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Cost Optimal Analysis of Positive Energy Buildings

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Abstract. This paper describes the cost optimal calculation method for the techno-economic assessment of Positive-Energy-Buildings (PEBs) and applies this evaluation framework to two case studies in different climate zones. The approach is based on the EU supplementing guideline 2012/C 115/01 and compares global costs and net primary energy demand of different energy technology packages. The case studies are residential buildings located in Valladolid, Spain (Mediterranean climate) and Helsinki/Kalasatama, Finland (Nordic climate). The results of the analysis reveals that not all PEB technologies are cost optimal and reduce global costs with current energy prices. Several factors affect the cost-effectiveness of the technologies, such as the shape of the building, the climate zone and the overall technological system in which they operate. Furthermore, results are very sensitive to calculation parameters such as electricity prices, discount rate and calculation period. The cost optimal analysis of case studies in different climate zones indicates that PV and a change of the heating system are in most cases cost optimal technology solutions that reduce net primary energy demand and global costs. Lessons learned from this research can contribute to the definition of comprehensive evaluation frameworks aimed at optimizing, disseminating and replicating PEBs in Europe.

Keywords: Positive Energy Building, Positive Energy District, Cost Optimal Analysis, Technoeconomic Analysis, Sustainability

1. Introduction

Positive Energy Buildings (PEBs) may be an integral part of comprehensive approaches towards sustainable urbanisation and decarbonisation of the European building stock, which is currently responsible for about 36% of all CO_2 emissions in Europe [1]. The new Energy Performance of Buildings Directive (EPBD) revision [2] requires Zero Emission standard for all new buildings after 2030 (2028 for public buildings) and a complete decarbonisation of the European building stock by 2050. The design of new PEBs and the refurbishment of existing buildings to PEB standard will therefore become an important element for the decarbonisation of the EU building stock in the next years. The new construction of PEBs and the refurbishment according to the PEB standard requires high initial investment costs, which will amortise to some extent over the entire lifetime of the building. An important question is to what extent and in which timeframe certain technology packages amortise. Therefore, the analysis of cost-optimal technology packages for PEBs is crucial for the upscaling and replication of the PEB concept.

This paper explores cost optimal technology packages for the transformation of reference renovations into PEBs through a cost-optimal analysis of two case studies. The demonstration cases are residential buildings that are located in two different climate zones (Nordic and Mediterranean climate zone) to ensure high replicability across Europe. The cost optimal analysis encompasses a comparison of global costs and net primary energy demand of different technology packages. As defined in the EU EPBD supplementing guideline 2012 [3], global costs are the net present value of all investment costs and all operation, maintenance, and energy costs for a defined calculation period over 30 years. Net primary energy demand includes the building's energy demand for space heating, space cooling, ventilation, DHW and lighting. Out of this analysis, general conclusions on the cost effectiveness of PEB technology packages are derived.

This paper is structured as follow: section 2 presents the methodological framework of the cost-optimal analysis; section 3 summarizes the results of scenarios and, finally, section 4 formulates and derives conclusions and perspectives based on the research findings.

2. Method

This section provides a general overview on the cost optimal calculation methods according to the EU guideline 2012/C 115/01 [3] and outlines the evaluation approach for global cost and net primary energy demand. In addition, section 2.2 describes the building case-studies: a new multi-storey residential building located in Helsinki/Kalasatama (Finland) and an existing building renovated according to the PEB standard, located in Valladolid (Spain).

2.1 Cost Optimal Methodology

The methodological basis for the cost optimal analysis of technology packages is the EU methodology framework 2012/C 115/01 which is a supplementing guideline of the EU EPBD (2018/844/EU). The guideline establishes a comparative methodology framework for the calculation of cost-optimal levels of minimum energy performance requirements for buildings and building elements. The framework defines the calculation method of primary energy demand and global costs in terms of Net Present Value [3].

2.1.1 Global Cost

The calculation of the global cost considers all initial investment costs and the Net Present Value of operation and maintainance costs. Furthermore the NPV of the annual energy costs as well as the NPV of revenues from renewable energy feed-in of the whole calculation period are considered in the global costs, as oulined in equation 1.

$$C_G = C_I + \sum_{n=1}^{p} \frac{C_{OM}(n)}{(1+d)^n} + \sum_{n=1}^{p} \frac{C_E(n)}{(1+d)^n} \quad (1)$$

with

C_G	Global cost [€]
C_I	Investment cost [€]
C_{OM}	Annual operation and maintainance cost [€]
C_E	Annual energy cost [€]
d	Discount rate
p	Calculation period (30 years for residential buildings)

Investment costs (without VAT) include all capital cost for the construction and implementation of energy efficiency measures and RES installations. As the investment is done before the calculation period, no discount factor has to be considered. Investment costs are adjusted by the expected lifetime of the technology package in relation to the calculation period. Thus discounted residual values are subtracted to the investment costs if the technology lifetime is higher than the calculation period. If the technology lifetime is lower than the calculation period, discounted replacement cost are added to the initial investment costs.

The parameter operation and maintenance costs (C_{OM}) includes the NPV of all annual costs for operation and maintainance over the overall calculation period. As the costs are considered as NPV, the annual costs are discounted with discount rate "d" as described in equation 1. The calculation of global costs was carried out for a time period of 30 years, based on the recommended calculation period for residential buildings defined in the EU cost-optimal-framework guideline [3].

