D4.2: Optimized nZEB-solution sets

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

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

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Optimized nZEB-solution sets

Authors:
Benjamin Köhler[1], Essam El-Nagar[1], David Venus[2], Federico Garzia[3],

Authors (Contributors):
Mustafa Abunofal[1], Björn Berggren[4], Christian de Nacquard[5], Klara Meier[6,] Davide Torriglia[7], Mirco Balachia[7], Giovanni Tumminia[8], Gerold Köhler[9], Thomas Stöcker[9]

[1]Fraunhofer Institute for Solar Energy Systems, Heidenhoftsraße 2, D-79110 Freiburg
[2]AEE - Institute for Sustainable Technologies, Feldgasse 19, A-8200 Gleisdorf
[3]eurac research Institute for Renewable Energy, Via Volta 13/A, IT-39100 Bozen/Bolzano
[4]Skanska Sverige AB, Rasundavagen 2, SWE-16983 Solna
[5]Bouygues Construction, avenue Eugène Freyssinet 1, FR-78280 Guyancourt
[6]ATP sustain GmbH, Karlstraße 66, D-80335 München
[7]3i group, Via Galimberti 36, IT-15121 Alessandria
[8]Italian National Research Council Institute for Advanced Energy Technologies" Nicola Giordano ", Salita Santa Lucia Sopra Contesse, 5, IT-98126 Messina
[9]Köhler & Meinzer GmbH & Co KG, Junkersring 14, D-76344 Eggenstein-Leopoldshafen

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FOREWORD

This report summarises results of Work Package 'WP04 – Cost reduction potentials for nZEB technologies', task 4.2 'Development of low costs solutions sets (construction concepts, building technical systems including renewables)'. It is 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. 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.
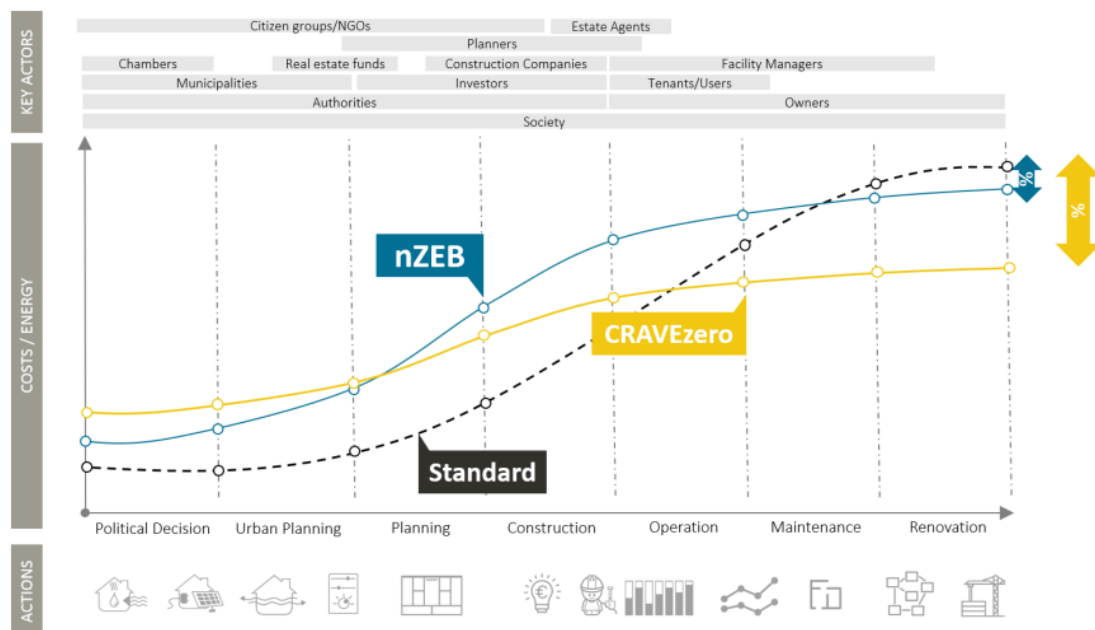

Figure 1: CRAVEzero approach for cost reductions in the life cycle of nZEBs.

EXECUTIVE SUMMARY

Nearly-zero energy buildings (nZEBs) can be constructed and operated economically already today. For realising these buildings integrated planning and optimisation of the building design is essential. A focus must be on the reduction of the energy demand by good quality building envelopes and the minimisation of energy demand through passive approaches. Passive approaches in the context of the deliverable at hand are the building orientation, the window-to-wall ratio, optimal use of solar gains, daylighting control and natural ventilation to minimise ventilation and cooling energy demands. The effects of passive approaches highly depend on local surroundings like climate conditions and the direct surrounding of the building (neighbouring buildings etc.). Minimizing the energy demand of the building also allows reducing the needed technical installations (HVAC) and thereby supports the realisation of low-tech buildings.

Even if a building is optimally designed for local (climate) conditions there will always be a remaining energy demand, which has to be covered as efficient as possible to large extent by on-site renewable energies. Many technologies needed for realising nZEBs are already available. However, the identification of suitable technology sets for different site/ side conditions is still challenging. Furthermore, depending on the overall goal of a project (mini-mise costs, CO_2 emissions or other goals) can lead to different optimal technology sets. Therefore, a clear definition of the goal as early as possible in the planning process is essential.

The deliverable at hand is divided into two major parts. In the first part of the deliverable, a general overview of technologies and approaches to realise nZEBs are described. Furthermore, the methodology used for identifying optimal technology sets is described. In this part, on the one hand, the method applied in other work packages of the project, which are relevant for the analysis in this document is summarized. On the other hand the methodology for the assessment of passive approaches, which is the focus of the deliverable, is described.

In the second part of the document the results are described and discussed. In the first part of this section, technology sets of the parametric analysis conducted in work package WP06 are described in detail. The focus is set leading to highest and lowest costs (net present values NPV) and highest and lowest CO_2 emissions. In the second part, the results of the detailed building simulation to assess the effects of passive approaches are described. Therefore, the case study Parkcarré is used as a basis. Several variants of the passive strategies are simulated on an hourly basis and for three different climate regions.

In the following, some main results and findings are presented:

- High costs / NPVs are often associated with a high energetic standard of the building envelope and complex HVAC systems/ heating systems
- Low NPV variants usually have a minimized HVAC system and can be considered as low-tech buildings. The variants with low NPVs often have lower CO_2 emissions than the ones with the highest NPV. However, to achieve low cost and low emissions buildings, efficient user behaviour is necessary.
- Besides the technical parameters, the user behaviour and climate conditions have a significant effect on the energy demand and thereby the life cycle costs and CO_2 emissions of a building
- The impact of passive approaches highly depends on the climate conditions; while in regions, in which the heating demand is dominating, the south orientation of the building is the best, orienting a building to north results in the lowest energy demands and LCC in regions with a high cooling demand.
- The assessed passive approaches have the most considerable effect in regions with high cooling energy demand.

Contents

LIST OF FIGURES

LIST OF TABLES

LIST OF ABBREVIATIONS

CHP	Combined Heat and Power
COP	Coefficient of Performance
DH	District Heat
DHW	Domestic Hot Water
EER	Energy Efficiency Ratio
EPBD	Energy Performance of Building Directive
EPS	Expanded Polystyrene
GSHP	Ground Source Heat Pump
HP	Heat Pump
HVAC	Heating, Ventilation and Air Conditioning
IAQ	Indoor Air Quality
IEA	International Energy Agency
KPI	Key Performance Indicator
kWp	Kilowatt peak
LCC	Life Cycle Cost
NPV	Net Present Value
nZEB	Nearly Zero-Energy Building
NZEB	Net Zero-Energy Building
ÖGNB	Österreichische Gesellschaft für Nachhaltiges Bauen (Austrian Sustainable Building Council)
PH	Passive House
PHPP	Passive House Planning Package
PV	Photovoltaic
RES	Renewable Energy Sources
SA	Sensitivity Analysis
WLC	Whole-Life Costing
WP	Work Package

1. INTRODUCTION

1.1. OBJECTIVE

The aim of the deliverable is the development and description of technology sets, which (i) minimize the energy demand by applying passive (design) approaches and (ii) reduce the life cycle cost of the building as a whole.

Many technologies needed for realising nZEBs are already available. However, the identification of suitable technology sets focusing on passive (design) approaches to minimize the energy demand is still a challenge and not carried out comprehensively. Thereby, only a few, out of many possible technology sets are considered and assessed in traditional planning processes.

A detailed optimisation and parametric analysis of different technology sets for the CRAVEzero case study buildings with a focus on active technologies is carried out in WP06 of CRAVEzero.. The deliverable at hand focuses on the analysis of different passive approaches on the energy demand. The assessment is carried out for different climate conditions.

Additionally, the currently planned/built technology sets, as well as suggested improvements and optimal sets identified in WP06, are described and shown in simplified system schematics. The improved technology sets are described in-depth, and possible cost developments based on the cost curves developed in deliverable D4.1 are derived.

The basis for the results presented in the following are:

- Detailed technology analysis presented in deliverable D4.1 (Köhler et al., 2018),
- Detailed descriptions of the technologies installed in the CRAVEzero case studies,
- Methodology and results of WP06 (Life cycle cost reduction of new nZEB), in which a multi-objective optimisation is carried out for several case studies and
- LCC assessments in WP02 and WP06.

1.2. TASKS

In the deliverable at hand, two major tasks as described in the project proposal are addressed. The tasks are briefly introduced in the following.

The first task is the assessment of the technical performance and life cycle costs for nZEB technologies and solution sets as well as the development of a solution matrix regarding cost savings of more durable, technical solution sets for nZEBs.

The second task is the definition of low-tech technologies / technology sets and materials with re-

duced renovation and maintenance costs. Passive approaches for the building design (amongst others building orientation or window-to-wall ratio) and building services like lighting, heating, cooling and ventilation are assessed in depth for different climate conditions.

The focus of the deliverable is the assessment of low-tech / passive building approaches.

2. TECHNOLOGIES

The relevant active and renewable technologies for realising nZEBs are described in deliverable 4.1 (Köhler et al., 2018). They are briefly described in chapters 2.1 and 2.3. Passive approaches / technologies are described in chapter 2.2. The description of passive technologies and the discussion of low- vs. high-tech (chapter 2.4) are based on work conducted in the frame of the deliverable at hand.

2.1. ACTIVE TECHNOLOGIES

A central aspect of realising nZEBs is the minimisation of the energy demand for conditioning and operating a building through insulation and other passive technologies and strategies. However, there will always be a remaining energy demand for building services like heating, cooling, ventilation or lighting. The remaining energy demand must be provided as efficiently as possible and to large extents by renewable energy. In the following, major active technologies are briefly described based on deliverable D4.1 "Guideline II: nZEB Technologies", which are:

- Heating and hot-water:
  - Heat pump (air & ground source)
  - District heat
  - Condensing biomass boiler
- Cooling systems
- Mechanical ventilation (additional with heat recovery):
  - Central ventilation
  - Decentralised ventilation
- Thermal storage
- Electrical storage (Li-based).

The various technologies have different potentials for further cost reductions. Fossil fuel-based technologies (oil and gas boilers) have the lowest cost reduction potential of only about 1% and 9% respectively until 2050. High cost reductions are expected for comparably new technologies, which are necessary for decarbonising (i) the electric power system and / or (ii) decarbonising the heating sector. For air heat pumps a cost reduction of 11 % to 44 % and for ground-source heat pumps of 8 % to 34 % is expected (Köhler et al., 2018). Even higher reductions are expected for PV-systems (-41 % to -

56 %, compare (Köhler et al., 2018)). The cost reduction potentials of all technologies assessed in deliverable D4.1 are shown in Figure 2.

Established, fossil fuel-based technologies (oil and gas **boilers**) have comparably high CO_2-emissions, which contradict the climate protection goals of the EU. Therefore, they will lose market shares leading to only a small increase in the cumulative production volume. A slightly higher market share is predicted for biomass boilers, which are more environmentally friendly. However, the expected cost reduction of approx. 14 % until 2050 is also comparably low.

Heat pumps are expected to play a major role in the future heating (and probably cooling) sector, especially in an energy system mainly based on fluctuating renewable energies as they couple the electricity and heating sector. Therefore, a strong market increase is expected to result in high-cost reductions of more than 20 % by 2050.

Central and decentralised **ventilation** systems are of major importance for air-tight energy-efficient buildings. They supply fresh air, reduce ventilation heat losses when equipped with heat recovery systems and assure good air quality. Especially in airtight buildings ensuring good air quality is almost impossible without mechanical ventilation. The market for ventilation systems will most likely grow in the coming decades, and ventilation systems are installed in most new constructions. This leads to cost reductions of around 46 % - 52 % by 2050 for these technologies.

Thermal and electrical storages are essential in an energy system based on fluctuating renewable energies. They can bridge gaps between supply and demand for at least several hours or even days;

long-term storages are usually not installed in single buildings. Both storage types have substantial cost reduction potentials of about 29 % (thermal) and 65 % (electrical) by 2050.

With increasing indoor comfort requirements and further global warming, the need for **air conditioning/ cooling** is increasing leading to a strong market increase and associated cost reduction potentials for cooling technologies of about 29 % by 2050. Reversible heat pumps can be used both for heating in winter and cooling in summer, minimizing the number of needed technologies in a building.

PV is an established renewable energy source with a global market. In all future scenarios for energy systems with low greenhouse gas emissions, PV at buildings plays a key role in meeting emission targets and generating the required amount of renewable electricity. High cost reduction potentials are expected as fast market development is indispensable until 2050 for the achievement of the climate and emission targets of the Paris Agreement (Köhler et al., 2018). The cost reduction potential is around 50 % by 2050. In addition to established PV systems (mainly roof-top installation), building-integrated PV (**BiPV**) is a promising and growing new field.

