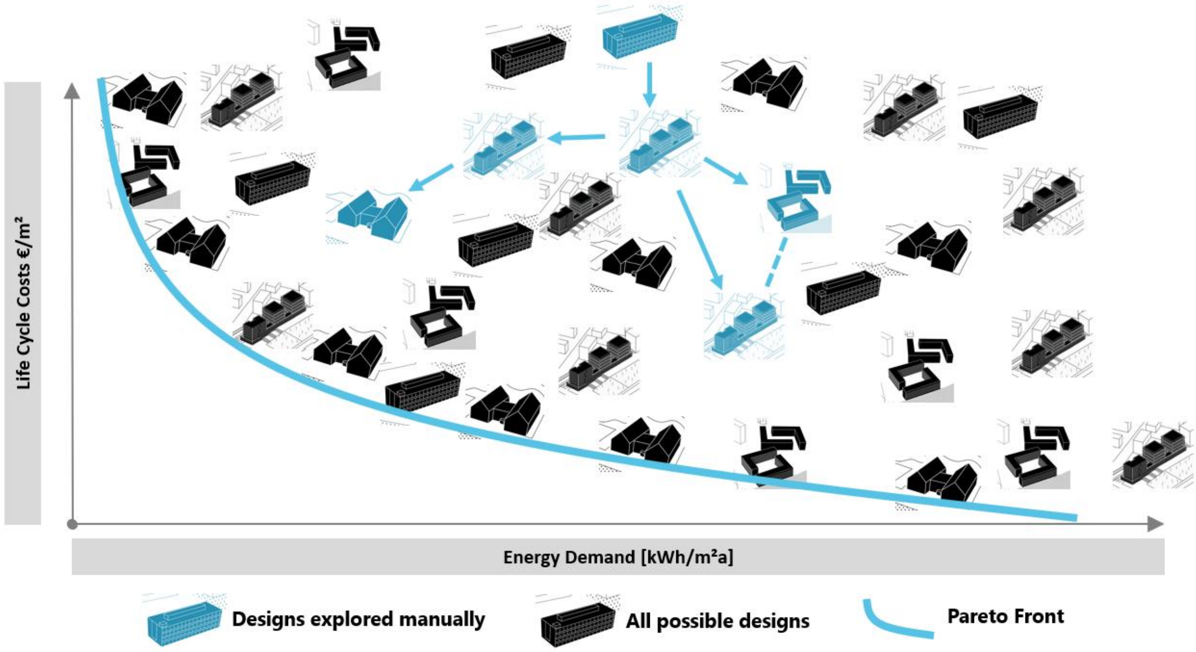
Report on nZEB life cycle costs



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.

CRAVEzero - Grant Agreement No. 741223
WWW.CRAVEZERO.EU

Co-funded by the Horizon 2020

Framework Programme of the European Union

Report on nZEB life cycle costs

David Venus[1], Tobias Weiß[1], Regina Höfler[1], Federico Garzia[2],
Roberta Pernetti[2], Eduardo Vázquez-López[3]

[1]AEE - Institute for Sustainable Technologies, Feldgasse 19, A-8200 Gleisdorf
[2]eurac research Institute for Renewable Energy, Via Volta 13/A, IT-39100 Bozen/Bolzano
University of Seville, Calle San Fernando 4, ES-41004 Seville

February 2020

FOREWORD

This report was drafted within 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.

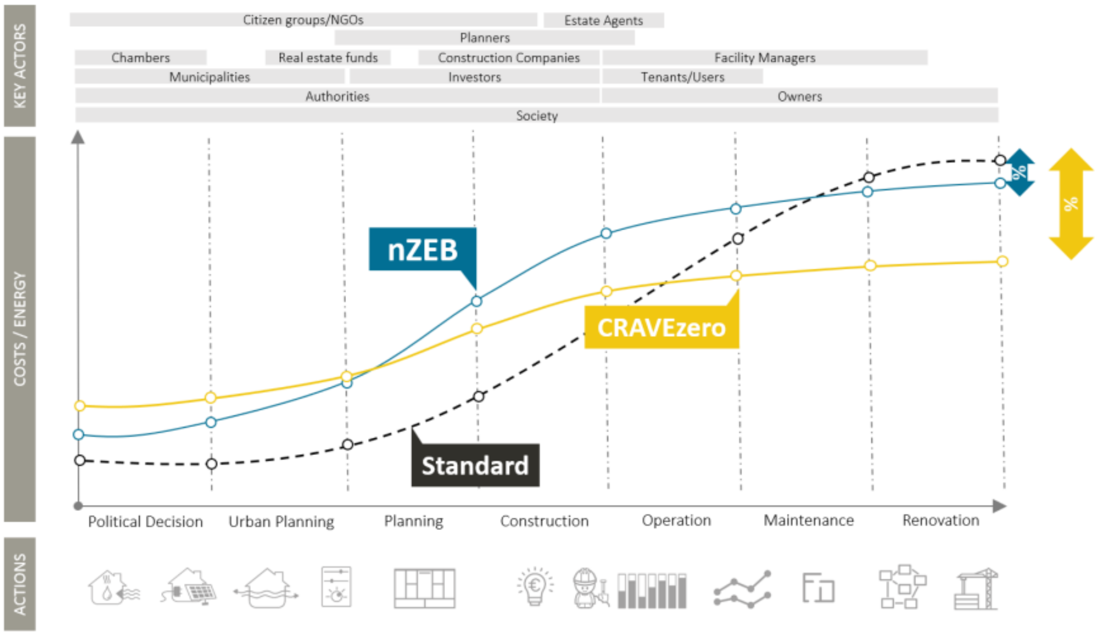


Figure 1: CRAVEzero approach for cost reductions in the life cycle of nZEBs.

Published by AEE INTEC, Austria

EXECUTIVE SUMMARY

This deliverable is a consistent continuation of the work in WP6 of the CRAVEzero project on the energetic-economic optimization of highly efficient buildings in all life cycle phases.
The method for this investigation was developed earlier in the CRAVEzero project and documented in Deliverable D6.1 "Parametric models for buildings and building clusters: Building features and boundaries". In Deliverable D6.2, the method was applied to the five CRAVEzero case studies Aspern IQ, Alizari, Isola Nel Verde, Les Heliades and MORE to perform parametric calculations and to perform multi-objective energy and cost analysis over the life cycle of the buildings.
In this Deliverable D6.3, this work was continued and parametric calculations were performed for the case studies Väla Gård, NH Tirol, iR-headquarter and Green Home Nanterre, with the focus on the analysis of the influence of geographical and financial boundary conditions on the defined key performance indicators financing costs, life cycle costs, balanced primary energy demand and balanced CO_2 emissions[1]. A particular focus was set on the influence of the location on the results. Therefore different parameter settings were calculated for three different locations, representing Northern Europe, Central Europe and Southern Europe. In total, more than 96,000 variants were calculated and analysed in this Deliverable. Together with the work that has been done in the other two Deliverables (D6.1 and D6.2) in total, more than 360,000 variants were calculated and analysed for the ten case studies. Figure 2 shows as a summary the average costs of all ten case studies over the different phases of the life cycle. All results are also available as interactive dashboard on the CRAVEzero pinboard, which can be found here: http://www.cravezero.eu/pinboard/PinboardMain/PinboardMain.htm

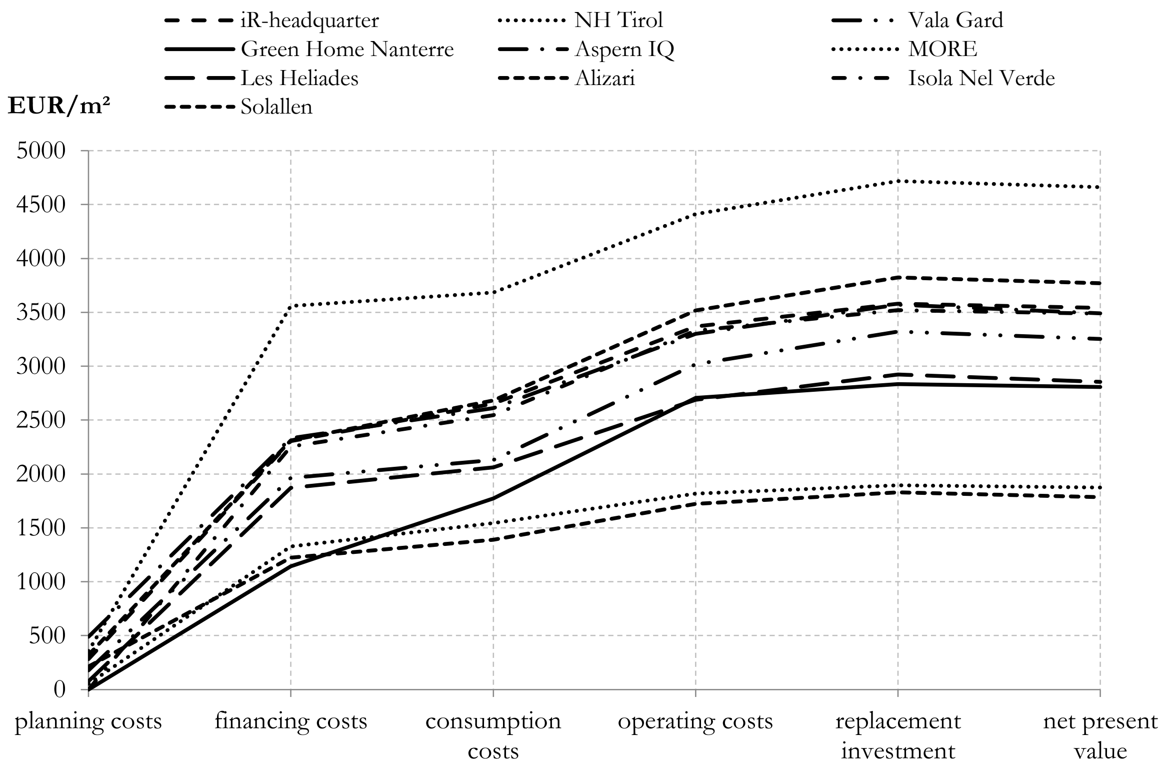


Figure 2: Average specific costs (EUR/m²) in the different phases of all case studies that were investigated within the CRAVEzero project

[1] The „term" balanced consideres both the weighted grid imports and exports (e.g. PV feed-in).

Another focus of this Deliverable D6.3 was on the evaluation of the upstream costs as well as on the development of a methodology for the end-of-life analysis. The upstream costs were also estimated for the case studies Väla Gård, NH Tirol, iR-headquarter and Green Home Nanterre. Cost parameters, which were collected by the different project partners and countries, served as a basis. Upstream costs include the costs that municipalities and/or developers have to incur in order to guarantee the public infrastructure required for a construction project. Figure 3 and Figure 4 show exemplary results of the calculation.

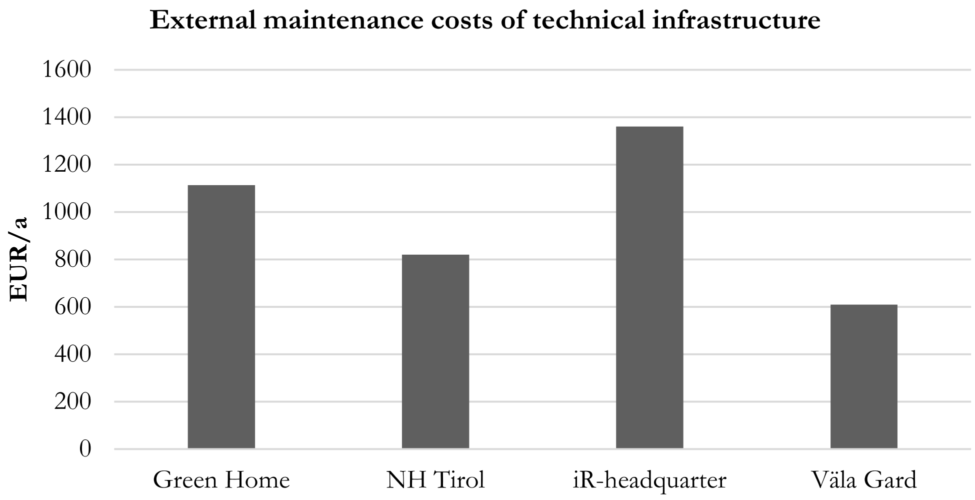


Figure 3: Extract from the results of the calculation of upstream costs - external maintenance costs of technical infrastructure

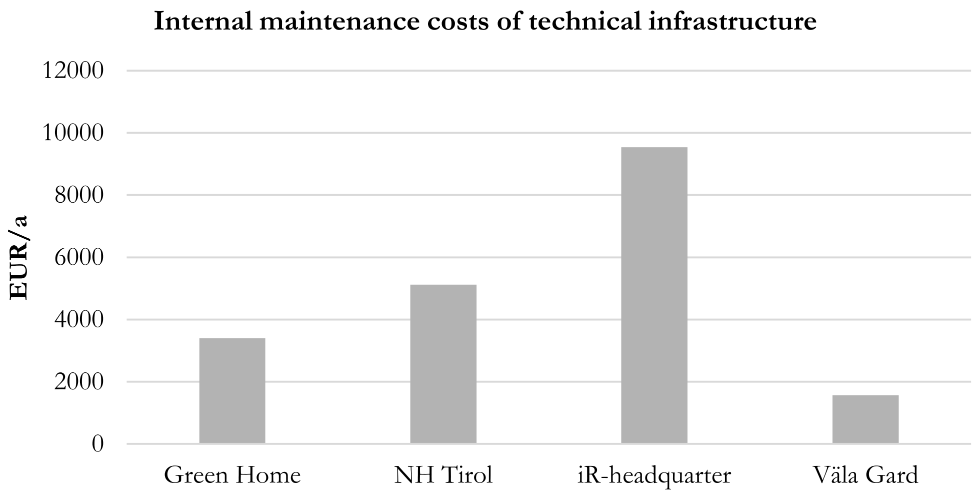


Figure 4: Extract from the results of the calculation of upstream costs - internal maintenance costs of technical infrastructure

Contents

LIST OF FIGURES

LIST OF TABLES

CHAPTER 1

INTRODUCTION

1. INTRODUCTION

1.1. OBJECTIVE

The CRAVEzero parametric exhaustive search approach provides the chance to make the best decisions as early in the planning process as possible to increase the odds of realizing multi-objective energy performance goals for nearly-zero energy buildings (nZEBs). Negative trade-offs of multiple project objectives can be highlighted together with the findings of key combinations of variables. This information results in optimized investment and life cycle costs, providing a more cost- and energy-efficient building.

This deliverable is a consistent continuation of the work in WP6 of the CRAVEzero project on the energetic-economic optimization of highly efficient buildings in all life cycle phases. The method for this investigation was developed earlier in the CRAVEzero project and documented in Deliverable D6.1. In Deliverable D6.2, the method was applied to the five CRAVEzero case studies Aspern IQ, Alizari, Isola Nel Verde, Les Heliades and MORE to perform parametric calculations and to perform multi-objective energy and cost analysis over the life cycle of the buildings.

In this Deliverable D6.3, this work was continued and parametric calculations were performed with the focus on the analysis of the influence of geographical and financial boundary conditions on the defined key performance indicators financing costs, life cycle costs, balanced primary energy demand and balanced CO_2 emission. The investigations were performed for the four case studies Väla Gård, NH Tirol, iR-headquarter and Green Home Nanterre.

1.2. STATE OF THE ART / PROBLEM DESCRIPTION

Possible cost saving potentials in planning and construction of high performing nearly zero-energy buildings (nZEBs) with advanced energy standards are often not sufficiently assessed, as only a few, out of numerous possible variants of technology sets are considered in the traditional planning process. Until now, in many countries planning and analysis are not carried out in parallel, and the alternative technical options are discarded at an early stage (exceptions exist of course). If, on the other hand, possible variants are realistically compared in the planning phase, a profound decision can be made.

The aim is to provide rapid feedback that gives architects more confidence in their decision between alternatives on energy and cost performance. nZEB-design is a multi-objective optimization problem where stakeholder interests' conflict with each other.

By automating the simulation inputs and intelligently interpreting the results for report creation, CRAVEzero reduces the time to understand performance from several hours to a few minutes.

Nearly all building projects go through the following design process (see Figure 5).

- **Predesign:** In Predesign, the key design parameters of the project are worked out. This includes site selection, program confirmation, preliminary project cost estimates, scope and schedule analyses.
- **Schematic Design:** The architect, consultants, and design team prepare conceptual plans for the project, showing spatial relationships, scale, and building form of the project at this stage.

- **Design Development:** This stage takes the sketch prepared during the schematic design stage and develops them a step further. Structural and other building systems are planned, key building materials are decided upon, building components are sized, and code compliance is confirmed.
- **Construction Documents:** Once the owner and the architect have agreed with the plans, construction documents can start getting prepared. Construction documents contain specifications of finished materials, structural and mechanical systems.
- **Construction:** Once the construction documents are completed, the design team gets involved in the proper execution of the project.

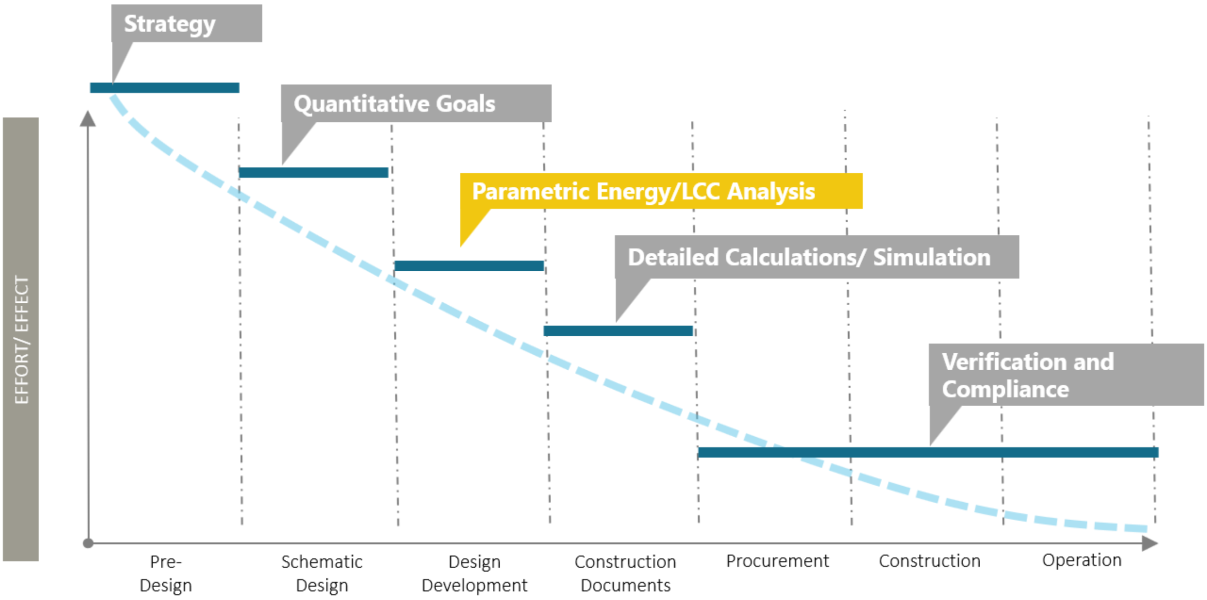


Figure 5: Influence, measures and decisions in the individual phases of the life cycle

In the early stage of building design, it is easy and inexpensive to make significant design changes to reach the best solution. With each stage of design, more details are added, so it becomes more challenging and costly to make changes during the progression to further stages. Traditionally, during the design process for a building's energy system the architects sends the initial building designs to engineers, who then test out a variety of energy system scenarios over the course a few weeks. During the time, when the engineers are able to come back with an analysis, the architects have often made significant design changes. This process can not only lead to less-efficient and more-expensive HVAC systems, renewable energy systems and envelope qualities, but this also usually leads to longer project timelines, unexpected construction issues, delays and budget overruns. The multi-objective exhaustive search used in the CRAVEzero project makes it easier, faster and therefore cheaper to plan new nZEBs by helping to identify the most cost-effective and energy-efficient solutions, all while reducing the risks of redesign, delay and budget overruns.

Figure 6, known as MacLeamy curve (IDEAbuilder, 2012), shows how the effort and cost of design changes can be minimised at an earlier stage of the design process when the effect can be maximum. The aim is to facilitate the integration of building energy and life cycle cost calculations in the early stages of the building design. The MacLeamy's curve is a well-known concept of how shifting decision making in building design early into the process leads to great benefits in building performance and cost. It is very costly to change the technical solution sets to reach nZEB in late design development. Hence, early-stage energy and life cycle cost analysis is vital for cost-effective nZEBs.

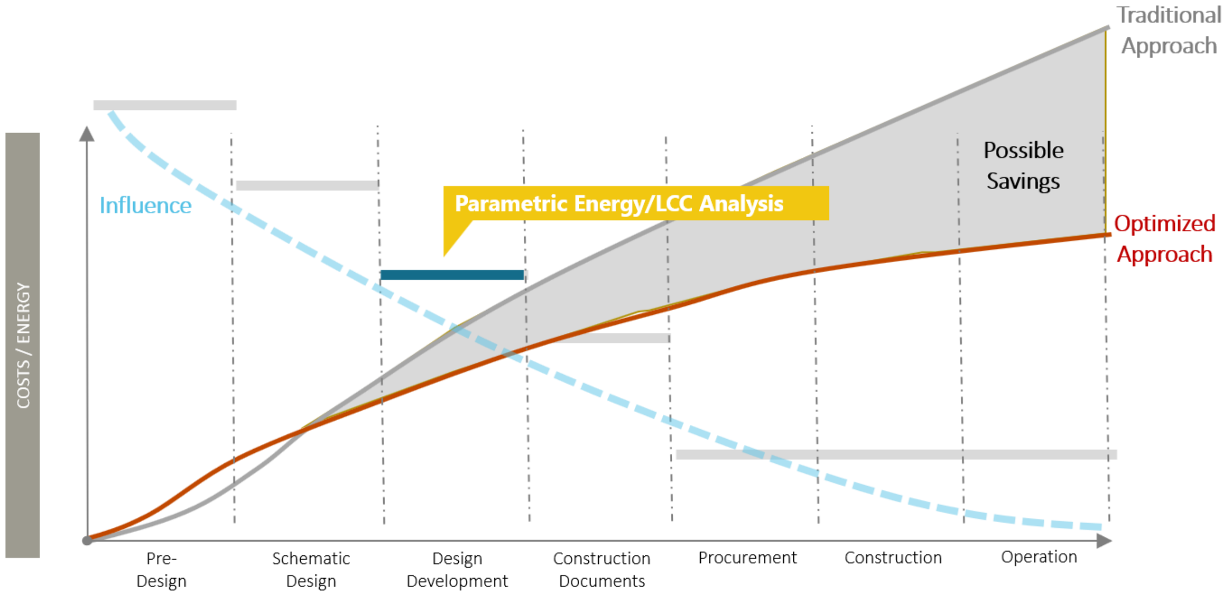


Figure 6: Decisions in the early phases of project development have a strong influence on life cycle costs

The multi-objective exhaustive search used in CRAVEzero creates a parametric design space to analyse more alternatives faster than with conventional methods. Rapid feedback on the impact design decisions have on energy and cost performance can be given in an automated way. Multi-objective exhaustive search allows to meet or exceed operational energy efficiency targets all within the same workflow, as well as to monitor costs throughout the whole life cycle to ensure that the most sustainable design is also the most cost-effective.

Figure 7 demonstrates the definition and variation of a typical parametric design space for a CRAVEzero case study.

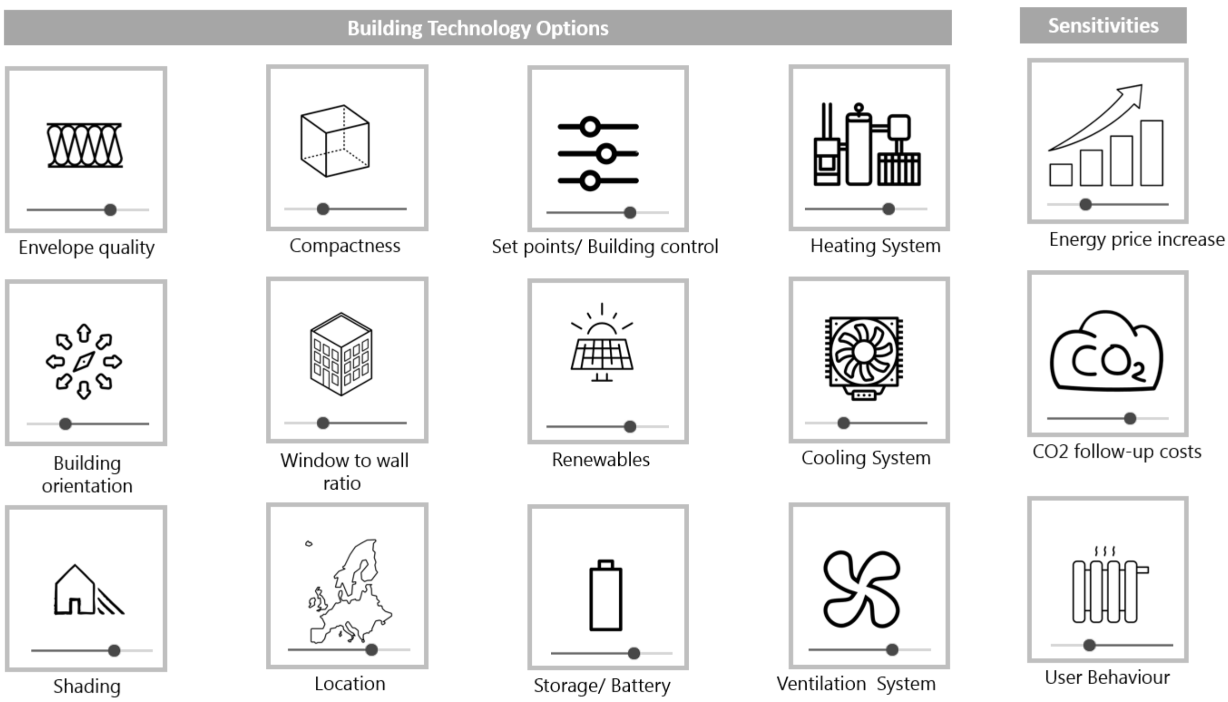


Figure 7: Definition and variation of a typical parametric design space for the CRAVEzero case studies

CHAPTER 2

GEO-CLUSTER ANALYSIS AND IMPACT ON LIFE CYCLE COSTS

2.GEO-CLUSTER ANALYSIS AND IMPACT ON LIFE CYCLE COSTS

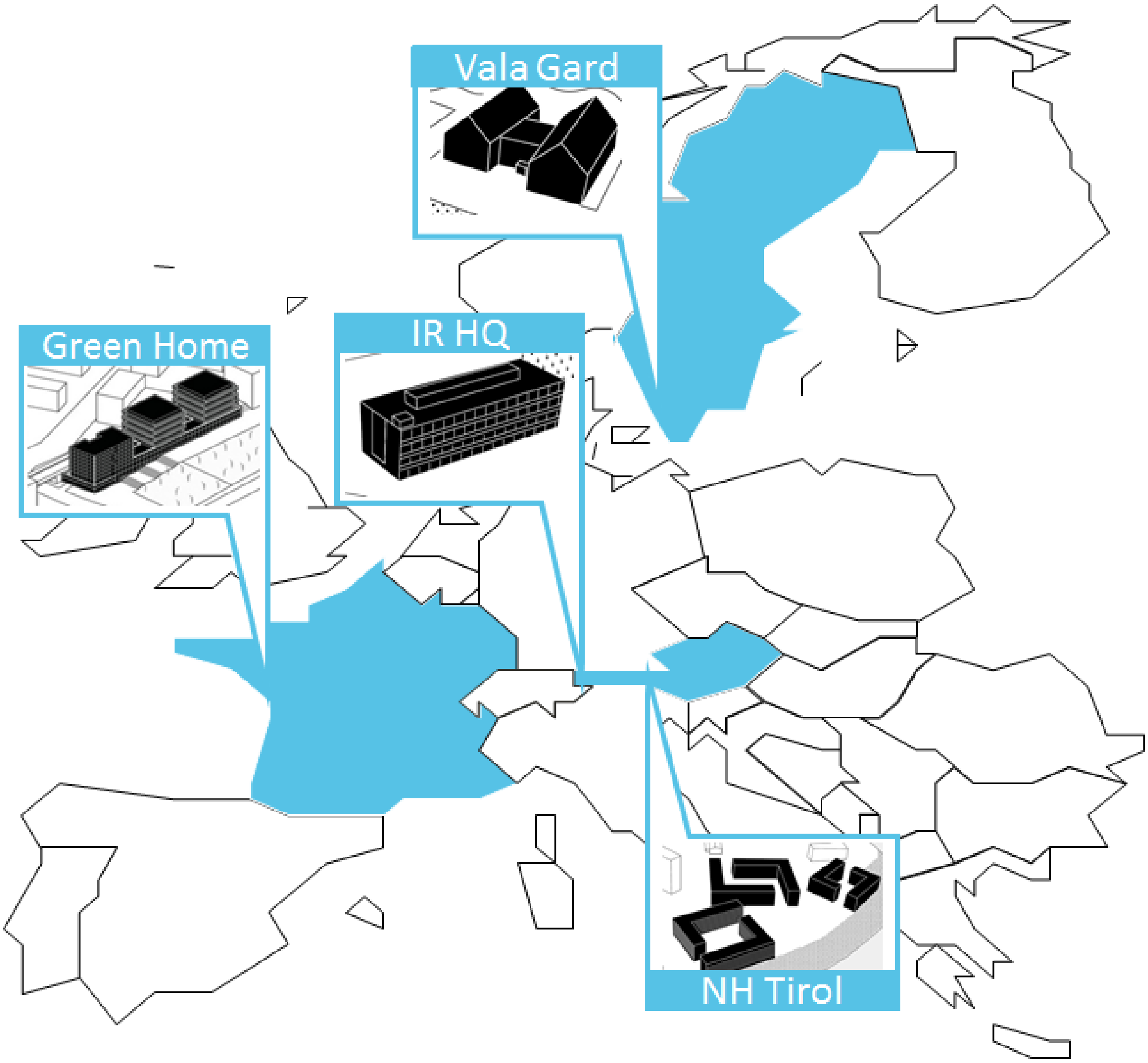


Figure 8: Schematic representation of the four case studies and their location within Europe

A basic understanding of the existing climate conditions is vital for making decisions on the performance design. Depending on the location and climatic conditions, different solutions can be advantageous. For this reason, the Deliverable D6.3 focuses also on the investigation of the influence of the climate and the location on the design decision.

To investigate the influence of the location on the key performance indicators, the defined parameter sets were combined with three different location-dependent boundary conditions, representing Northern Europe (Helsingborg – Sweden), Central Europe (Innsbruck – Austria) and Southern Europe (Rome – Italy).

In further consequence, the energy performance and cost calculations were adapted to these three locations. For the energy performance calculation, climatic data files were generated with Meteonorm 7.1.8.29631. Figure 9 shows a comparison of the horizontal radiation and the exterior temperature of the three different locations. It is apparent that Rome and Innsbruck have a similar horizontal radiation at the beginning (January until May) and at the end of the year (September until December). In the remaining months the horizontal radiation is, as expected, higher in Rome. The biggest difference is visible in July, with a radiation of 200 kWh/m² per month in Rome and 176 kWh/m² per month in Innsbruck. Compared to Rome and Innsbruck, the horizontal radiation in Helsingborg is much lower at the beginning and at the end of the year. The lowest value is achieved in December with 8 kWh/m² per month. In the middle of the year the difference between the horizontal radiation in Innsbruck and in Helsingborg becomes smaller. The lowest deviation between the two locations is achieved in June with a difference of 8 kWh/m² per month.

Looking at the exterior temperature it is obvious that Rome has the highest temperatures in this comparison. Almost constantly over the year the average exterior temperature is 8°C higher than in Innsbruck. The monthly average exterior temperature in Helsingborg and Innsbruck are quite similar, with lower temperature in Helsingborg (except in the month January, November and December).

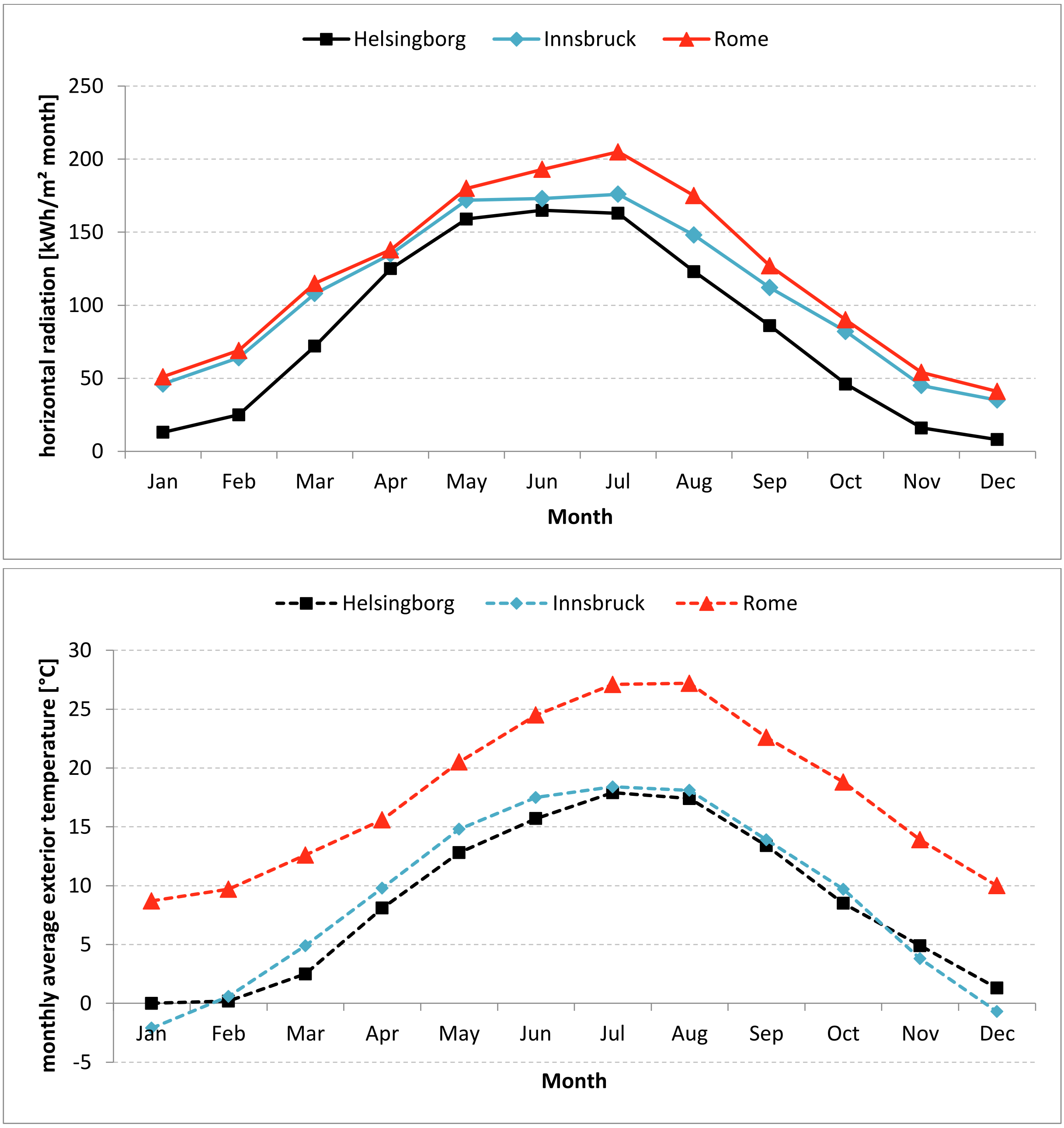


Figure 9: Horizontal radiation (top) and exterior temperature (bottom) per month of the three locations Helsingborg, Innsbruck and Rome

In the cost calculation, the construction cost index from (Eurostat, 2019) was used to attune the construction prices to the three countries. The construction cost index is provided quarterly (see Table 1). In this report, the values from 4th Quarter 2016 to 2nd Quarter 2019 were averaged. This average value was then used to attune the entire construction prices. The planning costs were, however, not adapted.

