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Abstract
This deliverable describes a “cost optimal analysis” of different technology packages of all four EXCESS demonstration projects. The pilot cases are multi-storey residential buildings located in four different climate zones. The main objective of the analysis is to define cost-optimal technology packages for all pilot cases. Several technology packages were defined for all demos and the cost optimal analysis methodology, based on a comparison of net primary energy demand and global costs, was applied. The analysis shows that not all technologies reduce global costs. Several factors impact 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. Energy prices also play a critical role for making PEB technologies economical. More clarity should be gained on the values of the flexibility offered by PEBs, as the related revenues could further reduce global costs. The analyses also revealed that there are situations, especially in Southern Europe, where the PEB standard can be reached in a cost effective way just with the integration of PV systems, as the PEB definition and the cost optimal framework do not distinguish between demand-side solutions (e.g. building envelope renovation) and RES generating technologies. Furthermore, the PEB definitions and the cost optimal framework do not explicitly consider seasonal minimum self-sufficiency rates in the calculation method which grades down all technologies with seasonal storage solutions. If PEBs and PEDs should

provide benefits to the overall energy system, incentives or tariff structures should be provided to keep self-sufficiency levels high across the entire year.

Keywords
PEB, Positive Energy Buildings, Cost optimality, global cost, cost effective, technology packages

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EXECUTIVE SUMMARY

This report explores cost optimal technology packages for the transformation of standard renovation scenarios to Positive Energy Buildings (PEBs) through a cost-optimal analysis of four EXCESS pilot projects. The pilot cases are multi-storey residential or office buildings located in four different climate zones (Nordic, Continental, Oceanic and Mediterranean climate zone) to ensure high replicability across Europe. The pilot buildings include a new residential building (Helsinki) as well as existing buildings to be renovated according to the PEB standard (Hasselt, Graz and Valladolid). The cost optimal analysis encompasses a comparison of global costs and net primary energy demand of different technology packages. Global costs, defined in the EU Energy Performance of Buildings Directive (EPBD) supplementing guideline 2012 [3], include the net present value of all investment costs and all operation, maintenance, and energy costs for a specified calculation period. The cost data were obtained, as primary data, from pilot leaders and technology providers in the EXCESS project. The net energy demands of different technology packages and scenarios were obtained from the energy simulations conducted in the context of EXCESS WP2 (task 2.6). The main objective of the global cost analysis is the comparison of different technology packages in order to define the cost-optimal technology packages for all pilot cases. Out of this analysis, general conclusions on the cost effectiveness of PEB technologies and technology packages are derived. Furthermore, the analysis reveals the economic payback period of PEB technologies and compares the global costs of PEB technology packages with technology packages required for the current nearly Zero-Energy Buildings (nZEB) legislative standard [2].

The analysis shows that several energy efficiency or renovation measures that were tested for reaching the PEB standard are not cost effective at current electricity prices. This means that the overall global cost increase (considering a calculation period of 30 years) for advanced energy efficiency or deep renovation scenarios (PEB scenarios) compared to the reference cases without renovations according to existing national standards. However, it should be noted that the results are very sensitive to changes in electricity prices. Higher energy prices increase the profitability of energy efficiency measures, while the economic benefit due to energy saving decreases when energy prices decrease, generating as a consequence a lower profitability of technological packages. On the other hand, deep renovation measures generate multiple benefits for the residents that are not considered in economic terms. Furthermore, the findings indicate that the use of some Renewable Energy Sources (RES) are more cost-effective than a deep renovation of the building envelope. The profitability of a renovation in the space heating system strongly depends on the costs of gas and electricity. Several technologies in EXCESS provide flexibility to the energy system at local level. This leads to additional revenue streams that were however not yet systematically considered and would improve the profitability of PEBs. The report also shows that a system view on costs is necessary. In this regard, individual technologies may not be cost efficient but they can be enabling technologies that make the entire technology system cost efficient. Finally 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.

TABLE OF CONTENTS

EXECUTIVE SUMMARY **3**

1 INTRODUCTION **7**

1.1 Purpose and scope of the document 7

1.2 Structure of the document 7

2 METHODOLOGY **9**

2.1 Method 9

2.2 Cost-optimal methodology 9

2.3 Global cost 9

2.3.1 Calculation method 9

2.3.2 Investment cost 9

2.3.3 Operation and maintenance cost 10

2.3.4 Energy cost 10

2.4 Net primary energy demand 10

2.5 Calculation parameters 12

2.6 Limitations of the approach 13

3 COST OPTIMAL ANALYSIS OF PEB CASE STUDIES **14**

3.1 Spanish case-study 14

3.1.1 Building design 14

3.1.2 Scenarios and technology packages - Spain 15

3.1.3 Results of cost optimal analysis – Spain 18

3.2 Finnish case-study 23

3.2.1 Building design 23

3.2.2 Scenarios and technology packages - Finland 24

3.2.3 Results of cost optimal analysis – Finland 26

3.3 Belgium case-study 30

3.3.1 Building design 30

3.3.2 Scenarios and technology packages - Belgium 31

3.3.3 Results of cost optimal analysis – Belgium 32

3.4 Austrian case-study 36

3.4.1 Building design 36

3.4.2 Scenarios and technology packages - Austria 36

3.4.3 Results of cost optimal analysis - Austria 38

3.5 Comparison with reference costs and cost ranges of selected technologies 40

4 SENSITIVITY ANALYSIS 43

4.1 Sensitivity analysis - electricity prices 43

4.2 Sensitivity analysis - discount rate 44

5 CONCLUSIONS 46

6 REFERENCES 48

LIST OF FIGURES

Figure 1: Sankey Diagram for the calculation of net primary energy demand. 11
Figure 2: Pilot case Spain – Historical building in Valladolid 14
Figure 3: Energy system scheme of the Spanish pilot-case 15
Figure 4: Cost optimal analysis Spain – all technology packages 18
Figure 5: Cost optimal analysis Spain – comparison of heating system 19
Figure 6: Cost optimal analysis Spain – comparison of envelope scenarios 21
Figure 7: Cost optimal analysis Spain – comparison of PV scenarios 21
Figure 8: Finland pilot-case, residential building in Kalasatama Helsinki. 23
Figure 9: Finland pilot-case, energy system layout 24
Figure 10: Cost optimal analysis Finland 27
Figure 11: Cost optimal analysis Finland – thermal system scenarios 28
Figure 12: Cost optimal analysis Finland – PV and PVT scenarios. 28
Figure 13: Hasselt demonstrator site. 30
Figure 14: Cost optimal analysis Belgium – all technology packages 33
Figure 15: Cost optimal analysis Belgium – analysis of cogeneration unit and thermal system 34
Figure 16: Cost optimal analysis Belgium – analysis of PV and PVT system. 34
Figure 17: Cost optimal analysis Belgium – analysis of wind turbine 35
Figure 18: Pilot case Austria – PEB as former industrial building.. 36
Figure 19: Cost optimal analysis Austria – all technology packages. 39
Figure 20: Cost optimal analysis Austria – analysis of technologies 39
Figure 21: System cost comparison of conventional and BIPV roofing solutions. 42
Figure 22: Sensitivity analysis electricity costs – Spain. 43
Figure 23: Sensitivity analysis electricity costs – Finland.. 44
Figure 24: Sensitivity analysis discount rate – Spain. 45
Figure 25: Sensitivity analysis discount rate – Finland. 45

LIST OF TABLES

Table 1: Description of renovation scenarios for building subsystems. 16
Table 2: Energy demand and global cost of technology packages – Spain....................................... 17
Table 3: Summary of the main parameters for the economic analysis - Spain 18
Table 4: Description of energy renovation scenarios for building sub-systems. 25
Table 5: Energy demand and global cost of technology packages – Finland.................................... 26
Table 6: Parameters of analysis - Finland 26
Table 7: Description of scenarios for building sub-systems.. 31
Table 8: Energy demand and global cost of technology packages – Belgium. 32
Table 9: Parameters of analysis - Belgium 32
Table 10: Description of energy renovation scenarios for building sub-systems. 37
Table 11: Energy demand and global cost of technology packages – Austria. 38
Table 12: Parameters of the analysis – Austria. 38
Table 13: PEB/nZEB comparison in investment costs and global costs 41
Table 14: PVT cost in the next 5-10 years 41
Table 15: Parameter for sensitivity analysis electricity. 43
Table 16: Parameter for sensitivity analysis - discount rate. 44

1 Introduction

1.1 Purpose and scope of the document

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 proposed new Energy Performance of Buildings Directive (EPBD) revision requires Zero Emission standard for all new buildings after 2030 (2027 for public buildings) and a complete decarbonisation of the European building stock by 2050 [2]. On this line, the design of new PEBs and the refurbishment of existing buildings from a PEB perspective will become an important element for the decarbonisation of the economy in the next years. The EXCESS (FlEXible user-Centric Energy positive houseS) project intends to outline possibilities to transform nearly-Zero Energy Buildings into Positive Energy Buildings as well as presenting opportunities and limitations.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 report explores cost optimal technology packages for the transformation of reference renovations into PEBs through a cost-optimal analysis of the four EXCESS pilot projects. The analysis of the EXCESS pilots is the starting point for further cost assessments and sensitivities in the course of the project. The demonstration cases are multi-storey residential buildings that are located in four different climate zones (Nordic, Continental, Oceanic and Mediterranean climate zone) to ensure high replicability across Europe. The pilot buildings include a new residential building (Helsinki) as well as existing buildings renovated according to the PEB standard (Hasselt, Graz and Valladolid). 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], the global cost is 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. The cost data were obtained from interviews with pilot leaders and technology providers. The net energy demands of different technology packages and scenarios derive from the energy simulations conducted under EXCESS task 2.6.

The main objective of the global cost analysis is the comparison of different technology packages in order to define the cost-optimal technology packages for all pilot cases. Out of this analysis, general conclusions on the cost effectiveness of PEB technology packages are derived. Furthermore, the analysis reveals the payback period of PEB technologies and compares global costs of PEB technology packages with technology packages required for the current nZEB legislative standard.

1.2 Structure of the document

This section presents the structure of the document.

Chapter 2 elaborates the methodological framework of the cost-optimal analysis. It starts with a general overview on the cost optimal calculation methods according to the EU guideline 2012/C 115/01 [1]. This section is followed by a detailed description of the calculation method for global cost and net primary energy demand.

Chapter 3 describes the buildings' characteristics of all pilot cases as well as the energy layout and the heating configuration of the pilot cases. In addition, the chapter provides a detailed description of the simulated renovation scenarios and technology packages as well as the most relevant energy and cost values for each technology package. Finally, the results of the cost optimal analysis for different technology packages are outlined and each technology is analysed in detail.

Chapter 4 discusses the results of the sensitivity analysis carried out for different values of electricity costs, feed-in tariffs and discount rates. On the other hand, chapter 5 summarizes the main findings and draws general conclusions from the results obtained in the previous chapters.

Task leader and leader of WP5 is Joanneum Research (JR). The partners who contribute to T5.1 are CENER, VTT, Vito, AEE Intec and Urb Atelier. VTT, Vito and AEE Intec provided the input data for the pilots in Finland, Belgium and Austria. Urb Atelier and CENER provided the data for the Spanish pilot case. Furthermore, CENER supported on the creation of cost-optimal calculation sheet and the interpretation of the results.

2 Methodology

2.1 Method

The EPBD (2018/844/EU) defines a cost-optimal methodology to benchmark minimum requirement for the energy performance of buildings and building components. In the present analysis, this cost-optimal methodology is applied to pilot cases, considering several combinations of technologies and technology packages. This chapter describes the detailed calculation method and all relevant parameters of the analysis. It starts with a general explanation of the cost-optimal methodology. This is followed by a description of the calculation method and the content of global cost and net primary energy demand, which are the two central parameters of the methodology. Finally, all relevant parameters and assumptions of the analysis are described and the boundaries of the analysis are outlined.

2.2 Cost-optimal methodology

The methodological basis for the cost optimal analysis of technology packages to which this report refers 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 [2]. According to this evaluation framework, the cost-optimal analysis described in this report was developed.

2.3 Global cost

2.3.1 Calculation method

Global cost are quantified in terms of Net Present Value (NPV). 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.

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

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)

Subsections 2.3.2, 2.3.3 and 2.3.4 provide a detailed description of the cost categories included in the global cost parameter.

2.3.2 Investment cost

Investment costs (without VAT) include all capital cost for the construction and implementation of renovation measures and energy efficiency measures. The investment is done before the calculation period and therefore no discount factor has to be considered. Investment costs are adjusted by the lifetime of the technology package in relation to the calculation period. This means that 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, replacement cost are added to the initial investment costs. Residual values and replacement costs are considered as NPV by considerating the discont rate.

2.3.3 Operation and maintenance cost

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 done for a calculation period of 30 years, based on the recommended calculation period for residentail buildings defined in the EU cost-optimal-framework guideline [2]. This means that operation and maintainance costs are discounted and summed up for a period of 30 years.

2.3.4 Energy cost

The calculation of energy cost (C_E) is shown in equation 2.

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

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 defined by the amount of electricity purchased from the grid and the purchasing price of electricity. The purchasing price of electricity contains also VAT and grid related costs. 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}.

2.4 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 report, 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. In the present work calculations are performed with and without plug loads in order to analyze the impact of plug loads caused by residents. Onsite renewable energy supply is also considered in the equation as a subtractive term as it reduces the net primary energy demand. It should be noted that primary energy means that the demand and supply of electricity and the demand of gas and district heating, is multiplied by the specific net Primary Energy Factor (PEF).

Equation 3 describes the detailed calculation method of net primary energy demand for technology packages, as used in the current cost optimal analysis of EXCESS project.

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

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 to primary energy factor*
PEF_g	*Gas to primary energy factor*

The definition and calculation of the net primary energy demand is in line with the PEB definition developed within the EXCESS project and defined in WP1 as follows: "EXCESS defines a Positive Energy Building (PEB) as an energy efficient building that produces more energy than it uses via renewable sources, with a high self-sufficiency rate and high energy flexibility, over a time span of a year."

The Sankey Diagram, in Figure 1, illustrates the calculating scheme of the net primary energy demand according to the EU cost optimal framework.