Solar thermal systems are also already widespread and still have an expected cost reduction potential of approx. 38 % by 2050. Solar thermal collectors can also be integrated into the building envelope (e.g. the façade) and replace elements leading to overall lower costs for realising nZEBs.
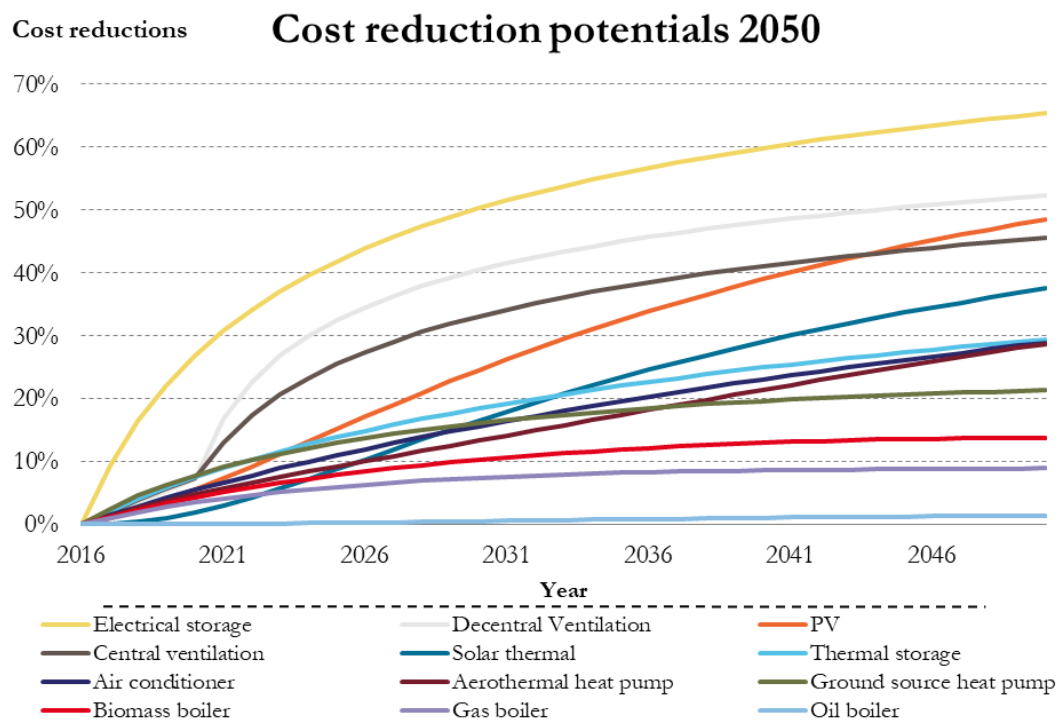
Figure 2: Cost reduction potentials of major nZEB technologies calculated with the top-down learning curve approach; Source (Köhler et al., 2018).

2.2. PASSIVE TECHNOLOGIES AND APPROACHES

Passive technologies can have a positive influence by reducing the energy requirements of buildings without energy-consuming conversion technologies. Passive aspects should already considered during planning phases but rather seldom detailed and combined to optimize and maximize efficiency.

The passive approaches described in the following are:

- Insulation (material, thickness)
- Optimisation of the building design (window-to-wall ratio, orientation)
- Shading
- Daylighting

- Natural ventilation
- Night cooling
- Thermal mass

Without adequate **insulation**, nZEBs can hardly be realised. It is essential to reduce the overall energy demands, especially concerning heating demand in moderate and cold climates. However, for established and widespread insulation materials, no further cost reduction is expected. Only new/ innovative materials and improved mounting processes are expected to decrease the costs of insulation.

The **optimisation of the building design** influences the effects of several approaches described below. The window-to-wall ratio as well as the overall window area have a strong influence on (i) the heating demand as windows usually have the highest U-value of all envelope elements, (ii) overheating and cooling demand in rooms / zones with large glazed areas leading to high solar gains (desired in winter, but not in summer) and (iii) energy demand for lighting due to the availability of daylight inside the building. Besides that windows and other openings in the façade are necessary for free ventilation and night cooling approaches. Furthermore, the overall orientation of a building highly influences the abovementioned parameters. The optimal orientation of a building can differ depending on the local climate conditions and other site conditions like, e.g. orientation of the building site and neighbouring buildings. The orientation of the whole building, as well as window location and sizes, should be optimised in order to minimize heating, cooling and lighting energy demands.

Shading systems are not nZEB specific but needed in all buildings. In the following, different approaches are described due to the importance of adequate shading for the reduction of heat gains in summer and optimisation in winter as well as to avoid glare.

Shading is required to avoid high heat gains in summer and thereby limit the cooling energy demand. This is even gaining importance as the window area especially in non-residential buildings is increasing. The increased window area raises the solar gains in winter and thereby reduces the heating demand. The focus in the northern hemisphere must be windows with east, south and west orientation.

Two types of shading systems can be distinguished:
- Flexible/ controllable shading
- Fixed/ stationary shading

Flexible shading systems are e.g. venetian blinds or systems directly integrated in the window and systems which can change their properties depending on the solar irradiation (e.g. electro or gas chromic windows).

Between flexible and fixed shading systems are **structured windows**. They reflect or deflect the light depending on the irradiance angle. According to (Wagner et al., 2013) the following functionalities can be achieved with structured windows and façade elements:
- Direction-selective shading with diffuse light aperture
- Diffuse light guiding
- Sunlight guiding
- Light transport
- Light diffusion

Façade greening and plants can also provide (flexible) shading. The plants can either be planted in the ground, integrated in the wall/ façade or any combination of the two. If plants losing their leaves during winter are used, solar gains are avoided in summer and enabled during winter (Pfoser, 2014). Plants can supplement other mechanical shading systems, and they can be used in combination with all kinds of facades (Pfoser, 2014). Some plants/ planting systems achieve reduction ratios comparable to jalousie (0.62 to 0.30) and absorb 40 to 80 % of the irradiation. Plants offer several additional services/ advantages like air filtering, humidification (evaporation) and thereby cooling, which is supportive for night cooling and night/ free ventilation. These effects can reduce the outside surface temperature of a façade by 2 – 10 K (Pfoser, 2014). Additionally green roofs are often mandatory to hold rainwater and to support microclimate by evaporative cooling

Fixed and stationary shading systems are balconies, roof overlaps and cantilevers in the façade. They have the highest effects at south-oriented facades (Voss et al., 2005).

Daylighting

The share of lighting in the electricity consumption and the total electricity consumption for lighting in Germany decreased since 1996 (Federal Ministry

for Economic Affairs and Energy, 2015). Reasons are the increased efficiency of light sources, control gears and reflection materials in light bulbs. It is assumed that the electricity consumption for lighting in buildings can be reduced by 50 % to 82 % until 2050 (licht.de - Fördergemeinschaft Gutes Licht, 2008; Wietschel et al., 2010). An improved use of daylight can play a major role for the reduction in the future. Daylight strategies have to be combined with shading systems as the use of solar shading to avoid overheating in summer can lead to the need for artificial light.

For increasing the usage of the available daylight an appropriate dimensioning of windows and sufficient distances between buildings are essential. Furthermore, the sunlight distribution in rooms can be improved by e.g. reflecting surfaces and other optical improvements. There are already sun protection systems/ jalousies, which deflect the direct irradiance to the ceiling reducing the direct irradiation close to the window and increasing the available sunlight in the interior of the room (Jakobiak, 2005). Through the reduction or even avoidance of direct irradiation, solar gains are also reduced in summer, which reduces cooling loads.

In addition light redirecting systems like, e.g. light tubes can be used to reach areas of the building without windows. These systems collect light outside the building and direct it to the inside (Jakobiak, 2005).

In contrast to mechanical ventilation with large ventilation systems, **free ventilation** uses pressure and temperature differences between the in- and outside of a building and between different building zones. By controlled and automated opening of windows and openings in the roof with electric motors, air circulation and change can be realised without additional fans. Thereby, in moderate climates up to 60 % of the end energy for ventilation and air conditioning could be saved compared to conventional ventilation and air conditioning systems (Zentralverband Elektrotechnik- und Elektroindustrie e.V., 2013). Reasons are the omission of fans and the increased air change during night to cool down the building structure. The equivalent savings are 30 to 60 kWh/(m²a) of electricity, cooling and heating energy depending on the heating demand, building type and air conditioning system.

There are three main concepts for free ventilation (Eicker and Schulze, 2012), namely one-sided window opening, vertical transverse flow system of ventilation and chimney/ natural draft ventilation.

The concept of one-sided window opening only considers the opening of windows in one room/ zone; it is the easiest concept and possible in all rooms with windows, which can be opened.

Vertical transverse flow systems of ventilation/ cross ventilation are more effective. They make use of pressure differences on two sides of a building as well as draughts. For effective free air flow through the building has to be assured. This can be achieved by open doors in the building or other openings e.g. above or below doors.

In addition to draughts and pressure differences, chimney/ natural draft ventilation uses the chimney effect. In order to realise the concept, open staircases, atriums or similar open rooms/ spaces or other possibilities for a natural airflow from ground to top floor are needed and cross ventilation has to be avoided.

According to (Eicker and Schulze, 2012) air change rates of $1 - 2$ h^{-1} are possible with one-sided window opening, $2 - 22$ h^{-1} with vertical transverse flow systems and $5 - 16$ h^{-1} with chimney/ natural draft ventilation. Necessary effective opening / cross section areas are between 1 % and 3 % of the ventilated ground floor area. Especially vertical transverse and natural draft ventilation can cause high draughts in a building, which can cause discomfort. Therefore, these concepts are especially suitable for ventilation outside the occupancy hours of a building / zone (e.g. night ventilation with additional positive effects on cooling loads and demands as described below).

For efficient passive and **night cooling** thermal loads/ gains (solar and internal) have to be stored in the building mass during the day and released during the night when the ambient temperature is lower. The cooling during the night can be achieved either by an increased air change rate or – if available – by increasing the flow rate (and probably temperature) of the cooling fluid e.g. in thermo-active building systems (TABS), in which the ceiling is equipped with capillary tubes. Both approaches use the advantage of low ambient temperatures during the night.

The higher air change rate can be realised by ventilators/ mechanical ventilation system or by free convection. For efficient night cooling the minimisation of heat loads, which is required for the realisation of nZEBs anyway, is a pre-requisite. This can be achieved by insulation, shading, efficient equipment and the possibility to store heat in the building mass. The building mass has to be accessible for air in order to fulfil the task. Suspended ceilings or elevated floors should be avoided. Local climate conditions and the neighbourhood also have a strong influence on the possibilities and effectiveness of night cooling concepts.

The activation and usage of the **thermal mass** of a building was already mentioned as an important pre-requisite for night cooling. In the building mass, heat from solar and internal gains can be stored during the day and cooled down with a higher effi-ciency during the night. By cooling down the building mass during night, cold can be stored in the building mass, which avoids a fast heating-up of the building during the day. The activation can be achieved passively or in combination with active systems like (TABS), which are established, innovative systems for surface heating and cooling with significant economic and ecological potential. TABS cool or heat the building structure using tubes integrated into the building elements to condition the interior climate either entirely or as a support system. Through the activation of the building mass and due to the heat inertia high temperatures for cooling and low temperatures for heating can be used. This enables an easier and efficient integration of renewable energies, increases the efficiency of cold and heat generation and flattens the heating and cooling load profile.

2.3. RENEWABLES

Without the use of renewable energies, nearly/ net zero-energy buildings can't be realised as there will always be a remaining energy demand for heating, cooling, ventilation and lighting, which cannot be further reduced. In the following, the most important renewable energies for buildings are briefly described based on D4.1 "Guideline II: nZEB Technologies" (Köhler et al., 2018). These are photovoltaic, solar thermal, geothermal and biomass.

PV modules play a key role in realising nZEBs as the electricity generated on-site reduces the end energy delivery and thereby the energy demands of the building. The modules use the radiant energy of the sun to generate electricity. Important technical parameters to describe a PV system are the nominal power in kilowatt peak (kW_p), the energy output (kWh) and the specific yield (kWh/kW_p). The annual energy production depends on the solar radiation and the site conditions (shading from neighbouring buildings or trees, temperature, clouds…).

The efficiency of PV modules ranges from 14 % to 22 % (Philipps and Warmuth, 2017). The technical lifetime is usually guaranteed for 20 years. However, the panels function far longer and have a total lifespan of up to 30 years or more (Wirth, 2018).

Solar thermal collectors provide heat for domestic hot water and /or space heating by converting solar radiation into usable heat. Furthermore, the heat can be used in industrial processes if the achieved temperature is high enough. Solar thermal energy reduces or replaces the demand for energy from fossil fuels and other end energy carriers. The efficiency of solar thermal collectors is around 60 %. Energy losses are due to convection, reflection, radiation, heat conduction and absorption. In the past years, the market for solar thermal collectors installed on buildings was difficult and in many European countries shrinking.

Geothermal energy can be used to cool and heat a building through a heat pump or a heat exchanger (Eicker et al., 2011). The possibilities to use geothermal energy are highly dependent on the characteristics of the ground at the building site. If the temperature is too low in the ground, heat pumps are needed. However, in several areas the ground temperature is high enough to be directly used with a heat exchanger.

Biomass is used in boilers and stoves for heat and hot water generation. The boilers function similar to fossil fuel burning boilers. They can provide high-temperature heat from renewable sources. They are already widespread and can easily replace fossil fuel based boilers also in existing buildings.