Equation 2 shows the calculation of energy cost (C_E).

$$C_E = C_{ED} - R_{ES} - R_{DR} \quad (2)$$

with

C_{ED}	Cost for electricity purchase (excluding plug loads)
R_{ES}	Revenues for electricity supply
R_{DR}	Revenues from demand response services

The cost for electricity purchase (C_{ED}) is reflects the amount of electricity purchased from the grid and the purchasing price of electricity as well as grid related costs and VAT. Revenues from electricity supply (R_{ES}) are constituted by the amount of electricity supplied to the grid and the feed-in tariff. Potential revenues from demand response services are considered in the parameter R_{DR}.

2.1.2 Net Primary Energy Demand

Net primary energy demand is defined as annual overall energy use in terms of primary energy. As for the analysis described in this paper, the net energy demand parameter includes energy use for space heating and cooling, ventilation, DHW and lighting. Electricity for household appliances or plug loads are usually not included in net primary energy demand when the cost optimal calculation method is used. Onsite renewable energy supply is also considered in the equation as a subtractive term as it reduces the net primary energy demand. Equation 3 describes the detailed calculation method of net primary energy demand for technology packages, as used in the present cost optimal analysis.

$$E_P = E_d * PEF_e + G_d * PEF_g - E_s * PEF_e \quad (3)$$

with

E_P	*Net primary energy demand*
E_d	*Electricity demand from grid*
E_S	*Electricity supply to grid*
G_d	*Gas demand*
PEF_e	*Electricity primary energy factor*
PEF_g	*Gas primary energy factor*

2.1.3 Computational parameters

The main computational parameters are described in detail in the list below.

Discount rate: The discount rate reflects the opportunity cost of capital or the expected rate of return in nominal terms (inflation not considered). The discount rate has a high impact on the results, as the profitability of energy efficiency measures decreases as the discount rate increases. For the present analysis, a discount rate of 3% is used which is in line with the EU cost optimal guideline and the European Commission's 2009 Impact Assessment guidelines.

Calculation period: The calculation period defines the period of time used for the evaluation of the net present value of global costs. The calculation period is defined by the so-called refurbishment cycle of a building, which is the timeframe after which a building has to be refurbished. The calculation period used in this analysis is set at 30 years, as proposed by the EU cost-optimal guideline for residential buildings. If the expected lifetime of a technology is higher or lower than 30 years, investment costs are adjusted accordingly.

Primary Energy Factor: The PEF differs across Member States since the primary sources may differ and the amount of energy required for transportation or processing varies. Therefore, primary energy factors should be defined by Member States based on national, regional or local annual, and possibly also seasonal weighted averages according to article 9 of the EPBD [4]. To ensure comparability between case studies, PEF used in this analysis for electricity is defined to be equal to the value of 2.1 for both cases. This means that a unit of electricity requires an input of 2.1 units of primary energy, with an average efficiency of ~47%.

Electricity price: Estimating electricity prices for the future is challenging, especially considering that in recent years there have been high fluctuations in the electricity prices for households.

For the present analysis, an electricity price of 0.2€/kWh and a feed-in tariff of 0.1€/kWh are assumed, based on the expected decline of levelized cost of electricity and the increase in the electricity demand in the upcoming years [5].

2.2 Case-studies description

2.2.1 Mediterranean case-study

The Spanish case study (Figure 1) is a protected classical Renaissance palace (XVI century), located in the historical centre of Valladolid, Spain. After renovation, the building will have a useful floor area of 1089 m^2. Due to the heritage protection of the building, the envelope of the building has to be upgraded without modifying the exterior appearance of the façade, including the size, number and position of windows. In addition, high performance HVAC systems will be installed, as well as the renewable energy systems that the architectural protection allows, in order to maximize the self-consumption of on-site generated RES.

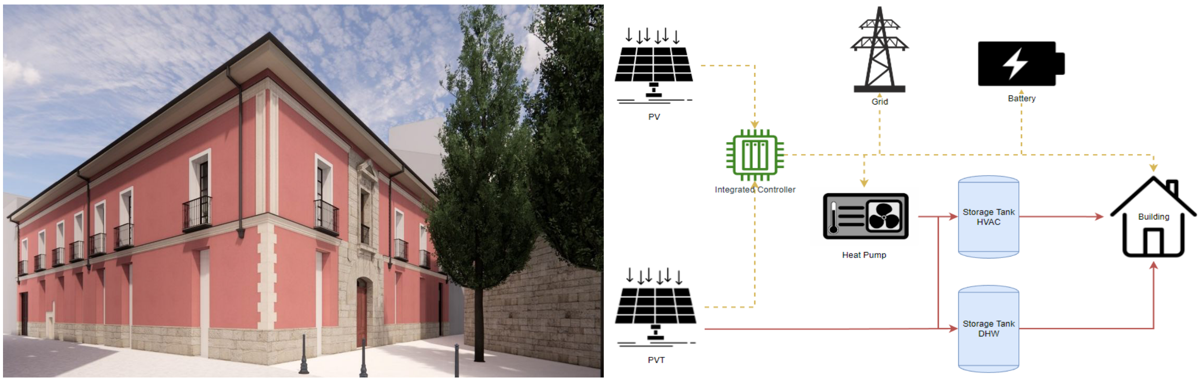

Figure 1: *Building and energy system scheme of Mediterranean case study.*

As shown in Figure 1, the solution designed for this building to meet the PEB standard relies on the design and deployment of an innovative smart energy system. This system integrates different components and technologies: a centralized aerothermal heat pump with on-site renewable energy production (51.4 kW PV), together with a thermal energy storage system for DHW and a 30 kWh ion-lithium battery. The produced PV energy will supply energy to the building on a collective self-consumption mode, and the surplus will be stored in the batteries. When the batteries are fully loaded, the PV will feed the grid or possibly the neighboring buildings. Furthermore, a high-performance building envelope with innovative materials and solutions is deployed, to minimize the thermal energy demand of the building.