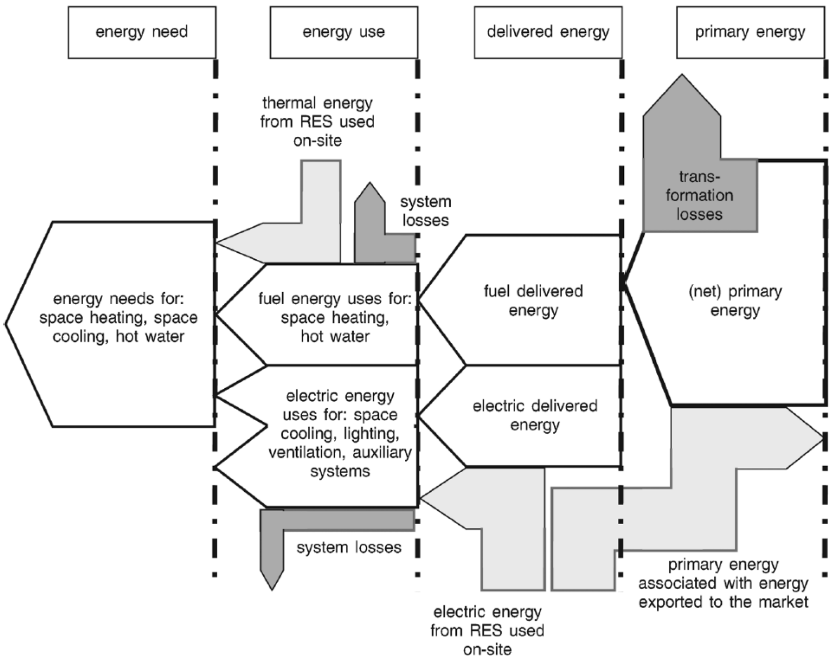

Figure 1: Sankey Diagram for the calculation of net primary energy demand [3]

As shown in Figure 1, the direction of the calculation ranges from energy needs to energy sources. This means that the calculation of energy performance involves: *a)* the evaluation of the thermal energy need for each use of the building (space heating, cooling, DHW); *b*) the calculation of the final energy demand for heating and all energy uses, minus the energy losses and considering the availability of thermal energy generation from local RES; *c*) the calculation of the electric and fuel delivered energy (as an energy input), both from the sorrounding energy grids and form on-site renewable energy systems; and finally *d*) the quantification of the net primary energy use ad the transformation losses.

According to the cost optimal approach, all energy uses are expressed with a primary energy indicator. As a result, the renewable energy production technologies could be in direct competition with energy efficiency measures that reduce energy demand. This is in line with the EPBD and the cost optimal methodology which seeks for the technology package that represents the least global costs without favouring or discriminating a certain technology [1].

2.5 Calculation parameters

Discount rate:

The discount rate reflects the opportunity cost of capital or the expected rate of return. The rate is expressed in real terms, which means that inflation is not taken into account. 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 [1]. In addition, a sensitivity analysis, for discount rates of 0% and 6%, was performed.

Calculation period:

The calculation period defines the period of time used for the calculation 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 as explained in Subsection 2.3.2.

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 [3]. To ensure comparability between pilots and to reduce complexity, PEF used in this analysis for electricity is defined to be equal to the value of 2.1 for all pilot 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 hat in recent years there have been high fluctuations in the electricity prices for households. Within the economic evaluation approach discussed in this report, 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 [3] [4]. To estimate the sensitivity of the results to changes in electricity prices, sensitivity analysis for higher electricity costs (0.3 and 0.4 €/kWh) and higher electricity selling prices (0.15 and 0.2 €/kWh) were also carried out.

Self-consumption and self-sufficiency ratio:

For the data gathering process and the calculation of the net primary energy demand of all technology packages, self-consumption rate and self-sufficiency rate are used as Key Performance Indicators (KPIs) [6]. Equations 4 and 5 show the formulation of the energy KPIs:

$$\text{Self-consumption rate} = \frac{energy\ self-consumption\ from\ local\ RES}{total\ local\ RES\ production} \quad (4)$$

$$\text{Self-sufficiency rate} = \frac{energy\ self-consumption\ from\ local\ RES}{total\ energy\ demand} \quad (5)$$

As shown, the Self-sufficiency rate is defined as the ratio between the electricity demand covered by on-site renewable energies and the total electricity demand. Self sufficiency is an important parameter for PEB as it defines the resilience of the building and the degree of reliance of the building on the electrical grid. On the other hand, the Self-consumption rate informs on the amount of local energy production self-consumed simultaneously by the building.

2.6 Limitations of the approach

This section discusses the limitations of the methodology adopted for the evaluation of global cost and cost optimal solution applied on the current PEB definition. As for the net Primary Energy Demand, it should be noted that it does not inform about the self sufficiency rate. Therefore, the analysis does not include a comparison of self sufficiency for different technology packages as it aimed only at quantifing global costs.

Another limitation of the calculation method is related to the evaluation of CO_2 emissions. The EU cost optimal framework focus on the costs of greenhouse gas emissions only for the calculation of the macroeconomic cost optimum. Therefore, for the cost optimal analysis previously described and implemented in this study, the costs for greenhouse gas emissions are not considered.

The global cost calculation framework does also not consider additional benefits such as improvement in the thermal comfort conditions of the occupants through air ventilation, space cooling or insulation of the building envelope. In this regard, options that improve air quality or user comfort are not ranked correctly (i.e. from a more comprehensive and holistic perspective) as despite the additional costs and energy demands are included in the comparison, the additional non-monetary benefits are not taken into account.

The currently available definitions of PEB lead to another limitation. PEBs require an annual self sufficiency rate of more than 100%. Therefore, in some climatic zones (e.g. Southern Europe), the PEB status can be achieved by high export of renewable energy into the energy grid in summer and high off take from the grid in winter, using the grid as seasonal storage. The PEB definition does not specify a limit value for the self-sufficiency rate that has to be met during the year. It only defines that PEBs should ensure a high self sufficiency rate and a negative net primary energy demand. As the degree of self-sufficiency over longer timeframes are not taken into account in this analysis, all technologies that improve longer term self-sufficiency rates (e.g. batteries, heat storage in buildings or underground seasonal heat storage) are disadvantaged as these additional benefits are not valued in the cost-optimal framework.

3 Cost optimal analysis of PEB case studies

This section describes the scenarios developed within the cost optimal analysis and discusses the main results achieved for all four demo-sites.

3.1 Spanish case-study

3.1.1 Building design

The Spanish demo case is located in the historical centre of Valladolid, a city characterized by a mild climate, with cold winters and hot summers. It is a protected classical Renaissance palace (XVI century). The project consists of an overall renovation of the internal distribution of the building in order to create nine dwellings, five of them in a duplex typology. After renovation, the building will have a useful floor area of 1089 m^2. Due to the heritage protection of the building, to minimize the energy demand, the envelope of the building has to be upgraded without modifying the exterior appearance of the façade, including the size and 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 2: Pilot case Spain – Historical building in Valladolid

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 and 1.5 kW PVT for DHW), 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 for daily use. When the batteries are fully loaded, the PV will feed the grid or possibly the neighbouring buildings. In this last case, an energy community will be established. PVT will be also installed to supply domestic hot water. The electro-mobility component will be integrated by deploying 2 EV charging stations, completing the EXCESS PEB concept as they further increase self-consumption rate. Furthermore, a high-performance building envelope with innovative materials and solutions will be deployed, to minimize the thermal energy demand of the building. Figure 3 shows the detailed layout of the energy system.

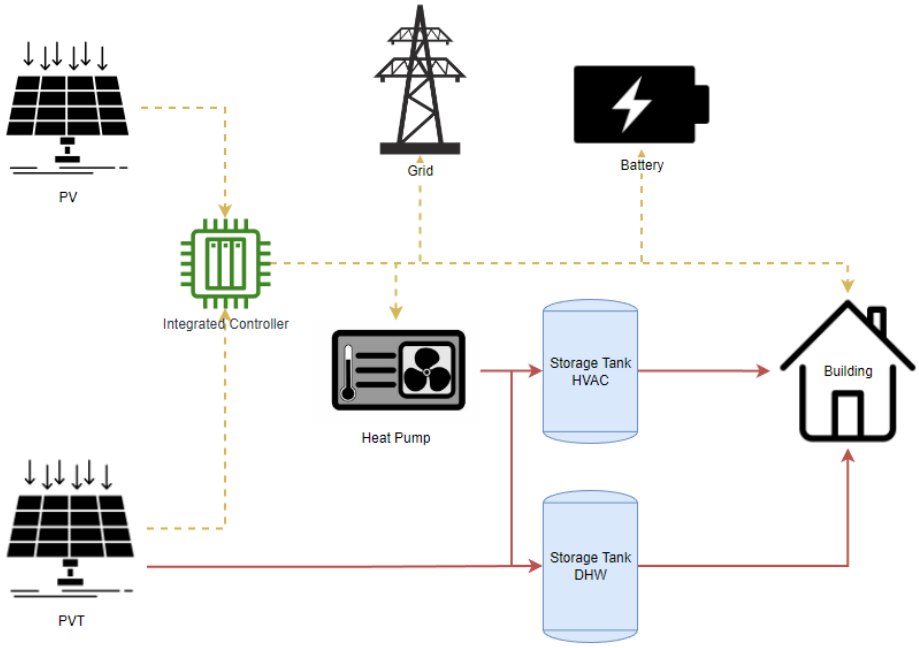

Figure 3: Energy system scheme of the Spanish pilot-case. Source: CENER

3.1.2 Scenarios and technology packages - Spain

This section describes the different technology packages that were defined and compared for the Spanish pilot case. Technology packages are combinations of different technology options (scenarios) for different building subsystems. Scenarios were defined for the envelope, the heating system, the renewable energy production system and the building management system.

Currently the heating system in Spain is dominated by gas and diesel boilers accounting for 56% of the heating generation, additionally biomass boilers account for another 22%. While there is a tendency of replacing boilers with aerothermal heat pumps, it is mostly on single family buildings and has not been widespread in multi-dwelling buildings due to the need of replacing radiators with low temperature emitters. However, according to European regulation, it is recommended to replace the gas heating systems with heat pumps in the next years to reach carbon neutrality of the building stock by 2035.

Therefore for this analysis, two scenarios are defined for the thermal system, TS1 and TS2. TS0 is the current state of the art gas heating system with solar thermal for DHW as it is currently prevailing in Spain. TS1 represents a scenario with an aerothermal heat pump as it is realized in the renovation of the Spanish pilot-case during the EXCESS project. Additionally, the potential for the installation of PVT for the generation of DHW, to further reduce the electricity demand, has been considered in TS2 in order to evaluate the techno-economic feasibility of this type of technology in this climate zone. The PVT installation has been dimensioned to meet the relatively low DWH demand during summer, in order to avoid generating excess heat in the hotter months.

According to the actual Spanish regulation, a building that complies with the minimum requirements stated in the Spanish Technical Code of Edification (CTE) is considered as nZEB. However, in Spain, the majority of the building renovations are very shallow, with 80% of the renovations achieving a reduction in non-renewable energy consumption lower than 3% with respect of the previous value. Taking this into account, different scenarios (D0, D1, D2) were defined for the building envelope. D0 represents a building renovation according to the minimum legislative requirements for renovation in Spain which is the standard of nZEB requirements. D1 represents a more ambitious renovation scenario, realized for the EXCESS demo-cases and aimed at further reducing the energy demand to achieve the PEB status. Scenario D2 includes a ventilation heat recovery unit that further reduces heat energy demand. The transmittance (U) values for each building component and scenario are shown in Table 2.

In addition, different energy layouts and scenarios were also defined for the PV facility. PV1a and PV2a represent scenarios based on the installation of PV panels on the roof of the building, without electrical storage devices. PV2b represents the scenario realized within the EXCESS project, based on the inclusion in the energy layout of a 51.4 kW_p PV system with a 30 kWh battery energy storage managed by an advanced building energy management system.

Overall, Table 1 summarizes the several renovation scenarios for each subsystem and describes the corresponding initial investment costs.

Table 1: Description of renovation scenarios for building subsystems.

	Scenario	**Description**	**Investment costs [€]**	**Investment costs per unit [€/(m² or kW or kWh)]**	**Expected technology lifetime [y]**
Building envelope	D0	Baseline Spanish regulation envelope; U-value of envelope [W/(m² K)]: walls 0.41, roof 0.35, floor 0.65, windows 1.8	143 700	131 €/m²	50
	D1	High efficiency envelope; U-value of envelope [W/(m² K)]: walls 0.13, roof 0.1, floor 0.27, windows 0.87	269 100	247 €/m²	50
	D2	High efficiency envelope D1 plus heat recovery unit **(EXCESS scenario)**	318 600	292 €/m²	50
Thermal system	TS0	Gas heating with boiler and solar thermal for DHW	78, 300	348 €/kW	15
	TS1	Aerothermal heat pump (40 kW) with floor heating	156 200	3905 €/kW	20
	TS2	Aerothermal heat pump (40kW) with PVT (2.8kW) for DHW **(EXCESS scenario)**	164 600	3905 €/kW HP 3000 €/kWp PVT	20
PV facility	PV0	no PV	0	0 €/kWp	n.a.
	PV1a	22.75 kWp (70 panels each 375Wp), no storage	48 000	2110 €/kWp	25
	PV2a	51.38 kWp (70 panels each 375Wp), no storage	95 900	1866 €/kWp	25
	PV2b	51.38 kWp (70 panels a 375Wp), 30kWh battery energy storage **(EXCESS scenario)**	149 900	1866 €/kWp PV 1800 €/kWh bat.	25
Building management system	CS0	Baseline monitoring - control for heaters	4 100	n.a.	30
	CS1	Standard monitoring - control for space heating/cooling floor	15 000	n.a.	30
	CS2	Advanced Building Energy Management System **(EXCESS scenario)**	58 500	n.a.	30

As listed in Table 2, the scenarios for each building system were combined to several technology packages. Combinations that are not reasonable (e.g. advanced control (CS2) without PV) were neglected from the analysis. Table 2 also shows the most important cost and performance data of all simulated technology packages.

Table 2: Energy demand and global cost of technology packages – Spain.