2.4. LOW VS HIGH TECH

The integration of new and renewable energy using technologies often leads to increasing complexity of HVAC systems and overall building service concepts. One reason is that renewable heating technologies like heat pumps and solar thermal collectors are still often combined with (fossil) peak and back-up boilers resulting in two instead of one heat generator in a building. Furthermore, for the integration of renewables low-temperature heating systems like e.g. floor heating systems are required as they result in higher efficiencies. However, in some cases, the available heating areas may not be large enough, and additional radiators are needed. This again leads to an increased complexity due to the need of two or more heat (and cold) distribution networks for the different required temperature levels.

In order to reduce the complexity of building systems, the reduction of energy demands by passive approaches is essential. The energy efficiency of a building can be increased by good insulation, free ventilation, night cooling and adequate shading to avoid overheating in summer. However, in most cases, buildings will still need heating and / or cooling devices (an exception is e.g. the case study Green Home Nanterre, in which no heating system is installed; compare chapter 5.3.7). The remaining energy demands should be satisfied with easy to install and robust technologies, which is the fundamental idea of low-tech approaches. The still needed active devices to supply the necessary ventilation, cooling and heating must operate as efficiently as possible, consuming only a small amount of energy and use as many onsite renewables as possible.

All passive technologies and approaches face natural limits. One example is that merely increasing the insulation thickness cannot achieve a zero energy loss and eventually, the energy saving achieved by adding more insulation material is not worth the additional investment. The most significant energy saving effect is achieved with the first centimetres of insulation.

Another advantage of reduced complexity of the systems is that they are easier to operate and main-tain. The more difficult operation of highly complex/ high-tech building systems is often criticised by building operators.

Besides the described low-tech/ passive approach to realise nZEBs, highly efficient buildings can be realised with very complex energy concepts combining several different energy generators, storages and distribution systems on-site. Many modern buildings currently follow this high-tech approach: The more recent and intelligent technology installed the better. The increased technology need is associated with higher upfront planning and investment costs. Furthermore, the operation of the systems needs expert know-how as they are more challenging to operate and maintain. On the other hand, different technologies in one building also have some advantages. They offer redundancies as probably needed peak- or back-up boilers can supply the building with the required energy if the heat pump (or any other renewable system) currently cannot deliver the energy or is in planned maintenance.

Furthermore, it offers possibilities to operate every single technology with the highest possible efficiency. When storage capacities and technologies for a fuel switch from electricity to other energy carriers and vice versa are available, the building can also be operated grid supportive. Under current market conditions, this is not economically feasible, especially for smaller buildings. Still, it can change in the future with the development of flexibility markets and the need to use and store fluctuating renewable electricity in energy systems with RES shares.

Generally, one can say that the minimization of energy demands in buildings is a central cornerstone of the energy transformation and the switch to an energy system based on renewables all over Europe. Passive approaches and low-tech building concepts can play a key role here. However, to make use of the available and generated renewable energy, some probably partly sophisticated technologies are needed for reacting on fluctuating energy supply. Central technologies, which therefore also have to be installed in buildings, are thermal and electrical storages and heating and cooling technologies, which allow a fuel-switch when required.

3. METHODOLGY FOR THE DEFINITION OF "OPTIMIZED" TECHNOLGY SETS

Finding cost-optimal solutions for nearly zero-energy buildings was part of the work packages 4 and 6 of the CRAVEzero project. While WP04 focused on cost reduction potentials of different relevant technologies until 2050 (D4.1; (Köhler et al., 2018)), the energy flexibility of buildings (D4.3; (Köhler et al., 2019)) and the effects of passive approaches by detailed building simulation (deliverable at hand), in WP06 parametric analysis were conducted. In the following, the method of WP06 is shortly described. Furthermore, the methodology for the analysis of passive approaches is described in detail.

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

The following description is based on (Venus et al., 2019; Weiß et al., 2019). The term "parametric analysis" in the multi-objective building life cycle optimization of WP06 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 (compare (Venus et al., 2019; Weiß et al., 2019)). 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)).

With the applied method all possible variant combinations are investigated. The major difference to the method applied in WP04 is that dynamic building simulations to analyse a building can take several hours. Thereby, it is hardly possible to calculate thousands of variants with a manageable amount of computing time, which is possible with the brute-force algorithm. The analysis in work package 6 is based on a monthly energy balancing tool (PHPP), with which each calculation can be performed much faster.

The main difference between a conventional design method and the parametric optimization with an exhaustive search method is shown in Figure 3. The multi-objective building life cycle cost and performance optimization allows finding optimal solutions among a huge number of possible variants.

The methodology to calculate the life cycle costs of several thousand variants automatically was developed by AEE INTEC together with the Energieinstitut Vorarlberg (EIV). It is based on an improvement of the "KoPro LZK+" calculation method by Energieinstitut Vorarlberg and AEE INTEC. The time needed for the calculations is reduced by using existing energy demand calculations of a building with PHPP and the life cycle costs are calculated with the CRAVEzero life cycle cost tool.
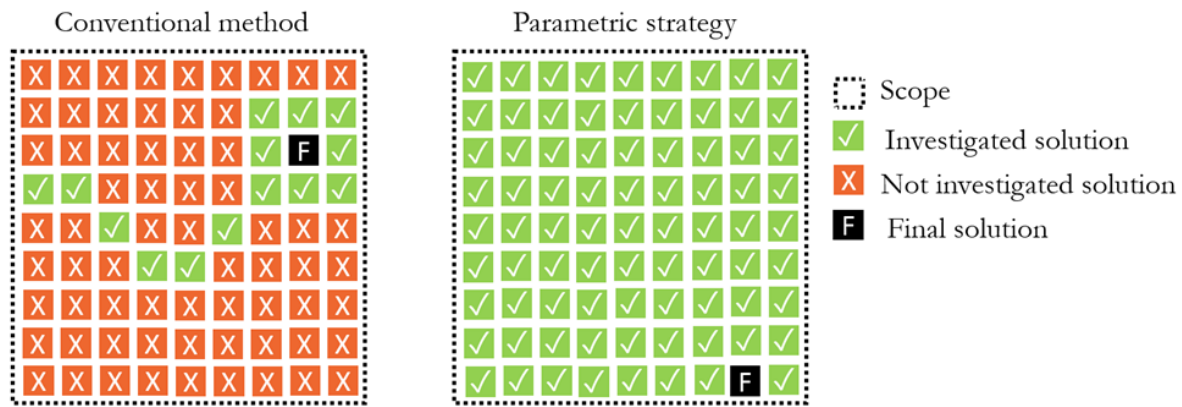
Figure 3: Comparison of conventional optimisation method vs. parametric analysis (Hatt et al., 2018)

3.2. LCC ANALYSIS

In WP02, cost and energy consumption information from all case studies was collected to perform a Life Cycle Cost (LCC) calculation. The data collection and developed LCC calculation tool are structured according to the approach provided by two main sources:

1. Standard ISO 15686-5: 2008
2. European Code of Measurement, elaborated by the European Committee of the Construction Economists.

In ISO 15686-5: 2008 the principles and features of an LCC calculation are provided. The second source describes an EU-harmonized structure for the breakdown of building elements, services, and processes. The applied method focuses on design,

construction, and operation costs (including maintenance costs). As most case studies in the project are relatively new, information about costs related to the end-of-life are not available. Therefore, these costs were not considered in the evaluation. The approach and included/ considered phases are illustrated in Figure 5.

In the assessment within CRAVEzero a period of 40 years was selected for the LCC calculation. In the ISO standard the Net Present Value (NPV), which is the sum of the discounted costs, revenue streams, and value during the phases of the selected period are defined as the LCC of a building. Furthermore, costs are ordered according to the associated life cycle phase.
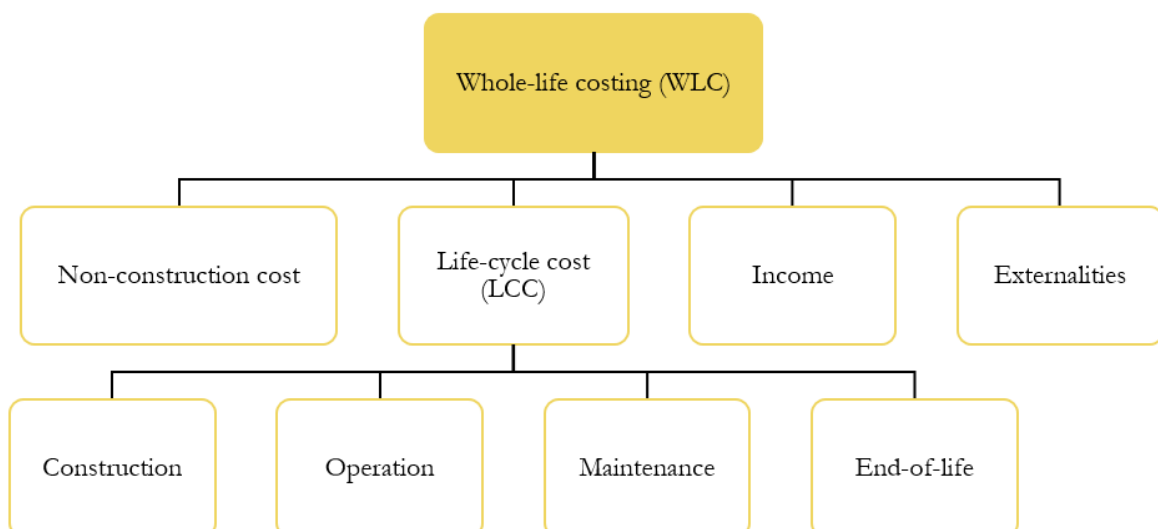
Figure 4- WLC structure according to ISO 15686-5: 2008.
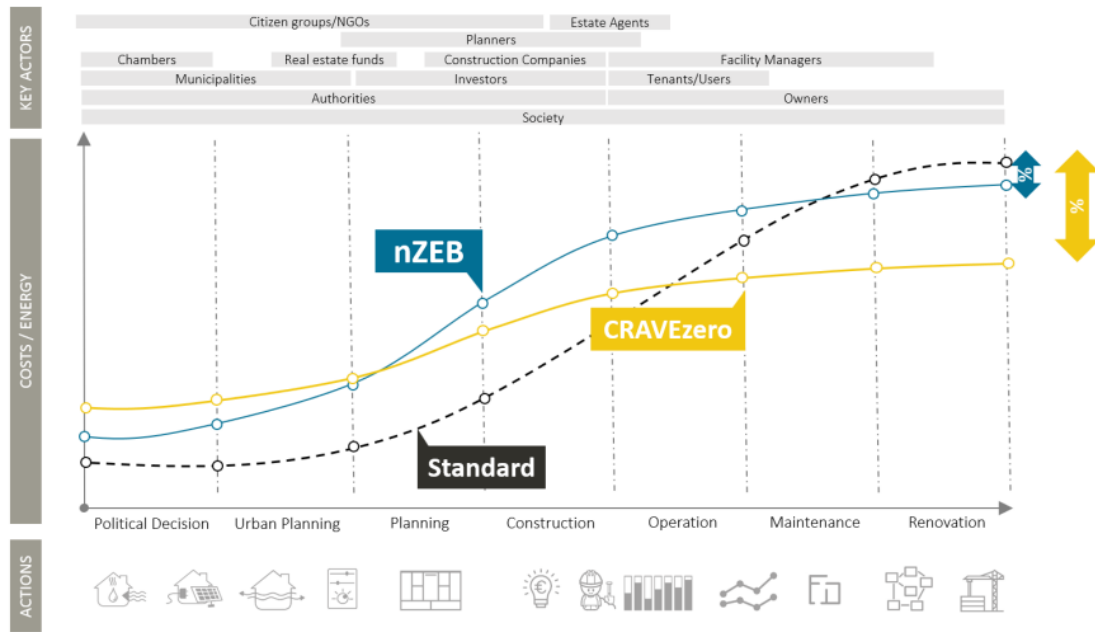
Figure 5: Life cycle costing according to ISO 15686:2008.

3.3. DETAILED ANAYLSIS OF PASSIVE APPROACHES

For the detailed analysis of passive approaches and measures to reduce the energy demand of a building, the case study Parkcarré located near Karlsruhe in Southern Germany was taken as a basis (with some simplifications in the architectural design). Parkcarré is a residential multi-family building with four stories and a net floor area of 1.189 m². For the approaches described in the following chapters several iterations/ variations are assessed. Furthermore, three different climate data sets are used to analyse the effect of different weather/ climate conditions on the effectiveness of the passive approaches (except free ventilation: for this approach only the effect on the cooling demand in Italy was analysed).

The used climate data sets are:

- Stuttgart (Southern Germany; base case/ moderate climate)
- Kiruna (Northern Sweden; cold climate)
- Palermo (Southern Italy; hot climate).