2.2.2 Nordic case-study

The Finnish case study (Figure 2) is a Positive Energy Building constituted by 8 floors and located at Kalasatama district, in the city of Helsinki. The pilot building has 51 apartments and a total heated area of around 4000 m^2. Figure 2 shows the building and the layout of the buildings energy system. The energy system contains a hybrid geothermal energy system that combines semi-deep geothermal energy wells with collectors in ~600 meter deep boreholes, a 67kW multisource heat pump, building integrated PV panels (87 kWp) and solar thermal PVT (79 kWp) that will produce electricity and heat for the building and recharge the bedrock. The heat pump is compatible with multiple primary sources (ground and solar sources) and multiple operating modes (active heating and cooling). To increase temperature levels to a suitable level for space heating and domestic hot water, the hybrid energy system utilises heat from the PVT panels, ventilation and ground source with heat pumps.

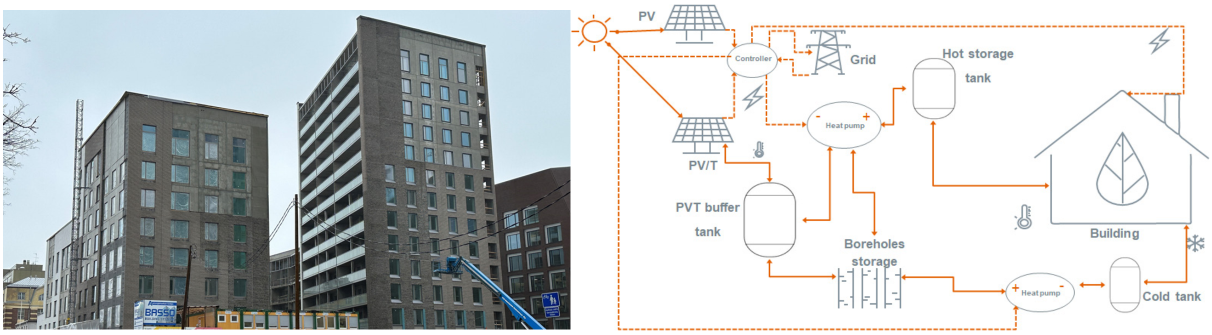

Figure 2: *Building and energy system scheme of Finish case study.*

3. Results and discussion

This section outlines the results of the simulated renovation scenarios and technology packages as well as the most relevant energy and cost values for each technology package. The section is divided into two sub-sections, 3.1 and 3.2, respectively for the Mediterranean and Nordic case-study.

3.1 Mediterranean case-study

3.1.1 Scenarios and Technology Packages

For the cost optimal analysis of the Spanish pilot case, global cost and net primary energy demand were calculated for several technology packages. Technology packages are combinations of different technology options (scenarios) for different building subsystems. As listed in Table 1, scenarios were defined for the envelope, the heating system, the renewable energy production system and the building management system. The table also shows the corresponding investment cost and the expected lifetime for each technology.

Table 1: *Description of renovation scenarios for building subsystems of the Mediterranean case-study.*

	Scenario	Description	Investment costs [€]	Expected lifetime [y]
Building envelope	D0	Baseline Spanish regulation envelope; U-value [W/(m^2 K)]: walls 0.41, roof 0.35, floor 0.65, windows 1.8	143 700	50
	D1	High efficiency envelope; U-values [W/(m^2 K)]: walls 0.13, roof 0.1, floor 0.27, windows 0.87	269 100	50
	D2	High efficiency envelope D1 plus heat recovery unit	318 600	50
Thermal system	TS0	Gas heating with boiler and solar thermal for DHW	78, 300	15
	TS1	Aerothermal heat pump (40 kW) with floor heating	156 200	20
	TS2	Aerothermal heat pump (40kW) with PVT (2.8kW) for DHW	164 600	20
PV facility	PV0	no PV	0	n.a.
	PV1	22.75 kWp (70 panels each 375Wp), no storage	48 000	25
	PV2a	51.38 kWp (70 panels each 375Wp), no storage	95 900	25
	PV2b	51.38 kWp (70 panels a 375Wp), 30kWh battery energy storage	149 900	25

The defined scenarios for each building subsystem, were combined to several technology packages as listed in Table 2. Combinations that are not reasonable were neglected from the analysis. Table 2 shows the most important cost and performance data of all simulated technology packages.

Table 2: *Energy demand and global cost of technology packages for the Mediterranean case-study.*

