a), while the other versions (B/W_HP and A/W_HP) require 33.6 kWh/(m^2a). Despite its significantly improved construction, the passive house turns out to have an additional power requirement of 1.3 kWh/(m^2a) for heating and domestic hot water (including electrical auxiliary energy), due to the lesser seasonal performance factor (SPF) of the compact unit compared to the variant using a ground-coupled heat pump. The power demand of version A/W_HP, which features a less efficient heat pump than the baseline version, exceeds the demand of version B/W_HP by 3.1 and that of the passive house by 1.7 kWh/(m^2a). The output of the PV plant is derived from the requirement to completely cover the building's electrical energy need for heating, domestic hot water, and for domestic appliances in the annual energy balance. Correspondingly, the diverging power requirements of the examined versions result in different outputs of the required PV plants. These range between 5.2 and 5.7 kWp. Given a space requirement of 7 m²/kWp, the roof surface area will be large enough in any case (maximum: 40% of the roof surfaces, see Table 2).

The determined energy parameters are compiled in Table 3.

Table 3: Energy parameters of the single-family home under investigation

Single-family house	B/W_HP	A/W_HP	PH	
Energy need for heating	33.6	33.6	13.0	kWh/(m²a)
Power requirement for heating	12.4	15.5	13.8	kWh/(m²a)
Self-consumption rate	39.6	38.5	38	%
Power demand of PV system	5.2	5.7	5.4	kWp
Space requirement of PV system	36.2	40.0	37.8	m²

The model for determining the associated self consumption rates (given in the annex) produces slightly diverging results for the different versions. In Fig. 8 one can see that the passive house version is able to use a minor share of solar radiation to supply the building in the transitional seasons (particularly in March). Compared to the other concepts, the building with the air-to-water heat pump (A/W_HP) is distinguished by a higher self-supply rate of the electricity consumed during summer months, as its PV system is the one with the highest rated output (Fig. 8).

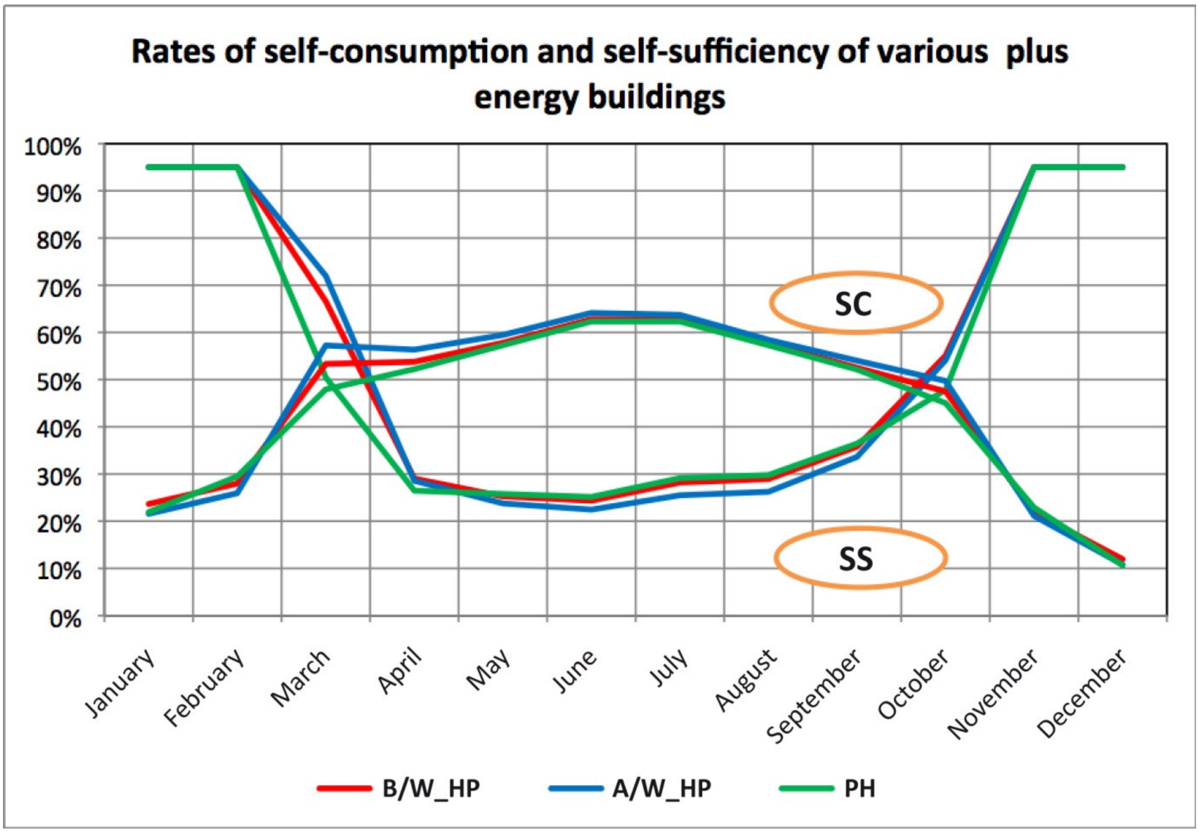


Fig. 8: Rates of self consumption (SS) and self coverage (SC) of variant *plus energy houses*

The monthly profiles of power generation and power demand and the resulting monthly purchase and feeding-in volumes are illustrated in Fig. 9 (baseline version with brine-to-water heat pump).

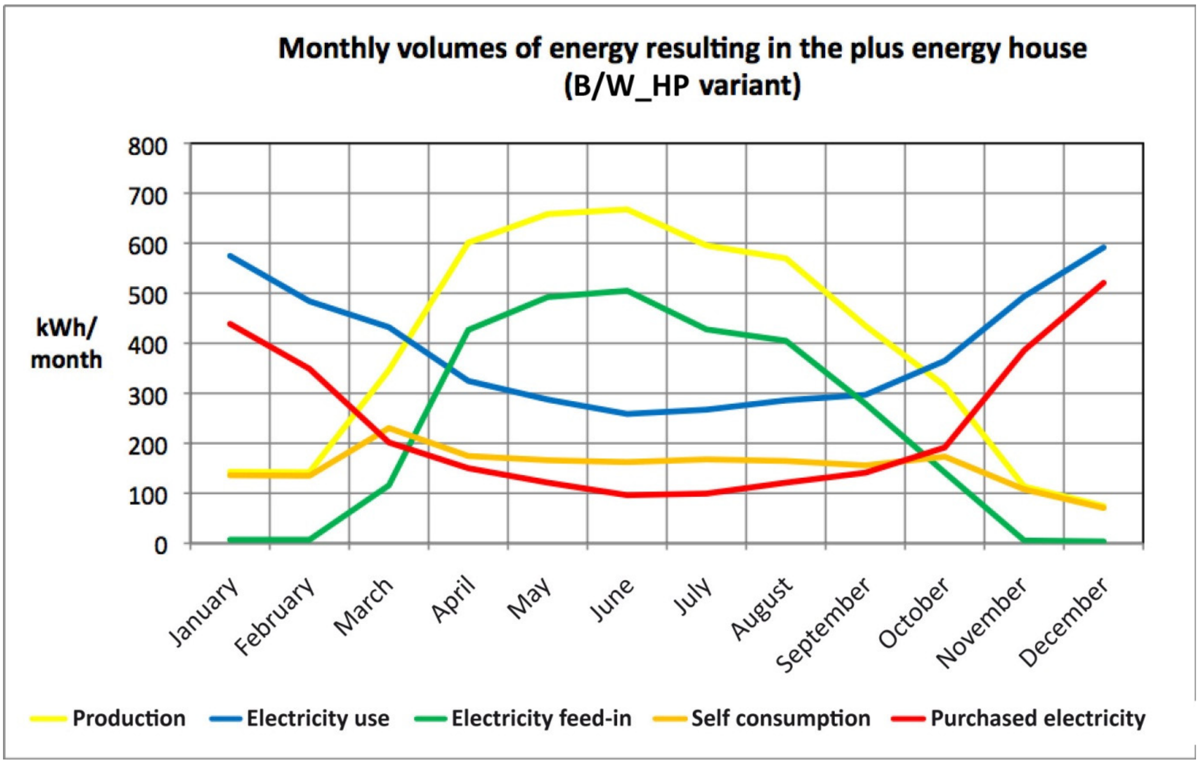


Fig. 9: Monthly volumes of energy in the *plus energy house* (supply: B/W_HP)

Due to the different self-consumption rates of the various building constructions, the resulting operative electricity prices (which are calculated using the formula explained in Chapter 2.4) are also slightly deviating:

Operative electricity price = costs of solar power production + (1 – self-consumption rate) * (purchase price of electricity – feed-in price)

The most favourable operative electricity price is equal to 26.0 ct/kWh (net) and results when using a brine-to-water heat pump for supply; however, the scenario using an air-to-water heat pump and the passive house version result in a price of 26.2 ct/kWh, which is only marginally higher. Hence, the operative electricity prices still remain about 25 % above the current purchase price of electricity.

This price difference will, however, rapidly decrease if the above described "learning curve" of the PV installation is extrapolated under the assumption that the purchase price of electricity will continue to increase. Even conservative assumptions of a price development in the amount of the rate of inflation (1.6 %) suggest that the price curves of the purchase price of electricity and the operative electricity price will intersect in 2016 at the latest. Already in 2020 the operative electricity price will undershoot the purchase price of electricity by some 15 % (Fig. 10).