The building is subdivided into sixteen thermal zones. Each apartment, as well as the staircases, is defined as a zone. There are three apartments in each story (one two-room, one three-room and one four-room apartment; twelve in total). Figure 6 illustrates the building. The assessed approaches to minimize the energy demand are:

- Building orientation
- Window-to-wall ratio
- Daylighting availability and control
- Fixed external shading
- Natural ventilation

The iterations/ variations for each parameter are described in the following. The results are described in chapter 4.1.
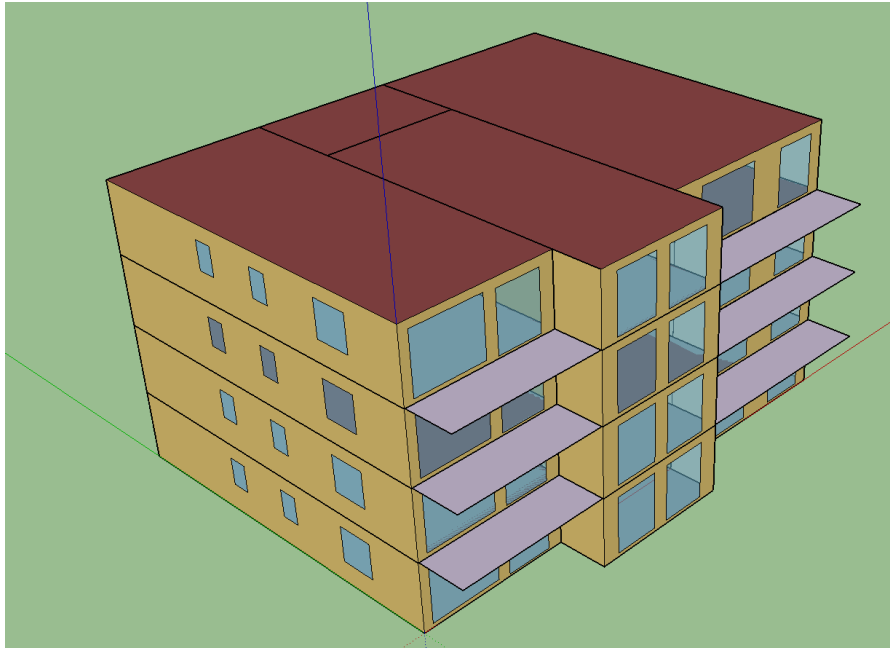
Figure 6: Illustration of the case study Parkcarré; screenshot from SketchUp Make.

3.3.1.BUILDING ORIENTATION

The optimal orientation of a building differs between climate regions. Additionally, it can be influenced by other site conditions like neighbouring buildings and infrastructures. The original orientation of Parkcarré is south (see Figure 7). To find the optimal building orientation eight iterations are conducted: orientation to the south, south-west, west, north-west, north, north-east and east. The best orientation is the one with the lowest heating, cooling and lighting energy demand. Most new buildings in Central Europe are south orientated.
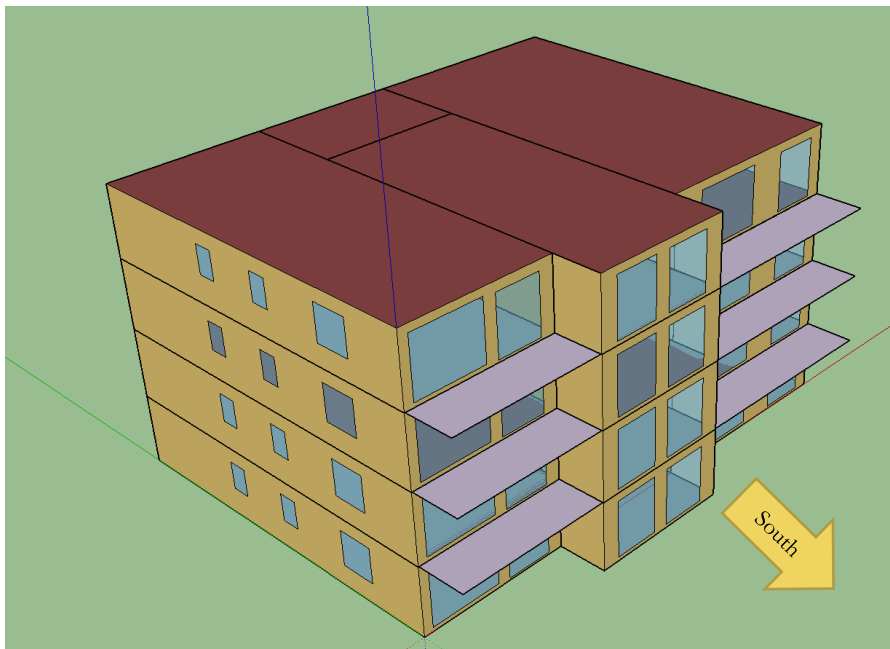
Figure 7: Building oriented to the South (Original Orientation)

3.3.2.WINDOW-TO-WALL RATIO

The second assessed parameter is the window-to-wall ratio (WWR). The windows usually have the highest U-value of all envelope elements. Therefore, the window-to-wall ratio and window overall area have a strong influence on the total heating and cooling demand and load. There is also an influence on the energy demand for lighting as changing the WWR affects the daylight availability inside the building. Besides that, windows are needed for free ventilation and night cooling approaches which can help to achieve excellent thermal conditions and reduce cooling demands during the day (see chapter 3.3.5). To find the best WWR three itera-

tions are conducted in which the area of the windows and thereby the WWR at different sides of the building is changed.

All adjustments of the WWR are assessed in the original orientation of the building (south). The first iteration (increasing the WWR on the east side) is shown in Figure 8 (left). The right illustration in Figure 8 shows the increase of the WWR on the west side. The increases (area and WWR) of all iterations are summarized in Table 1.

In the third iteration, the WWR on two sides of the building (east and west) are increased, leading to an increase of the overall gross WWR to approx. 34 %.

Table 1: Summary of changes of the window area and window-to-wall ratio of all assessed variations.

Variation	Changed building side	Overall window area [m²]	WWR [%]
Base Case		167.2	22.4
WWR1	East side	210.0	28.2
WWR2	West side	177.8	23.9
WWR3	East and west side	251.3	33.8
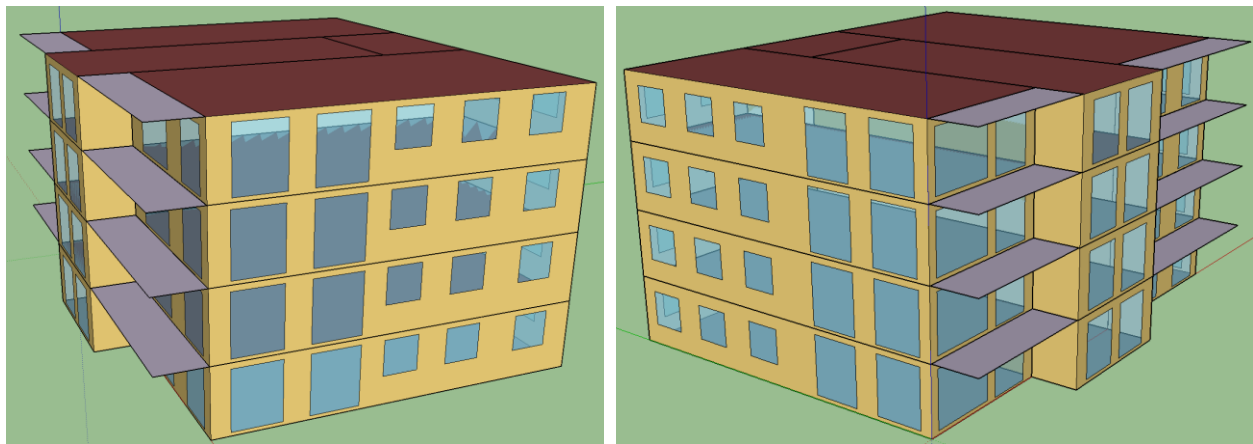
Figure 8: Increased window-to-wall ratio on east side (left) and west side (right).

3.3.3.DAYLIGHTING

The use of daylight is a promising approach to increase the overall efficiency of buildings. Increasing and controlling the availability of daylight is strongly interconnected with the realised window sizes and window-to-wall ratio, optimal building

orientation and the installation of shading systems to avoid overheating and glare.

In the simulation, there are two main components used to control the artificial light in the respective zones by dimming the lights or completely switch-

ing them off depending on the amount of daylight available inside the building (daylighting sensors and illuminance map, see Figure 9).

The daylighting control object consists of a single lighting sensor which is connected to a thermal zone. The function of the daylighting control object is to measure the radiance for sunlight to be able to determine the needed amount of artificial light inside each zone.

The illuminance map consists of a rectangle with a grid representing map data points. It also has to be associated with a thermal zone (usually the same thermal zone of daylighting control).

The use of daylighting control is assessed for each WWR and the approach with additional fixed external shading. Daylighting control is applied in each apartment of the building.
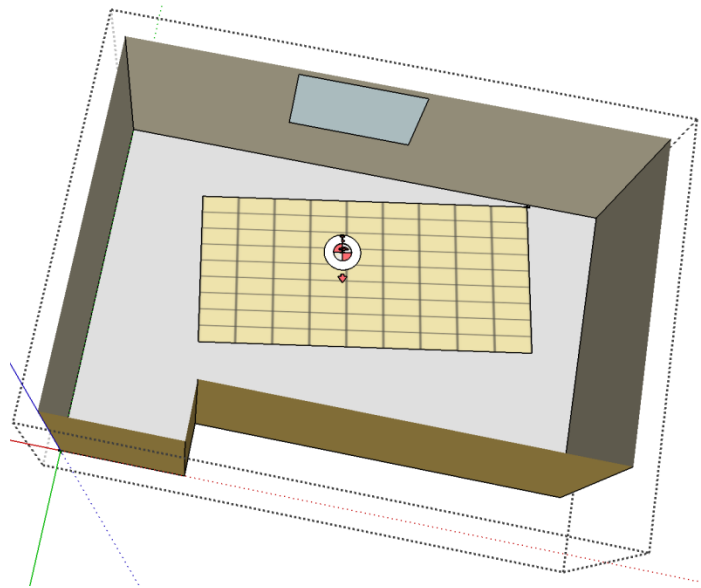
Figure 9: Daylighting control using daylighting sensor and illuminance map in EnergyPlus™

3.3.4. FIXED EXTERNAL SHADING

The fourth passive approach assessed is fixed shading. Shading is required to avoid high solar gains in summer and thereby limit the cooling energy demand as well as the avoidance of glare inside the building. Increased window areas increase the solar gains in winter and thereby reduce the heating demand. However, the higher gains in summer increase the cooling demand. Therefore, fixed shad-

ing, which allows high gains in winter and low gains in summer, is needed.

The additional fixed shading is installed above the big windows at the east and west side of the building as well as the middle (2-room) apartment on the south side of the building. Furthermore, the correlation between the shading system and the daylight control is analysed (see chapter 3.3.3). The approach is illustrated in Figure 10.
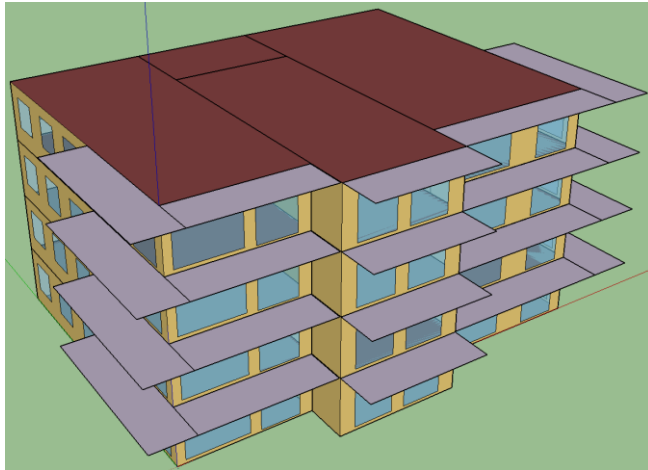
Figure 10: External shading system in the roof and the third floor including the daylighting-controlled rooms

3.3.5.NATURAL VENTILATION

Natural or free ventilation uses pressure and temperature differences between the in- and outside of a building and between different building zones. Natural ventilation can be applied through a controlled and automated opening of windows and other openings in the building envelope (e.g. skylights). In moderate climates, up to 60 % of the end energy for ventilation and air conditioning could be saved compared to conventional mechanical ventilation and air conditioning systems (Zentralverband Elektrotechnik- und Elektroindustrie e.V., 2013).

Natural ventilation is simulated in all apartments through three iterations. Free ventilation is based on a schedule as well as maximum and minimum indoor and outdoor temperatures. The difference in the three iterations is the opening area and accepted ambient air temperature:

- First variation: in each three and four-room apartments 1.5 m² to the north and 4 m² to the south; in the two-room apartment 3.5 m² to the south; minimum allowed outdoor temperature 18°C.

- Second variation: in each apartment 1.5 m² to the north (except two room apartments) and 6 m² to the south; minimum allowed outdoor temperature 18°C.

- Third variation: like second variation, but minimum allowed outdoor temperature 17°C.