Envelope	Thermal system	PV facility	Building management system	Gas demand [kWh/(m²y)]	Electricity demand (incl. plug loads) [kWh/(m²y)]	Electricity demand w/o plug loads) [kWh/(m²y)]	Electricity production [kWh/(m²y)]	Net Primary Energy demand wo plug loads [kWh/(m²y)]	Global costs wo plug loads [€/m²]
D0	TS0	PV0	CS0	77	36	22	0	139	637
D1	TS0	PV0	CS0	60	36	22	0	117	671
D2	TS0	PV0	CS0	42	36	22	0	97	669
D0	TS1	PV0	CS1	0	64	50	0	106	587
D1	TS1	PV0	CS1	0	58	44	0	93	649
D2	TS1	PV0	CS1	0	53	39	0	82	679
D0	TS2	PV0	CS1	0	63	49	0	102	582
D1	TS2	PV0	CS1	0	56	42	0	89	644
D2	TS2	PV0	CS1	0	51	37	0	78	674
D0	TS0	PV1a	CS0	77	36	22	31	74	650
D1	TS0	PV1a	CS0	60	36	22	31	53	684
D2	TS0	PV1a	CS0	42	36	22	31	32	682
D0	TS1	PV1a	CS1	0	64	50	31	41	587
D1	TS1	PV1a	CS1	0	58	44	31	28	651
D2	TS1	PV1a	CS1	0	53	39	31	18	682
D0	TS2	PV1a	CS1	0	63	49	31	38	584
D1	TS2	PV1a	CS1	0	56	42	31	24	648
D2	TS2	PV1a	CS1	0	51	37	31	14	679
D0	TS0	PV2a	CS0	77	36	22	62	10	680
D1	TS0	PV2a	CS0	60	36	22	62	-12	713
D2	TS0	PV2a	CS0	42	36	22	62	-32	711
D0	TS1	PV2a	CS1	0	64	50	62	-23	609
D1	TS1	PV2a	CS1	0	58	44	62	-37	673
D2	TS1	PV2a	CS1	0	53	39	62	-47	706
D0	TS2	PV2a	CS1	0	63	49	62	-27	606
D1	TS2	PV2a	CS1	0	56	42	62	-40	672
D2	TS2	PV2a	CS1	0	51	37	62	-51	704
D0	TS0	PV2b	CS0	77	36	22	62	10	711
D1	TS0	PV2b	CS0	60	36	22	62	-12	745
D2	TS0	PV2b	CS0	42	36	22	62	-32	742
D0	TS1	PV2b	CS1	0	64	50	62	-23	641
D1	TS1	PV2b	CS1	0	58	44	62	-37	706
D2	TS1	PV2b	CS1	0	53	39	62	-47	737
D0	TS2	PV2b	CS1	0	63	49	62	-27	639
D1	TS2	PV2b	CS1	0	56	42	62	-40	704
D2	TS2	PV2b	CS1	0	51	37	62	-51	736
D1	TS1	PV2b	CS2	0	56	42	62	-40	717
D2	TS1	PV2b	CS2	0	52	38	62	-50	749
D1	TS1	PV2b	CS2	0	55	41	62	-44	715

Table 2: Cont.

D2	TS2	PV2b	CS2	0	50	36	62	-53	748
D0	TS2	PV2b	CS2	77	36	22	0	139	637
D1	TS2	PV2b	CS2	60	36	22	0	117	671

3.1.3 Results of cost optimal analysis – Spain

This section outlines the results of the cost performance analysis. Table 3 shows the parameters used for the economic evaluation procedure. In addition, section 4 presents a sensitivity analysis for other calculation parameters.

Table 3: Summary of the main parameters for the economic analysis - Spain

Parameter	Value
Calculation period [y]	30
Discount rate [%]	3
Electricity price [€/kWh]	0.2
Gas price [€/kWh]	0.12
Electricity selling tariff [€/kWh]	0.1
PEF gas [-]	1.2
PEF electricity [-]	2.1

Figure 4 shows the net primary energy demand and global cost of all technology packages with and without plug loads. For the Spanish pilot case, plug loads of 14 kWh/(m^2 y) are assumed. It can be seen that 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.

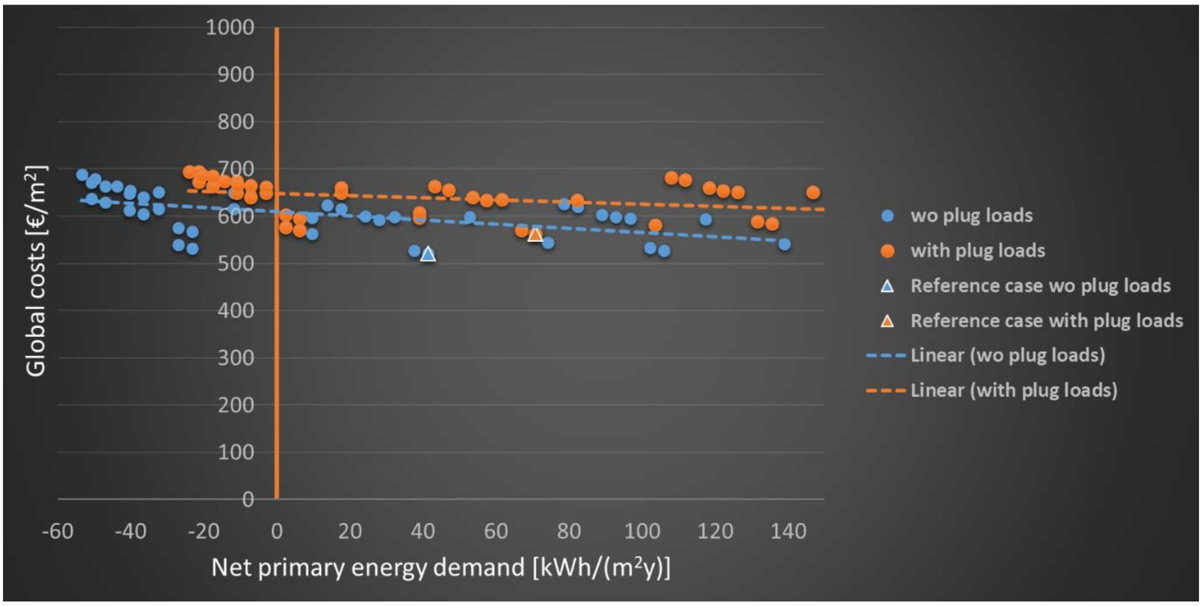

Figure 4: Cost optimal analysis Spain – all technology packages

Figure 4 also shows trend-lines which indicate that a reduction of net primary energy demand does not significantly increase global costs for technology packages with a positive energy balance. The slope of the trend-line starts to increase below a net primary energy demand of zero (PEB level), which leads to the conclusion that PEB level can be achieved for the Spanish demo without a significant increase of global costs. A further decrease of net primary energy demand however increases global costs. On the other hand, Figure 4 also shows the difference between a standard renovation according to the nZEB standard and a renovation scenario compliant with the PEB standard.

In order to analyse the scenarios of each building system in detail, additional cost curves were created and analysed as outlined in the following paragraphs.

Analysis of thermal system scenarios:

Figure 5 shows the cost-performance curves for different scenarios of the heating system. The blue lines represent scenarios with building envelope defined as D0. While the other lines refer to the combinations of sub-scenarios described in detail in Table 3.

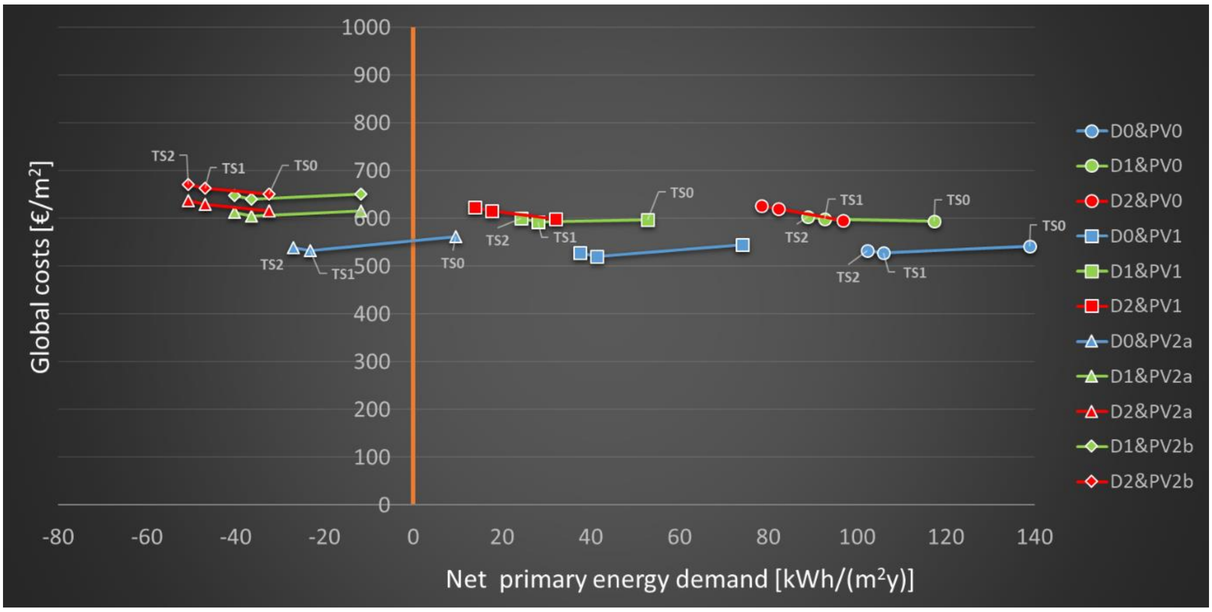

Figure 5: Cost optimal analysis Spain – comparison of heating system

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 costs for electricity. 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. However, this result may be strongly influenced by the shape and size of the building. In first place, as the Spanish demo is a small building, there are just a few dwellings, resulting in a low DHW consumption. This condition limits the amount of PVT that can be installed without generating excess heat during summer (otherwise the cost would be higher due to heat dissipaters) and that means that the PVT installation as well as fixed investment and installation cost of the tank and water distribution is high compared with the installed power. Secondly, the shape of the building (low height and large surface area) provides a large roof area that can be used to generate electricity with a less space-efficient technology such as PV. In the case of a tall building with a small roof, it is probable that it would be better to use PVT over PV to generate more energy with the available space to reach the PEB goal. Additionally, during the summer months, when the production of PVT is higher, the COP of the aerothermal heat pump is also higher as well as the surplus of PV, which competes with the generation of PVT. Therefore, it can be concluded that PVT may not be a cost-effective technology in the Spanish demo case given the shape of the building and current material prices and installation costs.

Overall, it can be said that a switch from gas heating system to aerothermal heat pump heating system leads to a significant reduction in net primary energy demand as the heat pump has much higher efficiency (COP > 3) 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. A detailed sensitivity analysis is presented in chapter 4.

Analysis of envelope scenarios:

Figure 6 analyses the different scenarios developed for the energy renovation of the building envelope. It can be seen 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. thermal comfort; increase in asset values; decrease in the cooling needs, especially if as expected the temperature will rise in the next decades) 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.

It is interesting to highlight 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 beneficial than an efficient heating system with aerothermal heat pump. As a consequence, the interdependencies of the cost of technologies and the conclusions, based on global costs analysis, should be always taken at the technology system level.

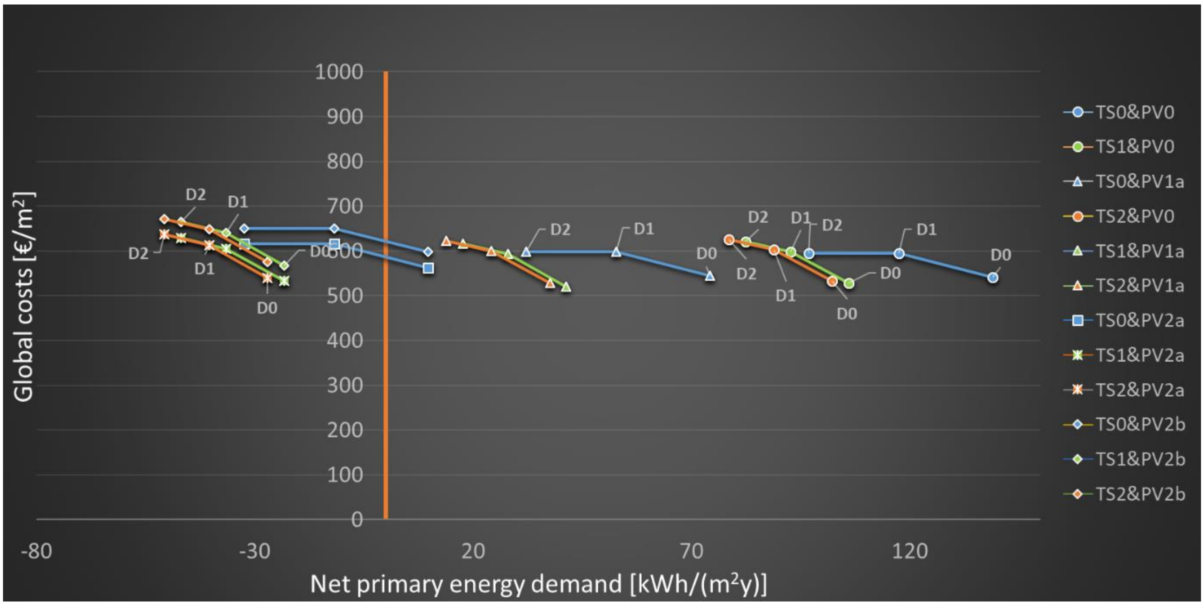

Figure 6: Cost optimal analysis Spain – comparison of envelope scenarios

Analysis of photovoltaic scenarios:

Figure 7 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 (electricity grid purchasing price as upper limit) which would further increase the profitability of the PV system.

Figure 7 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 effective in the Spanish pilot case as net primary energy demand is not much affected but global costs increase.

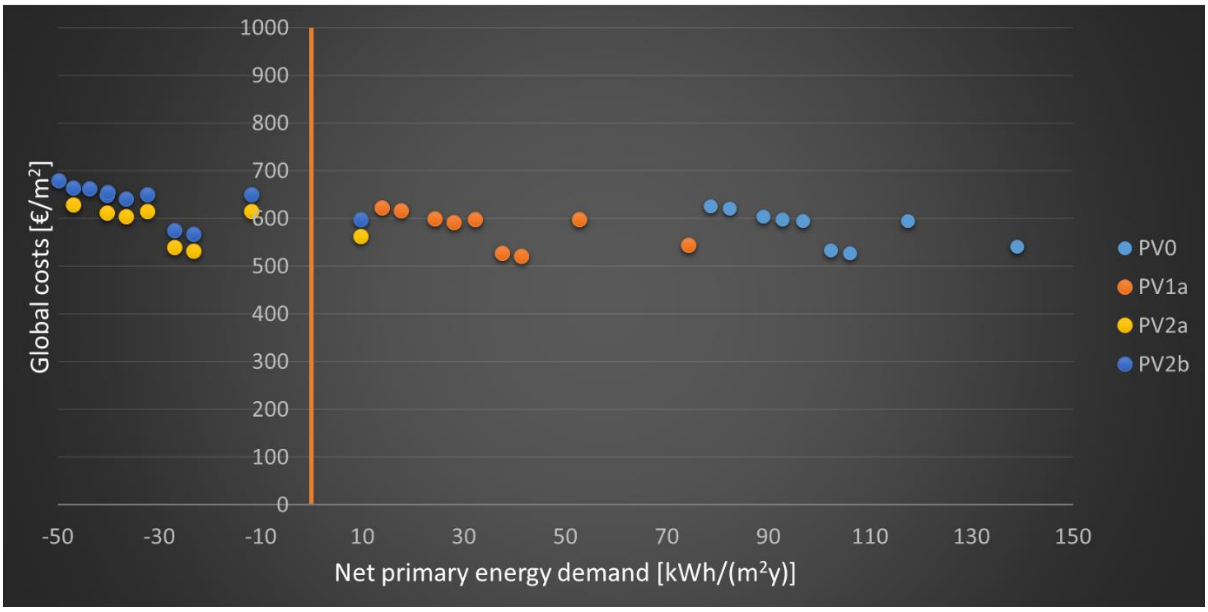

Figure 7: Cost optimal analysis Spain – comparison of PV scenarios

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 demo case. The most important technology for the achievement of PEB standard is Photovoltaic. Due to advantageous shape of the building (low height with high built surface area), a very high amount PV facilities in relation to the useful floor size can be installed.

