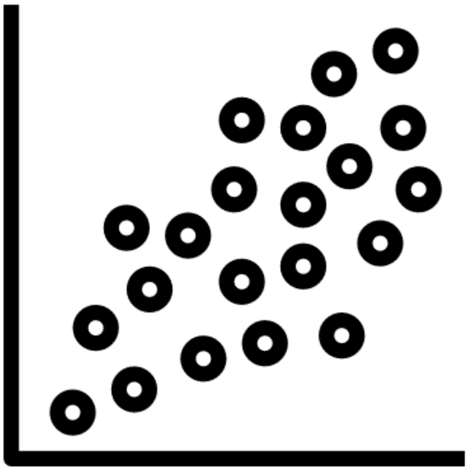
Parametric models for buildings and building clusters:
Building features and boundaries



COST REDUCTION AND MARKET ACCELERATION FOR VIABLE NEARLY ZERO-ENERGY BUILDINGS

Effective processes, robust solutions, new business models and reliable life-cycle costs, supporting user engagement and investors' confidence towards net zero balance.

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Framework Programme of the European Union

Parametric models for buildings and building clusters:

Building features and boundaries

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FOREWORD

This report summaries first activities and results of Work Package 'WP06 – Life-cycle cost reduction of new nZEB', part of the Horizon2020 - CRAVEzero project.

Cost optimal and nearly zero-energy performance levels are principles initiated by the European Union's (EU) Energy Performance of Buildings Directive, which was recast in 2010. These will be significant drivers in the construction sector in the next few years because all new buildings in the EU from 2021 onwards have to be nearly zero energy buildings (nZEBs); public buildings need to achieve the standard already by 2019.

While nZEBs realised so far have clearly shown that the nearly-zero energy target can be achieved using existing technologies and practices, most experts agree that a broad-scale shift towards nearly zero-energy buildings requires significant adjustments to current building market structures. Cost-effective integration of efficient solution sets and renewable energy systems are the major challenges.

CRAVEzero focuses on proven and new approaches to reduce the costs of nZEBs at all stages of the life-cycle (see Figure 1). The primary goal is to identify and eliminate the extra costs for nZEBs related to processes, technologies, building operation and to promote innovative business models considering the cost-effectiveness for all stakeholders in the building's life-cycle.

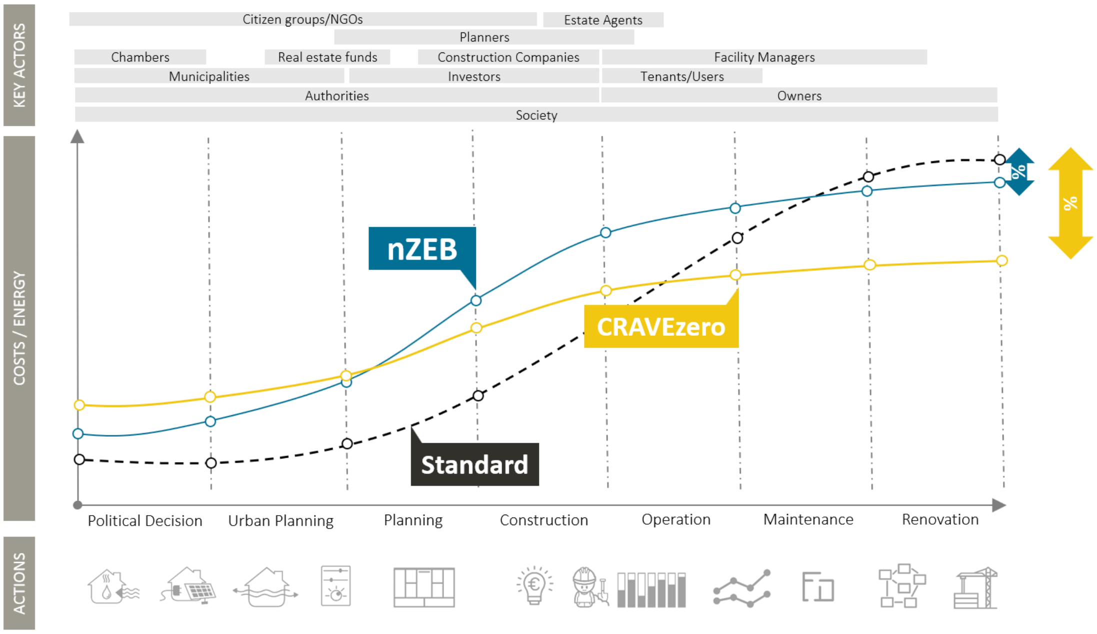

Figure 1: CRAVEzero approach for cost reductions in the lifecycle of nZEBs.

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EXECUTIVE SUMMARY

Already today buildings can be realised in the nearly zero and plus energy standard. These buildings achieve extremely low energy demands and low CO_2 emissions and can be operated economically. For this reason, the motivation in the CRAVEzero project is not only based on the energy characteristics of buildings, but also on their life-cycle costs. However, the broad market deployment of these buildings is progressing very slowly so far, as methods and processes for the cost-optimal integration of efficiency measures and renewable energies are not yet sufficiently described and therefore not yet common. As a consequence - many poorly planned buildings are criticised for the fact that the actual energy consumption of highly efficient buildings is higher than the predicted demand and that high-efficiency standards are expensive and uneconomical. The influence of the user behaviour of such energy efficient buildings is another aspect, which has to be considered to evaluate the impact on the energy consumption of the building.

The identification of suitable methods for the energetic-economic optimisation of highly efficient buildings in all life-cycle phases is a prerequisite for the broad market implementation.

In the energetic-economic optimisation of buildings, there are different interests of the actors and, derived from this, different perspectives, time expectancies and goals. There are the tenants/users, the real estate agents, building contractors, planner, property managers, investors, owners and also companies which are directly or indirectly involved within the building process

On the basis of the results, the statement is confirmed: nZEBs are economical. It can now be shown that the additional costs of efficiency measures are so low that highly efficient buildings have the lowest life-cycle costs. nZEB measures only have a small percentage influence on construction costs, but can reduce CO_2 emissions many times over. When considered over the service life, these measures are usually cost-neutral or even economical.

The following points can be summarised in detail:

- The energy standard has a small influence on the building and construction costs. Energy efficiency is therefore not a major cost driver in construction.

- The additional construction costs of nZEBs are compensated in the life-cycle of most technologies even without subsidies.

- The cost optimum of primary energy demand and CO_2 emissions is in the range of nearly zero and passive houses. Highly insulated envelopes and highly efficient windows are usually economical even without subsidies. This is also due to the long service life of these components in comparison to HVAC systems.

- The optimum cost curve in relation to CO_2 emissions is very flat. Low emissions and energy requirements can therefore be achieved with different energy concepts as long as the envelope is very efficient. This means architectural and conceptual freedom.

- It is shown that energy efficiency and economic efficiency are not contradictory strategies, but can complement each other very well.

- The parametric simulation results showed that the variance in the financing costs (20 %) and the net present value (15 %) is relatively low, whereas the primary energy demand (66 %) and the CO_2 (73 %) emission vary in a broader range.

- It is possible to find a solution set with nearly equal financing cost and/or net present values, but with less primary energy consumption and/or CO_2 emissions.

- The sensitivity analysis showed that the interest rate and the inflation of energy costs had the highest influence on the LCC costs. Further important factors were the maintenance cost, electricity costs and the cost of the structural elements with a medium influence on the LCC costs.

- The user behaviour had a major influence on the total energy consumption of a building. A highly efficient building can at least support the user to further reduce his energy consumption.

This report describes the methodology and data used for the building simulation and parametrisation approach to quantify possible cost and energy savings of nZEBs throughout the life-cycle. Furthermore, three different methodologies are prototypically tested.

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1. INTRODUCTION

1.1. Objective

This report focuses on three methodologies for the parametrical implementation of cost reduction potentials for nearly zero energy buildings. The parametric analysis is implemented within the CRAVEzero case studies as described in D2.2 serving as a baseline for further optimisation and also acting as frontrunner projects showing that nZEBs can be realised in a cost-efficient way. The evaluation of cost reduction potentials includes design, construction, commissioning, maintenance, operation and end-of-life phase. This report therefore lays the basis for a structured life-cycle cost and energy analysis. The aim is to rate different nZEB technologies, processes, solution-sets and business models on the existing cases in order to raise the maximum potential of cost reduction in the upcoming reports within this work package. Measurable nearly zero (or beyond) primary energy consumption and CO_2 emissions over the whole life-cycle will be pointed out as well. This first report of WP06 focuses on the definition of the methodology for the parametric analysis and a first parametric model focusing on cost reduction of nZEBs (based on case studies analysed in WP02) is applied and tested.

1.2. State of the Art / Problem Description

Although efficient technologies for zero and plus energy buildings are available on the market, many factors are slowing down their broad marked implementation. Cost and construction time overruns of zero and plus energy buildings due to unclear requirements, unclear processes and the lack of knowledge about these technologies are still the standard in the construction industry. There is great potential for processes and cooperation between urban and spatial planners, municipalities, energy suppliers, investors and property developers, construction companies, building users, facility managers, as well as renovation, dismantling and waste disposal companies.

In the early planning phases, the client and architect are faced with the decision to define the architectural concept, the type and quality of the envelope and the technical equipment of the building. Often the amount of the construction costs is used as a determining factor, while the operational costs play no or only a minor role. The decision for zero or plus energy and the actions to be taken are usually done in a late phase and therefore have a significant impact on the building and construction costs. This is often due to the fact that the focus of the cost analysis in early stages is on only one stakeholder, usually the owner/builder. Processes and thus costs that occur after completion of the building, such caused by the energy use by the tenants/owners but also costs for maintenance and repairs or even refurbishment or demolition of the building are hardly taken into account in the cost considerations at the beginning of the planning phase.

One possibility would be to consider the costs over the entire life-cycle, or at least a longer period of time of the building. Often zero and plus energy concepts are rejected due to high investment costs and uncertainties about their actual performance (costs, energy, comfort).

Previous work in this field either only depicts partial areas or is often not sufficiently based on reliable data from buildings that have already been realised. In the following, the planning and optimisation processes for highly energetically and economical buildings will be examined more closely. This procedure will be demonstrated using three different methodologies within prototypical CRAVEzero frontrunner buildings.

2. MULTI-OBJECTIVE BUILDING LIFE-CYCLE COST AND PERFORMANCE OPTIMIZATION

This chapter applies a multi-objective optimisation approach to investigate a specific problem, in this case the effect of nZEB design variables on energy, environmental and economic performance.
It addresses a methodological approach to better understand the effects that nZEB design variables have on the whole life-cycle of a building and how it can be implemented as part of the design process.
Combining the CRAVEzero life-cycle cost tool with state-of-the-art energy calculation methods and a parametric optimisation tool to minimise the energy and CO_2 related emissions of buildings. A simulation-driven design process with detailed and parametric analysis showed that reduced construction cost by 20 %, reduced life-cycle costs by 15 %, primary energy demand by 66 % and CO_2 emissions by 73 % could be achieved compared within the nZEB variants.

This approach has been guided by the following key questions:

- Which are the nZEB variables that determine the relative importance of their impact on energy, environmental and economic performance?
- What is the relative importance of the main nZEB design variables, considering a wide range of performance indicators?
- Which are the numerical parameters that describe best the nZEB design variables, and thus can be used to reduce life-cycle costs and related CO_2 emissions of nZEBs

The general aim of this chapter is furthermore to contribute to the development of methodological approaches that provide a more comprehensive understanding of the design variables, specifically in terms of their effects on energy, environmental and economic performance of office buildings and residential buildings. Such an approach is especially important to simplify the decision-making process during the early planning phase of nZEBs. In this phase consistent and reliable information is required to guide the design strategies and achieve high-performance buildings with a reasonable investment, optional and overall predicted life-cycle costs.

2.1. Methodology

In the traditional planning process, the client, architect and specialist consultant develop a building with the relevant technical equipment and building services. In many cases, everyone optimises in their associated area, and thus the building project as a whole is being lost out of sight. In the traditional planning process usually, only a few variants are considered and are often not planned and analysed at the same time, but discarded at an early stage. Thus, it can happen that at the end a building is built and in operation, it turns out that, e.g. the running costs are extremely high. If, on the other hand, several variants are being compared in the planning phase, including life-cycle costs, a sound decision can be made already in advance.

The term "multi-objective parametric analysis" in this report defines a method in which a series of calculations are run by a computer program, systematically changing the value of parameters associated with one or more design variables. The key feature of this approach is that it allows evaluating the effect of individual design variables on energy, costs and environmental parameters in one step.
Problems associated with the design of buildings often comprise conflicting or contradictory objectives, such as minimising energy consumption while investment costs are increased, or reducing both CO_2 emissions and increasing life-cycle costs. As a result, in recent years the multi-objective optimisation analysis has become more popular

than the single-objective analysis (Hamdy and Mauro, 2017).
The multi-objective approach is based on the concept of pareto frontier: a solution is optimal when no other feasible solution improves one of the objectives without affecting at least one of the other. In that case, the multi-objective algorithms generate a set of solutions, known as the pareto front. If the problem includes only two objectives, the Pareto front is a two-dimensional curve. This concept can also be applied to three or more objectives, although the results are more difficult to analyse. It is also important to note that this approach, rather than finding a single optimal solution, seeks to explore a set of optimal solutions and evaluate various trade-offs among them (Chiandussi et al., 2012).

- Conventional optimization: “search“ of possible solutions based on empirical values (Figure 2, left picture)
- Optimisation using “extreme value search algorithms”
- “Brute-force method” with a study of all possible solutions (Figure 2, right picture)

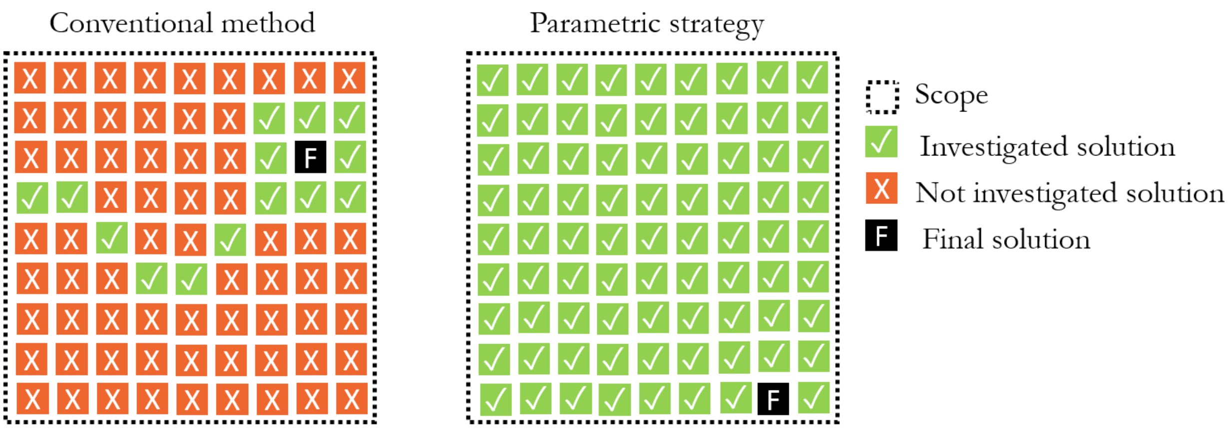


Figure 2: Multi-objective building life-cycle cost and performance optimisation

The advantage of the manual search of the optima usually lies in the manageable number of variants and thus the moderate effort. The disadvantage, as shown in Figure 2, is that only a local optimum can be found and not the best global solution.
Optimisation using a "parametric optimiser" offers the advantage that the variants are optimised for a specific goal or cost function and can be found more or less precisely depending on the optimisation function. However, it does not allow any statement on maxima, minima or statistical distributions of the variants. In addition, it is difficult to consider the additional benefits described above, as these often cannot be described as hard target values, e.g. monetary.
With the brute-force method or the investigation of all possible variant combinations, all solutions are considered. It therefore offers the advantage that statistical evaluations can be made, distributions can be derived, and the additional benefits can also be considered for selected variants. A big disadvantage is a very large number of variants (several thousand), which can only be calculated automatically. It also restricts the calculation methods. If, for example, dynamic building simulations are used to optimise a building, where each simulation takes several hours, it is not possible to calculate thousands of variants with a manageable amount of computing time. By multi-objective building life-cycle cost and performance optimisation, it is possible to find optimal solutions, among huge numbers of possible combinations of variables. Various decision variables can be considered for the building envelope, the heating system, the ventilation and air conditioning (HVAC) systems, on-site energy generation systems or financing schemes/ business models. Examples of the objectives are: minimisation of environmental impacts (energy consumption, carbon emissions etc.), costs (investment costs, operating costs, life-cycle costs), equipment size (energy generation units, HVAC system etc.), and/or maximisation of indoor air

quality, energy efficiency, etc. These can be achieved individually, as single objectives, or simultaneously, as multi-objective optimisation. The constraint functions may indicate satisfying, or not violating, different criteria -e.g. thermal comfort level, total investment cost limit, primary energy limit etc. (Wright et al., 2002).

The method of energy-economic optimisation is shown in Figure 3:

- Design, first pre-optimizations.
- Determination of target values and goals
- Determination of the parameters to be varied and their levels, e.g. envelope quality, heating system, window size, window quality.
- (Automated) energy demand calculations according to energy certificates or the passive house project planning package, dynamic building simulation.
- Calculation of the life-cycle costs of each variant, taking into account promotion, maintenance, replacement investments and residual value.
- Evaluation and presentation of results.

Together with the Energieinstitut Vorarlberg (EIV), AEE INTEC developed a method to automatically calculate the life-cycle costs of thousands of variants as part of the "KoPro LZK+" project. The automated calculation for many variants, which was used in this report:

- Is a further development of the "KoPro LZK+" calculation method by Energieinstitut Vorarlberg and AEE INTEC.
- Reduction of time expenditure by using existing energy demand calculations of a building with the passive house project planning package PHPP.
- The life-cycle costs are calculated with the CRAVEzero life-cycle tool.
- Automation of the calculation by VBA macros in MS-Excel©.

With this method, more than 31.000 different variants could be calculated in a manageable amount of time for one prototypical CRAVEzero case study. In most cases, a building has to be calculated several times, because input errors and missing inputs, which are caused by the combinatorics of the parameters, can often be detected only during the subsequent result evaluation:

a) The simulation models have been defined in such a way that standard comfort levels are always met, depending on the user behaviour.

b) A wide range of building performance indicators have been used in the analyses, including final and primary energy demand, CO_2 emissions, and initial, operational, renovation, maintenance costs as well as the overall life-cycle costs over 40 years time span.

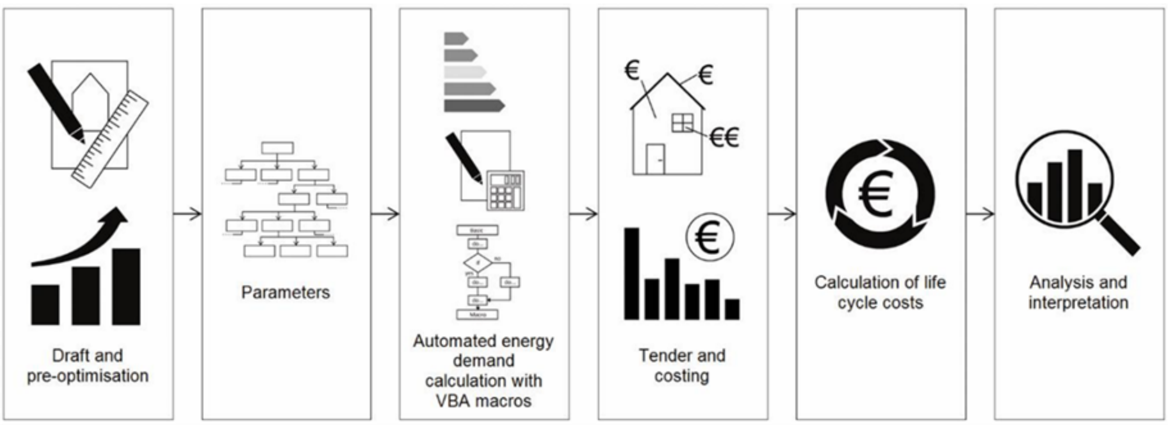


Figure 3: Method of energy economic optimisation in CRAVEzero (Hatt T. et al.)

2.2. Assumptions and Boundary Conditions

The construction costs of the building, for the analysed case study, were provided by the project partner Skanska. The building has already been constructed, and real cost data is available. The costs for the varied technologies and building elements were also directly provided by Skanska. The cost for the PV- systems and the ground source /air heat pump were derived from the component database of KoPro LZK+ and CRAVEzero (WP4). All costs are reported as "net costs" (excluding VAT). Land costs and excavation costs were taken into account. Due to the steady increase of the construction costs in the EU during the last decades (Figure 4), it is necessary to apply an index correction to cost data, which had a different reference year than the real building. The real cost data was provided by Skanska on the basis of the year 2015.

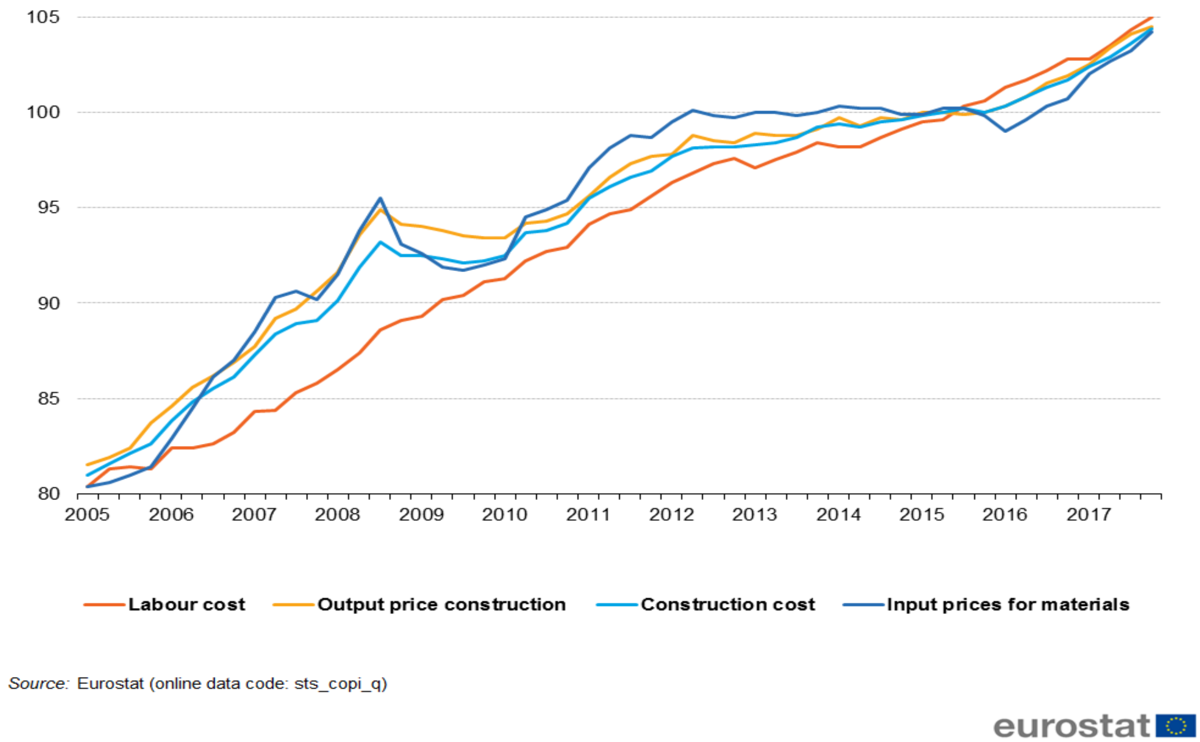


Figure 4: EU-28 cost index of construction prices, construction cost and cost components 2005 – 2017, unadjusted data (2015 = 100) (https://ec.europa.eu/eurostat/statistics-explained/index.php/Construction_producer_price_and_construction_cost_indices_overview).

The considered building is located in Sweden, and a climate data file was generated for the area of Växjö with Meteonorm 7.1.8.29631, since there was no climate data available in the surrounding area.
The economic evaluation of the variants is based on an observation period of 40 years (Table 1), which was previously defined in D2.2 (Deliverable D2.2: Spreadsheet with LCCs). This observation period was chosen because this duration is feasible for private housing, as well as for property developers. As financing scheme, a bank loan was chosen with a credit period time of 25 years and an interest rate of 3 %. The equity interest rate for the equity investment was set to 1,51 %, the inflation rate to 2 % and the discount rate of the used capital investment was 3 %. All these values were taken from the CRAVEzero LCC-Tool. The different technical maintenance costs and lifespans of the different components are taken into account and based on the gathered data in D2.2 and the CRAVEzero database of WP4. Cost drivers can also be determined by evaluating individual parameters in relation to costs. The following cost items are taken into account: total costs, financing costs, energy costs including basic fees, replacement investments, operation costs, maintenance costs, repairs and residual values. The energy costs also take into account the revenues from the grid feed-in of the electricity generated on the building from renewable sources (e.g. PV electrici-

ty). No additional follow-up costs such as administration, insurance, cleaning, security services, building services and demolition costs are included in this report. Rental incomes are not taken into account. All costs are calculated using the "CRAVEzero life-cycle cost tool", which was developed in the project KoPro LZK+ and CRAVEzero.

Table 1: Boundary condition for economic evaluation

Economic boundary conditions	Reference
Observation period of life-cycle cost	40 years
Equity interest rate	1,51 %
Inflation rate	2 %
Discount rate	3 %
Credit period	25 years
Interest rate bank credit	3 %

2.3. Energy Prices and Price Increase

The energy costs are calculated for each variant. Based on the energy demand of each variant the calculation of the resulting cost of each energy carrier (namely district heating and electricity) was determined on the basis of final energy consumption. If PV is present in the specific variant (three different levels: no PV, 72,8 kWp or 131 kWp), the electricity demand was reduced by the share of self-consumption of the PV-electricity. The PV surplus electricity, which cannot be used directly in the building, was fed back to the grid at significantly lower rates (0,03 €/kWh). The electricity price was derived from Eurostat values and is 0,187 €/kWh in the standard scenario. The overall annual energy cost (electricity and district heating) were determined on the basis of final energy consumption and the associated energy prices. The resulting life-cycle cost was taking an energy price increase over the observation period into account by an annual percentage energy price increase (Table 2).

Table 2: Energy prices and net energy price increases as boundary conditions of the economic efficiency calculation

ENERGY CARRIERS	NET PRICES SWEDEN	UNIT	PRICE INCREASE [%]
Electricity	0,187	€/kWh	1,0
District heating	0,05	€/kWh	1,0
PV Feed-in grid	0,03	€/kWh	1,7

2.4. Maintenance Costs

To consider the costs during the operational phase of the building life-cycle maintenance cost were applied as fraction of the investment costs per year. These maintenance costs were gathered from the LCC-spreadsheet of the case study Solallén (see D2.2). For the parameters which are not covered in the case study, these factors were conducted from the CRAVEzero database of WP4. The most important building elements are listed in Table 3. The operation and maintenance costs affect only the building life-cycle after the construction phase. These costs are particularly relevant for future owners, building operations and property manager.

Table 3: Summary of the most important maintenance costs and intervals

POSITION	ACTIVITY	INTERVAL	TODAY'S COSTS (NET)	UNIT
Exterior wall	Maintenance	Annually	1,5 % of Invest	€/a
Floor construction	Maintenance	Annually	1,5 % of Invest	€/a
Flat roof construction	Maintenance	Annually	1,5 % of Invest	€/a
Windows and doors	Maintenance	Annually	1,5 % of Invest	€/a
Ventilation system with heat recovery	Maintenance	Annually	4,0 % of Invest	€/a
Air distribution system	Cleaning and maintenance	Annually	6,0 % of Invest	€/a
District heating transfer station	Maintenance	Annually	3,0 % of Invest	€/a
Ground source heat pump	Maintenance	Annually	3,0 % of Invest	€/a
Air heat pump	Maintenance	Annually	3,0 % of Invest	€/a
Thermal collectors	Maintenance	Annually	1,0 % of Invest	€/a
PV system	Maintenance	Annually	1,0 % of Invest	€/a

2.5. Replacement of Renewal

The replacement of the construction components is necessary, especially for active components. The components of the building envelope have a high technical lifetime and will be not rebuilt, but demolition costs arise at the end of the life-cycle. Active components of the building equipment are typically renewed several times during the lifetime of the whole building. In this report, an observation period of 40 years is chosen, which is a relatively low expected lifetime for the building envelope. This has to be adjusted if a higher observation period will be chosen. The building elements with a lifespan lower than the observation period, are reinvested, and the remaining residual value is deducted after the observation period. Table 4 lists the technical lifetime of the building elements, which were gathered from the D2.2 and the CRAVEzero database of WP4.