4. RESULTS OF PASSIVE APPROACHES

In the following the results of simulation of the passive approaches for all three assessed climate regions are described. As the additional effect of external shading is considered in the assessment of window-to-wall ratio and daylighting, there is no extra chapter on this passive approach, but the effect is described in the respective chapters 4.1.2 and 4.1.3. In Figure 11 the specific energy demand for lighting, heating and cooling of the base case in the different considered climate regions is shown. It can be seen that the thermal energy demand (space heating and cooling) is by far the dominating factor. As the energy demand for hot water generation is not influenced by the assessed passive approaches this energy demand is not plotted and considered in the following. Furthermore, cooling is usually not provided in residential buildings in Germany and Sweden and therefore the theoretical cooling demand as plotted in Figure 11 is also not taken into account in the following assessment of the effect on the energy demand and LCC in these climate regions. The specific energy demand for lighting, heating and cooling in the base case in Germany is 23.89 kWh/(m²a), in Sweden 69.61 kWh/(m²a) and in Italy 38.97 kWh/(m²a).
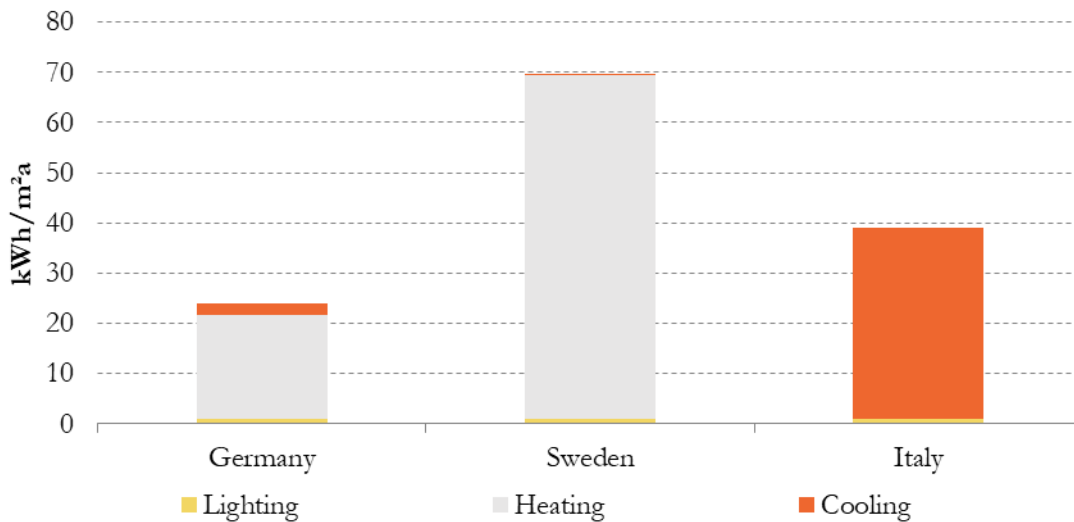
Figure 11: Specific energy demand for lighting, heating and cooling of the base case in the different assessed climate regions

4.1. SIMULATION RESULTS OF PASSIVE APPROACHES

4.1.1. BUILDING ORIENTATION

The building orientation has a high influence on the heating and cooling demand of buildings. The results of the simulations are summarized in Figure 12. In the figure, the heating demand depending on the building orientation for Germany is shown in the graph at the top, for Sweden in the middle and for Italy (cooling demand) at the bottom.

For **Germany**, the lowest heating demand is obtained with a south orientation of the building (base case), followed by south-east and south-west orientation. The highest heating demand with

27,355 kWh/a is obtained with an orientation to north-west (compare Table 2). The heating demand is increased by approx. 18 % compared to the base case. Generally, all orientations to the north have much higher heating demands (+17 to 18 %) compared to southern orientations (+7 %).

For **Sweden** (see Table 3), the results are comparable. However, the relative increase of the heating demand is lower than in Germany, but starting from a much higher heating demand in the base case. The increase of the north-east, north and

north-west orientation is approx. 8 %. The increase for the south-east and south-west orientation is 3 %. For the locations in the northern hemisphere where heating is dominating a building's energy demand, the south orientation shows the best results.

In southern **Italy** (Table 4) the cooling demand is the dominating energy demand in a building. The best building orientation with respect to minimizing the cooling demand is the north orientation. In this case the demand is reduced by 5 %. The worst result is obtained when the building is orientated to the east. The cooling demand in this case increases by 21 %, followed by the west orientation with an increase of 11 %.

Table 2: Changes (absolute and relative) of the heating demand due to a differing building orientation in Germany.

	South (Base)	South-east	East	North-east	North	North-west	West	South-west
Specific heating demand [kWh/(m²a)]	20.72	22.17	23.51	24.42	24.22	24.45	24.16	22.09
Change compared to base case	-	+7 %	+13 %	+18 %	+17 %	+18 %	+17 %	+7 %

Table 3: Changes (absolute and relative) of the heating demand due to a differing building orientation in Sweden.

	South (Base)	South-east	East	North-east	North	North-west	West	South-west
Specific heating demand [kWh/(m²a)]	68.47	70.57	72.79	74.00	74.06	74.03	73.42	70.19
Change compared to base case	-	+3 %	+6 %	+8 %	+8 %	+8 %	+7 %	+3 %

Table 4: Changes (absolute and relative) of the cooling demand due to a differing building orientation in Italy.

	South (Base)	South-east	East	North-east	North	North-west	West	South-west
Specific heating demand [kWh/(m²a)]	37.94	40.96	45.96	40.85	36.02	40.87	42.30	40.92
Change compared to base case	-	+8 %	+21 %	+8 %	-5 %	+8 %	+11 %	+8 %
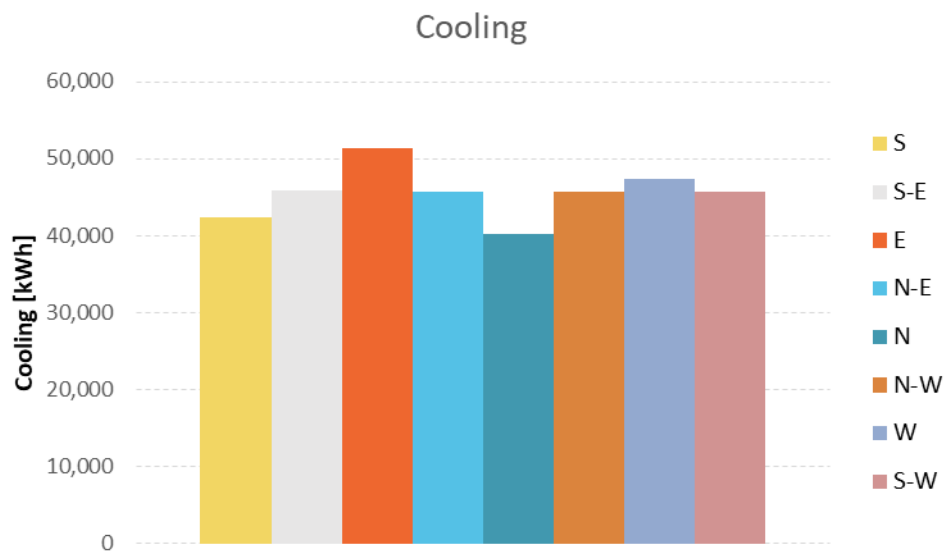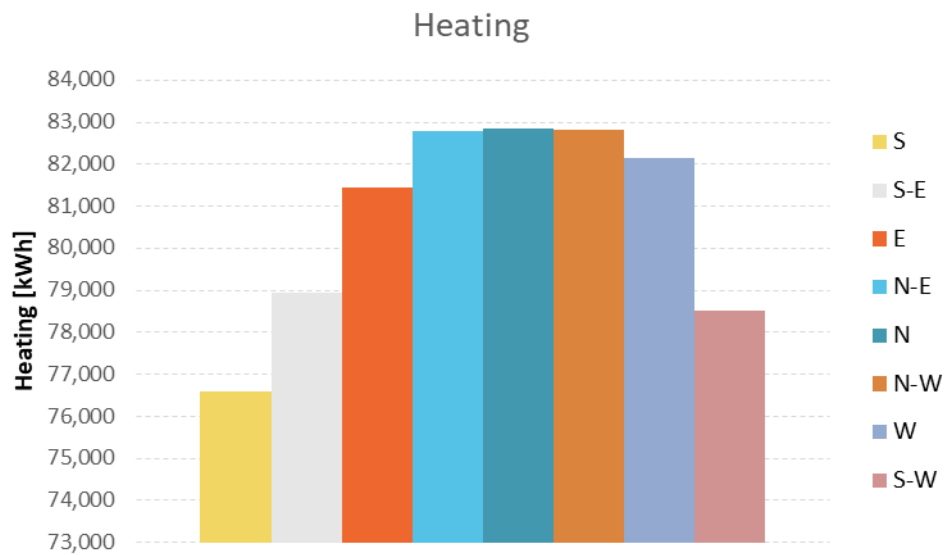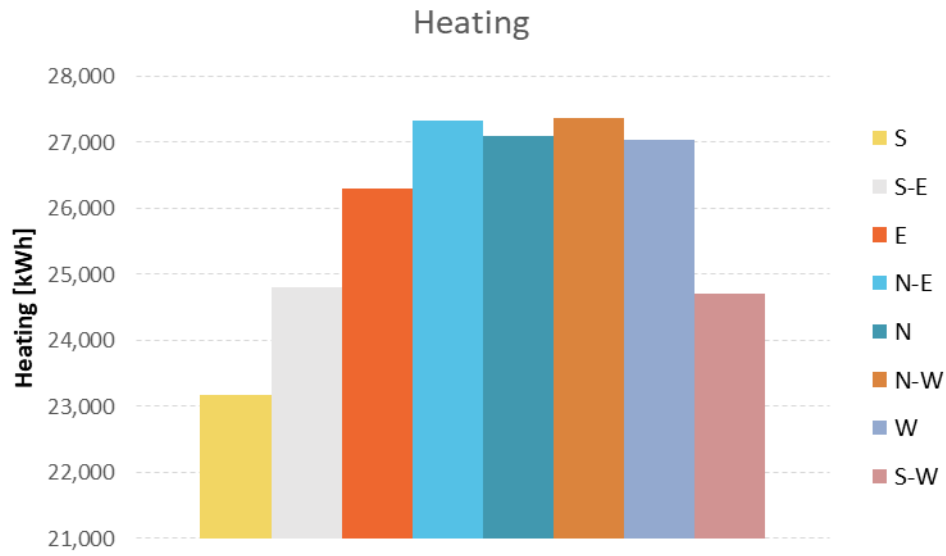
Figure 12: Effect of the building orientation on the heating demand in Germany (top), Sweden (middle) as well as the cooling demand in Italy (bottom)

4.1.2. WINDOW TO WALL RATIO

Besides the building orientation, the window-to-wall ratio also has a high influence on the heating and cooling demand and – if daylighting control is implemented – also on the electricity demand for lighting. The results of the simulations are summarized in Figure 13. In the figure, the heating demand depending on the WWR for Germany is shown at the top, for Sweden in the middle and for Italy (cooling demand) at the bottom.

For **Germany**, the lowest heating demand is obtained with an increase of the WWR at the east and west side of the building (WWR3; definition of WWR-variations see chapter 3.3.2). Compared to the base case, the heating demand is reduced by 12 %. If additional external shading is added to this variant, no heating demand reduction is achieved. Also increasing the WWR on the east side of the building decreases the heating demand (-6 %), while an increase of the WWR on the west side increases the heating demand (+3 %; compare Table 5).

For **Sweden** (see Table 6), the results are comparable. However, the relative decrease of the heating demand is lower than in Germany. An increase of the WWR on the east and west side of the building

leads to a decrease of the heating demand of 2 % and an increase of the WWR on the east façade leads to an even smaller decrease of 1 %. Also in this case increasing the WWR on the west façade leads to an increase of the heating demand. Adding additional fixed external shading elements to the variant WWR3 increases the heating demand compared to the base case as needed solar gains during the heating season are shielded.

In southern **Italy** (Table 4) the cooling demand is the dominating energy demand in a building and therefore only the effects on the cooling demand were analysed. An increase of the WWR is also increasing the cooling demand. Comparing an increase on the east and west façade the results show that increasing the WWR on the east side leads to a higher increase (+32 %). The higher influence of the east side on the cooling demand was already observed in the analysis of the building orientation. The highest increase of the demand is observed when the WWR is increased on the east and west side of the building (+64 %). If additional fixed external shading is considered in this case, the increase is much lower (+22 %).

Table 5: Changes (absolute and relative) of the heating demand due to changes in the window-to-wall ratio in Germany.

	Base Case	WWR1	WWR2	WWR3	WWR3-Shading
Specific heating demand [kWh/(m²a)]	20.72	19.42	21.29	18.29	20.72
Change compared to base case	-	-6 %	+3 %	-12 %	-

Table 6: Changes (absolute and relative) of the heating demand due to changes in the window-to-wall ratio in Sweden.

	Base Case	WWR1	WWR2	WWR3	WWR3-Shading
Specific heating demand [kWh/(m²a)]	68.47	67.54	69.75	66.78	69.39
Change compared to base case	-	-1 %	+2 %	-2 %	+1 %

Table 7: Changes (absolute and relative) of the cooling demand due to changes in the window-to-wall ratio in Italy.