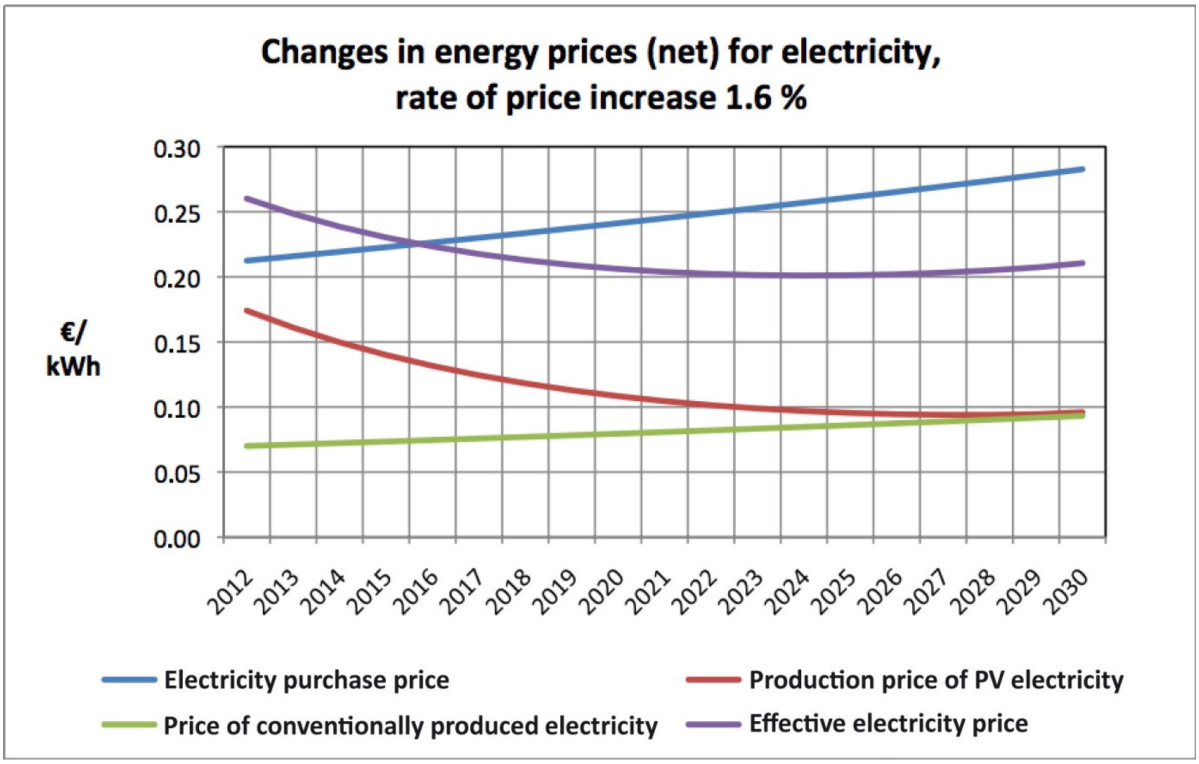


Fig. 10: Energy price movements, rate of price increase 1.6% (supply: brine-to-water heat pump)

In the first instance, grid parity of the operative price of electricity for the supply of buildings means that from this moment on there will be direct economic benefits (even in times of stagflation) for new buildings thermally conditioned by electrically driven heat pumps (due to the use of PV systems), even if no government subsidies (EEG, Renewable energy Sources Act) are being paid. When assessing the overall cost-effectiveness of the direct use of PV plants for supplying energy to a building this is only an intermediate step, however: any comparison of the building supply concepts in- or excluding self-produced solar power must not be based on the current costs, but rather on the cumulative cost of energy, which will result from the expected operating time of the technical equipment and the energy generation system. A supply concept including self-use of self-produced power will profit from the fact that the production costs for solar power (which result solely from the investment costs) will remain fixed over the entire period of analysis. In contrast, purchased energy prices (which remain relevant for slightly more than 60 % of the energy demand) are equally dependent on market developments as buildings that are not supplied with PV systems. The same is assumed for the remuneration of the amounts of electricity fed into the grid.

Based on a PV plant service life of 25 years for both building variants (both with and without PV plant) the cumulative cost of energy is expected to develop as shown in Fig. 11 (scenario: energy price increase amounting to the long-term average inflation rate of 1.6%) and Fig. 12 (scenario: energy prices rising by 1.4 percept above the inflation rate of 1.6 %).

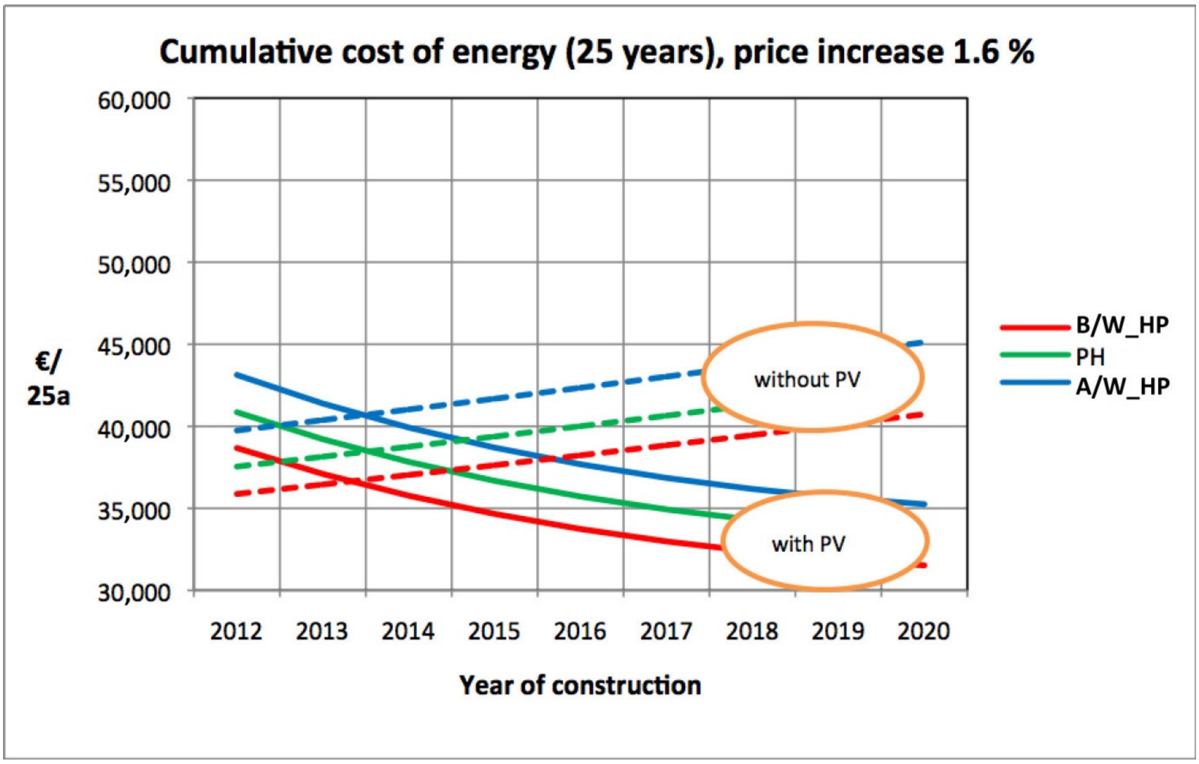
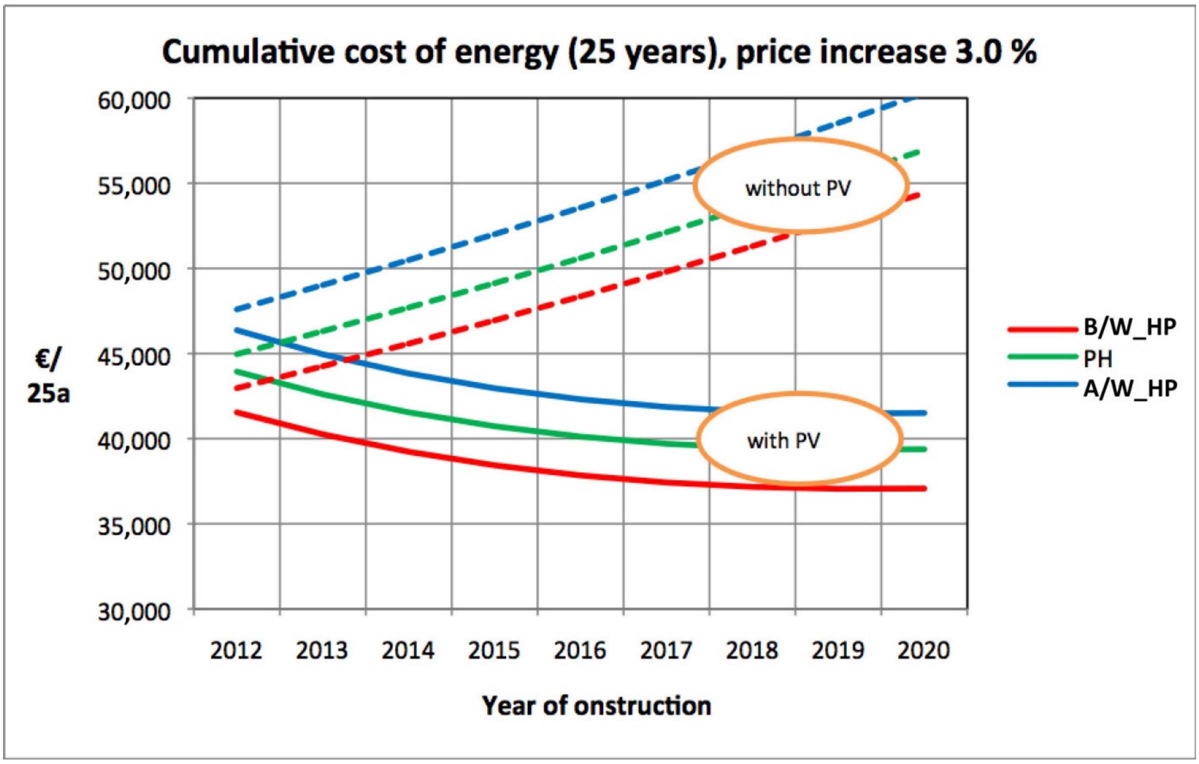


Fig. 11: Cumulative cost of energy (25 years), price increase of 1.6 %



Cig. 12: Cumulative cost of energy (25 years), price increase of 3.0 %

Currently, economic disadvantages will only be implied if one expects a low progression in energy prices in the order of the overall inflation rate; this applies to both variants of the single-family home with a supply concept featuring an integrated PV plant. But even based on this price scenario for purchased energy, economic benefits due to integrating PV systems will materialize for both building variants for construction years from 2014, at the latest. Buildings to be constructed in 2020 or later will profit from cost benefits due to using solar power in the order of approximately 12 %.