Table 4: Technical lifetime of prototypical nZEB elements

POSITION	TECHN. LIFETIME (YEARS)	POSITION	TECHN. LIFETIME (YEARS)
Exterior wall	40	Air heat pump	20
Floor construction	40	Buffer storage	20
Flat roof construction	40	Thermal collectors	20
Windows and doors	40	Ventilation unit with heat recovery	15
External sun protection	40	Air ducts, air distribution system	30
Interior wall and elements	40	Compressor cooling	15
Kitchen and bathroom furniture	40	Free cooling	40
Electric network	25	PV - modules	25
Heat distribution network	30	PV - inverter	15
Floor heating	40	Cables for PV and Inverter	40
District heating transfer station	20	Building automation system	40
Ground source heat pump	20		

2.6. Variants and Sensitivity Analysis

The results of the life-cycle cost analysis strongly depend on the selected input parameters. To gather the impact of the parametric model, sensitivity studies are carried out. The user behaviour identified as influencing factor was addressed by defining three different levels (Table 5). level 1 (efficient) represents an ideal user, level 2 (standard) is defined as a standard user, and level 3 (inefficient) defines a user who operates the building in a not energy-efficient way.

Table 5: Parameter levels of user behaviour

USER BEHAVIOUR	Level 1	Level 2	Level 3
T_{room} (during heating period)	21 °C	22 °C	23 °C
DHW-demand (at 60°C)	29 l/d	33,3 l/d	48,5 l/d
Misuse of external blinds during winter time	0 %	+10 %	+20 %
Electrical loads	20 kWh/(m²a)	26,6 kWh/(m²a)	35 kWh/(m²a)
Additional window ventilation during winter time	0,0 1/h	+0,05 1/h	+0,1 1/h

The first part of the evaluation was focussed on the specific parametric models with the standard user behaviour (Level 2 in Table 5) and the standard energy tariffs (listed in Table 2). The second part of the sensitivity analysis is focused on the robustness of the technologies, which means the influence of the user on the energy performance as well as on the life-cycle cost.

2.7. General Parameters for Parametric Models of the CRAVEzero Case Studies

The following general parameters were identified during a workshop within the CRAVEzero consortium. The parameters were checked according to the practicality of the CRAVEzero approach.

Table 6: General parameter models for nZEBs

CLASSI-FICA-TION	PARAMETER	UNIT	LEVEL 1	LEVEL 2	LEVEL 3	LEVEL 4	LEVEL 5	LEVEL 6	LEVEL 7
Building / Envelope	General	-	Location	Glass to surface area	Orientati-on of building	Shading of exter-nal ob-jects	Building density		
	Location	-	Graz	Vienna	Stock-holm				
	Glass to surface area	%	As built	20	30	40	50		
	Overall construc-tion	-	Minimum require-ments	Passive house std.	Pre-fabricated facade	Pre-fabricated house	Different Glazing		
	Windows	-	Glazing	Shading	Mainte-nance	Orientati-on	Size		
	Doors	-	Glazing	Mainte-nance	Orientati-on	Size			
	Walls	-	Conductiv ity	Insulation	Thermal mass	Thickness			
Ventilation	Type	-	Window	Air extract unit	Central Vent. Unit	Decentral Vent. Unit	Mixed Ventilati-on		
	Heat recovery	%	60	70	80	90			
Heating System	Generation	-	Pellet boiler	Wood-chip boiler	Gas con-densing boiler	District heating	Geother-mal heat pump	Ground-water heat pump	Air heat pump
	Distribution	-	Direct	Con-centric pipes	4 pipe-systems	2 pipe-systems	2 pipe systems @35°C	Decentral storages	
	Dissipation	-	Air	Radiator	Floor heating system	Wall heating system			
Cooling	Generation	-	Heat pump	Absorpti-on heat pumps	Passive cooling systems				
	Distribution	-	Air	Water					
Solar thermal	Area	m²	5	10	15	25	50	100	
	Operation	-	DHW only	Heating only	DHW+ heating				
	Collector	.	Flat plate	Vaccum tube	PVT				
PV	Power	kWp	5	10	25	50	100	200	
	Battery	kWh	5	10	25	50	100	200	
	Operation	-	Full feed-in	Surplus feed-in	E-Mobility	Contrac-ting			
User Behaviour	Room tempera-ture – heating	°C	20	21	22	23	24		
	Room tempera-ture - cooling	°C	24	25	26	27	28		
	DHW - demand	-	Low	Standard	High				

	Shading	-	As built	Ideal	Standard	High		
	Household electricity	-	Efficient	Standard	Not efficient			
	Lighting	-	Automatic controlled high eff.	Automatic controlled std. eff.	Automatic controlled low eff.	Manual controlled high efficiency	Manual controlled std. efficiency	Manual controlled low efficiency
	Window Ventilation	-	Ideal	Standard	High			
Business models	PV	-	Equity financing	Contracting	Energy flat rate			
	Funding	-	None	Current scenario	Enhanced subsidies	Decreased subsidies	Incentives	
Pricing	Sensitivity	%	None	Low	Standard	High		
	Increase in energy price	%/a	None	Low	Standard	High		
	Primary energy	€/kWh	Low	Standard	High			
	Electricity	€/kWh	Low	Standard	High			
	CO2	€/ton	15	30	50			

2.8. Parametric Models – Case Study Solallén

Figure 5: Case study Solallén

General information

- Owner: Brf Solallén (Tenant owned)
- Architect: Skanska Teknik
- Energy concept: Net ZEB
- Location: Växjö (Sweden)
- Construction Date: 2015
- Net floor area: 1.778 m²

Key technologies:

- Well insulated and airtight
- Balanced ventilation with heat recovery
- Ground source heat pump
- Photovoltaic panels

The seven, freestanding buildings (Figure 5) are well insulated and using 50 % less energy according to the national Swedish building code requirement. Each building has an annual energy demand of 30 kWh/m², a photovoltaic system on the roof and a geothermal heating and cooling system, which led to a net zero primary energy balance. During the construction phase, a reduction of 37 % of embodied carbon saving was achieved by using foundation materials efficiently and minimising construction equipment.
The CRAVEzero approach was prototypically implemented in the case study Solallén based on the already gathered building data of one of the seven buildings in PHPP, where the energy demands and yields were scaled up to the total demand and yield of the seven buildings. The life-cycle costs of all seven buildings were gathered from the CRAVEzero LCC-Tool (from WP2), as well as from the CRAVEzero database of WP4. According to the defined general parameters in the previous chapter a set of ten different parameters with three to four levels are defined for the case study Solallén (Table 7) by Skanska. The parameters consist of passive actions (parameter 1, 2, 3), active actions (parameter 4, 5, 6, 7, 8), user actions (parameter 9) and economic actions (parameter 10). The following chapters contain a detailed description of the varied parameters and their impact related to the reference case in D2.2.

Table 7: Overview of the parameters and their different levels (one building)

PARAMETER	LEVEL 1	LEVEL 2	LEVEL 3	LEVEL 4
Parameter 1: Insulation	Floor-slab: 200 mm insulation Exterior walls: 250 mm insulation Roof: 450 mm insulation	Floor-slab: 300 mm insulation Exterior walls: 455 mm insulation Roof: 600 mm insulation	Floor-slab: 400 mm insulation Exterior walls: 600 mm insulation Roof: 750 mm insulation	
Parameter 2: Air tightness	n50: 1,5 1/h	n50: 0,84 1/h	n50: 0,04 1/h	
Parameter 3: Windows	1,10 W/(m²K)	0,90 W/(m²K)	0,70 W/(m²K)	
Parameter 4: Ventilation	SFP: 1,75 η: 80 %	SFP: 1,5 η: 85 %	SFP: 1,25 η: 90 %	
Parameter 5: Heating	District heating ∞ kW_{th} SCOP: 1,0	Ground source heat pump: 4 kW_{th} SCOP: 3,5	Ground source heat pump: 5 kW_{th} SCOP: 5,0	Extract air heat pump 1,8 kW_{th} SCOP: 2,5
Parameter 6: PVs	No PV	0,0347 kW_p/m^2_{GFA}	0,0624 kW_p/m^2_{GFA}	
Parameter 7: Solar Thermal	No solar thermal	0,0334 m^2_{col}/m^2_{GFA}, standard flat plate collector used for DHW	0,0667 m^2_{col}/m^2_{GFA}, vacuum tubes used for DHW and heating	
Parameter 8: Cooling	Compressor cooling: 3 kW_{th} SCOP: 3	Free cooling/boreholes: 1 kW_{th} SCOP: 20	Free cooling/boreholes: 2 kW_{th} SCOP: 20	
Parameter 9: User behavior	Plug loads and lighting: 20 kWh/(m²a) DHW: 15 kWh/(m²a)	Plug loads and lighting: 26,6 kWh/(m²a) DHW: 17,2 kWh/(m²a)	Plug loads and lighting: 35 kWh/(m²a) DHW: 25 kWh/(m²a)	
Parameter 10: Energy tariffs	Electricity: 0,06 €/kWh District heating: 0,035 €/kWh	Electricity: 0,08 €/kWh District heating: 0,05 €/kWh	Electricity: 0,1 €/kWh District heating: 0,065 €/kWh	

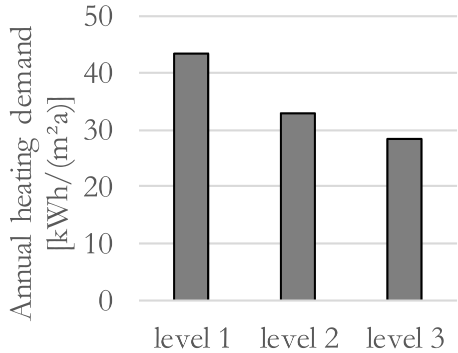
The following chapters include a detailed description of each parametric model is based on the reference case (Table 8). Each parametric model was applied to the reference case, and the influence on the specific heat demand of the building was evaluated. The parametric model of the user behaviour (level 1, level 2 and level 3 in (Table 8) were compared with the reference case. For the parametric models without a direct influence on the specific heat demand of the building (heating system, PV, cooling demand) other evaluation was carried out.

Table 8: Parameter levels of user behaviour including the reference case

USER BEHAVIOUR	LEVEL 1	LEVEL 2	LEVEL 3	REFERENCE
$T_{room\ (during\ heating\ period}$	21 °C	22 °C	23 °C	20 °C
DHW-demand (at 60°C)	29 l/d	33,3 l/d	48,5 l/d	33,3 l/d
Misuse of external blinds during winter time	0 %	+10 %	+20 %	0 %
Electrical loads	20 kWh/(m²a)	26,6 kWh/(m²a)	35 kWh/(m²a)	26,6 kWh/(m²a)
Additional window ventilation during winter time	0,0 1/h	+0,05 1/h	+0,1 1/h	0,0 1/h

2.8.1. INSULATION (PARAMETER 1)

The insulation thickness has a major influence on the heating demand of a building. The insulation of the envelope (all buildings) was varied for the insulation on the floors, the walls and the roofs. The total surface areas are: floors 2.099 m², external walls 1.325 m² and roofs 2.106 m². The insulation thickness of each level was inserted in PHPP, which results in different construction thickness and U-values.



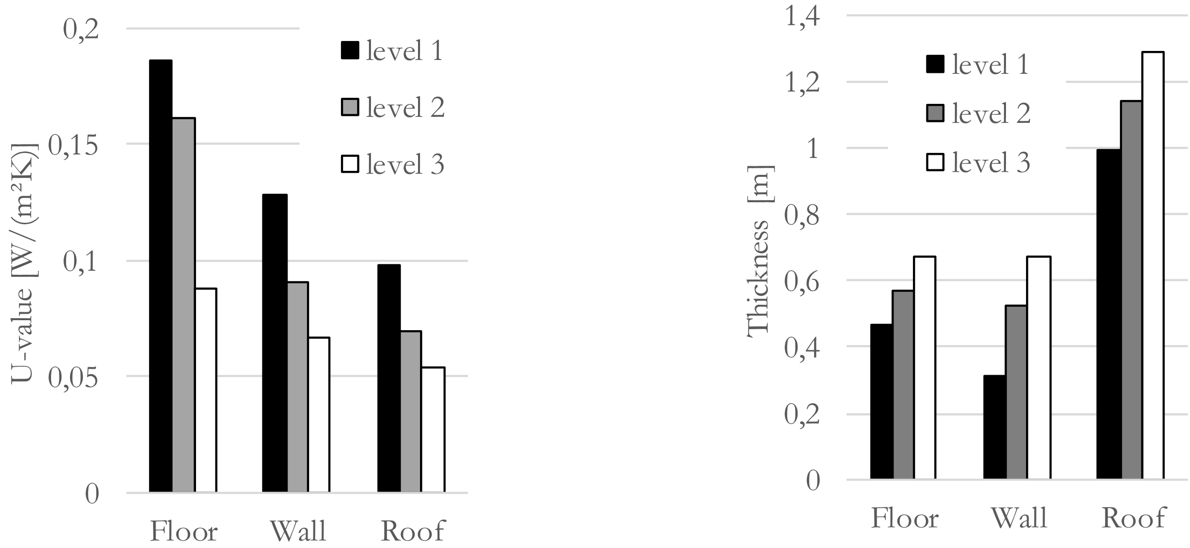


Figure 6: Annual heating demand (top figure), U-value (left figure) and total construction thickness (right figure) of each insulation levels at reference conditions

The additional costs for the different insulation thicknesses include additional structural costs to take up the insulation. The gathered construction costs of each level based on an estimation of the industry partner. The total construction costs (floor, wall and roof) has a share of 43 % (level 1), 48 % (level 2) and 51 % (level 3) from the construction costs (2.535.764 € in D2.2, demo case 9). The considered lifespan was 40 years (economic observation period), and the maintenance costs were 1,6 % of the investment cost per year.

2.8.2.AIRTIGHTNESS (PARAMETER 2)

Air tightness influences the heat demand of a building by altering the air exchange with the ambient (Figure 7). This parameter is accounted by the air change rate (at pressure test n_{50}, DIN EN 13829[1]). The air change rate of the envelope was varied from 0,4 to 1,5 1/h. The investment costs of this parameter were mainly driven by a higher cost of building supervision, sensitisation of workers, especially with openings of the building envelope and less material costs. The share in the construction costs (D2.2) of the first level was 0,3 %, of the second level 0,5 % and 0,6 % of the third level.

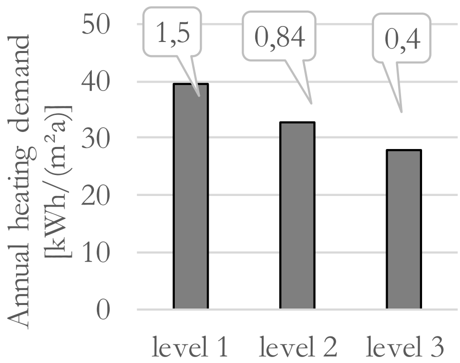


Figure 7: Annual heating demand of each airtightness level at reference conditions

2.8.3.WINDOWS (PARAMETER 3)

The windows, as part of the building envelope, affect the heating demand due to their heat losses and their solar transmittance. The glazing of the building (94 m² in total) varies in three levels. The first level consists of glazing with a total U-value (including thermal bridges) of 1,1 W/(m²K) and a g-value of 0,8. The second level has a U-value of 0,9 W/(m²K) and a g-value of 0,58. The third level has a U-value of 0,7 W/(m²K) and a g-value of 0,37. Figure 8 shows the annual heating demand of each level at the reference condition. The share in the construction costs (D2.2) of the first level was 6,6 %, of the second level 6,7 % and 7,3 % of the third level of the construction costs (D2.2).

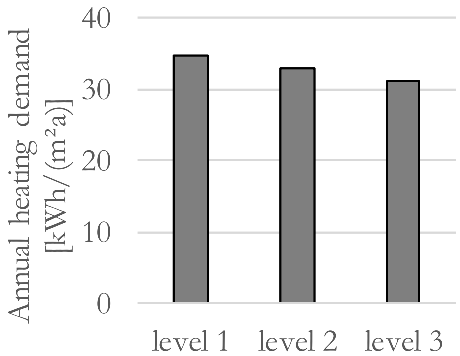


Figure 8: Annual heating demand of each window level at the reference condition

[1] DIN EN 13829, Thermal performance of buildings – Determination of air permeability of buildings – Fan pressurization method (ISO 9972:1996, modified); German version EN 13829:2000

2.8.4.VENTILATION (PARAMTER 4)

A ventilation unit with heat recovery was considered with different SFP-values. The first level has a SFP of 1,75 Ws/m³ with a heat recovery efficiency of 80 %. The second level has a SFP of 1,5 Ws/m³ and a heat recovery efficiency of 85 %. The third level has a SFP of 1,25 Ws/m³ and a heat recovery efficiency of 90 %. The annual heating demand varies from 34,7 kW (level1) to 31,1 kW (level3) in Figure 9. The share in the construction costs (D2.2) of the first level was 3,1 %, of the second level 3,2 % and 3,4 % of the third level.

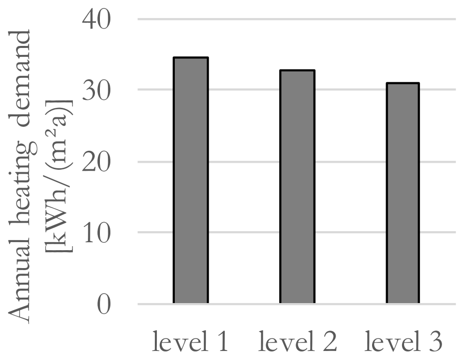


Figure 9: Annual heating demand of each ventilation level at reference conditions

2.8.5.HEATING (PARAMETER 5)

The heating system fully covers the heat demand for space heating and domestic hot water, as well as the heat losses of the distribution systems. The first level (district heating) based on a district heating transfer unit (efficiency of 95 %), which is connected to a district heating grid (efficiency of 85 %) driven by a biomass boiler (efficiency of 85 %). The second and the third level based on a ground source heat pump of with power of 4 kW_{th} and a SCOP of 3,5, respective 5 kW_{th} and SCOP of 5. The thermal properties of clay were applied to the boreholes properties in PHPP, and resulting temperatures were calculated on a monthly basis, regarding to the heat extraction rate. The fourth level based on an exhaust air heat pump with a power of 1,8 kW_{th} and a SCOP of 2,5. The first level, district heating, has the highest final energy demand for heating due to the lower overall efficiency (resulting efficiency of 69 %) of 34,6 kWh, followed by the exhaust heat pump (level 4) of 26,0 kWh (Figure 10). The less efficient ground source heat pump has a final energy demand of 16,4 kWh (level 2) and 10,5 kWh for the more efficient ground source heat pump (level 3). The share of the construction costs (D2.2) of the first level was 4,4 %, of the second level 4,3 %, of the third level 4,9 % and 1,5 % of the fourth level. The cost of heat distribution (floor heating) was excluded in this percentage.

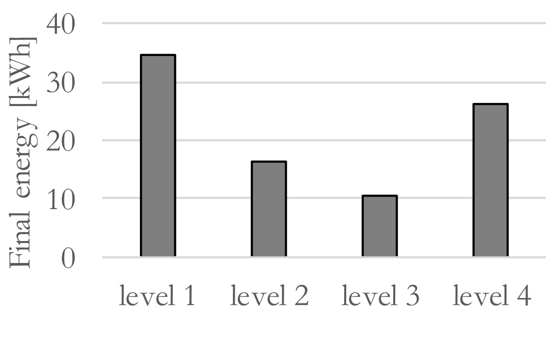


Figure 10: Final energy demand of the four levels of the heating system (district heating, ground source heat pump and air heat pump) at reference conditions

2.8.6. PV (PARAMETER 6)

This parameter consists of a no PV level and two PV levels with different sizes of module area. All of the modules were located on the roof of the building and were horizontal aligned. Level 1 has no PV included, level 2 has a peak power of 0,0347 kW_p/m^2_{GFA} and level 3 of 0,0624 kW_p/m^2_{GFA}. The costs were separated in PV-modules, inverter and wiring. The figure on the right shows the electricity demand and the amount of PV self-consumption and PV- feed into the grid. The share of the construction costs (D2.2) of the second level was 4,9 % and 8,4 % of the third level.

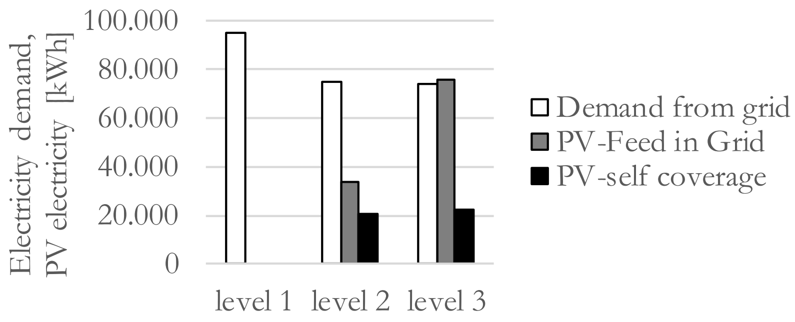


Figure 11: Total electricity demand of the building, PV surplus feed-in grid and PV self-coverage of each PV-level at reference conditions

2.8.7. SOLAR THERMAL (PARAMETER 7)

The gain from solar thermal collector was considered at three levels, without solar thermal, a solar thermal system for domestic hot water support with 0,0334 m^2_{col}/m^2_{GFA} of flat plate collector and the third level is a solar thermal system for space heating and domestic hot water supply with a specific collector area of 0,0667 m^2_{col}/m^2_{GFA} vacuum tube collectors. The share of the second level 4,9 % and 8,4 % of the third level of the construction costs (D2.2).

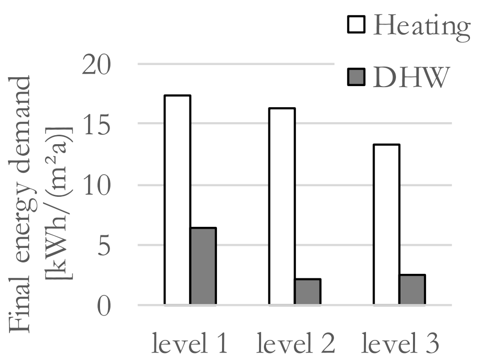


Figure 12: Residual final energy demand (Final energy demand reduced by solar thermal heat) of heating and domestic hot water demand for different solar thermal levels at the reference condition

2.8.8. COOLING (PARAMETER 8)

The building has a relatively low designed cooling demand of 0,2 kWh/(m²a). In the first level is a compressor cooling, where the additional cooling unit (3 kW_{th} with a SCOP of 3) is placed inside the building envelope. The other two levels use the boreholes of the ground source heat pumps to operate in free-cooling operation (1 kW_{th} and 2 kW_{th} for each building). Compared to level 2 and level 3, the invest costs of a compressor cooling unit is higher. The free cooling mode is only available in combination with level 2 and level 3 of the heating variants (parameter 5), because of the usage of the ground source heat pump. The share of the construction costs (D2.2) of the first level was 0,5 %, of the second level 0,2 % and 1,0 % of the third level.

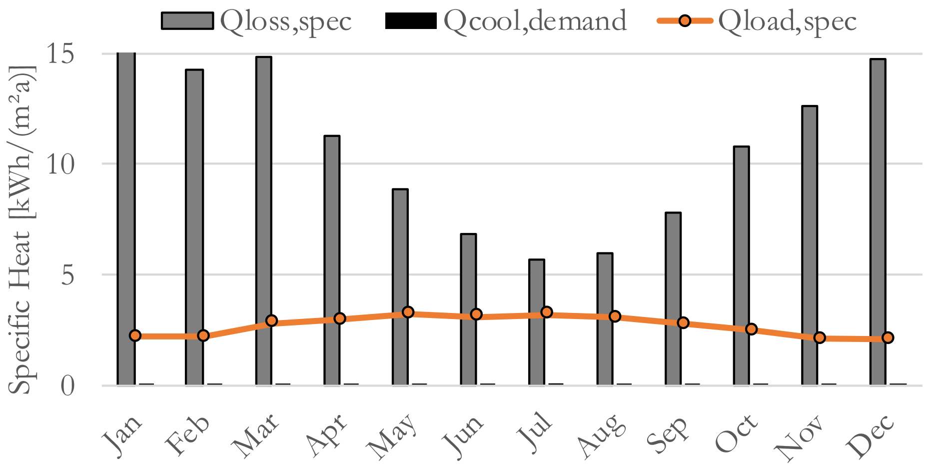


Figure 13: Heat losses, cooling demand and internal loads at the reference condition on a monthly basis

2.8.9. USER BEHAVIOUR (PARAMETER 9)

The active and passive technology measures are evaluated with different user behaviour. It shows how the building and the integrated components perform under different operation conditions. The three-level of user behaviour were listed in Table 17. A distinction was made between level 1 (efficient), level 2 (standard) and level 3 (not efficient). As a reference a standard heat demand at 20 °C room temperature (reference) is shown in the right figure. The parameter level affects the room temperature, the domestic hot water demand, shading during winter and additional electrical loads and is finally represented by the energy demand. The varied parameter levels were summarised in Table 17. The effect on the final energy demand is shown in Figure 14.

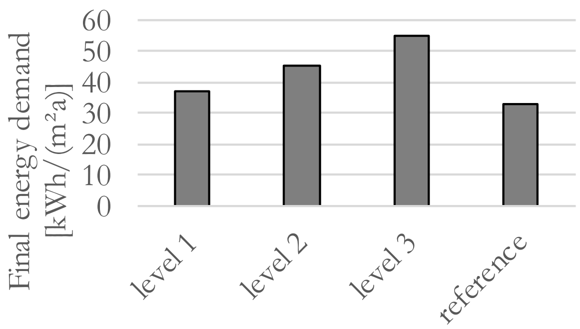


Figure 14: Annual final energy consumption of each level of the user behaviour and reference conditions

2.8.10. ENERGY TARIFFS (PARAMETER 10)

The last parameter, energy tariffs are facing the scenarios with different energy prices (electricity, district heating cost, PV- remuneration) and the annual increase of the energy prices over the observation period. As a baseline for the electricity price, 0,187 € was taken from the CRAVEzero LCC-Tool. This energy price was increased and decreased for 0,02 €, which was the difference between the former defined variants. The district heating costs were adopted. Table 9 gives a comparison of the used levels supplemented by a reference case with no increase of the energy costs.

Table 9: Parameter levels of energy tariffs

	LEVEL 1	LEVEL 2	LEVEL 3	REFERENCE
Electricity costs	0,187 €/kWh	0,207 €/kWh	0,167 €/kWh	0,187 €/kWh
District heating costs	0,05 €/kWh	0,065 €/kWh	0,035 €/kWh	0,07 €/kWh
PV Feed-in grid	0,03 kWh	0,03 €/kWh	0,03 €/kWh	0,03 €/kWh
Increase in electricity costs	1,0 %/a	2,0 %/a	0,5 %/a	0,0 %/a
Increase in district heating costs	1,0%/a	2,0 %/a	0,5 %/a	0,0 %/a
Increase in PV feed-in remuneration	1,7 %/a	2,7 %/a	0,7 %/a	0,0 %/a

2.9. Calculation Results

2.9.1. COST CURVES OVER THE LIFE-CYCLE OF BUILDINGS

Based on the developed method and the defined parameters calculations of the energy and cost performance of the case study Solallén were performed. This chapter includes the presentation of the most important results on:

- Energy performance - primary energy demand, CO_2 emissions
- Cost efficiency - investment costs, life-cycle costs

The analysis is performed for each parameter individually and in combination.