	Base Case	WWR1	WWR2	WWR3	WWR3-Shading
Specific heating demand [kWh/(m²a)]	37.94	50.18	46.09	62.31	46.45
Change compared to base case	-	+32 %	+21 %	+64 %	+22 %
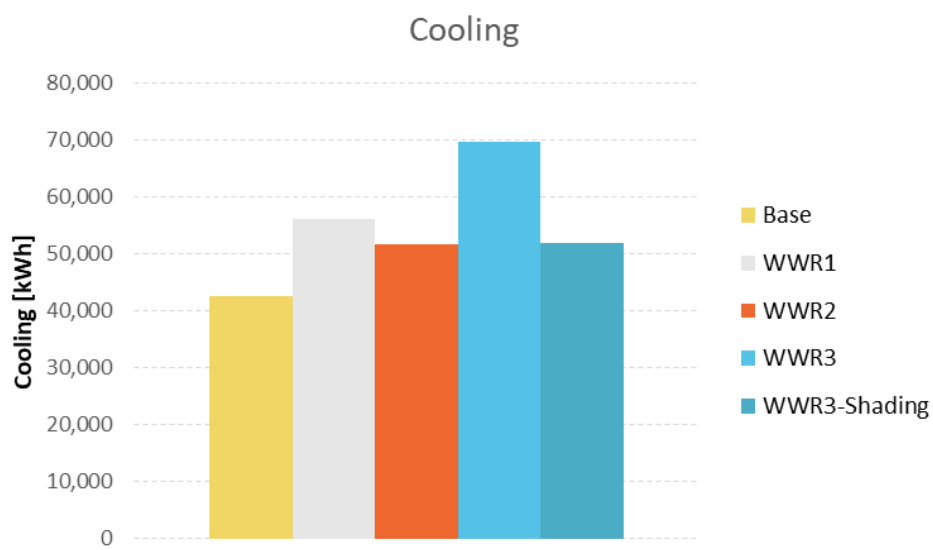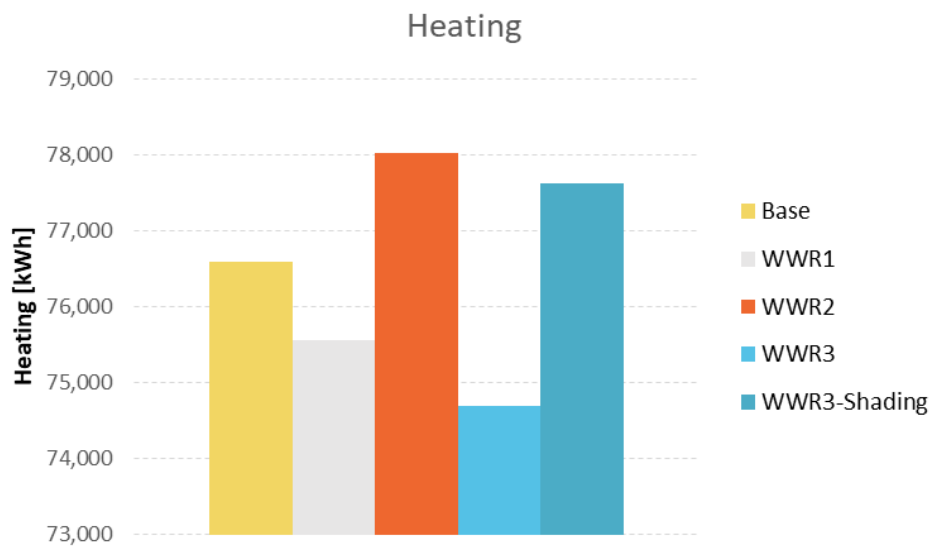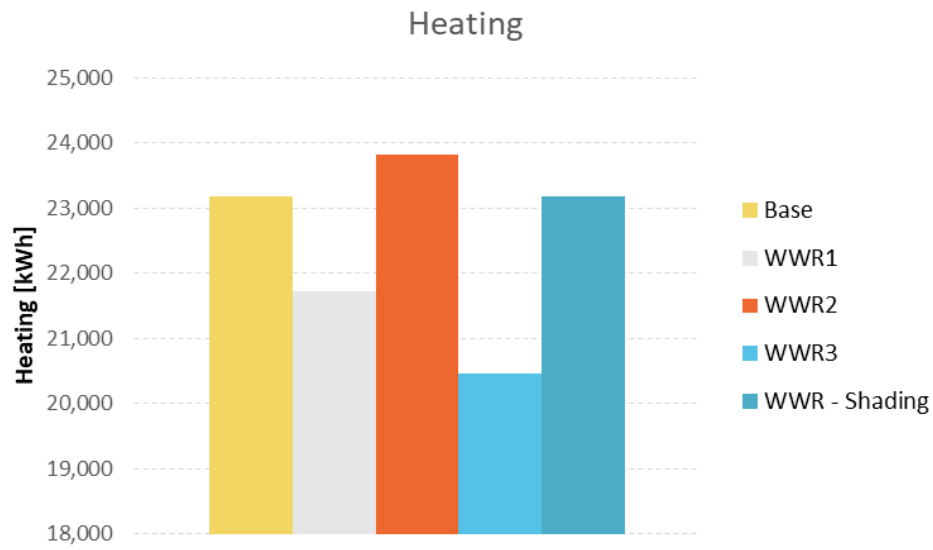
Figure 13: Effect of the window-to-wall ratio on the heating demand in Germany (top), Sweden (middle) as well as the cooling demand in Italy (bottom)

4.1.3.DAYLIGHTING

Using the available daylighting in buildings as much as possible is crucial for minimizing the electricity demand for lighting. However, as the efficiency of artificial lighting was increased in the past years due to the broad roll out and installation of LEDs, the saving effect in absolute numbers of daylighting control is small.

The results of the detailed simulations are summarized in Figure 14. In the figure, the electricity demand for lighting for Germany is shown in the graph at the top, for Sweden in the middle and for Italy (cooling demand) at the bottom.

For **Germany** (see Table 8), adding daylighting control to the base case in each apartment already reduces the electricity demand by 4 %. The lowest demand is obtained in the variant with an increase of the window-to-wall ratio at the east and west side of the building (WWR3) and the integration of daylighting control in each apartment (-6 % compared to the base case). Adding additional external shading to this variant slightly increases the electricity demand again. However, there is still a reduction of 5 %.

For **Sweden** (see Table 9), the results are comparable. However, the relative decrease of the electricity demand is lower than in Germany. Implementing daylighting control in the base case reduces the electricity demand by 3 %. The lowest absolute demand is achieved in the variant with the highest window-to-wall ratio (WWR3; 1,085 kWh/a; -5 % compared to base case). Like in Germany, installing additional external shading slightly increases the electricity demand in the variant WWR3, but compared to the base case there is still a reduction in the energy demand.

In southern **Italy** (Table 10) the effects of daylighting control are the highest. Implementing this control strategy for artificial lighting in the base case decreases the electricity demand for lighting by 6 %. Like for the other two climate regions, the lowest electricity demand is achieved with the highest window-to-wall ratio (-9 %). Also in southern climate regions, adding external shading increases the electricity demand for lighting again, but the positive effects on the cooling demand (see above) are higher than the negative effect on the electricity demand for lighting.

Table 8: Changes (absolute and relative) of the electricity demand for lighting due to the implementation of daylighting control in the base case and with different window-to-wall ratios in Germany.

	Base Case	Base Case with day-lighting control	WWR1 with day-lighting control	WWR2 with day-lighting control	WWR3 with day-lighting control	WWR3 – Shading with day-lighting control
Electricity demand lighting [kWh/a]	1,147	1,104	1,089	1,099	1,075	1,087
Change compared to base case	-	-4 %	-5 %	-4 %	-6 %	-5 %

Table 9: Changes (absolute and relative) of the electricity demand for lighting due to the implementation of daylighting control in the base case and with different window-to-wall ratios in Sweden.

	Base Case	Base Case with day-lighting control	WWR1 with day-lighting control	WWR2 with day-lighting control	WWR3 with day-lighting control	WWR3 – Shading with day-lighting control
Electricity demand lighting [kWh/a]	1,147	1,110	1,097	1,107	1,085	1,095
Change compared to base case	-	-3 %	-4 %	-4 %	-5 %	-5 %

Table 10: Changes (absolute and relative) of the electricity demand for lighting due to the implementation of daylighting control in the base case and with different window-to-wall ratios in Italy.

	Base Case	Base Case with day-lighting control	WWR1 with day-lighting control	WWR2 with day-lighting control	WWR3 with day-lighting control	WWR3 – Shading with day-lighting control
Electricity demand lighting [kWh/a]	1,147	1,084	1,062	1,081	1,047	1,062
Change compared to base case	-	-6 %	-7 %	-6 %	-9 %	-7 %
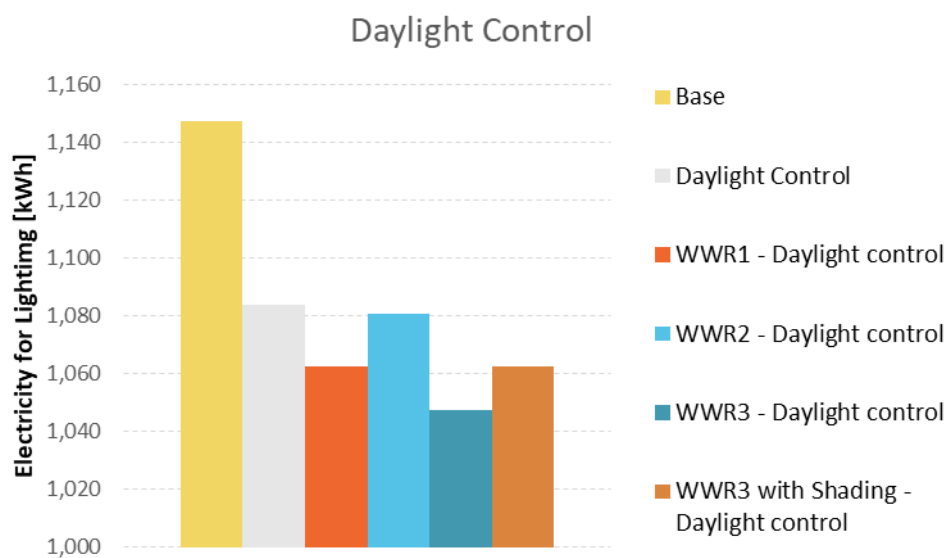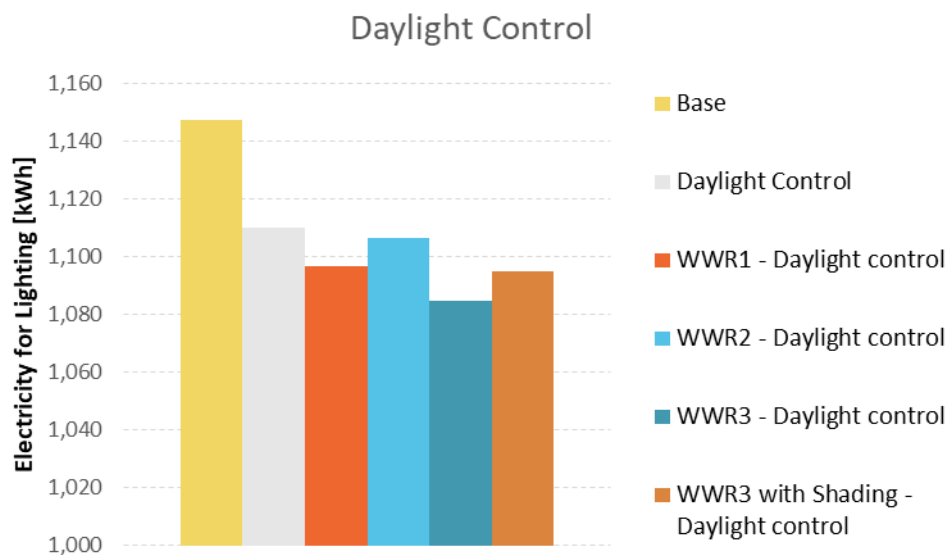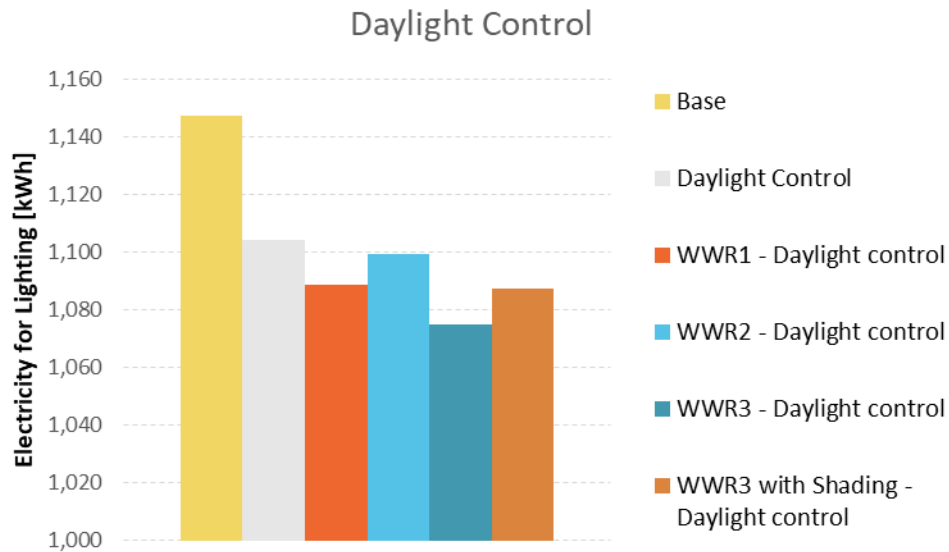
Figure 14: Effect of daylighting control on the electricity demand for lighting in Germany (top), Sweden (middle) and Italy (bottom)

4.1.4. NATURAL VENTILATION

The effect of natural ventilation is mainly relevant for the cooling demand. Therefore – as described above – natural ventilation was only analysed for the climate data of/ location in Italy. The results of the detailed simulation are summarised in Table 11 and shown in Figure 15. As can be seen, free ventilation strategies can lead to comparably high savings in the cooling energy demand of up to 22 %. The highest reduction is achieved in the variant with large opening areas and a reduced allowed minimum outdoor temperature of 17°C, which might be considered too cold from residence.

However, a reduction of the minimum allowed outdoor temperature has a very high effect on the actual energy demand. The effect is comparable to an increase in the allowed indoor temperature during the cooling season, which also has a large effect on the cooling energy demand.

The results show that there must be an optimal opening area. The increase of the opening area between Vent1 and Vent2 also slightly increases the cooling energy demand and one can conclude that the defined areas for free ventilation in this case are already too large.

Table 11: Change (absolute and relative) of the cooling demand due to natural ventilation in Italy.