Assuming an electricity price increase of 3 % (that is 1.4 %, adjusted for inflation), which is still significantly below the price progression of the last few years, PV-generated power will reduce costs also for new buildings that are going to be raised in 2012. In this scenario, the cumulative cost of energy for buildings constructed in 2020 or later will be about 31 % less than for the reference building that does not use power generated by a PV system.

7. Sensitivity analyses of different *plus energy building* variants

When comparing the different supply concepts of the building, the version featuring the brine-to-water heat pump performs better than the passive house construction with regard to the mere cost of energy, even without considering the photovoltaic power generated. Due to the higher rate of self consumption, benefits will be intensified if self-produced solar power is included in the electricity supply. Notwithstanding, this relative advantage must not be misinterpreted as a general rejection of plus energy building concepts based on passive house constructions. Rather, the heat pump system‘s seasonal performance factor that actually has to be achieved needs to be accounted for. Thus, the passive house version of the building that is supplied by an air-to-water heat pump is superior with regard to the cumulative cost of energy. Anyway, current technical developments imply that the assumed seasonal performance factors of air-to-water heat pumps could soon be regularly surpassed in new constructions [21], provided that the low flow temperature of the heating system (which was assumed in this study) will be realised in practice.

a) Impact of domestic power requirements

In case this development should materialize, the appreciation of the building concept is yet by no means concluded. In fact, one has to consider that the different constructional standards are characterized by a divergent sensitivity with regard to the practical consumption of domestic electricity because the resulting internal heat loads will have a greater share in reducing the energy need for heating, the better the building's thermal insulation is executed. Although the specific domestic electricity consumption of 18 kWh/(m²a), which is assumed in this study, is far from defining the lower limit of what can be achieved by energy-conscious users in conjunction with high-efficiency domestic appliances (without compromising convenience!), this value is quite ambitious in comparison to actual, measured average consumption rates of more than 30 kWh/(m²a). For instance, if one assumed a specific domestic electricity consumption of 30 kWh/(m²a) p. a. this would result in almost equal costs: the cumulative, overall energy-supply costs in the passive house and in the building provided with a brine-to-water heat pump would be almost identical. Hence, the passive house might prove favourable in terms of the overall energy performance in cases of above-average domestic electricity consumption (proceeding on the assumptions for the technical systems made here). Vice versa, the two versions using water-based heat distribution systems provide better opportunities for saving energy by optimising domestic operation.

A possibly diverging sensitivity of the different plus-energy building concepts also needs to be observed when considering the other options of structural and technical building equipment.

b) Impact of integrating a solar thermal plant for domestic water heating

Since the collectors of solar thermal plants are in direct competition with the photovoltaic modules for the areas required for installation, aesthetic and ecologic, but mainly technical and economic aspects need to be included when discussing whether they could be a reasonable complementary technology for *plus energy houses*. In terms of aesthetics, a quick answer is found in favour of uniformly covering suitable building envelopes with PV modules in the case of conventional solar thermal concepts used for partial DHW heating and/or space heating support.

In the following, the economic aspects will be considered using the example of a solar thermal plant, which covers 60 % of the gross energy need of 17 kWh/(m²a) for DHW heating [22] by providing 0.6 kWh/(m²a) of auxiliary power [11]. For all the building variations, this measure will mainly reduce the summer power requirement of the heat generating units used for DHW heating, with the result that less electrical power output of the PV plant is necessary to achieve full coverage of the power requirement in the annual balance. Power reductions are equal to 0.35 kWp when using a brine-to-water heat pump, 0.38 kWp for heat supply by an air-to-water heat pump and 0.47 kWp for the passive house construction. Likewise, the seasonal performance factors of the heat pumps are affected by integrating the solar thermal plant in the supply concept, however not in the same way. While this measure induces a minor decrease (from 2.6 to 2.5) of the seasonal performance factor in the passive house, a slight increase (from 3.7 to 3.8) is noted in the building with an air-to-water heat pump and even a significant increase (from 4.8 to 5.3) in the case of the brine-to-water heat pump. These changes do not indicate a change in the efficiency of the heat generators proper, but are due to the fact that the solar thermal plant interferes in different operating situations, which are essentially governed by the respective relation between heat source and heat sink temperatures.

Accordingly, the integration of a solar thermal plant in the heat supply systems of *plus energy houses* will have different impacts on the feasible cost savings for the other versions, too. The costs that may be saved in the analysis period of 25 years on account of the solar thermal plant are visualized in Fig. 13.

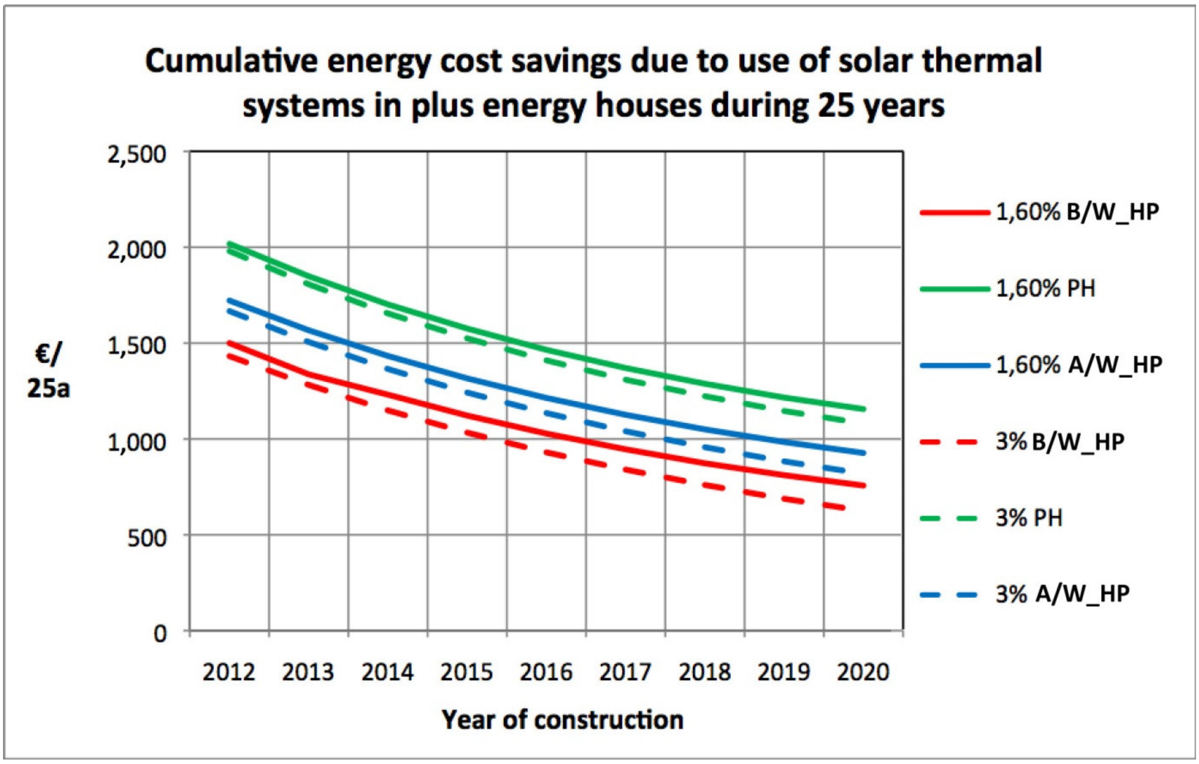


Fig. 13: Cumulative energy cost savings during 25 years, achieved by integrating a solar thermal plant in the heat supply systems of *plus energy houses* (rates of price increase: 1.6 % and 3.0 %)

Concerning the energy costs that can be saved during a solar thermal plant operating period of 25 years (as specified in Fig. 13) it can be stated that already today the costs required for installing this technology significantly exceed possible cost savings in the passive house case; in the other versions, installation costs clearly exceed potential savings. If the rate of the energy-price increase exceeds the rate of inflation, cost savings will decrease in all building variants, because the volume of costs saved is less than the cost reduction achieved by using the PV system. The cost-effectiveness of the investment would be further reduced by considering the annual costs of financing and maintenance, which have been excluded here. Proceeding on the assumption made in this study, namely that the photovoltaic system will completely cover the power demand in the annual balance, the energy contribution of the solar system for domestic water heating does not provide any added value (neither with regard to economy nor ecology), which is why it is not considered to be an appropriate option for *plus energy houses*.