Envelope	Thermal system	PV facility	Gas demand [kWh/(m² y)]	El. demand (incl. plug loads) [kWh/(m² y)]	El. demand w/o plug loads) [kWh/(m² y)]	El. production [kWh/(m² y)]	Net Primary Energy demand wo plug loads [kWh/(m² y)]	Global costs wo plug loads [€/m²]
D0	TS0	PV0	77	36	22	0	139	637
D1	TS0	PV0	60	36	22	0	117	671
D2	TS0	PV0	42	36	22	0	97	669
D0	TS1	PV0	0	64	50	0	106	587
D1	TS1	PV0	0	58	44	0	93	649
D2	TS1	PV0	0	53	39	0	82	679
D0	TS2	PV0	0	63	49	0	102	582
D1	TS2	PV0	0	56	42	0	89	644
D2	TS2	PV0	0	51	37	0	78	674
D0	TS0	PV1	77	36	22	31	74	650
D1	TS0	PV1	60	36	22	31	53	684
D2	TS0	PV1	42	36	22	31	32	682
D0	TS1	PV1	0	64	50	31	41	587
D1	TS1	PV1	0	58	44	31	28	651
D2	TS1	PV1	0	53	39	31	18	682
D0	TS2	PV1	0	63	49	31	38	584
D1	TS2	PV1	0	56	42	31	24	648
D2	TS2	PV1	0	51	37	31	14	679
D0	TS0	PV2a	77	36	22	62	10	680
D1	TS0	PV2a	60	36	22	62	-12	713
D2	TS0	PV2a	42	36	22	62	-32	711
D0	TS1	PV2a	0	64	50	62	-23	609
D1	TS1	PV2a	0	58	44	62	-37	673
D2	TS1	PV2a	0	53	39	62	-47	706
D0	TS2	PV2a	0	63	49	62	-27	606
D1	TS2	PV2a	0	56	42	62	-40	672
D2	TS2	PV2a	0	51	37	62	-51	704
D0	TS0	PV2b	77	36	22	62	10	711
D1	TS0	PV2b	60	36	22	62	-12	745
D2	TS0	PV2b	42	36	22	62	-32	742
D0	TS1	PV2b	0	64	50	62	-23	641
D1	TS1	PV2b	0	58	44	62	-37	706
D2	TS1	PV2b	0	53	39	62	-47	737
D0	TS2	PV2b	0	63	49	62	-27	639
D1	TS2	PV2b	0	56	42	62	-40	704
D2	TS2	PV2b	0	51	37	62	-51	736
D1	TS1	PV2b	0	56	42	62	-40	717
D2	TS1	PV2b	0	52	38	62	-50	749
D1	TS1	PV2b	0	55	41	62	-44	715

3.1.2 Results of cost optimal analysis

Figure 3 shows the net primary energy demand and global cost of all technology packages with and without plug loads. There are some technology packages with a net primary energy demand below 0. Those combinations produce more energy than they consume and, therefore are classified as PEB combinations. If plug loads are included in the calculation, net primary energy demand and global costs increase. As a result, the amount of technology packages reaching the PEB standard decrease.

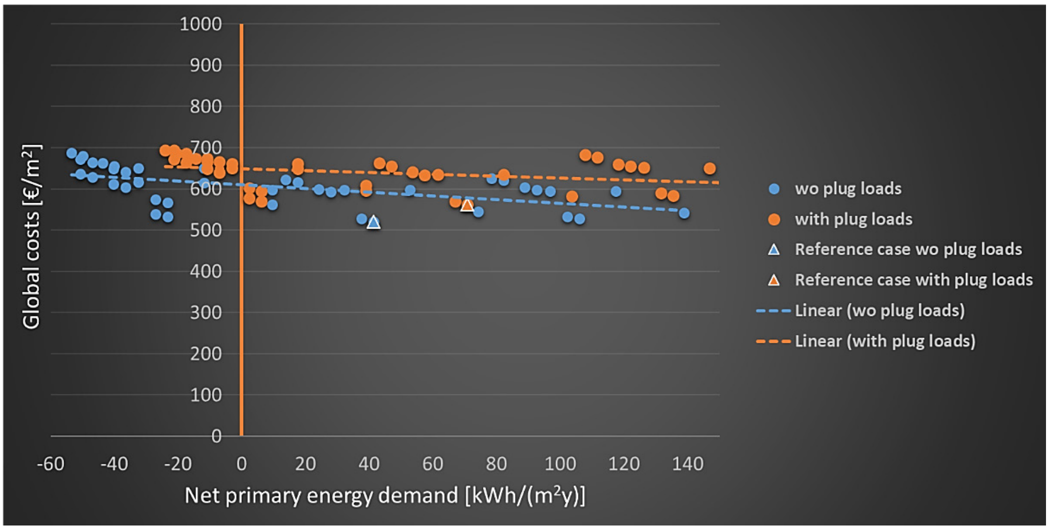

Figure 3: *Cost optimal analysis – all technology packages for the Mediterranean case-study.*

Analysis of thermal system scenarios: Figure 4 shows the cost-performance curves for different scenarios of the heating system. The blue lines represent scenarios with building envelope defined as D0. Results indicate that an improvement of the heating system reduces global cost and net primary energy demand for all scenarios with basic envelope insulation (D0). Therefore, a replacement of the heating system from gas heating (TS0) to aerothermal heat pump TS1 is cost effective as it significantly reduces global costs for a calculation period of 30 years. The reason is that the aerothermal heat pump reduces the required electricity demand for heating and thereby the cost for electricity significantly.

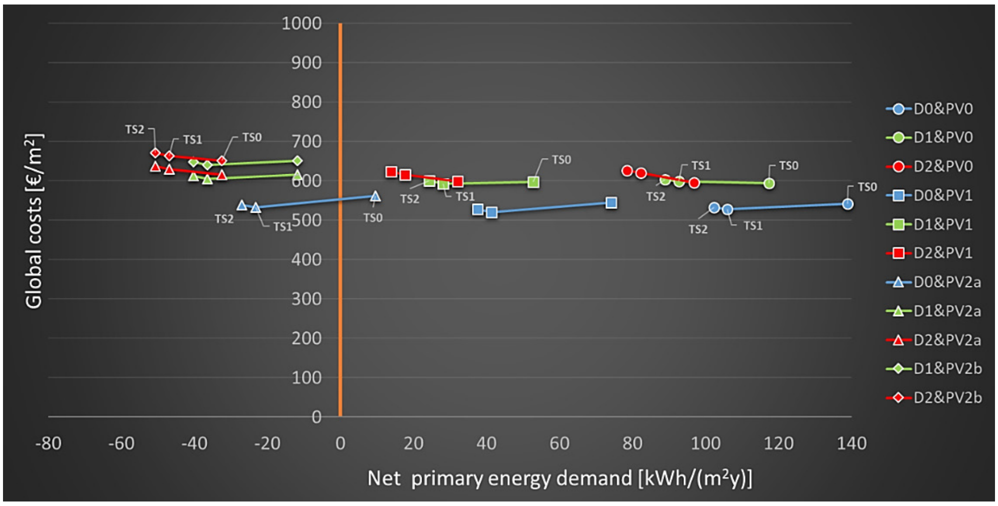

Figure 4: *Cost optimal analysis – comparison of heating systems for the Mediterranean case-study.*