	Base Case	Vent1	Vent2	Vent3
Cooling demand [kWh/a]	42,445	34,170	34,722	33,057
Specific heating demand [kWh/(m²a)]	37.94	30.54	31.04	29.55
Change compared to base case	-	-19 %	-18 %	-22 %
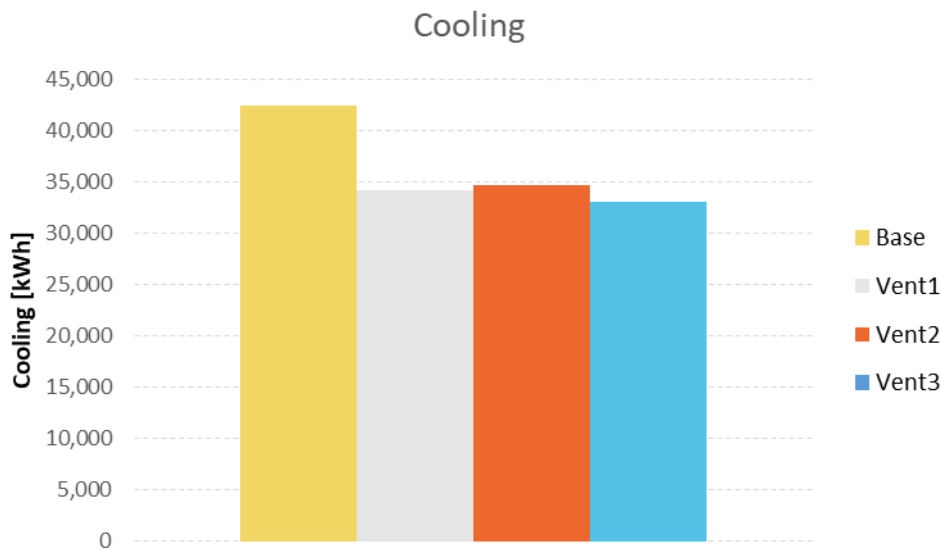
Figure 15: Effect of natural ventilation on the cooling demand in Italy.

4.2. LIFE CYCLE COSTS

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The developed LCC-sheet assessing the life cycle costs of Parkcarré is used as a basis for the analysis of the effects of the described passive approaches on the overall LCC of the respective case study. As a slightly simplified architectural design of the building was used for the detailed simulations some adjustments to the original LCC-sheet developed in WP02 had to be done. The adjustments are made for:

- Total area of the external wall facing ambient air
- Total window area
- Treated floor area and treated volume

To perform comparable calculations the specific investment and energy costs are calculated from the original file and are taken as inputs for the new calculations. The design costs for the building are assumed to be constant. As the main effect with respect to the LCC is related to the investment costs of walls and windows the focus of the following analysis is the variation of the window-to-wall ratio. In addition, the effects on the LCC due to increased or reduced specific heating and cooling demands for the different building orientations and the implementation of daylighting control in the variant with the highest WWR are briefly described. The considered time period is 40 years. As the purpose of the simulation at different locations was the analysis of the climate effects on the energy consumption, differences of the construction costs between Germany, Sweden and Italy are neglected in the LCC analysis. The considered costs are:

- Design costs
- Construction costs
- Operation and maintenance costs
- Costs for the consumed energy.

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As described in the previous chapters, the passive approaches WWR and daylighting control can reduce the energy demand for heating and lighting in **Germany**. As the south orientation (base case) has the best results with respect to the heating demand, all other variations have a negative effect in the LCC of the building as the energy costs are higher.

As can be seen in Figure 16 the base case has the lowest life cycle costs of all assessed variants. This means that with respect to building orientation and window-to-wall ratio. However, it has to be mentioned that the differences of the LCC in the considered time period are extremely low; in most cases the increase compared to the base case is below

1 % and the highest increase is only 1.3 %. The specific LCC is shown in Figure 17.

As can be seen in Figure 18 the share of the energy costs (only costs associated with the energy consumed without taking into account benefits from renewable energy generation on-site) in all variants is only 9 – 10 %. The dominating costs are the construction as well operation and maintenance (without energy costs) costs with a share of 43 – 45 % and 31 – 32 % respectively. Therefore, cost savings due to the comparably low energy savings achieved with passive approaches only have a small impact on the overall LCC. On the other hand, additional costs due to larger window areas increase the LCC.

Figure 16: Life cycle costs of the building Parkcarré at the location Germany.
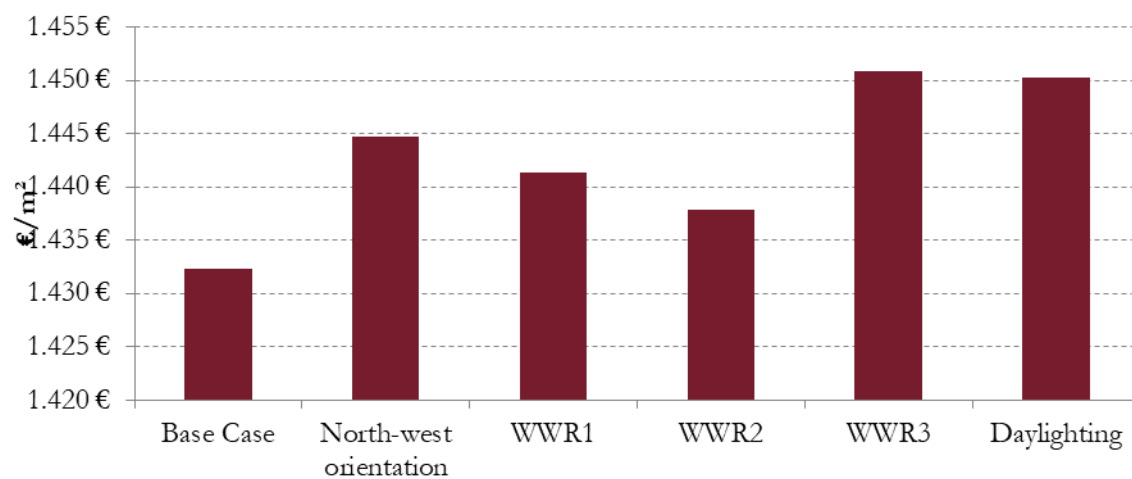
Figure 17: Specific overall Life cycle costs of the building Parkcarré at the location Germany.

Base Case
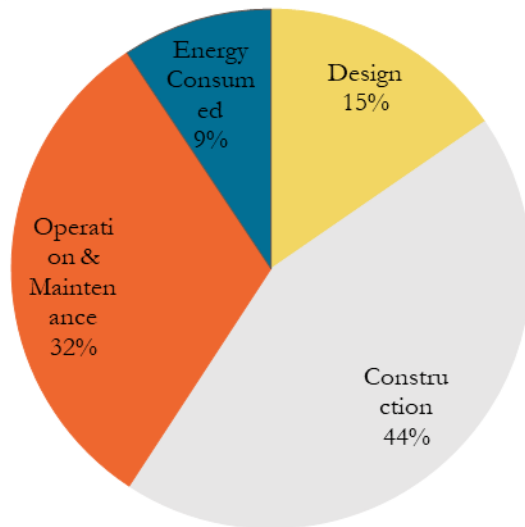
North-west orientation
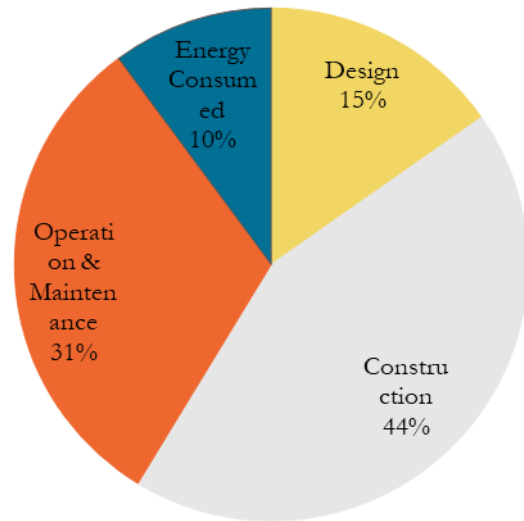
WWR1
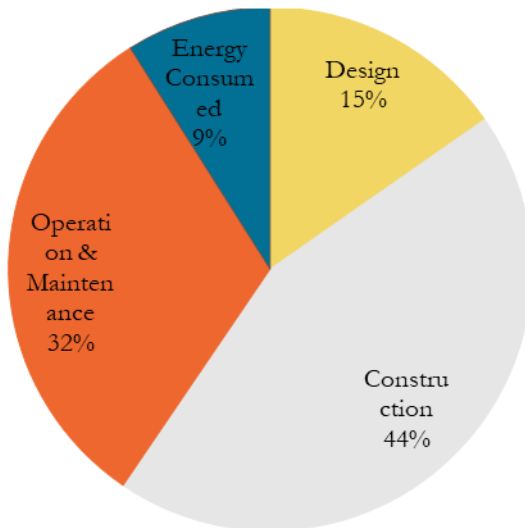
WWR2
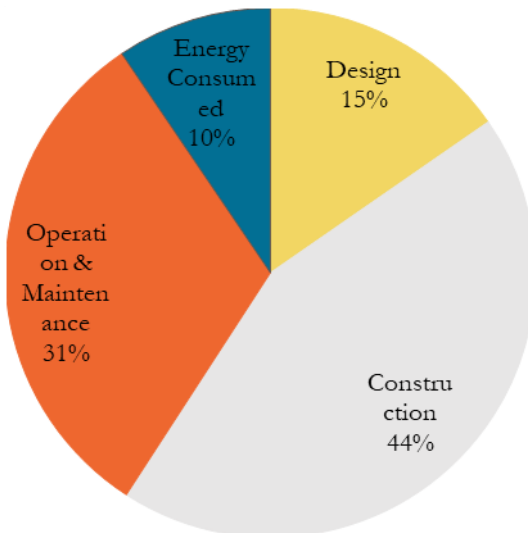
WWR3
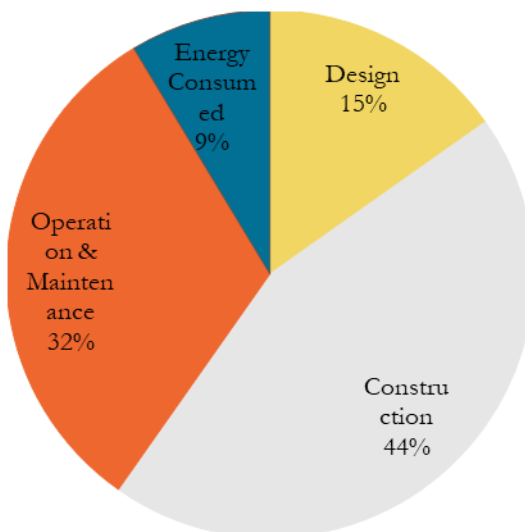
Daylighting
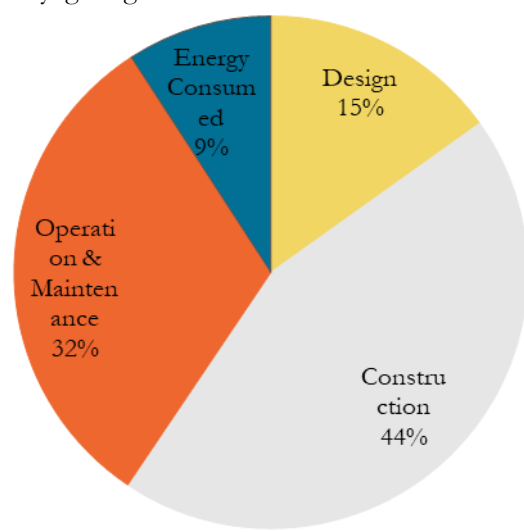
Figure 18: Life cycle costs of the building Parkcarré at the location Germany: share of the assessed cost groups in the overall LCC.

For **Sweden**, the importance of energy costs is larger than in Germany due to the much higher heating demand and therefore, the influence of energy savings due to passive approaches on the LCC is larger. However, as shown in Figure 19 also for Sweden the base case has the lowest LCC of all assessed variants. With respect to building orientation and window-to-wall ratio the base case is the best variant. However, it has to be mentioned that the differences of the LCC in the considered time period are extremely low; the increase compared to the base case is between 0.5 % and 1.7 %. The specific LCC is shown in Figure 20.