In the last few years, however, more effort has been put into new approaches to integrate solar and heat-pump systems. These concepts are mainly based on the idea that solar heat should not be used directly (or only a small part of it); rather, it should be used indirectly to increase the heat source temperature, because in this way solar heat can be utilized on a low temperature level in conjunction with a higher solar thermal efficiency factor. Due to system-specific technicalities, this concept is not suitable for the heat sources air and water, but for ground-coupled heat pump supply systems in the *plus energy house* this concept in principle seems to be plausible. The conclusions presented in current studies are, however, somewhat disappointing:

“All in all, the research studies clearly showed that in systems employing heat pumps the direct use of solar energy is most preferable. In this way it is not necessary to use the heat pump to generate thermal energy; hence the direct use of solar thermal energy will yield the greatest savings in electrical energy“ [23].

From the technical point of view it seems to be more promising to follow a modified approach which does not use thermal collectors but includes a cooling circuit for the PV modules instead, so as to raise the heat source temperature for the heat pump while improving the efficiency of the solar power plant during summer months.

c) Impact of thermal insulation (example: external wall)

It is actually much more difficult to identify the economically most favourable thermal insulation quality for external building components than to assess the economic impact of integrating a solar thermal plant. Problems arise particularly with respect to the building component “external wall“, for which very different constructions and compositions are offered, which are likely to induce correspondingly high diverging cost effects due to their different energy qualities. Merely for the passive *plus energy house* the assessment is non-critical as the ambitious U-values do not have to withstand isolated economic efficiency calculations but need to be evaluated in connection with a heating system, which supplies heat to the building through the ventilation system and is thus limited to a maximum building heating load of 10 W/m². Economic optimization is hence achieved by minimizing any possible exceedance of the heating load requirement; in doing so, the high sensitivity of the passive house concept (compared to the variation of internal loads) needs to be considered in order to avoid that an eventual improvement of the household energy performance will have to be paid for by compromising thermal comfort in the heating season.

When discussing the economically most favourable envelope quality for the other two *plus energy houses* one has to bear in mind that - assuming complete self-sufficiency (in terms of the annual balance) in covering the power demand with photovoltaic electricity - the variation of the U-values is ecologically neutral. This means that an improved energy performance of the external building components (the annual balance still being neutral) will not improve the building’s ecological quality, apart from minor effects concerning grid use.

In a first approximation, the costs for the additional thermal insulation considered can be calculated against the costs saved due to the reduced power demand of the PV plant. Improving the initial external wall U-value of 0.24 W/(m²K) by an R-value of 1 m²K/W to achieve a target U-value of 0.19 will reduce the power demand of the PV plant (which is required to maintain a neutral annual balance) by 0.11 kWp when using a brine-to-water heat pump (B/W_HP) and by 0.16 kWp when using an air-to-water heat pump (A/W_HP).

Based on 2012 energy prices, lower PV plant investment costs result, namely 247 € less (B/W_HP) or 345 € less (A/W_HP); this corresponds to 1.36 € (B/W_HP) or 1.89 € (A/W_HP) per square meter of the external wall surface. The saved investment costs have to be weighed against average additional costs for improving the external wall insulation, which amount to 5.85 €/(m^2R) [24] and hence cannot come anywhere near being covered if only investment costs are considered. With relation to the above described price developments, saved investments amounting to 0.85 €/(m^2R) (B/W_HP) and 1.18 €/(m^2R) (A/W_HP) result for buildings constructed in 2020; these have to be compared to additional expenses for improving the energy performance of the external walls of 6.64 €/(m^2R) (based on an inflation rate of 1.6 %), related to one square meter of the external wall surface. Even when using particularly inexpensive composite thermal insulation systems, which were found to have a basic price of 4.10 €/(m^2R) in own investigations, further improvements of the thermal insulation will not provide any benefits if only investment costs are considered.

This comparison is not sufficient for a substantial economic efficiency analysis, because it implies 100 % self use of electricity, which cannot be achieved; it does, however, show that in cases where application of high-quality thermal insulation requires considerable effort, the PV plant provides a simple, low-cost alternative to compensate for the deficits.

To answer the question whether improving the energy performance of external walls (compared to the assumed baseline value of 0.24 W/(m^2K)) will be profitable for a *plus energy house* in standard cases, one should refer to the achievable cumulative energy cost savings. The cost saving potential due to improving the standard of thermal insulation by ΔR = 1 m^2K/W, related to a surface area of 1 m^2 of the external wall surface and a time period of 25 years, is shown in Fig. 14.

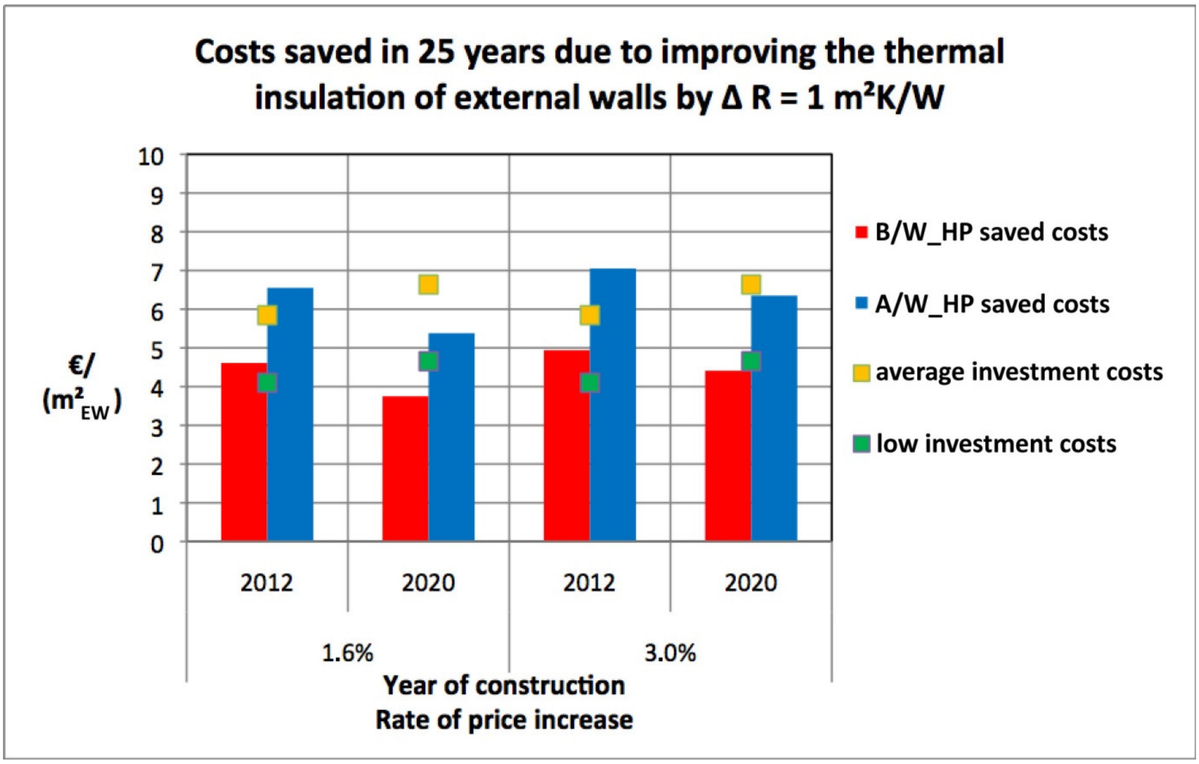


Fig. 14: Costs saved due to additional thermal insulation of external walls, baseline U-value 0.24 W/(m²K) for *plus energy houses* (B/W_HP and A/W_HP with PV plant)

When identifying an economically favourable standard of thermal insulation, investment costs for thermal insulation are not the only important factor; the efficiency of the selected heat pump is also significant (see Fig. 14). Under the aspect of a favourable energy cost situation, the building featuring the brine-to-water heat pump and an external wall U-value of 0.24 W(m²K) has already approximated the achievable economic optimum. Improving the U-value by ΔR = 1 m²K/W will allow for potential cost savings per square meter wall surface that almost equal the required investment costs (calculations based on 2012 figures). With regard to buildings raised after 2012, the data presented in Fig. 14 even suggest a possible reduction in the quality of thermal insulation - an effect, which could still be enhanced in the medium term, if electricity storage units can be successfully integrated in order to improve the self-consumption rate. On the other hand, a minor improvement of the insulation level presently seems to be recommendable for the building featuring the air-to-water heat pump, while for later years of construction - depending on the price development - a reduction of the U-value below 0.24 W/(m²K) will only be profitable in the case of particularly inexpensive insulation systems, under consideration of the investment costs.

The strong impact of the photovoltaic plant as an integral component in the building energy supply system towards a more moderate insulation level in the medium term is reflected in a comparison of the results presented in Fig. 14 with an analogous analysis for the buildings without a solar power plant (see Fig. 15).