It can be seen that for all technology packages with envelope D1 (green lines), the change of the heating system from TS0 to TS1 is almost cost neutral in terms of global costs but significantly reduces net primary energy demand. For all scenarios with envelope D2, a change of the heating system is not cost effective as the energy cost savings are too low to compensate the higher investment costs. A change from TS1 (aerothermal heat pump) to TS2 (aerothermal heat pump + PVT for DHW) further reduces net primary energy demand but also increases global costs. Overall, it can be said that a switch from gas heating system to aerothermal heat pump system leads to a significant reduction in net primary energy demand as the heat pump has a much higher efficiency compared with gas heating. This reduced energy demand leads to a reduction in electricity costs, which can fully compensate the higher investment costs for scenarios with a high heating demand (D0). For technology packages with a reduced heat energy demand (D1 or D2) the energy cost savings of the aerothermal heat pump compared to gas heating are lower which makes the change less profitable. However, it has to be noted that the results are very sensitive to costs of electricity and gas.

Analysis of envelope scenarios: Figure 5 analyses the different scenarios developed for the energy renovation of the building envelope. It shows that an improvement in the thermo-physical characteristics of the building envelope reduces net primary energy demand but at the same time increases global costs. This means that the higher investment costs cannot be fully paid back within the calculation period. Therefore, additional benefits of a new envelope (e.g. improvement in thermal comfort; increase in asset values) should be considered in the investment decision to improve profitability. Furthermore, since the building stock will last for decades, it is advisable to look at such long-term benefits that may not be relevant in the short term.

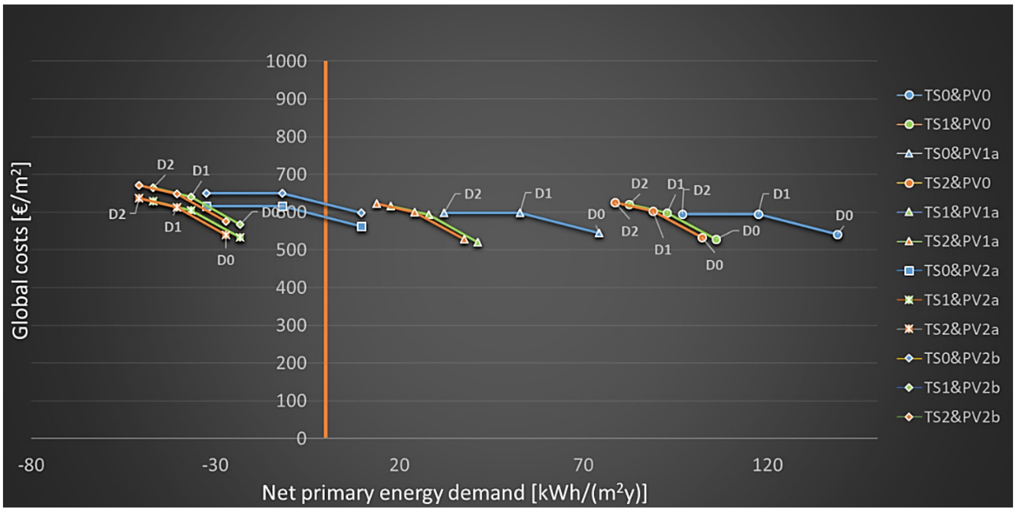

Figure 5: *Cost optimal analysis – comparison of envelope scenarios for the Mediterranean case-study.*

It should be noted that the increase of global costs is lower for technology packages with TS0 (gas heating) and higher for technology packages with heat pump (TS1 & TS2). The reason is that for an inefficient heating system, which requires a high amount of energy, the improvement of the building envelope is more important. Consequently, the interdependencies of the cost of technologies and the conclusions, based on global costs analysis, should be always taken at the technology system level.

Analysis of photovoltaic scenarios: Figure 6 shows global costs and net primary energy demand for different PV scenarios. It can be seen that an increase in PV area (change from PV0 to PV1 and further to PV2) reduces net primary energy demand without an increase of global costs. This leads to the conclusion that PV is a profitable technology that pays off within the calculation period. In the case electricity is sold within an energy community and no grid fees have to be paid, the electricity selling price might be higher which would further increase the profitability of the PV system.