The net present value of a building or a specific parametric model is the result of the costs in the individual phases of the building life-cycle. In this case, the following costs were considered:

- Planning costs
- Financing costs
- Consumption costs incl. PV own use and PV feed-in
- Operating costs
- Replacement investment
- Residual value

In total, more than 31.000 different variants were calculated. For the results in Figure 15 the energy tariff was set to a standard value (reference value), and also the user behaviour was set to standard, which was level 3. This resulted in about 2.000 variants. The minimum, average and maximum values of all those variants were plotted below, indicating the range of the costs in each phase of the building life-cycle. The decline of the net present value is caused by the residual value of the building components, which did not reach the end of their lifespan after the reinvestment. Their residual values are deducted at the end of the observation period.

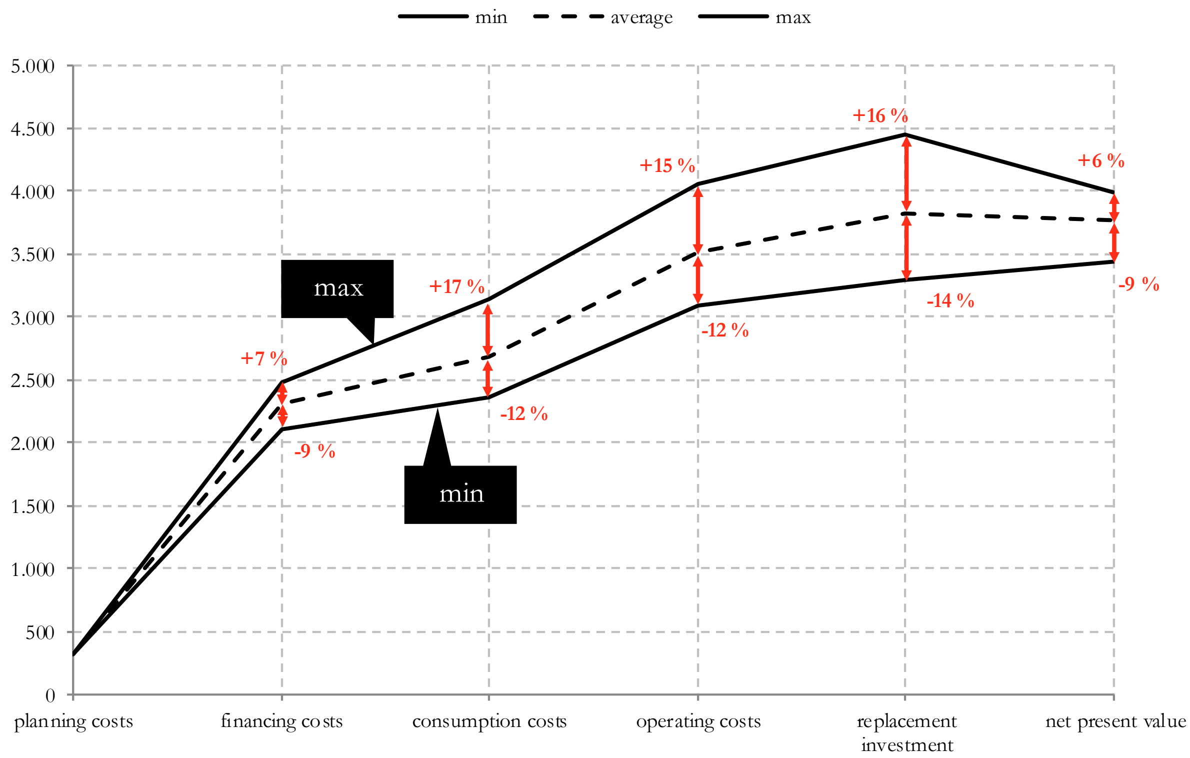


Figure 15: Specific costs (€/m²) in the different phases of the case study Solallén over the whole life-cycle of the building; range between the different parameters indicated as minimum (min), average and maximum (max) values; percentages represent the deviation from the average (energy tariff standard/user behaviour standard / without consideration of subsidies)

Figure 16 shows the cost curve for two different variants of the parametric calculations. For the nearly zero-energy building (nZEB) the variant with the highest net present value was plotted. In comparison to that, the variant with the lowest net present value was selected and illustrated. This variant is called "CRAVEzero".

The percentages in the figure represent the possible cost reductions of the CRAVEzero variant in comparison to the nZEB variant. In this case, 6 % to 9 % reductions in each phase is possible.

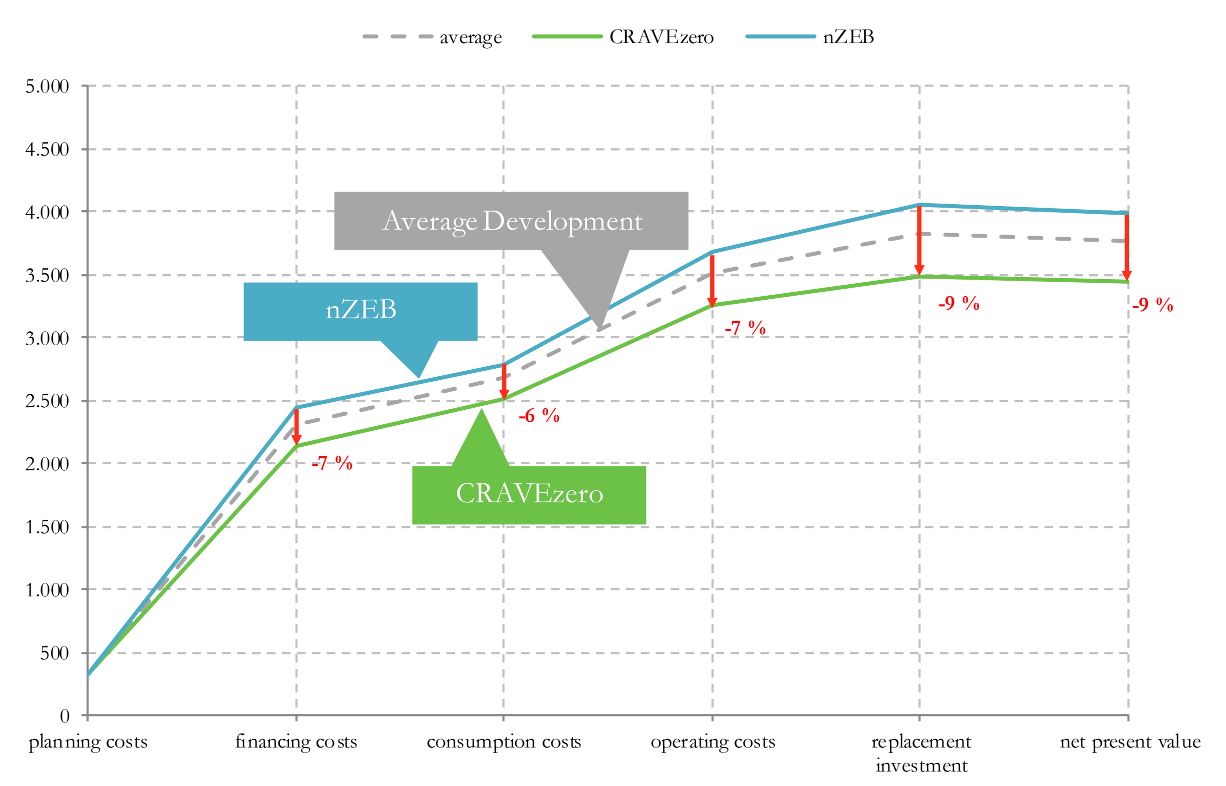


Figure 16: cost performance (€/m²)of the case study Solallén over the whole life-cycle of the building, comparison of nZEB variant with a building according to the CRAVEzero approach and the average value from Figure 15 (energy tariff standard/user behaviour standard / without consideration of subsidies)

2.9.2.COST EFFICIENCY

In this Deliverable the financing costs and the net present value (representing the life-cycle costs over the whole lifespan) was defined as indicators for the cost efficiency. Figure 17 shows the overall results of the case study Solallén. Here the financing costs of all investigated parameters are shown in relation to the balanced CO_2 emissions.

"Balanced" in this case means that the self-consumption of the PV system was considered, transferred into CO_2 emissions (and in further consequence also into primary energy) by the conversion factors for electricity and then subtracted from the calculated CO_2 emissions (respectively primary energy demand). Written as a formula, the balanced CO_2 emissions were calculated as follows:

$$CO_2 \text{ emissions balanced } [\frac{kg}{m^2a}] =$$

$$CO_2 \text{ emissions } [\frac{kg}{m^2a}] - \text{self-consumption of PV } [\frac{kWh}{m^2a}] \text{ x conversion factor of electricity } [\frac{kg}{kWh}]$$

Figure 17 allows the following short analysis:

- The financing costs range between 2.100 €/m² and 2.500 €/m². This is a range of about 20 %.
- The balanced CO_2 emissions range between 14 kg/(m²a) and 52 kg/(m²a). This is a range of about 70 %.

Furthermore, the analysis shows that similar financing costs can be achieved by the variants leftmost in the diagram and the variants rightmost. With these similar financing costs, the balanced CO_2 emission can be reduced by nearly 70 %.

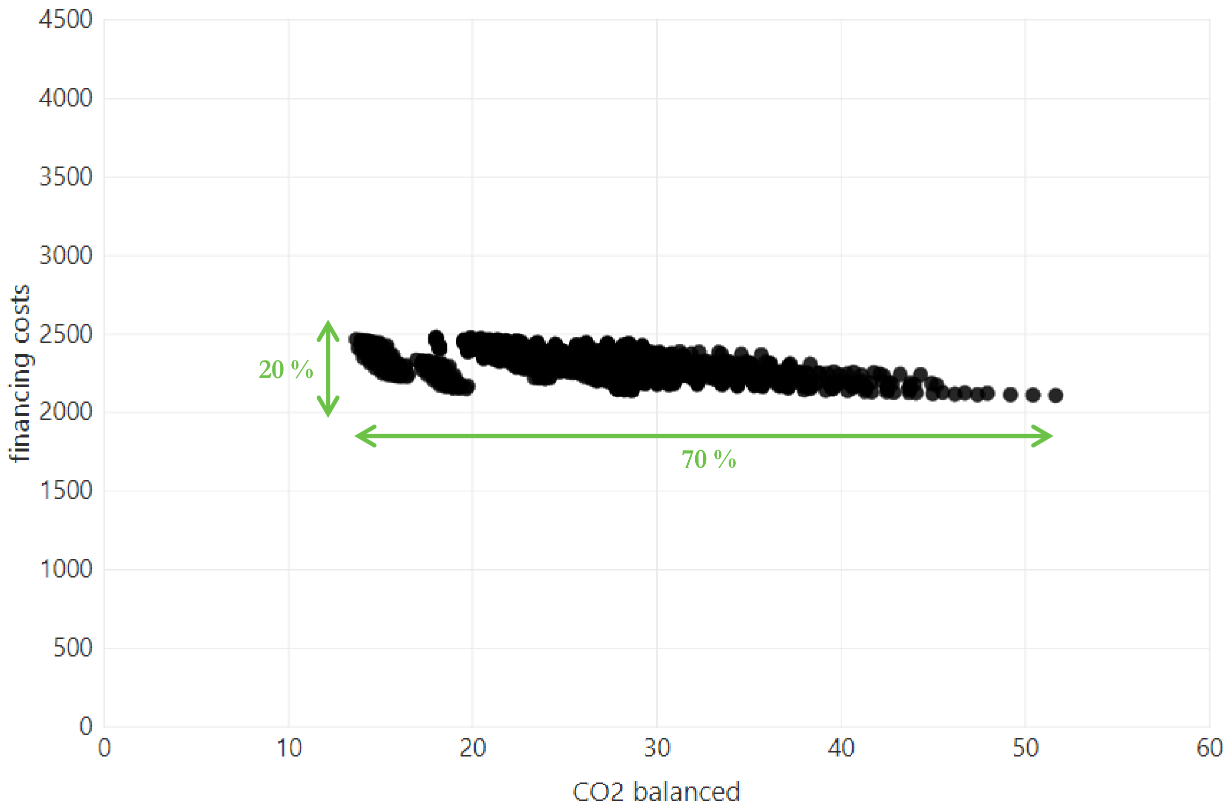


Figure 17: financing costs (€/(m²)) in relation to the balanced CO_2 emissions ($kg_{CO2}/(m^2a)$) of all variants of the case study Solallén (related to the treated floor area of the PHPP / CO_2 factors PHI / without consideration of subsidies).

Looking at the net present value of all calculated parameters in relation to the balanced CO_2 emission in Figure 18 the results look quite similar:

- The net present value ranges between 3.500 €/m² and 4.000 €/m². This is a range of about 15 %.
- The balanced CO_2 emissions range between 14 kg/(m²a) and 52 kg/(m²a). This is a range of about 70 %.

The difference here is the fact that the lower the balanced CO_2 emissions, the lower also the net present value. This is the proof that under the given boundary conditions CO_2 emission reductions can be achieved while reducing the net present value of the building over the whole life-cycle at the same time.

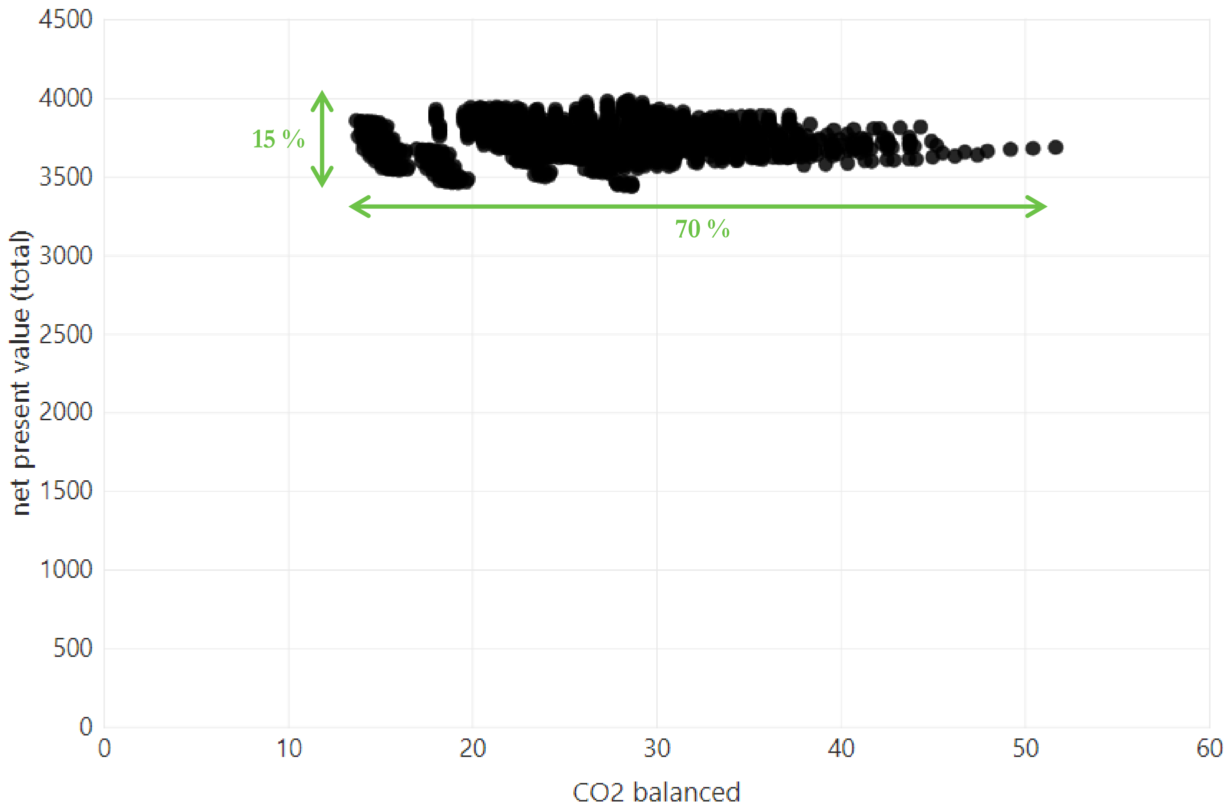


Figure 18: net present value (€/m²) relation to the balanced CO_2 emissions ($kg_{CO2}/(m^2a)$) of all variants of the case study Solallén (related to treated floor area of the PHPP / energy tariff standard / user behaviour standard / CO_2 factors PHI / without consideration of subsidies / no CO_2 credit for electricity fed into the grid).

Not shown at this point is the analysis of the financing costs and the net present value in relation to the balanced primary energy demand.
The results look quite similar, achieving primary energy reductions of 66 % between the variant with the lowest and the highest balanced primary energy demand (range of 83 kWh/(m²a) to 243 kWh/(m²a)). Therefore, no separate presentation was made.

2.9.3. COMBINING ENERGY PERFORMANCE AND COST EFFICIENCY

Scatter plots were used to analyse the energy performance in combination with cost efficiency. This was done for single technologies and technology combinations.

For every single technology, the net present value was compared to the balanced CO_2 emissions and the balanced primary energy demand. The results of this analysis are shown in the following figures.

Figure 19 shows the influence of the building envelope on the net present value, the balanced CO_2 emission and the balanced primary energy demand. The analysis shows that the improvement of the insulation from level 1 to level 3 reduces the CO_2 emission and primary energy demand only slightly, but results in a higher net present value.
The reason for that is the already improved insulation standard of level 1 wherein further consequence an additional improvement does not lead to the desired reductions of CO_2 and primary energy.

Envelope

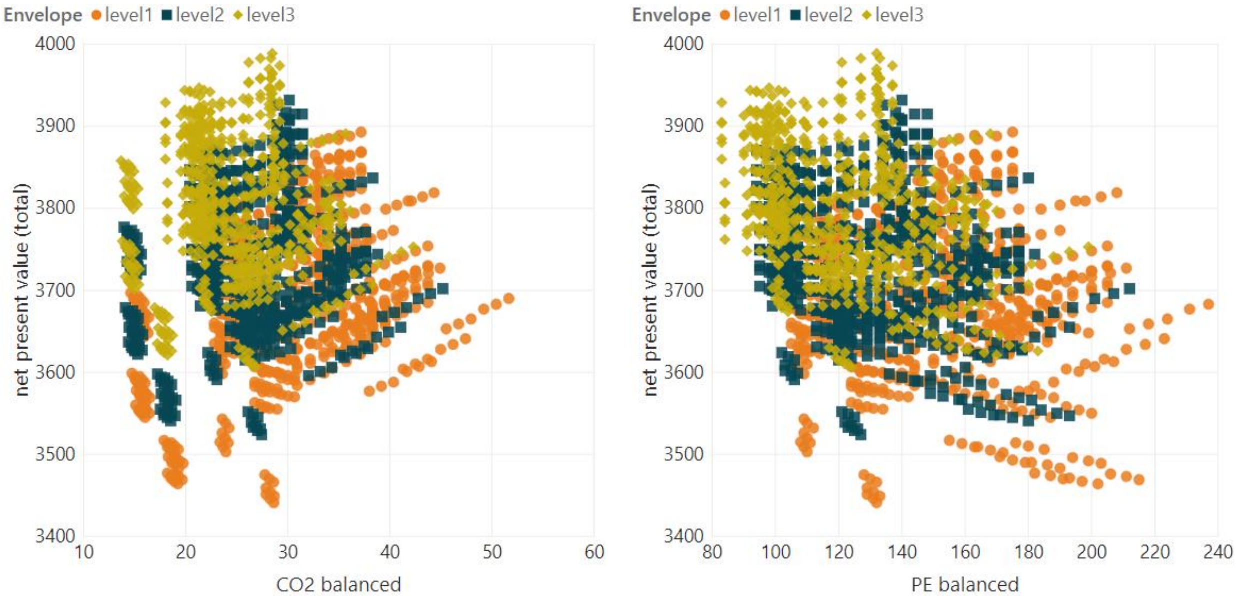


Figure 19: analysis of the influence of the building envelope on the net present value, the balanced CO_2 emissions (left) and the balanced primary energy demand (right) (related to treated floor area of the PHPP / energy tariff standard / user behaviour standard / CO_2 and PE factors PHI/ without consideration of subsidies / no CO_2 or PE credit for electricity fed into the grid).

The analysis of the influence of the windows and doors, as well as the airtightness of the building envelope in Figure 20, shows in no uncertain manner that the improvement of windows, doors and airtightness definitely makes sense. Under the assumed calculation parameters, the improvement leads to reduced CO_2 emissions, primary energy demand and net present value.
An exception concerns those variants which are heated by district heating. Here, especially with regard to the CO_2 emissions, there is no potential for savings due to the improved windows, doors and airtightness.

Further investigations of the ventilation in Figure 21 show that the calculated variants are all quite similar and show no difference in net present value, CO_2 emissions and primary energy demand. That means that the expected difference between the three levels cannot be shown by the developed calculation method.

Windows Doors Airtightness

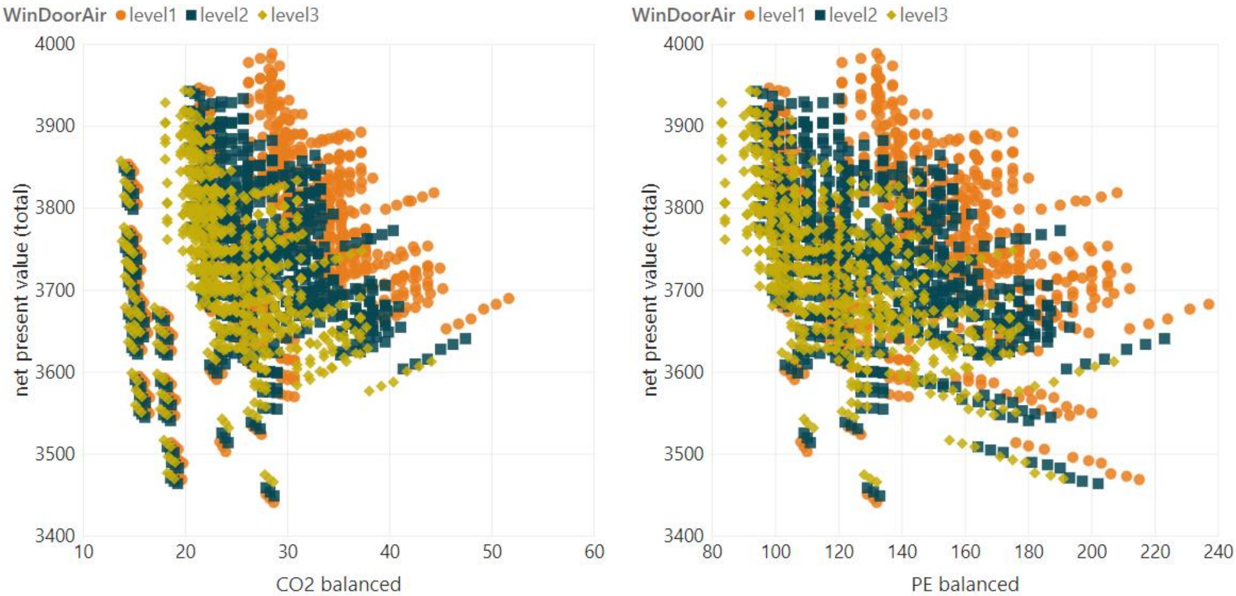


Figure 20: analysis of the influence of the quality of the windows and doors as well as of the airtightness of the building on the net present value, the balanced CO_2 emissions (left) and the balanced primary energy demand (right) (related to treated floor area of the PHPP /energy tariff standard / user behaviour standard / CO_2 and PE factors PHI/ without consideration of subsidies / no CO_2 or PE credit for electricity fed into the grid).

Ventilation

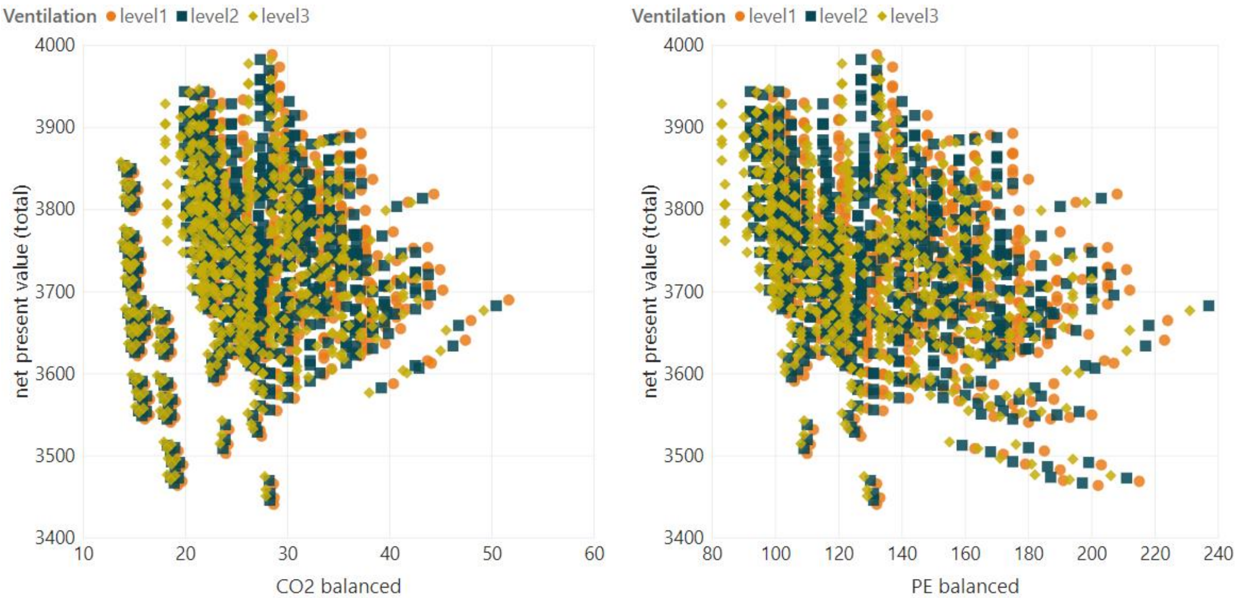


Figure 21: analysis of the influence of the ventilation on the net present value, the balanced CO_2 emissions (left) and the balanced primary energy demand (right) (related to treated floor area of the PHPP / energy tariff standard / user behaviour standard / CO_2 and PE factors PHI/ without consideration of subsidies / no CO_2 or PE credit for electricity fed into the grid).

Figure 22 shows the analysis of the different heating systems. Independent of all other parameters the district heating system (level 1) achieves the lowest CO_2 emissions by far. All investigated heat pump systems achieve similar results for the CO_2 emissions and the net present value.

Looking at the balanced primary energy demand the situation is different. Here the district heating is not the one with the lowest primary energy demand. Instead the heat pump systems achieve lower values. The lowest net present value is achieved by the air source heat pump (level 4).