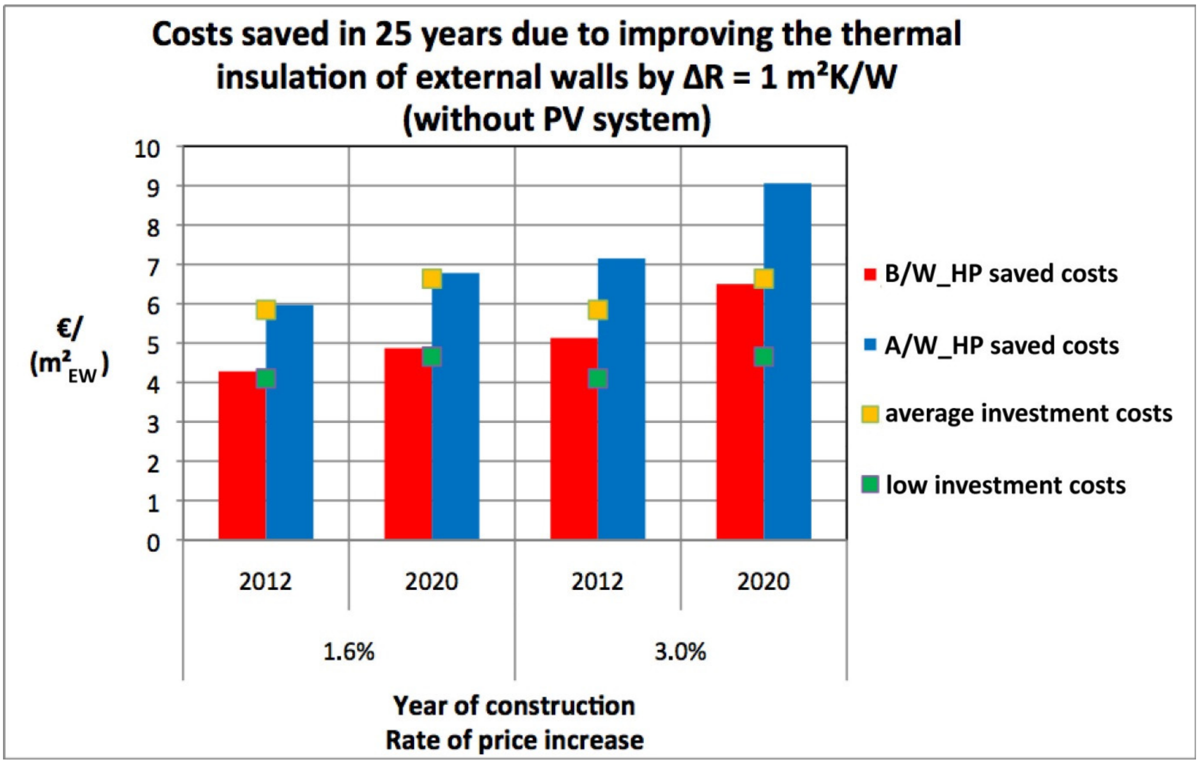


Fig. 15: Costs saved due to additional thermal insulation of external walls (EW), baseline U-value 0.24 W/(m²K) for reference buildings (B/W_HP and A/W_HP without PV plant)

8. Cost comparison of single-source *plus energy houses* and buildings with fuel-based supply concepts

More important than clarifying the internal relationship between the building concepts that feature exclusively electrical energy supply is the fundamental statement that integration of PV technology in the heat supply to buildings will be profitable from 2014 at the latest, i.e. will provide economic benefits besides environmental advantages. Based on an energy price increase of 3 %, this will even be the case if the PV power yield is assumed to be 20 % less due to unfavourable orientations or inclination angles. Such a yield loss will only shift the date from which the solar plant investments will be self-sustaining to 2017 and later realize cost reduction potentials also here.

The consequences derived from this insight are reaching far beyond the building concepts on a single-source electrical supply basis that are considered in the present study. Thus, self-consumed solar power will not only reduce costs and increase economic and environmental advantages of electrical heat supply; it will also improve the competitiveness of *plus energy houses* compared to similar new buildings featuring other supply concepts. Admittedly, alternative heat-supply concepts for auxiliary and domestic electricity will also trigger a cost-reducing effect which, however, is clearly weaker; under economic aspects, these concepts will hence lag behind the single-source strategies analysed here. Figures 16 and 17 show the potential cost containment for different supply concepts following the integration of a PV plant for two scenarios of the expected energy price development. They demonstrate three different types of Plus Energy Buildings (B/W_HP, PH and A/W_HP) plus a fuel based solution for heating in combination with PV for auxiliary and domestic electricity (FBH).

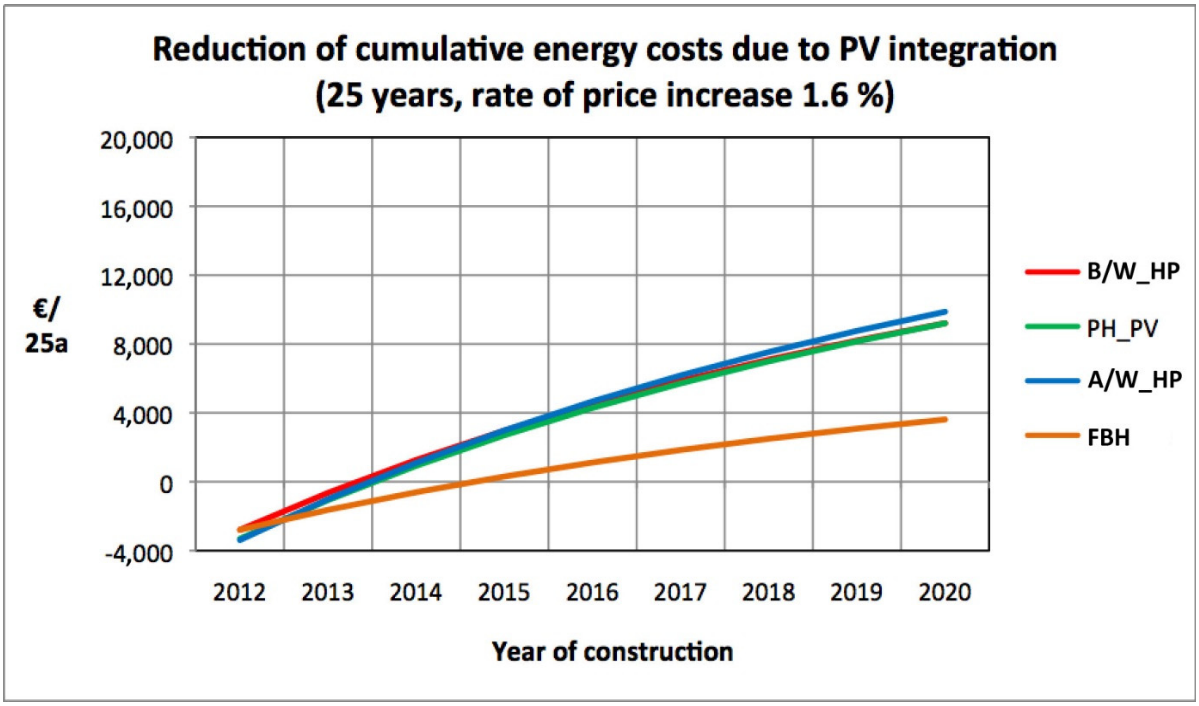


Fig. 16: Reduction of cumulative energy costs due to PV integration (rate of price increase 1.6%)

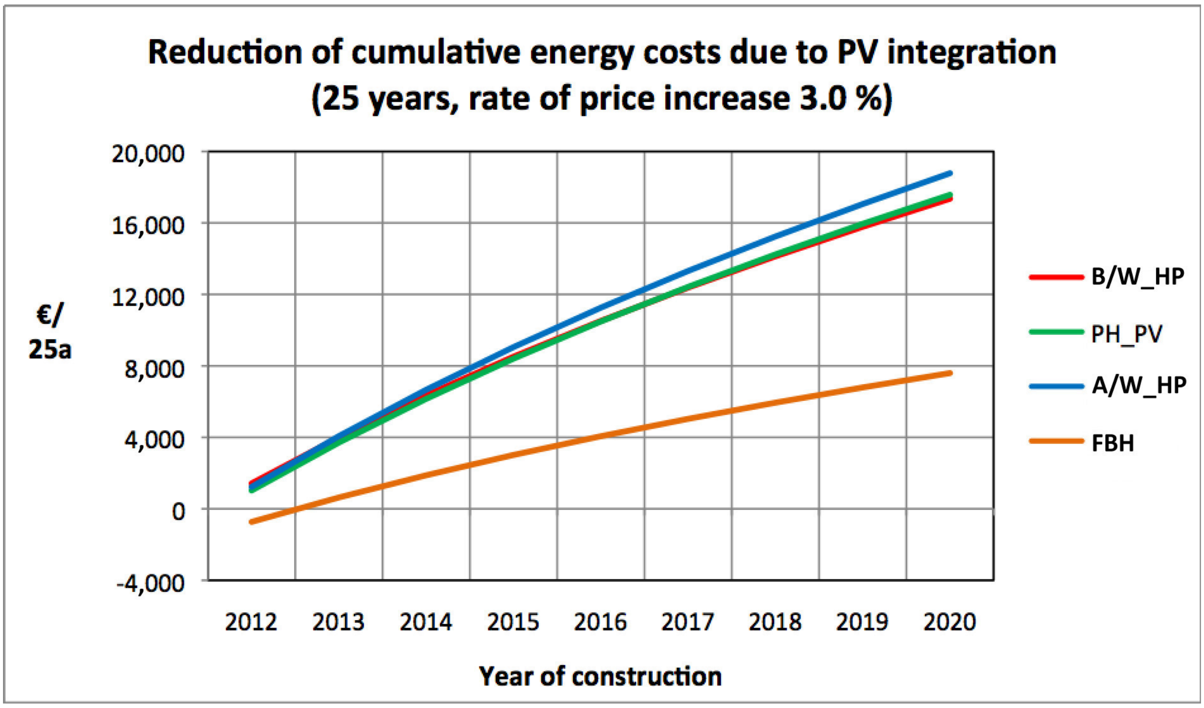


Fig. 17: Reduction of cumulative energy costs due to PV plant integration (rate of price increase 3.0%)

Not only does the cost containment of single-source supply-concepts set in earlier compared with fuel-based alternatives, irrespective of the energy price scenarios it is also about twice as much, providing correspondingly higher cost advantages when price increase rates are high.