A new heating system and an improvement of the building envelope further reduces net primary energy demand. The new heating system can be considered as almost cost effective 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 effective 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-effective 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 Finnish case-study

3.2.1 Building design

The Finnish case study is a Positive Energy Building constituted by 8 floors and located at Kalasatama district, in the city of Helsinki. The city centre is typically equipped with a District Heating (DH) network and buildings are a mixture of residential and commercial buildings. The demo building is a mixed-use building and includes residential apartments, commercial spaces and a restaurant at the first floor.

Kalasatama area is a perfect place to demonstrate PEBs, as it is part of City of Helsinki's Re-thinking Urban Housing programme, which aims to increase the quality and appeal of living in blocks of flats and integrate new personalised solutions into it.

The pilot building will have 51 apartments and a total heated area of around 4000 m^2. Figure 8 shows the building which is near to completion of construction works.

Figure 8: Finland pilot-case, residential building in Kalasatama Helsinki.

The energy system in place for the Kalasatama PEB is a hybrid geothermal energy system. It 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 needs to be 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 heat with heat pumps. The building structure, heating, ventilation and air conditioning is designed as energy efficient as possible. To optimise the overall energy system performance, an integrated smart control system enables demand response and two direction electricity trade.

In the Finnish PEB demo case, there are two main systems, one is the building and the second one is the energy system. As both of these systems are integrated together, a control that can maximize the performance of the energy system is needed. The main framework and components of the energy systems are shown in Figure 9.

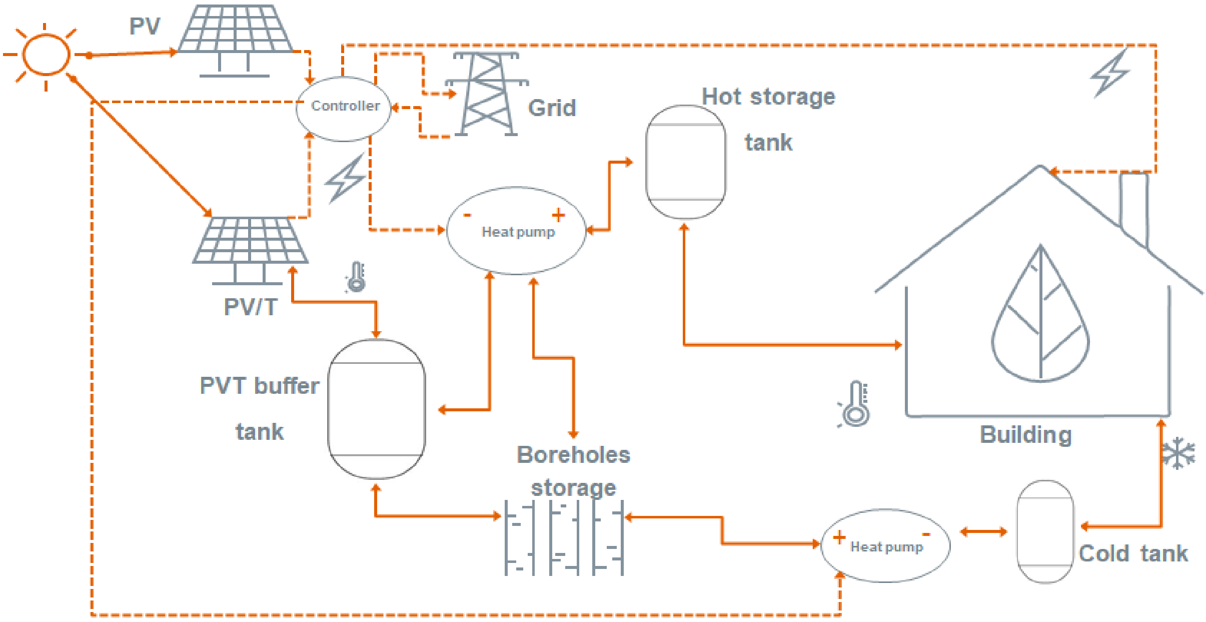

Figure 9: Finland pilot-case, energy system layout

3.2.2 Scenarios and technology packages - Finland

This section describes the different technology packages defined and compared for the Finnish pilot-case. Technology packages are combinations of different technology options for the thermal system and the renewable energy production system.

Official Statistics of Finland show that the residential sector used 61 TWh energy in 2020 (65 TWh in 2019) [5]. One third of this consumption was electricity, one third was district heating and 20% wood based energy. The space heating of residential buildings used two thirds of energy (39 TWh). The most common energy sources were district heating, wood and electricity, presenting 82% of heating energy consumption. The next common energy source is heat pumps. The electricity consumption in residential sector 22 TWh consists of 45% for space heating, 39 % for domestic appliances and the rest for domestic hot water and heating of sauna.

Energy efficiency legislation in Finland is based on EU building energy efficiency directive 2010, and amendment in 2018 (2010/31/EU, 2018/44/EU). The implementation is based on Maankäyttö- ja rakennuslaki (132/1999). The renovation strategy 2020-2050 is targeting to energy efficient and low carbon buildings before 2050 and gives targets for energy efficiency, cost optimal renovation measures, their financing and policy actions enhancing building renovation towards energy efficiency and low carbon heating [6].

For the thermal system, five different scenarios were analysed. 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, as described in the previous subsection. Table 4 summarizes the different energy renovation options for each building system.

Table 4: Description of energy renovation scenarios for building sub-systems.

	Scenario	Description	Investment costs [€]	Investment costs per unit [€/kW]	Expected technology lifetime [y]
Envelope	D0	Standard envelope acc. current nZEB standard; 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 HP, no PVs, no PVT, no cooling)	45 000	300	30
	TS1	Air to water heat pump, 150 kW, COP 2.5	225 000	1500	30
	TS2	Geothermal heat pump system, 150 kW, traditional boreholes with < 300m, COP 3.5;	375 000	2500	30
	TS3	Geothermal heat pump system incl. cooling, 150kW, traditional boreholes with < 300m, COP 4;	420 000	2800	30
	TS4	Geothermal heat pump system incl cooling, 150 kW, new innovative ~600 m deep boreholes (drilling technology and heat exchangers collector), seasonal borehole storage, tanks; COP 4.5;	450 000	3000	30
PVT device	PVT0	no PVT	0	0	n.a.
	PVT1	67kW$_P$ DualSun PVT panels (315 m^2) on roof	250 000	3731	30
BiPV device	PV0	No PV	0	0	n.a.
	PV1	87 kWp building integrated PV system (347 m^2 façade southwest)	240 000	2758	30

The scenarios for each building system were combined to 15 technology packages as listed in Table 5. Combinations that are not reasonable were neglected from the analysis. In addition to that, Table 6 also shows the most important cost and performance data of all simulated technology packages.

Table 5: Energy demand and global cost of technology packages – Finland.

Envelope	Thermal system	PV facility	PVT facility	Gas demand [kWh/m²y]	Electricity demand (incl. plug loads) [kWh/m²y]	Electricity demand w/o plug loads) [kWh/m²y]	Electricity production [kWh/m²y]	Net Primary Energy demand wo plug loads [kWh/m²y]	Global costs wo plug loads [€/m²]
D0	TS0	noPV	noPVT	0	60	57	0	120	359
D0	TS1	noPV	noPVT	0	33	30	0	64	313
D0	TS2	noPV	noPVT	0	29	26	0	55	348
D0	TS3	noPV	noPVT	0	28	26	0	54	357
D0	TS4	noPV	noPVT	0	27	25	0	51	366
D0	TS0	PV1	noPVT	0	60	57	8	103	375
D0	TS1	PV1	noPVT	0	33	30	8	46	329
D0	TS2	PV1	noPVT	0	29	26	8	38	364
D0	TS3	PV1	noPVT	0	28	26	8	37	373
D0	TS4	PV1	noPVT	0	27	25	8	34	382
D0	TS0	PV1	PVT1	0	60	57	24	70	394
D0	TS1	PV1	PVT1	0	33	30	24	13	348
D0	TS2	PV1	PVT1	0	29	26	24	5	382
D0	TS3	PV1	PVT1	0	28	26	24	4	392
D0	TS4	PV1	PVT1	0	27	25	24	1	400

3.2.3 Results of cost optimal analysis – Finland

This section outlines the results of the cost performance analysis for the Finnish case-study.

Table 6 shows the parameters used for the economic calculation. A sensitivity analysis for other parameters is presented in chapter 4.

Table 6: Parameters of analysis – Finland

Parameter	Value
Calculation period [y]	30
Discount rate [%]	3
Electricity price [€/kWh]	0.2
Gas price [€/kWh]	0.12
Electricity selling tariff [€/kWh]	0.1
PEF gas [-]	1.2
PEF electricity [-]	2.1

Figure 10 illustrates the net primary energy demand and global cost of all technology packages with and without plug loads. For the Finnish pilot case, plug loads of only 12.7 kWh/(m^2 y) are assumed. 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 lead to a PEB solution. 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 facilities. Another reason is the rather cold climate that leads to a relatively high energy demand for space heating compared to other geographical areas in the European Union.

Figure 10 also shows the difference between a standard renovation according to the nZEB standard (in yellow) and an energy renovation scenario according to the PEB standard. It can be seen that global costs increase with a reduction of net primary energy demand (from nZEB to PEB). A detailed analysis of all building technologies is shown in the following paragraphs.

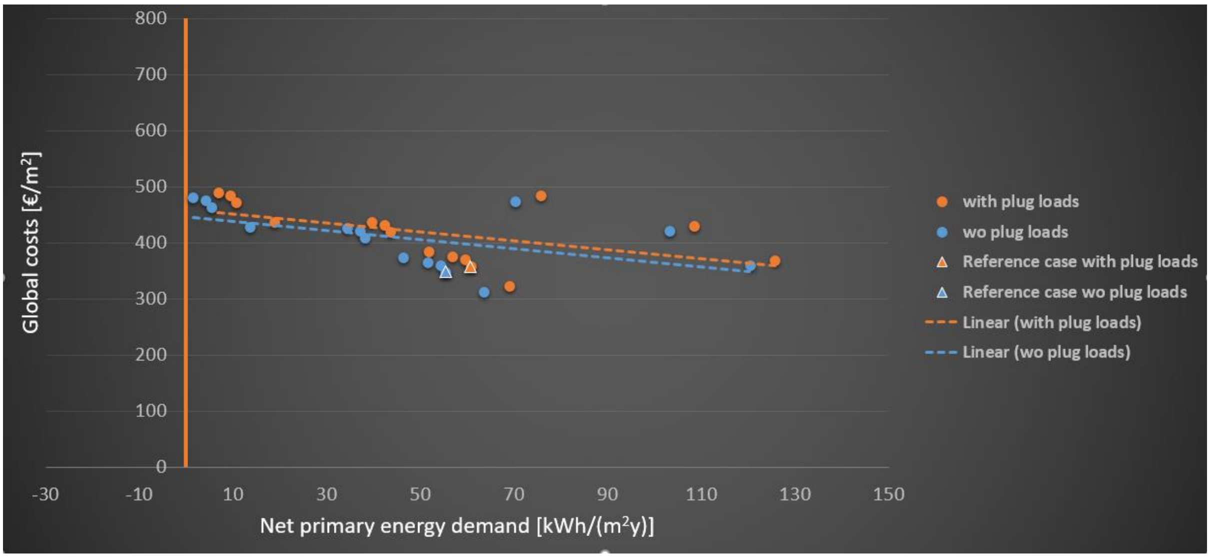

Figure 10: Cost optimal analysis Finland – all technology packages

Analysis of thermal system scenarios:

Figure 11 shows the cost-energy curves for all thermal system scenarios. It can be seen that a change from a thermal system with gas heating (TS0) to an efficient state of the art 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, it can be concluded that a heat pump with traditional boreholes (TS1) is the most cost-effective 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 present additional benefits. Those additional benefits such as increased comfort cannot be considered in the present analysis, which reveals another limitation of the cost optimal methodology.

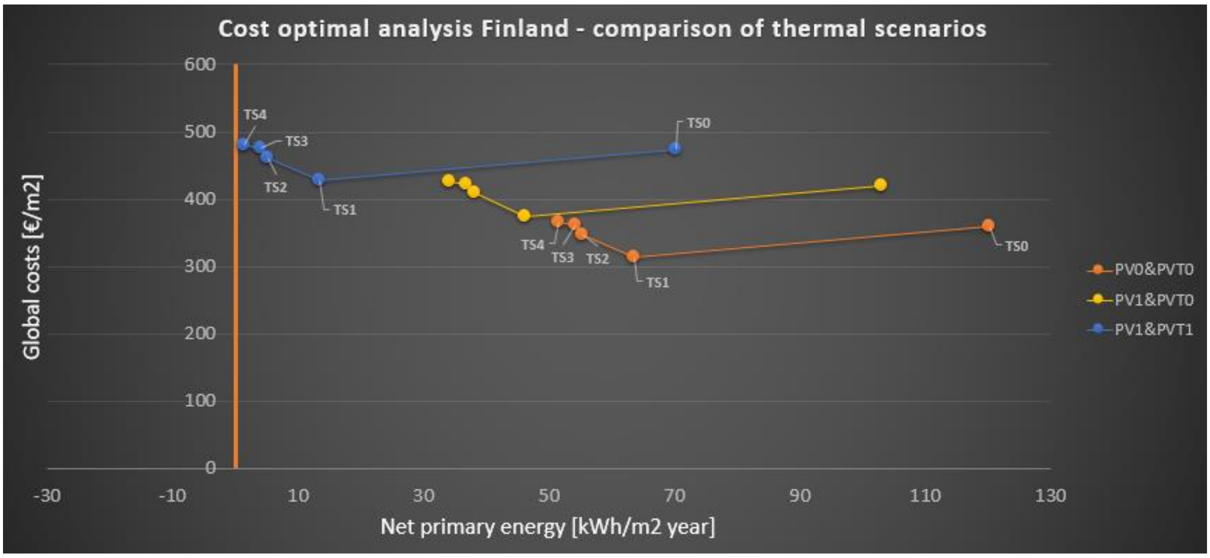

Figure 11: Cost optimal analysis Finland – thermal system scenarios

Analysis of PV and PVT scenarios:

Figure 12 shows cost-performance curves for different building integrated PV and PVT scenarios. It can be seen 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 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.