Table 1: Construction cost of new residential buildings index (2015 = 100)

COUNTRY	2016 Q4	2017 Q1	2017 Q2	2017 Q3	2017 Q4	2018 Q1	2018 Q2	2018 Q3	2018 Q4	2019 Q1	2019 Q2	Average
Austria	101.5	103.1	104	104.2	105.1	106	107.2	107.7	107.6	107.7	108.6	105.7
France	101.5	101.8	102.7	103.0	102.9	103.1	104.8	106.9	105.1	106.6	107.7	104.2
Italy	100.5	100.6	100.8	100.9	101.1	101.5	101.7	102.8	103.0	102.9	102.5	101.7
Sweden	103.2	103.7	104.6	105.3	106.0	107.4	108.8	109.6	110.2	110.5	112.4	107.4

Summarizing Table 1, these are the factors used in the parametric calculations to investigate the influence of the location on the investment costs as well as on the life cycle costs:

- Austria – reference for Central Europe: 105.7
- France: 104.2
- Italy – reference for South Europe: 101.7
- Sweden – reference for Northern Europe: 107.4

To consider the influence of the different locations on the results, furthermore, also different energy prices were used in the calculations. Table 2 gives an overview of the used energy prices of the different energy carriers in Austria, France and Italy.

Table 2: Energy prices as boundary conditions of the economic efficiency calculation

ENERGY CARRIERS	AUSTRIA	ITALY	SWEDEN	UNIT
Natural Gas	0.060	0.095	0.125	EUR/kWh
Electricity	0.187	0.216	0.220	EUR/kWh
District heating	0.090	0.100	0.090	EUR/kWh
Wood pellets	0.050	0.070	0.050	EUR/kWh
PV feed-in tariff	0.048	0.070	0.060	EUR/kWh

Figure 10 shows some first results of the influence of the location on the financing costs, the life cycle costs, the balanced primary energy demand and the balanced CO_2 emissions. Details and further results can be found in chapter 6.

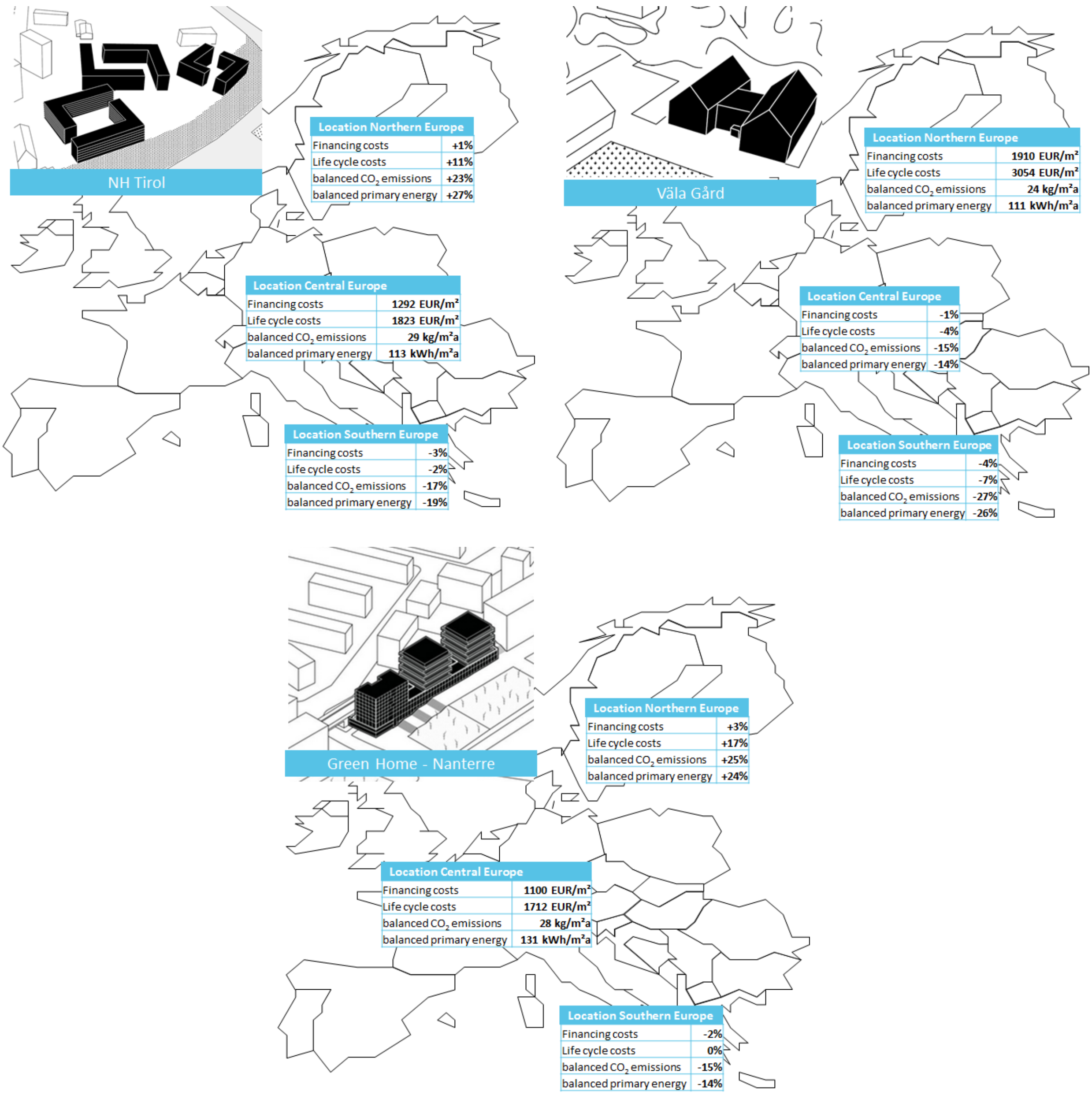


Figure 10: Results of the geo-cluster analysis of the case studies NH Tirol (top left), Väla Gård (top right) and Green Home Nanterre (bottom)

CHAPTER 3

DESCRIPTION OF THE CASE STUDIES AND THE INVESTIGATED PARAMETERS

3. DESCRIPTION OF THE CASE STUDIES AND THE INVESTIGATED PARAMETERS

3.1. VÄLA GÅRD

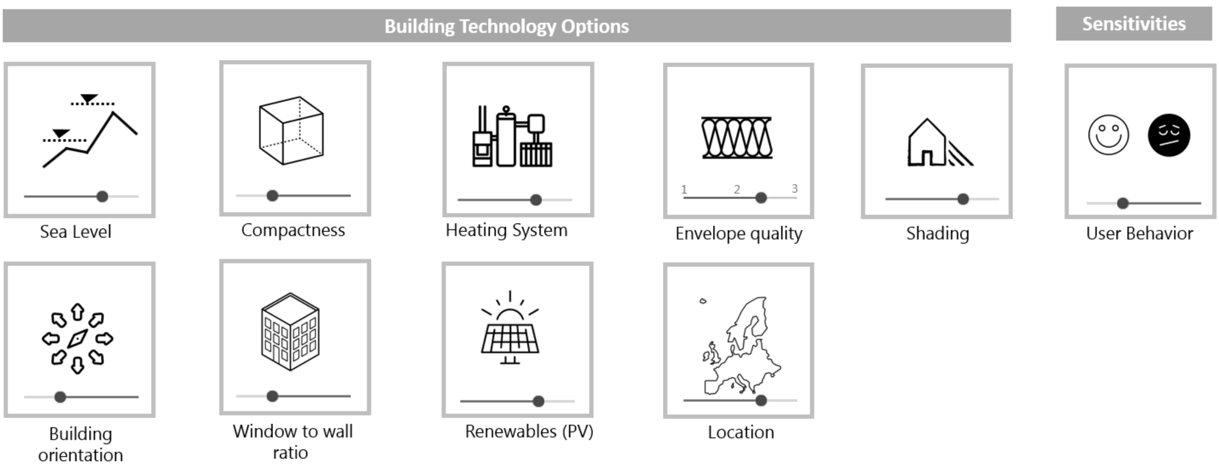
General information

- Owner: Skanska Sverige AB
- Architect: Tengbom
- Energy concept: Net ZEB
- Location: Helsingborg (Sweden)
- Year of construction: 2012
- Net floor area: 1670 m²

Key technologies

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

Väla Gård is composed of two buildings used as an office. The building was constructed with a high level of insulation. So for example a prefabricated 120 mm concrete wall with 200 mm graphite EPS plus 95 mm mineral wool was used. Heat and hot tap water are produced by a geothermal heat pump that can be used for cooling too. A demand-controlled ventilation system is used to ensure air quality, a photovoltaic system produces electricity on-site. As a consequence of all these green initiatives the building has been certified under Leadership in Energy and Environmental Design (LEED) at the highest level, LEED Platinum.



Different parameters and levels were investigated. These are shown in Table 3. Table 4 to Table 6 on the next page show the investment costs and technical data of each investigated parameter. Information on the parameter "user behaviour" can be found in chapter 4.

Table 3: Investigated parameters and levels of the case study Väla Gård

PARAMETER	LEVEL 1 ◓	LEVEL 2 ◕	LEVEL 3 ●
User behaviour	Not efficient	Standard	Efficient
Compactness (area of the thermal envelope)	-20 %	As built	+ 20 %
Window area	-20 %	As built	+ 20 %
Shading of neighbouring buildings	No shading	Rural area	City
See level	0 m	300 m	1000 m
Location	Northern Europe	Central Europe	Southern Europe
Orientation	As built	+90°	+180°
Envelope quality	National standard	As-built (= nZEB)	Passive house
Heating system	Natural gas	As-built (= ground source heat pump)	District heating
PV	No PV	68 kWp	

Table 4: Investment costs and technical data for the parameter "envelope quality" of the case study Väla Gård

PARAMETER	LEVEL 1: NATIONAL STANDARD	LEVEL 2: nZEB	LEVEL 3: PASSIVE HOUSE
Costs of external walls	431 EUR/m²	458 EUR/m²	465 EUR/m²
U-value of external walls	0.20 W/m²K	0.11 W/m²K	0.09 W/m²K
Costs of floor	218 EUR/m²	232 EUR/m²	242 EUR/m²
U-value of floor	0.15 W/m²K	0.11 W/m²K	0.09 W/m²K
Costs of roof	331 EUR/m²	348 EUR/m²	366 EUR/m²
U-value of roof	0.11 W/m²K	0.09 W/m²K	0.07 W/m²K
Costs of windows	604 EUR/m²	610 EUR/m²	660 EUR/m²
U-value of windows	1.10 W/m²K	0.94 W/m²K	0.80 W/m²K

Table 5: Investment costs and technical data for the parameter "heating" of the case study Väla Gård

	LEVEL 1: GAS CONDENSING BOILER	LEVEL 2: AS BUILT	LEVEL 3: DISTRICT HEATING
Cost	85,000 EUR	195,000 EUR	75,000 EUR
Power / COP	30 kW / Eff = 90 %	30 kW / COP = 3.0	30 kW / Eff = 95 %

Table 6: Investment costs for the parameter "PV" of the case study Väla Gård

	LEVEL 1: NO PV	LEVEL 2: 68 kWp
Costs	-	159.948 EUR

3.2. NH TIROL

General information

- Owner: Neue Heimat Tirol
- Architect: Architekturwerkstatt din a4
- Energy concept: cogeneration unit wood + solar thermal energy (DHW) + air system with heat recovery
- Location: Innsbruck (Austria)
- Years of construction: 2008-2009
- Net floor area: 7493 m² (1 building)

Key technologies

- Centralized pellet boiler

This is one of the largest residential complexes built according to the passive house approach in Europe. Heating is supplied by a pellet boiler and a gas condensing boiler, whereby approx. 80 % of the annual energy requirement (without consideration of the solar system) is covered by district heating. Due to the low heating demand, only the outer surfaces (edge zones) are heated by means of a floor heating system. The remaining heat input is provided by the mechanical ventilation with heat recovery.
Table 7 gives an overview of the parameters and levels that were investigated for the case study NH Tirol in this Deliverable. More information on the parameters "envelope quality" and "heating system" is shown in the tables that follow afterwards.

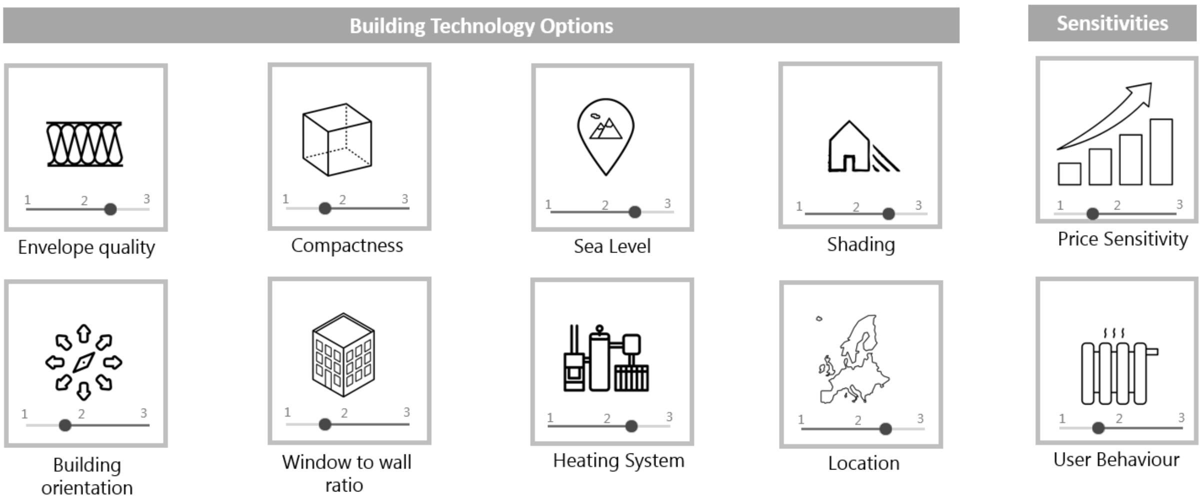


Table 7: Investigated parameters and levels of the case study NH Tirol

PARAMETER	LEVEL 1 ◓	LEVEL 2 ◕	LEVEL 3 ●
User behaviour	Not efficient	Standard	Efficient
Compactness (area of the thermal envelope)	-20 %	As built	+ 20 %
Window area	-15 %	As built	+ 15 %
Shading of neighbouring buildings	No shading	Rural area	City
Sea level	0 m	300 m	1000 m
Location	Northern Europe	Central Europe	Southern Europe
Orientation	As built	+45°	+90°
Envelope quality	National standard	Mean value	As-built (=passive house)
Heating system	Natural gas	As-built (=district heating)	District heating + pellets

Table 8: Investment costs and technical data for the parameter "envelope quality" of the case study NH Tirol

PARAMETER	LEVEL 1: NATIONAL STANDARD ◓	LEVEL 2: MEAN VALUE ◕	LEVEL 3: AS BUILT ●
Costs of external wall insulation	65 EUR/m²	75 EUR/m²	88 EUR/m²
U-value of external wall	0.341 W/m²K	0.186 W/m²K	0.120 W/m²K
Costs of floor insulation	No additional insulation	33 EUR/m²	48 EUR/m²
U-value of floor	0.353 W/m²K	0.164 W/m²K	0.107 W/m²K
Costs of roof insulation	34 EUR/m²	48 EUR/m²	60 EUR/m²
U-value of roof	0.20 W/m²K	0.109 W/m²K	0.077 W/m²K
Costs of windows	330 EUR/m²	470 EUR/m²	640 EUR/m²
U- value of windows	1.40 W/m²K	1.07 W/m²K	0.73 W/m²K

Table 9: Investment costs and technical data for the parameter "heating" of the case study NH Tirol

	LEVEL 1: GAS CONDENSING BOILER	LEVEL 2: AS BUILT	LEVEL 3: DISTRICT HEATING + PELLETS
Costs	2,180,000 EUR	1,872,000 EUR	1,932,000 EUR
Power / COP	2600 kW	2600 kW	2600 kW (district heating)+ 300 kW (pellets)

3.3. IR-HEADQUARTER

General information

- Owner: I.+R. Schertler Alge GmbH
- Architect: Dietrich Untertrifaller Architekten
- Location: Lauterach (Austria)
- Years of construction: 2011-2013
- Net floor area: 2759 m²

Key technologies

- Reversible geothermal heat pump

The new corporate headquarters of the i+R Group were designed with a focus on the aspects of greater comfort, natural materials, and renewable energy. The building has been designed to obtain the LEED Certification. The building is notable for its high comfort levels, high-quality daylight, renewable energies (heat pumps, geothermal heat, and photovoltaic plant), compact building form, recycled materials and the use of timber as a natural material.

In this Deliverable different parameters and levels were investigated with focus on technological parameters. Information on these investigated parameters (and levels) of the case study iR-headquarter are given in Table 10, the information to the investment costs and the technical data, which were used for the parametric calculations follow in Table 11 to Table 15.

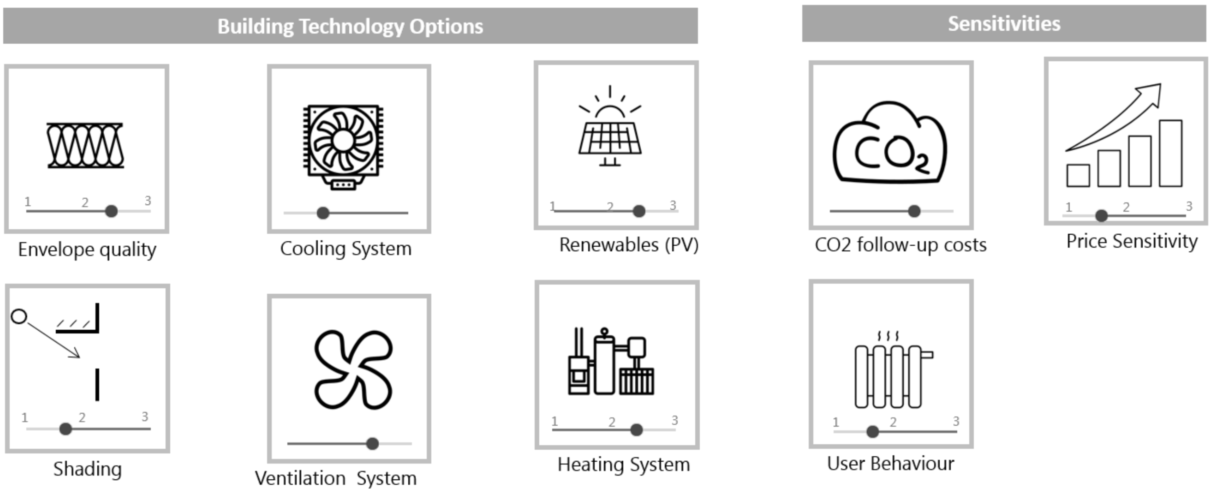


Table 10: Investigated parameters and levels of the case study iR-headquarter

PARAMETER	**LEVEL 1**	**LEVEL 2**	**LEVEL 3**	**LEVEL 4**
Sensitivity	Standard	High	Low	PHPP default
CO_2 follow-up costs	100 EUR/t_{CO2} a	200 EUR/t_{CO2} a	300 EUR/t_{CO2} a	0 EUR/t_{CO2} a
User behaviour	Not efficient	Standard	Efficient	PHPP default
Envelope quality	National standard	Mean value	As-built (=passive house)	
Ventilation	Window ventilation	Mechanical ventilation with HR	Extract air unit	
Heating	Natural gas	As-built (= heat pump)	Wood pellets	
Cooling	Window cooling	As-built	Compression cooling	
PV	No PV	245 kWp	491 kWp	
Shading (fixed elements on the south side)	0.5 m overhang	1.5 m overhang	2.5 m overhang	

Table 11: Investment costs and technical data for the parameter "envelope quality" of the case study iR-headquarter

PARAMETER	LEVEL 1: NATIONAL STANDARD	LEVEL 2: MEAN VALUE	LEVEL 3: AS BUILT
Costs of external wall insulation	50 EUR/m²	56 EUR/m²	79 EUR/m²
U-value of external walls	0.320 W/m ²K	0.232 W/m²K	0.142 W/m²K
Costs of floor insulation	49 EUR/m²	51 EUR/m²	53 EUR/m²
U-value of floor	0.196 W/m²K	0.186 W/m²K	0.177 W/m²K
Costs of roof insulation	39 EUR/m²	44 EUR/m²	51 EUR/m²
U-value of roof	0.200 W/m²K	0.163 W/m²K	0.121 W/m²K
Costs of windows	470 EUR/m²	560 EUR/m²	640 EUR/m²
U-value of windows	1.70 W/m²K	1.23 W/m²K	0.76 W/m²K

Table 12: Investment costs for the parameter „ventilation" of the case study iR-headquarter

	LEVEL 1: WINDOW VENTILATION	LEVEL 2: AS BUILT MECH.VENT. + HR	LEVEL 3: EXTRACT AIR UNIT
Costs	11,200 EUR	120,000 EUR	33,800 EUR

Table 13: Investment costs for the parameter "heating" of the case study iR-headquarter

	LEVEL 1: NATURAL GAS	LEVEL 2: AS BUILT	LEVEL 3: WOOD PELLET
Costs	127,000 EUR	204,000 EUR	143,000 EUR

Table 14: Investment costs for the parameter „cooling" of the case study iR-headquarter

	LEVEL 1: WINDOW COOLING	LEVEL 2: AS BUILT	LEVEL 3: COMPRESSION COOLING
Costs	No additional costs	26,400 EUR	124,000 EUR

Table 15: Investment costs for the parameter „PV" of the case study iR-headquarter

	LEVEL 1: NO PV	LEVEL 2: 245 kWp	LEVEL 3: 491 kWp
Costs	-	190,000 EUR	371,000 EUR

3.4. GREEN HOME NANTERRE

General information

- Owner: Condominium ownership
- Architect: Atelier Zündel Cristea
- Location: Nanterre (France)
- Year of construction: 2019
- Net floor area: 9267 m²

Key technologies

- Triple-glazed windows
- Decentralized ventilation with 96 % heat recovery
- Heat recovery on greywater (with a water-to-water heat pump)

Green Home is a plus-energy residential building located in Nanterre, France. The special feature of this building is that it operates without heating and cooling systems. This building has very low energy needs (80 % less than a conventional one), thanks to a bioclimatic approach and a well-insulated envelope (external insulation, triple glazing, and thermal bridge optimization) close to passive house standard. As a result, a double flux ventilation system with 95 % heat recovery is enough to meet almost 100 % of the heating needs of the apartments. No heating system has been implemented, except for a small electric heater in the ventilation system, used when the outside temperature is very low. A centralized heat pump with very high efficiency (performance coefficient equal to 7) uses the heat recovery of greywater to produce domestic hot water. Green Home was designed to consume less than 23 kWh/m²a primary energy for heating, cooling, ventilation, lighting and domestic hot water, which is almost 3 times less than what is required by the RT2012 (the French thermal regulation for buildings).

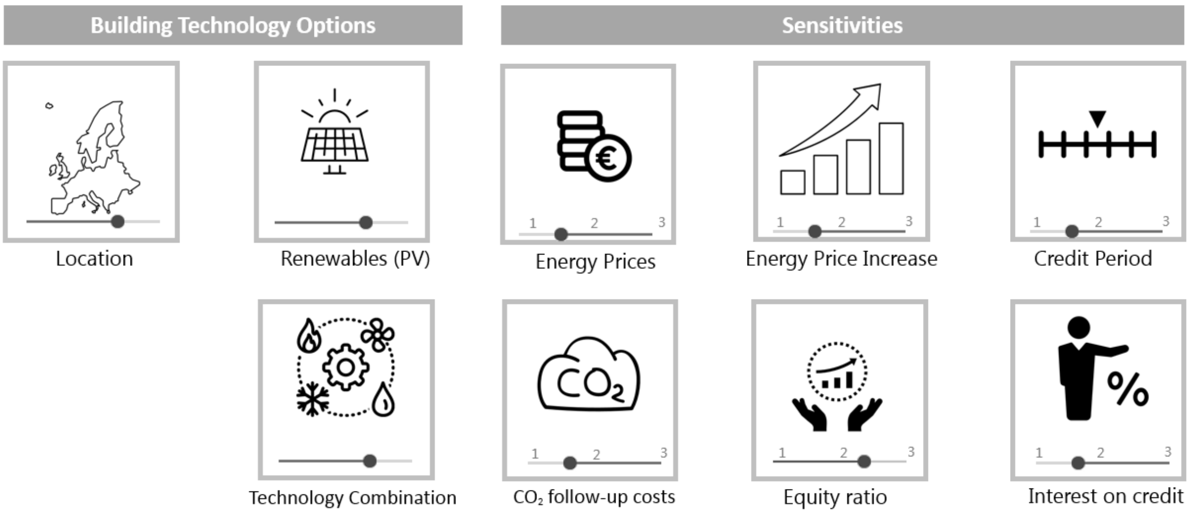


Table 16 shows the defined parameters of the case study Green Home Nanterre. Additionally also the three respectively four different levels of each parameter are mentioned. Table 17 to Table 19 give an overview of the investment costs and technical data of each parameter.

Table 16: Investigated parameters and levels of the case study Green Home Nanterre

PARAMETER	LEVEL 1	LEVEL 2	LEVEL 3
Credit period	10 a	20 a	30 a
Interest on credit	0.9 %	1.1 %	1.3 %
Equity ratio	10 %	15 %	20 %
Energy prices	Current energy prices	Current energy prices + 50 %	Current energy prices + 100 %
CO_2-follow-up costs	0 EUR/t_{CO2} a	40 EUR/t_{CO2} a	80 EUR/t_{CO2} a
Energy price increase	2 %/a	4 %/a	6 %/a
Location	Northern Europe	Central Europe	Southern Europe
Technology combination of building envelope and heating	National standard envelope + natural gas heating	As-built	
PV	No PV	133 kWp	

Table 17: Investment costs and technical data for the parameter "building envelope" of the case study Green Home Nanterre

	LEVEL 1: NATIONAL STANDARD	LEVEL 2: AS BUILT
Costs of external walls	195 EUR/m²	435 EUR/m²
U-value of external walls	0.35 W/m²K	0.202 W/m²K
Costs of floor	160 EUR/m²	160 EUR/m²
U-value of floor	0.25 W/m²K	0.25 W/m²K
Costs of roof	150 EUR/m²	241 EUR/m²
U-value of roof	0.25 W/m²K	0.078 W/m²
Costs of windows	550 EUR/m²	297 EUR/m²
U and g-value of windows	1.70 W/m²K	0.83 W/m²K

Table 18: Investment costs for the parameter "heating" of the case study Green Home Nanterre

	LEVEL 1: NATURAL GAS	LEVEL 2: AS BUILT
Costs	648,683 EUR	150,376 EUR

Table 19: Investment costs for the parameter "PV" of the case study Green Home Nanterre

	LEVEL 1: NO PV	LEVEL 2: 133 kWp
Costs	-	274,397 EUR

CHAPTER 4

ASSUMPTIONS AND BOUNDARY CONDITIONS

4.ASSUMPTIONS AND BOUNDARY CONDITIONS

4.1. BOUNDARY CONDITION FOR ECONOMIC EVALUATION

The construction costs of the buildings (as shown in the previous chapters) were provided by the project partners ATP, Bouygues and Skanska. All buildings have already been constructed, and therefore real cost data was available. The costs for the varied technologies and building elements were also directly provided by those project partners. If necessary, assumptions were made according to the CRAVEzero database of WP4. All costs are reported as "net costs" (excluding VAT). Land costs and excavation costs were on principle taken into account. The considered buildings are located in Austria, France and Sweden. Therefore climate data files were generated with Meteonorm 7.1.8.29631.

The economic evaluation of the variants is based on an observation period of 40 years (see also Table 20), which was previously defined in Deliverable D2.2 "Spreadsheet with LCCs". As for the 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 are based on the gathered data in D2.2 and the CRAVEzero database of WP4. These lifespans have also been already used in the Deliverables D6.1 and D6.2. Cost drivers can also be determined by evaluating individual parameters in relation to costs. The following cost items are taken into account: financing costs (planning and construction), 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 electricity). 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 projects KoPro LZK+ and CRAVEzero.

Table 20: Boundary conditions for the economic evaluation

ECONOMIC BOUNDARY CONDITIONS	REFERENCE
Observation period	40 years
Equity interest rate	1.51 %
Inflation rate	2 %
Discount rate	3 %
Credit period	25 years
Interest rate bank credit	3 %

4.2. MAINTENANCE COSTS

To consider the costs during the operational phase of the building, life cycle maintenance costs were applied as a fraction of the investment costs per year. These maintenance costs were gathered from the LCC-spreadsheets (see Deliverable 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 21. 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 managers.

Table 21: Summary of the most important maintenance costs and maintenance intervals

POSITION	ACTIVITY	INTERVAL	SHARE OF INVESTMENT COSTS	UNIT
Exterior wall	Maintenance	Annually	1.5 %	EUR/a
Floor construction	Maintenance	Annually	1.5 %	EUR/a
Flat roof construction	Maintenance	Annually	1.5 %	EUR/a
Windows and doors	Maintenance	Annually	1.5 %	EUR/a
Ventilation system with heat recovery	Maintenance	Annually	4.0 %	EUR/a
Air distribution system	Cleaning and maintenance	Annually	6.0 %	EUR/a
District heating transfer station	Maintenance	Annually	3.0 %	EUR/a
Ground source heat pump	Maintenance	Annually	3.0 %	EUR/a
Air heat pump	Maintenance	Annually	3.0 %	EUR/a
Thermal collectors	Maintenance	Annually	1.0 %	EUR/a
PV system	Maintenance	Annually	1.0 %	EUR/a

4.3. REPLACEMENT AND 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. Note: The end-of-life analysis was not included in the parametric energy and costs calculations but a separate chapter was dedicated to this topic (see chapter 9). 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 22 lists the technical lifetime of the building elements, which were gathered from the D2.2 and the CRAVEzero database of WP4, and which have already been used in the Deliverables D6.1 and D6.2.

Table 22: 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		

4.4. ENERGY PRICES AND PRICE INCREASE

The energy costs were calculated for each investigated variant based on the final energy demand of the variant. If PV was present in the specific variant, 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 (see Table 23). The electricity price was derived from the LCC tool in WP2 and cross-checked with the values from the partners.

Table 23 gives an overview of the used energy prices of the different energy sources in Austria, France, Italy and Sweden.

Table 23: Energy prices as boundary conditions of the economic efficiency calculation

ENERGY CARRIER	AUSTRIA	FRANCE	ITALY	SWEDEN	UNIT
Natural Gas	0.060	0.086	0.095	0.125	EUR/kWh
Electricity	0.187	0.146	0.216	0.220	EUR/kWh
District heating	0.090	Not relevant	0.100	0.090	EUR/kWh
Wood Pellet	0.050	Not relevant	0.070	0.050	EUR/kWh
PV feed-in tariff	0.048	0.060	0.070	0.060	EUR/kWh

For the case study iR-headquarter also a scenario was defined, in which the price sensitivity was investigated (the parameter is called "sensitivity"). In this scenario the energy price increase and the feed-in tariffs were adapted. In total four different levels were defined and investigated. Table 24 shows the assumptions on these four levels.

Table 24: Energy price and feed-in tariffs in the four levels of the parameter „sensitivity"

	LEVEL 1: STANDARD	LEVEL 2: HIGH	LEVEL 3: LOW	LEVEL 4: PHPP DEFAULT
Energy price increase per year	1.0 %	2.0 %	0.5 %	0 %
Increase of PV feed-in tariff per year	1.7 %	2.7 %	0.7 %	0 %

4.5. ANALYSIS OF THE USER BEHAVIOUR

Additionally, also a sensitivity analysis was carried out to investigate the influence of different user behaviour on the results. As already indicated in the description of the investigated parameters of each case study, four different user behaviours, which range from inefficient user behaviour (level 1), over a standard user behaviour (level 2) to efficient user behaviour (level 3). For comparison also the default settings from PHPP were used (level 4).

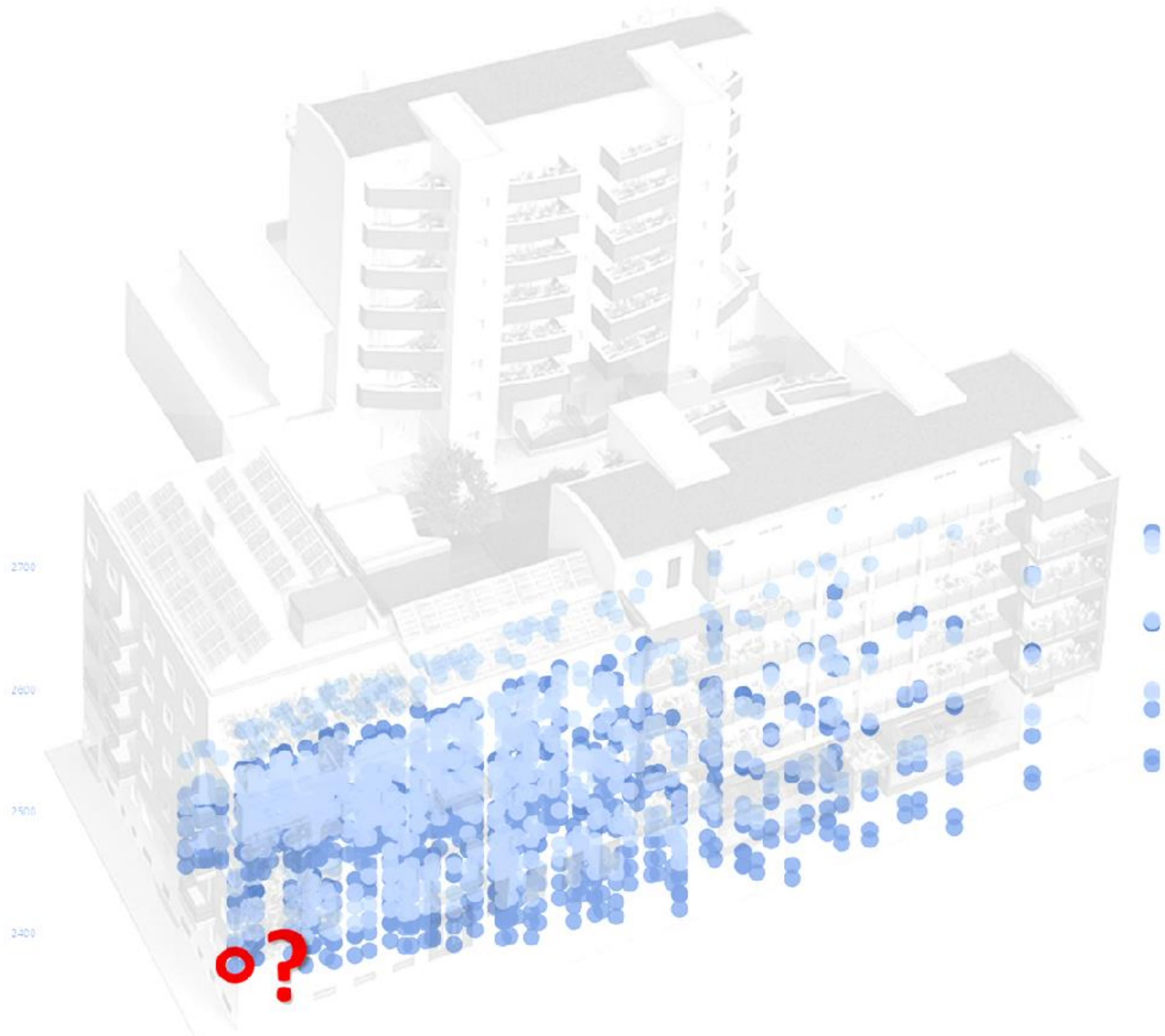
Table 25 gives an overview of the four different user behaviours and the parameters that were varied.