Heating System

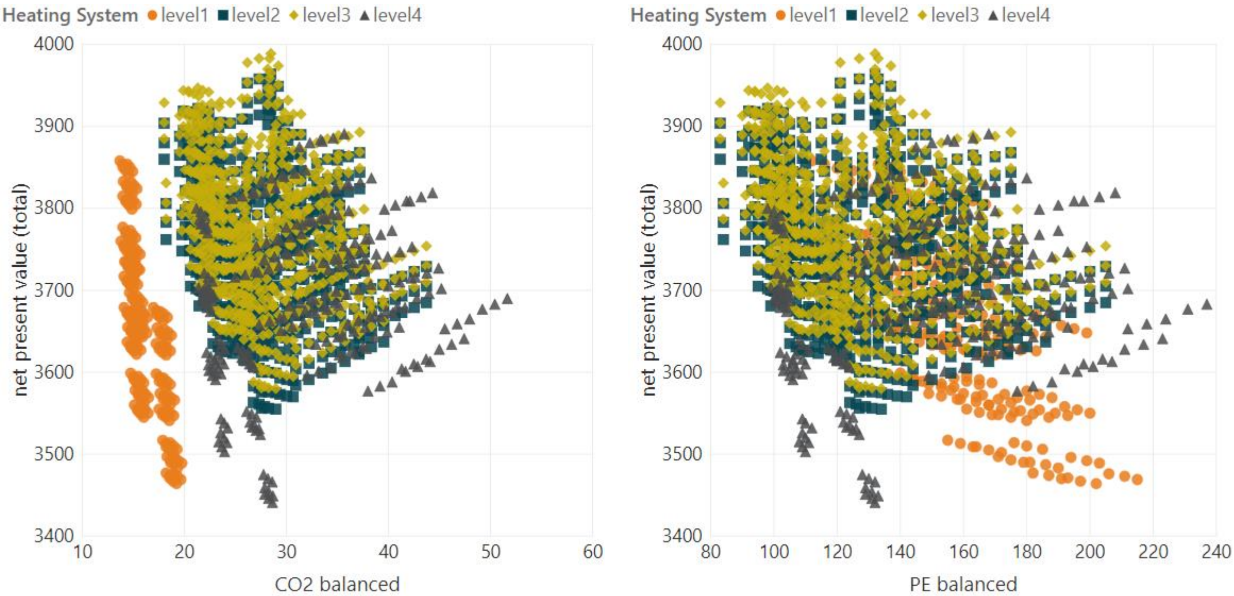


Figure 22: analysis of the influence of the heating system of the building on the net present value, the balanced CO_2 emissions (left) and the balanced primary energy demand (right) (related to treated floor area of the PHPP / energy tariff standard / user behaviour standard / CO_2 and PE factors PHI/ without consideration of subsidies / no CO_2 or PE credit for electricity fed into the grid).

Cooling

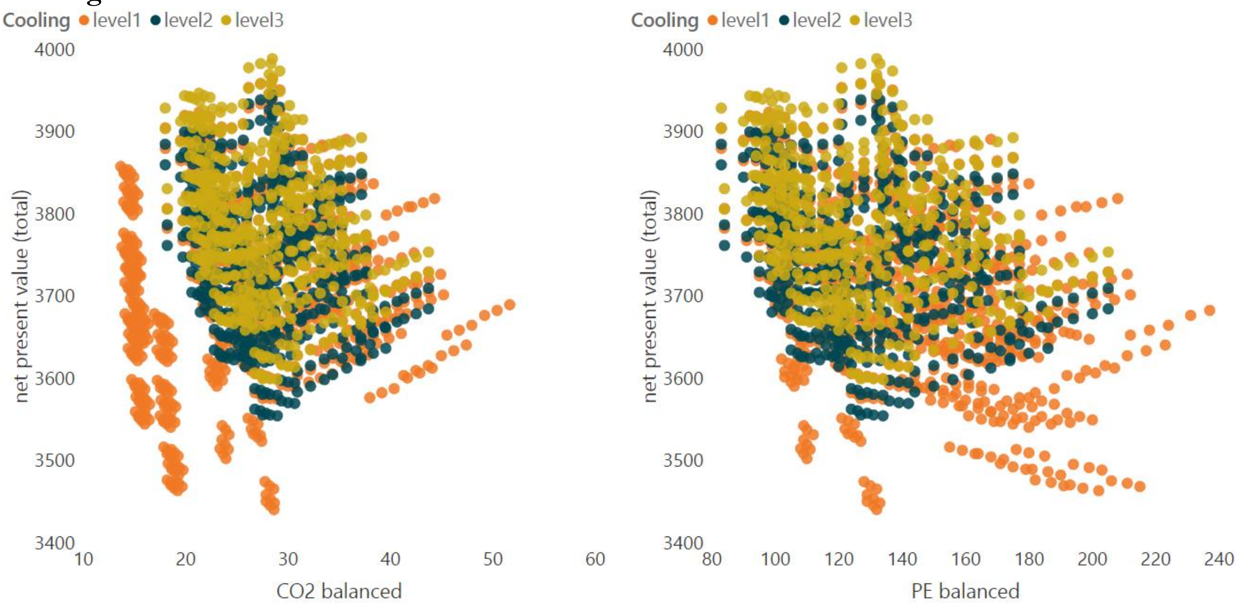


Figure 23: analysis of the influence of the cooling system on the net present value, the balanced CO_2 emissions (left) and the balanced primary energy demand (right) (related to treated floor area of the PHPP / energy tariff standard / user behaviour standard / CO_2 and PE factors PHI/ without consideration of subsidies / no CO_2 or PE credit for electricity fed into the grid).

The influence of the solar thermal system on the calculation results is shown in Figure 24. Looking at the balanced CO_2 emission on the left side, the results show that a larger solar thermal system (level 3) definitely makes sense for all investigated heat pump systems. In this case, the CO_2 emissions and the net present value can be reduced. For the solar thermal systems in combination with district heating, this statement cannot be confirmed as the solar thermal system does not reduce the emission but leads to increased life-cycle cost.

Looking at the primary energy demand on the right side, here the solar thermal systems result in lower primary energy and net present values in all investigated cases.

The analysis of the influence of the PV system in Figure 25 shows possible reductions of CO_2 emissions and primary energy demand by increasing the PV size (from level 1 to level 3). But as a result of this increase of the PV size also the net present values increases. In this comparison level 2 would be the optimum.

Solar thermal system

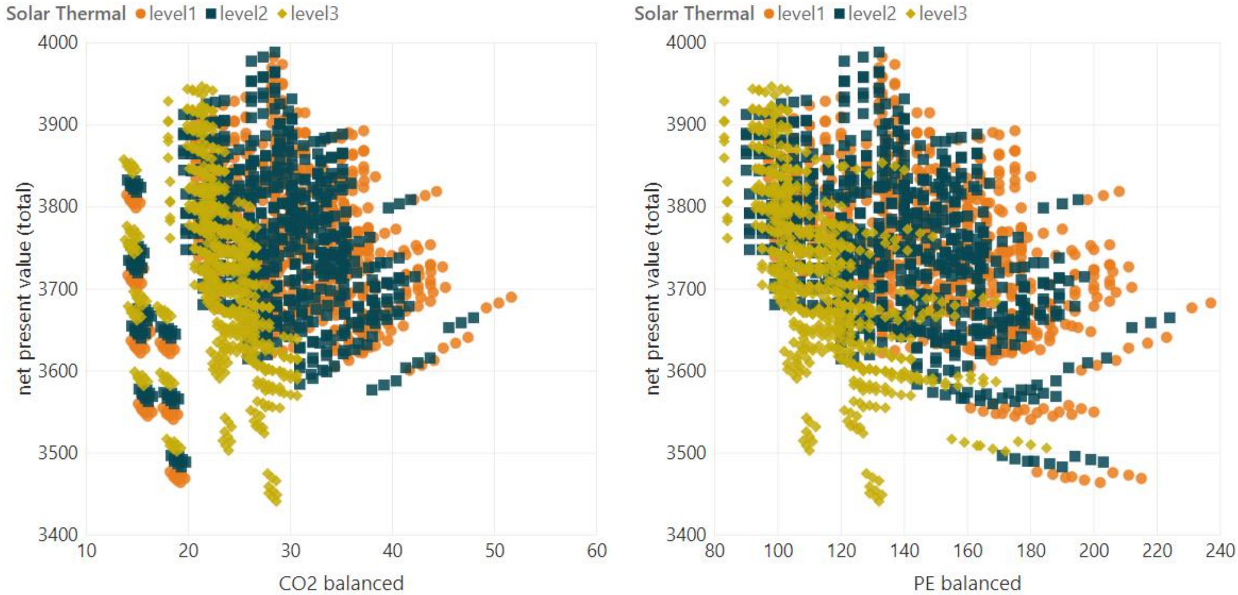


Figure 24: analysis of the influence of the ventilation on the net present value, the balanced CO_2 emissions (left) and the balanced primary energy demand (right) (related to treated floor area of the PHPP / energy tariff standard / user behaviour standard / CO_2 and PE factors PHI/ without consideration of subsidies / no CO_2 or PE credit for electricity fed into the grid).

PV

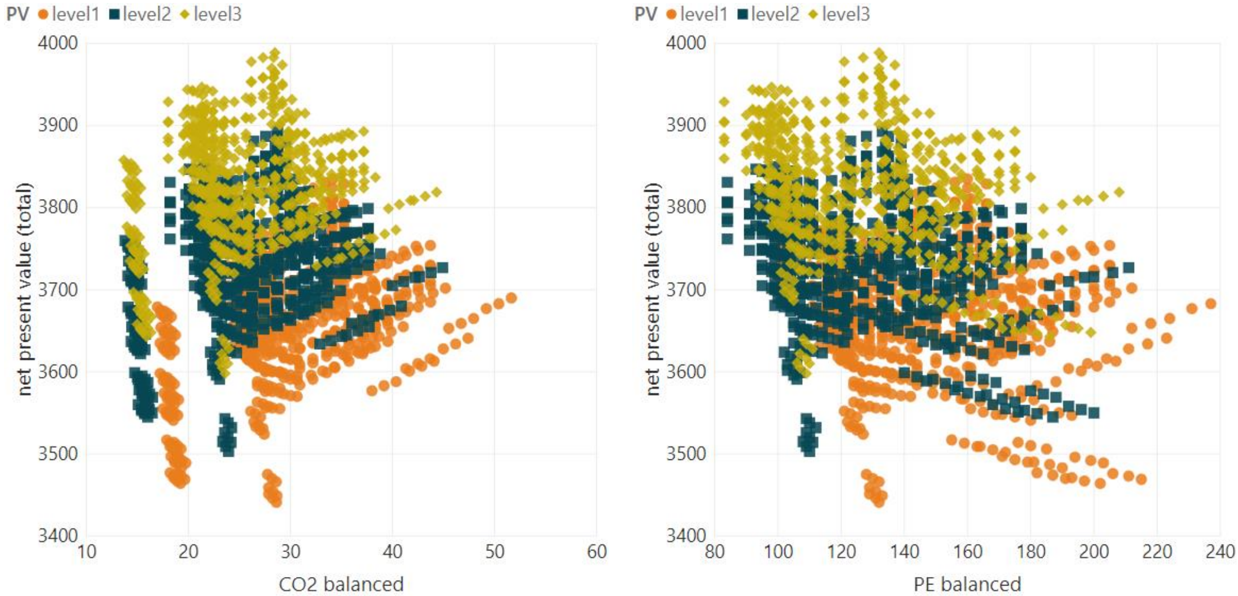


Figure 25: analysis of the influence of the PV system on the net present value, the balanced CO_2 emissions (left) and the balanced primary energy demand (right) (related to treated floor area of the PHPP / energy tariff standard / user behaviour standard / CO_2 and PE factors PHI/ without consideration of subsidies / no CO_2 or PE credit for electricity fed into the grid).

In a second step different combinations of technologies were investigated to test the influence on net present value, CO2 emissions and primary energy demand again. Following Figure 26 and Figure 27 show exemplary evaluations of different technology options.

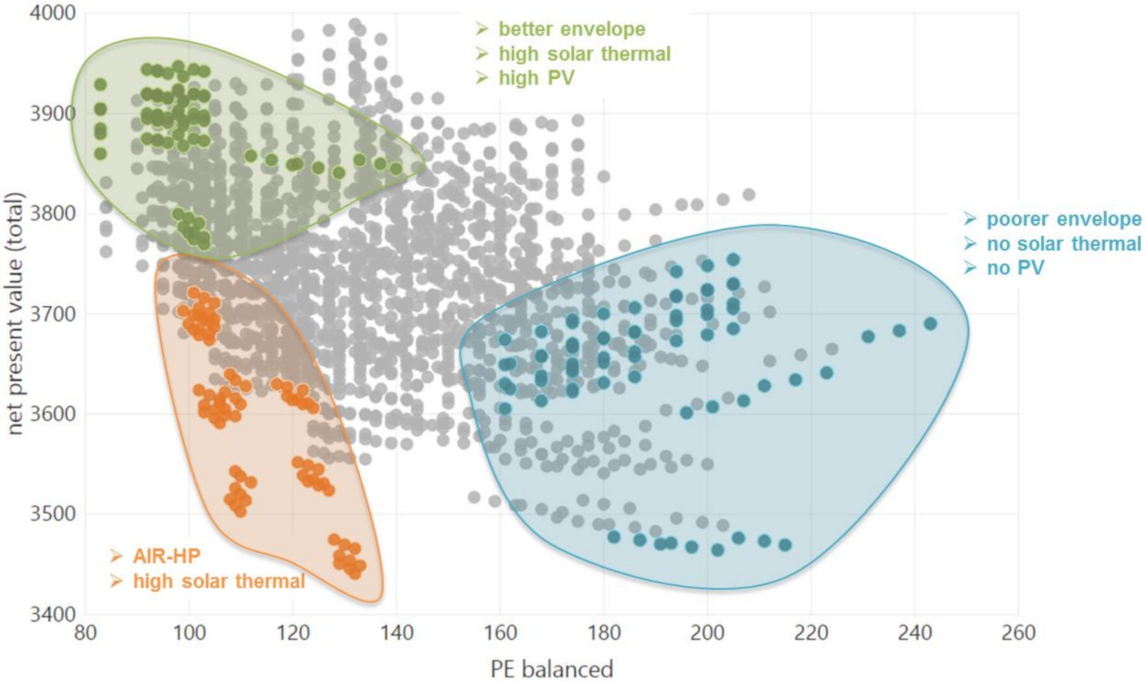


Figure 26: analysis of the balanced primary energy demand related to the net present value for the different technology combinations (related to the treated floor area of the PHPP / energy tariff standard/user behaviour standard / PE factors PHI / without consideration of subsidies / no PE credit for electricity fed into the grid).

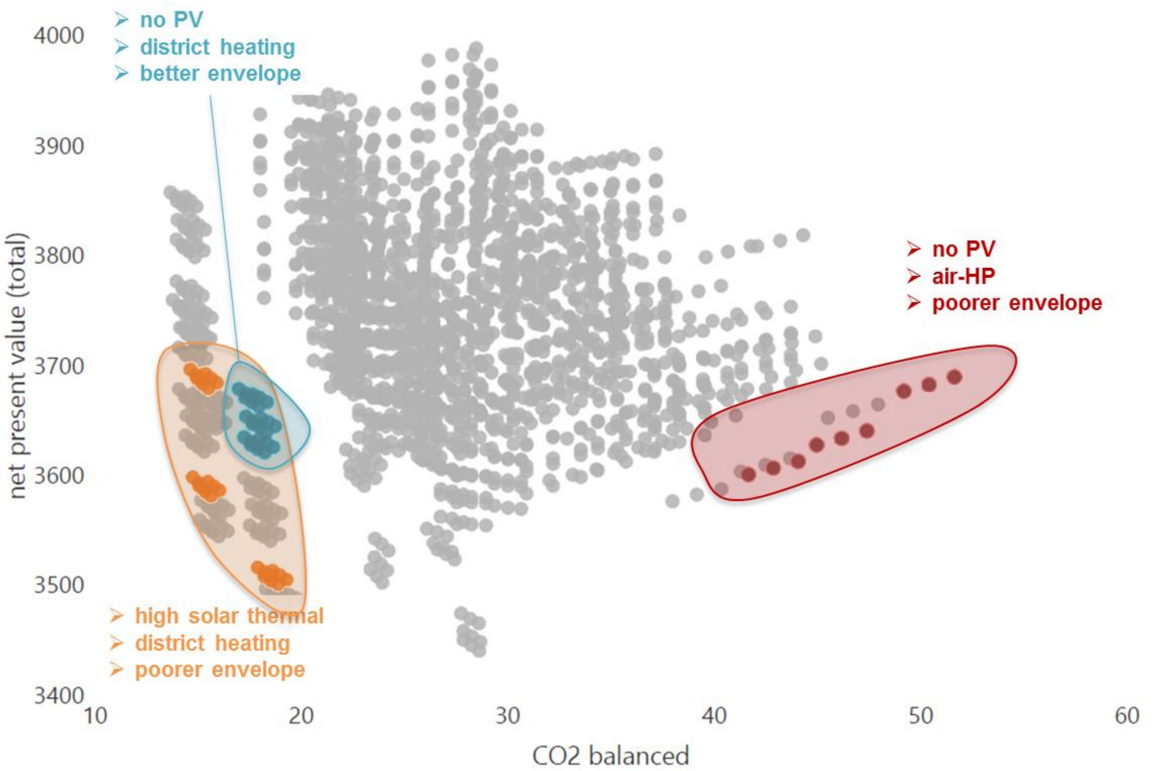


Figure 27: analysis of the balanced CO_2 emissions related to the net present value for the different technology combinations (related to the treated floor area of the PHPP / energy tariff standard/user behaviour standard / CO_2 factors PHI/ without consideration of subsidies / no CO_2 credit for electricity fed into the grid).

Another possibility of combining the results of the energy performance calculation and the calculation of the cost efficiency was tested by giving the indicators balanced primary energy demand, balanced CO_2 emissions, financing costs and net present value different importance. For each indicator, the minimum value and the maximum value were accounted with a score from 0 (e.g. the highest CO_2 demand) to 100 (e.g. the lowest CO_2 demand). This rating was applied to all four indicators. Based on the weighting factors in Table 10, each ranking score was weighted, which means the share of each indicator on the total score. Using the balanced CO_2 emissions as an example, the weighted factor of 5 means a share of 31 % of the overall summed ranking of the indicators. So those 100 variants could be determined which fulfil the set importance most (top 100).

Table 10: Weighting factors of indicators

	WEIGHTED FACTOR	SHARE
Balanced primary energy demand	3	19 %
Balanced CO2 emissions	5	31 %
Net present value	5	31 %
Financing costs	3	19 %

The result of the calculation is shown in Figure 28. For each technology, those 100 variants are indicated which achieve the best results according to the defined weighting.

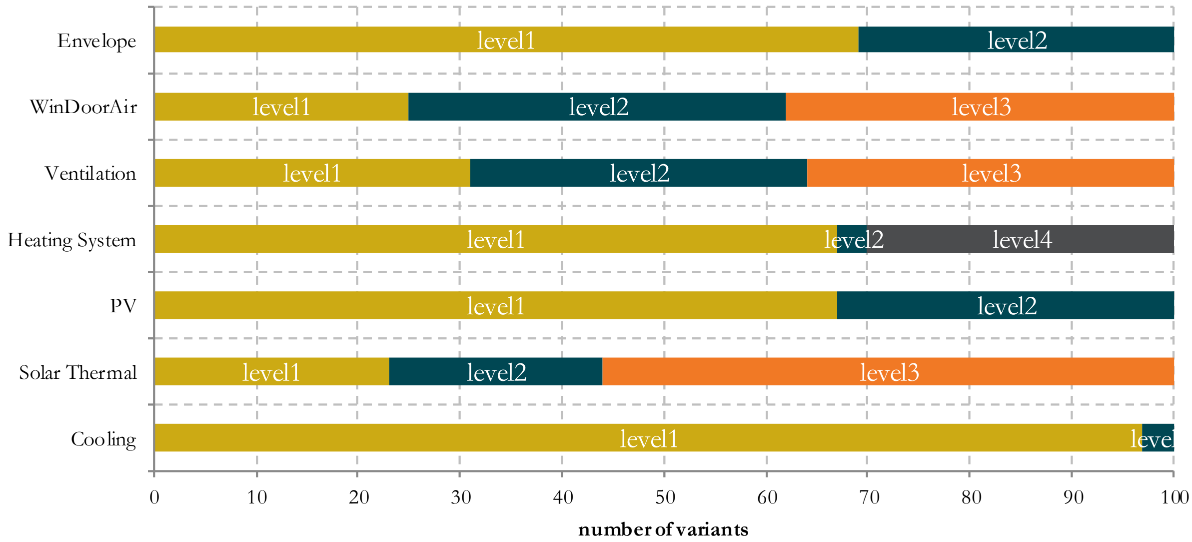


Figure 28: determination of the 100 variants per technology which achieve the best results according to the defined weighting of balanced primary energy demand, balanced CO_2 emission, net present value and financing costs (energy tariff standard / user behaviour standard / CO_2 and PE factors PHI/ without consideration of subsidies / no CO_2 or PE credit for electricity fed into the grid).

2.10. Sensitivity Analysis - Effects of nZEB Design Variables on Energy and Environmental Performance

The sensitivity of the individual technologies to the indicated performance indicators “balanced CO_2 emission”, “balanced primary energy demand”, “financing costs” and “net present value” was investigated. For this purpose boxplots were produced to show the sensitivity of all investigated technologies on the named indicators. In addition, mean and standard deviation values are summarised in the tables below the boxplots.
These results indicate the sensitivity of the investigated performance indicators for the multi-objective building life-cycle cost and performance optimisation.

The visualisation of the results is separated into two parts:

- Part 1: technologies that could be counted as “energy efficiency measures” or “passive measures”, like insulation of the building envelope, improved u-values of windows and doors, improved airtightness or mechanical ventilation
- Part 2: technologies counted as part of the “energy supply system” or “active measures, like heating system, cooling system, solar thermal installation or PV system

For all these investigations the energy tariff and user behaviour were not varied. In both cases, the setting “standard” was used to produce the results and figures.

Figure 29 shows the sensitivity of the energy efficiency measures on the defined indicators.

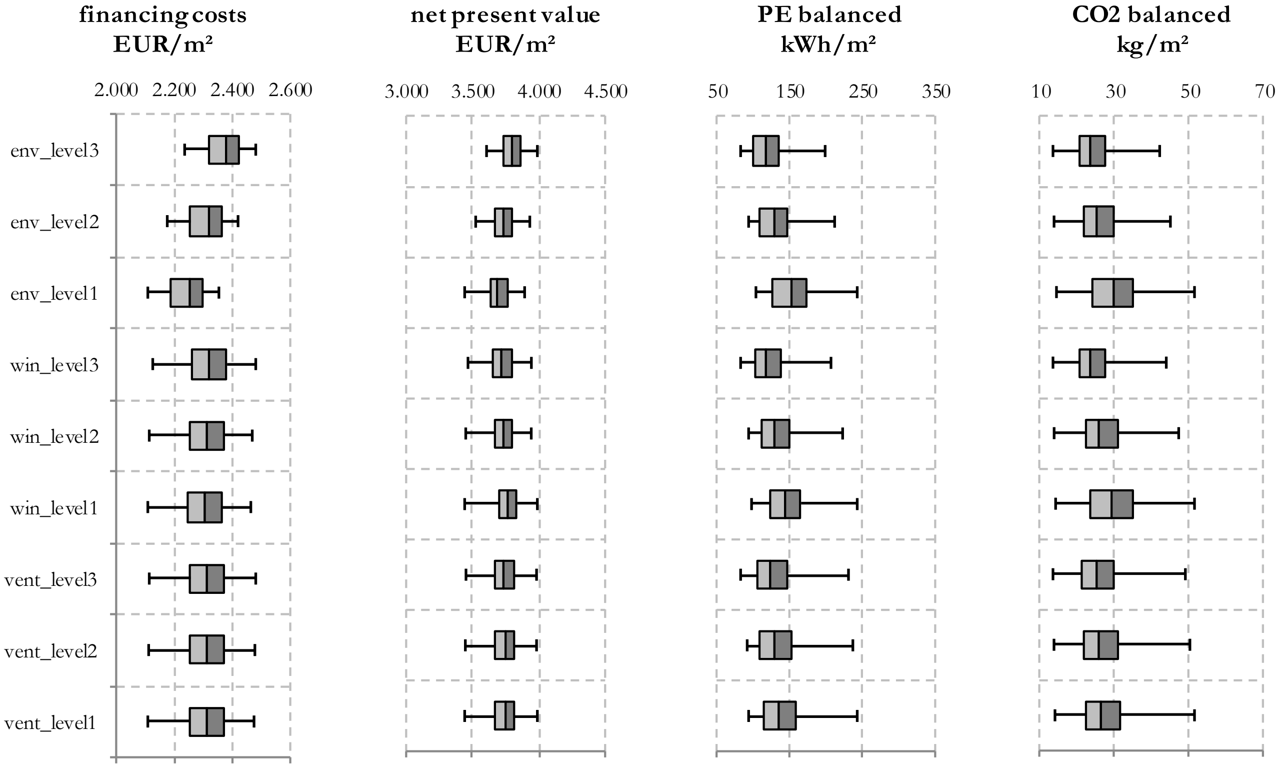


Figure 29: Sensitivity of the financing costs, the net present value, the balanced primary energy (PE) demand and the balanced CO_2 emissions to the energy efficiency measures
Key: "env"…building envelope; "win"…windows, doors and airtightness; "vent"…ventilation

Table 11: Mean value and standard deviation for the investigated building envelopes

BUILDING ENVELOPE	FINANCING COSTS (EUR/M2)	NET PRESENT VALUE (EUR/M2)	PE BALANCED (KWH/M2A)	CO2 BALANCED (KG/M2A)
Level 1				
median	2.253	3.688	152	30
standard deviation	59	94	29	7
Level 2				
median	2.320	3.729	128	26
standard deviation	59	84	24	6
Level 3				
median	2.380	3.796	119	24
standard deviation	59	82	23	5

Table 12: Mean value and standard deviation for the investigated windows, doors and the airtightness of the building

WINDOWS DOORS AIR-TIGHTNESS	FINANCING COSTS (EUR/M2)	NET PRESENT VALUE (EUR/M2)	PE BALANCED (KWH/M2A)	CO2 BALANCED (KG/M2A)
Level 1				
median	2.305	3.769	144	29
standard deviation	78	103	29	7
Level 2				
median	2.310	3.737	130	26
standard deviation	78	95	26	6
Level 3				
median	2.321	3.724	119	24
standard deviation	78	91	24	5

Table 13: Mean value and standard deviation for the investigated ventilation solutions

VENTILATION	FINANCING COSTS (EUR/M2)	NET PRESENT VALUE (EUR/M2)	PE BALANCED (KWH/M2A)	CO2 BALANCED (KG/M2A)
Level 1				
median	2.310	3.744	134	27
standard deviation	78	99	29	7
Level 2				
median	2.312	3.744	130	26
standard deviation	78	98	28	7
Level 3				
median	2.315	3.740	124	25
standard deviation	78	97	27	6

When the difference in median value and the standard deviation is small, it is assumed that the indicator is not sensitive.

The results show that for the case study Solallén and the regarded energy efficiency measures the investigated performance indicators are not very sensitive. Most likely the primary energy demand and CO_2 emissions are. The financing costs and the net present value are not sensitive, even if there is a shift of the values due to the regarded building envelope.

Similar to the results for the energy efficiency measures, Figure 30 shows the sensitivity analysis of the energy supply measures.