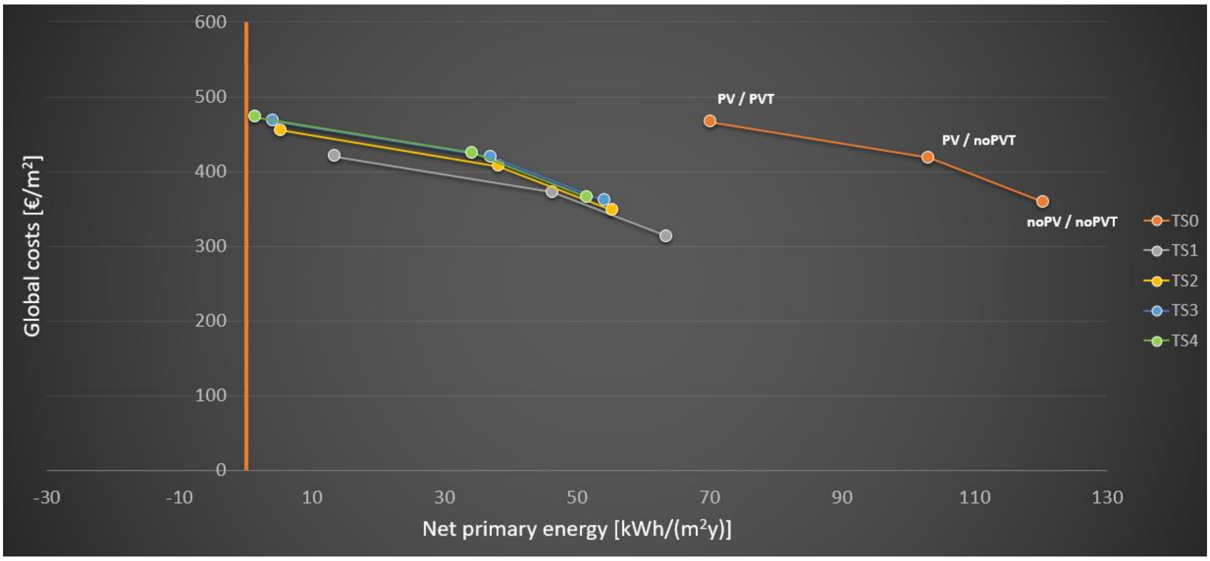

Figure 12: Cost optimal analysis Finland – PV and PVT scenarios.

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 photovoltaic. The cost optimal analysis showed that the EXCESS technologies 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 with a calculation period of 30 years. 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.

3.3 Belgium case-study

3.3.1 Building design

The demo site in Hasselt (BE) is part of a larger new-built residential area and it was completed in 2018. The project consists of 68 apartments and 22 houses intended for social housing. The Excess demonstrator is a part of this residential area including four apartment buildings with 20 dwellings. The residential units are connected to a small District Heating network which is heated by different thermal energy sources (geothermal heat pumps, gas-fired geothermal heat pumps and backup gas-fired boilers).

Figure 13: Hasselt demonstrator site.

In each residential unit, a substation is installed to use the local District Heating network for space heating and domestic hot water production. In the Excess project the building will be converted to a Positive Energy Building. This will be achieved by implementing innovative solutions developed within the Excess project, such as:

- PVT panels for renewable heat and electricity
- Multi-source and direct controlled heat pump
- PV panels for renewable electricity
- MPC controller for optimization of the energy flows onsite
- Activation of thermal and electrical flexibility in the heat interface units within the apartments

The buildings were constructed taking into account the EPBD requirements on energy efficiency at the time of construction a few years ago. Each year these requirements are updated and as from 2025 the following targets are introduced for new residential buildings:

- Maximum U-values: roof, floor and wall: U_{max} = 0.24 W/(m² K), windows: 1.5 W/(m² K), doors and gates: 2 W/(m² K)
- Ventilation requirements
- Limitation on potential overheating
- Annual energy production from solar > 15 kWh/(m² y)
- Heating on low temperature (< 45°C)
- No fossil fuel-based systems allowed

The requirements on low temperature heating and solar energy production were not yet in place at the time the demo site was designed.

3.3.2 Scenarios and technology packages - Belgium

This subsection describes the different technology packages that were compared in this analysis in terms of global costs and net primary energy demand. Technology packages are defined by combinations of different scenarios for the thermal system, PV and PVT facility and a co-generation unit. Scenarios were defined for the thermal system, PV/PVT facility, cogeneration and the wind turbine. The details of the scenarios are listed in Table 7. Cost for the envelope were not considered in the calculations as the high efficient envelope was already part of the existing building.

Table 7: Description of scenarios for building sub-systems.

	Scenario	Description	Investment costs [€]	Investment costs per unit [€/kW]	Expected technology lifetime [y]
Envelope	D0	U-value of envelope [W/(m^2 K)]: walls 0.19, roof 0.14, floor 0.24, windows 1.59	-	-	30
Thermal system	TS0	Current state of the art heating system with gas boilers	15 000	300 €/kW	20
	TS1	Controllable Geothermal heat pump, 50 kW; (EXCESS scenario)	50 000	1000 €/kW	20
Wind turbine	WIND0	No Wind turbine	0	0 €/kW	20
	WIND1	Wind turbine 5 kW$_e$ (small scale vertical axis wind turbine)	30 000	6000 €/kW	20
PV facility	PV0	no PV	0	0 €/kWp	20
	PV1a	44 kWp PV on roof (EXCESS scenario)	66 000	1500 €/kWp	20
	PV2	88 kWp PV on roof	132 000	1500 €/kWp	20
PVT facility	PVT0	No PVT	0	0 €/kWp	n.a.
	PVT1	44 kWp PVT on roof (EXCESS scenario)	180 000	4090 €/kWp	20
Cogeneration unit	CG0	No cogeneration unit	0	0 €/kW	n.a.
	CG1	With cogeneration unit, 5.5 kW$_e$	30 000	5500 €/kW	10

The scenarios for each building system were combined to overall 19 technology packages as listed in Table 8. Combinations which are not reasonable (e.g. PV2 with PVT due to space restrictions) were neglected from the analysis. Table 8 also shows the most important cost and performance data of all simulated technology packages.

Table 8: Energy demand and global cost of technology packages – Belgium.

Thermal system	Wind turbine	PV facility	PVT facility	Cogeneration unit	Gas demand [kWh/m²y]	Electricity demand (incl. plug loads) [kWh/m²y]	Electricity demand w/o plug loads) [kWh/m²y]	Electricity production [kWh/m²y]	Net Primary Energy demand wo plug loads (kWh/m²y)	Global costs wo plug loads (€/m²)
TS0	WIND0	PV0	PVT0	CG0	96	19	7	0	130	424
TS1	WIND0	PV0	PVT0	CG0	0	41	29	0	61	258
TS0	WIND0	PV1	PVT0	CG0	96	19	7	22	84	443
TS1	WIND0	PV1	PVT0	CG0	0	41	29	22	15	267
TS0	WIND0	PV0	PVT1	CG0	96	19	7	22	84	544
TS1	WIND0	PV0	PVT1	CG0	0	39	26	22	9	357
TS0	WIND0	PV1	PVT1	CG0	96	19	7	44	38	567
TS1	WIND0	PV1	PVT1	CG0	0	39	26	44	-37	375
TS0	WIND0	PV0	PVT0	CG1	110	19	7	15	115	470
TS1	WIND0	PV0	PVT0	CG1	56	32	19	15	75	377
TS0	WIND0	PV1	PVT0	CG1	110	19	7	37	69	494
TS1	WIND0	PV1	PVT0	CG1	56	32	19	37	29	396
TS0	WIND0	PV0	PVT1	CG1	110	19	7	37	69	595
TS1	WIND0	PV0	PVT1	CG1	56	30	18	37	26	493
TS0	WIND0	PV1	PVT1	CG1	110	19	7	59	22	619
TS1	WIND0	PV1	PVT1	CG1	56	30	18	59	-20	517
TS1	WIND0	PV2	PVT0	CG0	0	41	29	44	-32	282
TS1	WIND0	PV2	PVT0	CG1	56	32	19	59	-17	420
TS1	WIND1	PV1	PVT1	CG0	0,00	39	26	44	-38	381
TS1	WIND1	PV2	PVT0	CG0	0	41	29	44	-32	289

3.3.3 Results of cost optimal analysis – Belgium

This section outlines the results of the cost performance analysis for the Belgium case-study. Table 9 shows the parameters used for the economic calculation. A sensitivity analysis for other evaluation parameters is described in chapter 5.

Table 9: Parameters of analysis – Belgium

Parameter	Value
Calculation period [y]	30
Discount rate [%]	3
Electricity price [€/kWh]	0.2
Gas price [€/kWh]	0.12
Electricity selling tariff [€/kWh]	0.1
PEF gas [-]	1.2
PEF electricity [-]	2.1

Figure 14 shows the net primary energy demand and global cost of all technology packages with and without plug loads. For the Belgium pilot case, plug loads of 12.4 kWh/m²year are assumed. This value is based on measurement data from buildings with similar characteristics on the Cordium site in Kuringen.

It can be seen that there are some technology packages with a net primary energy demand below 0. Those combinations are PEB combinations as they produce more energy than they consume.

The chart also shows the difference between nZEB and PEB as well as a trend-line, which indicates that a reduction of net primary energy demand also reduces global costs. As noted above, the cost for the envelope were not considered. However, as the dataset presents a very high variance, the correlation is not very robust. Therefore, a detailed analysis of all building systems elements was carried out as outlined below.

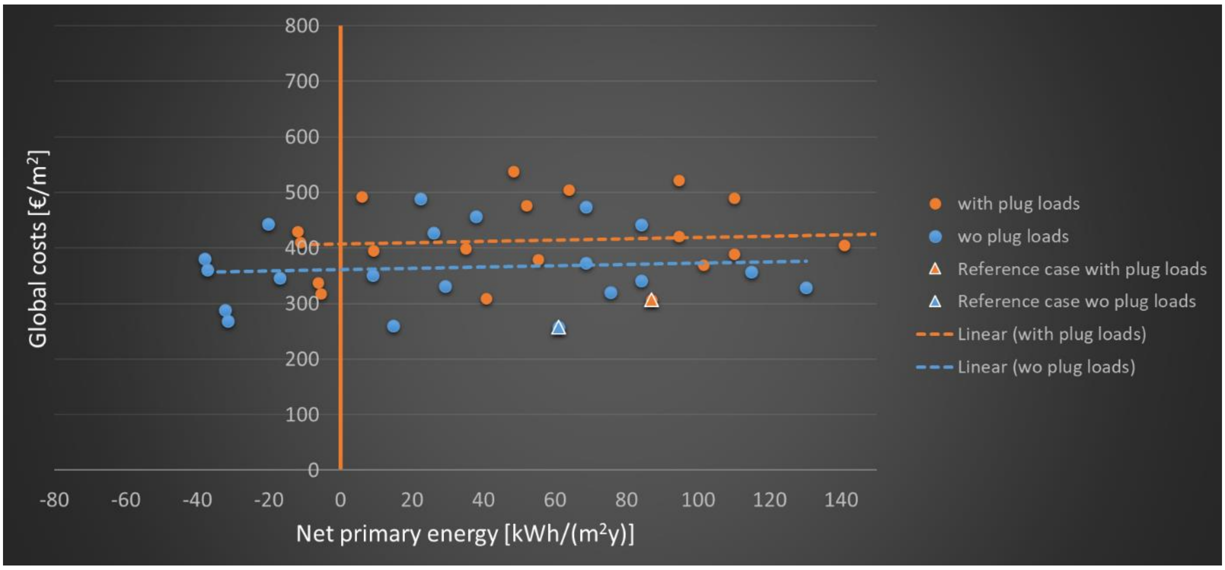

Figure 14: Cost optimal analysis Belgium – all technology packages

Analysis of thermal system and cogeneration unit:

Figure 15 shows cost-performance curves for different heating system and cogeneration scenarios. It can be seen that the cogeneration unit reduces the net primary energy demand and increases global costs for technology packages with gas heating system (TS0). For technology packages with geothermal heat pump (TS1), the micro-cogeneration unit increases net primary energy demand and global costs. Therefore, it can be concluded that the micro-cogeneration unit is not cost-effective.

Furthermore, Figure 15 shows the cost and performance of the thermal systems. It can be seen that the improvement of the thermal system from gas heating to geothermal heat pump reduces net primary energy demand and global costs. Therefore it can be concluded that a change of the heating system from gas heating (TS0) to geothermal heating (TS1) is cost effective. In other words, a change of the heating system is profitable and has a payback period within with the calculation period of 30 years.

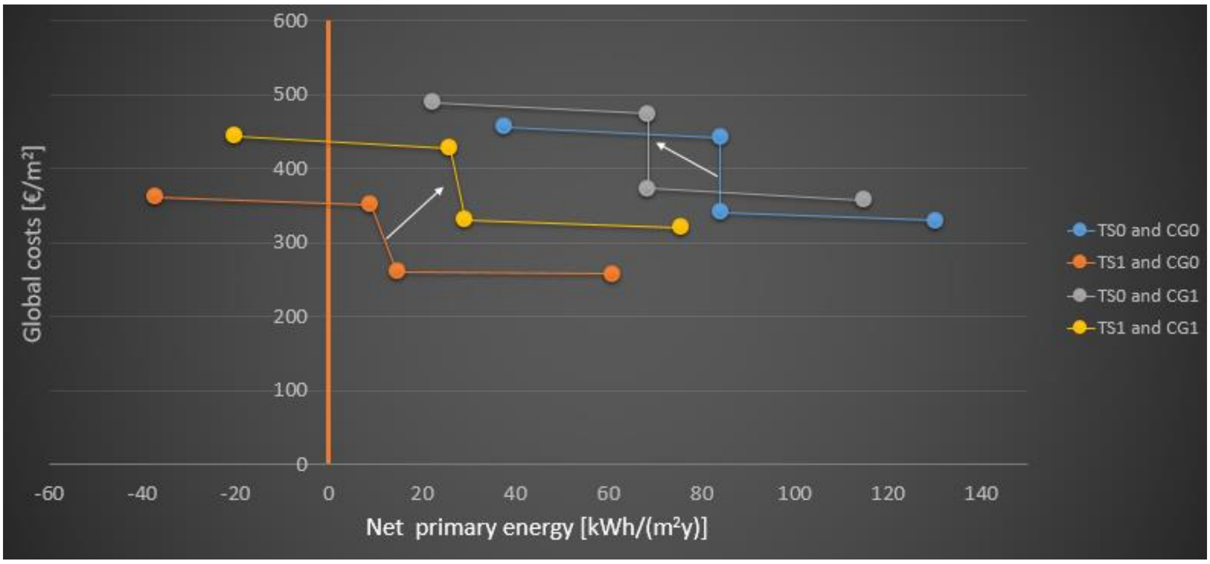

Figure 15: Cost optimal analysis Belgium – analysis of cogeneration unit and thermal system

Analysis of PV and PVT scenarios:

Figure 16 shows global costs and net primary energy demand of different PV and PVT scenarios. It can be seen that an increase of PV reduces net primary energy demand without significant increase of global costs (change from PV0&PVT0 to PV2&PVT0). Therefore, it can be concluded that the PV is a cost-effective technology for the achievement of PEB level in the Belgium pilot-case. The installation of PVT also reduced net primary energy demand but at the same time increases global costs. Therefore PVT is not cost effective with current material and installation cost. But it has to be mentioned that PVT is used to store excess heat in the ground and thereby regenerates the seasonal storage in the bedrock. In some applications, e.g. densely settled area with high heat energy demand, the regeneration of the BTES with PVT excess heat is a must have criteria for the usage of a geothermal heating system. On the same line, in the Finnish demo case the PVT system is crucial for the efficient long lasting operation of the thermal system. However, the global cost calculation methodology cannot consider this additional benefits in the calculation.