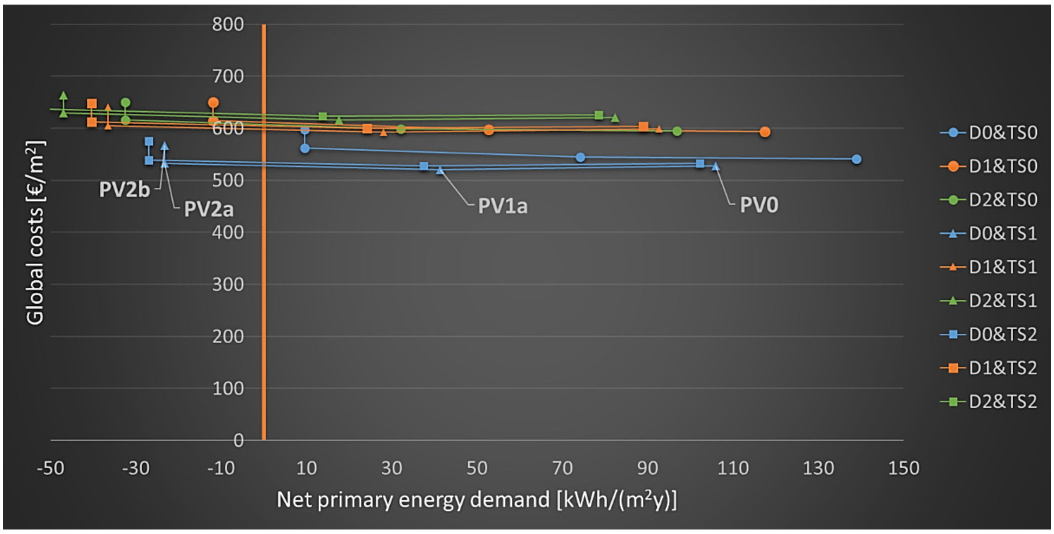

Figure 6: *Cost optimal analysis Spain – comparison of PV scenarios*

Figure 6 also reveals that PV is a crucial technology for the Spanish pilot case as there is no PEB scenario possible with PV0 or PV1. Furthermore, the chart shows that a battery energy storage system is not cost optimal in the Spanish pilot case as net primary energy demand is not affected but global costs increase. An additional economic analysis shows that battery energy storage systems would be profitable if the difference of electricity price and feed-in tariff is higher than 0.3€/kWh. Another possibility for the improvement of profitability would be the consideration of revenues from Demand Response (DR) services and flexibility services. As the extent of such additional revenues is still under investigation, the involvement of those revenues is beyond the scope of the present analysis. Overall, it can be concluded that PEB standard can be achieved in the Spanish case study. Due to advantageous shape of the building (low height with high built surface area), a very high amount of PV facilities in relation to the useful floor size can be installed. A new heating system and an improvement of the building envelope reduces net primary energy demand. The new heating system can be considered as almost cost optimal as it reduced net primary energy demand and only slightly increases global costs (depends on envelope scenario and electricity price). The improvement of the envelope is not cost-optimal as global costs increase for an improvement of the envelope from D0 to D1 and further to D2 at current energy prices and if the reduction of future cooling needs and other additional benefits are neglected. Therefore, the cost-optimal technology package of the Spanish demo building is the combination of a high PV area (PV2) with an aerothermal heat pump (TS1) and an envelope according to the minimum requirement of the Spanish regulation (D0).

3.2 Finish Case Study

3.2.1 Scenarios and Technology Packages

For the thermal system, five different scenarios were analyzed. The baseline scenario TS0 represents a state of the art fossil-based district heating system in Finland, as it is the case in the pilot area. TS1, TS2 and TS3 describe state of the art heat pump scenarios with different functionalities. The scenario TS3 represents an innovative thermal system that was realized within the EXCESS project. It contains a geothermal heat pump with tanks and 600m deep boreholes for seasonal energy storage. Table 3 summarizes the different technology scenarios for each building subsystem.

Table 3: *Description of technology scenarios for building subsystems of the Nordic case-study.*

	Scenario	Description	Invest-ment costs [€]	Expected lifetime [y]
Envelope	D0	Standard envelope; U-values of envelope [W/(m^2 K)]: walls 0.16, roof 0.09, floor 0.14, windows 0.6;	-	30
Thermal system	TS0	Baseline (district heating, no PV/PVT, no cooling)	45 000	30
	TS1	Air to water heat pump, 150 kW, COP 2.5	225 000	30
	TS2	Geothermal heat pump system, 150 kW, traditional boreholes with < 300m, COP 3.5;	375 000	30
	TS3	Geothermal heat pump system incl. cooling, 150kW, traditional boreholes with < 300m, COP 4;	420 000	30
	TS4	Geothermal heat pump system incl cooling, 150 kW, ~600 m deep boreholes, seasonal borehole storage, tanks; COP 4.5;	450 000	30
PVT	PVT0	no PVT	0	n.a.
	PVT1	67kW$_P$ DualSun PVT panels (315 m^2) on roof	250 000	30
BiPV	PV0	No PV	0	n.a.
	PV1	87 kWp building integrated PV system (347 m^2 façade southwest)	240 000	30

As listed in Table 4, the scenarios for each building system were combined to 15 technology packages. Combinations that are not reasonable were neglected from the analysis. In addition to that, Table 4 also shows the most important cost and performance data of all simulated technology packages. The gas demand is zero for all scenarios.

Table 4: *Energy demand and global cost of technology packages for the Nordic case-study.*

Envelope	Thermal system	PV facility	PVT facility	El. demand (incl. plug loads) [kWh/m^{2}y]	El. demand w/o plug loads) [kWh/m^2 y]	El. production [kWh/m^2 y]	Net Primary Energy demand wo plug loads [kWh/m^2 y]	Global costs wo plug loads [€/m^2]
D0	TS0	noPV	noPVT	60	57	0	120	359
D0	TS1	noPV	noPVT	33	30	0	64	313
D0	TS2	noPV	noPVT	29	26	0	55	348
D0	TS3	noPV	noPVT	28	26	0	54	357
D0	TS4	noPV	noPVT	27	25	0	51	366

D0	TS0	PV1	noPVT	60	57	8	103	375
D0	TS1	PV1	noPVT	33	30	8	46	329
D0	TS2	PV1	noPVT	29	26	8	38	364
D0	TS3	PV1	noPVT	28	26	8	37	373
D0	TS4	PV1	noPVT	27	25	8	34	382
D0	TS0	PV1	PVT1	60	57	24	70	394
D0	TS1	PV1	PVT1	33	30	24	13	348
D0	TS2	PV1	PVT1	29	26	24	5	382
D0	TS3	PV1	PVT1	28	26	24	4	392
D0	TS4	PV1	PVT1	27	25	24	1	400

3.2.2 Results of Cost optimal analysis

Figure 7 illustrates the net primary energy demand and global cost of all technology packages with and without plug loads. It can be seen that there are no technology packages with a net primary energy demand below 0. This means that there are no technology packages which could reach PEB level. One central reason is the shape of the building. The building has 8 floors but only a small built surface area and therefore reduced possibilities for renewable energy generation with PV or PVT. Another reason is the cold climate that leads to a relatively high energy demand for space heating compared to other geographical areas in the European Union. Global costs increase with a reduction of net primary energy demand (from nZEB to PEB).