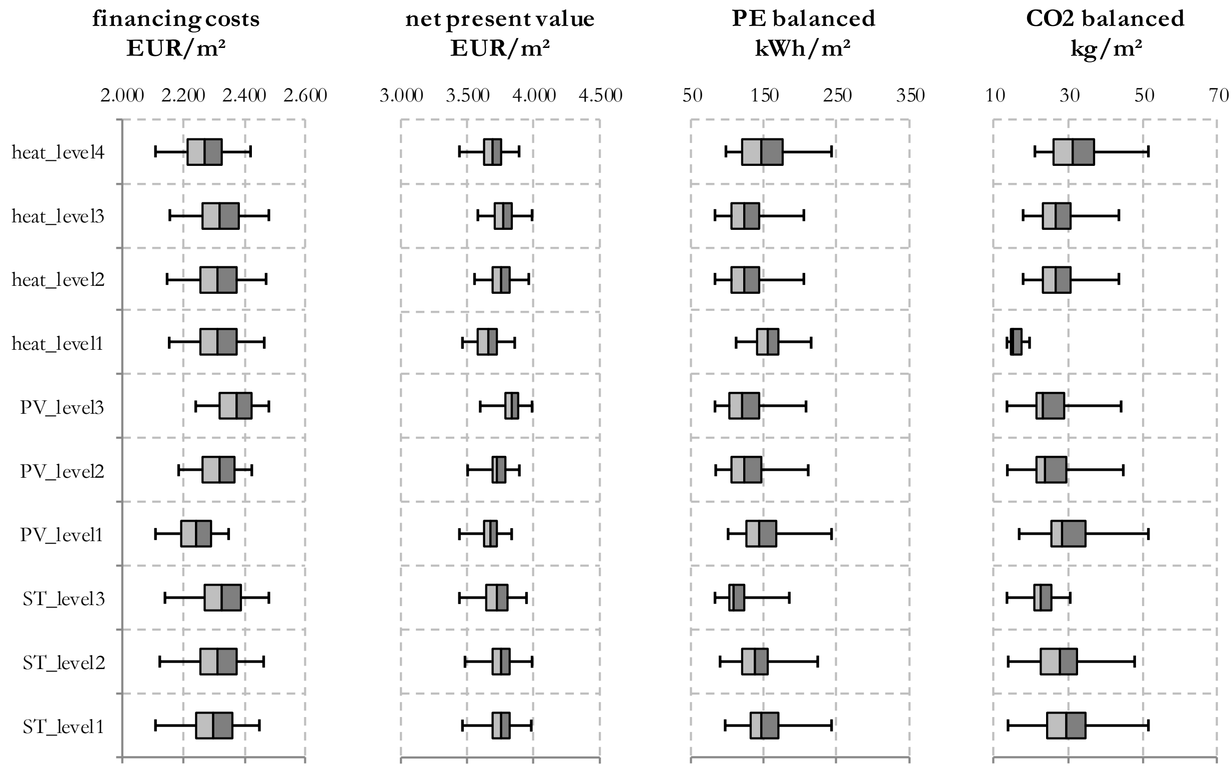


Figure 30: sensitivity of the financing costs, the net present value, the balanced primary energy (PE) demand and the balanced CO_2 emissions to the energy supply measures
Key: "heat"…heating system; "PV"…PV installation; "ST"…solar thermal installation

Table 14: Mean value and standard deviation of the investigated solar thermal systems

SOLAR THERMAL	FINANCING COSTS (EUR/M2)	NET PRESENT VALUE (EUR/M2)	PE BALANCED (KWH/M2A)	CO2 BALANCED (KG/M2A)
Level 1				
median	2.298	3.750	148	30
standard deviation	77	92	27	7
Level 2				
median	2.312	3.748	138	28
standard deviation	77	94	26	7
Level 3				
median	2.329	3.724	110	23
standard deviation	77	104	17	4

Table 15: mean value and standard deviation of the investigated PV systems

PV	FINANCING COSTS (EUR/M2)	NET PRESENT VALUE (EUR/M2)	PE BALANCED (KWH/M2A)	CO2 BALANCED (KG/M2A)
Level 1				
median	2.244	3.673	144	29
standard deviation	57	76	27	7
Level 2				
median	2.320	3.731	122	24
standard deviation	57	72	26	6
Level 3				
median	2.376	3.828	121	24
standard deviation	57	71	26	6

Table 16: Mean value and standard deviation of the investigated heating systems

HEATING	FINANCING COSTS (EUR/M2)	NET PRESENT VALUE (EUR/M2)	PE BALANCED (KWH/M2A)	CO2 BALANCED (KG/M2A)
Level 1				
median	2.314	3.654	156	15
standard deviation	76	99	21	2
Level 2				
median	2.311	3.748	123	27
standard deviation	77	85	25	5
Level 3				
median	2.320	3.773	123	27
standard deviation	77	85	25	5
Level 4				
median	2.269	3.689	147	32
standard deviation	76	97	34	7

A look at the results shows that, in contrast to the results for the energy efficiency measures, the selected indicators react very sensitive to energy supply technologies. For example, the balanced CO_2 emissions are very sensitive to the chosen heating system and also to the solar thermal system (but less to the PV system).

Sensitivity is also seen looking at the balanced primary energy, but not as clear as for balanced CO_2 emissions.

The influence of the PV system is most evident in the financing costs.

2.11. Robustness

The robustness of a building can be tested by assessing the design performance indicators for different user behaviours. The performance of a robust building will show less variation due to the difference in user types than a less robust building. Therefore, the deviation in the results of the calculated performance indicators can be used as a measure of robustness. In order to assess robustness, it is necessary to define the user behaviour, which can be characterised as follows in Table 17.

Table 17: Investigated user behaviour

USER BEHAVIOUR	efficient	standard	Not efficient
T_{room}	21 °C	22 °C	23 °C
DHW-demand (at 60°C)	29 l/d	33,3 l/d	48,5 l/d
Misuse of external blinds during winter time	0 %	+10 %	+20 %
Electrical Loads	20 kWh/(m²a)	26,6 kWh/(m²a)	35 kWh/(m²a)
Additional window ventilation during winter time	0,0 1/h	+0,05 1/h	+0,1 1/h

The results of the analysis are shown in Figure 31 and Table 18.

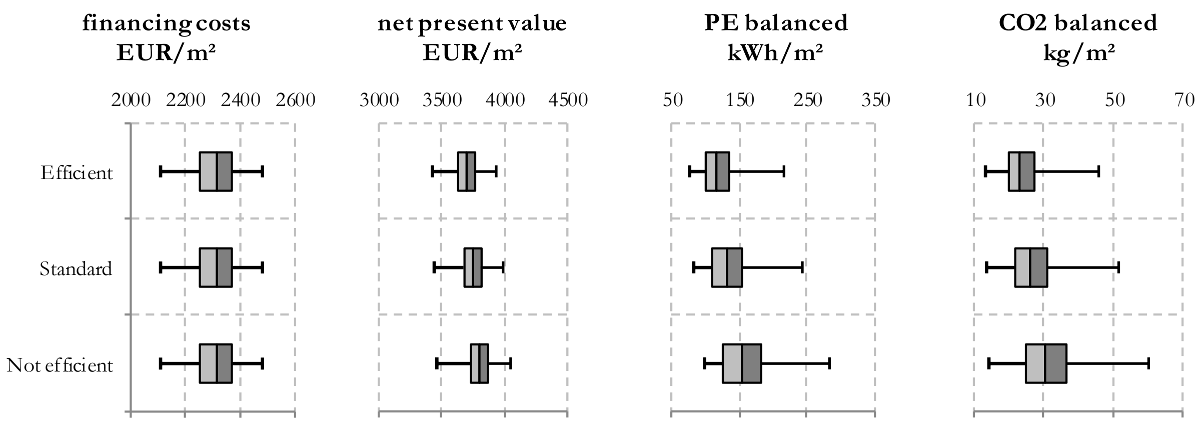


Figure 31: Testing the robustness of the building by analysing the sensitivity of the financing costs, the net present value, the balanced primary energy (PE) demand and the balanced CO_2 emissions to different user behaviour

Table 18: Mean value and standard deviation of the investigated user behaviour

USER BEHAVIOUR	FINANCING COSTS (€/M²)	NET PRESENT VALUE (€/M²)	PE BALANCED (KWH/M²A)	CO2 BALANCED (KG/M²A)
Not efficient				
median	2.344	3.958	154	30
standard deviation	187	260	35	9
Standard				
median	2.344	3.895	132	26
standard deviation	187	259	28	7
Efficient				
median	2.344	3.852	116	23
standard deviation	187	260	24	6

2.12. Findings and Results

Determining the best global solutions for nZEB design variables, in terms of energy, environmental and cost performance, is not an easy task, mainly because the variables affect each other through processes that are often not linear, and the optimisation goal of each variable can change significantly based on the optimisation goal and the importance of the key performance indicators (financing costs, net present value, primary energy demand, CO_2 emissions)

Among the main findings are the following:

- The range between the highest and lowest value is:
  - Financing costs: 20 % or 400 €/m²
  - Net present value: 15 % or 500 €/(m²a)
  - Balanced CO_2 emissions: 73 % or 38 kg/(m²a)
  - Balanced primary energy demand: 66 % or 160 kWh/(m²a)

- The influence of the parametric models on the balanced CO_2 emissions and balanced primary energy demand can be summarised as follows:
  ("+"…influence existing, "+/-"…partial influence, "-"…no influence):

Table 19: Findings of parametric model analysis

TECHNOLOGY	CO2 EMISSIONS	PRIMARY ENERGY
building envelope	+/-	+
windows, doors and airtightness	+	+
ventilation	-	-
heating	+	-
cooling	+	-
solar thermal	+/-	+
PV	-	-

- The sensitivity analysis shows:
  - For the regarded energy efficiency measures the investigated performance indicators are not very sensitive. Most likely the primary energy demand and CO_2 emissions are. The financing costs and the net present value are not sensitive, even if there is a shift of the values due to the regarded building envelope.
  - In contrast to the results for the energy efficiency measures, the selected indicators react very sensitive to energy supply technologies. For example, the balanced CO_2 emissions are very sensitive to the chosen heating system and also to the solar thermal system (but less to the PV system).

2.13. Interactive Dashboard/ Results Viewer

The results of the multi-objective building life-cycle cost and performance optimisation of the CRAVEzero case study Solallén is furthermore integrated into the "CRAVEzero pinboard" as an interactive dashboard (http://www.cravezero.eu/thepinboard/). The dashboard allows a further multi-perspective view into the analysis results, with visualisations that represent different findings and insights from the dataset described in this chapter.

Figure 32 shows a screenshot from the web-based interactive dashboard.

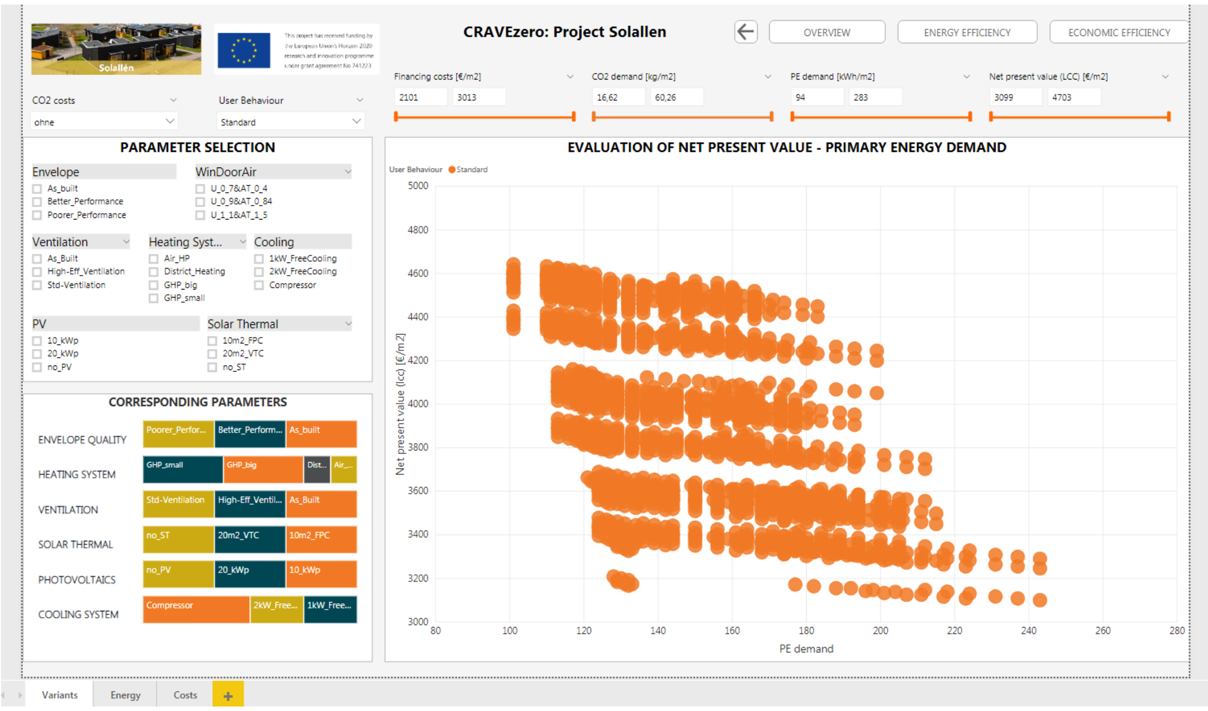


Figure 32: Web-based interactive dashboard of the derived results for the case study Solallén

How to use the interactive dashboard

The dashboard consists of three pages/ tabs as can be seen in Figure 32 where the "variant overview" page is displayed. The visualisations in the interactive dashboard represent a piece of information like for example the life-cycle costs or relating CO_2 emissions of selected variants. Within the dashboard, users can add and remove data, change visualisation types, and apply filters. The idea of this interactive dashboard is to allow users of the pinboard to dig into the data and discover insights and look for optimal solutions that can also be applied for their nZEB developments. The web-report is highly interactive and highly customizable, and the visualisations update as the underlying data changes. Buttons at the bottom of a report can be used to navigate between pages. Also reports can be viewed full-screen, and users can save/print a screenshot of the report using the print option.

Interaction with filters

Filters/slicers allow users of the dashboard to narrow the cost and energy-related data that is visualised on a page. Multiple filters, as shown in Figure 32 can be selected to narrow down the dataset. To remove a filter, users can deselect all filtered values. Example: All variations of the life-cycle cost and performance optimisation are initially shown for the building. Selecting, for example, a special heating system or filtering a life-cycle cost range in the visualisations shows only data for that heating system or life-cycle cost range in the visualisations.

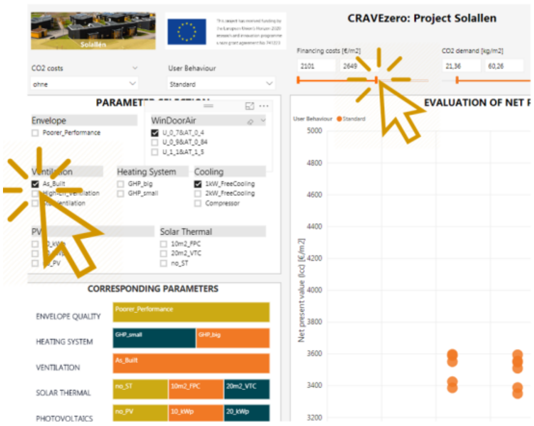


Figure 33: Filters and slicers

Cross-highlighting related visualizations

The visualisations on a single report are "connected" to each other. If one or more values are selected in one visualisation, other visualisations will change based on that selection.

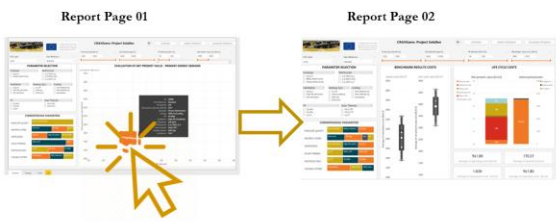


Figure 34: Cross highlighting of different visualisation pages

Hover effects of visuals

If the cursor is placed on a variant, users can find out more about a selected variant. The cursor needs to be placed over any visual element in the dashboard in order to view detailed data.

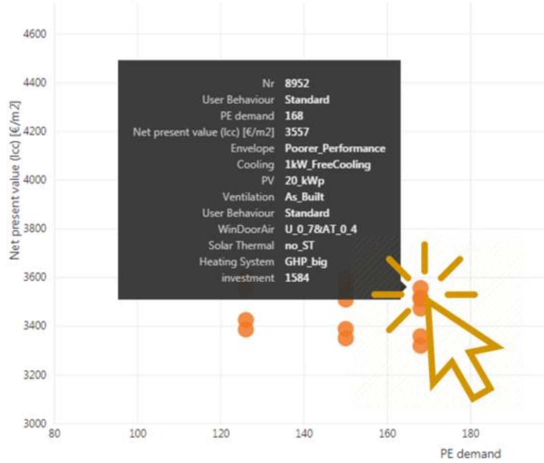


Figure 35: "Mouse over" effect of a selected visual element

Export dashboard data

Data can be exported out of the visual via the **Export data option**. The resulting .csv file will contain all the data presented in a visual and will respect any filters applied to the data.

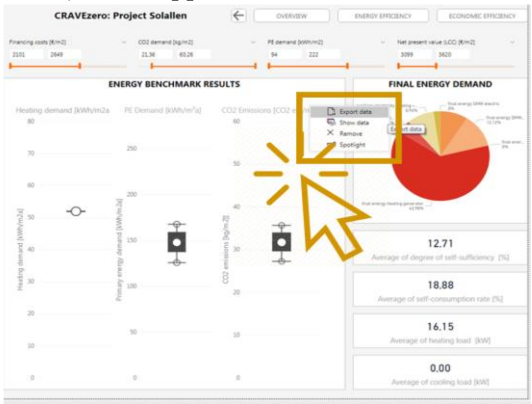


Figure 36: Data export option

3.LCC SENSITIVITY ANALYSIS

In recent years, the implementation of life-cycle cost (LCC) analysis is increased, since it is a helpful approach for assessing cost structures of building assets. Nevertheless, as stated in (Di Giuseppe et al., 2017) and (Wang et al., 2012), the LCC analysis presents a limitation due to the notable simplifications and assumptions usually made for the input parameters, the complex cost structure and the uncertainties in predicting future events that may affect the results. (Di Giuseppe et al., 2017) continues pointing out that a proper cost analysis requires on the one hand quality of input data, on the other hand, accurate long-term forecasts of these values over the analysed lifespan. The difficult access to this type of data leads to uncertainty in LCC methods, limiting their application.
Hence, a first step to tackle the uncertainty issue, which affects the LCC results collected within the framework of the task 2.2, is to perform a sensitivity analysis (SA).
SA measures the effect on the outputs, caused by input variation, due to uncertainty or risk. In the case of life-cycle costing, SA determines the outcome on LCC, by increasing and decreasing input parameters. In this way it is possible to define uncertainty-adjusted LCC ranges, allowing decision makers to concentrate on the analysis of the most critical parameters (Langdon, 2007).
SA can be performed in different ways. Before displaying the implemented methods, the set of input parameters and their variation range must be selected. On the one hand, when a fixed range, from technical literature, norms or from the data collection of the case studies, was available, such as in the case of interest rate or energy cost, this range was adopted. On the other hand, when a fixed range was not available, for example in the case of building features, the baseline value was arbitrarily varied of ±10 %.
SA was performed applying and testing two methods. The first one consists of a differential sensitivity analysis. This represents the simplest screening technique. In the second step, the elementary effects method was implemented.

3.1. Methodology

Differential sensitivity analysis

This method belongs to the class of the One Factor At a Time (OAT) screening techniques. In differential analyses, all parameters are set equal to their baseline value. Then, the impact on the LCC of one parameter at a time is investigated, keeping the other parameters fixed. Calculation of the sensitivity index is performed as follows:

$$s\,\% = \frac{\frac{\Delta \mathrm{O}}{\mathrm{O_{un}}}}{\frac{\Delta \mathrm{I}}{\mathrm{I_{un}}}}$$

Where:

- s%: Sensitivity index
- ΔO: Output variation
- O_{un}: Baseline value
- ΔI: Input variation
- I_{un}: Baseline value

Elementary effects method

An elementary effect is defined as a change of the output caused by a change in a single input parameter while keeping all other model parameters fixed. Therefore, as pointed out in Roberti et al. (2015), to obtain robust sensitivity measures, more elementary effects per parameter have to be computed, varying directions of change and base values. The paper continues illustrating that, since the total number of possible elementary effects associated with a single parameter grows exponentially with the number of parameters, usually only a reduced part of the possible elementary effects can be analysed. Therefore, to choose combinations carefully, the first step of this method is to generate the so-called Design of Experiment (DoE). The DoE is a series of factor value combinations, with the following properties:

- in each combination, every factor takes one out of four values obtained by dividing the respective range into three equidistant parts. A combination consists of 25 values, one for each factor;

- the first combination is selected randomly;
- each successive combination is then obtained from the previous one by varying exactly one value by a fixed increment or decrement, whereas the other values are kept fixed. Starting from the base value, always a parameter is changed by two-thirds of its range, thereby ensuring that each elementary effect was selected with equal probability (Morris, 1991).

This is done until the value of each factor has changed exactly once. This process leads to 26 combinations (the number of factors plus one), called a trajectory. By repeating this process, each time starting from a different (because chosen at random) combination, 10.000 trajectories are created. From these 10.000 trajectories, 10 trajectories are selected in the following way. 100 times 10 trajectories from the 10.000 available trajectories are selected. The 10 trajectories are those with the maximum sum of the distances between a pair of trajectories. In this way, a good exploration of the design space with only 260 simulations is ensured (CASTAGNA et al.).

An elementary effect associated with a factor *i* is given by:

$$EE_i^j = \left(y(c_{k+1}) - y(c_k)\right)$$

y is the outcome, the LCC in this specific case. c_k and c_{k+1} denote two consecutive combinations which differ only by the *i*-th factor value. The mean elementary effect associated with a factor *i* is then given by the average of the single elementary effect associated with that factor:

$$\mu_i = EE_i = \frac{1}{r}\sum_{j=1}^{r} EE_i^j$$

where *r* is the number of trajectories (equal to 10 in this DoE). The following two sensitivity indicators are used to display the results of the analysis:

$$\mu_i^* = EE_i = \frac{1}{r}\sum_{j=1}^{r} \left|EE_i^j\right|$$

$$\sigma_i^2 = \frac{1}{r-1} = \frac{1}{r}\sum_{j=1}^{r} \left(EE_i^j - \mu_i\right)^2$$

μ_i^* is the absolute mean of the single elementary effects associated with factor *i*. σ_i^2 is the variance of the elementary effects associated with factor *i*.

The elementary effects method was proven to be a very good compromise between accuracy and efficiency (Campolongo et al., 2007). With this method, SA can be carried out for different combinations of input values, analysing the effects of parameters interactions. The main limitation is that, while the impact of a given variable is investigated, the other parameters remain unchanged. Even if the interactions of the parameters cannot be investigated in a global perspective, this characteristic permits to determine which parameter causes the greatest effect.
Ultimately, this method is useful for identifying critical LCC assumptions, but it has limited effectiveness in providing a comprehensive sense of overall uncertainty since it is not possible to have probabilistic distributions of the input parameters.

3.2. Case Studies

Two case studies have been selected for the SA: Résidence Alizari located in Malaunay, France and Solallén located in Växjö, Sweden. These cases have been chosen because of the detailed cost data breakdown, in comparison to other case studies.

Résidence Alizari is a building consisting of 31 apartments, electricity generation via photovoltaic panels, heating system with a biomass boiler and improved thermal insulation. Solallén is a housing association, which consists of seven multi-family houses including 21 apartments in total. Improved insulation and airtightness, together with ground source heat pump, photovoltaic panels and balanced ventilation with heat recovery are the main characteristics.

The inspected input parameters of the case studies are on the one hand boundary conditions since typically uncertainty issues affect boundary conditions such as interest rate, energy cost and its inflation rate, maintenance cost (as a % of the construction cost) and operational cost data. On the other hand, building features are investigated. Table 20 shows, for the selected input parameters, the baseline value and the variation ranges.

Table 20: Input parameters – Résidence Alizari

PARAMETER	BASELINE	RANGE	PARAMETER	BASELINE	RANGE
Energy cost heating [€/kWh]	0,046	0,059-0,028	PV production [kWh]	29.201	32.121-26.281
Electricity cost cooling [€/kWh]	0,155	0,169-0,127	Windows insulation [€]	59.876	65.864-53.888
Energy cost DHW [€/kWh]	0,046	0,059-0,028	Flat roof insulation [€/m²]	43	47-39
Electricity cost household elt. [€/kWh]	0,155	0,169-0,127	External walls insulation [€/m²]	87	96-78
Electricity price PV production [€/kWh]	0,155	0,169-0,127	Windows [€]	94.024	103.426-84.622
Inflation energy cost [%]	1,0%	7,0 % - (-1,5 %)	Heating system [€]	177.845	195.629-160.060
Interest rate [%]	1,5 %	5,0 % - 0,25 %	Mechanical ventilation [€]	93.092	102.401-83.782
% Maintenance costs construction [%]	1,5 %	2,0 % - 1,0 %	Electric system [€]	150.791	165.870-135.712
% Maintenance costs HVAC [%]	-	±10,0 %	Hydraulic system [€]	91.322	100.454-82.190
Lifespan maintenance HVAC [years]	-	±10,0 %	Photovoltaic system [€]	83.000	91.300-74.700
Heating consumption [kWh]	35.459	39.005-31.913	Site and external work [€]	292.303	321.533-263.072
Cooling consumption [kWh]	5.420	5.961-4.878	Shading system [€]	41.757	45.933-37.581
DHW consumption [kWh]	94.842	104.326-85.358	Structural elements [€]	686.773	755.450-618.095
Household electricity consumption [kWh]	79.424	87.366-71.481			

Table 21: Input parameters – Solallén

PARAMETER	BASELINE	RANGE	PARAMETER	BASELINE	RANGE
Electricity cost Heating [€/kWh]	0,187	0,207-0,162	Household elt. consumption[kWh]	47.258	51.983-42.532
Electricity cost cooling [€/kWh]	0,187	0,207-0,162	PV production [kWh]	7.900	8.690-7.110
Electricity cost DHW [€/kWh]	0,187	0,207-0,162	Flat roof insulation_1 [€/m²]	22,3	25-20
Household elt. cost [€/kWh]	0,187	0,207-0,162	Flat roof insulation_2 [€/m²]	37,3	41-34
Electricity price PV production [€/kWh]	0,187	0,207-0,162	Floor next to ground insulation [€/m²]	31,9	35-29
Inflation energy cost [%]	1,6 %	6,0 %-(-5,0 %)	External insulation External walls [€/m²]	25,5	28-23
Interest rate [%]	1,5 %	5,0 %-0,25 %	Windows (A5) [€]	89.104	98.014-80.193
% Maintenance costs construction [%]	1,5 %	2,0 %-1,0 %	Heating system [€]	150.339	165.373-135.305
% Maintenance costs HVAC [%]	-	±10,0 %	Mechanical Ventilation [€]	53.120	58.431-47.808
Lifespan maintenance HVAC [years]	-	±10,0 %	Electric system [€]	57.960	63.756-52.164
Heating consumption [kWh]	32.688	35.956-29.419	Hydraulic system [€]	15.373	16.911-13.836
Cooling consumption [kWh]	785	863-706	Photovoltaic System [€]	90.125	99.138-81.113
DHW consumption [kWh]	11.138	12.251-10.024	Shading system [€]	10.710	11.781-9.639

Different sources have been used to define the input parameters. Some baseline values comes from the data provided by the project partners within the task 2.2 (e.g. energy and electricity costs and building features costs). For those not provided or not available in the data collection, such as interest rate and energy price variation, the sources are the following:

- Energy cost heating, DHW, Inflation energy cost:
  - Résidence Alizari - Pellets: http://developpement-durable.bsocom.fr
  - Solallén – Electricity: Prices of electricity for households in Sweden from 2008 to 2017 - www.statista.com
- Electricity cost (cooling and household), Inflation in electricity cost:
  - Résidence Alizari – Electricity: Prices of electricity for households in France from 2008 to 2017 - www.statista.com
  - Solallén – Electricity: Prices of electricity for households in Sweden from 2008 to 2017 - www.statista.com
- Interest rate: Federal Reserve Economic Data: https://fred.stlouisfed.org
- Maintenance costs as % of construction costs: 1,5 %
- HVAC maintenance costs as % of construction costs: EN 15459:2018

3.3. Results

3.3.1. DIFFERENTIAL SENSITIVITY ANALYSIS

Differential SA inspects one factor at a time, therefore, in this study, the input parameters have been divided into the two classes of factors, boundary conditions and building features. The objective is to highlight their role within the same class better. The results show that in the case of Résidence Alizari, the factor "% maintenance costs" within the boundary conditions and the factor "structural elements" within the building features are the input parameters which variation mainly affects the LCC (Figure 37 and Figure 38). Furthermore, Figure 37 reports how the electricity consumption for the household and the electricity cost occupy the third and the fourth position among the most relevant boundary conditions parameters.