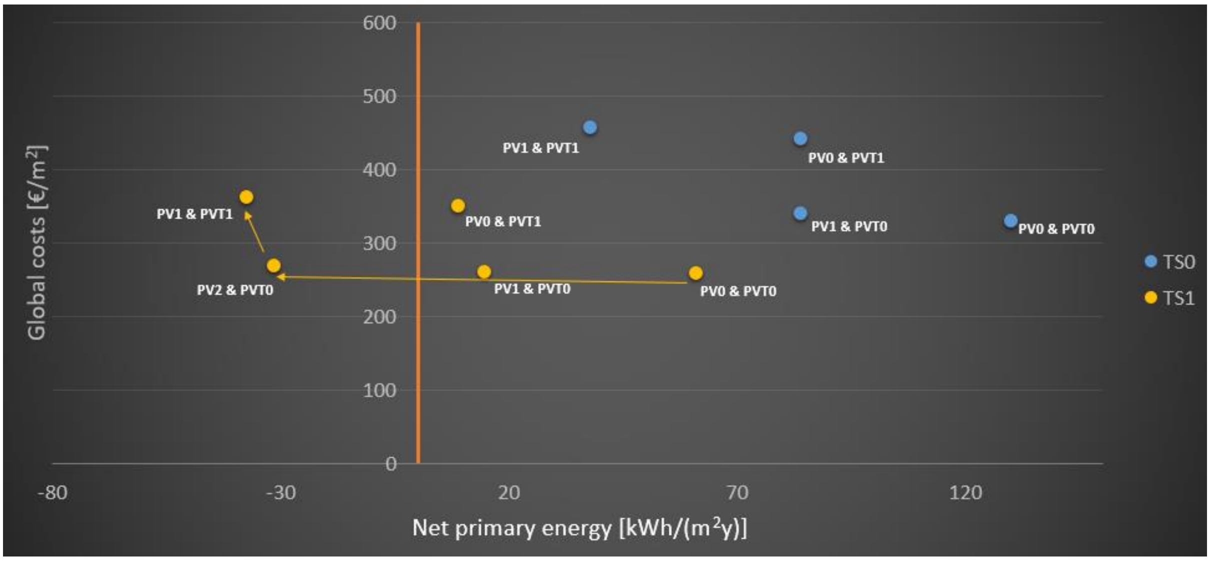

Figure 16: Cost optimal analysis Belgium – analysis of PV and PVT system.

Analysis of wind turbine scenarios:

Figure 17 shows the difference in global costs and net primary energy demand of technology packages with wind turbine and without wind turbine. It can be seen that the wind turbine slightly decreases net primary energy demand but increases global costs. Therefore it can be concluded that this small scale vertical axis wind turbine is not cost-effective. One reason is that the expected electrical output of the wind turbine in the Belgium demo is far less than a standard horizontal axis wind turbine of similar size due to the relatively low wind speed which was measured on the demo site during the last year.

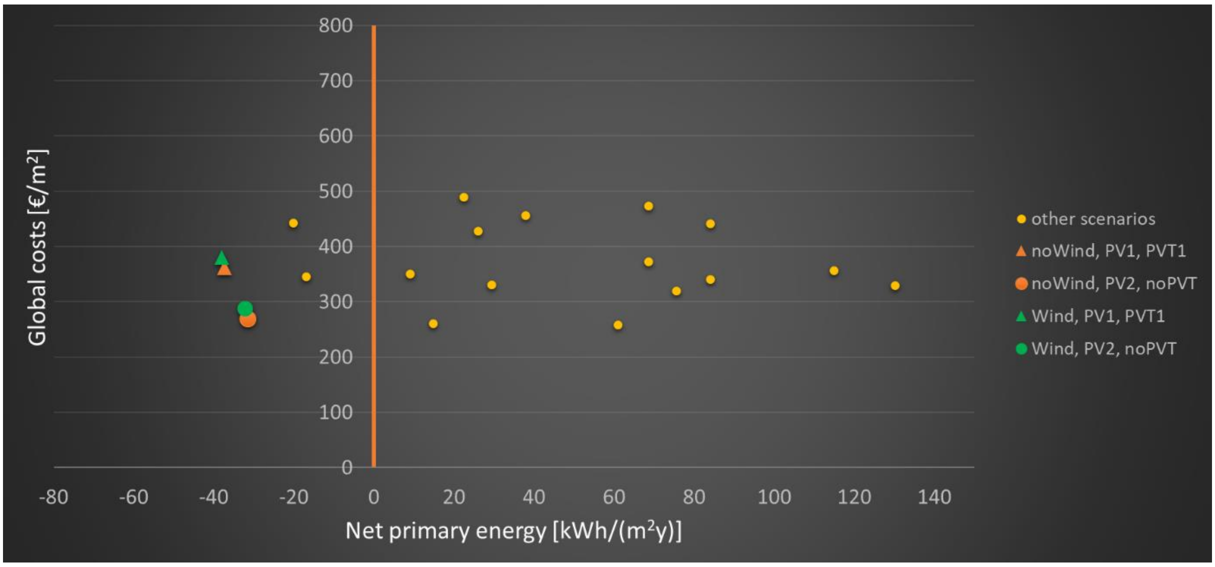

Figure 17: Cost optimal analysis Belgium – analysis of wind turbine

As a result, the most cost effective PEB technology package in the Belgium pilot-case is based on the combination of PV and geothermal heat pump.

3.4 Austrian case-study

3.4.1 Building design

The Austrian EXCESS Demo case is located in the “Tagger-Werk”, a former industrial area in the south of Graz, the second-largest city in Austria. Lying southeast of the Alps in the Styria region, the city's weather and climate is mainly influenced by the Mediterranean rather than the North Atlantic, resulting in a high hourly average of sunshine per year.

The EXCESS demo case, a former feed production silo, is part of a 19 building strong complex with about 31.000 m² gross floor area. Upon completion, the EXCESS positive energy silo will become an office building.

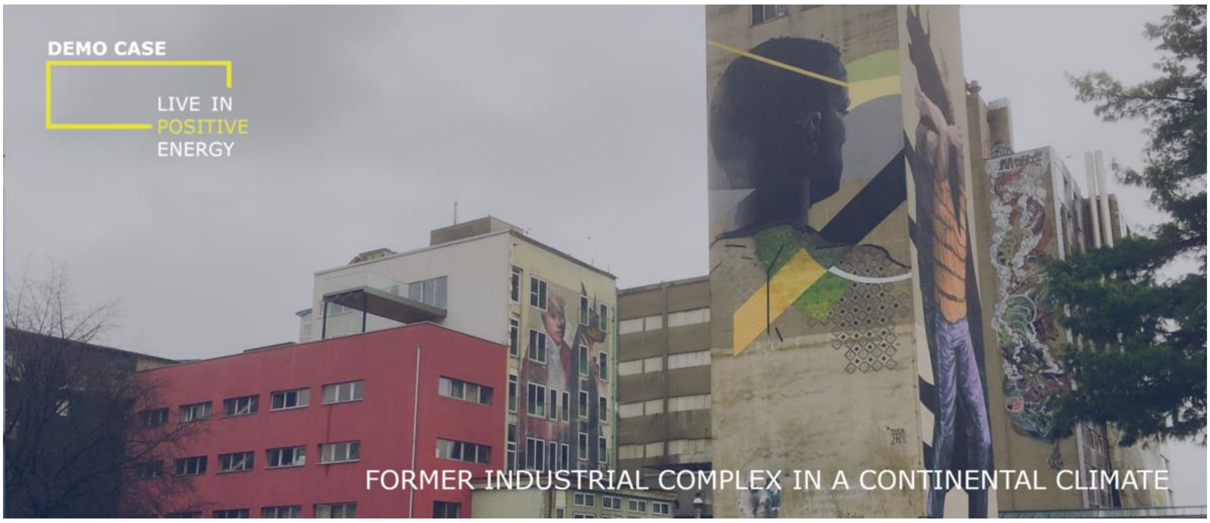

Figure 18: Pilot case Austria – PEB as former industrial building.

A positive energy house standard will be achieved by activating the existing thermal mass of the building structure via pre-fabricated multifunctional facade elements including integrated PVs to supply the heat, cold and electricity demand of the building.

The energy supply for the entire area will be ensured primarily through locally produced renewable energy (solar energy, groundwater heat pumps, small size hydropower). Innovative elements for load shifting, storage, user integration and interaction with the local electricity grid will be integrated and coupled with a smart and predictive control system in order to achieve maximum energy flexibility.

3.4.2 Scenarios and technology packages - Austria

This subsection describes the different technology packages compared in this analysis in terms of global costs and net primary energy demand. Technology packages are defined by combinations of different scenarios for the building envelope, the heating system, PV facility and building management system. Table 10 describes the different scenarios for each sub-system.

Austria has started in defining the national goals for 2030 and beyond based on the latest EPBD revision. The Austrian national plan defines a nZEB as an energy-efficient building with a thermally well-insulated envelope and an efficient heating system. The detailed minimum energy performance requirements are defined in the national building renovation directive (OIB Guideline 6).

Two different scenarios were defined for the building envelope. D0 represents a standard renovation of the envelope according to the latest requirements of OIB guideline 6. It contains an insulation of the roof with polystyrene (EPS), insulation of walls with mineral wool and upgrading the windows (U=1.3 W/m^{2}K). D1 represents an energy renovation scenario based on the use of multifunctional façade elements. This elements contain an insulation layer and an external wall heating system. This scenario implies the insulation of the roof with standard polystyrene (similar to D0) and the installation of windows with a lower trasmittance value (U=0.85 W/(m^2 K)) compared to the reference ones.

Three different scenarios were defined for the heating system. TS0 represents a state-of-the-art gas heating system as it is prevalent in many existing buildings in Austria. TS1 represents a ground water heat pump with floor heating. TS2 represents a ground water heat pump feeding mainly the active façade and a partial floor heating system. This scenario can, therefore, only be combined with the envelope scenario D1 (multifunctional façade element).

Table 10: Description of energy renovation scenarios for building sub-systems.

	Scenario	**Description**	**Investment costs [€]**	**Investment costs per unit [€/(m^2 or kW)]**	**Expected technology lifetime [y]**
Envelope	D0	Standard renovation of envelope according Austrian legislation requirements; Interpolated average U-value of envelope: 0.39 W/(m^2 K)	394 985	340 €/m^2	25
	D1	Multifunctional façade element (incl thermal circuit for wall heating, insulation, fixture for BiPV); Interpolated average U-value of envelope: 0.27 W/(m^2 K) (walls 0.15, roof 0.17, floor 0.51, windows 0.85) – **EXCESS scenario**	610 830	526 €/m^2	40
Thermal system	TS0	Gas heating system with floor heating	138 778	2523 €/kW	25
	TS1	Ground water heat pump with floor heating	164 178	2985 €/kW	25
	TS2	Ground water heat pump with only partial floor heating system – **EXCESS scenario**	92 196	1676 €/kW	25
Building integrated PV	BiPV0	no PV	0	0 €/kWp	0
	BiPV1	44kWp (260m^2) building integrated PV	50 100	1138 €/kWp	20
	BiPV2	88kWp (520m^2) building integrated PV - **EXCESS scenario**	100 200	1138 €/kWp	20
Building management system	C0	Standard control	0	n.a.	0
	C1	Active demand response control	27 000	n.a.	30

The scenarios for each building system were combined to overall 11 technology packages as listed in Table 11. This table also shows the most relevant cost and performance data of all analysed technology packages.

Table 11: Energy demand and global cost of technology packages – Austria.

Envelope	Thermal system	BiPV facility	Building management system	Gas demand [kWh/(m²y)]	Electricity demand (incl. plug loads) [kWh/(m²y)]	Electricity production [kWh/(m²y)]	Net Primary Energy demand wo plug loads [kWh/(m²y)]	Global costs wo plug loads [€/m²]
D0	TS0	BIPV0	C0	58,7	18,8	0,0	110	784
D0	TS0	BIPV1	C0	58,7	18,8	26,8	54	769
D0	TS0	BIPV2	C0	58,7	18,8	53,5	-2	774
D1	TS2	BIPV0	C0	0	36,3	0,0	76	829
D1	TS2	BIPV1	C0	0	36,3	26,8	20	809
D1	TS2	BIPV2	C0	0	36,3	53,5	-36	811
D1	TS2	BIPV2	C1	0	36,3	53,5	-36	831
D0	TS1	BIPV0	C0	0	39,3	0	83	756
D0	TS1	BIPV1	C0	0	39,3	26,75	26	738
D0	TS1	BIPV2	C0	0	39,3	53,5	-30	740

3.4.3 Results of cost optimal analysis - Austria

This section outlines the results of the cost performance analysis for the Austrian case-study. Table 12 shows the main economic parameters used for the calculation. A sensitivity analysis for other parameters is discussed in chapter 5.

Table 12: Parameters of the analysis – Austria.