Thanks to the integration of PV plants in the building supply, single-source concepts perform better than competing supply strategies, also with regard to the cumulative total cost of energy. This is shown by a comparison of different supply strategies for the exemplary single-family home, the construction of which corresponds to the buildings that are heated by heat pumps; the same diseconomy of scale (cost progression) as for the purchase price of electricity is assumed for gas and wood prices (Table 4).

Table 4: Fuel prices and performance ratios of fuel-based supply concepts

	Energy price 2011	Performance ratio
Gas-condensing heaters	7 ct/kWh	100 %
Wood heating system	4.5 ct/kWh	85 %

The comparison presented in Fig. 18 considers maintenance costs, chimney sweep's fees etc. including an annual price increase rate of 1.6 %. Plant investment costs were included with an annuity factor related to a 20-year period of amortization. The input data for investment and operating costs are taken from [25]. Costs incurred for the additional auxiliary energy input of fuel-based systems and special tariffs for heat pumps were not accounted for.

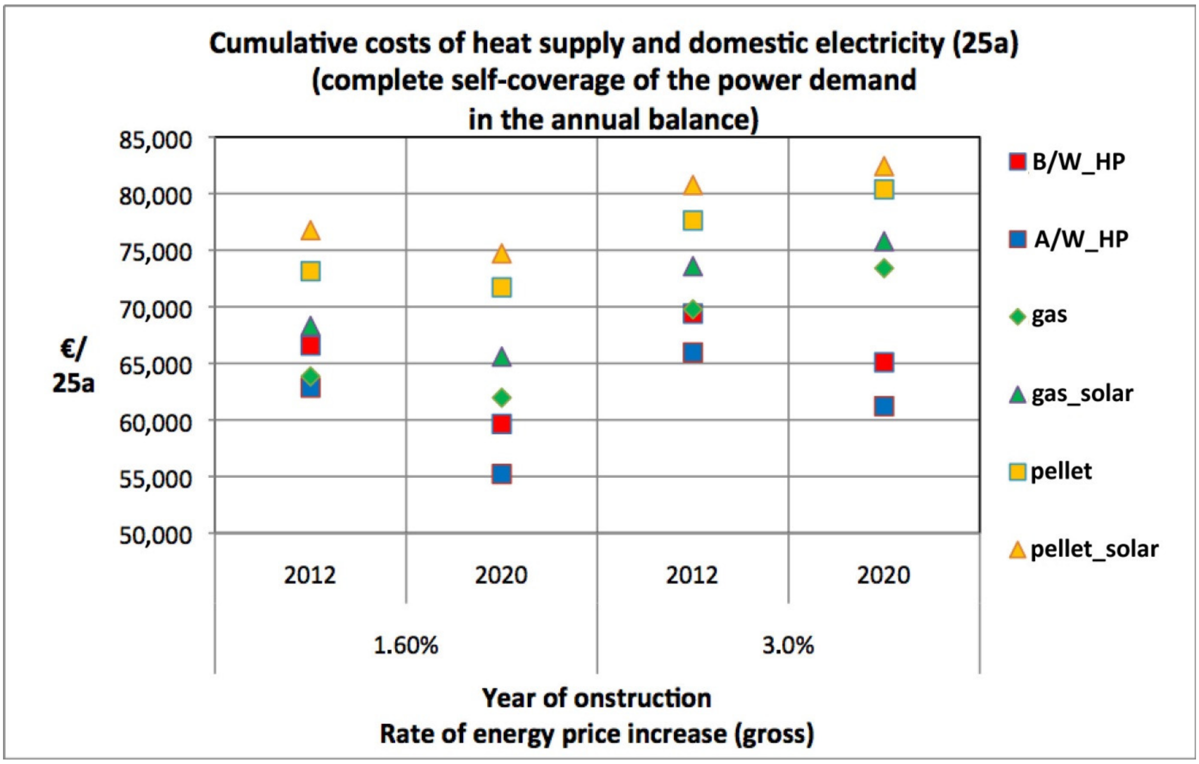


Fig. 18: Cumulative energy costs of heat supply and domestic electricity for different supply concepts

Fig. 18 visualizes the cost containment due to self-generated electricity (for all variants examined), which can even compensate for (more than) minor increases in the energy purchase price. In the case of fuel-heated buildings though, cost containment is not sufficient to absorb higher price increase rates; electrically heated buildings, however, will clearly disconnect from the future price development even in these cases.

Most of all, however, this comparison of cumulative overall costs shows that due to the integration of PV power the heat-supply concepts using electrically driven heat pumps are definitely competitive with other equipment solutions - even without applying special heat pump tariffs (and, correspondingly, also without paying any basic fee for a power meter counting heat pump electricity). Particularly with regard to future building projects, this combination even promises to provide substantial economic advantages. It should be stressed, though, that electricity special tariffs are also to be considered for heating *plus energy houses*. In the case of major price increases, which are to be assumed particularly with regard to fuels, the economic advantages will also increase. This is all the more remarkable as the economically most favourable plant solutions also imply the highest environmental quality: neither the gas-heated versions nor those using a wood-heating system can achieve zero-energy requirement.

Of course, a "surplus standard" may be theoretically established in this case, too, if the fuel demand is compensated for in the balance calculations by considering additional feed-in volumes of electricity. This can be done both on the basis of a balance considering merely delivered energy or by weighting the primary energy use: for instance, the use of wood as a source of energy (with a primary energy factor of 0.2 per kWh) can be compensated for by one twelfth of the electricity volume, as electricity is currently weighted with a primary energy factor of 2.4 per kWh. If appropriate, also a combination of the compensation measures (namely, delivered energy and weighted primary energy) can be used as a criterion to verify *plus energy house* standards; in this case, however, only delivered energy can be referred to by definition. Both approaches fail to meet the above-described basic requirements with regard to a future energy supply system of buildings, particularly the requirement to minimize the use of stored energy. On the other hand, builders are burdened with additional financial loads because they are forced to produce electricity they cannot use in their own households at high cost if they want to realize a fuel-based *plus energy house*. The economic absurdity of such accounting models is not altered by the fact that builders are currently allowed to pass on these supplementary costs to the community of electricity consumers (due to EEG[1] payment regulations). This statement is neither a plea against EEG payment regulations nor against associated investments in PV plants on new buildings; it merely is a critical reflection on merging existing EEG regulations with the "plus energy" building standard within one definition. The respective optimization potentials may only be identified if a clear distinction is made between the technical and economic options for using self-generated PV electricity to supply buildings on the one hand and the mechanisms laid down in the EEG funding instrument on the other hand. **With regard to the design of *plus***

[1] EEG = Erneuerbare-Energien-Gesetz, Germany's Renewable Energy Sources Act

***energy houses*, the biggest economic advantages will be realized by combining power production with a single-source supply concept based on electricity.**

9. Comparison of the "fuel efficiency" of the supply concepts

In Chapter 2 the main challenge to successfully provide a regenerative basis for the energy supply system was identified as the necessity to minimize the demand for – both renewable and non-renewable – fuels as stored energy. This challenge is met by single-source plus houses using self-generated solar electricity that fully covers the annual power demand. Achieving full self-sufficiency in the annual balance, however, does not mean that the degree of self-sufficiency is actually 100 %, as major shares of the PV generated electricity have to be exported to the grid, while (mainly in the heating season) the purchase of power cannot be avoided. This purchased power, the main portion of which needs to be generated by thermal power stations, might be interpreted as indirect use of fuel and be chalked up to the *plus energy house* as understood in the present study. This would call into question the equivalence of exported and imported electrical energy that was assumed in this study; the issue of considering some conversion expense for the purchased power would be raised, which would, however, be opposed to the asymmetry of evaluation anchored in [12].

> Note: In the scope of an EnEV evaluation based on the new version of German standard DIN 18599 [12], using diverging primary energy factors for imported and exported electricity, a reduction in the heat losses will lead to a deterioration of the building's performance with regard to its primary energy use (with a neutral annual balance of delivered energy). Besides, the higher valuation of exported power compared to imported power - which is incomprehensible from the physical point of view - has another consequence: out of two given buildings with the same use of electricity, the building with the poorer PV plant integration (that hence causes higher energy costs) will receive the better primary energy rating!

But even if such a process of change is going to be considered, a single-source power supply concept is found to be clearly superior to possible alternatives. In Fig. 19 the building with a brine-to-water heat pump and the passive house are each compared to a fuel-based supply concept, assuming a boiler efficiency of 100 %. Further, utilisation of a PV plant is assumed, with the plant covering only the need for domestic and auxiliary electricity in the annual balance (based on a self-consumption rate of 30 %). In all cases, the purchased power is weighted with a factor of 1/0.55 to reflect the power generation in a modern gas-fired power plant (including power losses to the grid). The amount of electricity exported to the grid is then subtracted from the indirect fuel supply in order to obtain the net fuel demand.