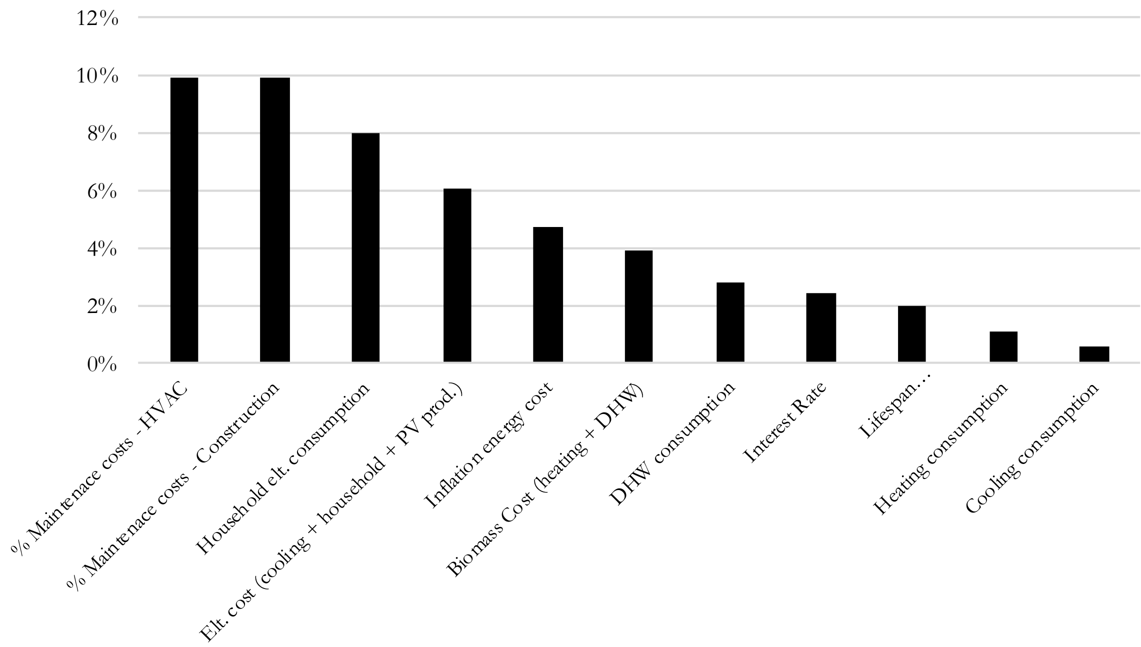


Figure 37: Sensitivity index (s %) of boundary conditions – Résidence Alizari.

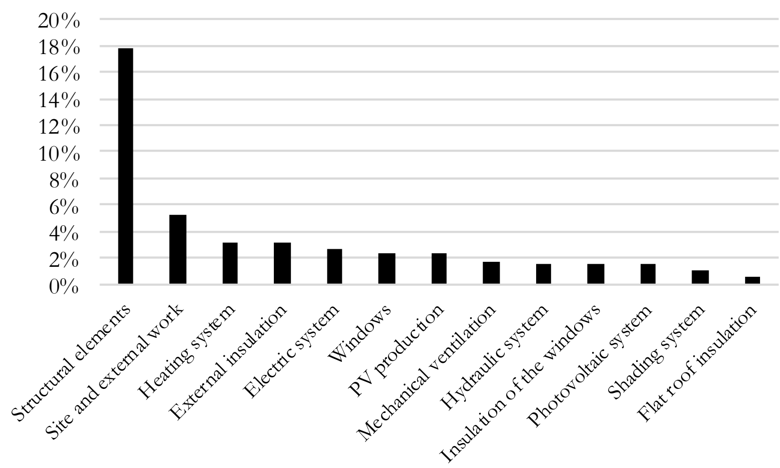


Figure 38: Sensitivity index (s %) of building features – Résidence Alizari.

The second case study, Solallén, show a similar result to the previous one. However, the electricity cost and the household electricity consumption present, in this case, a sensitivity index higher than the " % Maintenance costs". The reason lies in the type of energy supply system installed. In the Swedish case study, electricity is used for heating and DHW too, while in Résidence Alizari a biomass boiler is installed. This system configuration leads to a higher influence of the electricity parameter on the final LCC output.

Regarding building features, the heating system is the input parameter, which variation mainly affects the LCC (Figure 40). This result is related to the high construction cost, which was faced for the installation of a ground source heat pump combined with floor heating. Moreover, it is important to point out that the discrepancy between the two case studies in this class depends on the type of data collected in the LCC database. For example, in the case of Solallén, no detailed data breakdown about the structural elements was available.

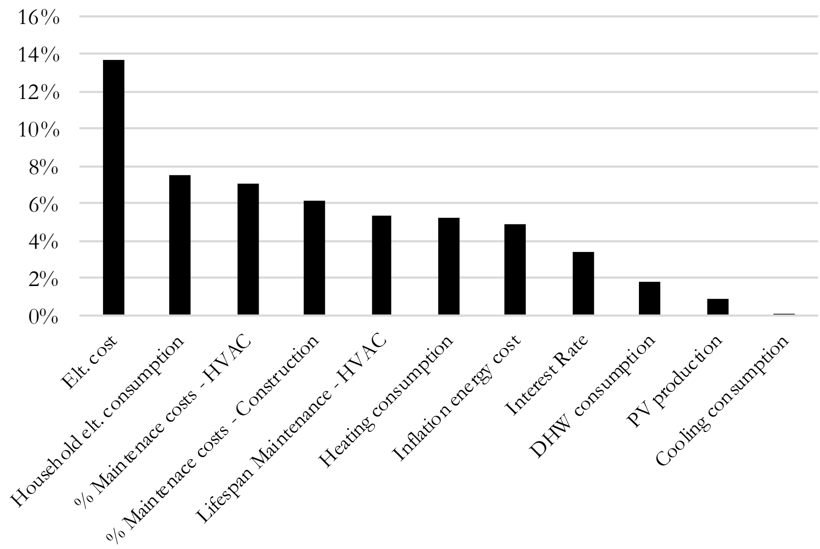


Figure 39: Sensitivity index (s %) boundary conditions – Solallén.

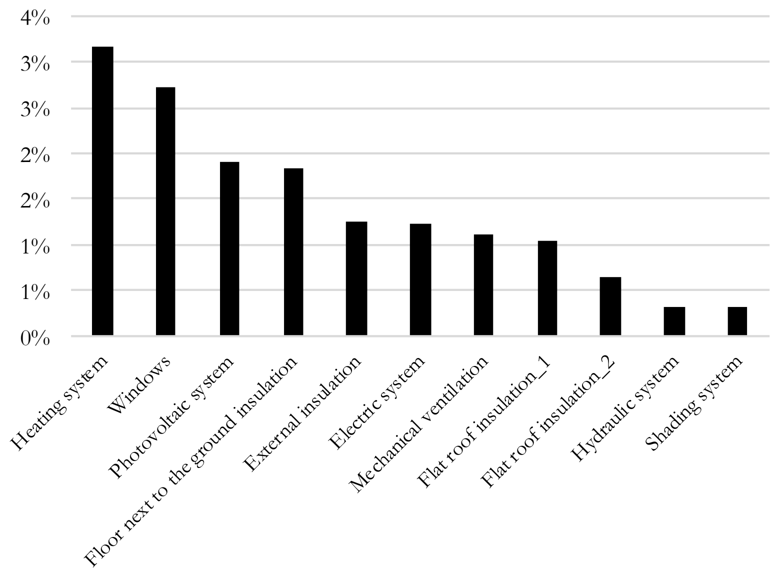


Figure 40: Sensitivity index (s %) building features – Solallén.

3.3.2.ELEMENTARY EFFECTS METHOD

The elementary effects method delivered an outcome with some analogies and some differences in comparison to the differential analysis. For both case studies, the results show that the input factors, which have by far the highest influence on the LCC output are inflation energy cost and interest rate (Figure 41 to Figure 44). These factors showed a medium sensitivity index in the differential SA. % maintenance cost, electricity cost and structural elements are still identified as relevant parameters.

It is possible to state that the inflation of energy cost does not have the highest impact when considered alone (differential SA); however, its stronger effect on the LCC output appears when combined with the variation of other parameters, in particular with the variation of electricity cost (parameter on which the inflation acts) and inflation rate.

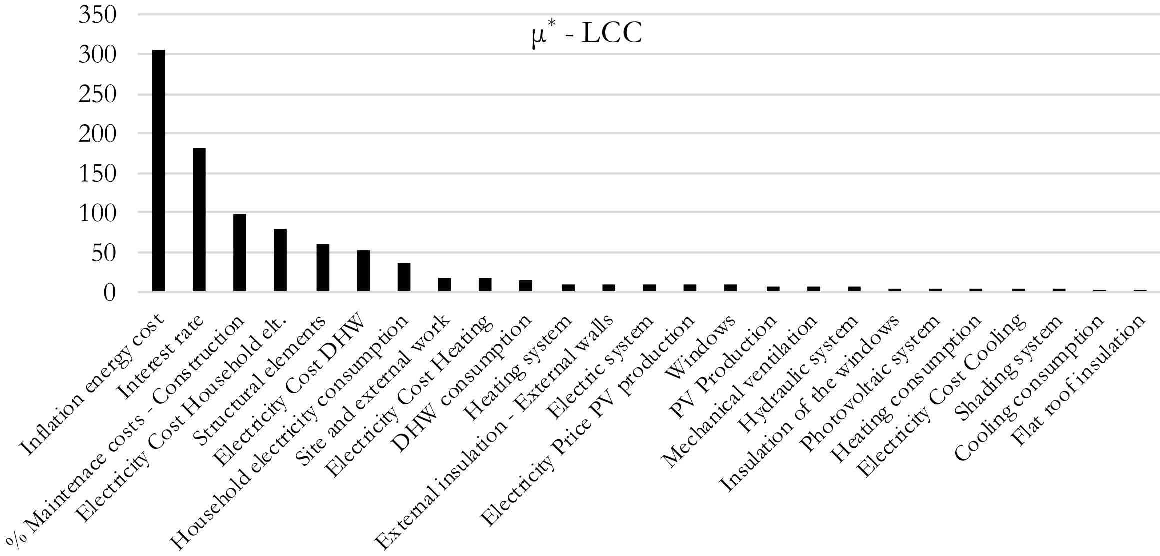


Figure 41: μ* for boundary conditions and building features – Résidence Alizari.

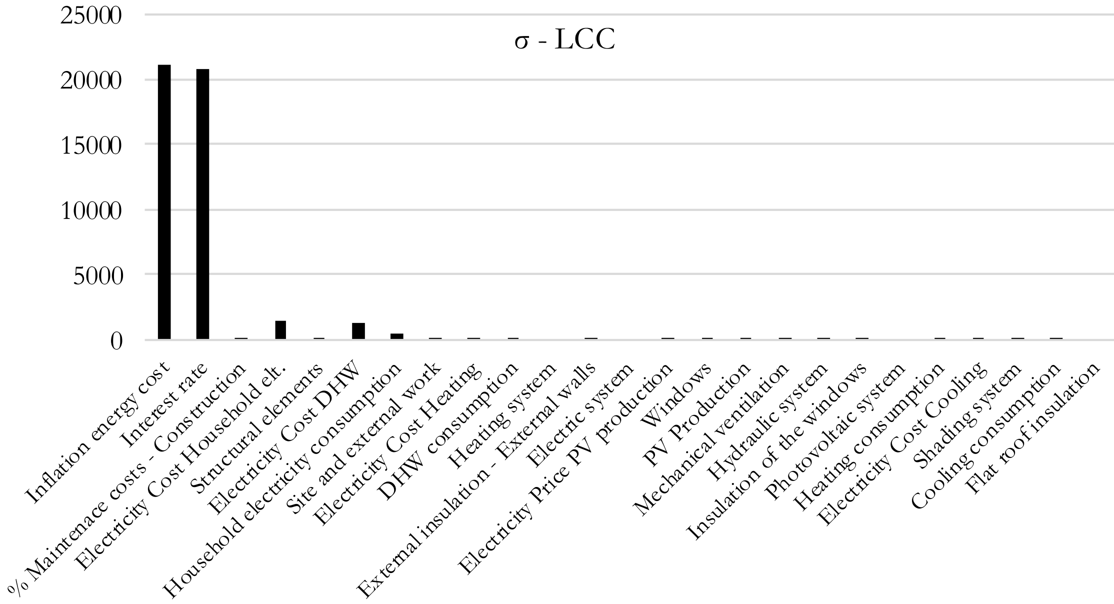


Figure 42: σ for boundary conditions and building features – Résidence Alizari.

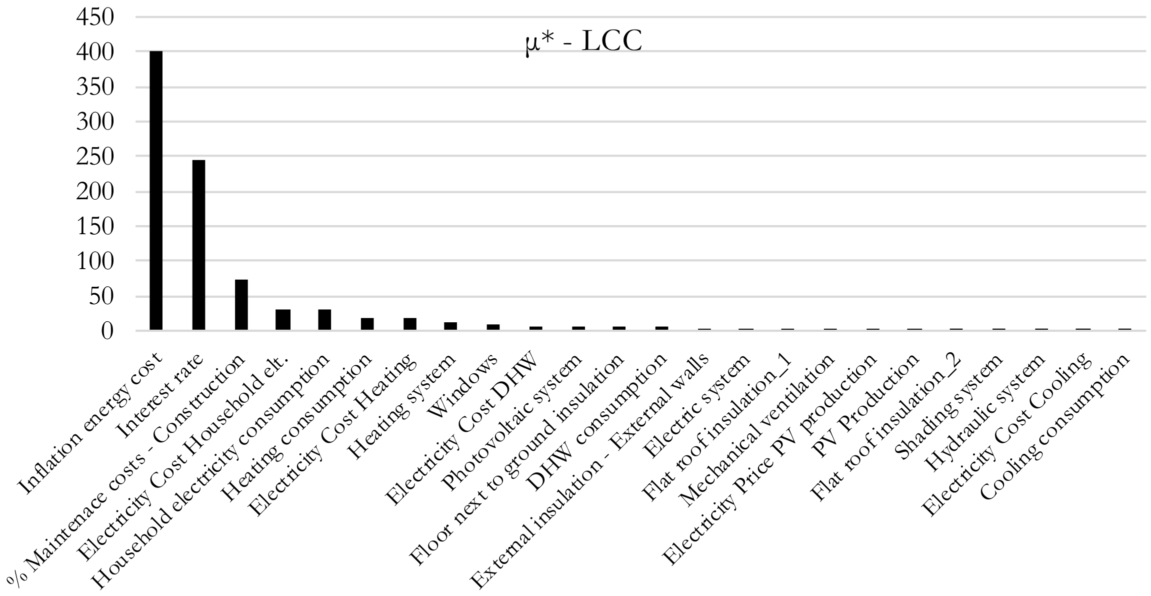


Figure 43: μ* for boundary conditions and building features – Solallén.

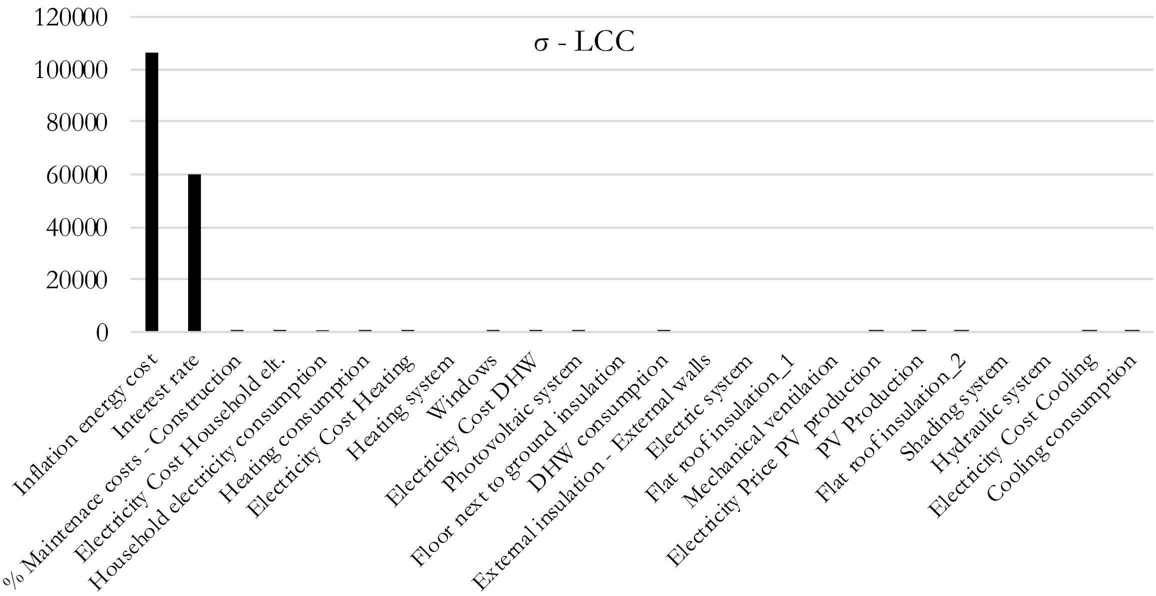


Figure 44: σ for boundary conditions and building features – Solallén.

To verify the correctness of the results obtained with the implemented DoE (see paragraph 3.1), in particular with the selected number of trajectories, another set of simulations was performed, with 20 and 40 trajectories respectively. The objective was to check whether the simulation reached the convergence. Figure *45* and Figure 46 display the results, showing a comparable outcome and confirming the initial design, which leads to reliable results, reducing the calculation effort considerably.

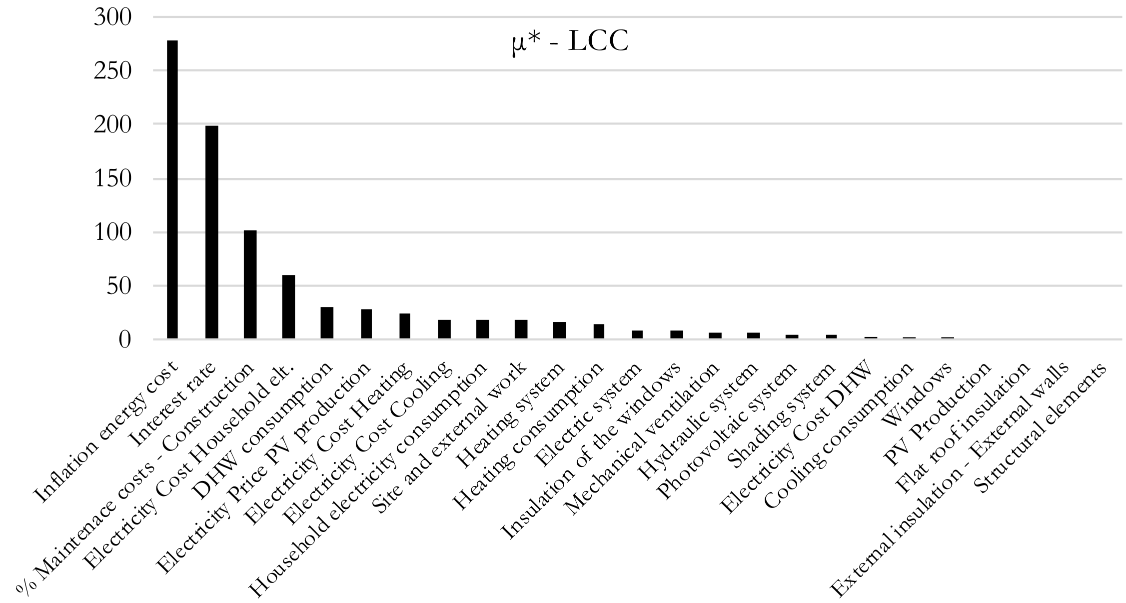


Figure 45: 20 trajectories – Résidence Alizari.

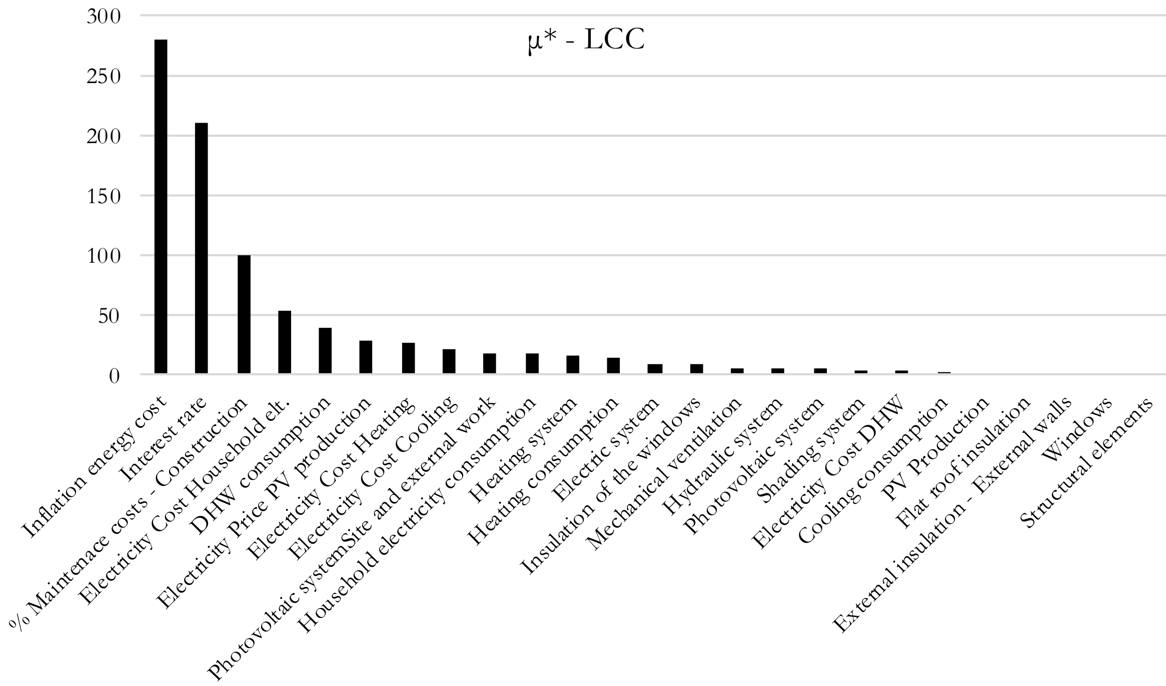


Figure 46: 40 trajectories – Résidence Alizari.

A further relevant outcome of the SA is the determination of the possible range in which the LCC calculation can vary, due to uncertainty and risk. This result allows decision-makers to have a reliable insight into the expected LCC. In Figure 47 and Figure 49 LCC values for every single simulation (40 trajectories, 1.000 simulations) have been plotted.

In the case of Résidence Alizari, the average LCC value is 2.740 €/m², with a range varying from 2.358 to 3.543 €/m². In the case of Solallén, the average LCC value is 2.705 €/m², with a range varying from 2.300 to 4.034 €/m². However, it is important to notice that 70 % of the values range within a smaller interval of 500 €/m² in particular between 2.537 and 2.965 €/m² for Résidence Alizari and 2.447 and 2.957 €/m² for Solallén.

Regarding the LCC values vs the energy costs (Figure 48 and Figure 50), R squared value (R^2) index confirms the strong correlation between the LCC value and the energy cost in both cases again.

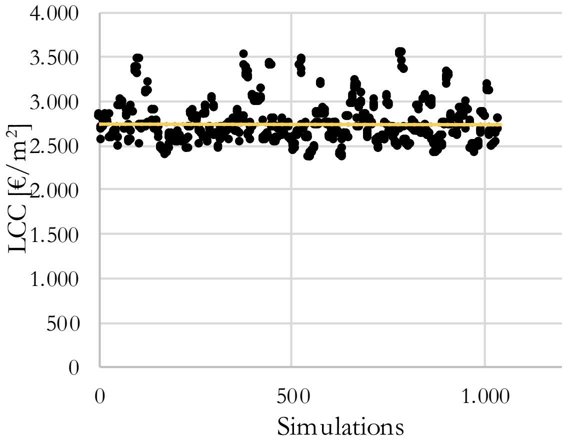


Figure 47: LCC vs simulations - Résidence Alizari.

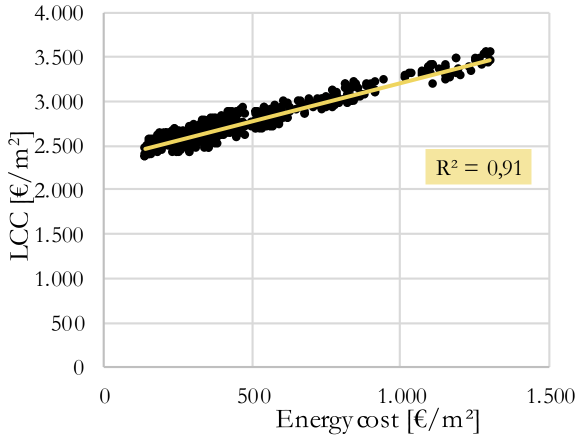


Figure 48: LCC vs Energy cost - Résidence Alizari.

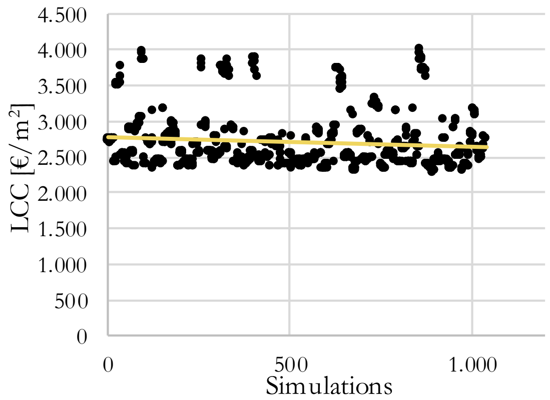


Figure 49: LCC vs simulations – Solallén.

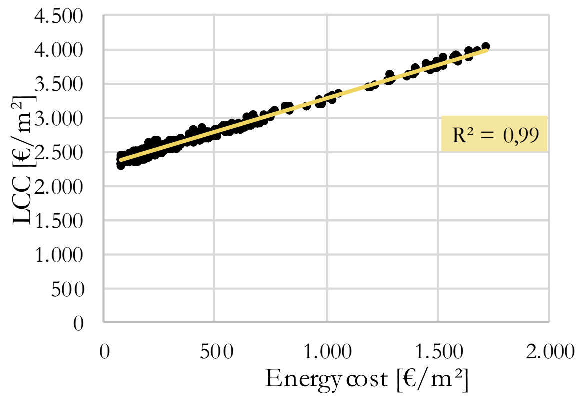


Figure 50: LCC vs Energy cost – Solallén.

Finally, the following charts display the LCC output for every single simulation for the first three most relevant factors (inflation energy cost, interest rate and % maintenance cost) where on the x-axis are plotted the four values obtained dividing the respective range into three equidistant parts were plotted. In both case studies, the eight highest simulations are those in which the parameter inflation energy cost assumes the highest value (5 % for Résidence Alizari and 6 % for Solallén) and the interest rate has the lowest value (0,25 % in both cases). In the same way, the eight lowest simulations are those which inflation energy cost has the lowest value (-0,15 % for Résidence Alizari and -5 % for Solallén) and the interest rate has the highest value (5 % in both cases).

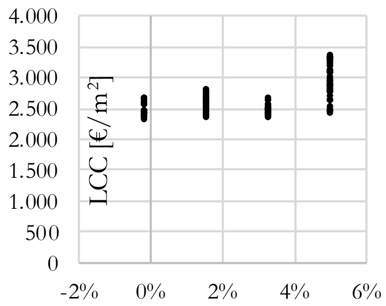


Figure 51: LCC vs. Inflation energy cost – Résidence Alizari.

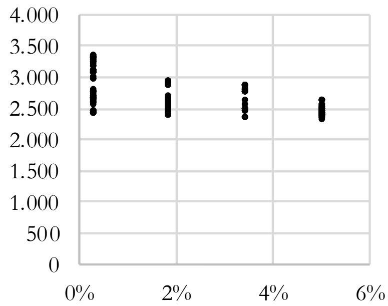


Figure 52: LCC vs. Interest rate – Résidence Alizari.

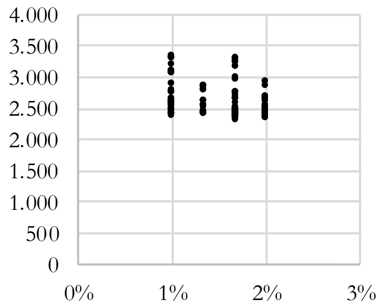


Figure 53: LCC vs. % Maintenance cost – Résidence Alizari.