Table 25: Description of the four different user behaviours

PARAMETER	LEVEL 1: NOT EFFICIENT	LEVEL 2: STANDARD	LEVEL 3: EFFICIENT	LEVEL 4: PHPP DEFAULT
T_{room} (during heating period)	23 °C	22 °C	21 °C	20 °C
DHW-demand (at 60°C)	48.5 l/d	33.3 l/d	29 l/d	33.3 l/d
Misuse of external blinds during winter time	+20 %	+10 %	0 %	0 %
Electrical loads	35 kWh/m²a	26.6 kWh/m²a	20 kWh/m²a	26.6 kWh/m²a
Additional window ventilation during winter time	+0.1 1/h	+0.05 1/h	0.0 1/h	0.0 1/h

CHAPTER 5

PARAMETRIC MULTI-OBJECTIVE ENERGY AND COST ANALYSIS IN THE LIFE CYCLE OF NEARLY ZERO ENERGY BUILDINGS



5.METHODOLOGY

5.1. EXHAUSTIVE SEARCH METHOD

The term "multi-objective exhaustive search / parametric analysis" in this report is defined by a brute-force algorithm 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. Brute-force is an exhaustive search method that systematically takes into account all possible variants for a given solution and checking whether each variant satisfies the problem statement (University of Washington, no date). It is based on trial and error where the computer's fast processing power is used to solve a problem, rather than to apply advanced genetic algorithms. Therefore, with the brute-force method and the investigation of all possible variant combinations, all solutions are considered. It offers the advantage that statistical evaluations can be made and distributions can be derived. The most significant benefit is that this concept can also be applied to more than two objectives or optimisation goals. It, therefore, provides a sound basis for a multi-target decision-making framework, so that different actors can decide between optimal solutions for different objectives. This approach seeks to explore a set of optimal solutions rather than to find a single optimal solution (Chiandussi *et al.*, 2012).

A big disadvantage is the vast number of variants, by solving the problem by checking all the possible causes which are slow. Due to its time complexity based on the limited computational power of calculation the possibility of several thousand variants, it also restricts the calculation methods. If, for example, dynamic building simulations are used to analyse a building, where each simulation takes several hours, it is hardly possible to calculate thousands of variants with a manageable amount of computing time. The difference between a conventional design method and the parametric optimization with an exhaustive search method is shown in following Figure 11.

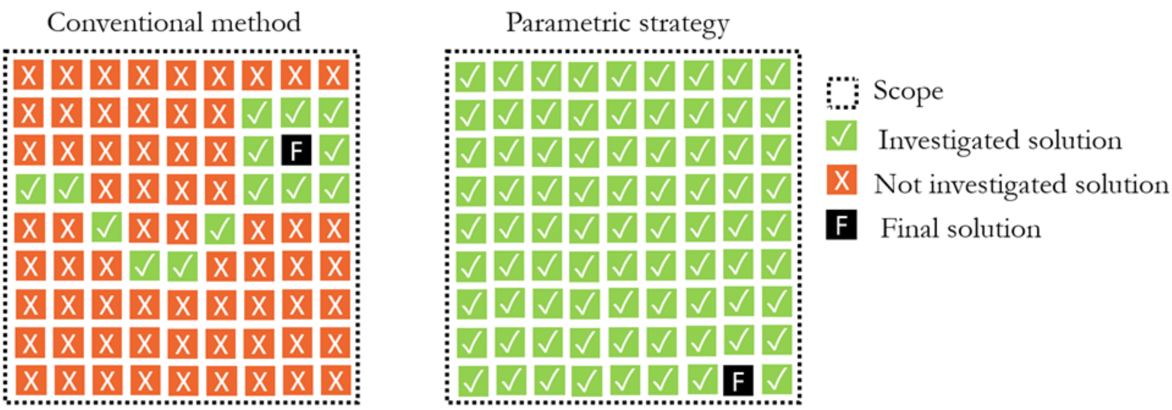


Figure 11: Comparison of conventional optimisation method vs parametric analysis (Hatt et al., 2018)

The advantage of the conventional search of the optima usually lies in the manageable number of variants and thus the reasonable effort. The disadvantage, as shown in Figure 11, is that only a local optimum can be found and not the best global solution or efficient neighbours. For example, it allows finding near-optimal design alternatives, not merely the optimum.

5.2. OPTIMIZATION PROCEDURE

The method of energy-economic analysis is shown in Figure 12.

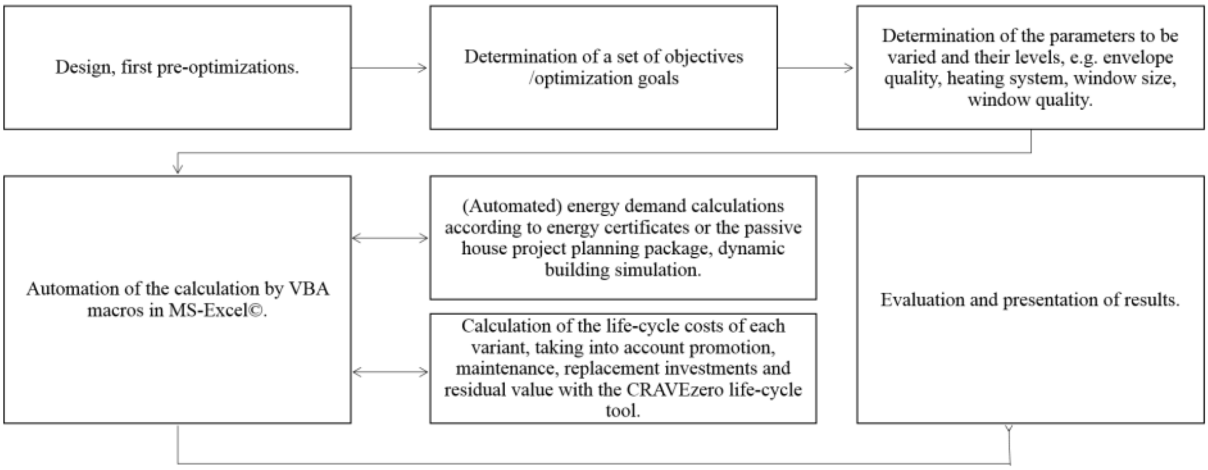


Figure 12: Method of energy-economic analysis - coupling between PHPP and CRAVEzero LCC tool

This method is based on the ISO 15686-5 (BSI ISO 15686-5, 2008) for life cycle cost calculation and the PHPP software (Passive House Institute, 2015) automated by a VBA macro that has been developed by the authors. With this method, several ten thousand different variants per case could be calculated in a manageable amount of time. The ISO 15686-5 provides the main principles and features of an LCC calculation, while the European Code of Measurement describes an EU-harmonised structure for the breakdown of the building elements, services, and processes, in order to enable a comprehensive evaluation of the building life costs in this study.

The software PHPP 9 has been used for energy performance analysis. This tool summarises all the information dealing with the energy-related features of the building components and services and provides a comprehensive overview of the technologies installed. By following this approach, the calculations are not directly comparable with national requirements, e.g. regarding the energy efficiency. This means that national legal requirements are subsequently not taken into account in the definition, calculation and analysis of variants and would require a separate control with national tools according to the national law.

5.3. LIFE CYCLE COST CALCULATION

According to the ISO 15686-5:2008, the LCC of a building is the Net Present Value (NPV), that is the sum of the discounted costs, revenue streams, and value during the phases of the selected period of the life cycle. Accordingly, the NPV is calculated as follows:

$$X_{NPV} = \sum_{n=1}^{p} \frac{C_n}{(1+d)^n}$$

C: costs occurred in year n;
d: expected real discount rate per annum (assumed as 1.51 %);
n: number of years between the base date and the occurrence of the cost;
p: period of analysis (40 years).

The analysis is based on standard values from EN 15459:2018 that provides yearly maintenance costs for each element, including operation, repair, and service, as a percentage of the initial construction cost. The input parameters and boundary conditions were described in chapter 4.

Table 26: Overview of the included costs of the life cycle cost calculation

			Life cycle phases	Included costs
Whole life cycle costs			1. Political decision and urban design phase	Non-construction costs (costs of land, fees and enabling costs, externalities)
	Life cycle cost	**Initial Investment**	2. Building design phase	Building design costs
			3. Construction phase	Construction and building site management costs
			4. Operation phase	Energy and ordinary maintenance costs
			5. Renovation phase	Repair and renovation costs
			6. Recycling, dismantling and reuse phase	Residual value of the elements

In order to provide a homogeneous and comparable estimation of the energy costs, the evaluation is based on the calculated energy demand by using the PHPP evaluation tool. In particular, for estimating both the costs and the revenues (due to the renewables installed), the energy produced from renewables is considered in the energy balance as a positive contribution to energy consumption, and the revenues from the renewables have been discounted from the energy costs.

5.4. KEY PERFORMANCE INDICATORS

The four main indicators used for the analysis of the calculation results are:

- financing costs
- life cycle costs
- balanced primary energy demand
- balanced CO_2 emissions.

The financing costs include costs for planning and actual investment in the form of the construction of the building (life cycle phases 2 and 3 from Table 26). The life cycle costs were described in chapter 5.3 and include the life cycle phases 2, 3, 4, 5 and 6 (only residual value) from Table 26.

"Balanced" in the case of primary energy and CO_2 emissions mean that the self-consumption of the PV system was considered, transferred into primary energy and CO_2 emissions by the conversion factors for electricity and then subtracted from the calculated primary energy demand and CO_2 emissions.

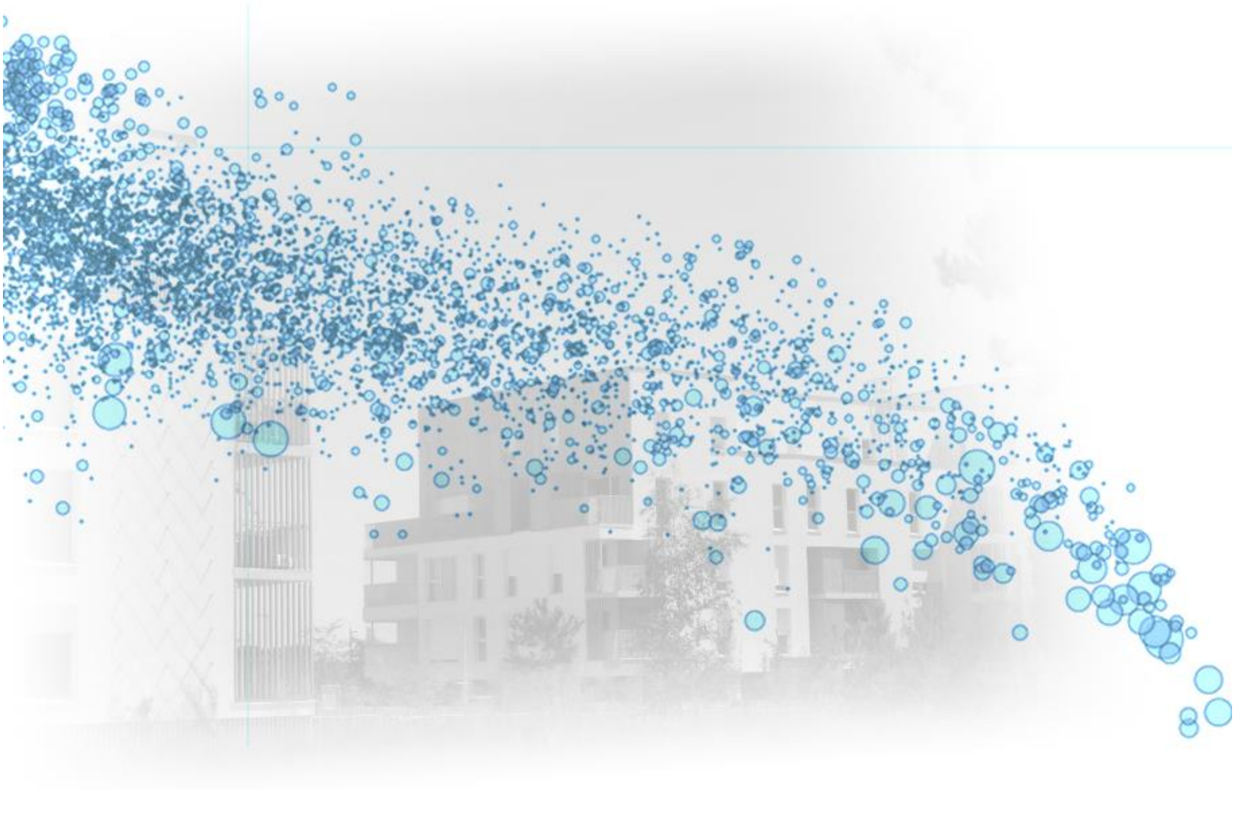
Written as a formula, using the balanced CO_2 emissions as an example:

$$\text{CO}_2\text{ emissions balanced } [\frac{kg}{m^2a}] =$$
$$\text{CO}_2\text{ emissions } [\frac{kg}{m^2a}] \text{ - self-consumption of PV } [\frac{kWh}{m^2a}] \text{ x conversion factor of electricity } [\frac{kg}{kWh}]$$

The primary energy demand and the CO_2 emissions only consider the energy respectively the emissions from the building operation. Energy and emissions from the building materials, so-called "grey energy" and "grey emissions" are not considered in this report and therefore nor included in these values.

CHAPTER 6

RESULTS OF THE PARAMETRIC ENERGY AND COST CALCULATIONS



6. RESULTS OF THE PARAMETRIC ENERGY AND COST CALCULATIONS

6.1. OVERALL RESULTS

At the beginning of chapter 6, some overall results are presented, giving an overview of the results of all four investigated case studies. Figure 13 shows the comparison of the financing costs and the balanced primary energy demand of the four case studies. Figure 14 shows the comparison of the life cycle costs and balanced CO_2 emissions. The results in these two figures allow the following analysis:

- The **financing costs range between 800 EUR/m² and 2500 EUR/m²a**. The lowest financing costs exist for the case study Green Home Nanterre, the highest for the case study iR-headquarter.
- The **life cycle costs of the four case studies range between 1400 EUR/m² and 4200 EUR/m²**. Due to the investigated parameters and the different influence of these, the highest and the lowest life cycle costs are achieved at the case study Green Home Nanterre.
- The **balanced primary energy demand ranges between 20 kWh/m²a and 250 kWh/m²a**, both values achieved at the case study Väla Gård.
- The **balanced CO_2 emissions lie in a range of 4 kg/m²a to 70 kg/m²a**. The lowest value is achieved by the case study Väla Gård, the highest value by the case study iR-headquarter.

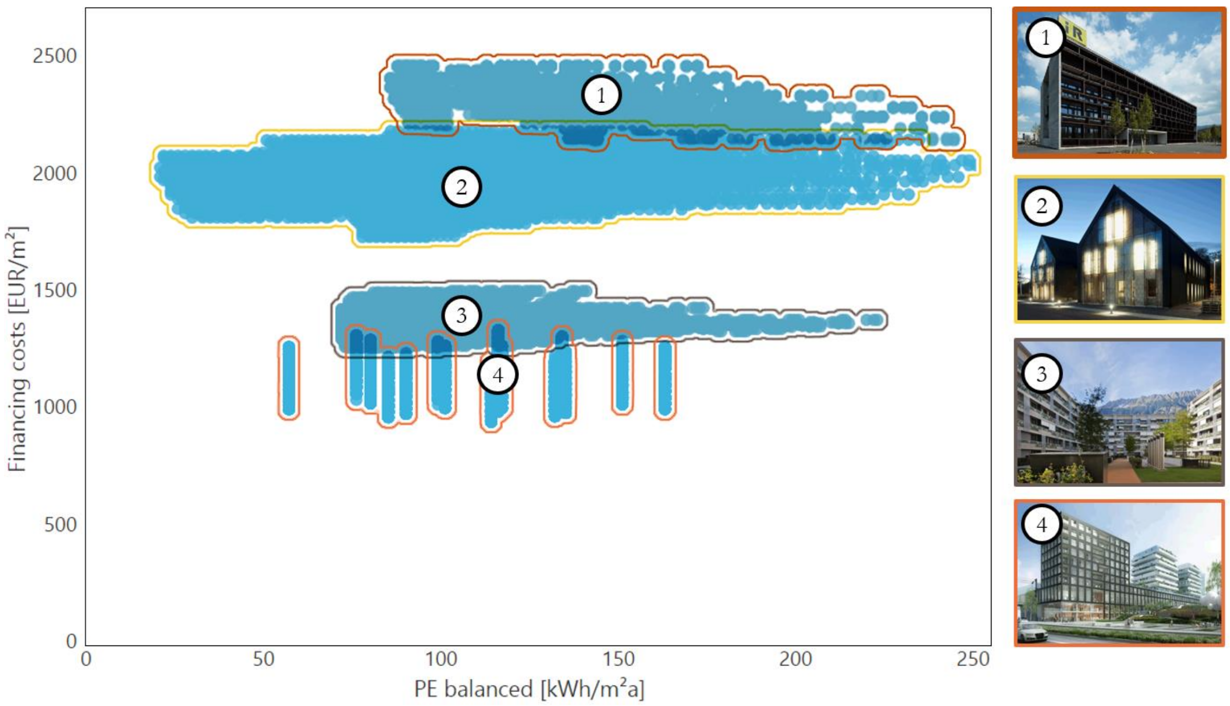


Figure 13: Financing costs (EUR/m²) in relation to the balanced primary energy (PE) demand (kWh/m²a) of all variants of the four case studies

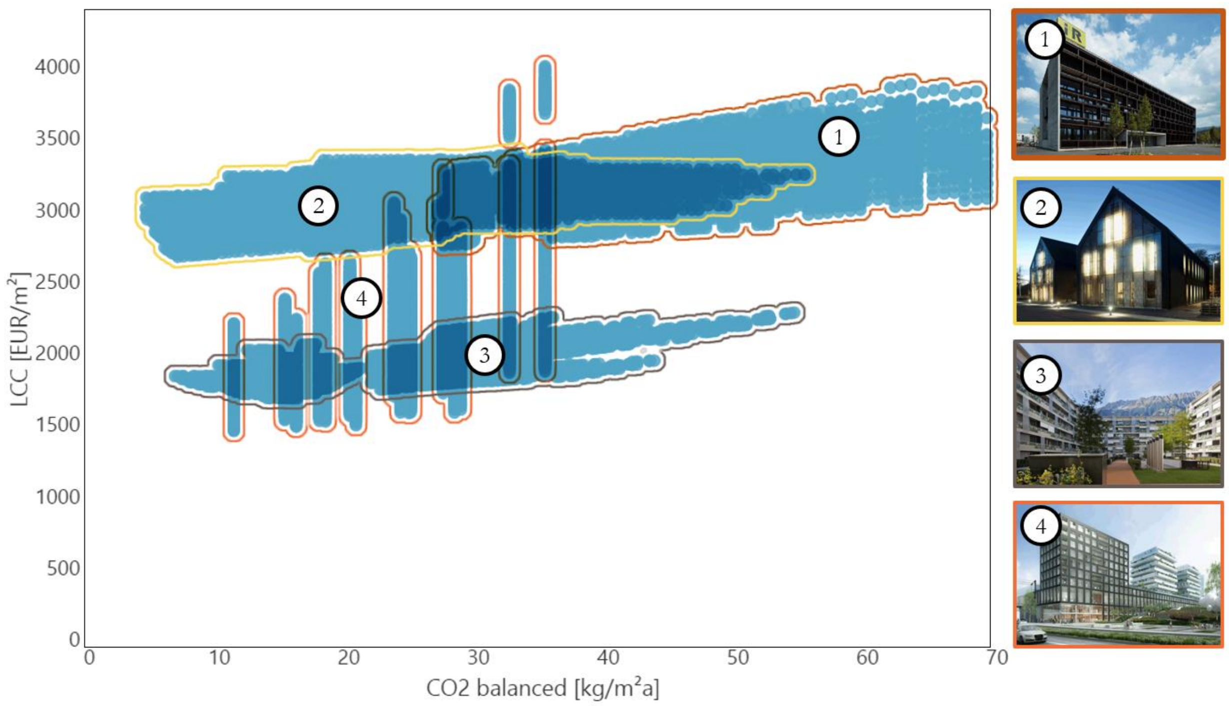


Figure 14: Life cycle costs (EUR/m²) in relation to the balanced CO_2 emissions (kg/m²a) of all variants of the four case studies

Further analysis of the overall results is shown in Figure 15. It shows the specific costs in the different phases of the life cycle of the four case studies. The minimum (min) and maximum (max) values indicate the min and max values per phase.

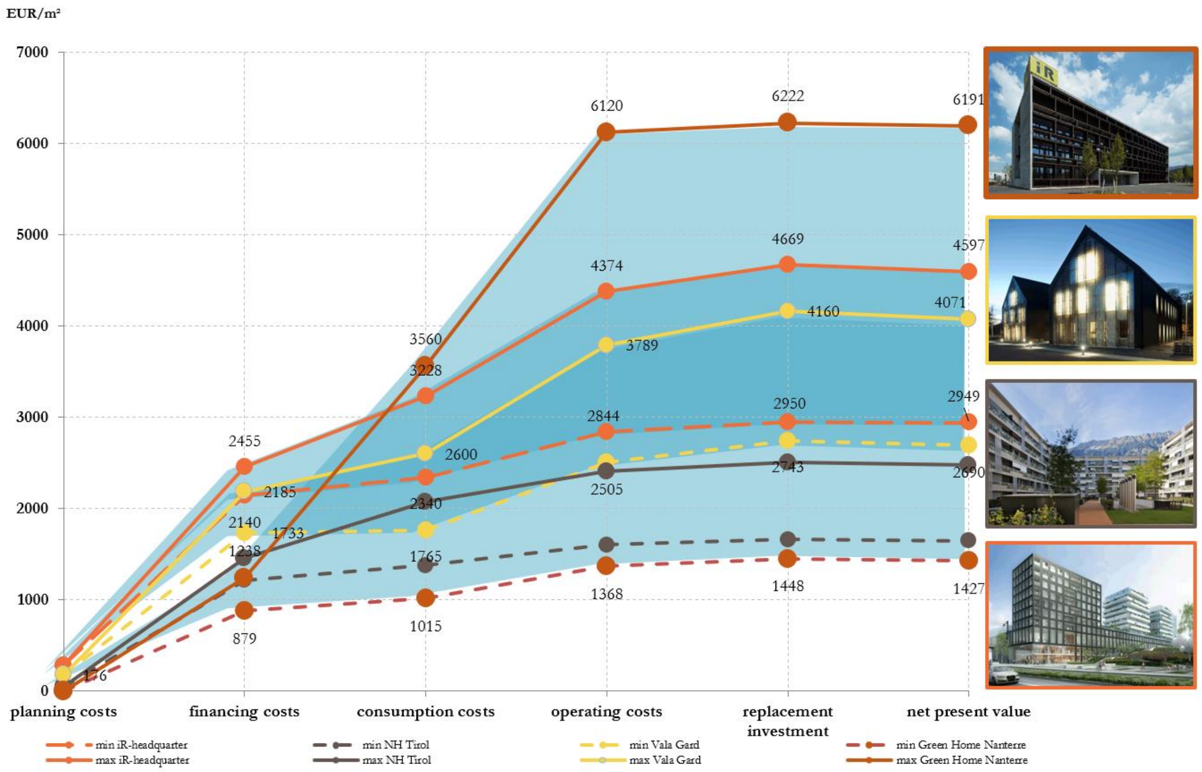
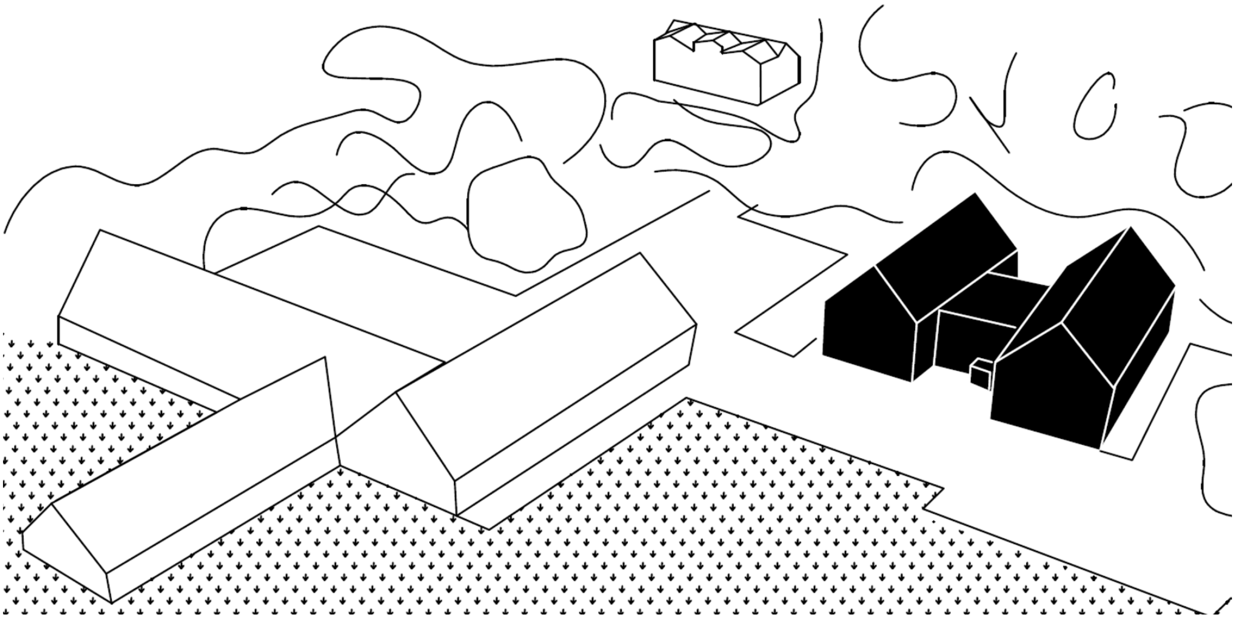


Figure 15: Specific costs (EUR/m²) in the different phases of the four case studies over the whole life cycle of the buildings; range between the different parameters indicated as the minimum (min) and the maximum (max) values; indicated values represent the min and max values per phase

6.2. CASE STUDY SPECIFIC RESULTS

6.2.1. VÄLA GÅRD



The focus of the investigation at the case study Väla Gard was on the architectural and urban planning factors. Therefore parameters like compactness, in the form of the area of the thermal envelope, the window area, shading of neighbouring buildings and the orientation were investigated. These parameters were combined with different technical parameters, describing the building envelope quality, the heating system and the PV system. As described in chapter 2 also three different locations (Northern Europe, Central Europe and Southern Europe) were calculated, to investigate the influence of the architectural, urban planning and technical parameters on the defined key performance indicators in three different climatic zones.

This chapter includes the calculation results of in total 39,366 different variants of the case study Väla Gard. For comparison of the results also a reference scenario was defined. This can be described by the following parameters:

- Standard user behaviour
- Thermal envelope quality according to the national standard
- Natural gas heating
- No PV system
- Compactness as-built
- Window area as-built
- Orientation as-built
- No shading by surrounding buildings
- Sea level: 0 m
- Location: Northern Europe

As overall result Figure 16 shows the specific costs in the different phases of the case study Väla Gard. The minimum and maximum values of all those variants are plotted in Figure 16, indicating minimum and maximum costs in each individual phase of the building life cycle.

The decline of the life cycle costs 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.

As mentioned before, for comparison reasons also the costs of the reference scenario are plotted (dashed line). This reference scenario is also the basis for the determination of cost-saving potentials. The indicated numbers show the deviation upwards and downwards. Looking at each phase of the building life cycle in detail, the results show that based on the reference scenario reductions between 9 % and 20 % are possible. In the other direction, the increases are in the range of 14 % to 23 %.

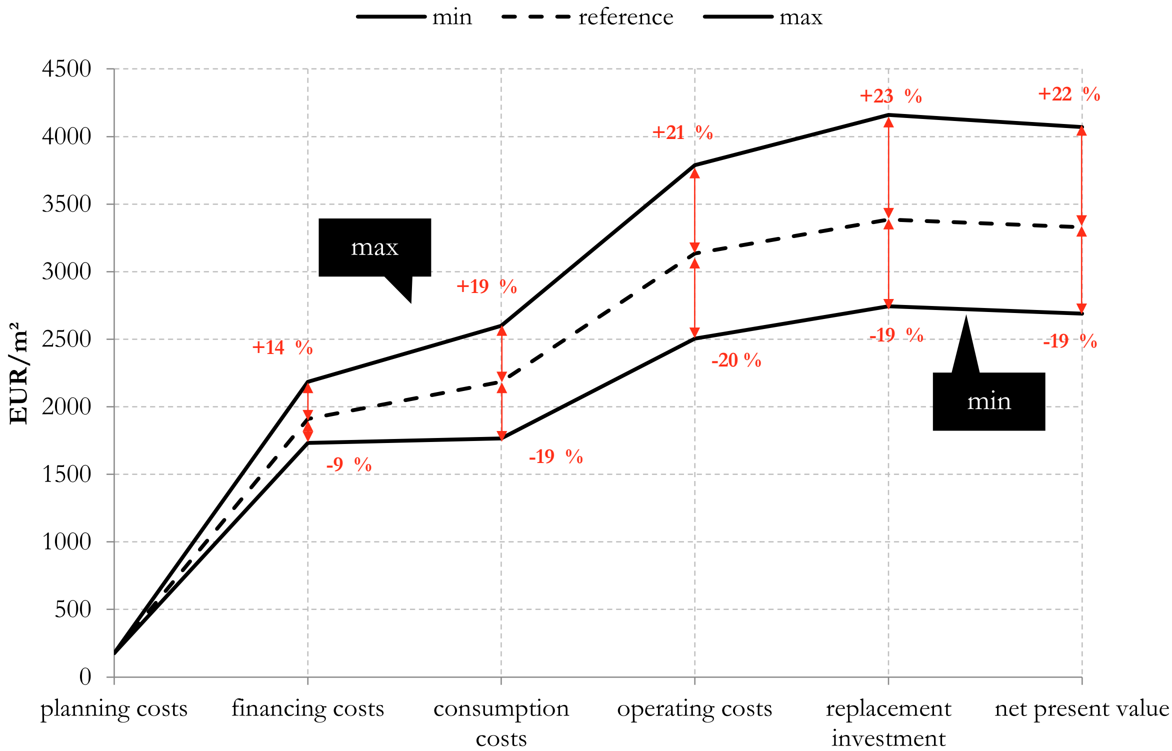


Figure 16: Specific costs (EUR/m²) in the different phases of the case study Väla Gard over the whole life cycle of the building; range between the different parameters indicated as the minimum (min), reference and the maximum (max) values per phase; percentages represent the deviation from the reference scenario

Figure 17 shows the cost curve for three different variants of the parametric calculations. For the nearly zero-energy building (nZEB) the variant with the highest life cycle costs was plotted. In comparison to that, the variant with the lowest life cycle costs was selected and illustrated. This variant is called "CRAVEzero". The dashed line is again representing the defined reference scenario (as described before).

In this figure, the percentages represent the possible cost reductions of the CRAVEzero variant in comparison to the nZEB variant. For the case study Väla Gard, this possible reduction is in the range of 13 % to 23 % in each phase.

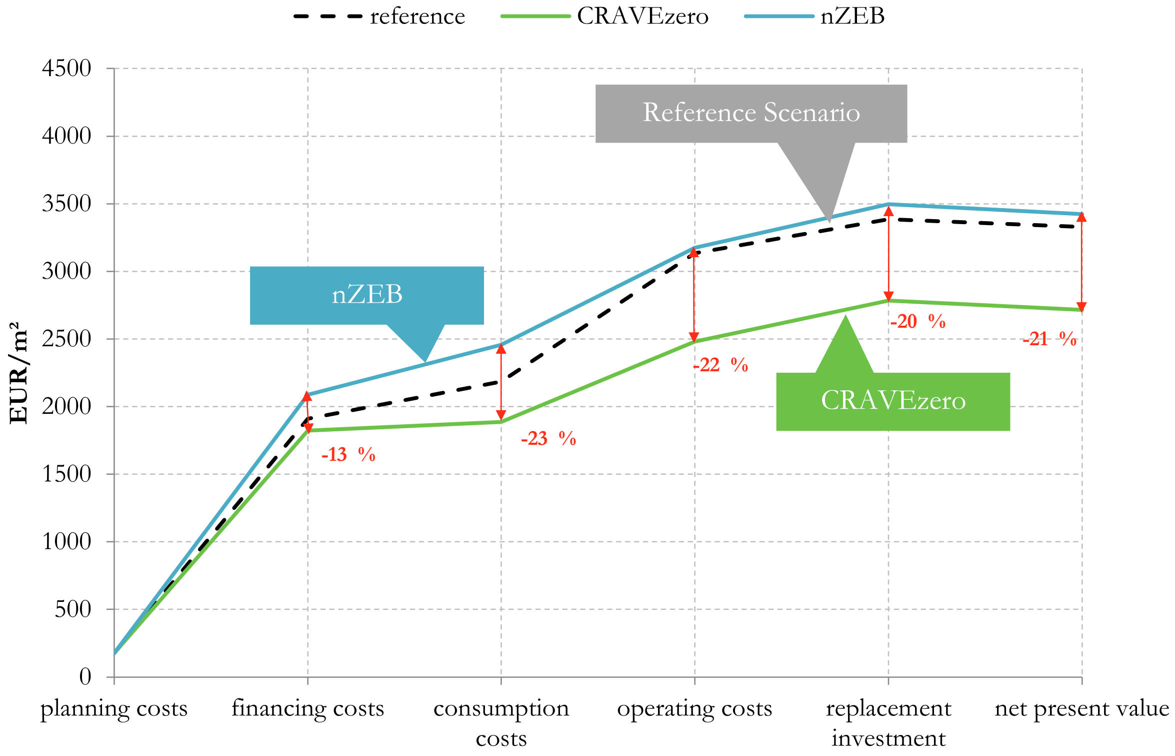


Figure 17: Cost performance (EUR/m²) of the case study Väla Gard over the whole life cycle of the building; comparison of nZEB variant with a building according to the CRAVEzero approach and the reference scenario

Further detailed evaluation of the calculation result is done by using parallel coordinate plots. This is one way to visualise multi-dimensional data. For the case study Väla Gard, an eight-dimensional graph is shown in Figure 18. This figure shows a parallel coordinate graph for five design parameters (compactness, orientation, window-wall-ratio, heating system and PV system) and the resulting investment costs, life cycle costs and balanced CO_2 emissions. For this, eight equally spaced vertical lines are plotted. The lines indicate the range of results, which is additionally supported by the parameter space graphic on the right side (scatter plot comparing the financing costs and the balanced CO_2 emissions).