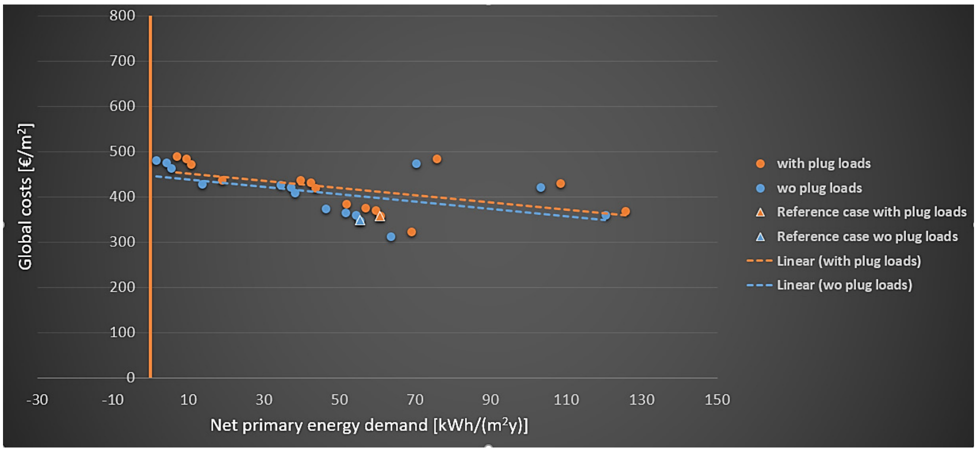

Figure 7: *Cost optimal analysis Finland – all technology packages*

Figure 8 shows the cost-energy curves for all thermal system scenarios. A change from a state of the art combustion based district heating system (TS0) to an efficient thermal system with geothermal heat pump (TS1) is cost effective as it reduces net primary energy demand and global costs. Additional improvements in the heating system (from TS2 to TS3 to TS4) can further reduce net primary energy demand through an increase in the efficiency of the heating system. The improvement of the efficiency of the heating system also increases global costs. This means that energy cost savings cannot offset the additional investment costs. Therefore, a heat pump with traditional boreholes (TS1) is the cost optimal scenario of the thermal system. It has to be noted that TS3 and TS4 also includes energy demand for cooling which increases net primary energy demand and global costs. Cooling provides additional thermal comfort and will get more important in the next years and decades. Furthermore, cooling can regenerate the bedrock by inserting heat energy in the boreholes. Therefore, TS3 and TS4 provide additional benefits, such as increased comfort that however cannot be considered in the present analysis.

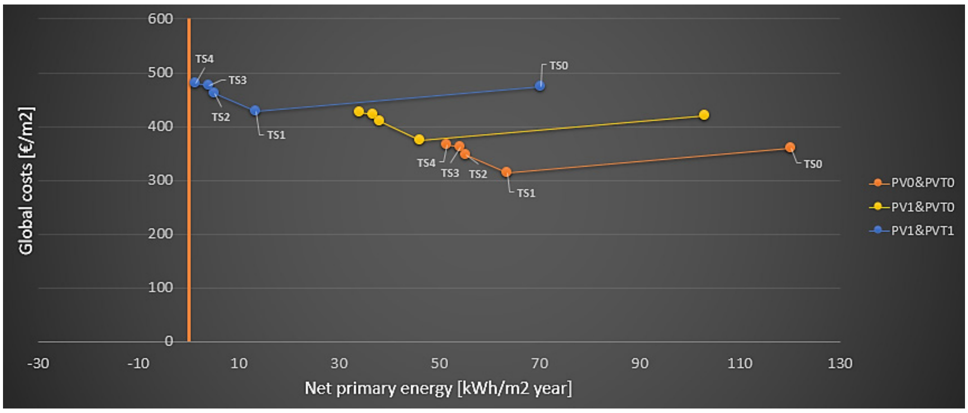

Figure 8: *Cost optimal analysis Finland – thermal system scenarios*

Figure 9 shows cost-performance curves for different BiPV and PVT scenarios. It shows that an increase in PV area reduces net primary energy demand but increase global costs. The reason is that the Finnish demo uses building integrated PV which is much more expensive than standard PV. PVT also reduces net primary energy demand but increases global costs. This means that both PV and PVT are not cost-effective technologies for the Finish case-study as the high investment costs cannot be compensated by energy savings and feed-in revenues within a calculation period of 30 years with the cost assumptions used in these calculations. However, it has to be mentioned that PVT can have positive aspects on the overall efficiency of the thermal system. The heat energy from PVT for example increases the heat pump efficiency at DHW generation as the heat pump COP increases with a lower target temperature of DHW. Furthermore, PVT helps to regenerate the bedrock during summer months which increases the COP during heating season and ensures correct long-term functionality of the thermal system.