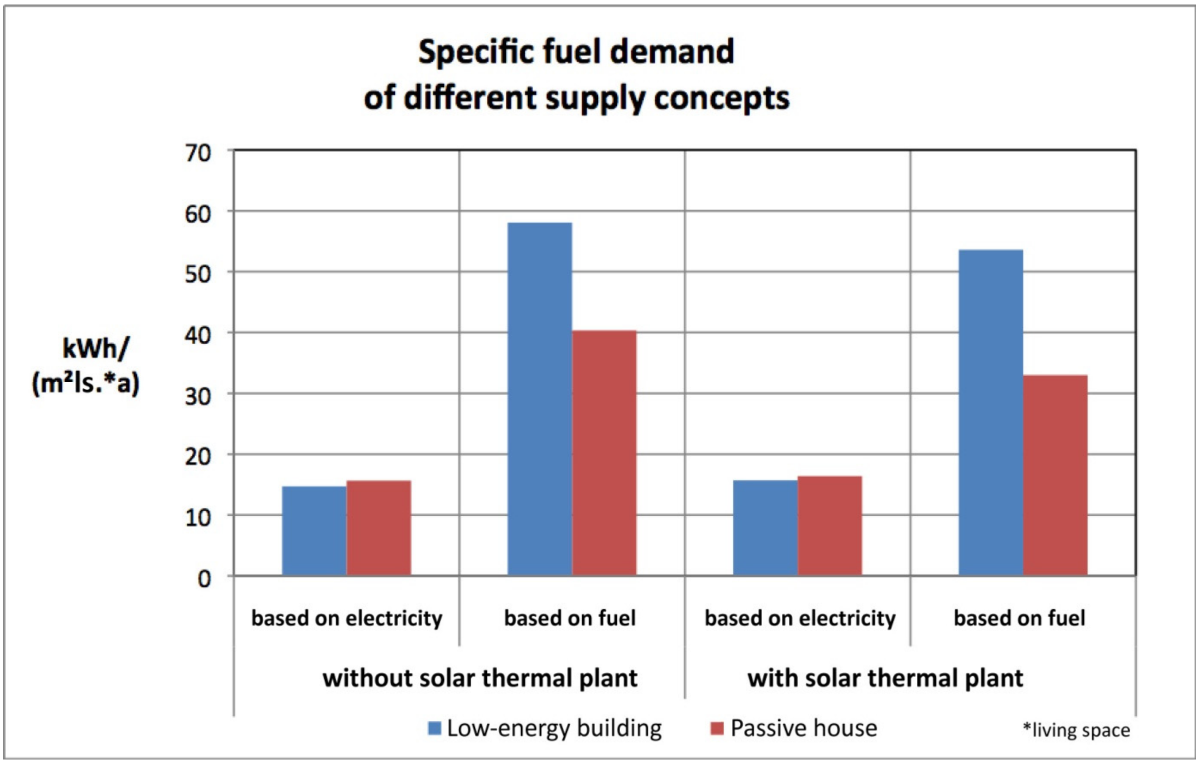


Fig. 19: Annual specific fuel demand for supply and domestic electricity according to different supply concepts

In the building supplied by a brine-to-water heat pump, the fuel efficiency differs by more than factor 4 compared to a similar low-energy building. There are also clear advantages for the electrically supplied passive house, the fuel efficiency of which turns out to be nearly three times better. In both cases a considerable - although reduced - efficiency gain in the order of factor 2 to 3.5 remains, even if a solar thermal plant is included. The solar thermal plant actually has a significant impact on the fuel efficiency of fuel-based systems, but hardly any in the case of single-source concepts.

10. Regulatory implications

It has been shown that the integration of PV plants in the heat supply of buildings will considerably contribute to reducing the overall costs of energy incurred during the amortization period of the technical building systems. Within an electrical, single-source operation supply concept this cost saving effect is not only economically and environmentally superior to alternative *plus energy building* concepts; it also has advantages over buildings that do not reach the threshold value of zero. In this context, potential cost reductions resulting from options to use temporary surplus electricity by fluctuating power exports to the grid (mainly from wind turbines) have been mentioned but not yet included in the economic assessment.

Cost reductions obtained by integrating PV plants in the energy supply to buildings do not place a burden on the national economy and relate to one of the largest sectors of final energy consumption. This involves 28 % of the overall need for delivered energy, with regard to private households alone.

For non-residential buildings, even better average results may be expected since the demand for electricity and the supply of solar power are clearly better synchronized, both on a daily (due to less early-morning and evening peak loads) and a seasonal level (increased energy need for cooling compared to the energy need for heating).

These insights call for fundamental consequences, among other things with regard to future amendments of the administrative law in so far as the energy demand of buildings is concerned, and particularly with regard to the German Energy Savings Directive EnEV (including its underlying standards). In concrete terms this might provide an option to surmount the antagonism between the EU requirement for a nearly-zero energy building standard [2] from 2020 and the high economic barriers posed by the efficiency rule stipulated in the German Energy Conservation Act EnEG [3]. A possible solution might be to closely approximate a target value (beyond zero), or even to bring forward the date for achieving this value.

Obviously, the consideration of PV plants as integral building components will widen the scope for tightening the energy requirements to new buildings. In any case, this applies to the achievable overall result, namely a final energy demand < 0. The reference that is made to final energy (delivered energy), which denies the superfluous (and in its current form even detrimental) primary energy assessment of various energy carriers, has a positive steering effect in favour of the economically and environmentally most beneficial supply concept. Regarding the performance of building envelopes, however, only a moderate price increase seems to be economically justifiable, owing to the reduced energy cost progression due to PV plants. Anyway, the isolated consideration of building envelopes in the context of *plus energy buildings* is methodically obsolete; for instance, secondary requirements to buildings are no longer necessary. With reference made to the final energy demand, it can be left to the builders or to the market which levers to choose in order to accomplish the target value < 0, without sacrificing a high standard of thermal insulation.

However, possibilities to simplify the energy requirements to new buildings are not yet fully exhausted by introducing the *plus energy building* as a standard for new constructions in conjunction with making reference to final energy. Particularly the present, unhappy co-existence of the German "Energy Savings Directive" (EnEV) and the "Renewable Energies Heat Act" (EEWärmeG) [26] can be overcome by securing fully renewable building energy supply. Another option could be to abandon the EnEV reference building method in favour of a specific required value, as this value – provided there is a unified normative calculation principle – can be formulated independently from building compactness and building use.

There is however, still need to discuss the appropriate amount of such a requirement value < 0. Both under the aspects of environmental protection and economic efficiency it would be desirable to cover the required volume of electricity by self-produced electricity as exactly as possible. As it is hardly possible to give a normative description of the individual shares of energy that are not used for the thermal conditioning of the building (including the energy need for domestic hot water) such a standard value cannot be specified. Consumption of domestic electricity hence can differ in two comparable apartments by factor 4. Moreover, it needs to be considered that tenants in rented buildings cannot be forced to use self-generated electricity. Another aspect in disfavour of too ambitious a target value is that this could possibly work as a negative incentive with regard to reducing the need for domestic electricity. It must also be kept in mind that the bigger and more compact the structure is, the less suitable roof surfaces will be available for installing the PV plant.

For a start, it is therefore recommended to leave it at a value that is not too far away from the "zero" limit - for example at a specific surplus share of 10 kWh in relation to the balance components heat, cold, DHW heating - when introducing the *plus energy building* as the required building standard. Should this result in a shortfall of the required overall energy supply it would at least be ensured, however, that the energy part-balances specified in the directive will be served by the PV plant at an increased rate of self consumption. This would, however, not improve the overall profitability of the building energy supply, but the profitability of the solar power plant as a new component to be included in building design.

In the foreseeable future, however, the German Renewable Energy Sources Act (EEG) payment regulations might anyway induce clearly higher balance surpluses in practice, as PV plants are dimensioned according to the suitable roof surfaces available. As a matter of fact, *plus energy houses* presently might come up almost automatically on the basis of current EEG payment tariffs - provided the planning of new constructions complies with the German Energy Savings Directive (EnEV) requirements and heat pumps are used for the building's heat supply. Currently, however, the EEG (Renewable Energy Sources Act) does not provide any incentive for combining the production of solar electricity with a building energy supply using electrically driven heat pumps. By contrast, in cases where special tariffs for electricity generated by heat pumps are available, the self-consumption of solar power for operating heat pumps even causes economic disadvantages compared to grid export. In conjunction with the primary-energy assessment approach specified in the Energy Savings Directive (EnEV), a negative incentive (dis-)encouraging the economically and ecologically reasonable combination is triggered even more, as balancing the low primary energy factors of the purchased (particularly the renewable) fuels against the high factors attributed to electricity will yield much more "noticeable" primary energy characteristics. At the interface between power and heat supply, namely at the *plus energy building*, the funding instruments (or the requirement instruments, respectively) that were designed under a sectoral focus, fail to opt for the economically and ecologically most favourable solution. This is symptomatic of an astonishing "paradoxicality of the energy turnaround".

In the meantime, the automotive industry has reached a consensus on the expectation that the future belongs to electrical drive technologies, although the exclusively renewable power supply of vehicles can hardly be ensured and despite the fact that many technical (but mostly economic) problems still remain to be solved. Thus, the question to be answered is 'when will the future arrive in the present?' In the construction sector, we are facing the reversed situation, however: the technical solutions to construct buildings as *plus energy houses* generating surplus electricity have been available for quite a long time. In applications of direct building supply, photovoltaic technology is taking a big step to cross the threshold of profitability. The single-source *plus energy building* no longer is just a future option, it is a present one. However, the necessary consensus on the fact that the future belongs to this concept still has to be reached.