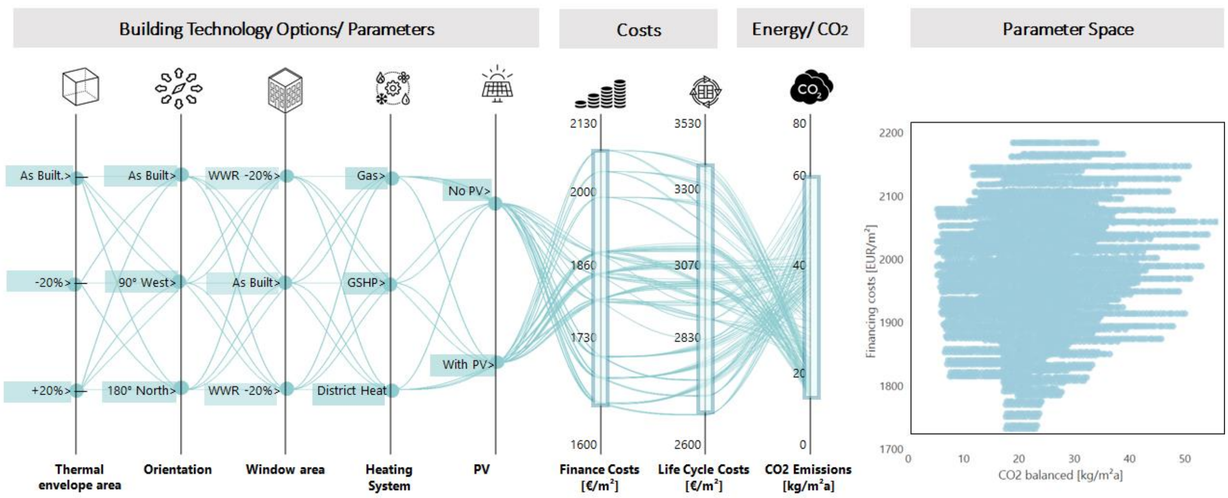


Figure 18: Eight-dimensional parallel coordinate plot for the case study Väla Gard

In Figure 19, the yellow line indicates the reference solution (as described at the beginning of this chapter). Tracing these lines enables beneficial combinations of design parameters to be identified and provides one way of visualising strategies. On the right side the parameter space is shown and the relation of the reference variant to all other possible solutions displayed as a scatterplot with balanced CO_2 emissions per square meter floor area on the x-axes and financing costs on the y-axes.

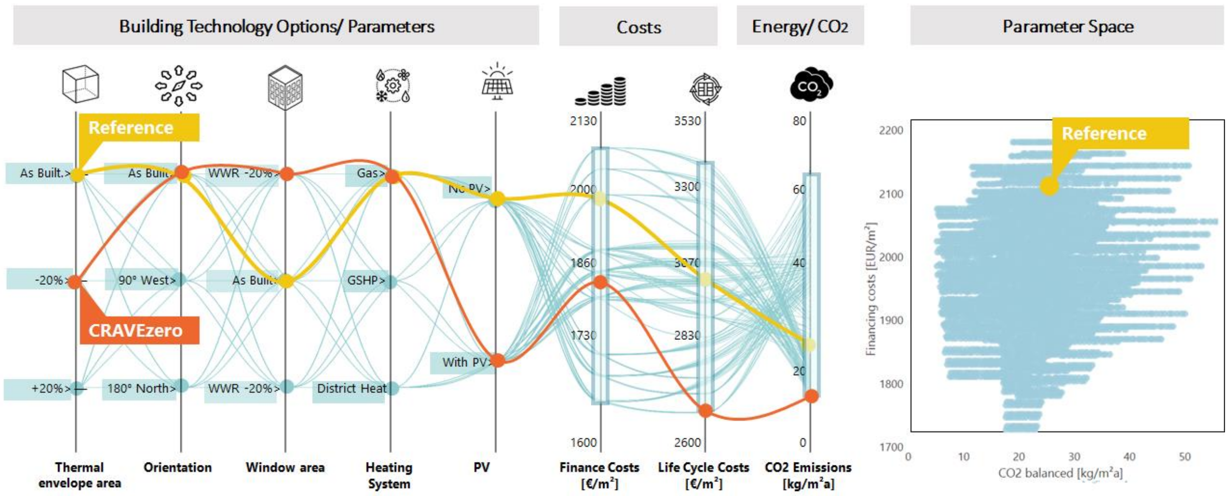


Figure 19: Eight-dimensional parallel coordinate plot for the case study Väla Gard, highlighting the reference scenario in yellow and the optimized CRAVEzero variant (from Figure 17) in red

In addition to the figures above Figure 20 shows a scatter plot, comparing the life cycle costs (LCC) and the balanced CO_2 emissions (CO_2). The grey dots represent the entire results, the yellow dot is the indication of the results of the reference scenario. In comparison to this reference scenario, some examples of results of individual parameters are shown (blue dots).

The analysis shows for example, changing the location of the building has a direct influence on the life cycle costs and the balanced primary energy demand. If the building would be constructed in Central or Southern Europe the life cycle costs and the balanced CO_2 emissions could be reduced. Also the switch to a passive house envelope or a nZEB envelope would reduce the life cycle costs and the balanced CO_2 emissions. An increase of the values noticeable at the parameters “sea level +1000 m” and “compactness +20 %”, which means that the area of the thermal envelope is increased by 20 %.

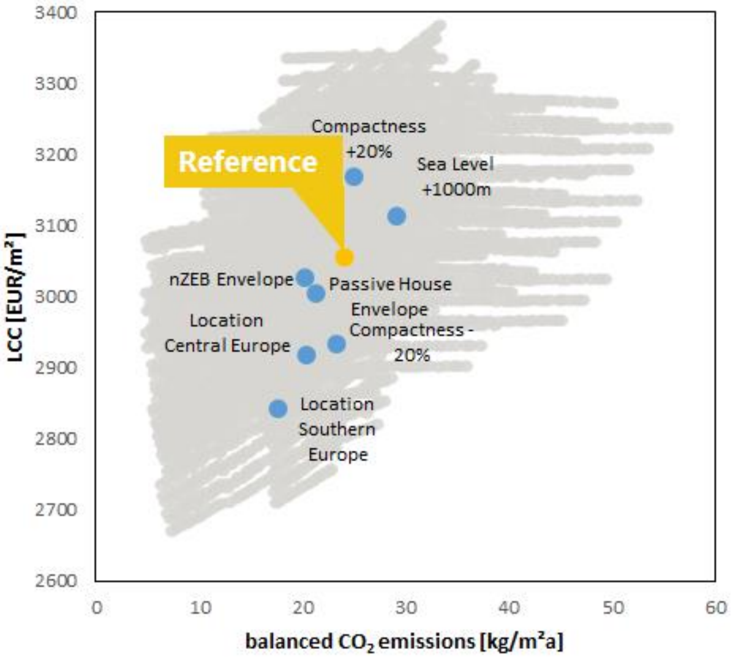


Figure 20: Comparison of the life cycle costs and the balanced CO_2 emissions of the reference scenario (yellow dot), examples (blue dots) and the entire results in the background (grey dots) for the case study Väla Gard

The following two figures show similar to the scatter plot in Figure 20, the results for selected technology combinations. So, a passive house envelope in combination with district heating, an increased area of the thermal envelope (by 20 %) and a window size which represents the actual built area (orange dots) was compared to a scenario where the building envelope quality fulfils the national requirements, the building is heated by a natural gas heating, the area of the thermal envelope, as well as the window area, are increased by 20 % (green dots) and a scenario where an nZEB envelope was combined with a ground source heat pump, a reduced window area (by 20 %) and an area of the thermal envelope which represents the parameter as-built (purple dots).

Figure 21 shows the comparison of the financing costs and the balanced primary energy demand for the selected technology combinations. Figure 22 shows the comparison of the life cycle costs and balanced CO_2 emissions.

The results show that the "orange-scenario" and the "green-scenario" achieve similar financing and life cycle costs, despite different envelope qualities and heating systems. The "purple-scenario" however, achieves reduced financing costs as well as reduced life cycle costs. The reason for that was identified in the reduced area of the thermal envelope and the reduced window area (compared to the other two scenarios). Regarding the balanced primary energy demand and the balanced CO_2 emissions, no big difference between the three highlighted technology combinations can be seen. In general, the value range is quite broad which leads to the conclusion that the influencing factors on the primary energy demand and the CO_2 emissions are others and diverse.

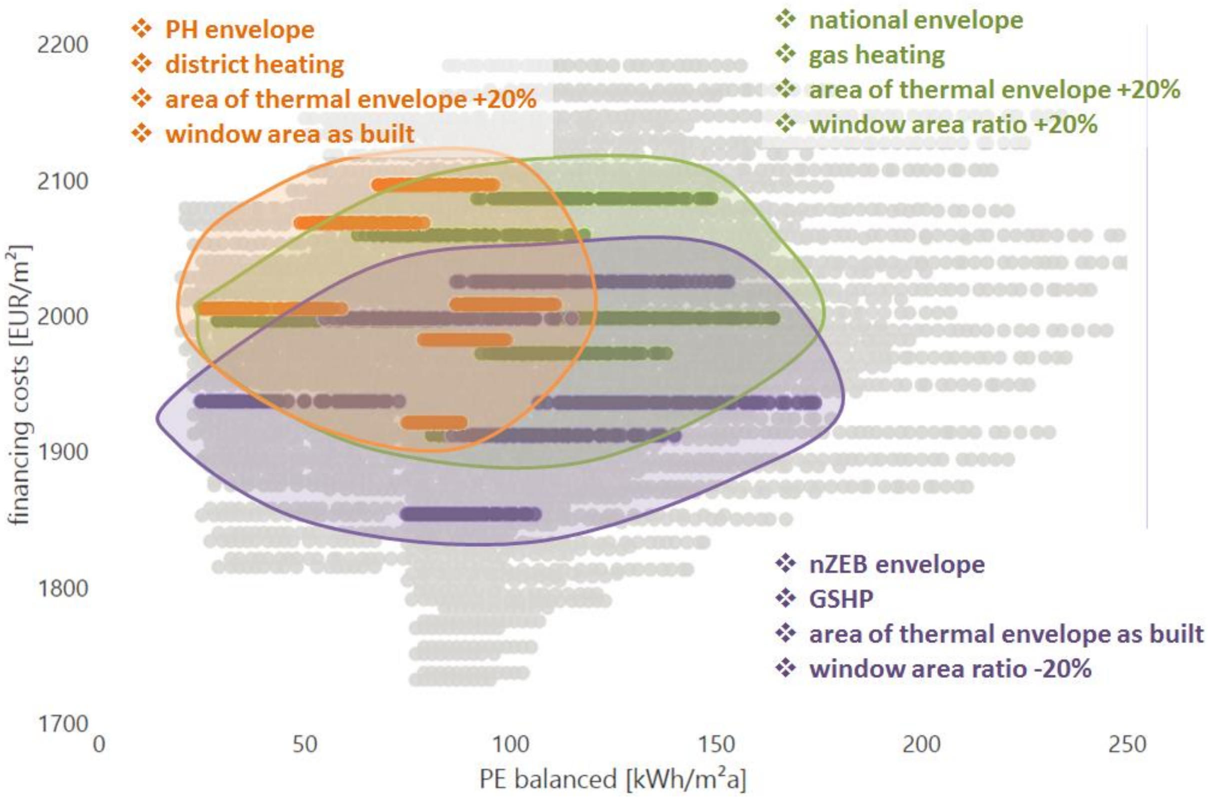


Figure 21: Analysis of the balanced primary energy (PE) demand related to the financing costs for different technology combinations of the case study Väla Gard

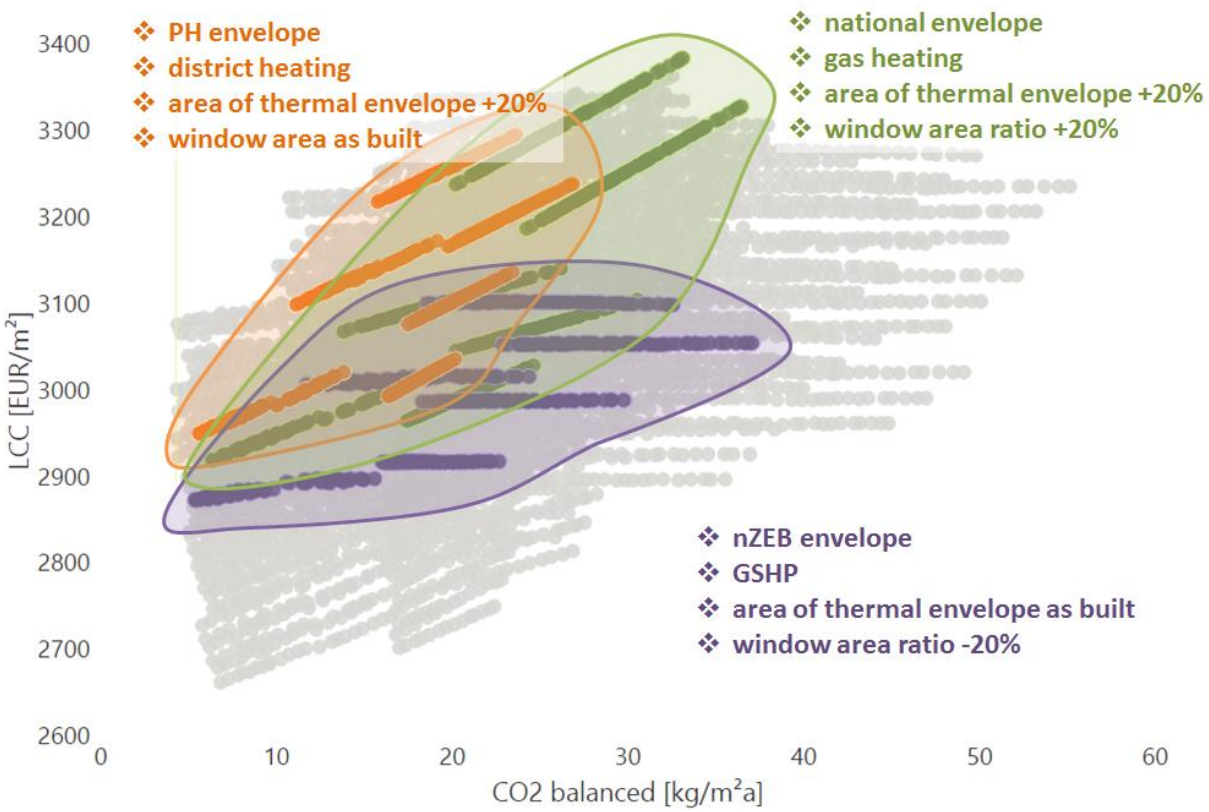


Figure 22: Analysis of the balanced CO_2 emissions related to the life cycle costs (LCC) for different technology combinations of the case study Väla Gard

The last evaluation results for the case study Väla Gard at this point is shown in Figure 23. It represents the graphical representation of the individual values in a matrix, compared to the reference scenario. For each of the key performance indicators, the reference scenario forms the starting situation. In the next step, only one parameter was changed at a time (in order as reported in the columns) and the result was compared to the reference value. The difference is expressed as a percentage. A negative value indicates a reduction, a positive value however points to an increase. Based on the value the matrix was coloured: reductions are green, an increase in red. Due to that colouring, this figure is also called "heat map".

		User behaviour		Compactness		Window to Wall Ratio		Sea Level		Orientation		Location		Envelope Quality	
	National Reference	Not efficient	Efficient	-20%	20%	-20%	20%	300 m	1000 m	+90°	+180°	Central Europe	Southern Europe	nZEB	Passive house
Investment Costs [€/m²]	1.718	0%	0%	-4%	4%	-1%	1%	0%	0%	0%	0%	-1%	-4%	1%	-1%
Life Cycle Costs [€/m²]	2.354	1%	0%	-4%	4%	-1%	1%	0%	2%	0%	0%	-4%	-7%	-1%	-2%
CO2 Emissions [kg/m²]	25	6%	-5%	-3%	3%	-1%	1%	3%	21%	3%	1%	-15%	-27%	-16%	-12%
PE Demand [kWh/m²a]	105	6%	-5%	-3%	4%	-1%	2%	4%	21%	3%	1%	-14%	-26%	-15%	-11%

Figure 23: Heat map of the entire parameters of the case study Väla Gard compared to the reference scenario

The next step is to estimate witch design parameters are most likely to be chosen to achieve the desired cost and energy performance goals for the case study Väla Gård. Therefore a linear inverse modelling approach was performed.

The performance objectives in different scenarios have been set as follows:

- S1: Objective - net present value limited to max 3,000 EUR/m²
- S2: Objective - balanced CO_2 emission limited to max 20 kg/m²a and balanced primary energy demand limited to max 85 kWh/m²a
- S3: Objective - financing costs limited to max 1,800 EUR/m²

The diagrams in Figure 24, Figure 25 and Figure 26 represent the probability distributions of the design parameters for different scenarios of objective from S1 to S3. The design parameters in these graphs represent the most significant ones computed out of the regression analysis based on the previous section. These graphs inform the designers of the possibilities they have for each parameter while being bounded to the associated energy or cost objectives. Moving from a limitation of the net present value (S1) to limiting the balanced CO_2 emissions and the balanced primary energy demand (S2) and finally low investment costs (S3) places more restrictions on each design parameter based on their importance in relation to the energy and cost objectives, and the dependencies between design parameters.

The probability distributions of design parameters in the first scenario, S1, where the net present value is limited to maximum 3000 EUR/m² are similar to uniform for shading system, user behaviour, orientation and compactness, which shows the lack of a strong design direction because of absence of an energy target. Considering only the net present value leads to solutions with standard envelope qualities, compact buildings, gas and district heating systems and since different countries are also considered a location in a Southern European country.

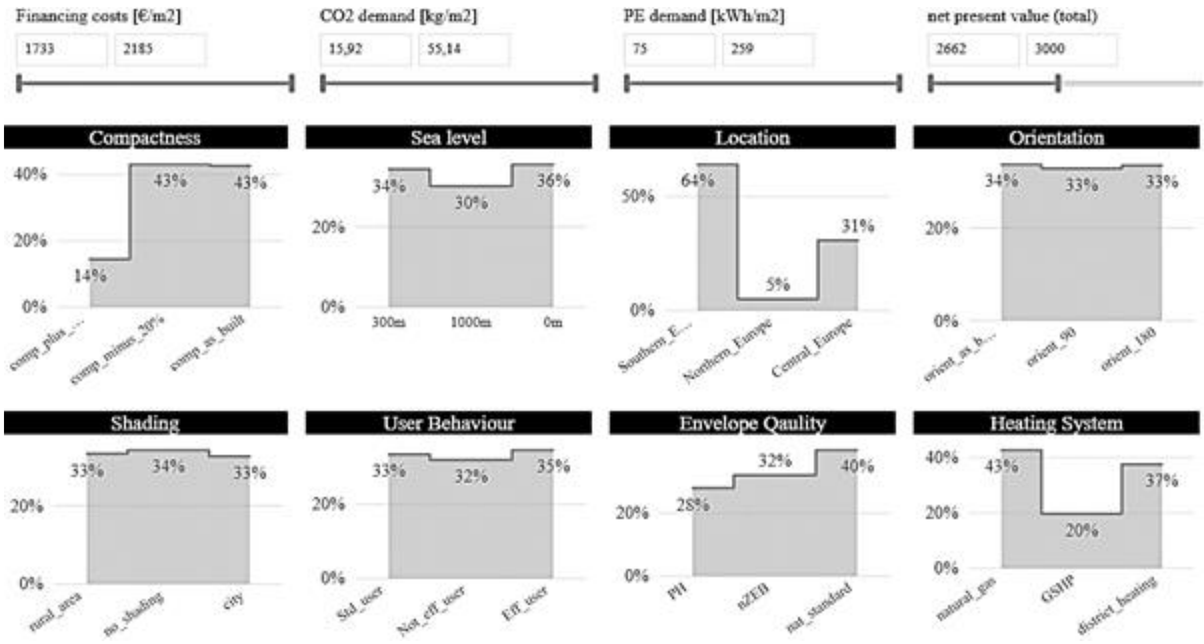


Figure 24: S1 - net present value limited to 3000 EUR/m²

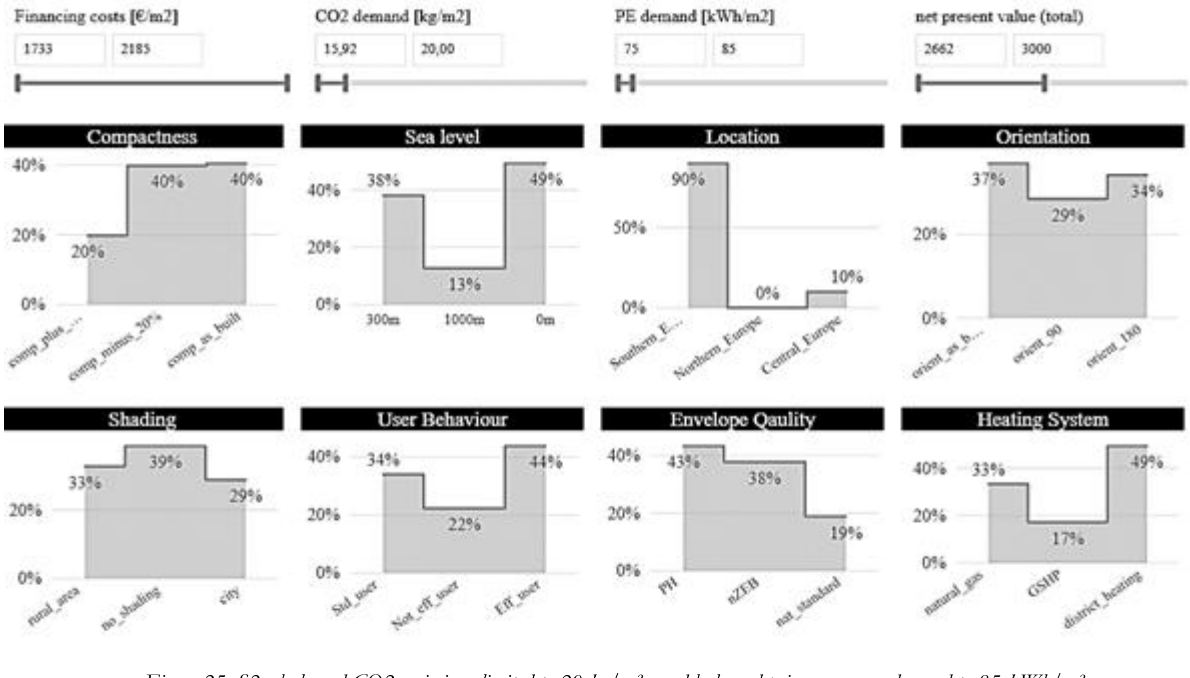


Figure 25: S2 - balanced CO2 emissions limited to 20 kg/m²a and balanced primary energy demand to 85 kWh/m²a

However, scenario 2, where next to a limitation of the net present value which is kept from S1 also the balanced CO_2 emissions is limited to max 20 kg/m²a and the balanced primary energy demand is limited to max 85 kWh/m²a suggests designers to optimize the envelope quality to achieve passive house standard and use district heating and considering the user behaviour to fulfil the nZEB energy target still keeping life cycle costs (Net-present value) low. This is not the final design solution for designers to make their decision upon. As mentioned in the introduction, design is an iterative process of decision making for building parameters while there are interdependencies between those parameters. The main concept of this method is for it to be implemented iteratively as each parameter is decided upon. In other words, as a designer decides on a building parameter, they define that parameter deterministically as one single value and run the inverse approach once again to see how that decision affects decisions on other parameters. In the third scenario (S3), after making decision of also limiting the financing costs to max. 1800 EUR/m², a further regression analysis was performed to see how this decision affects the rest of the parameters, which have been set in S1 and S2.

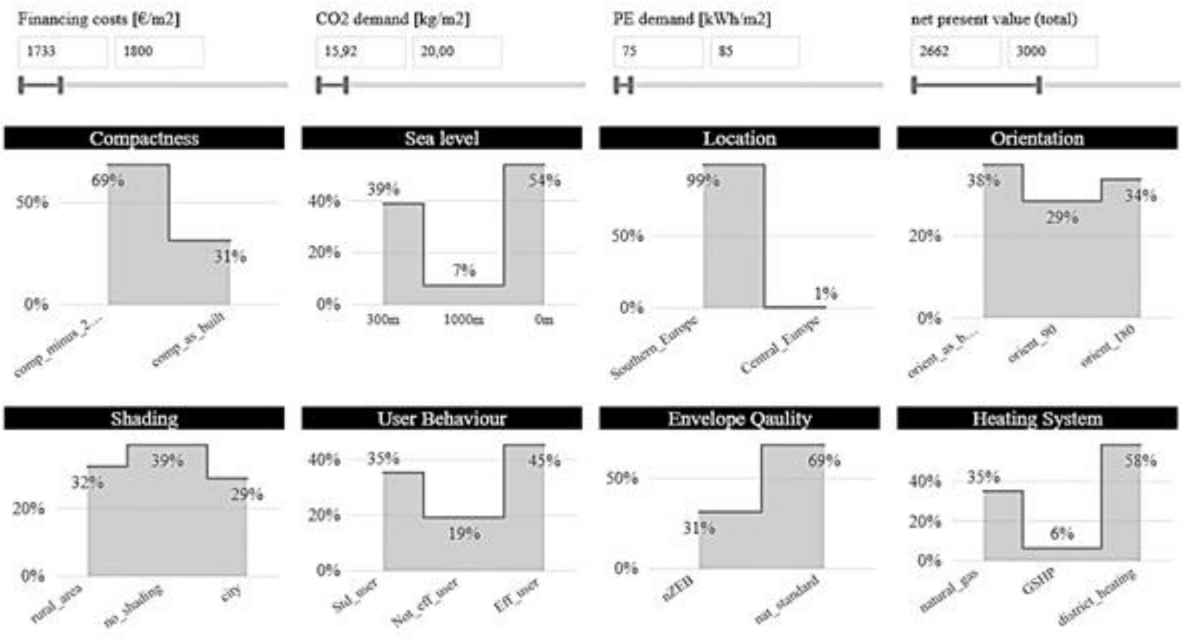
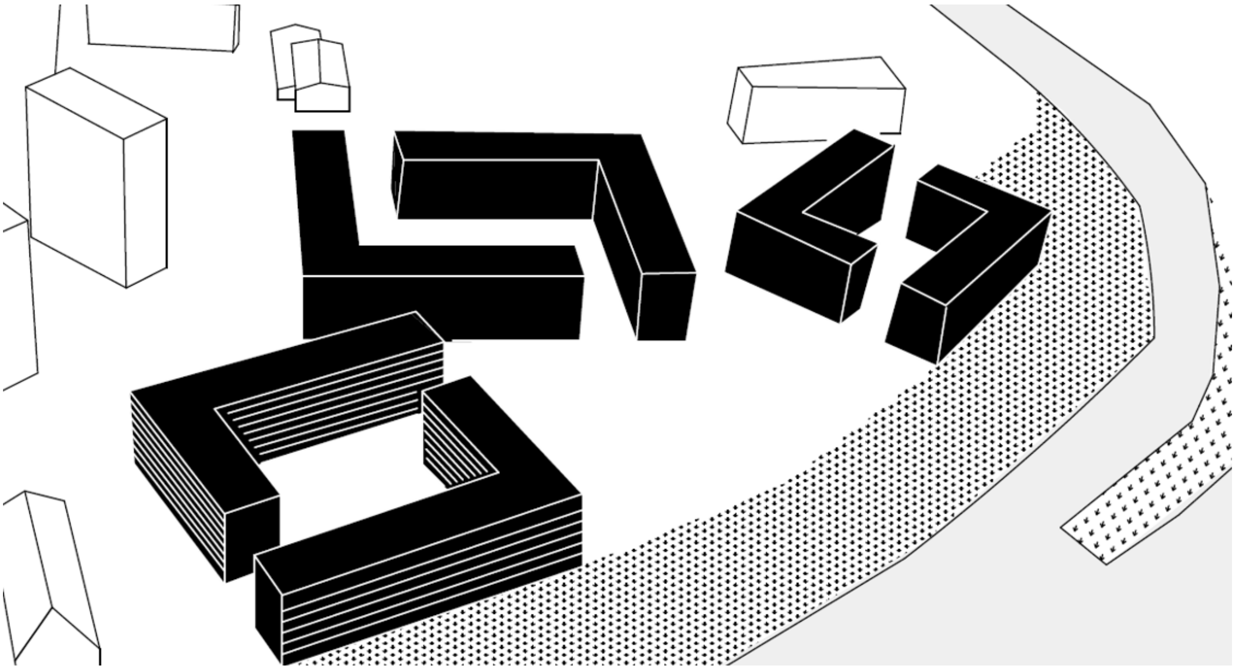


Figure 26: S3 - financing costs limited to 1800 EUR/m²

In the last scenario (S3) where we have a very aggressive target on financing costs next to the other limitations concerning energy and net-present value possible design parameters are further limited. It means that there are fewer possibilities for design with many restrictions on building parameters while different KPIs have to be fulfilled. Especially all derived solutions are now designed in Southern Europe caused by the lower construction costs and climatic conditions. Also, the necessity for a compact building now becomes essential. The envelope quality is now also restricted to national standard and nZEB envelope quality. Even though district heating is still a sustainable solution, ground source heat pump variants with these hard limitations on finance costs are hard to achieve limiting the solution space.

The linear inverse modelling procedure was proposed and developed that can generate a plausible range of design parameters given the preferred thermal energy performance at the early stage of an architectural design. This method deals with multiple performance objectives as input and inferences about the design parameters as output. It has been shown in the case study that such an approach also accounts for the iterative nature of an architectural design and promotes a step-by-step procedure for making a decision and updating information as each new decision is made. The results of the inverse modelling are probabilistic bracketing of each parameter that collectively will represent the feasible region of the design space. This can support a broad range of architectural design solutions while bounded in the defined energy and cost performance objectives.

6.2.2. NH TIROL



The focus of the investigation at the case study NH Tirol, was similar as done before for the case study Väla Gard, on the architectural and urban planning factors. Here again, parameters like compactness, in the form of the area of the thermal envelope, the window area, shading of neighbouring buildings and the orientation were investigated. These parameters were combined with different technical parameters, describing the building envelope quality and the heating system. In contrast to the case study Väla Gard, no PV system was investigated for the case study NH Tirol. But, again three different locations (Northern Europe, Central Europe and Southern Europe) were calculated, to investigate the influence of the architectural, urban planning and technical parameter on the defined key performance indicators.

This chapter includes the calculation results of in total 19,683 different variants of the case study NH Tirol. For comparison of the results also a reference scenario was defined. This can be described by the following parameters:

- Standard user behaviour
- Thermal envelope quality according to the national standard
- Natural gas heating
- Compactness as-built
- Window area as-built
- Orientation as-built
- No shading by surrounding buildings
- Sea level: 0 m
- Location: Central Europe

As overall result Figure 27 shows the specific costs in the different phases of the case study NH Tirol. The minimum and maximum values of all those variants are plotted, indicating the range of the costs in each individual phase of the building life cycle. As done also before, for comparison reason also the costs of the reference scenario are plotted (dashed line). This reference scenario is also the basis for the determination of cost-saving potentials. The indicated numbers show the deviation upwards and downwards. Looking at each phase of the building life cycle in detail, the results show that based on the reference scenario reductions between 6 % and 9 % are possible. In the other direction, the increases are in the range of 13 % to 37 %.

Compared to the results seen before for the case study Väla Gard (check Figure 15 and Figure 16), the cost curve of the reference scenario is closer to the minimum costs. Therefore the reduction potential is also lower.

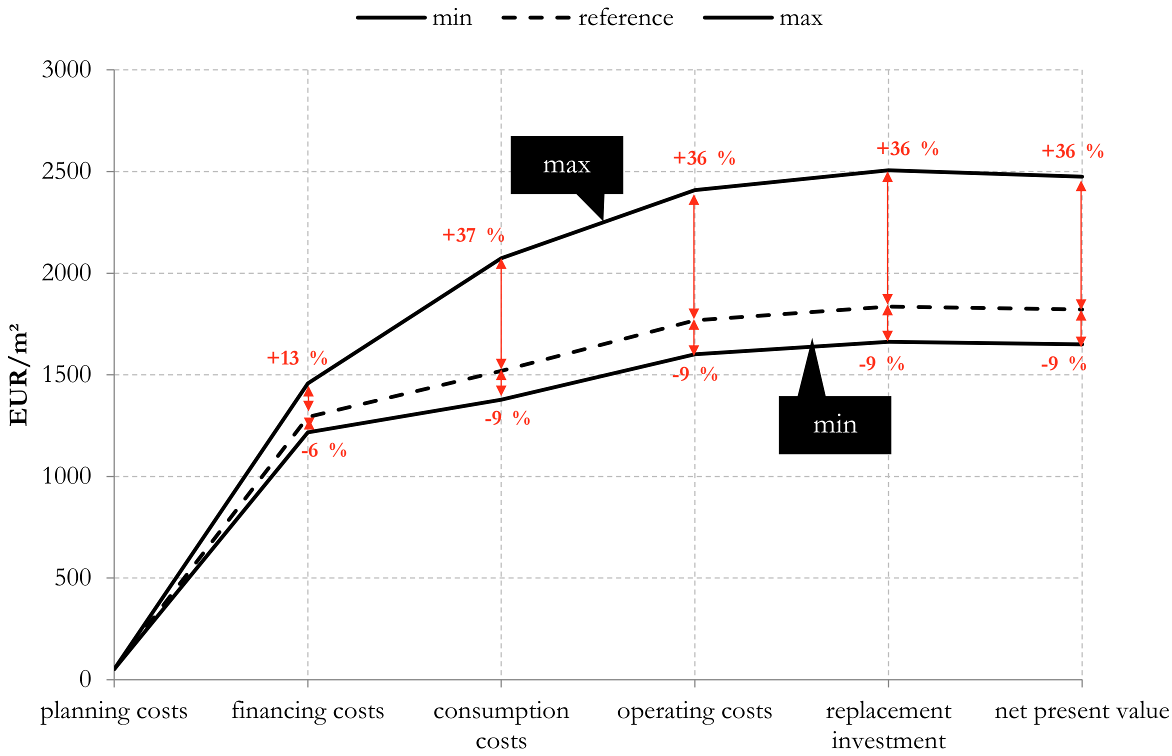


Figure 27: Specific costs (EUR/m²) in the different phases of the case study NH Tirol over the whole life cycle of the building; range between the different parameters indicated as the minimum (min), reference and the maximum (max) values per phase; percentages represent the deviation from the reference scenario

Comparing the results in Figure 27 with the results in Figure 28 it can be seen that the total reduction potentials between the maximum costs (nZEB) and the minimum costs (CRAVEzero) decrease, which is a result of the different approach (min/max values in each phase as seen in Figure 27 vs. min/max life cycle cost value as seen in Figure 28). In reality, the cost-saving potentials as seen in Figure 28 can be regarded as more realistic.