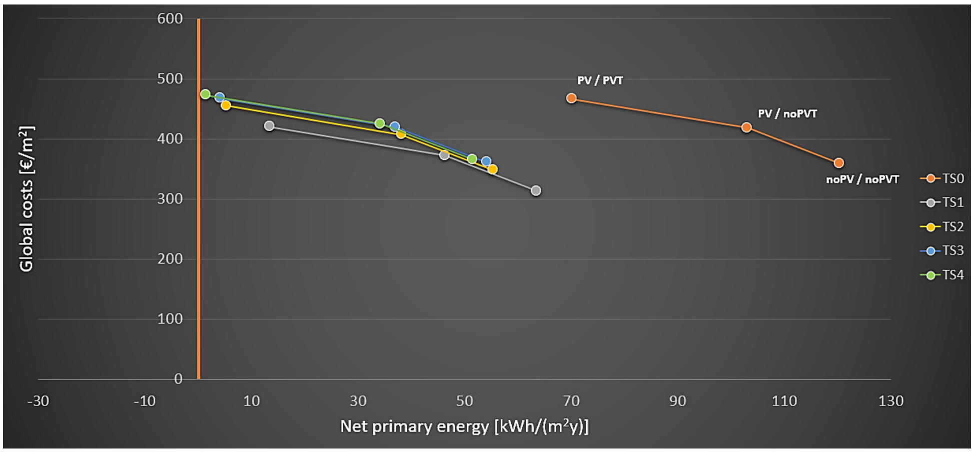

Figure 9: *Cost optimal analysis Finland – PV and PVT scenarios.*

Overall, it can be concluded that it is not possible to achieve PEB standard in the Finnish pilot case. The main reason is that the shape of the building does not allow for a high area of PV. The cost optimal analysis showed that the innovative heating system technologies (deep boreholes, multisource heat pump) significantly reduce net primary energy demand but also increase global costs. The high costs of the innovative heating system, building integrated PV and PVT cannot be compensated by the energy cost reductions. However, the system provides a seasonal storage and a high level of flexibility to the energy system which was not considered in terms of revenues.

4. Conclusions

The cost-optimal analysis in this paper showed that not all PEB technologies are cost-optimal and reduce global costs. According to the analysis discussed in this report, renewable energy production with PV can be considered as cost-optimal technology, as global costs decrease with an increase in PV area with current electricity prices (~0.2€/kWh) and electricity selling prices (~0.1€/kWh). The shape of the building is a crucial parameter for the cost-optimal realization of a PEB. If there is limited space for conventional PV, BiPV and PVT are key technologies for PEBs. However, BiPV and PVT are also more expensive than conventional PV. The change from a gas heating system or district heating system to a new high COP heat pump system is cost-optimal as it reduces net primary energy demand and global costs. However, the profitability of such a change is very sensitive to electricity prices and gas prices. If it is assumed that gas prices will decrease below 0.1€/kWh, the high investment costs for a new heating system with aerothermal or geothermal heat pump cannot be offset by energy cost savings.

Additional functionalities in the thermal heating system (such as deep boreholes and seasonal storage) increase global costs, as outlined in the results for the Finnish case study. The analysis showed that a geothermal heat pump with traditional 300m boreholes leads to lower global costs than the innovative thermal system of the Finnish case study with 600m deep boreholes, cooling system and thermal storage. The latter however provides a seasonal storage and a high level of flexibility to the energy system. PVT decreases net primary energy demand but increases global costs with current available PVT costs in the case studies. The main cost driver for this technology is the complex installation of the panels. At the same time in case of geothermal heat pumps less drilling cost arise. In applications with a high heat energy demand and little available space for the collector, PVT is highly relevant for the efficient functioning of a geothermal heating system. This example shows that it is necessary to have a systemic view on costs.

The analysis also revealed that there are situations, especially in Southern Europe, where the PEB standard can be reached just with PV and without deep renovation measures as the PEB definition and the cost optimal framework do not distinguish between demand-side solutions (e.g. building envelope renovation) and RES-based active technologies and account over one year. Furthermore, the PEB definitions and the cost optimal analysis do not explicitly consider seasonal minimum self-sufficiency rates in the calculation method which grades down all storage technologies. The monetarization of energy flexibility services can significantly alter this analysis as it will lower the levelized cost of storage technologies. However, as the flexibility markets are not a reality yet in many EU countries, it is yet to determine the economic impact of such services. Furthermore, additional benefits of PEBs that are not considered in the cost optimal methodology as for example increased comfort through cooling and ventilation should get higher attention as they may increase the value of properties. It is recommended to solve shortcomings of the cost optimal analysis approach with a future revision of European legislation and strategies (e.g. EPBD, EU cost optimal framework).

Overall, it can be said that several PEB technologies increase global costs with current electricity prices (0.2€/kWh). A change from nZEB to PEB standard leads to higher investment costs and in most cases also to higher global costs according to the research findings discussed in this paper. To support the realization of PEBs, either subsidies are needed to cover the additional costs that cannot be covered by energy cost savings or costs of greenhouse gas emissions increase to make energy cost savings more profitable. Also, more clarity should be gained on the values of flexibility provision of PEBs as the related revenues could further reduce global costs and increase profitability. In particular if PEBs and PEDs should provide benefits to the overall energy system, incentives or tariff structures should be provided that keep self-sufficiency levels high across the entire year.

Competing interests

The authors declare that they have no competing interests.

Data availability statement

The data was provided by the EXCESS project partners, knowing that the data will be published. There is no relevant additional data to this article beyond the presented content.

Underlying and related material

Additional data is shown in deliverable “D5.1 Report on cost optimal technological solutions for PEBs” of the EXCESS project (Link)

Authors contributions

Clemens Mayer: Conceptualization, Methodology, Formal analysis, Writing – original draft, review and editing. Andreas Tuerk: Conceptualization, Supervision, Writing – original draft, review and editing. Ilaria Marotta: Validation, Writing - review & editing. Raul Ciria Aylagas: Conceptualization, Writing – review and editing;

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