Parameter	Value
Calculation period [y]	30
Discount rate [%]	3
Electricity price [€/kWh]	0.2
Gas price [€/kWh]	0.12
Electricity selling tariff [€/kWh]	0.1
PEF gas [-]	1.2
PEF electricity [-]	2.1

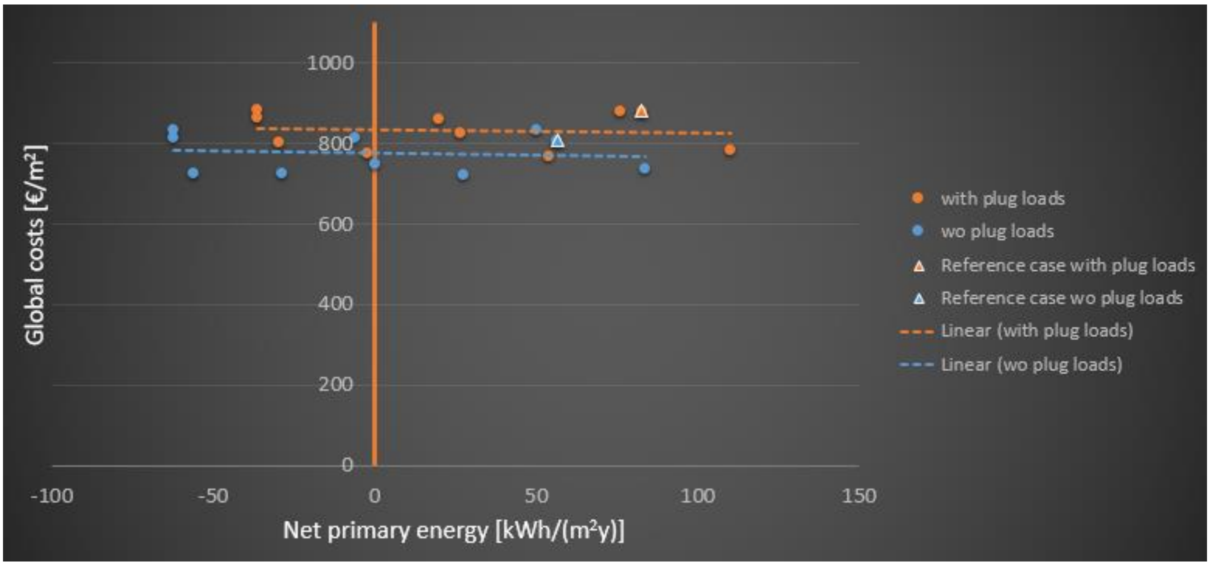

Figure 19: Cost optimal analysis Austria – all technology packages

Figure 20 shows the net primary energy demand and global cost of all technology packages with and without plug loads. For the Austrian pilot case, plug loads of 12.5 kWh/(m^2y) are assumed. It can be seen that there are technology packages with a net primary energy demand below 0. Those combinations are PEB combinations as they produce more energy than they consume. The chart also shows the difference between nZEB and PEB configurations.

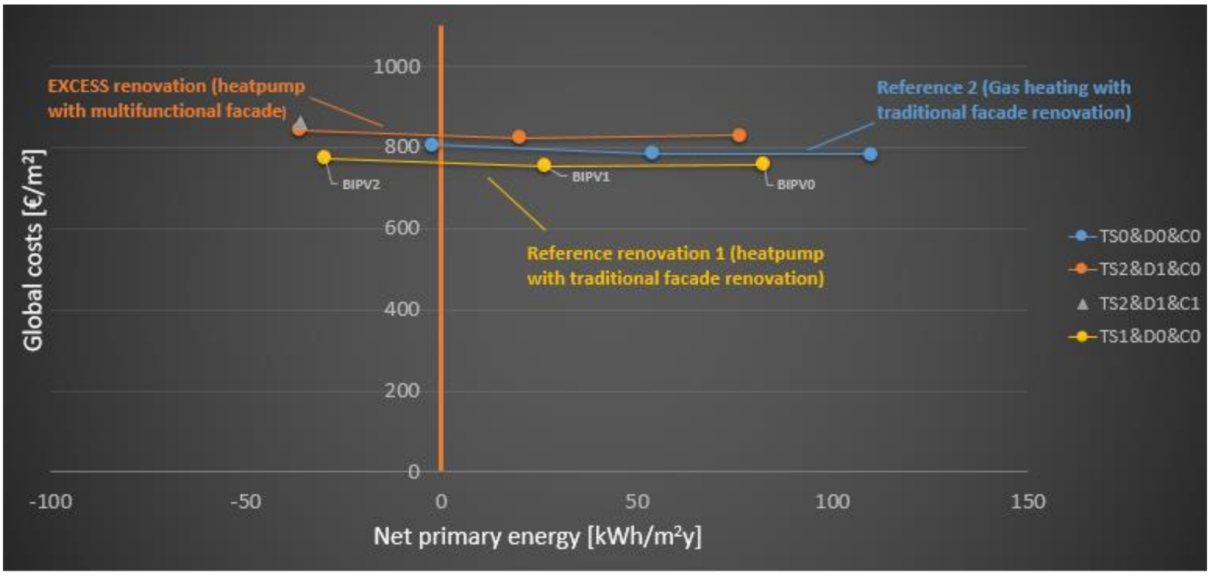

Figure 20: Cost optimal analysis Austria – analysis of technologies

Figure 20 shows the cost optimal analysis of all the different technologies. It can be seen, that building-integrated PV is a cost-effective technology package in the Austrian pilot-case, as it reduces net primary energy demand and global costs (from BiPV0 to BiPV2). A renovation from state-of-the-art gas heating system to a geothermal heat pump can be defined as cost efficient as it reduces net primary energy demand (from blue line to yellow line) and at the same time also reduces global costs due to a significant reduction in the energy cost. However, those results are very sensitive to gas and electricity prices.

The multifunctional façade element leads to an additional reduction in primary energy demand but increases global costs (from yellow line to orange line). Therefore, the multifunctional façade element cannot be rated as cost effective technology for the Austrian pilot-case. The multifunctional façade element (D1) leads to lower energy costs due to better insulation. The reduced energy costs cannot offset the higher investment costs compared to a standard envelope renovation (D0).

Figure 20 also shows that the advanced building energy management system (C1) is not cost effective. It increases global costs as the expected benefits are lower than the higher investment costs. The benefits of C1 are a higher self-sufficiency rate of the building as well as the complete areal (pilot is located in an area with several buildings). Furthermore the wall heating of multifunctional façade element in combination with an advanced BEM (C1) creates high flexibility potentials. These high flexibilities can lead to additional benefits such as an increased self-consumption rate on area level or decreased electricity grid cost, however these savings were not considered in the calculation.

Overall it can be concluded that the standard renovation (D0) combined with ground source heat pump (TS1) and a building integrated PV system is the most cost effective technology package of the Austrian demo. The multifunctional façade element is not cost effective according to the current analysis. Additional benefits such as a higher self-sufficiency rate (and therefore lower energy costs) on area level and other revenues from Demand Response and flexibility services (e.g. lower grid costs) have to be taken into account to make the multifunctional façade element profitable and cost effective. Testing this technology in the Austrian demo, however, showed potential for further cost decreases and it is expected that the technology becomes more competitive if it gets more mature and standardized.

3.5 Comparison with reference costs and cost ranges of selected technologies

This chapter presents some estimations of a comparison of EXCESS pilot cost with references cases but also illustrates the range of costs for PVT and BIPV that makes exact comparisons difficult.

One central target of the EXCESS project is to define the cost difference of PEBs compared to reference refurbishments costs or nearly zero energy buildings (nZEBs) in case of new buildings. The EPBD defines nZEB as buildings with high energy performance. The nearly zero or very low amount of energy required should be covered to a very significant extent by energy from renewable sources, including energy from renewable sources produced onsite or nearby [3].

The detailed energy performance definition of nZEBs is done by Member States. The minimum performance levels as well as the calculation method differs between Member States. Furthermore, not all Member States have defined a requirement regarding net primary energy demand. Therefore, in the context of the present analysis, an average net Primary Energy Demand of 50 kWh/(m^2 y) as nZEB reference case was defined. As there is no definition of PEBs in the EPBD, there is also no requirement regarding net Primary Energy Demand for PEBs defined by the EU or Member States. According to the PEB definition developed during the EXCESS project, the net Primary Energy Demand of PEBs must be below 0. Therefore, in the present study, those technology packages closest to 0 were defined as PEB(threshold) and compared with the reference scenarios. This means that costs of PEB technology packages with a net primary energy demand of ~0 kWh/(m^2 y) are compared with costs of technology packages with a net primary energy demand of ~50 kWh/(m^2 y). The comparison was also done for the EXCESS case, defined as PEB(EXCESS) in below comparison. For the Finnish demo case, PEB (threshold) and PEB (EXCESS) are the same technology packages as the Finnish EXCESS demo has a net primary energy demand close to 0. For all other demos, PEB(EXCESS) has a lower net primary energy demand then PEB(threshold).

Table 13: PEB/nZEB comparison in investment costs and global costs

	Spain	Finland	Belgium	Austria
PEB (threshold) / nZEB difference (investment cost)	15%	55%	65%	12%
PEB (threshold)/nZEB difference (global cost)	0%	35%	0%	0%
PEB (EXCESS) / nZEB difference (investment cost)	70%	55%	140%	15%
PEB (EXCESS)/nZEB difference (global cost)	20%	35%	40%	0%

Table 13 shows the PEB/nZEB difference in terms of investment costs and global costs for all pilots, both for reaching the minimum PEB threshold and for implementing the full demo settings (EXCESS cases). It can be seen that PEBs require higher investment costs compared to the reference case. The EXCESS cases require even higher investment costs than the PEB (threshold) scenarios as they aim for an even lower net primary energy demand.

Table 13 also shows the nZEB difference in terms of global costs for all pilots. It can be seen that the global cost difference for meeting the minimum PEB threshold is 0 for Spain, Belgium and Austria. Only the Finish case shows a global cost difference between PEB(threshold) and nZEB reference case. The reason is that for the Spanish, Austrian and Belgium pilots, the difference from nZEB (~50kWh/(m^2 y)) to PEB-threshold (~0 kWh/(m^2 y)) is realized mainly through an increase in the PV generation. As the PV technology is cost effective, global costs do not increase from nZEB to PEB(threshold) in those cases. As the shape of Finnish demo case does not allow for an increase in PV area, PEB(threshold) in Finland is reached by adding additional innovative functionalities to the thermal system (i.e. deep boreholes, thermal storage through PVT, etc.). As those additional functionalities are not cost effective as outlined in subsection 3.2, the PEB/nZEB KPI is much higher than for all other demo-cases. At the same time the large amount of flexibility the Finnish demo can provide to the grid was not considered.

The comparison also shows that the PEB(EXCESS)/nZEB difference in terms of global cost is lowest for the Austrian pilot case. The reason is that the reference case of the Austrian pilot has already high global costs as it represents a deep renovation with a change of heating system and façade insulation.

Cost ranges for PVT

Hybrid photovoltaic thermal panels (PVT) are an emerging technology that produce both electricity and hot water generating 2-4 times as much energy per square meter than a standard PV panel (Dualsun). In addition, the panels get cooled which increases the efficiency of electricity production. From the economic point of view and as can be seen in the Table 1, the PVT cost depends on the size (floor area) of the building.

Table 14: PVT cost in the next 5-10 years (Source: Dualsun).

Area [m^2]	CAPEX Turnkey (without VAT.) [€/m^2]
50	850
300	650
1000	550
2000	500

A major part (more than 50%) represents the installation costs. While the technology costs are expected to decrease, installing this technology will remain a time consuming process. To date, in some EU countries, there is a lack of installers capable of connecting both the electrical and thermal circuits. As a consequence, many installers are overbooked with a really fast growing solar market, and prefer simple PV products.

Cost ranges for Building Integrated PV (BiPV)

Building Integrated PV (BiPV) is a suitable technology especially where space for conventional PV is limited. As for the costs, Figure 2 illustrates the system cost comparison of conventional and BIPV roofing solutions. As shown in the Figure, active BiPV façade solutions are more expensive than standard façade cladding solutions. [7]

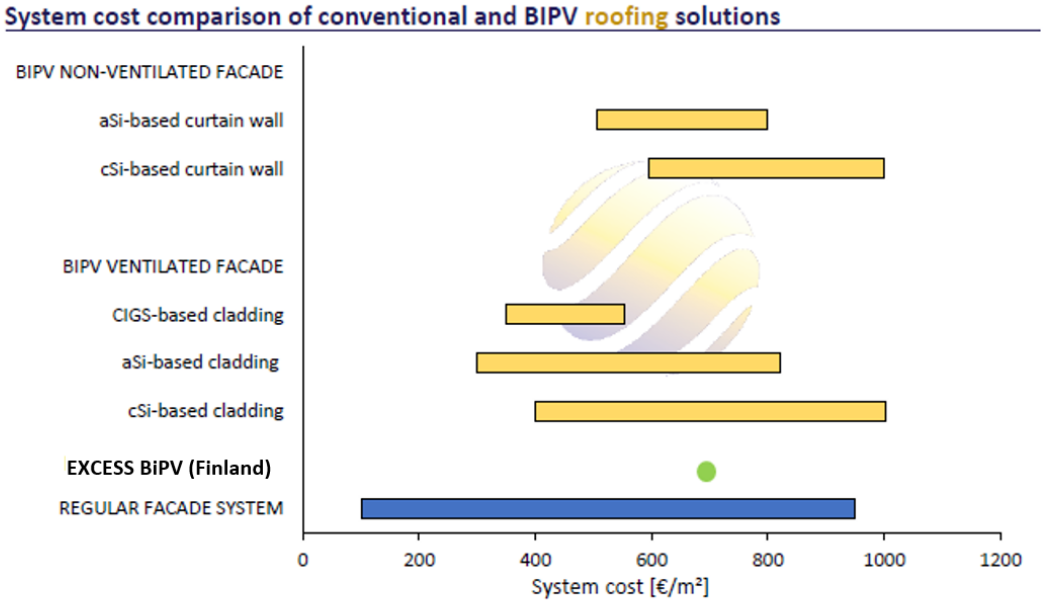

Figure 21: System cost comparison of conventional and BIPV roofing solutions [7]

However, BPIV solutions can substitute conventional construction materials such as concrete or glass and, therefore, can have additional functions than only electricity production. Therefore, active solutions are often more competitive from a system-level cost perspective, than the subsequent application of a PV system on a regular roofing solution [7].

4 Sensitivity analyses

4.1 Sensitivity analysis - electricity prices

This section shows the results of the cost-performance analysis for different electricity prices and electricity selling prices. The simulations were done for the pilot-cases located in Spain and Finland as for these countries many technology packages are simulated and a robust correlation trend-line can be derived. The parameters of the analysis are shown in Table 15.

Table 15: Sensitivity analysis (electricity) parameters

Parameter	Scenario 1	Scenario 2	Scenario 3
Calculation period [y]	30	30	30
Discount rate [%]	3	3	3
Electricity price [€/kWh]	0.2	0.3	0.4
Electricity selling tariff [€/kWh]	0.1	0.15	0.2
Gas price [€/kWh]	0.1	0.1	0.1
PEF gas [-]	1.2	1.2	1.2
PEF electricity [-]	2.1	2.1	2.1

Figure 22 and Figure 23 depict the results of the simulations of all three scenarios.