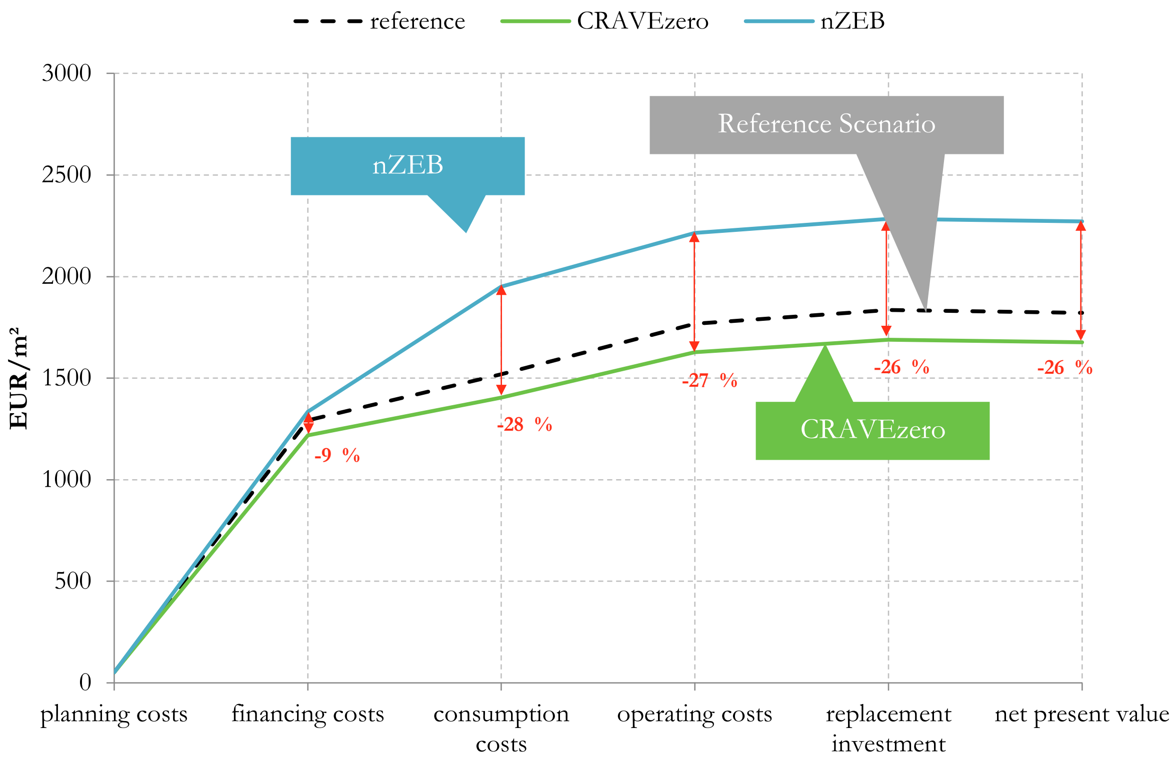


Figure 28: Cost performance (EUR/m²) of the case study NH Tirol over the whole life cycle of the building; comparison of nZEB variant with a building according to the CRAVEzero approach and the reference scenario

Further evaluation of the calculation result is also done by using parallel coordinate plots. For the case study NH Tirol, an eight-dimensional graph is shown in Figure 29. This figure shows a parallel coordinate graph for five design parameters (envelope quality, compactness, building orientation, window area and shading) and the resulting investment costs, life cycle costs and balanced CO_2 emissions. For this, eight equally spaced vertical lines are plotted.

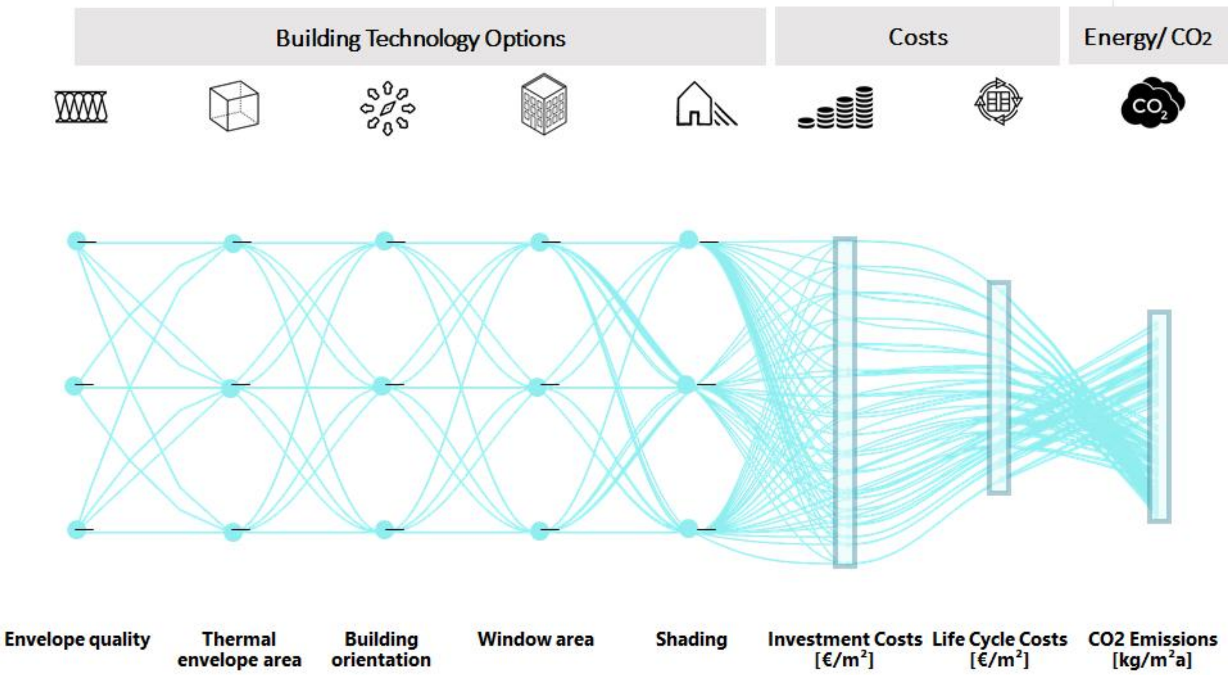


Figure 29: Eight-dimensional parallel coordinate plot for the case study NH Tirol

In Figure 30, the yellow line indicates the reference solution (as described at the beginning of this chapter). Tracing these lines enables beneficial combinations of design parameters to be identified and provides one way of visualising strategies.

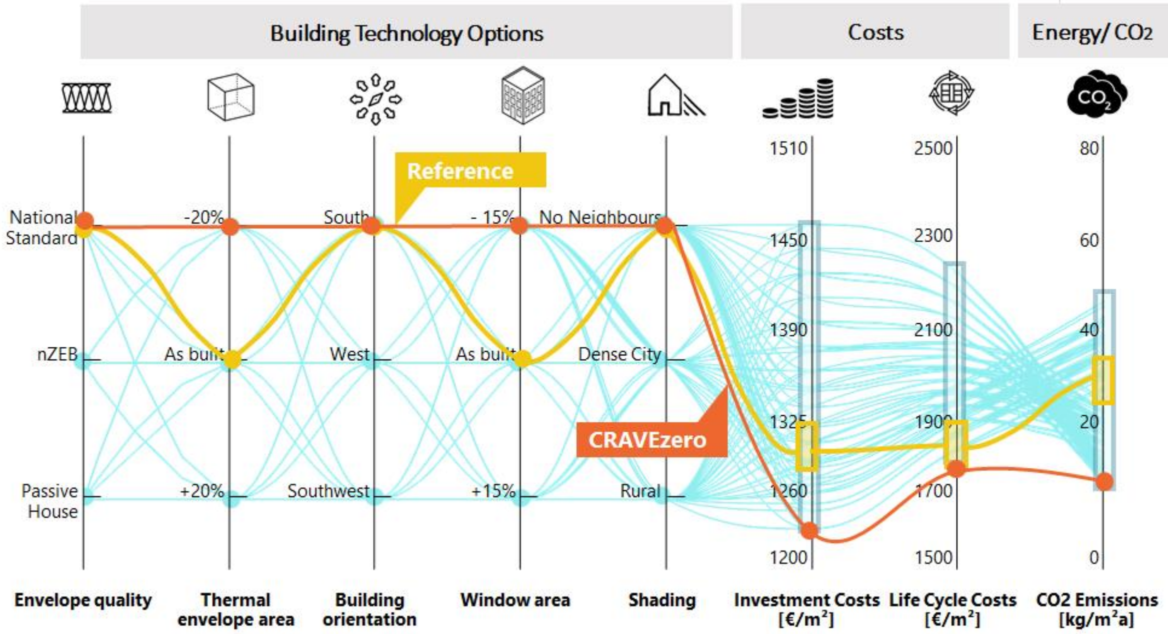


Figure 30: Eight-dimensional parallel coordinate plot for the case study NH Tirol, highlighting the reference scenario in yellow and the optimized CRAVEzero variant (from Figure 28) in red

In addition to the figures above, Figure 31 shows a scatter plot, comparing the life cycle costs (LCC) and the balanced CO_2 emissions. The grey dots represent the entire results, the yellow dot is the indication of the results of the reference scenario. In comparison to this reference scenario, some examples (blue dots) are shown. The analysis shows for example, that the biomass heating reduces CO_2 emissions and life cycle costs, the passive house envelope can also reduce the CO_2 emissions but increases the life cycle costs. The scenario where the building is situated in Northern Europe even leads to increased CO_2 emissions and increased life cycle costs.

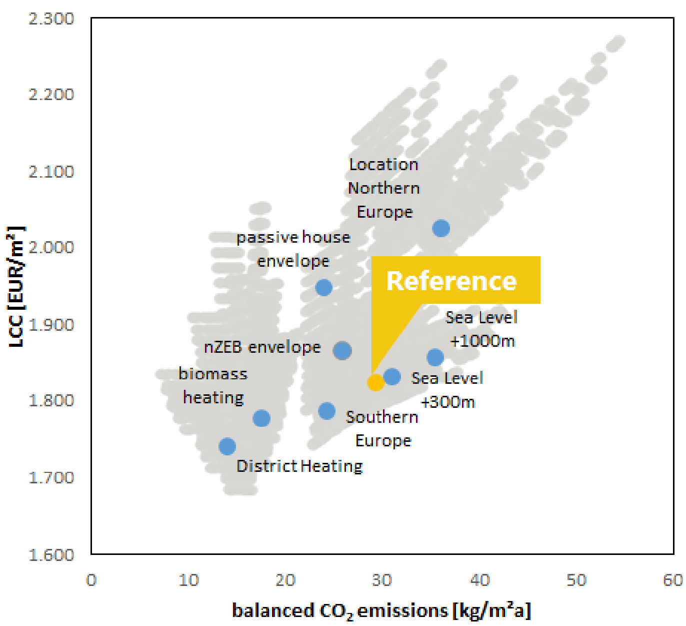


Figure 31: Comparison of the life cycle costs and the balanced CO_2 emissions of the reference scenario (yellow dot), examples (blue dots) and the entire results in the background (grey dots) for the case study NH Tirol

The following two figures show similar to the scatter plot in Figure 31, the results for selected technology combinations. So, a passive house envelope in combination with district heating and a city shading (orange dots) was compared to a scenario where a building with an envelope quality according to national standard was equipped with natural gas heating and is located in a city (green dots) and to a scenario where the building is equipped with a passive house envelope and has a reduced thermal envelope area and a reduced window area (purple dots).

Figure 32 shows the comparison of the financing costs and the balanced primary energy demand for the selected technology combinations. Figure 31 shows the comparison of the life cycle costs and balanced CO_2 emissions.

A very interesting finding can thereby be made by the direct comparison of the orange and the green scenario. The only difference between both scenarios is the quality of the thermal envelope as well as the heating system. All other parameters are equal, so also the shading situation (city shading in both cases). Looking at the results it is obvious that the combination passive house envelope and district heating leads to higher financing costs, but in fact, all other results prefer this technology combination. In all of the three other key performance indicators (life cycle costs, balanced primary energy demand and balanced CO_2 emissions) this technology combination achieves better results than the envelope quality according to a national standard in combination with gas heating (green dots).

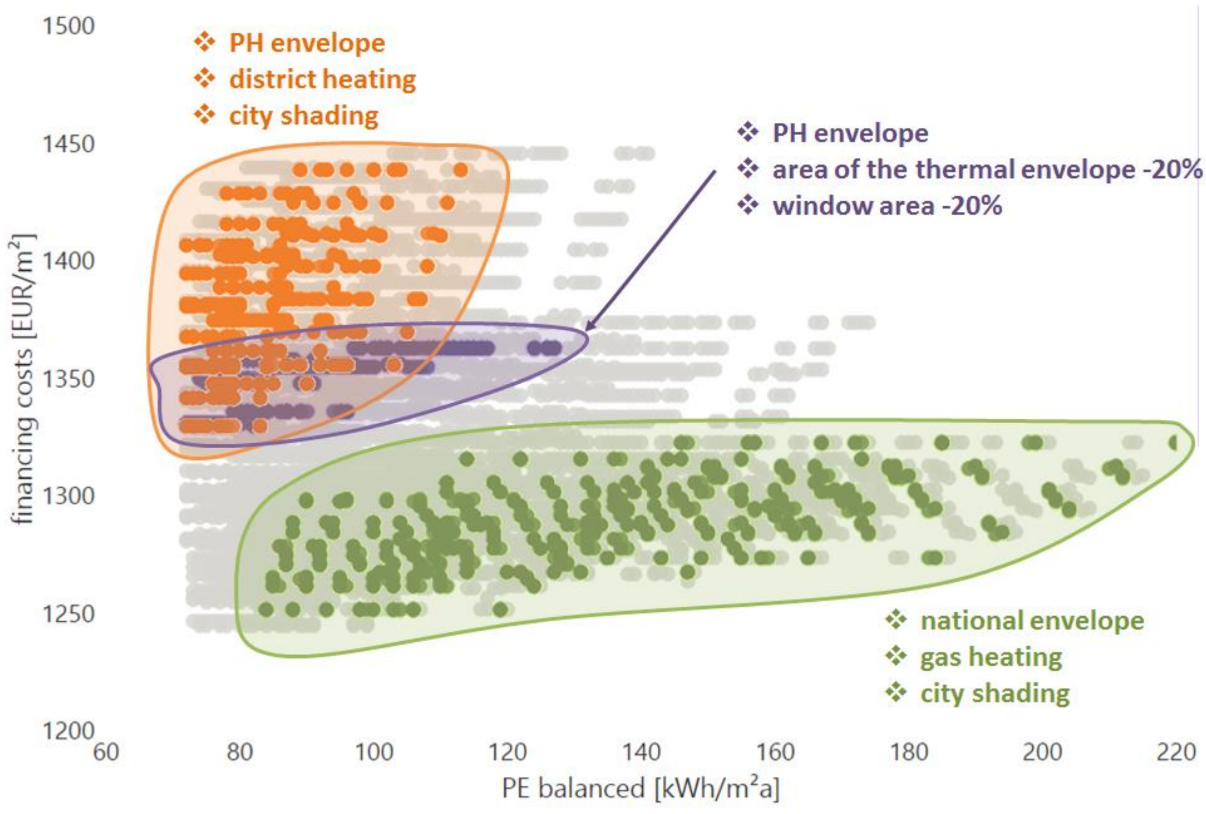


Figure 32: Analysis of the balanced primary energy (PE) demand related to the financing costs for different technology combinations of the case study NH Tirol

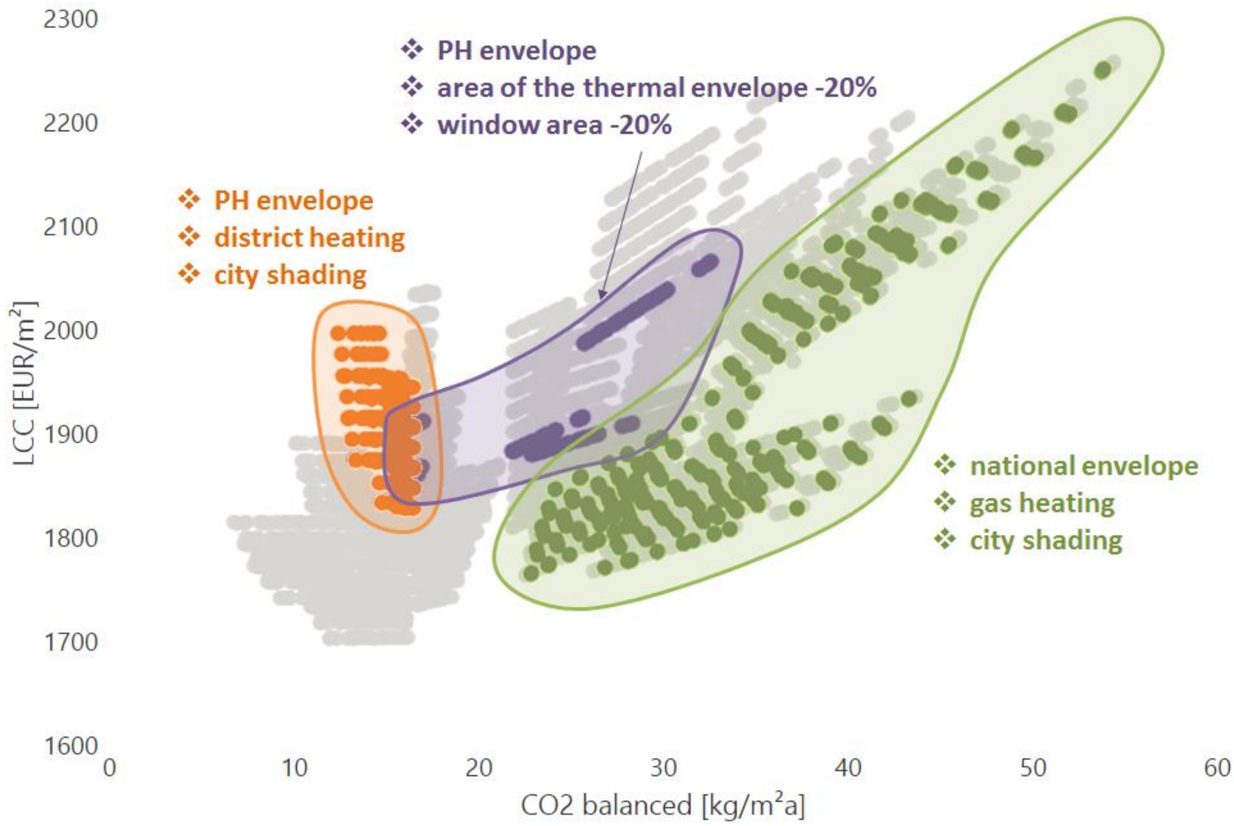


Figure 33: Analysis of the balanced CO_2 emissions related to the life cycle costs (LCC) for different technology combinations of the case study NH Tirol

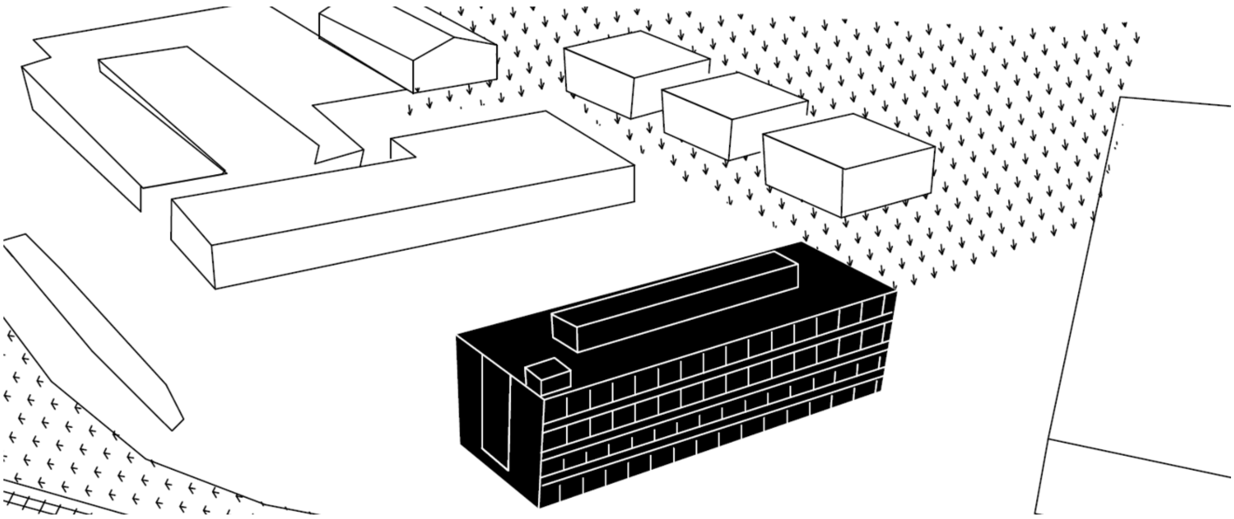
The heat map for the case study NH Tirol is visible in Figure 34. Again reductions compared to the reference scenario are highlighted in green and written as a negative value, an increase of the key performance indicator compared to the reference value is highlighted in red and written as a positive value.

The analysis shows that the passive house envelope has a high influence on all four key performance indicators and lead to increased financing and life cycle costs as well as to reduced CO_2 emissions and reduced primary energy demand. Further big influence can be seen by the location of the building. If the building is put up to 1000 m sea level or to Northern Europe, CO_2 emissions, primary energy demand and life cycle costs increase. Positive effects (reductions) can be investigated at the parameters "location – Southern Europe", "biomass heating" and "district heating". Here the switch to these parameters leads to reductions of almost all four key performance indicators. Not to be underestimated is also the influence of user behaviour. So can efficient user behaviour lead to CO_2 and primary energy reductions but easily also to an increase if the user behaviour is not efficient.

		Envelope Quality		Compactness		Window to Wall Ratio		Sea Level		Orientation		Location		Heating System		User Behaviour	
	National Reference	Passive House	nZEB	+20%	-20%	+15%	-15%	+300m	+1000m	+ 90°	+ 45°	Northern Europe	Southern Europe	Heating Biomass	District Heating	Efficient	Not efficient
Investment Costs [€/m²]	1292	8%	3%	1%	-1%	1%	-1%	0%	0%	0%	0%	1%	-3%	0%	-1%	0%	0%
Life Cycle Costs [€/m²]	1823	7%	2%	1%	-1%	1%	-1%	0%	2%	0%	0%	11%	-2%	-3%	-5%	0%	1%
CO2 Emissions [kg/m²]	29	-18%	-12%	3%	-3%	2%	-2%	6%	21%	-1%	-1%	23%	-17%	-40%	-52%	-5%	10%
PE Demand [kWh/m²a]	113	-21%	-14%	4%	-4%	3%	-3%	6%	24%	-2%	-1%	27%	-19%	-27%	-16%	-6%	12%

Figure 34: Heat map of the entire parameters of the case study NH Tirol compared to the reference scenario

6.2.3. IR-HEADQUARTER



In contrast to the two previously described case studies, the focus of the investigation for the case study iR-headquarter was on the influence of different technologies on the key performance indicators. Investigated parameters where therefore the quality of the building envelope, the ventilation system, heating and cooling systems as well as the size of the PV system. Additionally, three different shading systems were investigated, describing the fixed shading elements on the south side of the building. The evaluations were rounded off by examining the influence of different price sensitivity levels and the influence of CO_2 follow-up costs.

This chapter now includes the calculation results of in total 25,920 different variants of the case study iR-headquarter. For comparison of the results, and as done before, also a reference scenario was defined. This can be described by the following parameters:

- Standard price sensitivity
- No CO_2 follow-up costs
- Standard user behaviour
- Thermal envelope quality according to the national standard
- Window ventilation
- Natural gas heating
- Cooling by opening the windows
- 0.5m fixed shading overhang on the south side
- No PV system

As overall result Figure 35 shows the specific costs in the different phases of the case study iR-headquarter. The minimum and maximum values of all those variants are plotted, indicating the range of the costs in each individual phase of the building life cycle. As done also before, for comparison reason also the costs of the reference scenario are plotted (dashed line). This reference scenario is also the basis for the determination of cost-saving potentials. The indicated numbers show the deviation upwards and downwards. Looking at each phase of the building life cycle in detail, the results show that based on the reference scenario reductions between 7 % and 18 % are possible. In the other direction, the increases are in the range of 7 % to 30 %.

Figure 36 shows the cost curve for three different variants of the parametric calculations. For the nearly zero-energy building (nZEB) the variant with the highest life cycle costs was plotted. In comparison to that, the variant with the lowest life cycle costs was selected and illustrated. This variant is called "CRAVEzero". The dashed line is again representing the defined reference scenario (as described before). Here the cost reductions are in the range of 2 % to 17 % in each phase.

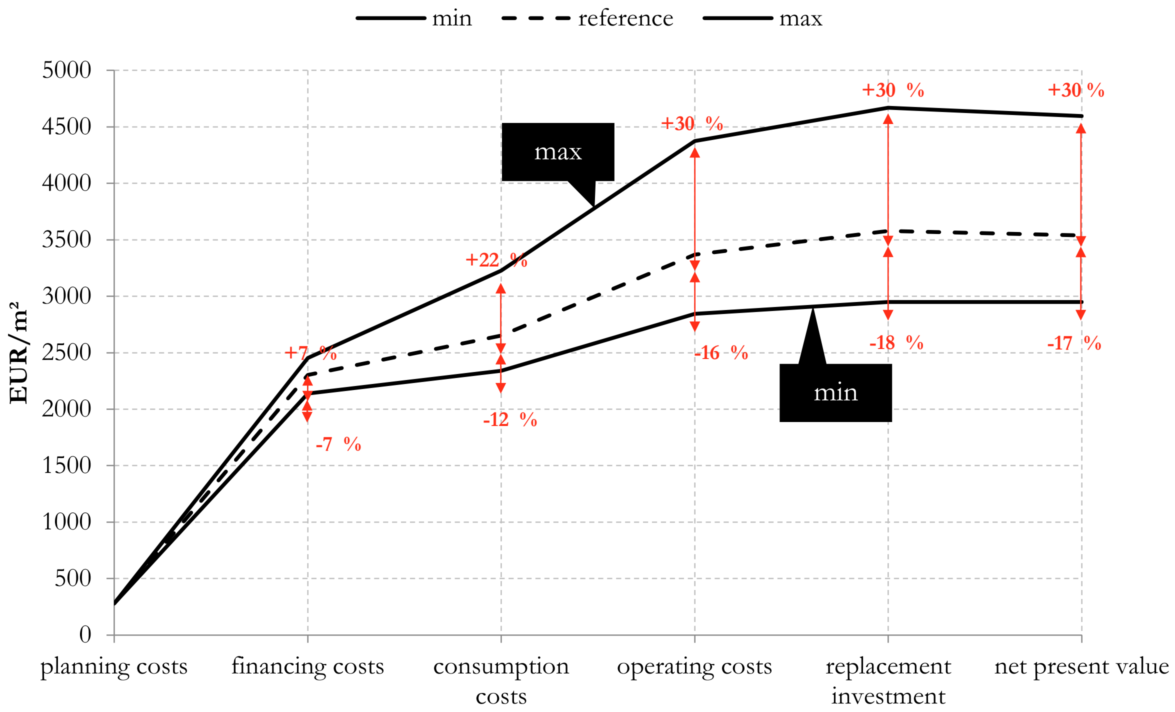


Figure 35: Specific costs (EUR/m²) in the different phases of the case study iR-headquarter over the whole life cycle of the building; range between the different parameters indicated as minimum (min), reference and maximum (max) values per phase; percentages represent the deviation from the reference scenario

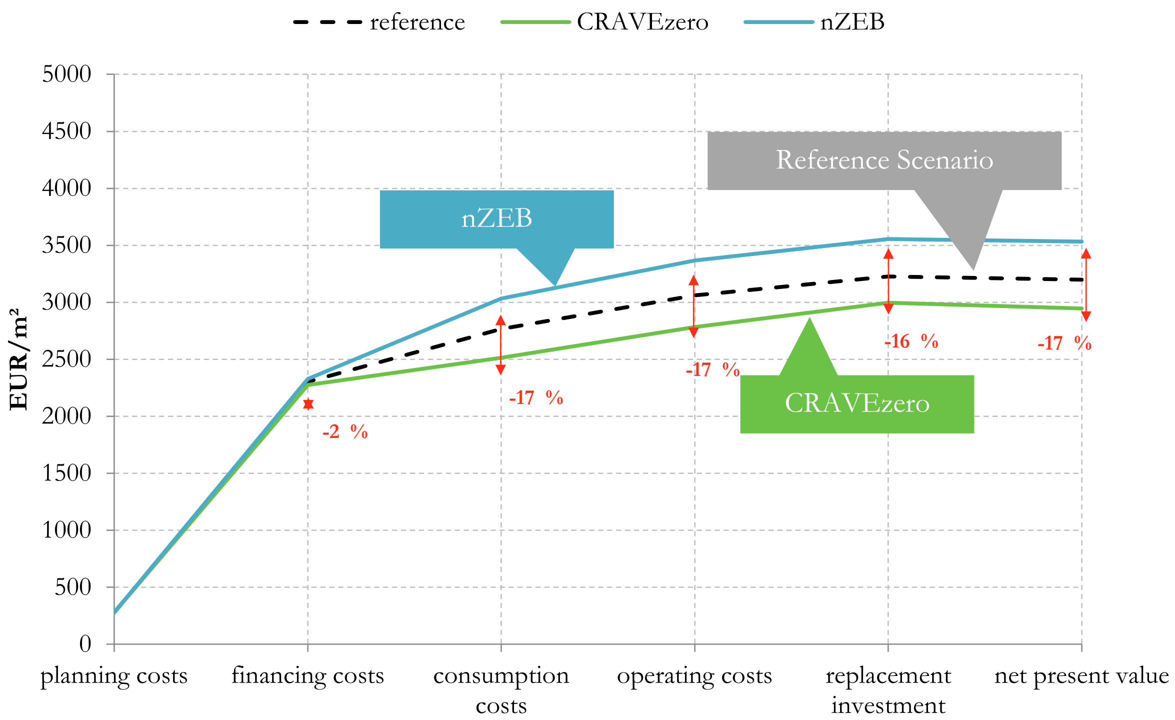


Figure 36: Cost performance (EUR/m²) of the case study iR-headquarter over the whole life cycle of the building; comparison of nZEB variant with a building according to the CRAVEzero approach and the reference scenario

A further evaluation of the calculation result is by using parallel coordinate plots are shown in Figure 37 and Figure 38. For the case study iR-headquarter five design parameters (envelope quality, heating system, cooling system, shading and PV system) were selected and referred to the resulting investment costs, life cycle costs and balanced CO_2 emissions. For this, eight equally spaced vertical lines are plotted. The lines indicate the range of results, which is additionally supported by the parameter space graphic on the right side (scatter plot comparing the life cycle costs and the balanced CO_2 emissions).

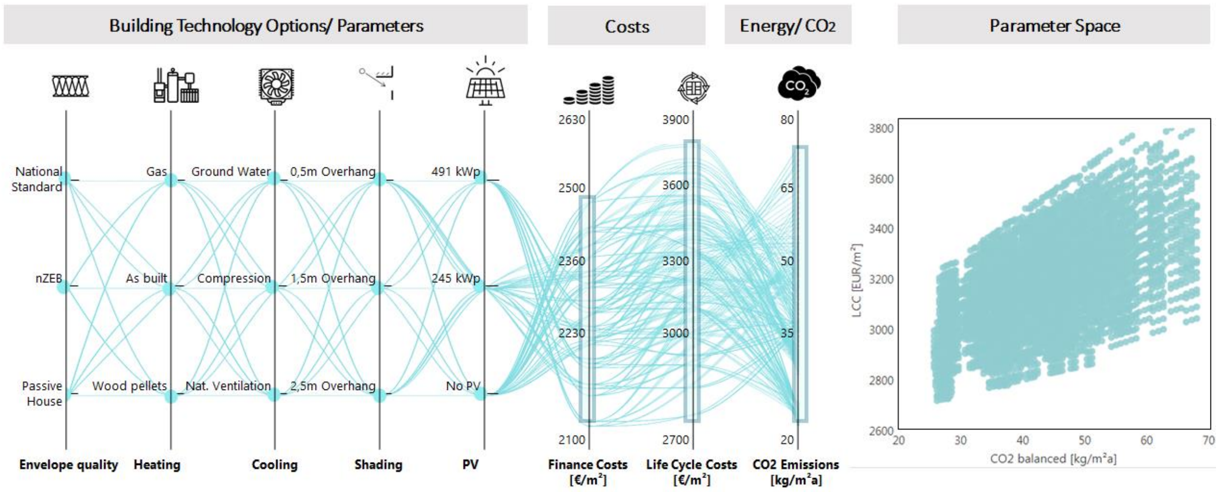


Figure 37: Eight-dimensional parallel coordinate plot for the case study iR-headquarter

The yellow line in Figure 38 indicates the reference solution (as described at the beginning of this chapter). Tracing these lines enables beneficial combinations of design parameters to be identified and provides one way of visualising strategies. On the right side the parameter space is shown and the relation of the reference variant to all other possible solutions displayed as a scatterplot comparing the balanced CO_2 emissions on the x-axes with the life cycle costs on the y-axes.

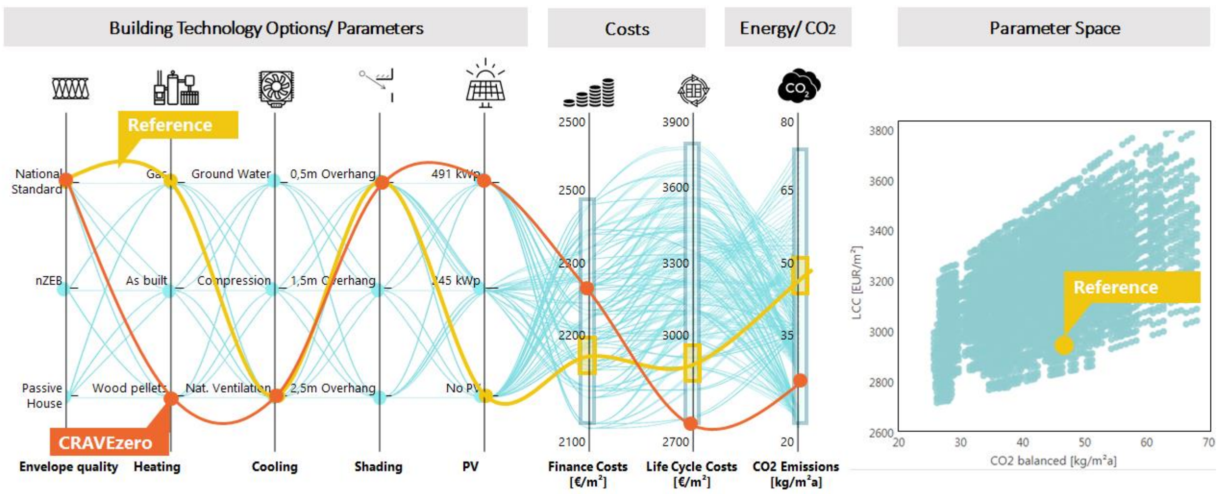


Figure 38: Eight-dimensional parallel coordinate plot for the case study iR-headquarter, highlighting the reference scenario in yellow and the optimized CRAVEzero variant (from Figure 36) in red

Following Figure 39 shows a scatter plot, comparing the life cycle costs and the balanced CO_2 emissions. The grey dots represent the entire results, the yellow dot is the indication of the results of the reference scenario. In comparison to this reference scenario, some examples of results of individual parameters are shown (blue dots). The analysis shows that, for example, the integration of a PV system would reduce the balanced CO_2 emissions and the life cycle costs. The balanced CO_2 emissions can be also reduced by a switch to a passive house envelope or a nZEB envelope and also by changing the habits to a more efficient use of the building.