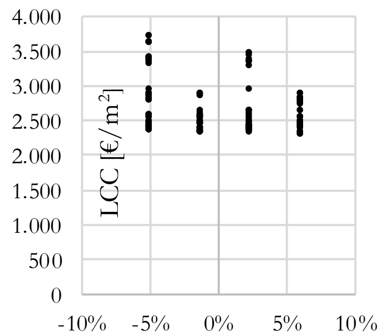


Figure 54: LCC vs. Inflation energy cost – Solallén.

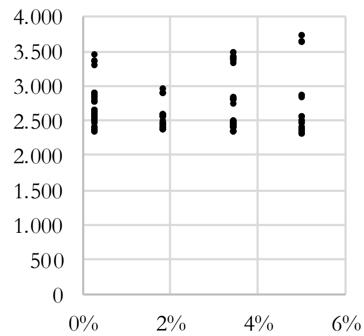


Figure 55: LCC vs. Interest rate – Solallén.

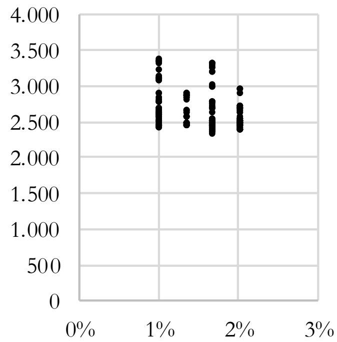


Figure 56: LCC vs. % Maintenance cost – Solallén.

3.4. Findings and Results

Drawing the conclusions about the SA conducted on boundary conditions and building features, the two methods can be considered complementary. The differential sensitivity analysis is the simplest one but allows inspecting the effect on the output of single factors. The elementary effects method instead, gives an overview of the interactions among parameters and their influence on the output.

These methods, from the point of view of the input parameters, are considered "deterministic approaches" since no probabilistic distributions are used for the inputs. Another class of approaches to SA are statistical (or probabilistic) methods, often implemented using Monte Carlo techniques (Wang et al., 2012). Probabilistic LCC analysis in building sector would provide a more realistic decision support about investments for energy efficient projects (Di Giuseppe et al., 2017), giving a better assessment of uncertainty and risk during the life-cycle of buildings.

As stated in (Mara and Tarantola, 2008) and (Nguyen and Reiter, 2015) the Monte Carlo-based SA consists of five major steps:

- Select the model to perform SA.
- Identify the set of input parameters and the probability distribution functions associated with them.
- Generate a sample of N input vectors for the model using a probability sampling method.
- Run the simulation model N times on the input sample to produce N corresponding outputs.
- Calculation of sensitivity indices.

The implementation of the Monte Carlo method is not object of this deliverable, but will be tackled in the next one: "D6.2 - Results of optimised nZEB parametric models".

4. LESSONS LEARNED - COMPARATIVE ANALYSIS OF THE HEATING ENERGY COSTS OF VARIOUS RESIDENTIAL BUILDINGS

As a regional housing company in Germany, CRAVEzero project partner Köhler & Meinzer has the advantage of mapping and controlling the entire process of project realisation of nZEBs in-house. This includes all planning and execution stages, beginning with the development planning and district development, over the architectural building planning, the control of the used house-technical energy concept, the construction management of the objects up to their marketing. Meanwhile, Köhler & Meinzer also act as property managers for the communities of more than 400 apartments that have been realised. From this administrative activity, they have a comprehensive database of operating and maintenance costs of the objects that have been built. In this chapter, Köhler & Meinzer drafted a comparative analysis of the energy consumption and operational costs of various residential buildings based on the CRAVEzero case study "Brussels". This chapter is an addition to the previous chapters that deal with parametric life-cycle models of nZEBs from a more theoretical, methodical point of view. In the following Köhler & Meinzer summarise their findings and their monitoring results of over 20 years' experience of nZEB planning, construction and operation.

4.1. Introduction

Beginning with the year 2008, the German multi-family dwellings analysed below were built according to Germanys Energy Saving Ordinance (EnEV[2]) in various insulation standards with different energy concepts.
It is needed to compare the consumption values calculated in theoretical building simulations with the values measured in reality. The cost-intensive improvement measures of the thermal building envelope and the building services technology could thus be checked for their effectiveness.

In a comprehensive questionnaire, a large number of building parameters were recorded. The following considerations, is focussed on the heating energy consumption of the individual apartments. The data was available as annual billing data from an external metering company for the building itself, as well as for each apartment.

Even if the focus is on the heating energy consumption of the apartments, further findings and correlations gained from the data analysis should also be included in the study.

[2] The EnEV defines the basic level of efficiency and is regularly updated on the basis of EU legislation. In Germany, the German Energy Saving Ordinance (EnEV) sets out specifications, which are used to calculate the transmission heat loss and the annual primary energy demand of a so-called reference building for each construction or renovation project.
A KfW-Efficiency House designates a KfW development bank (KfW) new construction and refurbishment standard. If a client decides to implement this KfW standard in his new building, he can receive certain promotional measures from KfW. The Federal Government is promoting the energy-efficient refurbishment and energy-efficient new construction of the KfW-Efficiency House through the KfW Development Bank. Supported by low-interest loans and grants.
A KfW -Efficiency House 100 must therefore consume at most as much primary energy as the reference building. In addition, the transmission heat loss must not exceed 115 %. The smaller the number the more energy efficient the house is. The least energy requirement is the efficiency house 40, whose primary energy requirement is only 40 % of the reference house. However, KfW bases its calculations on the outdated EnEV standard 2009 instead of the more recent EnEV 2014 (with changes in 2016).

4.2. Case Studies

4.2.1. ANALYSIS PROJECT „BRÜSSEL“, ENEV 2004, KFW-EFFICIENCY HOUSE 60

In the years 2008 - 2012, seven identical multi-family houses were built in the Brussels Ring in Eggenstein-Leopoldshafen with approx. 1.000 m² of living space, each with ten residential units (Figure 57). Six of the houses were built in pairs with a shared underground car park so that each two apartment buildings form a condominium community and thus a billing unit. The seventh building stands individually.

Figure 57: Pictures of Brüsseler Ring (left, middle), right visualisation

The buildings have different apartment sizes, ranging from one-bedroom apartments to five-room apartments (Figure 58). The energy concept and insulation standard of the thermal envelope were designed on the basis of the provisions of the 2004 EnEV KfW-Efficiency House 60. KfW-Efficiency House 60 means that the heating energy requirement of the building may not exceed 60 % of the maximum permitted by the currently applicable EnEV.

Figure 58: Brüsseler Ring – floor variants that can be implemented in this type of building

Table 22 showing the individual parameters of the buildings which were derived from planning documents and the bills of the property management. The focus of the evaluation was on the heating energy demand of the apartments.

Table 22: Brüsseler Ring 93+95 – cost and energy-related data

BRÜSSELER RING 93 + 95

Type of building	Multi-family House	
Net floor area (heated floor area)	2012,50 m²	
Year of construction	2010	
EnEV-standard	EnEV 2007/2009?	
Orientation	east-west	
Roof type	hipped roof	
Relation surface window / outer wall	26,85 %	
Relation heated NFA / volume	28,19 %	
Quality of wall + insulation	U=0,2 W/(m²K)	
Quality of window	U_w=1,1-1,7 W/(m²K)	double glazing
	g=0,55-1,0	
Quality of roof	U=0,22 W/(m²K)	
Thermal bridges	not considered	
Air-tightness	not considered	
Heating system	gas condensing boiler	
Ventilation	no	
Total energy consumption	137.777 kWh/a	
Total energy consumption	68,46 kWh/(m^2_{NFA}a)	
Total heating consumption	71974,70kWh/a	
Total heating consumption	35,76 kWh/(m^2_{NFA}a)	
Total heat consumption; level of efficiency	100.750 kWh/a	73,13 %
Total energy costs	9.544,86 €/a	0,0693 €/kWh
Total energy costs	4,74 €/(m^2_{NFA}a)	
% hot water	47,76 %	
% heating	52,24 %	
Number of residents		
Total additional charges	56.880,00 €	56.229,94 €
Relation total heating costs / total additional charges	8,66 %	

This heating energy requirement from the year 2017 of each of the total of 70 apartments is plotted in Table 23 ,depending on the size of the apartment and the situation in the building (storey). For each type of apartment on each floor, the average consumption and the maximum and minimum consumption were entered. Furthermore, the spread as well as the number of the apartment type recorded on the corresponding floor.

Table 23: Brüsseler ring 93+95 –heating consumption was compared depending on the floor and the number of rooms per apartment (in kWh/(m²a) and €/(m²a))

HEATING BRÜSSELER RING 89 + 91 ; 93 + 95 ; 103A + B ; 113

		1 ZW		**2 ZW**		**3 ZW**		**3 ZW PH**		**4 ZW**		**4 ZW**		**4 ZW PH**		**5 ZW**	
		38,80 m²		67,00 m²		82,20 m²		102,00 m²		109,60 m²		125,10 m²		128,00 m²		133,60 m²	
		kWh/ (m²a)	€/ (m²a)	kWh/ (m²a)	€/ (m²a)	kWh/ (m²a)	€/ (m²a)	kWh/ (m²a)	€/ (m²a)	kWh/ (m²a)	€/ (m²a)	kWh/ (m²a)	€/ (m²a)	kWh/ (m²a)	€/ (m²a)	kWh/ (m²a)	€/(m²a)
1st floor	**average**	**14,52**	1,01	**38,86**	2,74	**42,63**	2,99	-	-	**47,31**	3,10	**25,41**	1,75	-	-	**39,30**	2,70
	min	14,52	1,01	31,60	2,40	28,21	2,15	-	-	19,80	1,36	23,57	1,61	-	-	38,37	2,66
	max	14,52	1,01	47,80	3,27	55,61	3,81	-	-	73,03	5,00	27,25	1,89	-	-	40,38	2,76
	range	-	-	151,24 %	136,25 %	197,13 %	177,21 %	-	-	368,84 %	367,65 %	115,61 %	117,39 %	-	-	105,24 %	103,76 %
	number	1	1	3	3	3	3	-	-	6	6	2	2	-	-	3	3
2nd/3rd floor	**average**	**11,63**	0,80	**26,75**	1,85	**31,26**	2,19	-	-	**32,92**	2,27	**30,55**	2,12	-	-	**40,17**	2,89
	min	11,63	0,80	13,47	0,92	17,47	1,20	-	-	16,09	1,11	22,36	1,70	-	-	32,01	2,19
	max	11,63	0,80	50,26	3,44	52,62	4,00	-	-	60,28	4,18	41,63	2,85	-	-	67,73	5,15
	range	-	-	373,13 %	373,91 %	301,20 %	333,33 %	-	-	374,64 %	376,58 %	186,18 %	167,65 %	-	-	211,59 %	235,16 %
	number	1	1	9	9	9	9	-	-	11	11	4	4	-	-	4	4
4th floor	**average**	-	-	-	-	-	-	**38,19**	2,66	-	-	-	-	**49,81**	3,46	-	-
	min	-	-	-	-	-	-	22,13	1,53	-	-	-	-	29,50	2,04	-	-
	max	-	-	-	-	-	-	56,22	3,85	-	-	-	-	65,60	4,48	-	-
	range	-	-	-	-	-	-	254,04 %	251,63 %	-	-	-	-	222,37 %	219,61 %	-	-
	number	-	-	-	-	-	-	7	7	-	-	-	-	7	7	-	-

FINDINGS:

- Almost every apartment on each floor was able to operate in a low energy standard, or even in the passive house standard, despite the fact that buildings based on the EnEV 2004 do not nearly meet the requirements of the current Passive House standard.
- The decisive factor for the heating energy consumption of the individual dwelling is user behaviour. Based on the calculation according to the current German heating cost ordinance, spreads of the costs up to 300-400 % were detected. 30 % of the total heating energy consumption of the whole building was allocated to the living space of each apartment, the remaining 70 % of the measured consumption of heat meters were allocated to the rest of the apartments. Considering the heating demands of all apartments a maximum spread over 700 % were detected (Figure 59).
- Despite the large divergence of individual dwellings between each other, both the average value of each ten-family dwelling and the average value of all seventy dwellings examined are very close to the originally calculated value of 37 kWh/(m²a).

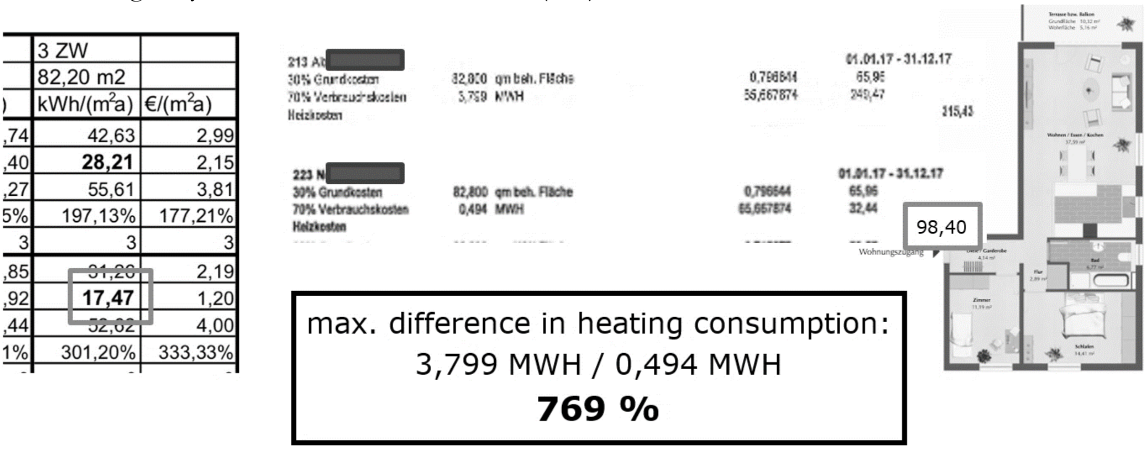
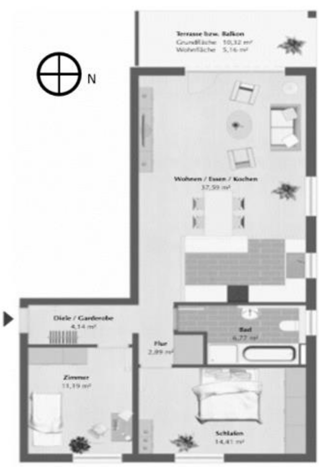


Figure 59: Maximum deviation found in the consumption comparison

Relevance of heating costs for the user



One goal of the research project CRAVEzero, is to increase the market penetration for nearly zero energy buildings (nZEBs). To increase the acceptance of the individual user, the heating costs gets special attention. In the following utility bill (
Table 24) of a north-facing, three-room apartment on the first floor of the Brussels project (Figure 60), heating costs are compared with the other ancillary costs. As a result, the share of heating costs was only 5 % of the total costs of the apartment. Looking at the total cost of living and assuming a rent of 10,00 €/m² living space, the heating costs had a share of only 0,8 %. For a user, the heating cost does not provide an incentive to put a focus on his considerations. However, the motivation of a user due to its high behavioural influence on the energy consumption is of decisive importance for the success of the energy turnaround.

Figure 60: The three-room apartment analysed in the following bill

Table 24: Typical calculation of the maintenance costs and listing of the total rental costs in relation to the heating costs on the example of an 82,2 m² large apartment

Individual billing resident N.

Accounting period	01.01.2017 until 31.12.2017		365 days			
Your accounting period	01.01.2017 until 31.12.2017	allocation formula	365 days		amounts	
Accounting position	distributed after	total	share	unit	total [€]	share
Costs						
Certain costs not to allocate to possible tenants						
Caretaker fees	accommodation unit	20,00	1,00	AU	5.040,00 €	252,00 €
Additional costs money transfer	co-ownership share	1.000,00	41,00	COS	171,10 €	7,02 €
Repair	co-ownership share	1.000,00	41,00	COS	867,99 €	35,59 €
Rent for the room for the OM	co-ownership share	1.000,00	41,00	COS	50,00 €	2,05 €
Subtotal, not allocatable costs					6.129,09 €	296,66 €
Certain costs to allocate to resident N. (01.01.2017 until 31.12.2017)						
Building service/care	accommodation unit	20,00	1,00	AU	7.147,98 €	357,40 €
Total heating consumption	external heating costs	20.699,97	577,64	€	20.699,97 €	
Heating costs	m2 heated floor area	1.000,00	82,20	m2	**98,40 €**	**65,96 €**
	MWH		0,49	MWH		**32,44 €**
DHW costs	m2 DHW area	1.000,00	82,20	m2		59,27 €
	m3 DHW		9,20	m3		76,60 €
Additional charges heating and hot water			343,37	€		343,37 €
General power	co-ownership share	1.000,00	41,00	COS	1.216,18 €	73,71 €
Cable fees	accommodation unit	20,00	1,00	AU	2.446,44 €	122,32 €
Waste disposal	co-ownership share	1.000,00	41,00	COS	1.949,60 €	79,93 €
Elevator costs	accommodation unit	20,00	1,00	AU	5.175,87 €	**258,79 €**
Insurance costs	co-ownership share	1.000,00	41,00	COS	3.480,12 €	142,69 €
Maintenance	co-ownership share	1.000,00	41,00	COS	530,10 €	21,74 €
Subtotal allocatable cost					42.646,26 €	1.634,22 €
Total Operating Costs					**48.775,35 €**	**1.930,88 €**

Relation heating costs / operating costs:		**98,40 € / 1.930,88 €**	5,1 %
Operating costs		1.930,88 €	
Costs of the appartment rental	82,2 m^2 x 10,00 €/m^2 x 12	9.864,00 €	
Total annual costs		11.794,88 €	
Relation heating costs / total annual costs:		**98,40 € / 11.794,88 €**	0,8 %

Relevance of heating energy consumption compared to the total energy consumption of nZEBs:

Adding to the total heat consumption of a building nor the power consumption of the users, the sum of actually measured in the apartments heating energy consumption (without plant and line losses) in the apartments were just 26 % of the total energy demand (Figure 61). As a consequence, instead of focusing on the heating energy requirements of the legislator, the energy consumptions of water heating, system and line losses as well as electricity consumption must become more important in the considerations of energy efficiency.

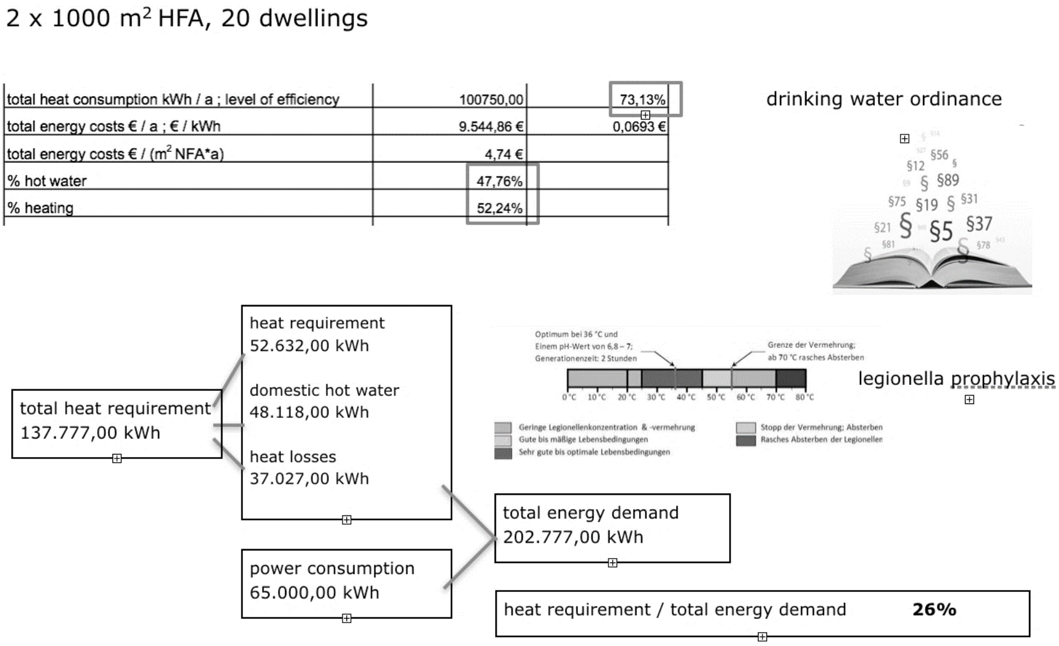


Figure 61: K&M example calculation for the case studies for the heating requirements in relation to the total energy demand. The drinking water ordinance is mentioned as it prescribes regular temperature increases in the circulation circuit to 60 ° Celsius for legionella prophylaxis

4.2.2.ANALYSIS PROJECT „BERLIN“, ENEV 2009, STANDARD

Due to tightened legislation of the minimum requirements of the at the time valid EnEV 2009, it was no longer possible to achieve them only by improving the insulation standard of the buildings. The previous energy concept of the buildings at Brussels Ring in Eggenstein-Leopoldshafen, including a gas condensing boiler and a solar thermal system, was extended with a decentralised ventilation system with heat recovery for each apartment for the multi-family houses at Berliner Allee 36 and 38 in Stutensee (Figure 62).

Figure 62: Pictures of case study: left Berliner Allee 38 and right visualisation of Berliner Allee 36

In Table 25 the heating energy consumption of these two buildings was analysed comprehensively. Despite the installation of these decentralised ventilation units with heat recovery, there were no significant differences between the individual values and the average consumption of the buildings in the Brussels Ring in Eggenstein-Leopoldshafen.

Table 25: Berliner Allee 36 and 38 –heating consumption was compared depending on the floor and the number of rooms per apartment (in kWh/(m²a) and €/(m²a))

HEATING BERLINER ALLEE 36; BERLINER ALLEE 38

		1 ZW		2 ZW		3 ZW		3 ZW PH		4 ZW		4 ZW PH		5 ZW	
		kWh/ (m²a)	€/ (m²a)	kWh/ (m²a)	€/ (m²a)	kWh/ (m²a)	€/ (m²a)	kWh/ (m²a)	€/ (m²a)	kWh/ (m²a)	€/ (m²a)	kWh/ (m²a)	€/ (m²a)	kWh/ (m²a)	€/ (m²a)
1st floor	average	-	-	45,70	3,21	57,74	4,19	-	-	55,15	4,10	-	-	62,66	4,40
	min	-	-	45,70	3,21	51,44	3,62	-	-	55,15	4,10	-	-	62,66	4,40
	max	-	-	45,70	3,21	64,03	4,76	-	-	55,15	4,10	-	-	62,66	4,40
	range	-	-	-	-	124,48 %	131,58 %	-	-	-	-	-	-	-	-
	number	-	-	1	1	2	2	-	-	1	1	-	-	1	1
2nd/3rd floor	average	-	-	22,44	1,58	37,14	2,76	-	-	38,95	2,78	-	-	-	-
	min	-	-	16,53	1,16	25,11	1,82	-	-	19,81	1,47	-	-	-	-
	max	-	-	28,35	1,99	49,73	3,70	-	-	60,43	4,25	-	-	-	-
	range	-	-	171,49 %	171,49 %	198,00 %	202,50 %	-	-	304,97 %	288,52 %	-	-	-	-
	number	-	-	2	2	2	2	-	-	6	6	-	-	-	-
4th floor (PH)	average	-	-	61,58	4,58	-	-	53,64	3,85	-	-	97,00	6,82	-	-
	min	-	-	61,58	4,58	-	-	39,09	2,91	-	-	97,00	6,82	-	-
	max	-	-	61,58	4,58	-	-	68,18	4,79	-	-	97,00	6,82	-	-
	range	-	-	-	-	-	-	174,39 %	164,98 %	-	-	-	-	-	-
	number	-	-	1	1	-	-	2	2	-	-	1	1	-	-

In Figure 63, the installation of the used ventilation devices is shown combined with an economic consideration for the buildings.

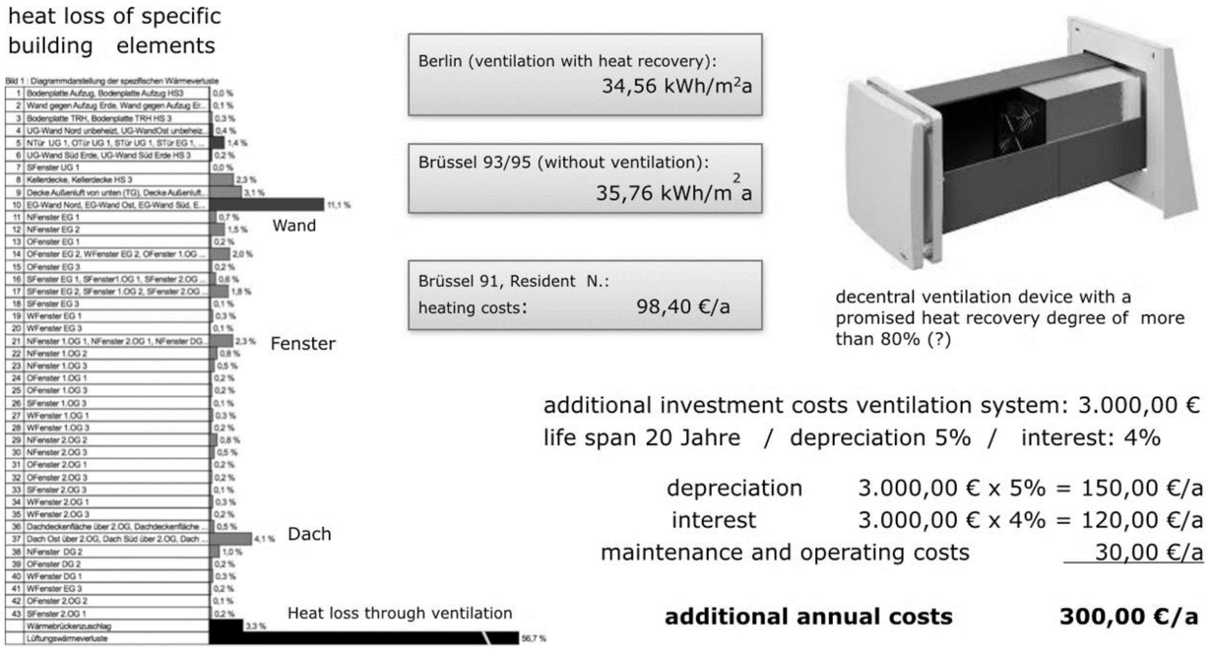


Figure 63: Overview of the heat loss through specific building elements in comparison with the ventilation loss and a model calculation of the costs for ventilation devices

Findings:

With a service life of 20 years, a depreciation of 5 %, an interest rate of 4 % to finance this additional investment, as well as the use of operating costs of 30,00 €/a, there are additional annual costs of approximately 300,00 €/a. Compared to the heating costs of the three-room apartment with 98,40 € per year, the additional investment costs of the ventilation devices, no significant savings were detected.

The additional gain in user comfort, as user-independent air exchange and operation at noisy locations without loss of comfort, let to no significant reduction in ventilation heat losses.

4.2.3.ANALYSIS PROJECT „BERCKMÜLLER 28“, ENEV 2014, STANDARD

The construction of this building based on the insulation standard and the energy concept of the buildings "Berliner Allee" in Stutensee (Figure 64).

Figure 64: Heating consumption and heating costs - marked numbers in red represent the heated floor area (1) and annual heating consumption (2) annual heating costs in €

Findings:

- The average heating consumption of all dwellings was 29,4 kWh/(m²a), whereas the building did not exceed the minimum requirements of the EnEV 2014.
- One apartment (07) was able to operate a three-person occupancy of a four-room apartment, with a heated area of 119 m², with annual costs of 87,55 €. The consumption reading on the heat meter was 1.065 MWh, which corresponds to a consumption of approx. 9 kWh/(m²a).

4.2.4. ANALYSIS PROJECT „PARKCARRÉ A“, ENEV 2014, KFW-EFFICIENCY HOUSE 55

The present multi-family house is located in the first construction phase of a neighbourhood development with other residential and commercial usage of buildings (Figure 65). In the basement of an old existing building, a gas-fired combined heat and power plant and a gas condensing boiler were installed to supply both the buildings of the first construction phase and the buildings of the second section under construction. The pent roofs of the new buildings are maximally occupied by photovoltaic collectors. The plant is operated by a local contractor.