It can be seen that the slope of the trend-line changes with a change of the electricity price and feed-in tariff. For an electricity price of 0.4€ and a feed-in tariff of 0.2€, global costs decrease with a reduction of Net Primary Energy Demand. For an electricity price of 0.2€ and a feed-in tariff of 0.1€, global cost increases with a reduction of net primary energy demand. Therefore, it can be concluded that the increase in electricity prices increases the profitability of PEB technologies.

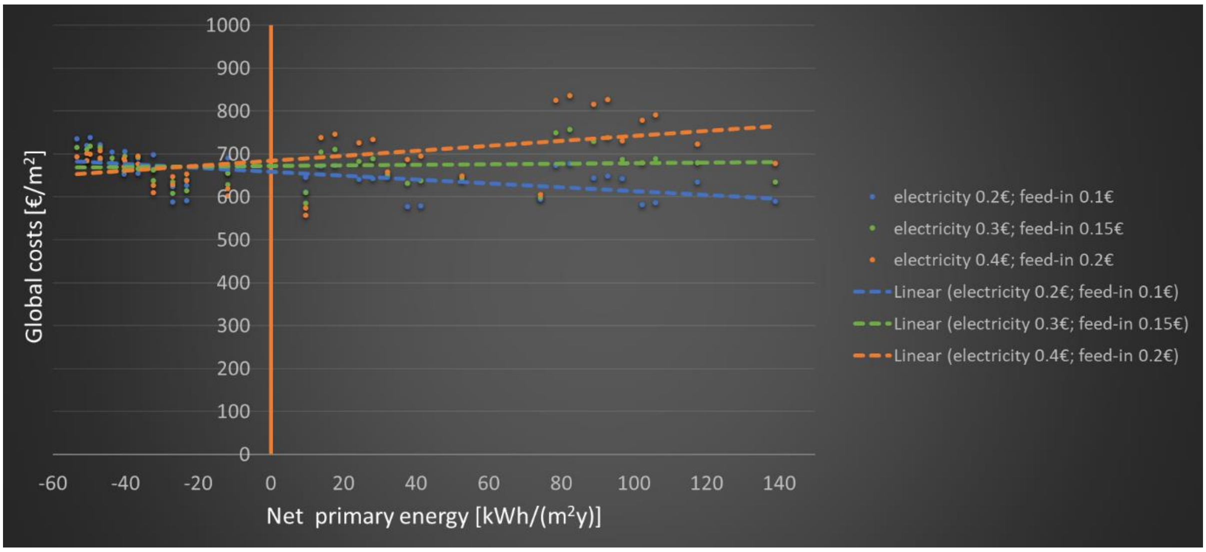

Figure 22: Sensitivity analysis electricity costs – Spain.

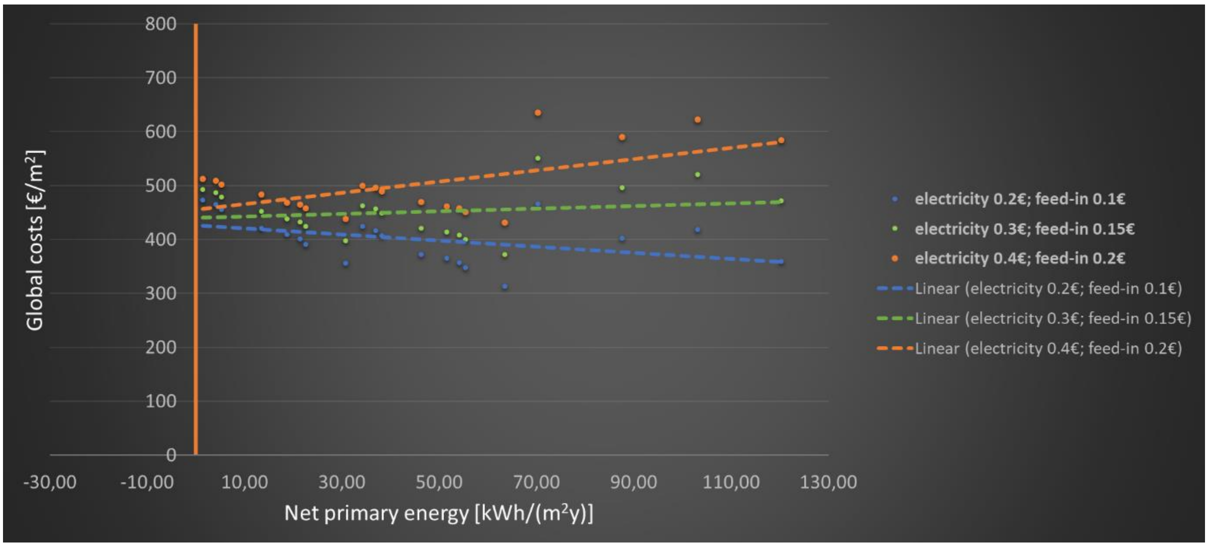

Figure 23: Sensitivity analysis electricity costs – Finland.

4.2 Sensitivity analysis - discount rate

This subsection shows the results of the cost-performance analysis for different discount rates. Also in this case, the simulations were performed for the pilot-cases located in Spain and Finland. Table 16 summarizes the main economic parameters used in the evaluation approach. Three different discount rates (0%, 3% and 6%) are used for the sensitivity analysis. The discount rate has an impact on investment costs as well as on operation, maintenance and energy costs. Investment costs are adjusted by residual values or replacement costs if the assumed technology lifetime differs from the calculation period. Residual values and replacement costs are adjusted with the discount rate. Operation, maintenance and energy costs are also discounted with a yearly discount rate for the whole calculation period.

Table 16: Parameter for sensitivity analysis - discount rate.

Parameter	Scenario 1	Scenario 2	Scenario 3
Calculation period [y]	30	30	30
Discount rate [%]	**0**	**3**	**6**
Electricity price [€/kWh]	0.2	0.2	0.2
Electricity selling tariff [€/kWh]	0.1	0.1	0.1
Gas price [€/kWh]	0.1	0.1	0.1
PEF gas [-]	1.2	1.2	1.2
PEF electricity [-]	2.1	2.1	2.1

Figure 24 and Figure 25 show the simulation results for different discount rates. It can be seen that the discount rate has a high impact on the slope of the trend-lines. An increase in the discount rate, decreases the profitability of PEB technologies as represented by the changes in the slope of the trend-line. An explanation is that future energy cost savings of PEBs are valued less and therefore technology packages with lower investment costs are preferred.

The differences in the height of the curves can be explained by a difference in replacement costs. As most technologies have lifetimes that are shorter than the calculation period, replacement costs have to be considered in the global cost calculation. As those replacement costs are adjusted with the discount rate, higher discount rates result in lower replacement costs.

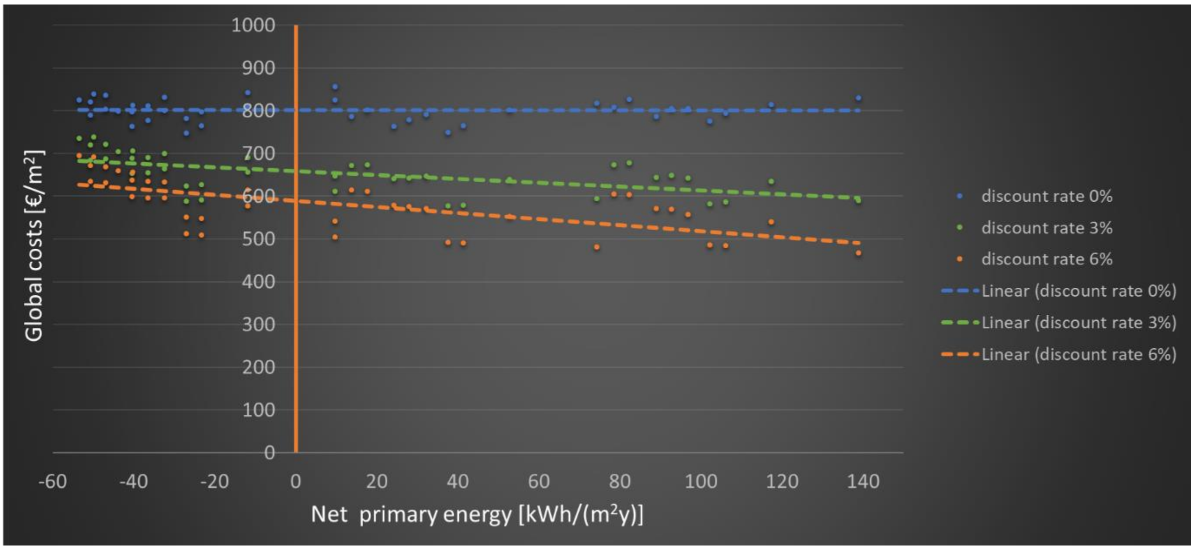

Figure 24: Sensitivity analysis discount rate – Spain.

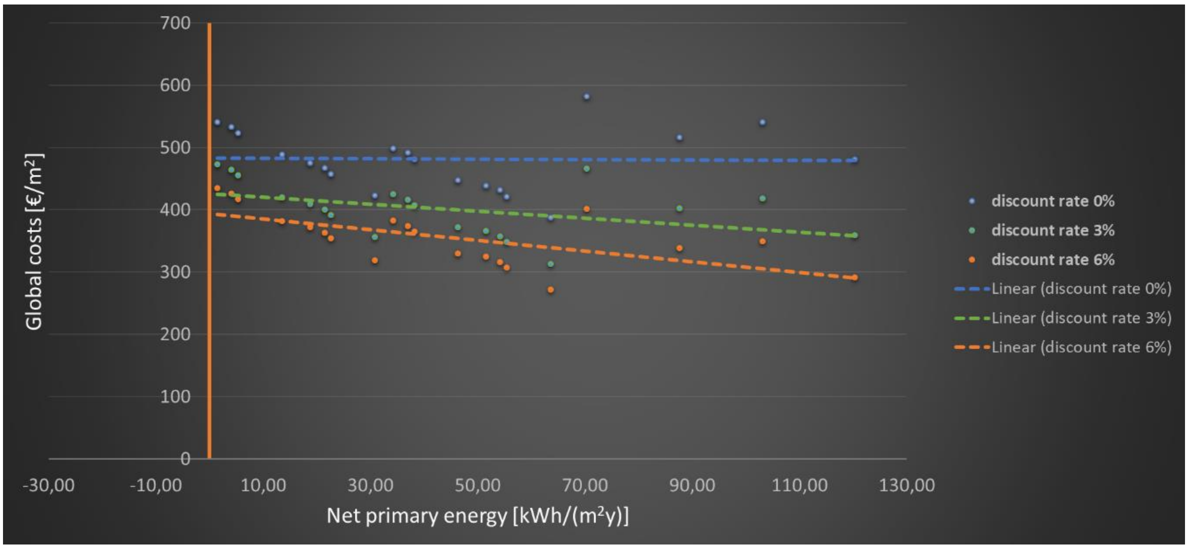

Figure 25: Sensitivity analysis discount rate – Finland.

5 Conclusions

The cost-optimal analysis highlighted the economic feasibility of achieving the Positive Energy Building (PEB) target for demo buildings in different climate zones.

Earlier analyses in the EXCESS project showed that the demo buildings in Spain, Austria and Belgium can technically achieve the PEB standard with different technology packages. The Finnish demo-case comes close to PEB standard but cannot fully achieve it. The two central reasons are the cold climate conditions and the shape of the Finish demo building.

The analysis showed that not all PEB technologies are cost effective and reduce global costs. According to the analysis in this report, renewable energy production with PV can be considered as cost-effective 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 effective realization of a PEB. If there is little 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 to a new heat pump system is cost effective 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. Furthermore, it can be concluded that 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 demo. 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 demo 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.

The cost effectiveness of PVT panels is difficult to assess. PVT decreases net primary energy demand but increases global costs with current available PVT costs in the pilot cases. The main cost driver for this technology is the complex installation of the panels. PVT has a high advantage if the roof is too small to provide sufficient PV energy to the building. Furthermore it has to be mentioned that PVT can be part of broader solutions such as in the Finnish pilot case where it provides heat to be stored in the boreholes and thereby thermally regenerate the bedrock that serves as seasonal storage. In applications with low cooling demand in combination with a high heat energy demand and little available space for the collector, PVT is highly relevant for the efficient functioning of the thermal system. This example shows that it is necessary to have a system view on costs. Even if individual technologies may not be cost efficient, they can be enabling technologies that make the entire system more cost efficient. Another example for the need of a systemic view on costs is the Austrian demo case that showed that a multifunctional façade element (wall heating, insulation, PV) as stand-alone technology is not yet a cost effective technology for the realization of a positive energy building with the current assumptions and calculation methodology. Additional benefits have to be taken into account (e.g. higher on-site self-sufficiency rate and thus lower energy cost in the neighbourhood or potential flexibility revenues). This could make the multifunctional façade elements more favourable and profitable than a typical deep renovation. In addition, optimizing this technology in the Austrian demo showed potentials for cost decreases (e.g. material costs) and we expect that the technology becomes competitive as it gets more mature.

Our analysis also illustrated the important role of installation costs for some of the technologies that were assessed. For example PVT installation cost amount at some 50% of the overall costs. Skilled installers and easy mounting systems may be able to reduce these cost elements.

The sensitivity analyses showed that all results are very sensitive to electricity prices and feed-in tariffs. With an electricity price of 0.4 €/kWh, almost all analysed technologies turn into cost effective technologies that reduce global costs. Due to an expected further decline of levelized cost of electricity production, we do not expect that the market price of electricity increases to a level of 0.4 €/kWh. Therefore only cost of greenhouse gas emissions (CO_2 tax or emission certificates) can raise electricity prices to a level that makes some PEB technologies profitable without dedicated subsidies. Another insight made is that some technologies such as BiPV have more functions than just electricity generation but can substitute conventional construction materials such as concrete or glass. This needs to be considered in cost comparisons. Also the climatic conditions are critical for the economic performance of technologies, such as for thermal systems.

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 also do not explicitly consider seasonal minimum self-sufficiency rates in the calculation method which grades down all technologies that provide seasonal storage. It is recommended to solve such shortcomings with future revisions of European legislation and strategies (e.g. EPBD, EU cost optimal framework). 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.

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.

Overall it can be said that several 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 analysis of the EXCESS pilot cases. To support the realization of PEBs, either subsidies are needed to cover the additional costs that cannot be covered by energy cost savings or a pricing of greenhouse gas emissions 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.

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