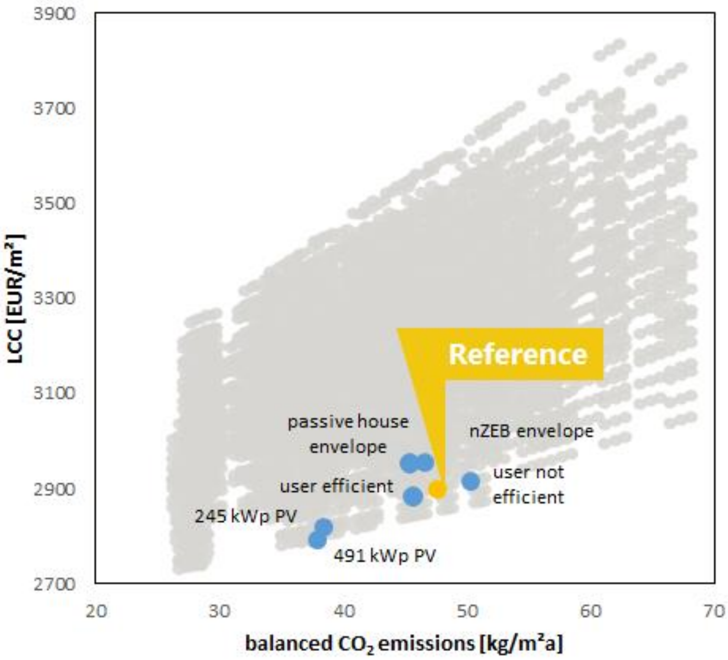


Figure 39: Comparison of the life cycle costs and the balanced CO_2 emissions of the reference scenario (yellow dot), examples (blue dots) and the entire results in the background (grey dots) for the case study iR-headquarter

The following two figures show similar to the scatter plot in Figure 39 the results for selected technology combinations. So, a passive house envelope in combination with pellet heating, a mechanical ventilation system with heat recovery and no PV system (green dots) was compared to a building with a thermal envelope quality according to the national regulations, that is equipped with natural gas heating and window ventilation (orange dots). The third technology combination in this comparison is based on an nZEB envelope, a heat pumps system and 491 kWp PV (purple dots).

In Figure 40 the financing costs are compared to the balanced primary energy demand, in Figure 41 the life cycle costs are compared to the balanced CO_2 emissions. The evaluation shows that the “purple-scenario” and “green-scenario” have higher financing costs than the “orange-scenario”. Looking at the life cycle costs, this difference is not evident any more. All three technology combinations achieve life cycle costs within a similar range. A difference between the scenarios is clearly visible when looking at the balanced primary energy demand and the balanced CO_2 emissions. Here the “green-scenario”, which is based on a passive house envelope, pellet heating and a mechanical ventilation system with heat recovery, can achieve lower values than the “orange-scenario”.

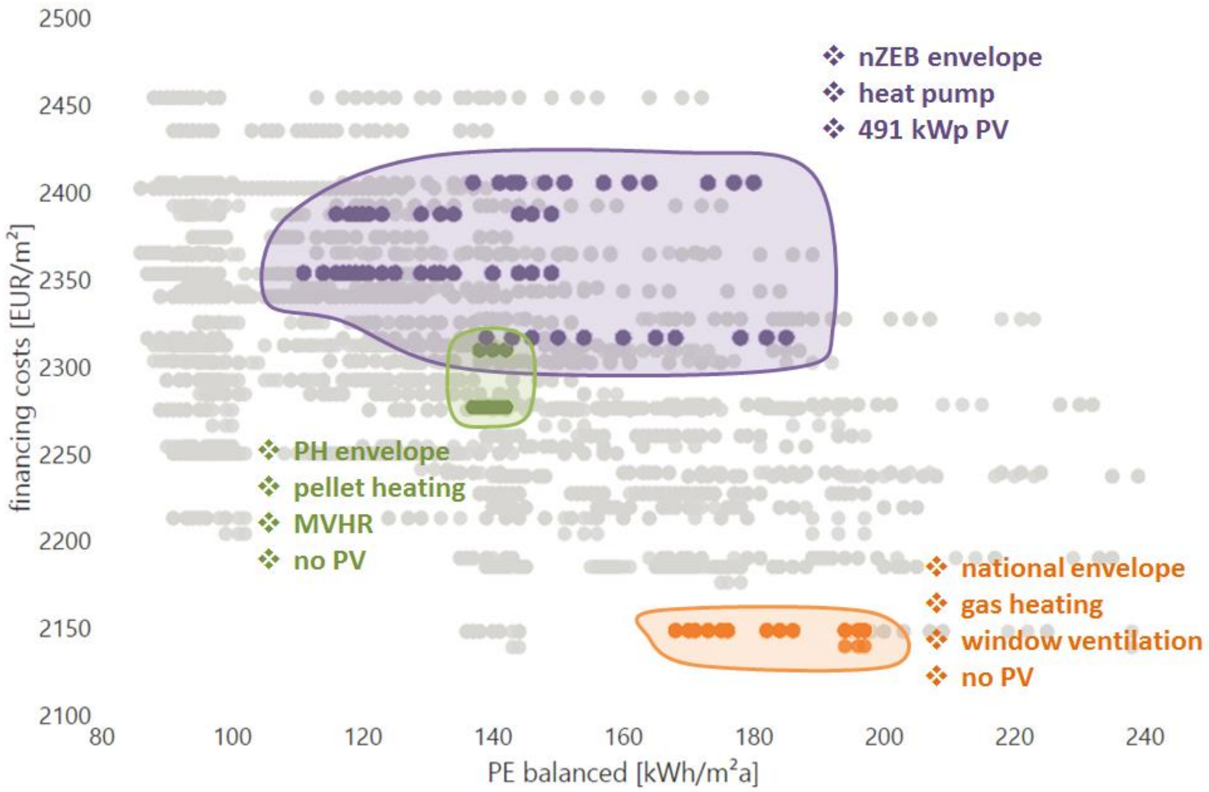


*Figure 40: Analysis of the balanced primary energy (PE) demand related to the financing costs for different technology combinations of the case study i*R-*headquarter*

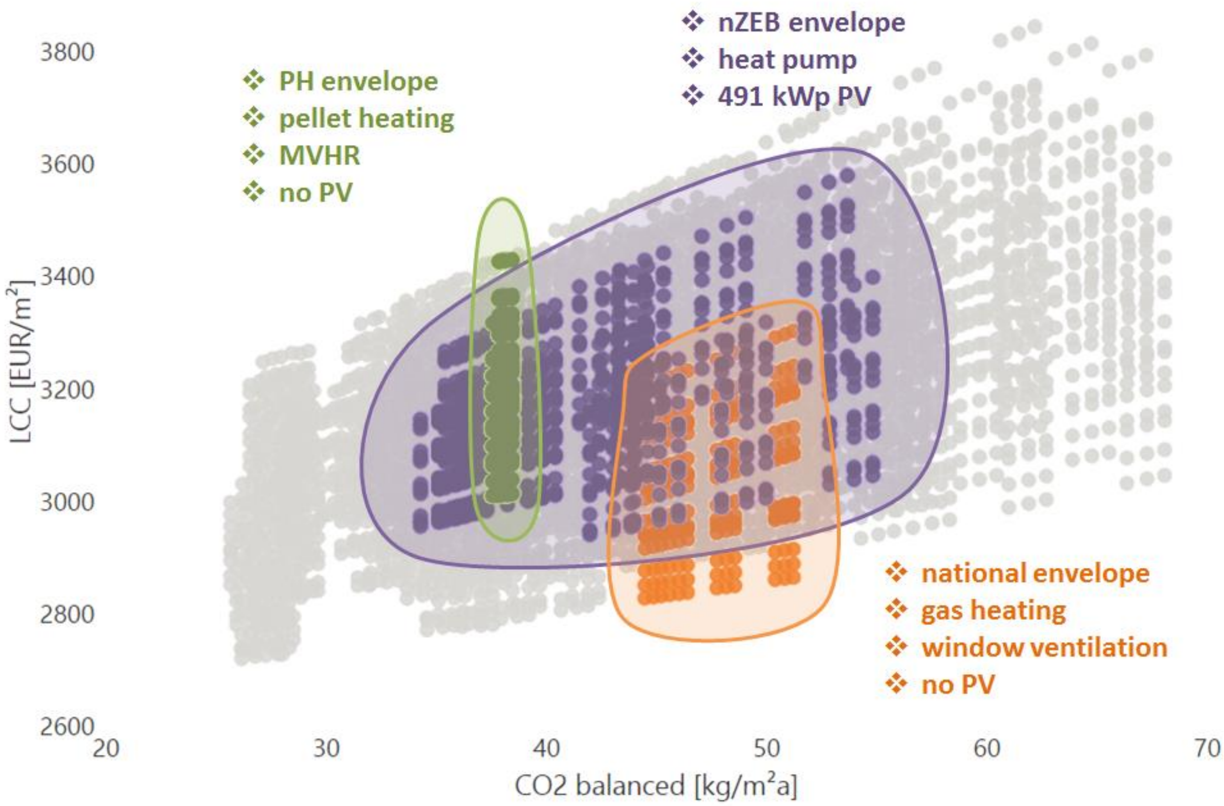


*Figure 41: Analysis of the balanced CO_2 emissions related to the life cycle costs (LCC) for different technology combinations of the case study i*R-*headquarter*

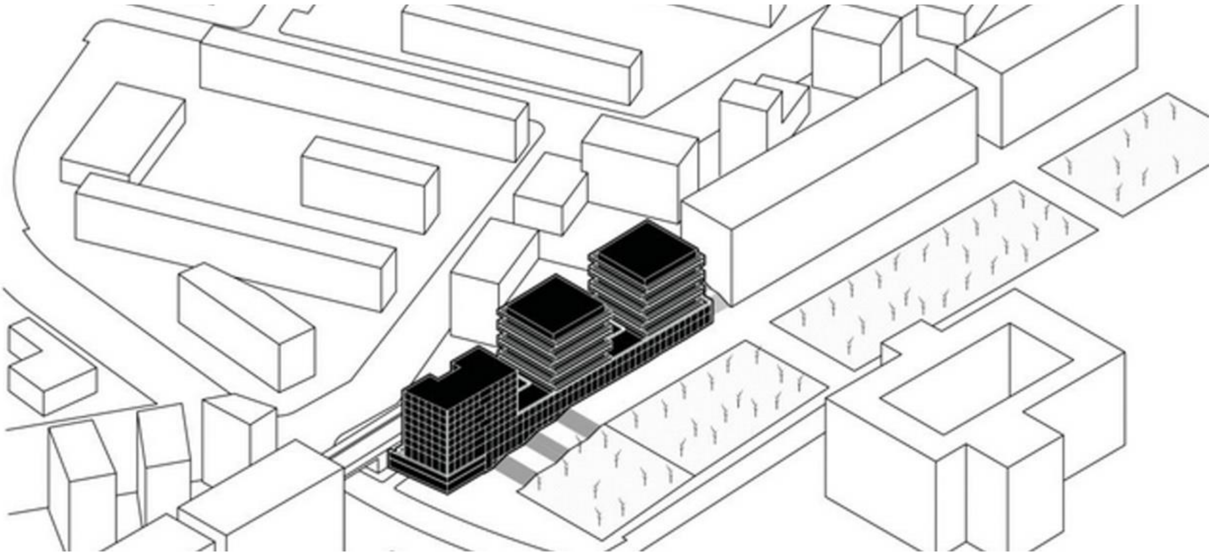
The heat map for the case study iR-headquarter is visible in Figure 42. Again reductions compared to the reference scenario are highlighted in green and written as a negative value, an increase of the key performance indicator compared to the reference value is highlighted in red and written as a positive value.

The analysis shows that the investigated parameters have a similar influence on the financing costs. Looking at the life cycle costs, the heating system, the cooling system and the PV system have small influence on the life cycle costs, all other parameters have almost no influence on that key performance indicator. The PV system is also the parameter which has the biggest influence on CO_2 emissions and the primary energy demand. In both cases, the integration of a PV system leads to a reduction of the values.

		Envelope Quality		Cooling		Shading (fixed elements on south)		PV		User behaviour	
	Reference	**nZEB**	**Passive house**	**Com-pressor**	**Ground Water**	**1.5 m overhang**	**2.5 m overhang**	**245 kWp**	**491 kWp**	**Not efficient**	**Standard**
Investment Costs [€/m²]	2149	2%	4%	3%	2%	0%	0%	3%	6%	0%	0%
Life Cycle Costs [€/m²]	2897	2%	4%	6%	3%	0%	0%	-3%	-4%	1%	0%
CO2 Emissions [kg/m²]	48	-2%	-5%	-7%	-7%	1%	2%	-19%	-20%	6%	-4%
PE Demand [kWh/m²a]	182	-3%	-5%	-9%	-9%	1%	2%	-24%	-25%	7%	-5%

Figure 42: Heat map of the entire parameters of the case study iR-headquarter compared to the reference scenario

6.2.4. GREEN HOME NANTERRE



The focus of the case study Green Home Nanterre was on the investigation on financial parameters in combination with technology options and the change of the location. For the financial aspects the parameters credit period, interest rate on credit, equity ratio, energy prices, energy price increase and CO_2 follow-up costs were defined and analysed. These parameters were combined with two technology combinations: in level 1 a thermal envelope according to national standard was combined with a natural gas heating, in level 2 the building was investigated as built. Furthermore, also two different levels of PV system were included in the parametric calculations. The definition of the three different locations was done as described in chapter 2.

This chapter includes the calculation results of in total 11,664 different variants of the case study Green Home Nanterre. For comparison of the results also the reference scenario was defined. This can be described by the following parameters:

- Thermal envelope quality according to the national standard
- Natural gas heating
- No PV system
- Credit period: 20 a
- Interest on credit: 1.1 %
- Equity ratio: 15 %
- Energy prices: current situation
- Energy price increase: 2 %/a
- No CO_2 follow-up costs
- Location: real location

As for the other case studies too, overall results were prepared to show the specific costs in the different phases of the case study Green Home Nanterre (see Figure 43 and Figure 44). The minimum and maximum values of all those variants are plotted, indicating the range of the costs in each individual phase of the building life cycle. As done also before, for comparison reason also the costs of the reference scenario are plotted (dashed line). This reference scenario is also the basis for the determination of cost-saving potentials. The indicated numbers show the deviation upwards and downwards. Looking at each phase of the building life cycle in detail, the results show that based on the reference scenario reductions between 7 %

and 21 % are possible. In the other direction, the increases are in the range of 22 % to 291 %. The cost curve of the reference scenario is, therefore, closer to the minimum costs. The difference between the minimum and maximum costs is very big. This is a result of the investigated parameter, especially the energy price, the annual energy price increase and the building location. The influence of these parameters is also visible in the heat map in Figure 50.

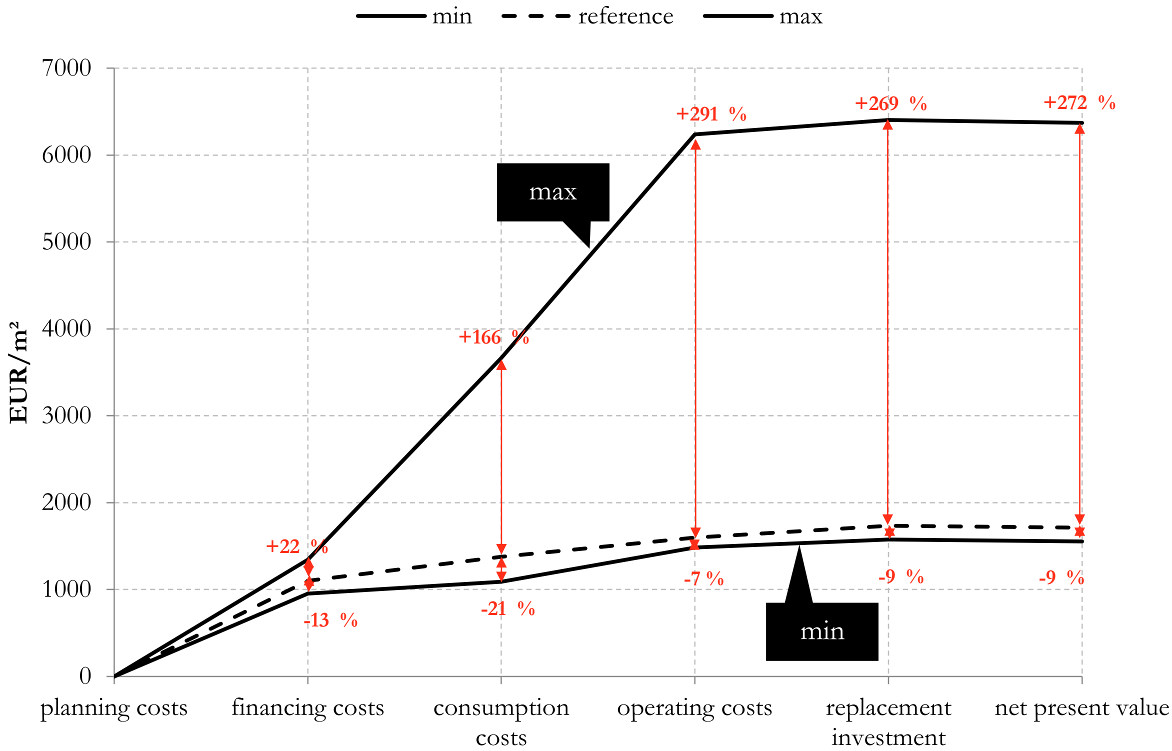


Figure 43: Specific costs (EUR/m²) in the different phases of the case study Green Home Nanterre over the whole life cycle of the building; range between the different parameters indicated as minimum (min), reference and maximum (max) values per phase; percentages represent the deviation from the reference scenario

The difference between the minimum and maximum costs per phase is nowhere near as big as at the case study Green Home Nanterre. As also seen later on in this chapter, the investigated parameters, especially the energy prices and the energy price increase, but also the location, have an enormous influence on the life cycle costs. Similar findings can be seen when looking at the results in Figure 44. Here also the costs of the reference scenario are located near to the optimum (CRAVEzero), resulting in quite low reduction potentials (referred to the reference scenario). The reduction potentials referred to the nZEB variant lie between 21 % and 68 %.

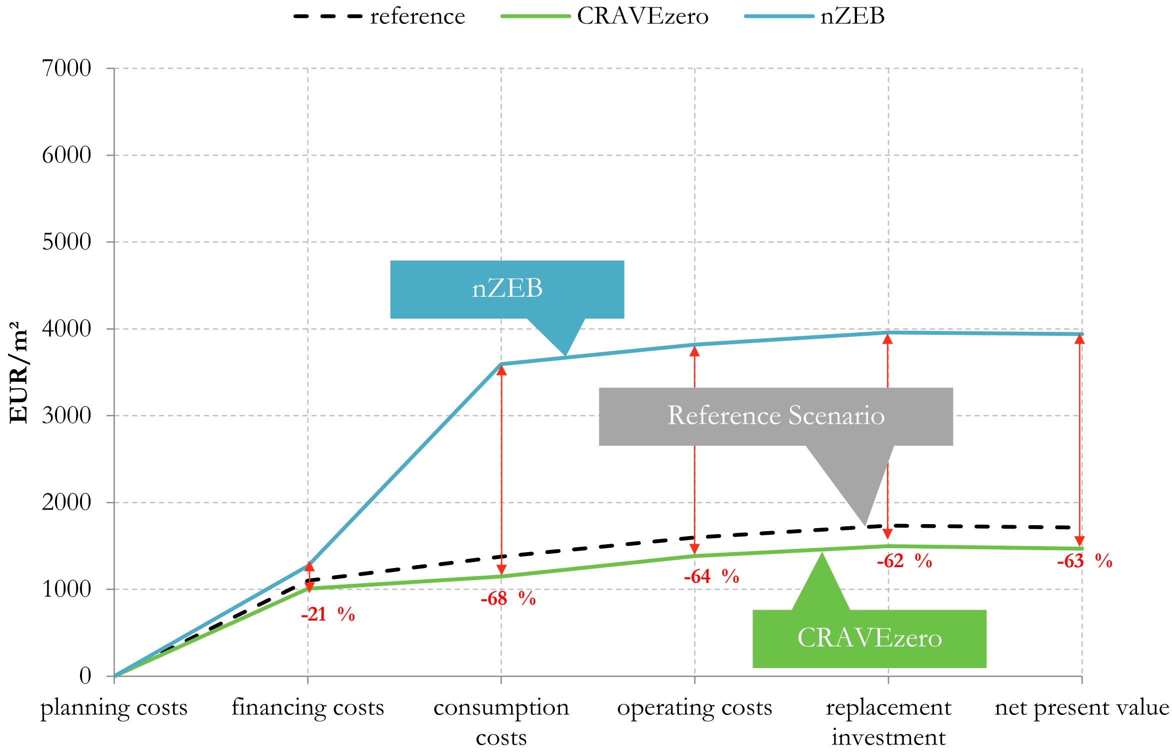


Figure 44: Cost performance (EUR/m²) of the case study Green Home Nanterre over the whole life cycle of the building; comparison of nZEB variant with a building according to the CRAVEzero approach and the reference scenario

The parallel coordinate plots for the case study Green Home Nanterre are visible in Figure 45. Again an eight-dimensional graph was prepared, including the parameters location, credit period, technology combination, interest on credit and equity ratio. On the results side again financing costs, life cycle costs and balanced CO_2 emissions are included. The lines indicate the range of results, which is additionally supported by the parameter space graphic on the right side (scatter plot comparing the life cycle costs and the balanced CO_2 emissions).

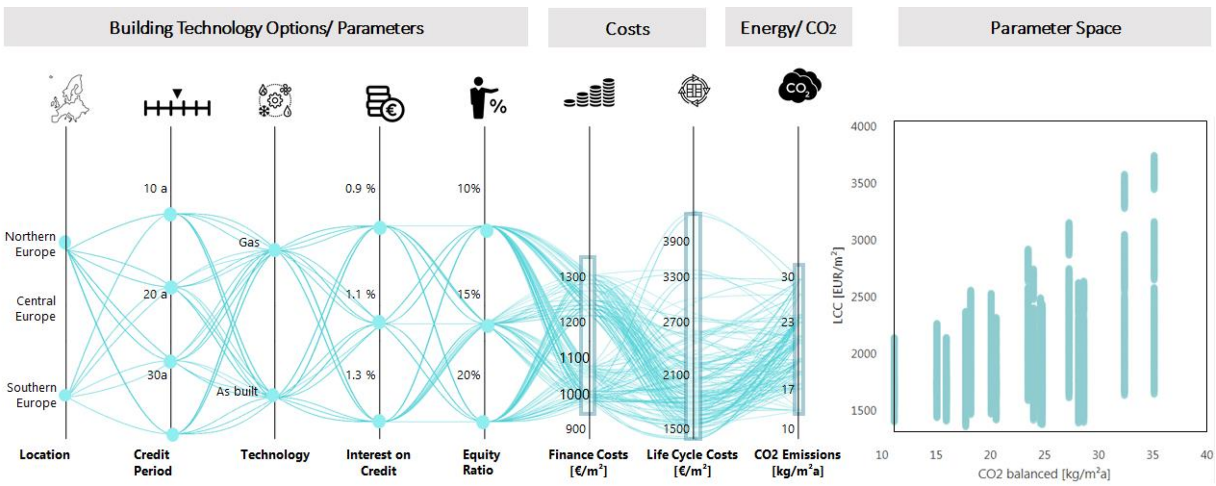


Figure 45: Eight-dimensional parallel coordinate plot for the case study Green Home Nanterre

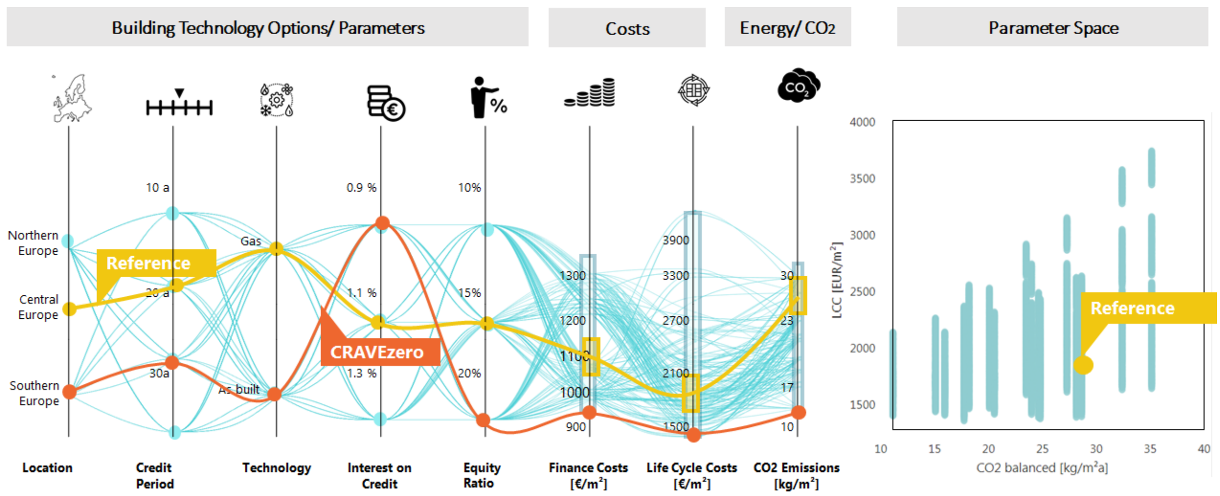


Figure 46: Eight-dimensional parallel coordinate plot for the case study Green Home Nanterre, highlighting the reference scenario in yellow and the optimized CRAVEzero variant (from Figure 44) in red

In Figure 46, the yellow lines indicate the reference solution (as described at the beginning of this chapter). Tracing these lines enables beneficial combinations of design parameters to be identified and provides one way of visualising strategies. On the right side the parameter space is shown and the relation of the reference variant to all other possible solutions displayed as a scatterplot, comparing the balanced CO_2 emissions and the life cycle costs.

In addition to the figures above Figure 47 shows a scatter plot, comparing the life cycle costs and the balanced CO_2 emissions. The grey dots represent the entire results, the yellow dot is the indication of the results of the reference scenario. In comparison to this reference scenario, some arbitrarily chosen examples of results of individual parameters are shown (blue dots). The analysis shows that changing the building envelope and heating system as well as the addition of a PV system can reduce the balanced CO_2 emissions and the life cycle costs. The change of the annual energy price increase has, as expected, a direct influence on the life cycle costs.

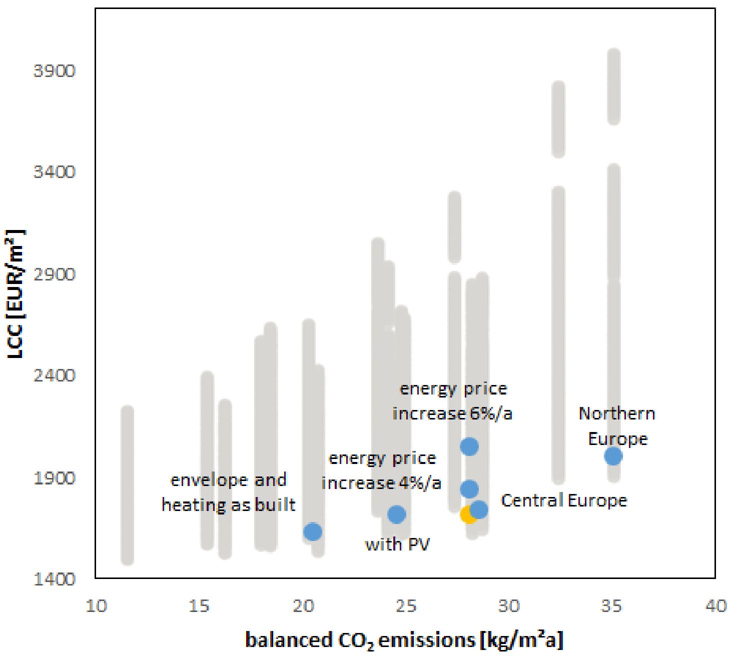


Figure 47: Comparison of the life cycle costs and the balanced CO_2 emissions of the reference scenario (yellow dot), examples (blue dots) and the entire results in the background (grey dots) for the case study Green Home Nanterre

The following two figures show similar to the scatter plot in Figure 47 the results for selected technology combinations. In the "green-scenario" the as-built envelope and heating were combined with no PV and a credit period of 20 years. This scenario was then compared to the "purple-scenario" where the as-built envelope and heating were combined with a PV system and as financial parameters, the energy price was set to 100 %, which means that to the current energy prices an addition of 100 % was considered. Additionally also the energy price increase was set to 6 %/a. The same financial parameters are also defined in the "orange-scenario" but here the envelope quality was set to the national standard, the heating system was set to natural gas and the PV system is excluded.

These technology combinations were analysed regarding the financing costs and the balanced primary energy demand in Figure 48 as well as regarding the life cycle costs and balanced CO_2 emissions in Figure 49.

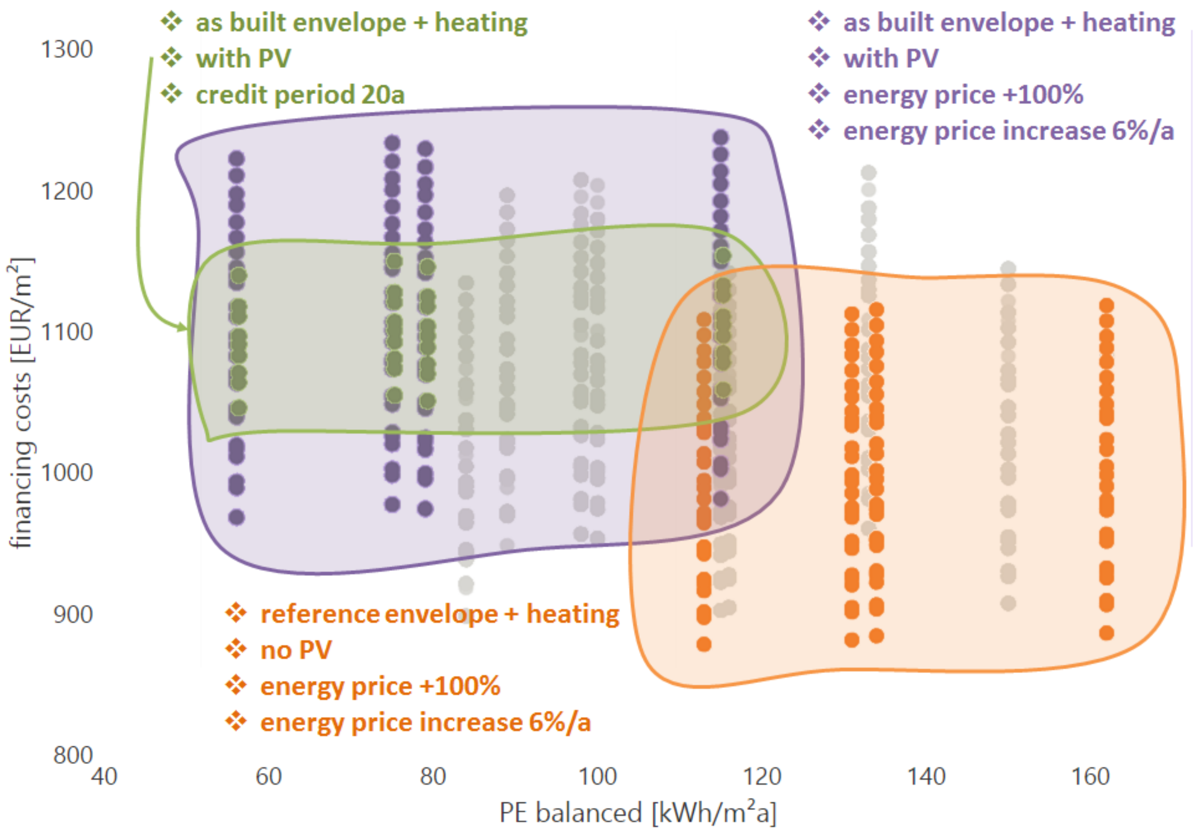


Figure 48: Analysis of the balanced primary energy (PE) demand related to the financing costs for different technology combinations of the case study Green Home Nanterre

The analysis of the results in Figure 48 and Figure 49 show that from the cost perspective the purple scenario achieves higher financing cost than the orange scenario, but on the life cycle perspective, this turns around. That means in a future scenario where the energy prices are double as high as today and furthermore, the annual energy prices increase is 6 %/a, investing in the better performing building envelope, heating and a PV system is advantageous.

But not only from the cost perspective point of view the purple scenario makes sense. Also when looking at the balanced primary energy demand and the balanced CO_2 emissions this technology combination has advantages compared to the orange scenario.

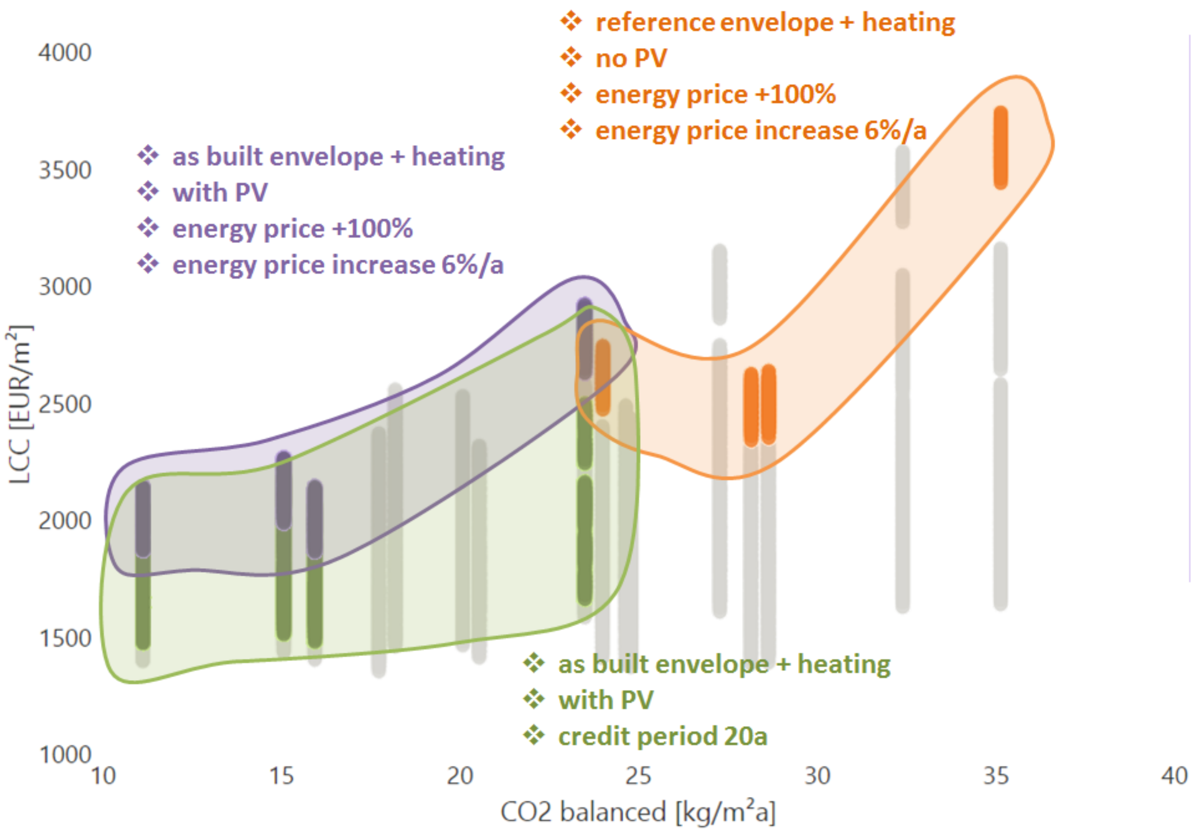


Figure 49: Analysis of the balanced CO_2 emissions related to the life cycle costs (LCC) for different technology combinations of the case study Green Home Nanterre

Figure 50 shows the heat map for the case study Green Home Nanterre. As done before, reductions compared to the reference scenario are highlighted in green and written as a negative value, an increase of the key performance indicator compared to the reference value is highlighted in red and written as a positive value. The analysis shows that the credit period has the biggest influence on financing costs. The biggest influence on the life cycle costs can be seen at the energy price, the annual energy price increase and also if the building is located in Northern Europe. In this cases an increase of the life cycle costs, compared to the reference scenario, of up to 20 % are possible. Reductions of the life cycle costs in this range were not identified. The biggest influence on the balanced CO_2 emissions and the balanced primary energy demand was investigated by switching the building envelope quality and heating system, by adding PV as well as by moving the location of the building within Europe. Due to these parameters the CO_2 emissions and the primary energy demand range between a reduction of up to 25 % and an increase of up to 25 %.