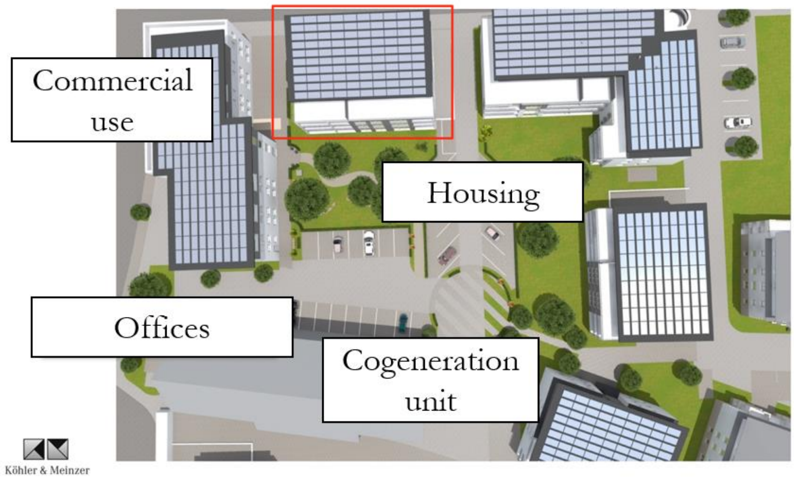


Figure 65: Overview of the quarter, all shown buildings are connected to the local heat and power plant and have PV

The following graph shows the energy balance of the first construction section (marked in red in Figure 66). Most of the electricity produced on site could be consumed locally, which was due to the high-power requirements of commercial users (Figure 66).

Figure 66: Front view of residential building (left), energy balance of the case study and overview (right)

Table 26 presents the parameters of the apartment building belonging to the ensemble were analysed and shown. The changes to the basic type "Brussels" were marked in red.

Table 26: Improved parameters to the model "Brüsseler Ring" and annual heating consumption per m2/

TYPE OF BUILDING	MULTI-FAMILY HOUSE	KFW-EFFICIENCY HOUSE 55
Net floor area (heated floor area)	1019,68 m²	
Year of construction	2016	
EnEV-standard	EnEV 2009	
Orientation	north-south	
Roof type	mono-pitch roof	
Relation surface window / outer wall	27,51 %	
Relation heated NFA / volume	25,35 %	
Quality of wall + insulation	U= 0,19 W/(m²K)	
Quality of window	U_w=0,6687-0,9213 W/(m²K)	U_g=0,6 W/(m²K)
	g=0,5	U_f=1,4 W/(m²K)
Quality of roof	U=0,194 W/(m²K)	
Thermal bridges	considered	
Air-tightness	considered	
Heating system	Heating plant decentral / PV	
Heat distribution (flow temperature)	radiator (70/55) as low-temperature heating, floor heating	
DHW (domestic hot water)		
Ventilation	decentralised ventilation with heat recovery	
Additional investment costs	planning phase	
	construction phase	
Total energy consumption	39840,00 kWh/a	
Total energy consumption	39,07 kWh/(m^2_{NFA}a)	
Total heating consumption	26979,65 kWh/a	
Total heating consumption	26,46 kWh/(m^2_{NFA}a)	
Total heat consumption; level of efficiency	39840 kWh/a	100,00 %
Total energy costs	8.225,66 €/a	0,2065 €/kWh
Total energy costs	8,07 €/(m^2_{NFA}a)	
% hot water	32,28 %	
% heating	67,72 %	
Number of residents		
Total additional charges	30.486,03 €	
Relation total heating costs / total additional charges	18,09 %	

Findings:

The realised energy concept of the buildings showed a low energy demand for heating, as well as, a high share of renewables and combined heat and power generation (CHP) on-site combined with a high self-consumption of the electricity of the quarter. This energy concept corresponds well to the direction of what is currently demanded and promoted by the legislator. However, this positive ecological view is opposed by a negative economic one. The following overview in Figure 67 shows the costs of different energy systems of different objects of K&M. The energy price for heating in the contracting model is 2.5 to 3.5 times higher compared to other energy concepts. Even if one takes into account that the heat price of the contracting model includes depreciation for the investment costs of the installed technology the large price difference is difficult to convey to the end customers.

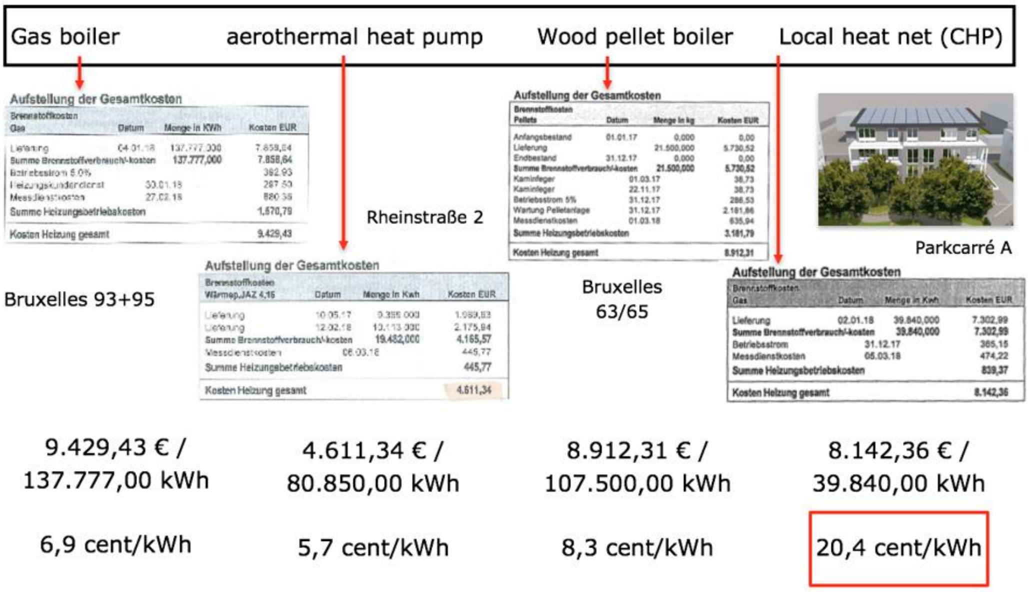


Figure 67: Comparison of the price per kWh depending on the heating system in the named projects

Further negative consequences resulted from the price structure of the current contracting model, which is the shown in Figure 68.

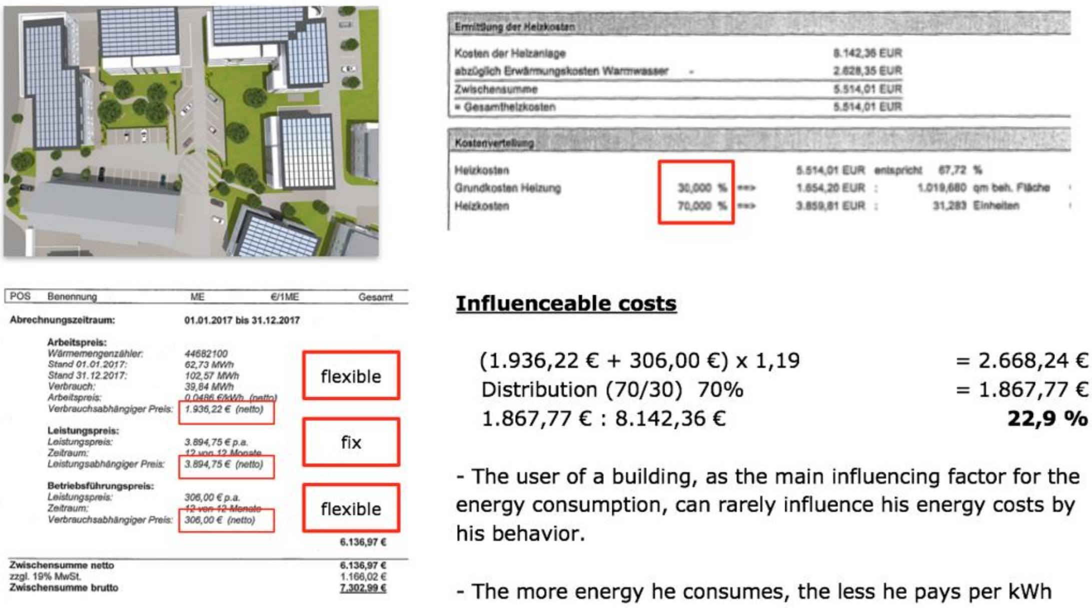


Figure 68: Calculation of the influence impact with high basic costs in the contracting model

The user of the building, as the main influencing factor for its heating energy consumption, can only slightly influence its energy costs due to the high fixed costs of the price model.

4.2.5.ANALYSIS PROJECT „PAUL KLEE“, ENEV 2004, KFW-EFFICIENCY HOUSE 40

The buildings went into operation at the end of 2017 and consumption data are not available right now. In the following, a theoretical consideration of the efficiency of the claimed subsidy is made.
Based on a heating energy consumption of 35 kWh/(m²a), as would be expected from a building constructed according to the minimum standard of the EnEV (see also evaluation "Brussels"), for the two buildings an annual consumption of approx. 35.000 kWh/a to be expected. The consumption of the buildings optimised for the KfW-Efficency 40 standard should amount to approx. 25.000 kWh/a in total. This means a saving of approx. 10.000 kWh/a. For this saving, a subsidy was used (repayment subsidy of 10.000 € for 12 apartments and interest subsidy on loans of the buyer) in the amount of more than 120.000 €. With this amount, it would have been possible to install a photovoltaic system for a power generation of more than 100.000 kWh/a. This subsidy could have produced ten times as much renewable energy in a year, as saving on building standards and building services, to achieve the KfW-Efficiency 40 standard.

Figure 69: Visualization and calculation model for subsidy efficiency

4.2.6.CONSIDERATIONS ON INSULATION THICKNESS

In the past ten years, K&M had continuously upgraded the planned buildings from the EnEV 2004 insulation standard, KfW-Efficiency 60 to the KfW-Efficiency 40 Standard of EnEV 2014. As a next step, it was obvious to consider the passive house standard. For this purpose, a theoretical consideration was made, referring to the ten-family house "Brussels", for upgrading the insulation of the external walls. The reference building "Brussels" has an external insulation of 16 cm with a heat conductivity of 0,035 W/(mK) (WLG035 according to EnEV). For passive houses, the insulation thickness is typically 30 cm, so that the effects of increasing the external wall insulation by 14 cm of insulation is determined. The measure of utilisation of a property is the base area number stated in the development plan of the municipality. The number 0,4 in the example means that 40 % of the land area can be covered with a building (Figure 70). The extremely high land costs in German metropolitan areas have the consequence that we always go to the upper limit of permissible.

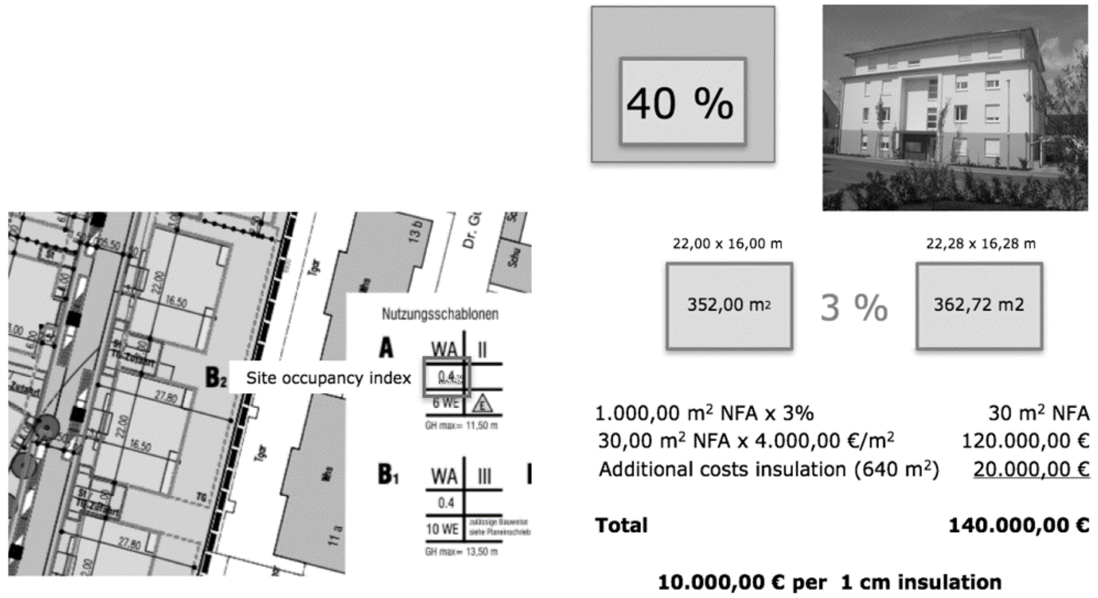


Figure 70: Cost calculation for the proclaimed insulation thickness of 30 cm in the passive house standard

Increasing the external wall insulation by 14 cm would result in exceeding the permissible base area number by 3 % as a result, so we will be forced to reduce the net cubature by 3 % in order to comply with the zoning determinations. This corresponds to approx. 30 m² of living space at the reference building. This reduction in the sale or rentable living space generates a reduction in revenue of around 120.000,00 €, based on a current market price of 4.000,00 €/m² living space. Summed with the additional costs for the insulation, the cost increase or reduction in revenue is 140.000,00 €.
How do the potential annual savings in heating energy relate to these costs? The following graph shows the heating costs of the building Brüsseler Ring 93 in Eggenstein-Leopoldshafen in the year 2017 and the possible influence of the improvement of the external wall insulation. A reduction in the transmission heat losses of the outer wall can in total effect the maximum heating costs of 274 €/a (Figure 71). In a simulation model, the amount of achievable reduction could easily be quantified. But what would the actual savings look like in a realistic field trial?

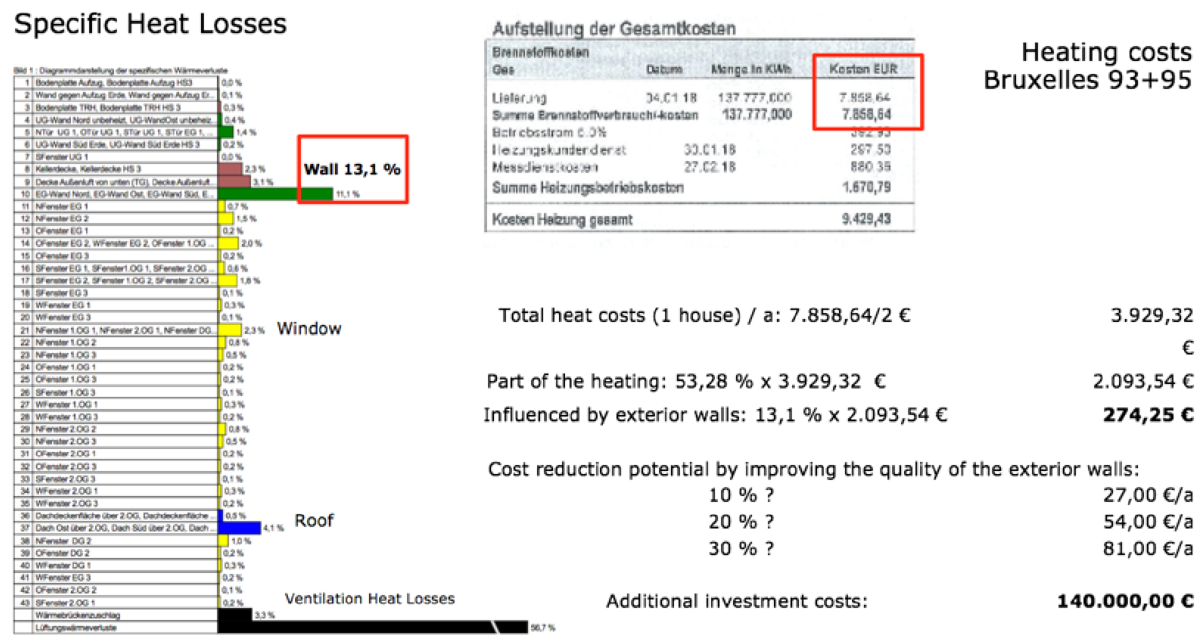


Figure 71: External wall: additional investment costs versus cost-saving potential

4.3. Summary

Bruxelles, 2009-2012
37,54 kWh/m²a
KFW 60, EnEV 2004

Berlin, 2010
34,56 kWh/m²a
EnEV 2009

Berckmüller 28, 2016
29,40 kWh/m²a
EnEV 2014

Parkcarré A, 2016
29,50 kWh/m²a
KFW 55, EnEV 2014

Figure 72: Development of building standards, building elements and tightening of the energy saving regulation (EnEV)

Over the course of almost ten years, the ten-family house type "Brussels" has been continuously improved from the EnEV Standard 2006 KfW-Efficiency 60 to the EnEV Standard 2014, KfW-Efficiency 55 (Figure 72). In essence, the following changes were made:

- Change of Orientation from East-West to North-South
- Triple instead of double glazing of the windows
- Improvement of the roof insulation
- Installation of a decentralised ventilation system with heat recovery
- Intensive observation and optimisation of thermal bridges
- Air leakage tests

Despite the large number of these measures, some of which are very cost-intensive, only an improvement in heating energy consumption of about 17 % was achieved on average. This number is particularly interesting when one considers that the spread of heating energy consumption for identical apartments is 300 - 400 %, the influence of the users is more than a multiple of the influence of the insulation and energy technology improvement of the building. This raises the key question of how to succeed in creating the energy transition in harmony with the user.
A positive finding is the fact that it is possible to operate every dwelling of the examined buildings, even those built on the basis of the EnEV 2004, in the passive house standard, in so far as the inhabitant adapts its usage behaviour accordingly. Even the average consumption of all buildings we examined are below the average consumption of passive houses in Vorarlberg examined in the following study (http://vorarlberg.orf.at/news/stories/2586260)

4.4. Findings and Results

- Focus on renewable on-site energy production

The main influencing factor for the energy consumption of a building is the user: The user can operate a standard EnEV house as a passive house or a passive house in a poor EnEV standard. Therefore, we should focus on building and using on-site renewable energy based on a well-insulated building envelope and efficient building services, rather than theoretically saving on expensive measures of insulation the buildings beyond nearly zero energy building level.

- Concentration of subsidies on the energetic improvement of existing buildings

Due to the high minimum standard of the German EnEV and the user behaviour described above, the actual difference in heating energy consumption between buildings meeting a good thermal standard and passive house envelopes is very low. Therefore, we should further focus on an effective cost-benefit ratio of subsidies and therefore promote energy improvements in the building stock.

- Consideration of ecological effects

We should undertake an overall ecological and economic analysis of all components and technologies we have implemented (taking life cycle analysis of building elements into account) to avoid measures with negative environmental impacts.

- Focus on hot water and electricity

Nearly all energy-saving regulations and laws apply to the heating of buildings. Current standard well-insulated houses consume more energy for domestic water and electricity than for heating the homes. Therefore, we should focus more on efficiency potential in terms of hot water and electricity consumption.

- Efficiency and Sufficiency

The unit used to measure energy consumption is kWh/(m²a). We continuously reduce the amount of kWh but are increasing the number of square meters per person more and more. Despite all efforts to increase efficiency, the total energy consumption still increases.

One of the key findings of the study is the fact that the user behaviour of the resident of a building has a significantly greater influence on its heating energy consumption than the quality of the thermal envelope or the efficiency of the building services. How is it possible to influence this behaviour in the sense of an economical use of energy?

The approach of making the building technology determine the room climate of the user by specifying a maximum room temperature or a defined air exchange is not realistic in a liberal society.

Another possibility is the drastic increase in energy costs through tax measures. Due to the low relevance of heating costs concerning total housing costs, this approach does not seem to be effective. Furthermore, this measure would hit the strongest households in older existing buildings, which may not be socially desirable either.

So only the approach with comprehensive education and information remains to motivate the building user to energetically economical behaviour.

Another central finding of our analysis is the discovery that the current thermal quality of the buildings we build enables the user to operate every apartment on each floor through an adapted behaviour as a low-energy or even a passive house. We have implemented these and other findings from our study in the current project "Luisengarten".

Outlook: Actual project: „Luisengarten“

Residential building, 20 units, 2.060 m² NFA, 2019, block heating (CHP), gas boiler, owner community as operator of the PV and CHP, battery storage, KfW-Efficiency 55 (Figure 73)

Figure 73: Visualisation of Luisengarten

Total consumption of electrical power:	60-65.000 kWh/a
Electrical power PV:	35.000 kWh/a
Electrical power CHP:	30.000 kWh/a
Battery storage:	27 kWh

Instead of theoretically saving further heating energy by further increasing the insulation thicknesses with the economic (and also ecological) consequences described in the study, we instead invested in the production of renewable energy based on the insulation standard according to EnEV KfW 55. The buildings will receive a PV system with a capacity of 30 kWp. To achieve the highest possible self-consumption, the system is supplemented by a battery storage with a capacity of 27 kWh.

In our study, we were unable to detect significant heating energy savings through the introduction of decentralised ventilation units with heat recovery. In the current "Luisengarten" project, we have therefore renounced this technique and invested the saved costs in the construction of a gas-powered CHP plant buffered by a gas-based peak-load boiler. The CHP takes over the base load of the heat supply of the residential complex and also generates additional electrical energy. This should be consumed on site as possible as the PV power. The billing of this tenant flow model, which is very complicated by law, is carried out by an external service provider.

PV system, CHP and electricity storage are in the ownership of the condominium community. The proceeds from the sale of the electricity to the users are credited to the maintenance account of the condominium community. This construction is the consequence of the unacceptably high heat price in the contracting model we analysed in our study.

Even though we consume a considerable amount of fossil energy with the CHP and the gas condensing boiler, we still consider this concept sustainable:
The Federal Republic of Germany will soon get off nuclear energy and will be out of coal energy by 2038. A large proportion of the energy production is then generated by systems that are weather-dependent or subject to daily fluctuations. For further future viability of the technology change the presence of an extensive gas network in Germany can play here an important role. It has the potential to be a significant contribution to the storage and transportation problems of energy in the medium term.
This means that in order to ensure the security of supply, on the one hand, there must (only in a few years) be a huge progress in large-scale storage and distribution of energy. On the other hand, enormous capacities for power generation have to be rebuilt. Gas-operated CHPs can be an important building block here, especially since they can also be operated with regenerative biogas or with gas from power to gas plants. The current promotion of this technology by the German legislator proves the comprehensibility.

In contrast to the existing buildings, heating energy consumption does not play the dominant role in the new buildings analysed. The need for energy for hot water production is almost the same, the consumption of electrical energy even higher. The latter is very user-dependent, which is why we have focused on generating electricity from renewable sources, instead of identifying savings potential that the resident will not use.

We see the cause of the high energy demand for hot water preparation in the storage of hot water, circulation and the prevention of Legionella. Here we rely on decentralised instead of central technical solutions. Each apartment receives its own water heating. As a result, the system losses are reduced, and legionella can no longer arise.
The analysis carried out in the study of the multi-family dwellings we built in recent years brought a wealth of findings, some of them very surprising. In our current project "Luisengarten", we draw the consequences for our company with the aim to build a sustainable low-energy building, where economic, ecological and social aspects are balanced.

5.CONCLUSION

Already today buildings can be realised in the nearly zero and plus energy standard. These buildings achieve extremely low energy demands and low CO_2 emissions and can be operated economically. For this reason, the motivation in the CRAVEzero project is not only based on the energy characteristics of buildings, but also on their life-cycle costs. However, the broad market deployment of these buildings is progressing very slowly so far, as methods and processes for the cost-optimal integration of efficiency measures and renewable energies are not yet sufficiently described and therefore not yet common. As a consequence - many poorly planned buildings are criticised for the fact that the actual energy consumption of highly efficient buildings is higher than the predicted demand and that high-efficiency standards are expensive and uneconomical. The influence of the user behaviour of such energy efficient buildings is another aspect, which has to be considered to evaluate the impact on the energy consumption of the building.
The identification of suitable methods for the energetic-economic optimisation of highly efficient buildings in all life-cycle phases is a prerequisite for the broad market implementation.
In the energetic-economic optimisation of buildings, there are different interests of the actors and, derived from this, different perspectives, time expectancies and goals. There are the tenants/users, the real estate agents, building contractors, planner, property managers, investors, owners and also companies which are directly or indirectly involved within the building process

On the basis of the results, the statement is confirmed: nZEBs are economical. It can now be shown that the additional costs of efficiency measures are so low that highly efficient buildings have the lowest life-cycle costs. nZEB measures only have a small percentage influence on construction costs, but can reduce CO_2 emissions many times over. When considered over the service life, these measures are usually cost-neutral or even economical.
The following points can be summarised in detail:

- The energy standard has a small influence on the building and construction costs. Energy efficiency is therefore not a major cost driver in construction.

- The additional construction costs of nZEBs are compensated in the life-cycle of most technologies even without subsidies.

- The cost optimum of primary energy demand and CO_2 emissions is in the range of nearly zero and passive houses. Highly insulated envelopes and highly efficient windows are usually economical even without subsidies. This is also due to the long service life of these components in comparison to HVAC systems.

- The optimum cost curve in relation to CO_2 emissions is very flat. Low emissions and energy requirements can therefore be achieved with different energy concepts as long as the envelope is very efficient. This means architectural and conceptual freedom.

- It is shown that energy efficiency and economic efficiency are not contradictory strategies, but can complement each other very well.

- The parametric simulation results showed that the variance in the financing cost (20 %) and the net present value (15 %) is relatively low, whereas the primary energy demand (66 %) and the CO_2 (73 %) emission vary in a broader range.

- It is possible to find a solution set with nearly equal financing cost and/or net present values, but with less primary energy consumption and/or CO_2 emissions.

- The sensitivity analysis showed that the interest rate and the inflation of energy costs had the highest influence on the LCC costs. Further important factors were the maintenance cost, electricity costs and the cost of the structural elements with a medium influence on the LCC costs.

- The user behaviour had a major influence on the total energy consumption of a building. A highly efficient building can at least support the user to further reduce his energy consumption.

6. TERMINOLOGY

6.1. Terms and Definitions

ACQUISITION COST

all costs included in acquiring an asset by purchase/lease or construction procurement route, excluding costs during the occupation and use or end-of-life phases of the life cycle

CAPITAL COST

initial construction costs and costs of initial adaptation where these are treated as capital expenditure

DISCOUNTED COST

resulting cost when the real cost is discounted by the real discount rate or when the nominal cost is discounted by the nominal discount rate

DISPOSAL COST

costs associated with disposal at the end of its life cycle

END-OF-LIFE COST

net cost or fee for disposing of a building at the end of its service life or interest period

EXTERNAL COSTS

costs associated with an asset that are not necessarily reflected in the transaction costs between provider and consumer and that, collectively, are referred to as externalities

MAINTENANCE COST

total of necessarily incurred labour, material and other related costs incurred to retain a building or its parts in a state in which it can perform its required functions

NOMINAL COST

expected price that will be paid when a cost is due to be paid, including estimated changes in price due to, for example, forecast change in efficiency, inflation or deflation and technology

OPERATION COST

costs incurred in running and managing the facility or built environment, including administration support services

REAL COST

cost expressed as a value at the base date, including estimated changes in price due to forecast changes in efficiency and technology, but excluding general price inflation or deflation

NET PRESENT VALUE

sum of the discounted future cash flows

6.2. Acronyms

CHP	Combined heat and power plant
col	Collector
CoC	Cost of capital
COP	Coefficient of performance
DHW	Domestic hot water
DoE	Design of experiment
DSM	Demand side management
GFA	Gross floor area
HFA	Heated floor area
HVAC	Heating, ventilation and air conditioning
LCC	Life-cycle costs
LCCA	Life-cycle costs approach
max	Maximum
min	Minimum
NFA	Net floor area
NPV	Net present value
NZEB	Net zero energy building(s)
nZEB	Nearly zero energy building(s)
OAT	One factor at a time
PE	Primary energy
PH	Passive House
PHPP	Passive house planning package
PV	Photovoltaic
RES	Renewable energy sources
SA	Sensitivity analysis
SCOP	Seasonal coefficient of performance
SFP	Specific fan power
WLC	Whole-life-cycle costs

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