Annex: Calculation principles

A Balancing method and technical building systems

The standards that are used to assess the energy performance of buildings [10; 11; 12] - for instance, when issuing building energy certificates according to the German Energy Savings Directive (EnEV) [1] - currently do not provide a sufficient basis for carrying out the calculations presented in this study. Mainly the monthly rates of self-consumed solar power and the monthly degrees of self-sufficiency cannot be precisely determined when using these tools. Neither do these standards allow for a balance integration of specific, monthly approaches regarding domestic electricity consumption.

In view of these shortcomings, the calculations for the present study were carried out using an Excel-based monthly balance sheet, which takes account of the above-mentioned aspects but otherwise follows the specifications made in these standards. The plant parameters will be integrated on the basis of simplified assumptions, as explained below.

The heat losses due to transmission and the remaining ventilation heat losses (heat recovery and infiltration depending on the n50-value being considered) will be balanced against the solar and internal sources of heat (related to an internal temperature of 20 °C). Here, heat gains through opaque building components will not be considered (just like when planning passive house projects following PHPP [27]). With regard to the utilization factor of the heat sources, all building types are assumed to be heavy-weight constructions.

By way of derogation from the above-mentioned standards, the resulting internal heat gains are not taken account of as blanket values: the internal heat gains are derived from the monthly domestic and auxiliary power requirement and - in the case of the single-family house - from the heat losses of the hot water storage tank. Metabolic heat is treated as an internal heat load using a factor of 0.3 W/m² [28], heat losses through cold water consumption and evaporation are considered.

The value of 17 kWh/(m²a) takes blanket account of the energy need for domestic hot water, thermal losses due to storage and distribution being considered [22]. Since the examined building does not have a basement and the DHW storage tank is hence located within the heated building envelope, storage losses of 4 kWh/(m²a) are included in the building's heat balance. The base-case electricity consumption (incl. lighting) is assumed to be 18 kWh/(m²a), corresponding to the target values for passive houses [28]. The consumption of domestic electricity is not expected to be equal in all months of the year: rather, a stepped exceedance of the average demand by a maximum of 20 % in the heating season and a stepped undershooting of up to 20 % in the summer months are assumed [20].

All building variants under investigation are carefully executed and provided with high-performance components. Either, the energy performance of the building envelope surfaces complies with passive house standards or exceeds the reference values specified in EnEV

2009 by about 15 %. Particularly with regard to thermal bridging and building airtightness, high-quality execution of the construction is mandatory for a *plus energy house*. This requirement is reflected by the assumed loss coefficient of the thermal bridges: 0.0 W/(m²K) for the passive house and 0.01 W/(m²K) for the other two variants, just like by the n_{50}-values of 0.5 h^{-1} (PH) and 1.0 h^{-1} (other variants).

But also the technical building equipment has to meet high standards in a *plus energy house*. In the passive house construction, the power consumption of the compact unit is only 40 W on average. In the versions supplied by heat pumps, the ventilation system can even be operated at an average power consumption of 20 W due to using decentralized aggregates with reduced pressure losses, however at a slightly lower efficiency (80 % compared to 85 %). (These values are based on the most efficient aggregates specified in [29]). The average power consumption of the high-efficiency heating-water distribution pump in the buildings using brine/water and air-to-water heat pumps is 20 W.

A monthly differentiation is made with regard to the coefficients of performance of the various heat pumps used, as particularly the values of the air-to-water heat pump are strongly depending on the seasonal variations of the heat source temperature. The assumptions made with regard to pump performance are based on practical results obtained for well-designed systems [29].

A mean annual generator COP of 4.8 (without accounting for thermal losses due to storage) results for the brine-to-water heat pump and of 3.8 for the air-to-water heat pump. Basically, these good values are due to the low, assumed flow-temperature of the underfloor heating system, as suggested by the reference values of 3.4 and 2.6 for a flow temperature of 55 °C (and values of 4.3 and 3.3 at a flow temperature of 35 °C). For the passive house, the COP was assumed to range between 2.2 (in the central months of the heating season) and 3.0 in March through October (average: 2.6).

B Determining the rate of self-consumption

The personal use of the solar power yield presents one of the key factors in the economic balance of supply concepts for *plus energy houses*. However, it is rather difficult to precisely determine this rate, as it is subject to a variety of uncertainties. On the one hand, this difficulty is due to the fundamental problem that not only solar power yields are subject to temporal fluctuation: likewise, the capacity and the temporal power-demand profile inside the building are also considerably depending on the equipment of the electric appliances, on the design of the heat supply system, and on individual user patterns. On the other hand, there is still a substantial lack of specific measurements and statistical analyses to provide information in this issue, which could produce a reliable picture of the situation. So far, the most detailed study on achievable self-consumption rates is based on simulations of the domestic electricity consumption in households different in terms of size and technical equipment [20].

The assumptions made for the expected self-consumption rates in the respective *plus energy houses* are based on the results that were obtained in this study for a four-person household that does not use electric storage. With regard to the consumption segments of domestic electricity and auxiliary power, the transfer is effected such that the specific fractions of self-sufficiency per month are slightly smoothed over in a first step. Subsequently, the potential improvements that were examined in the study - namely by "systematically optimizing consumption" and by "using energy-saving appliances" - will be included by adding a percentage value to the monthly shares of self-sufficiency.

The degrees of self-sufficiency that were determined in the simulation study are depending on the ratio of the solar radiation supplies and the power requirement. If this ratio is balanced in the annual account, the resulting curve of the self-sufficiency rate will be approximately sinusoidal, ranging from 12 % in December up to 45 % in the months of June and July. If there is a deviation from the balanced supply/demand ratio, the monthly rates can be adapted using the factor given below:

$$F = (\text{Solar power supply/ power requirement})^{0.36}$$

If the afore mentioned fractions of consumption are approximately covered by the solar power supply (by somewhat more than 50 %), the resulting rates of self-consumption and self-sufficiency (see Table 5) for the domestic and auxiliary power situation in the *plus energy buildings* are in good agreement with simulation results.

Table 5: Rates of self-consumption and self-sufficiency, related to the domestic electricity need and the auxiliary power need

	Simulation [20]	GV_SW	NV_LW	PH
Self-consumption rate	21.40 %	23.46 %	20.94 %	21.37 %
Self-sufficiency rate	36.20 %	36.07 %	36.07 %	36.27 %

The inclusion of the power requirement for supplying heat to the examined *plus energy houses* is based on the consideration that the heat pumps can be operated without degrading the rates of self-sufficiency and self-consumption that are related to domestic and auxiliary electricity. Particularly DHW heating proves to be sufficiently flexible to achieve almost full self-sufficiency in covering the power demand for heat supply (assumption 95 %) in the period from April to September - due to the buffer water storage tank and prioritized operation, depending on the solar power supply and other power requirements.

This consideration is not only supported by the fact that fivefold oversupply (at least 5.5 times more power than required) will result for all building configurations in these months (after deducting self-consumption of domestic and auxiliary electricity); also, PV output in the summer months clearly exceeds the average household load (including DHW heating) of the day/night cycle - even under cloudy skies with low solar radiation (e.g. 200 W/m²) during daytime hours.

However, one restriction must be made regarding the passive house version of the *plus energy building*, where the control of DHW heating is less flexible compared to the other configurations. On the one hand, the heat pump needs to utilise the heat source of the exhaust-air pipe for water heating, so there is only a scarce heat source available; on the other hand, the heat pump also needs to be synchronised with the operation of the ventilation unit, which in turn will reduce the options for load shifting. Here, a somewhat lower degree of self-sufficiency (90 %) is assumed for the summer months to account for the power requirement of the compact unit. For the between-season months of March and October, the load shifting potential of the heat pump electricity has to be assumed to be 10 percent lower, which is due to the reduced oversupply. It is assumed that the low amount of solar power that will be supplied in the core months of the heating season (from November through February) will be used almost completely due to the supply-controlled heat pump regulation. To prevent overestimation, unavoidable feed-in volumes are assumed to amount to 5 % of the total supply.

Table 6 specifies the monthly rates of self-consumption and self-sufficiency that result for the three examined versions of a single-family plus-energy house under the assumptions made above.

Table 6: Monthly rates of self-consumption and self-sufficiency for different *plus energy houses*

	Self-consumption rate			Self-sufficiency rate		
	B/W_HP	A/W_HP	PH	B/W_HP	A/W_HP	PH
January	95 %	95 %	95 %	23 %	21 %	22 %
February	95 %	95 %	95 %	28 %	26 %	29 %
March	68 %	74 %	51 %	54 %	58 %	49 %
April	29 %	29 %	26 %	54 %	57 %	52 %
May	25 %	24 %	26 %	58 %	60 %	57 %
June	24 %	22 %	25 %	63 %	64 %	62 %
July	28 %	25 %	29 %	63 %	64 %	62 %
August	29 %	26 %	30 %	58 %	59 %	57 %
September	36 %	33 %	36 %	53 %	54 %	52 %
October	56 %	55 %	48 %	48 %	50 %	45 %
November	95 %	95 %	95 %	22 %	21 %	23 %
December	95 %	95 %	95 %	12 %	11 %	11 %

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Plus energy houses, i.e. buildings that produce more energy than they consume, will play a key role in the imperative implementation of a future energy supply system. This study shows how competitive plus energy buildings can be implemented through combining photovoltaic systems with electrical systems of heat supply. Plus energy houses are technically feasible and economically successful. They are a concrete technical option. This residential buildings concept could thus serve as a basis for future legal requirements.

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