		Location		Techn. Combination	PV	Credit period		Interest on credit		Equity ratio		Energy price increase	
	Reference	Northern Europe	Southern Europe	as-built	133 kWp	10 a	30 a	0.9 %	1.3 %	10%	20%	4 %/a	6 %/a
Investment Costs [€/m²]	1100	3%	1%	4%	2%	8%	-7%	-2%	2%	2%	-2%	0%	0%
Life Cycle Costs [€/m²]	1712	17%	1%	-5%	0%	5%	-4%	-1%	1%	2%	-2%	7%	20%
CO2 Emissions [kg/m²]	28	25%	2%	-27%	-12%	0%	0%	0%	0%	0%	0%	0%	0%
PE Demand [kWh/m²a]	131	24%	2%	-24%	-12%	0%	0%	0%	0%	0%	0%	0%	0%

Figure 50: Heat map of the entire parameters of the case study Green Home Nanterre compared to the reference scenario

CHAPTER 7

INTERACTIVE DASHBOARD AND RESULTS VIEWER

7.INTERACTIVE DASHBOARD AND RESULTS VIEWER

The results of the multi-objective building life cycle cost and performance analysis of all CRAVEzero case studies have been integrated into the "CRAVEzero pinboard" as an interactive dashboard. The dashboard allows a further multi-perspective view into the analysis results, with visualisations that represent different findings and insights from the dataset.

The results of the CRAVEzero case studies can be found at the following link:

https://www.cravezero.eu/pinboard/Dashboard/DBInfo.htm

Figure 51 shows a screenshot from the web-based interactive dashboard.

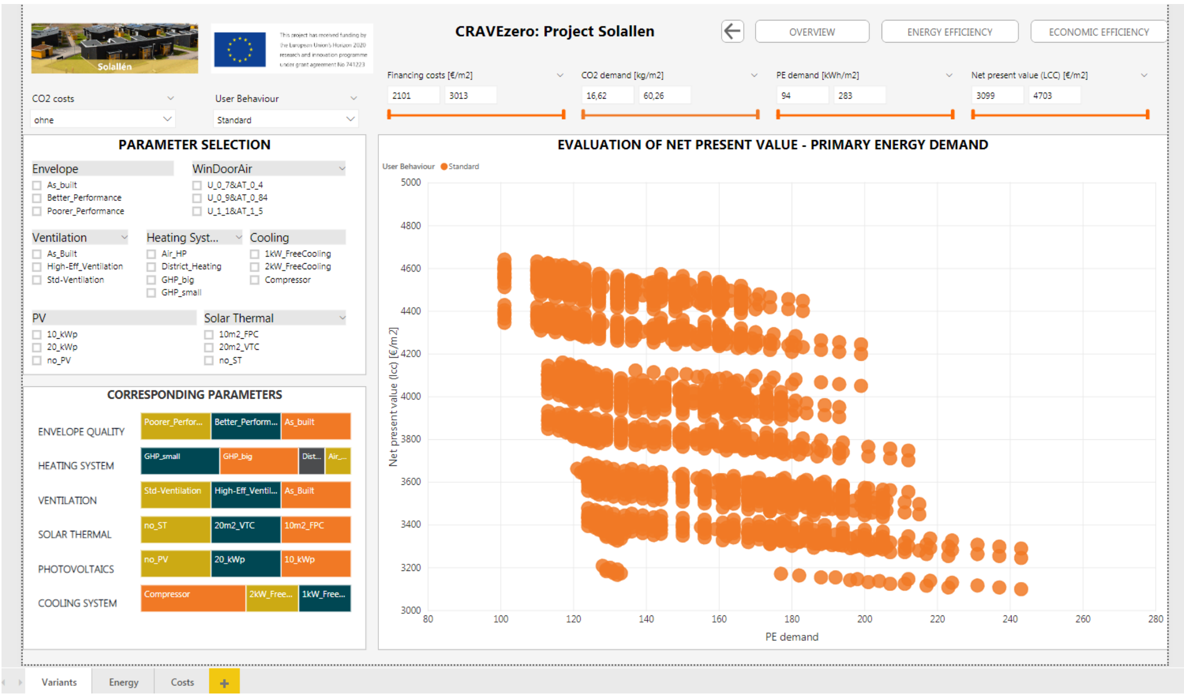


Figure 51: Web-based interactive dashboard of the derived results for the investigated case studies

How to use the interactive dashboard

The dashboard consists of three pages/ tabs as can be seen in Figure 51 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 52 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 show only data for that heating system or life cycle cost range in the visualisations.

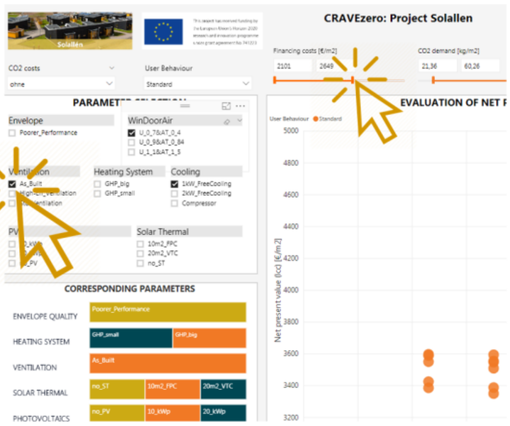


Figure 52: Filters and slicers

Cross-highlighting related visualisations

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.

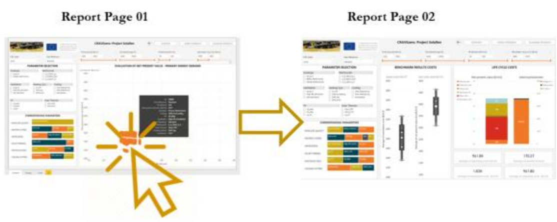


Figure 53: Cross highlighting of different visualisation pages

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.

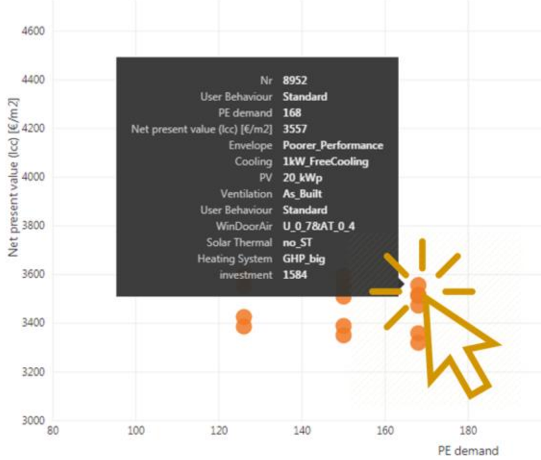


Figure 54: "Mouse over" effect of a selected visual element

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.

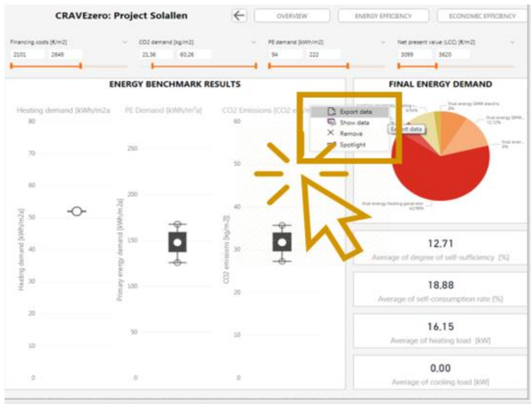


Figure 55: Data export option

CHAPTER 8

EVALUATION OF UPSTREAM COSTS

8. EVALUATION OF UPSTREAM COSTS

8.1. INTRODUCTION

In this chapter, the upstream costs are estimated for the four case studies Väla Gård, NH Tirol, iR-headquarter and Green Home Nanterre. Cost parameters, which were collected by the different project partners and countries, serve as a basis. Upstream costs include the costs that municipalities and / or developers have to incur in order to guarantee the public infrastructure required for a construction project.

Upstream costs usually consist of the following areas:

- **Data collection and provision:** The collection, documentation and maintenance of the existing infrastructure is a fundamental prerequisite for planning and efficient operation. Data is currently collected in digital GIS systems. The costs for updating the data concerning a new settlement belong to the upstream costs associated with a construction project.
- **Assessment and approval of a construction project:** In the course of the assessment and approval of a construction project the municipality's permit is used to inspect construction projects for compliance with the applicable regulations. The costs for this are usually borne by the developer - via a charge.
- **Planning and construction of infrastructure:** construction of roads, channels, energy supply and telecommunications systems. Some of the costs are charged directly or as a lump sum by the infrastructure operator to the property developer, such as costs for electrical connections and communication systems. For the sewer connection, fees are charged by the municipalities at their own discretion, whereby a framework is usually defined. The fee often depends on the built-up area. Other costs such as road construction are borne by the municipality and can be offset by taxes and other revenues.
- **Ecological costs:** The construction of new infrastructure and the use phase have ecological effects. These can be quantified as energy consumption and CO_2 emissions.

The energy consumption of a building does not have a direct impact on the upstream costs. The additional costs for zero and plus energy buildings can, nevertheless, arise as follows:

(1) **Data collection and provision:** Development and visualization of the potential for local sources of renewable energy - e.g. solar potential or possibilities for geothermal energy.
(2) **Assessment and approval:** If specific subsidies for highly efficient buildings are paid out, the assessment process must be adapted.
(3) **Planning and construction of the infrastructure:** The construction of the infrastructure is subject to changes if energy is also fed into the grid. These costs are usually covered by fees charged by the property developer. No changes are to be expected in canal and road construction.

There are several tools and guidelines for estimating the economic and ecological consequences of housing construction and for estimating the construction cost index. Examples are:

- Energy Performance Certificate for Settlements in Lower Austria (Emrich and Zeller, 2014)
- EUROSTAT (Eurostat, 2019)

In this project, the tool "Energy Performance Certificate for Settlements" (Emrich and Zeller, 2014) was used to calculate the upstream costs and adapted for the respective locations. For selected projects, the expenditure for the municipality and for the developer was evaluated and divided into construction and maintenance. In addition to the financial effects, the ecological effects are also analyzed. Table 27 and Table

28 show typical cost parameters for the construction and maintenance of the infrastructure of the different countries based on the Eurostat database (Eurostat, 2019).

Table 27: Cost indicators for the construction of building infrastructure based on (Eurostat, 2019) for the year 2019

INFRASTRUCTURE	CONSTRUCTION COSTS					
	AUSTRIA	ITALY	SWEDEN	GERMANY	FRANCE	UNIT
Roads (substructure (incl. shafts, drainage))	60	50	62	65	60	EUR / m²
Roads (upper structure (incl. sidewalk))	63	67	65	70	63	EUR / m²
Roads (infiltration)	100	94	104	160	99	EUR / m
District heating	400	520	414	400	397	EUR / m
Waste water disposal (mixed system)	200	189	207	220	198	EUR / m
Waste water disposal (sepa-ration system)	400	320	414	400	397	EUR / m
Water supply system	120	150	124	150	119	EUR / m
Gas supply	41	85	42	50	41	EUR / m
Power supply	35	75	36	35	35	EUR / m
Telecommunication net-work	70	51	73	70	69	EUR / m
Streetlighting	4	4	4	5	4	EUR / m
Green zones	45	16	47	40	45	EUR / m
Noise protection	540	480	559	540	536	EUR / m

Table 28: Cost indicators for the maintenance of building infrastructure based on (Eurostat, 2019) for the year 2019

INFRASTRUCTURE	MAINTENANCE COSTS					
	AUSTRIA	ITALY	SWEDEN	GERMANY	FRANCE	UNIT
Roads (substructure (incl. shafts, drainage))	1.00	0.94	1.03	1.01	0.99	EUR / m²
Roads (infiltration)	4.00	3.78	4.14	4.06	3.97	EUR / m
Waste water disposal (mixed system)	1.00	0.94	1.03	1.01	0.99	EUR / m
Waste water disposal (sepa-ration system)	2.00	1.89	2.07	2.03	1.98	EUR / m
Water supply system	1.00	0.94	1.03	1.01	0.99	EUR / m
Gas supply	1.50	1.42	1.55	1.52	1.49	EUR / m
Power supply	2.50	2.36	2.59	2.54	2.48	EUR / m
Green zones	2.50	2.36	2.59	2.54	2.48	EUR / m
Noise protection	0.75	0.71	0.78	0.76	0.74	EUR / m

8.2. CASE STUDIES

Based on the dimensions of the site plan, estimated values for the external development areas are calculated, which form the basis for further calculations. On the basis of these values, the development of the costs for external and internal development and their maintenance years was calculated by using the construction cost index and expected future changes in interest rates.

Table 29: Economic boundary conditions for the calculation of the upstream costs

PARAMETER	VALUE
Interest rate	1.7 %/a
Cost increase for maintenance / servicing	2.0 %/a

With the help of the cost parameters for the construction and maintenance of the building infrastructure from above, the costs for the external and internal infrastructure development and its maintenance were calculated. The **external development lengths** for water supply, wastewater and district heating supply as well as the length of the external street network are used to calculate the costs for street works and sewerage outside the property, which are financed by the public sector. The **internal development lengths** and the length of the internal street network are used to calculate the costs of road works and sewerage on the property, which are the responsibility of the developer. On the basis of this data, the costs incurred are calculated from the cost values per linear meter (m) or surface area (m²) of the infrastructure. The results of the calculations of external technical infrastructure costs financed by the public sector are shown in the tables below.

Table 30: External construction costs of the technical infrastructure of Green Home

Green Home					
External construction costs of technical infrastructure					
Street	1100 m²	x	110 EUR/m²	=	118,047 EUR
Water supply	50 m	x	119 EUR/m	=	5,950 EUR
Wastewater	50 m	x	396 EUR/m	=	19,800 EUR
District heating supply	40 m	x	396 EUR/m	=	15,840 EUR
					∑ 159,637 EUR
Energy consumption to build the external infrastructure					235,122 kWh
External maintenance costs					1,114 EUR/a

Table 31: External construction costs of the technical infrastructure of NH Tirol

NH Tirol					
External construction costs of technical infrastructure					
Street	700 m²	x	123 EUR/m²	=	86,100 EUR
Water supply	40 m	x	120 EUR/m	=	4,800 EUR
Wastewater	40 m	x	400 EUR/m	=	16,000 EUR
District heating supply	150 m	x	400 EUR/m	=	60,000 EUR
					∑ 166,900 EUR
Energy consumption to build the external infrastructure					170,066 kWh
External maintenance costs					820 EUR/a

Table 32: External construction costs of the technical infrastructure of iR-headquarter

iR-headqarter					
External construction costs of technical infrastructure					
Street	370 m²	x	123 EUR/m²	=	45,510 EUR
Water supply	330 m	x	120 EUR/m	=	39,600 EUR
Wastewater	330 m	x	400 EUR/m	=	132,000 EUR
District heating supply	40 m	x	400 EUR/m	=	16,000 EUR
					∑ 233,110 EUR
Energy consumption to build the external infrastructure					185,329 kWh
External maintenance costs					1,360 EUR/a

Table 33: External construction costs of the technical infrastructure of Väla Gard

Väla Gard					
External construction costs of technical infrastructure					
Street	350 m²	x	127 EUR/m²	=	44,450 EUR
Water supply	80 m	x	124 EUR/m	=	9,920 EUR
Wastewater	80 m	x	414 EUR/m	=	33,120 EUR
					∑ 87,490 EUR
Energy consumption to build the external infrastructure					103,573 kWh
External maintenance costs					609 EUR/a

The external construction costs result from necessary extensions to the public infrastructure network in order to ensure the internal development of the technical infrastructure. The costs of the internal technical infrastructure are specified below.

Table 34: Internal construction costs of the technical infrastructure of Green Home

Green Home					
Internal construction costs of technical infrastructure					
Street	100 m	x	123 EUR/m	=	12,300 EUR
Water supply	100 m	x	120 EUR/m	=	12,000 EUR
Wastewater supply	100 m	x	400 EUR/m	=	40,000 EUR
District heating supply	50 m	x	400 EUR/m	=	20,000 EUR
Green areas	800 m²	x	45 EUR/m²	=	36,000 EUR
					∑ 120,300 EUR
Energy consumption to build internal infrastructure					249,077 kWh
Internal maintenance costs					3,400 EUR/a

Table 35: Internal construction costs of the technical infrastructure of NH Tirol

NH Tirol					
Internal construction costs of technical infrastructure					
Street	200 m	x	123 EUR/m	=	24,600 EUR
Water supply	200 m	x	120 EUR/m	=	24,000 EUR
Wastewater	200 m	x	400 EUR/m	=	80,000 EUR
District heating supply	250 m	x	400 EUR/m	=	100,000 EUR
Green areas	900 m	x	45 EUR/m	=	40,500 EUR
					∑ 269,100 EUR
Energy consumption to build internal infrastructure					444,798 kWh
Internal maintenance costs					5,125 EUR/a

Table 36: Internal construction costs of the technical infrastructure of iR-headquarter

iR-headquarter					
Internal construction costs of technical infrastructure					
Street	360 m	x	123 EUR/m	=	44,280 EUR
Water supply	360 m	x	120 EUR/m	=	43,200 EUR
Wastewater	360 m	x	400 EUR/m	=	144,000 EUR
					∑ 231,480 EUR
Energy consumption to build internal infrastructure					341,075 kWh
Internal maintenance costs					9,540 EUR/a

Table 37: Internal construction costs of the technical infrastructure of Väla Gard

Väla Gard					
Internal construction costs of technical infrastructure					
Street	65 m	x	123 EUR/m	=	7,995 EUR
Water supply	65 m	x	120 EUR/m	=	7,800 EUR
Wastewater	65 m	x	400 EUR/m	=	26,000 EUR
Green areas	300 m²	x	45 EUR/m²	=	13,500 EUR
					∑ 55,295 EUR
Energy consumption to build internal infrastructure					307,350 kWh
Internal maintenance costs					1,571 EUR/a

8.3. RESULTS AND CONCLUSION

To enable a direct comparison of the following case studies Green Home, NH Tirol, iR-headquarter, Väla Gård, they were compared in terms of their external and internal technical infrastructure costs.

In Figure 56, the external maintenance costs of the four selected case studies were compared and presented in relation to the respective costs per year. The external maintenance costs depend on the areas operated in the individual case studies and the external technical infrastructure to be maintained in each case study.

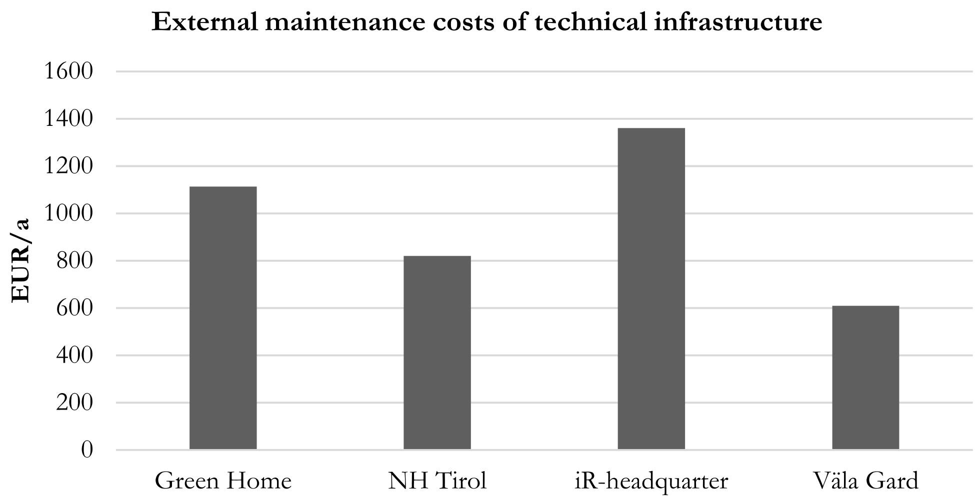


Figure 56: External maintenance costs of technical infrastructure

The internal maintenance costs presented below, result from the technical infrastructure to be maintained within the property. These costs are not provided by the public sector and are therefore to be covered by the operator. Due to the large internal area of the case study iR-headquarter, it is obvious that the costs in this case study are much higher than in the comparable study objects.

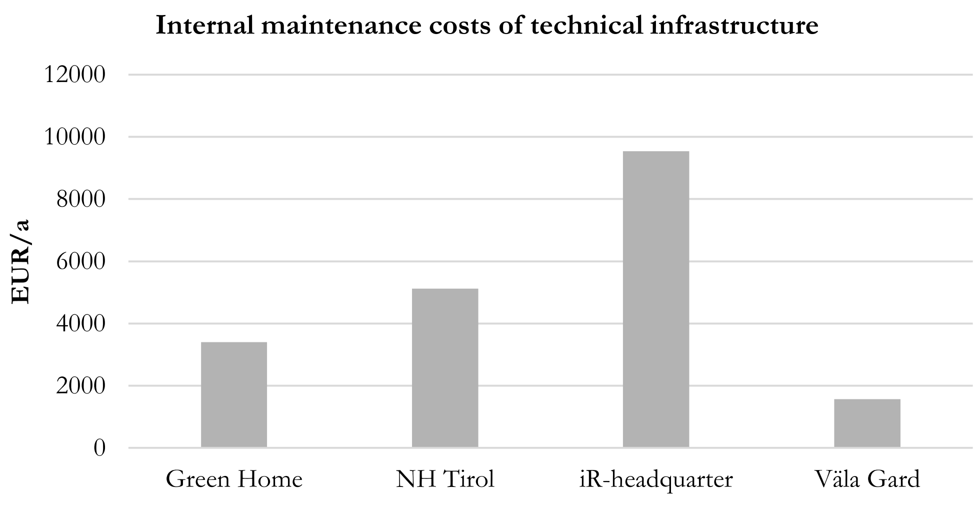


Figure 57: Internal maintenance costs of technical infrastructure

CHAPTER 9

END-OF-LIFE ANALYSIS

9.END-OF-LIFE ANALYSIS

9.1.1. INTRODUCTION

Among the life cycle stages defined by the ISO-15686-5:2017 for the LCC calculation, in WP2 the stage end-of-life (EOL) was not considered because no data from the case studies were available. In this WP the analysis was further developed, defining and including a methodology for the EOL cost calculation thanks to the contribution of the visiting PhD student Eduardo Vázquez-López from the University of Seville.

The processes taken into account in the EOL stage are demolition, transport and waste management of the building components. For each of these processes, the related costs have been calculated. In addition, it is important to point out that the European directive on waste (2008/98/EC) established in the waste legislation and policy that the EU Member States have to apply a waste management hierarchy where the recycling has as a higher priority than disposal. Therefore, a selective demolition has been adopted as a demolition method for this analysis, since it allows the separation and the later treatment of the generated waste.

9.1.2. METHODOLOGY

A demolition budget calculation was performed as developed by the University of Seville (Ramirez de Arellano 2014; Marrero et al., 2010). This identifies and quantifies all the building elements, assigning to them a unitary cost for the selective demolition or dismantling, used to obtain the total amount of the demolition cost. The methodology has been applied to the CRAVEzero case studies, adopting the breakdown of the elements as collected in WP2. The unitary costs assigned to each construction element are based on Andalusian Construction Cost Database (ACCD, 2017) (see Figure 58). As some of the technology sets were not included in the cost database, assumptions have been made for these elements.

Life Cycle Cost						DEMOLITION COST						
						ACCD code	CONCEPT	UCR	€/umDC	€/umBE	TDCi(€)	Tag (€)
CONSTRUCTION COSTS (Based on ISO15686)												
A	BUILDING											
A1	Roofs											6.522,56
A1.01	Flat roof											
A1.01	Unaccessible flat roof	Area	544	m^2	1					11,99	6.522,56	
		Insulation	24	cm		01WAA00001	SELECTIVE DEMOLITION ISOLATION PANELS	0,24	15,42	3,7		
	bitouminous	Water tightness layer	0,3	cm		01WAA00001	SELECTIVE DEMOLITION WATER LAYERS	0,03419118	15,42	0,53		
		Other punctual insulation wor	10	cm		01QIW90010	SELECTIVE DEMOLITION UNACCESIBLE FLAT ROOF	1	7,76	7,76		

Figure 58. Spreadsheet demolition cost – extract from the calculation

In a second step, waste generated in the selective demolition of the building has been evaluated. For this purpose, the method for quantifying waste from building construction elements developed by the ARDITEC research group of the University of Seville has been implemented (Ramirez de Arellano et al. 2002; Solis-Guzman et al., 2009). This method allows for calculating the volume of waste generated by each construction element. The apparent volume of each construction element is determined and then, the volume increase after the demolition process is calculated thanks to a bulk volume coefficient (Marrero et al, 2020).

Life Cycle Cost

CONSTRUCTION COSTS (Based on ISO15686)

					ARDITEC. WASTE VOLUME				
					Qi	CC	CT	VAD	DWv(m3)
A	BUILDING								
A1	**Roofs**								
A1.01	**Flat roof**								
A1.01	Unaccessible flat roof	Area	544	m^2	0,195733	0,243000	1,30	0,061832	171,850
		Insulation	24	cm					
	bitouminous	Water tightness layer	0,3	cm					
		Other punctual insulation wor	10	cm					

Figure 59. Waste volume calculation - extract from the calculation

In a third step, after identifying the volume of each type of waste present in the building elements, based on the information available from the building elements breakdown, using the density of each material the total weight is calculated (Figure 60). The waste has been classified according to chapter 17 of the European Waste List (EWL).

Life Cycle Cost

CONSTRUCTION COSTS (Based on ISO15686)

					ISOLATION				
					$\%V_{ik}$	$DWv_{k,i}$	$db_{k,i}$	$DWw_{k,i}$	Tg(t)
A	BUILDING								
A1	**Roofs**								4,57
A1.01	**Flat roof**								
A1.01	Unaccessible flat roof	Area	544	m^2	98,77%	169,730	0,027	4,570	

Figure 60. Waste materials calculation - extract from the calculation

Once the total weight of each waste present in the building has been obtained, a cost per ton of waste is applied in order to calculate the transportation cost and the waste management cost.

Since the EOL stage of the building has been set after 40 years from its construction, the costs need to be actualized by means of a discount rate of 1.51 % (see Deliverable 2.2.). General price inflation was not taken into account. Furthermore, it is necessary to establish a construction waste management scenario based on the current recycling state of construction and demolition waste in Europe (Institution of Civil engineers, 2008; Resource Efficient Use of Mixed Wastes Improving management of construction and demolition waste. Final report, 2017). Finally, the EOL cost was normalized according to the same method applied in Deliverable 2.2, which is based on the application of the European Construction Index (ECI). In this way, Spanish cost data could be translated and applied to the country of the analyzed case study.

9.1.3. RESULTS AND CONCLUSIONS

The above-displayed methodology has been applied to the case study "Résidence Alizari", located in France. It is a 5-storey residential building with a 2825 m² of ground floor area. The building features relevant for the EOL calculation are:

- Foundations and structure made of reinforced concrete
- Facades made of concrete walls and covered with interior and exterior insulation
- Triple-glazed windows
- Ventilation with heat recovery
- Pellet heating boiler
- Photovoltaic panels

The results show that the EOL cost of this building calculated according to ACCD prices is 375,174.22 EUR, with its net present value being 202,785.02 EUR (discount rate 1.51 % and service life 40 years). Normalizing the values with the ECI (Spain index 70.52 %), the resulting value is 287,556.75 EUR. The EOL cost obtained compared with the normalized cost of the other stages of the LCC, represents 5 % of the total LCC.

Table 38. Calculation steps of normalized EOLC

PARAMETER	VALUE
EOL Spain	375,174.22 EUR
Period of analysis	40
Inflation rate	-
Discount rate	1.51 %
EOL Spain NPV	202,785.02 EUR
EOL France NPV	298,685.19 EUR

The analysis of the costs of the processes of the EOL stage shows that the most influential is selective demolition cost, which represents 84 %, leaving the transport and management processes with 8 % (Figure 61).

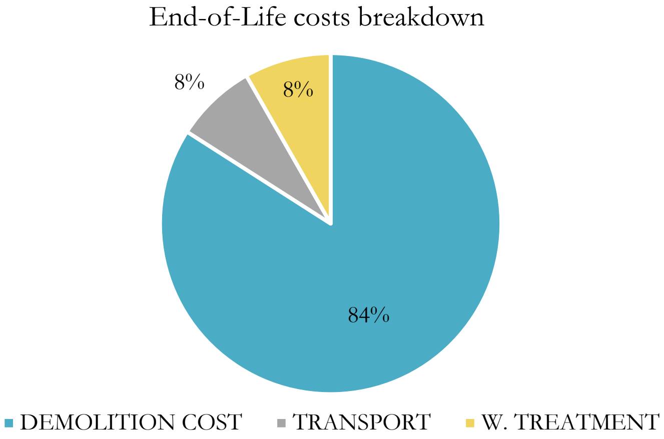


Figure 61. EOL costs breakdown

The detailed LCC is displayed in a breakdown of building elements (Figure 62). The results show that the structural elements have the greatest influence on EOL cost, accounting 75 % of the total cost, followed by the internal elements with 8 %.

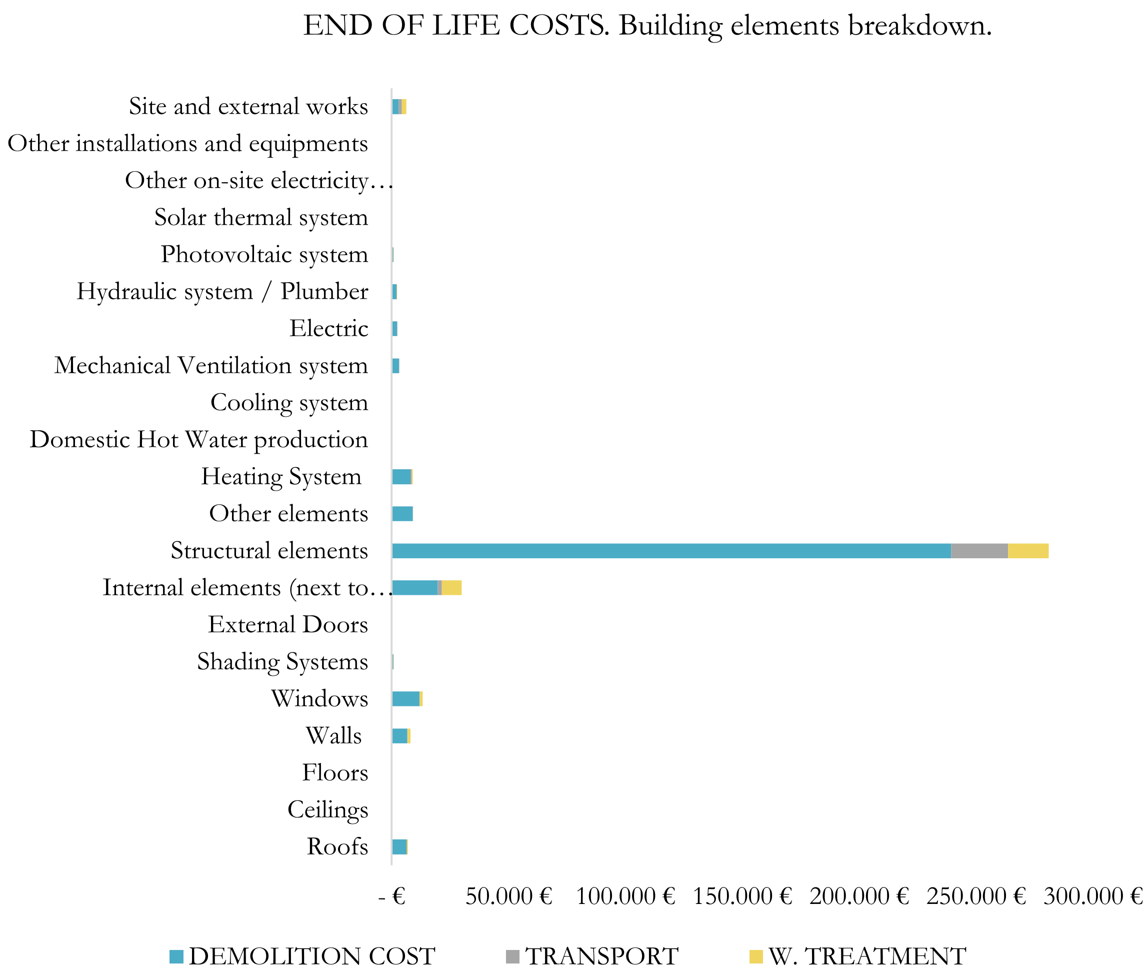


Figure 62. EOLC breakdown by building element

Therefore, to control the costs of the building's EOL stage it is necessary to maximize the efficiency of the building's structure and foundation design. At the same time, it is important to improve and promote recycling policies for the materials that make up foundations and structural elements of a building.

10. REFERENCES

BSI ISO 15686-5 (2008) 'BS ISO 15686-5:2008 - Buildings & constructed assets – Service life planning – Part 5: Life cycle costing', *International Standard*.

Chiandussi, G. *et al.* (2012) 'Comparison of multi-objective optimization methodologies for engineering applications', *Computers and Mathematics with Applications*. doi: 10.1016/j.camwa.2011.11.057.

Emrich, H. and Zeller, R. (2014) 'Energieausweis für Siedlungen - Handbuch'.

Eurostat (2019) 'Construction cost of new residential buildings'. Available at: https://ec.europa.eu/eurostat/tgm/table.do?tab=table&init=1&plugin=1&language=en&pcode=teiis510.

Hatt, T. *et al.* (2018) 'Kostenoptimierte Gebäude im Lebenszyklus.', in *economicum Session 7*.

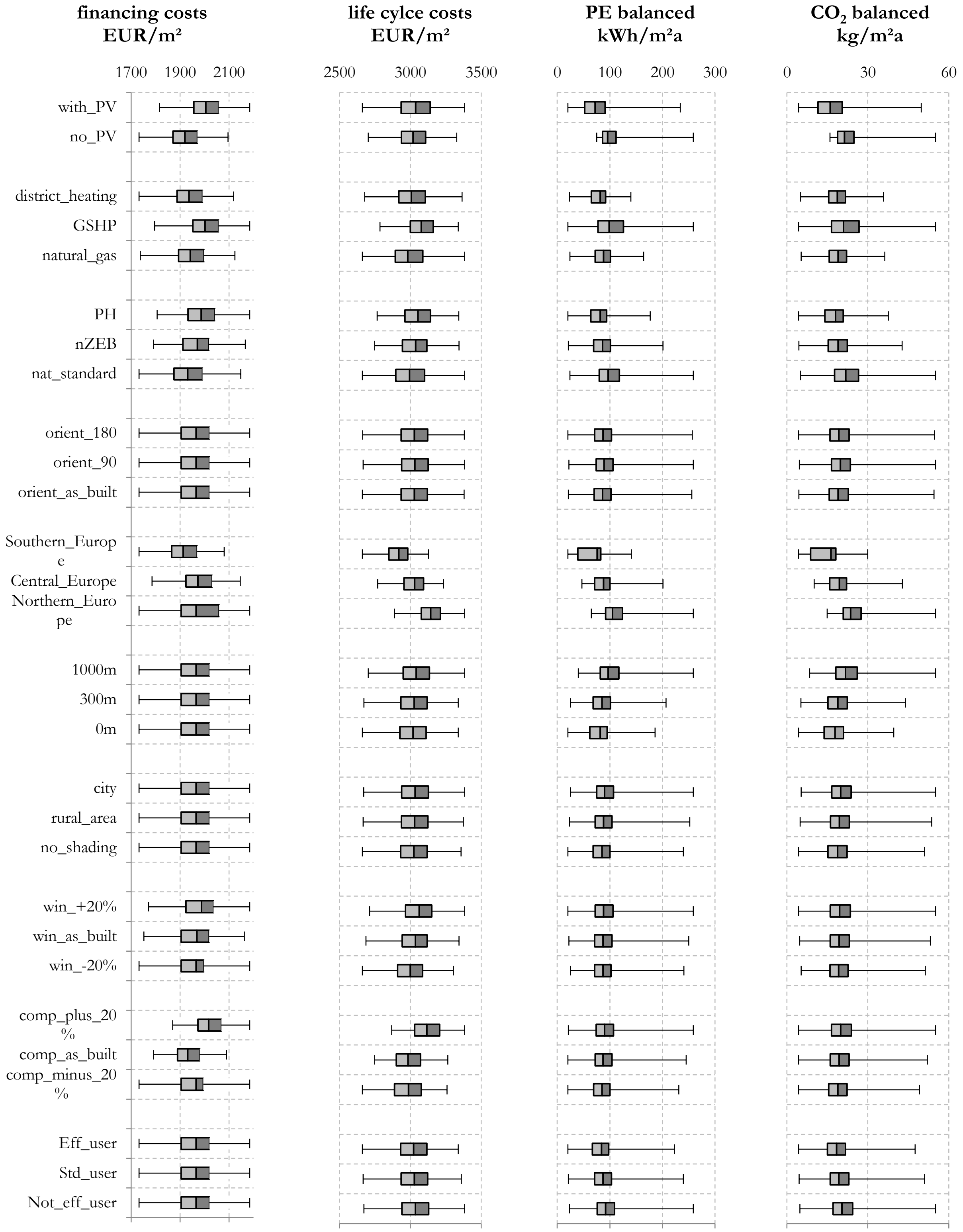
IDEAbuilder (2012) *The MacLeamy Curve - Real World BIM and IPD*. Available at: http://greghowes.blogspot.com/2012/06/macleamy-curve-real-world-bim-and-ipd.html.

Passive House Institute (2015) *Passive House Planning Package (PHPP)*, *passivehouse.com*.

University of Washington (no date) *Machine Learning: Clustering & Retrieval*.

11. APPENDIX

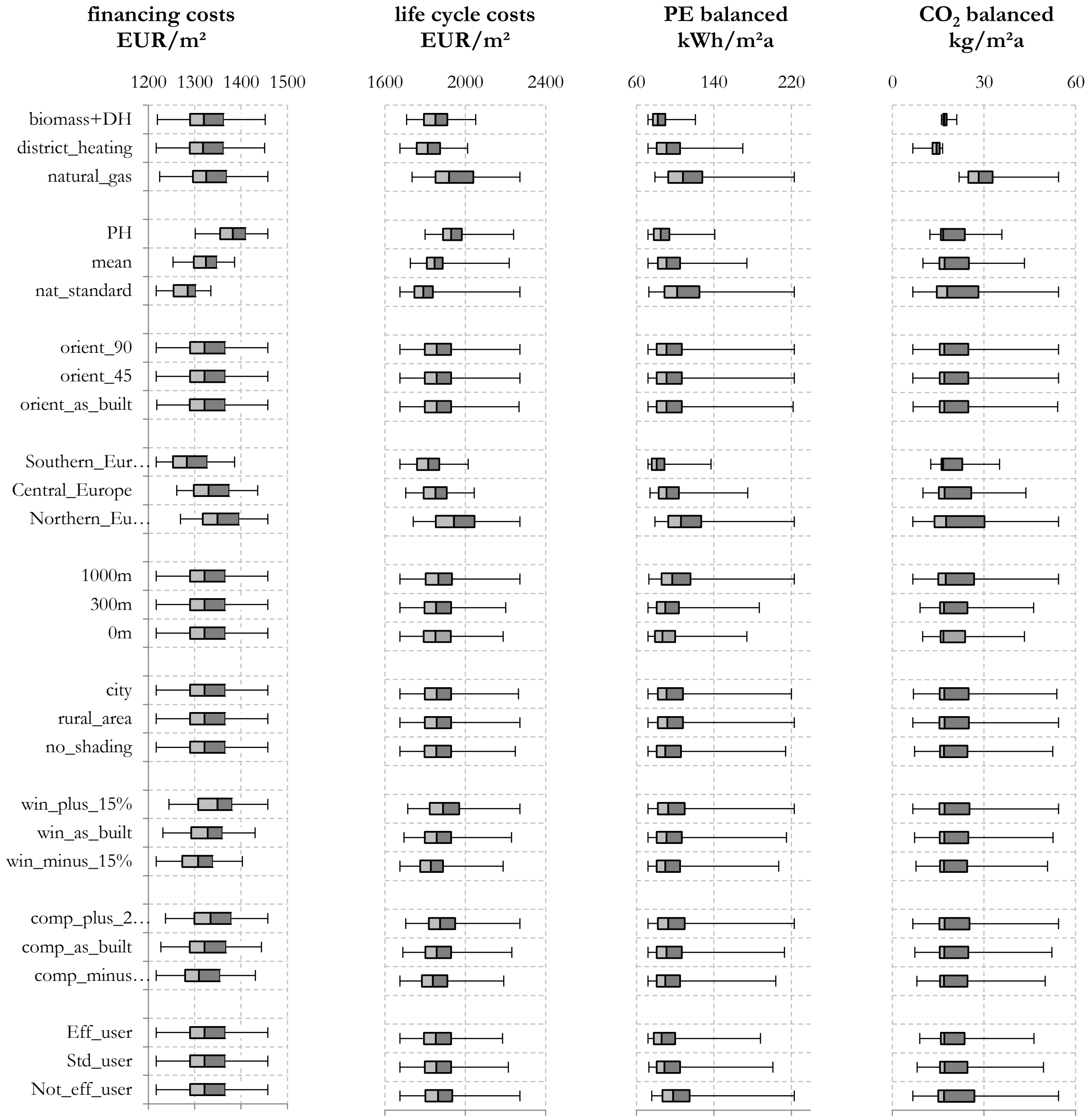
11.1. VÄLA GÅRD



		financing costs (EUR/m²)	life cycle costs (EUR/m²)	PE balanced (kWh/m²a)	CO_2 balanced (kg/m²a)
Not efficient user behaviour	minimum	1733	2673	23	5
	median	1966	3036	92	20
	maximum	2185	3383	259	55
	standard deviation	83	131	34	7
Standard user behaviour	minimum	1733	2667	21	4
	median	1966	3029	87	19
	maximum	2185	3359	240	51
	standard deviation	83	131	31	7
Efficient user behaviour	minimum	1733	2662	20	4
	median	1966	3023	84	18
	maximum	2185	3338	223	48
	standard deviation	83	130	29	6
Compactness -20 %	minimum	1733	2662	20	4
	median	1966	2987	85	19
	maximum	2185	3259	231	49
	standard deviation	83	126	30	6
Compactness as built	minimum	1792	2747	20	4
	median	1932	2984	87	19
	maximum	2090	3263	245	52
	standard deviation	66	107	32	7
Compactness +20 %	minimum	1870	2869	21	4
	median	2017	3116	90	20
	maximum	2185	3383	259	55
	standard deviation	68	110	34	7
Window area -20 %	minimum	1733	2662	25	5
	median	1966	3000	87	19
	maximum	2185	3303	241	51
	standard deviation	83	127	30	6
Window area as built	minimum	1752	2687	22	5
	median	1969	3035	87	19
	maximum	2163	3343	250	53
	standard deviation	82	128	32	7
Window area +20 %	minimum	1771	2712	20	4
	median	1988	3063	88	20
	maximum	2185	3383	259	55
	standard deviation	82	130	33	7
No shading	minimum	1733	2662	20	4
	median	1966	3025	85	19
	maximum	2185	3358	240	51
	standard deviation	83	131	31	7
Rural area shading	minimum	1733	2667	23	5
	median	1966	3030	88	19
	maximum	2185	3374	252	54
	standard deviation	83	131	32	7
City shading	minimum	1733	2670	25	5
	median	1966	3033	90	20
	maximum	2185	3383	259	55
	standard deviation	83	131	33	7
Sea level 0 m	minimum	1733	2662	20	4
	median	1966	3019	82	18
	maximum	2185	3337	186	40
	standard deviation	83	131	28	6
Sea level 300 m	minimum	1733	2673	25	5
	median	1966	3026	85	19
	maximum	2185	3338	207	44
	standard deviation	83	130	29	6
Sea level 1000 m	minimum	1733	2703	40	8
	median	1966	3040	97	22
	maximum	2185	3383	259	55
	standard deviation	83	129	33	7
Northern Europe	minimum	1733	2888	65	15
	median	1966	3143	105	24
	maximum	2185	3383	259	55
	standard deviation	83	91	29	6

		financing costs (EUR/m²)	life cycle costs (EUR/m²)	PE balanced (kWh/m²a)	CO_2 balanced (kg/m²a)
Central Europe	minimum	1786	2770	47	10
	median	1973	3030	88	19
	maximum	2146	3233	201	43
	standard deviation	75	93	22	5
Southern Europe	minimum	1733	2662	20	4
	median	1913	2918	76	16
	maximum	2080	3128	141	30
	standard deviation	72	93	24	5
Orientation as built	minimum	1733	2662	21	4
	median	1966	3028	86	19
	maximum	2185	3379	256	55
	standard deviation	83	131	31	7
Orientation +90°	minimum	1733	2666	22	5
	median	1966	3032	89	20
	maximum	2185	3383	259	55
	standard deviation	83	130	32	7
Orientation +180°	minimum	1733	2663	20	4
	median	1966	3029	87	19
	maximum	2185	3381	257	55
	standard deviation	83	131	32	7
National standard envelope	minimum	1733	2662	24	5
	median	1932	2994	97	22
	maximum	2148	3383	259	55
	standard deviation	87	141	37	8
nZEB envelope	minimum	1792	2747	21	4
	median	1972	3037	86	19
	maximum	2167	3343	201	43
	standard deviation	77	122	28	6
Passive house envelope	minimum	1806	2766	20	4
	median	1987	3054	82	18
	maximum	2185	3341	177	38
	standard deviation	77	122	25	5
Natural gas heating	minimum	1738	2662	24	5
	median	1942	2982	88	19
	maximum	2124	3383	164	36
	standard deviation	78	135	25	5
Ground source heat pump	minimum	1796	2785	20	4
	median	2003	3077	99	21
	maximum	2185	3338	259	55
	standard deviation	78	111	40	9
District heating	minimum	1733	2678	23	5
	median	1937	3007	82	19
	maximum	2119	3364	140	36
	standard deviation	78	128	22	5
No PV	minimum	1733	2702	75	16
	median	1920	3020	96	21
	maximum	2096	3327	259	55
	standard deviation	71	118	24	5
With PV	minimum	1816	2662	20	4
	median	2006	3038	72	16
	maximum	2185	3383	234	50
	standard deviation	72	142	32	7

11.2. NH TIROL

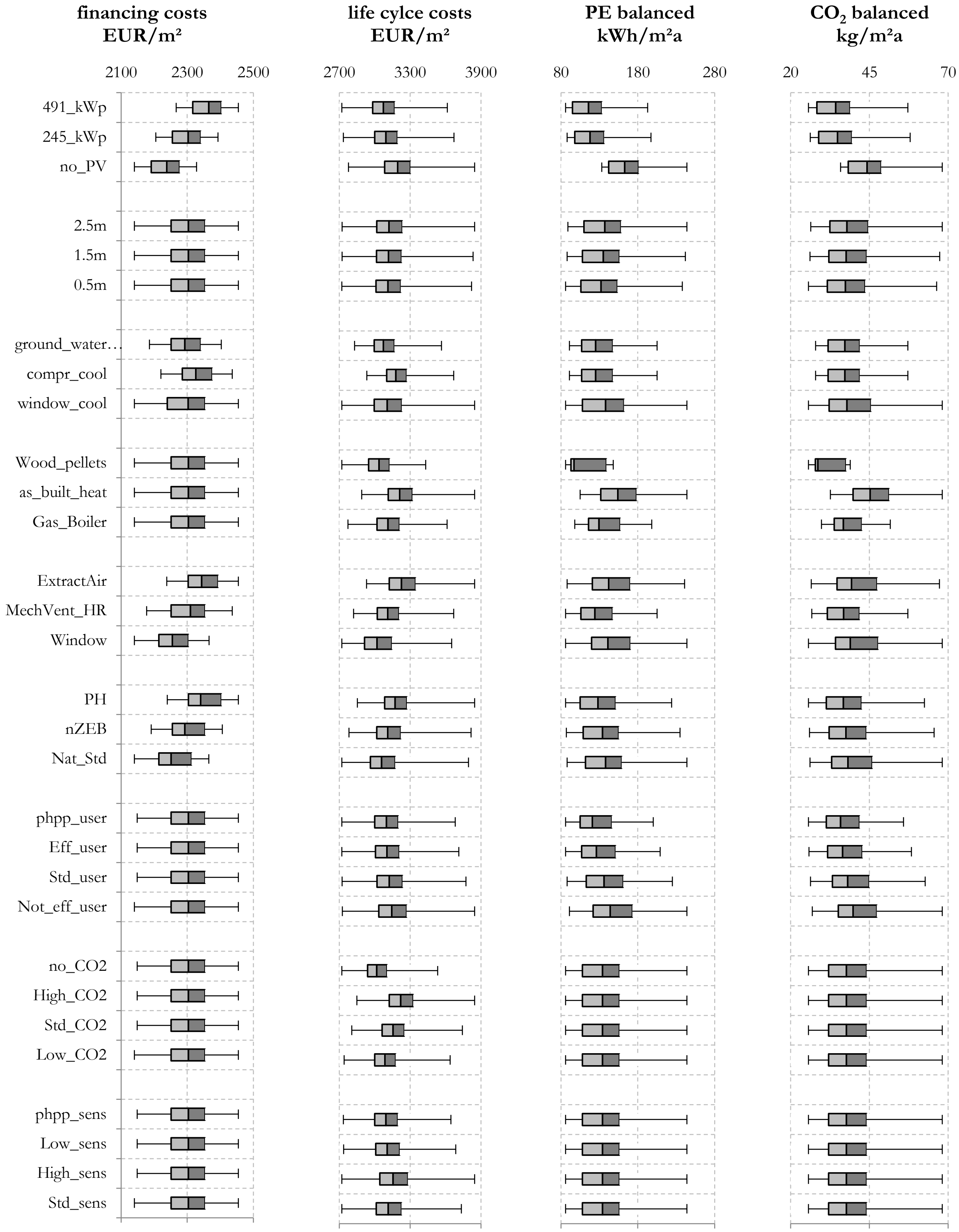


		financing costs (EUR/m²)	life cycle costs (EUR/m²)	PE balanced (kWh/m²a)	CO_2 balanced (kg/m²a)
Not efficient user behaviour	minimum	1217	1675	76	7
	median	1290	1801	87	15
	maximum	1321	1865	98	17
	standard deviation	1366	1935	115	27
Standard user behaviour	minimum	1217	1675	73	8
	median	1290	1798	81	16
	maximum	1321	1856	89	17
	standard deviation	1366	1929	105	25
Efficient user behaviour	minimum	1217	1675	72	9
	median	1290	1794	78	16
	maximum	1321	1853	86	17
	standard deviation	1366	1929	100	24
Compactness -20 %	minimum	1217	1675	72	8
	median	1279	1784	81	16

		financing costs (EUR/m²)	life cycle costs (EUR/m²)	PE balanced (kWh/m²a)	CO_2 balanced (kg/m²a)
	maximum	1309	1839	90	17
	standard deviation	1355	1911	105	25
Compactness as built	minimum	1227	1689	72	7
	median	1289	1801	81	15
	maximum	1321	1858	91	17
	standard deviation	1368	1930	107	25
Compactness +20 %	minimum	1237	1703	72	7
	median	1299	1818	82	15
	maximum	1334	1874	93	17
	standard deviation	1379	1949	110	25
Window area -15 %	minimum	1217	1675	72	8
	median	1273	1775	81	16
	maximum	1307	1828	90	17
	standard deviation	1339	1889	105	25
Window area as built	minimum	1231	1695	72	7
	median	1292	1799	81	15
	maximum	1328	1858	91	17
	standard deviation	1360	1929	107	25
Window area +15 %	minimum	1244	1714	72	7
	median	1307	1823	82	15
	maximum	1349	1889	93	17
	standard deviation	1381	1970	110	25
No shading	minimum	1217	1675	72	7
	median	1290	1797	81	16
	maximum	1321	1856	90	17
	standard deviation	1366	1929	106	25
Rural area shading	minimum	1217	1675	72	7
	median	1290	1798	82	15
	maximum	1321	1858	92	17
	standard deviation	1366	1930	108	25
City shading	minimum	1217	1675	72	7
	median	1290	1798	82	15
	maximum	1321	1858	91	17
	standard deviation	1366	1929	108	25
Sea level 0 m	minimum	1217	1675	72	10
	median	1290	1793	79	16
	maximum	1321	1852	87	17
	standard deviation	1366	1928	100	24
Sea level 300 m	minimum	1217	1675	72	9
	median	1290	1797	81	16
	maximum	1321	1855	90	17
	standard deviation	1366	1929	104	25
Sea level 1000 m	minimum	1217	1675	73	7
	median	1290	1802	86	15
	maximum	1321	1866	97	17
	standard deviation	1366	1934	116	27
Northern Europe	minimum	1269	1741	79	7
	median	1317	1853	93	14
	maximum	1349	1944	106	18
	standard deviation	1396	2046	127	30
Central Europe	minimum	1261	1704	74	10
	median	1298	1793	83	15
	maximum	1330	1851	91	17
	standard deviation	1375	1908	104	26
Southern Europe	minimum	1217	1675	72	13
	median	1253	1759	76	16
	maximum	1283	1816	81	17
	standard deviation	1327	1871	89	23
Orientation as built	minimum	1218	1675	72	7
	median	1289	1798	81	15
	maximum	1321	1858	91	17
	standard deviation	1366	1929	107	25
Orientation +45°	minimum	1217	1675	72	7
	median	1290	1798	81	16

		financing costs (EUR/m²)	life cycle costs (EUR/m²)	PE balanced (kWh/m²a)	CO_2 balanced (kg/m²a)
	maximum	1321	1858	91	17
	standard deviation	1366	1929	107	25
Orientation +180°	minimum	1217	1675	72	7
	median	1290	1798	81	16
	maximum	1321	1858	91	17
	standard deviation	1366	1929	107	25
National standard envelope	minimum	1217	1675	73	7
	median	1254	1746	89	15
	maximum	1285	1791	102	18
	standard deviation	1302	1838	125	28
Mean envelope	minimum	1253	1727	72	10
	median	1298	1809	82	15
	maximum	1324	1848	91	17
	standard deviation	1348	1888	105	25
Passive house envelope	minimum	1301	1800	72	12
	median	1355	1889	78	16
	maximum	1382	1929	85	17
	standard deviation	1410	1983	94	24
Natural gas heat-ing	minimum	1224	1735	79	22
	median	1296	1851	93	25
	maximum	1325	1920	108	28
	standard deviation	1369	2040	128	33
District heating	minimum	1217	1675	72	7
	median	1289	1758	81	13
	maximum	1318	1813	91	14
	standard deviation	1362	1875	105	15
Biomass + district heating	minimum	1219	1707	72	16
	median	1290	1794	77	17
	maximum	1320	1851	82	17
	standard deviation	1363	1910	90	18

11.3. IR-HEADQUARTER

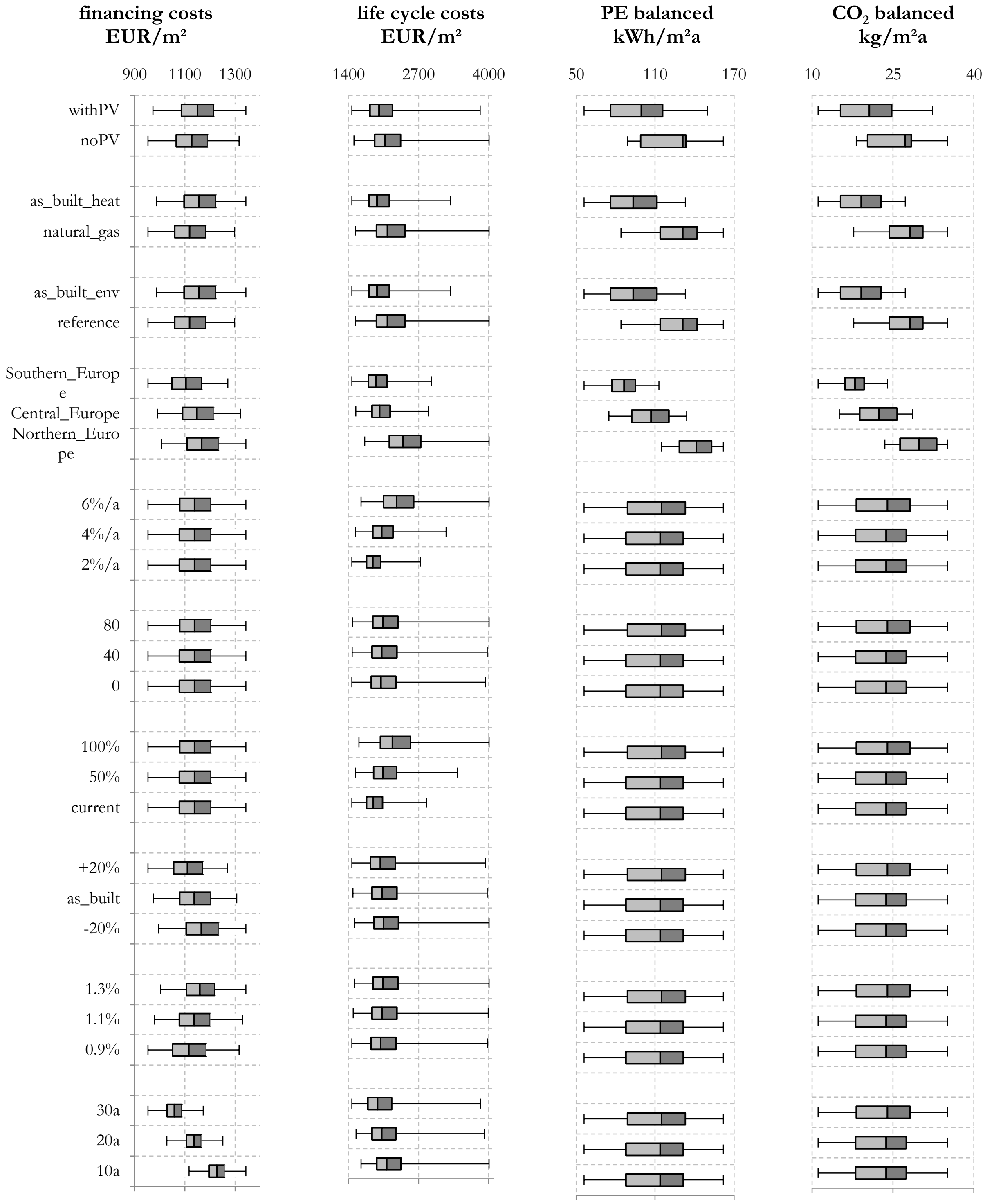


		financing costs (EUR/m²)	life cycle costs (EUR/m²)	PE balanced (kWh/m²a)	CO_2 balanced (kg/m²a)
Standard sensitivity	minimum	2140	2721	86	26
	median	2304	3013	108	32
	maximum	2455	3115	134	38

		financing costs (EUR/m²)	life cycle costs (EUR/m²)	PE balanced (kWh/m²a)	CO_2 balanced (kg/m²a)
	standard deviation	71	3227	156	44
High sensitivity	minimum	2149	2721	86	26
	median	2304	3042	108	32
	maximum	2455	3156	134	38
	standard deviation	70	3280	156	44
Low sensitivity	minimum	2149	2737	86	26
	median	2304	3009	108	32
	maximum	2455	3106	134	38
	standard deviation	70	3211	156	44
PHPP default sensitivity	minimum	2149	2735	86	26
	median	2304	3000	108	32
	maximum	2455	3094	134	38
	standard deviation	70	3195	156	44
Low CO2 follow-up costs	minimum	2140	2741	86	26
	median	2304	3000	108	32
	maximum	2455	3087	134	38
	standard deviation	71	3176	156	44
Standard CO2 follow-up costs	minimum	2149	2805	86	26
	median	2304	3062	108	32
	maximum	2455	3156	134	38
	standard deviation	70	3251	156	44
High CO2 follow-up costs	minimum	2149	2848	86	26
	median	2304	3123	108	32
	maximum	2455	3221	134	38
	standard deviation	70	3326	156	44
No CO2 follow-up costs	minimum	2149	2721	86	26
	median	2304	2940	108	32
	maximum	2455	3017	134	38
	standard deviation	70	3103	156	44
Not efficient user behaviour	minimum	2140	2726	91	27
	median	2304	3034	122	35
	maximum	2455	3145	144	40
	standard deviation	71	3270	173	47
Standard user behaviour	minimum	2149	2723	88	26
	median	2304	3019	113	33
	maximum	2455	3123	136	38
	standard deviation	70	3234	161	45
Efficient user behaviour	minimum	2149	2721	86	26
	median	2304	3006	107	32
	maximum	2455	3104	126	37
	standard deviation	70	3208	151	43
PHPP default user behaviour	minimum	2149	2721	86	26
	median	2304	3000	105	31
	maximum	2455	3098	121	36
	standard deviation	70	3199	146	42
National standard envelope	minimum	2140	2721	88	26
	median	2251	2962	112	33
	maximum	2365	3058	138	38
	standard deviation	60	3172	159	46
nZEB envelope	minimum	2191	2781	87	26
	median	2293	3017	109	32
	maximum	2406	3110	134	38
	standard deviation	60	3219	155	44
Passive house envelope	minimum	2240	2852	86	26
	median	2341	3083	105	31
	maximum	2455	3172	128	37
	standard deviation	60	3272	151	42
Window ventila-tion	minimum	2140	2721	86	26
	median	2255	2914	120	34
	maximum	2366	3019	141	39
	standard deviation	63	3144	170	48
Mechanical venti-lation with heat recovery	minimum	2177	2821	86	27
	median	2310	3022	106	32
	maximum	2436	3110	124	37

		financing costs (EUR/m²)	life cycle costs (EUR/m²)	PE balanced (kWh/m²a)	CO_2 balanced (kg/m²a)
	standard deviation	65	3205	147	42
Extract air ventilation	minimum	2238	2930	88	27
	median	2344	3123	121	35
	maximum	2455	3226	142	39
	standard deviation	64	3346	170	47
Natural gas	minimum	2140	2772	98	30
	median	2304	3019	116	34
	maximum	2455	3112	130	37
	standard deviation	70	3210	157	43
Heating as built	minimum	2140	2890	105	33
	median	2304	3115	132	40
	maximum	2455	3212	154	45
	standard deviation	70	3320	178	51
Wood pellets	minimum	2140	2721	86	26
	median	2304	2948	93	28
	maximum	2455	3037	97	29
	standard deviation	70	3124	139	38
Window cooling	minimum	2140	2721	86	26
	median	2303	2996	108	32
	maximum	2455	3105	138	38
	standard deviation	73	3228	162	46
Compressor cooling	minimum	2220	2933	91	28
	median	2326	3101	107	32
	maximum	2436	3178	125	37
	standard deviation	63	3270	148	42
Ground water cooling	minimum	2186	2829	91	28
	median	2293	2996	107	32
	maximum	2403	3073	125	37
	standard deviation	63	3165	148	42
0.5 m overhang shading	minimum	2140	2721	86	26
	median	2304	3011	106	32
	maximum	2455	3112	132	37
	standard deviation	70	3221	153	44
1.5 m overhang shading	minimum	2140	2723	88	26
	median	2304	3014	108	32
	maximum	2455	3117	135	38
	standard deviation	70	3227	156	44
2.5 m overhang shading	minimum	2140	2724	89	26
	median	2304	3017	110	32
	maximum	2455	3121	137	38
	standard deviation	70	3232	158	45
No PV	minimum	2140	2778	133	36
	median	2238	3085	142	38
	maximum	2328	3193	163	44
	standard deviation	48	3303	181	49
245 kWp PV	minimum	2205	2735	88	26
	median	2303	3000	98	29
	maximum	2393	3095	118	35
	standard deviation	48	3192	136	39
491 kWp PV°	minimum	2267	2721	86	26
	median	2365	2983	95	28
	maximum	2455	3074	116	34
	standard deviation	48	3169	133	39

11.4. GREEN HOME NANTERRE



		financing costs (EUR/m²)	life cycle costs (EUR/m²)	PE balanced (kWh/m²a)	CO_2 balanced (kg/m²a)
10a credit period	minimum	1117	1633	56	11
	median	1227	2108	114	24
	maximum	1343	4008	162	35
	standard deviation	46	397	28	6
20a credit period	minimum	1028	1539	56	11

		financing costs (EUR/m²)	life cycle costs (EUR/m²)	PE balanced (kWh/m²a)	CO_2 balanced (kg/m²a)
	median	1137	2016	114	24
	maximum	1251	3921	162	35
	standard deviation	43	397	28	6
30a credit period	minimum	953	1460	56	11
	median	1059	1939	115	24
	maximum	1173	3847	162	35
	standard deviation	43	397	28	6
0.9 % interest on credit	minimum	953	1460	56	11
	median	1116	1998	114	24
	maximum	1316	3982	162	35
	standard deviation	85	404	28	6
1.1 % interest on credit	minimum	978	1486	56	11
	median	1137	2019	114	24
	maximum	1329	3995	162	35
	standard deviation	80	403	28	6
1.3 % interest on credit	minimum	1003	1513	56	11
	median	1160	2039	115	24
	maximum	1343	4008	162	35
	standard deviation	75	402	28	6
10 % equity ratio	minimum	995	1504	56	11
	median	1166	2048	114	24
	maximum	1343	4008	162	35
	standard deviation	82	403	28	6
15 % equity ratio	minimum	974	1482	56	11
	median	1138	2019	114	24
	maximum	1307	3973	162	35
	standard deviation	78	403	28	6
20 % equity ratio	minimum	953	1460	56	11
	median	1111	1992	115	24
	maximum	1270	3939	162	35
	standard deviation	74	402	28	6
Current energy prices	minimum	953	1460	56	11
	median	1139	1861	114	24
	maximum	1343	2846	162	35
	standard deviation	81	248	28	6
Current energy prices + 50 %	minimum	953	1527	56	11
	median	1139	2037	114	24
	maximum	1343	3427	162	35
	standard deviation	81	354	28	6
Current energy prices + 100 %	minimum	953	1594	56	11
	median	1139	2215	115	24
	maximum	1343	4008	162	35
	standard deviation	81	463	28	6
no CO2 follow-up costs	minimum	953	1460	56	11
	median	1139	2000	114	24
	maximum	1343	3940	162	35
	standard deviation	81	399	28	6
40 EUR/t_{CO2} CO2 follow-up costs	minimum	953	1467	56	11
	median	1139	2018	114	24
	maximum	1343	3974	162	35
	standard deviation	81	403	28	6
80 EUR/t_{CO2} CO2 follow-up costs	minimum	953	1474	56	11
	median	1139	2038	115	24
	maximum	1343	4008	162	35
	standard deviation	81	407	28	6
2 %/a energy price increase	minimum	953	1460	56	11
	median	1139	1849	114	24
	maximum	1343	2731	162	35
	standard deviation	81	227	28	6
4 %/a energy price increase	minimum	953	1524	56	11
	median	1139	2014	114	24
	maximum	1343	3212	162	35
	standard deviation	81	314	28	6
6 %/a energy	minimum	953	1630	56	11

		financing costs (EUR/m²)	life cycle costs (EUR/m²)	PE balanced (kWh/m²a)	CO_2 balanced (kg/m²a)
price increase	median	1139	2291	115	24
	maximum	1343	4008	162	35
	standard deviation	81	462	28	6
Northern Europe	minimum	1007	1702	115	23
	median	1167	2408	142	30
	maximum	1343	4008	162	35
	standard deviation	80	482	18	5
Central Europe	minimum	991	1536	75	15
	median	1149	1976	107	22
	maximum	1321	2881	134	29
	standard deviation	79	257	22	5
Southern Europe	minimum	953	1460	56	11
	median	1105	1911	87	18
	maximum	1271	2939	113	24
	standard deviation	76	279	20	5
Reference building envelope quality	minimum	953	1531	84	18
	median	1119	2123	131	28
	maximum	1298	4008	162	35
	standard deviation	78	446	23	5
Building envelope as built	minimum	987	1460	56	11
	median	1157	1931	94	19
	maximum	1343	3288	133	27
	standard deviation	80	315	23	5
Natural gas heating	minimum	953	1531	84	18
	median	1119	2123	131	28
	maximum	1298	4008	162	35
	standard deviation	78	446	23	5
Heating as built	minimum	987	1460	56	11
	median	1157	1931	94	19
	maximum	1343	3288	133	27
	standard deviation	80	315	23	5
No PV	minimum	953	1500	89	18
	median	1127	2078	131	27
	maximum	1316	4008	162	35
	standard deviation	80	413	23	5
With PV	minimum	973	1460	56	11
	median	1150	1966	100	21
	maximum	1343	3843	150	32
	standard deviation	81	385	28	6