As can be seen in Figure 21 the share of the energy costs in all variants is 18 – 20 %, which is twice as much as in Germany due to the higher heating demand. The dominating costs are the construction as well operation and maintenance (without energy costs) costs with a share of 39 – 40 % and 28 % respectively. Possible cost savings due to passive approaches have a higher influence on the LCC compared to Germany, however, the increase in the heating demand due to higher window areas, which have a high U-value, exceed additional solar gains, which reduce the energy demand. The negative effects of large windows are more relevant than the positive ones. Furthermore, the additional costs due to larger window areas increase the LCC. Also the achieved electricity savings due to daylighting control only lead to a minimal reduction of the LCC as the electricity costs only have a small share in the overall LCC.
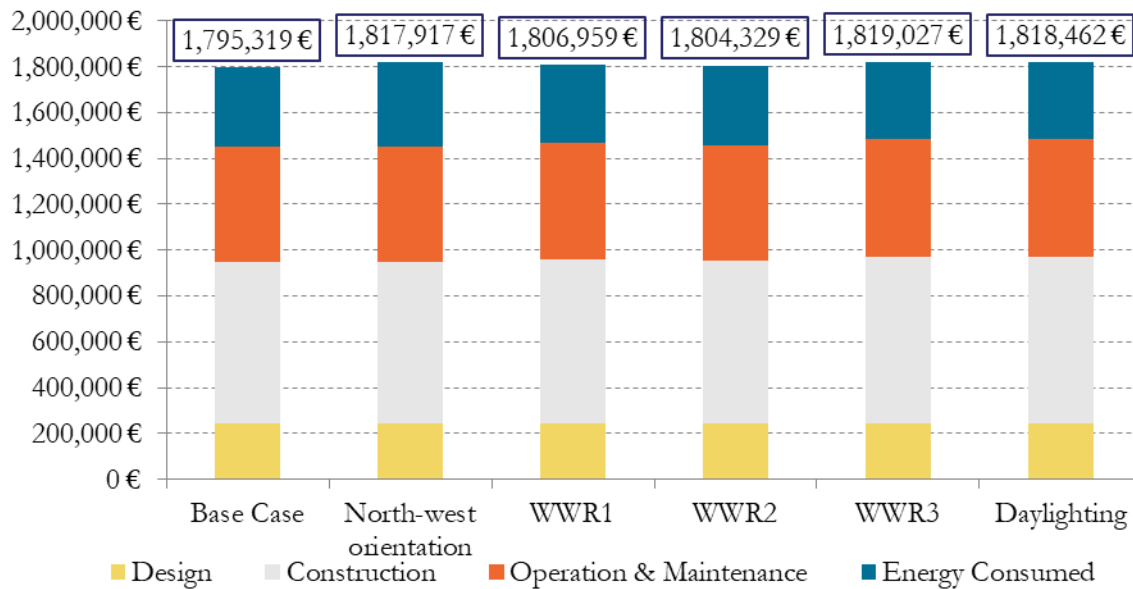
Figure 19: Life cycle costs of the building Parkcarré at the location Sweden.
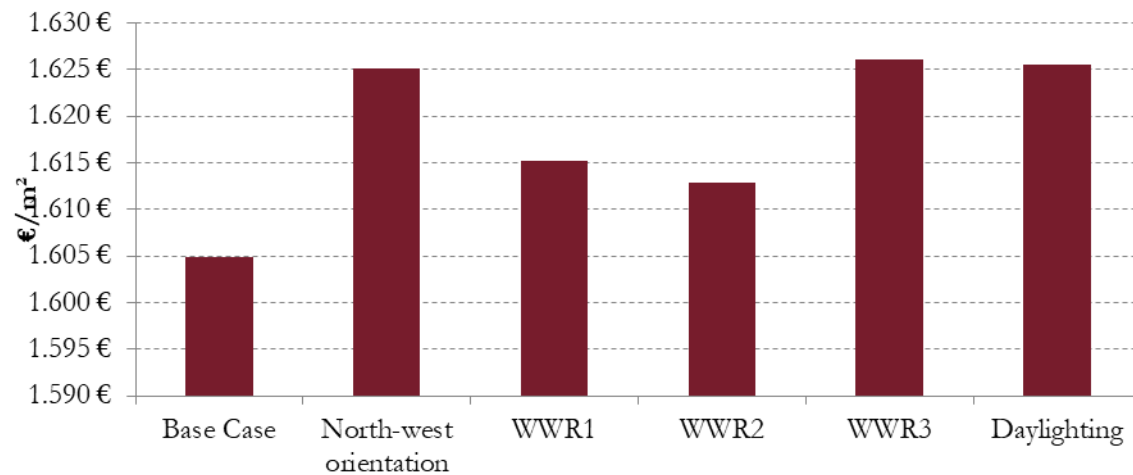
Figure 20: Specific overall Life cycle costs of the building Parkcarré at the location Sweden.

Base Case
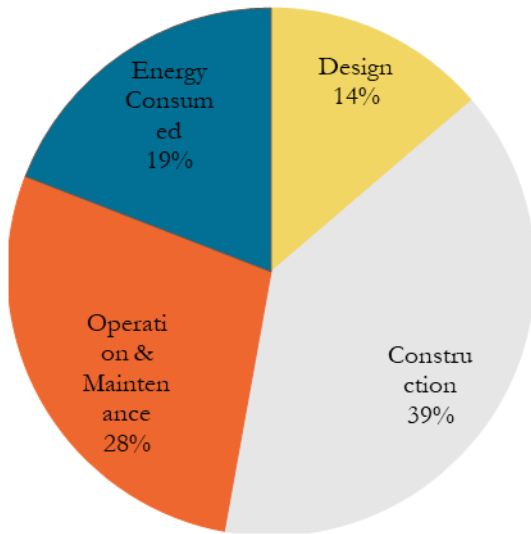
North-west orientation
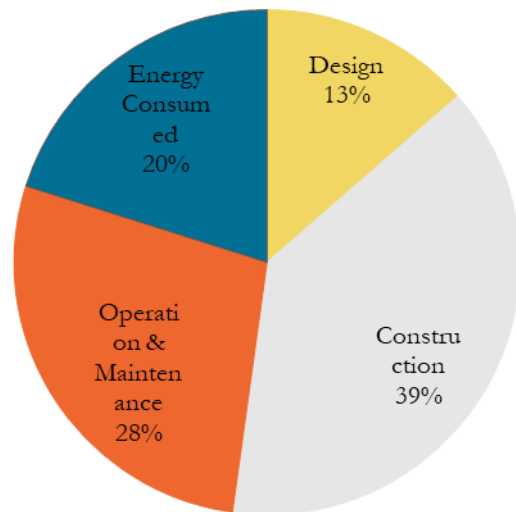
WWR1
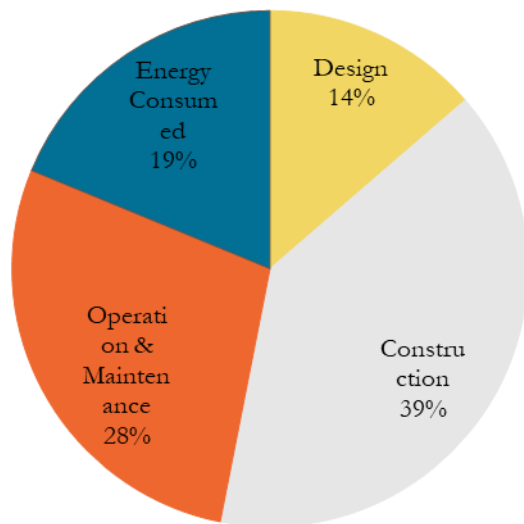
WWR2
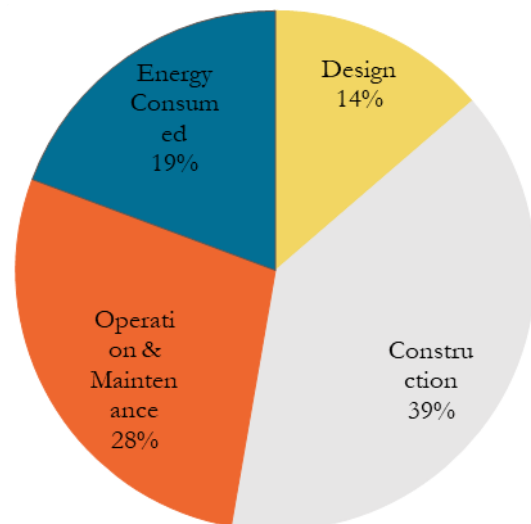
WWR3
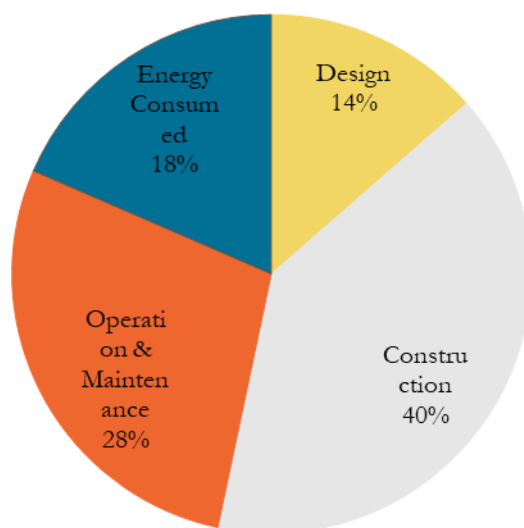
Daylighting
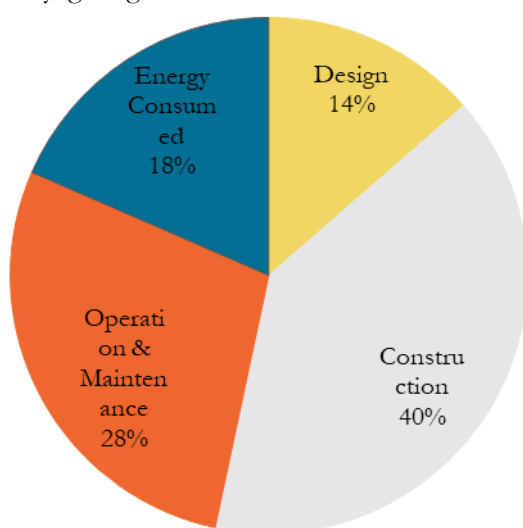
Figure 21: Life cycle costs of the building Parkcarré at the location Sweden: share of the assessed cost groups in the overall LCC.

In contrast to the previous two cases, heating is not the dominating energy demand in **Italy**. Here, cooling plays a more important role. Therefore, also the installed technologies in the building were changed and the costs of cooling facilities were taken into account instead of the costs for heating technologies. The investment and associated operation and maintenance costs for the cooling facilities are lower than the costs for the heating facilities leading to a lower total LCC of the base case compared to the heating cases above. Furthermore, instead of analysing three different window-to-wall ratios (WWR), only the variants WWR1 and WWR3 were assessed and the effect of free ventilation was added to the analyses (variant Vent3). For the calculation of the electricity demand for cooling an efficiency (EER) of the cold generation of 3.012 is assumed based on (Joint Research Centre of the European Commission JRC C.6, 2018).

The north orientation has the best results with respect to the cooling demand, which is the dominant energy demand for the climate conditions in southern Italy. The effect can be seen in the results presented in Figure 22. The LCC of the variant with north orientation is approx. 6,000 € lower than the LCC of the base case (-0.4 %).

As can be seen in Figure 22 the increase of the window-to-wall ration also increases the LCC. There are two major effects: the increased window area increases the construction costs and the resulting additional solar gains lead to higher energy demands for cooling and thereby increase the costs for the energy consumed. The highest LCC occurs with an increased window-to-wall ratio on the east and west side (WWR3). It is 7.5 % higher than the base case. Natural ventilation on the other hand has a positive effect on the LCC. The energy demand for cooling is decreased by 22 % compared to the base case leading to a decrease of the LCC of 1.9 %. The specific LCC is shown in Figure 23.

As can be seen in Figure 24 the share of the energy costs (only costs associated with the energy consumed without taking into account benefits from renewable energy generation on-site) in all variants is only 11 − 17 % and thereby higher than in the other climate regions. The reason for the higher share is the high energy demand for cooling and the fact that electricity is used for the cold generation, which is more expensive than district heat, which is assumed to supply the heating demand in Germany and Sweden. The dominating costs are the construction as well operation and maintenance (without energy costs) costs with a share of 42 − 44 % and 26 − 28 % respectively. Compared to the other climate regions, cost savings due to the energy savings achieved with passive approaches has a higher impact on the overall LCC.
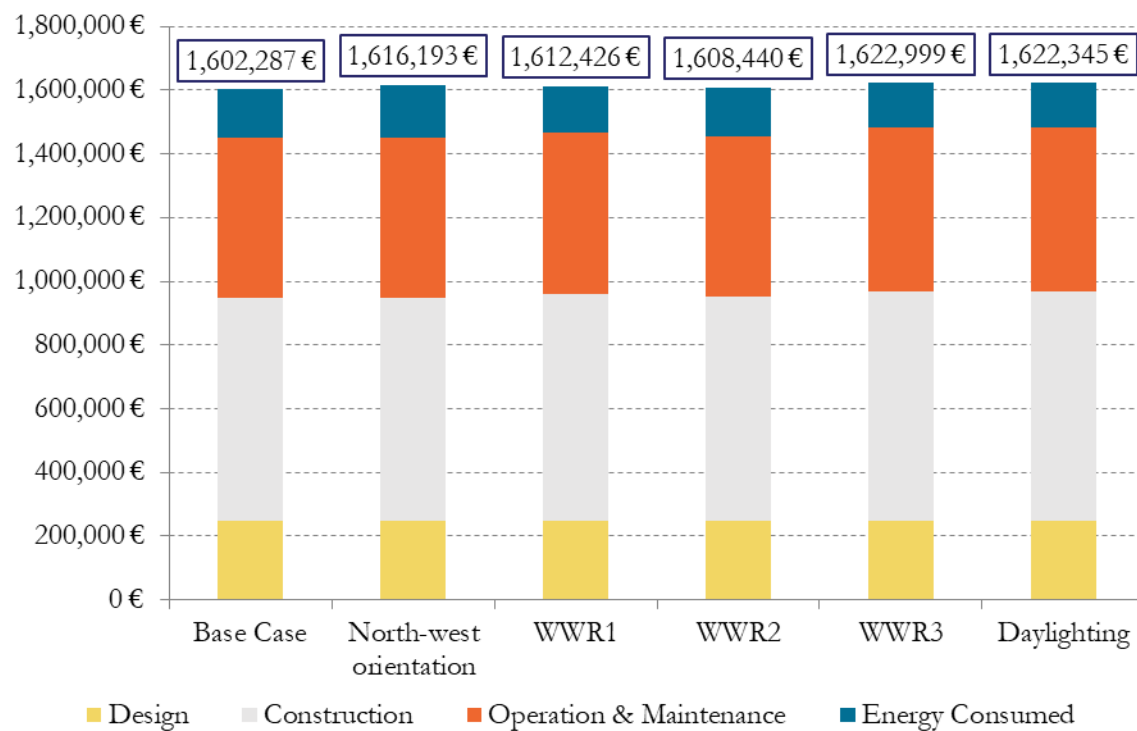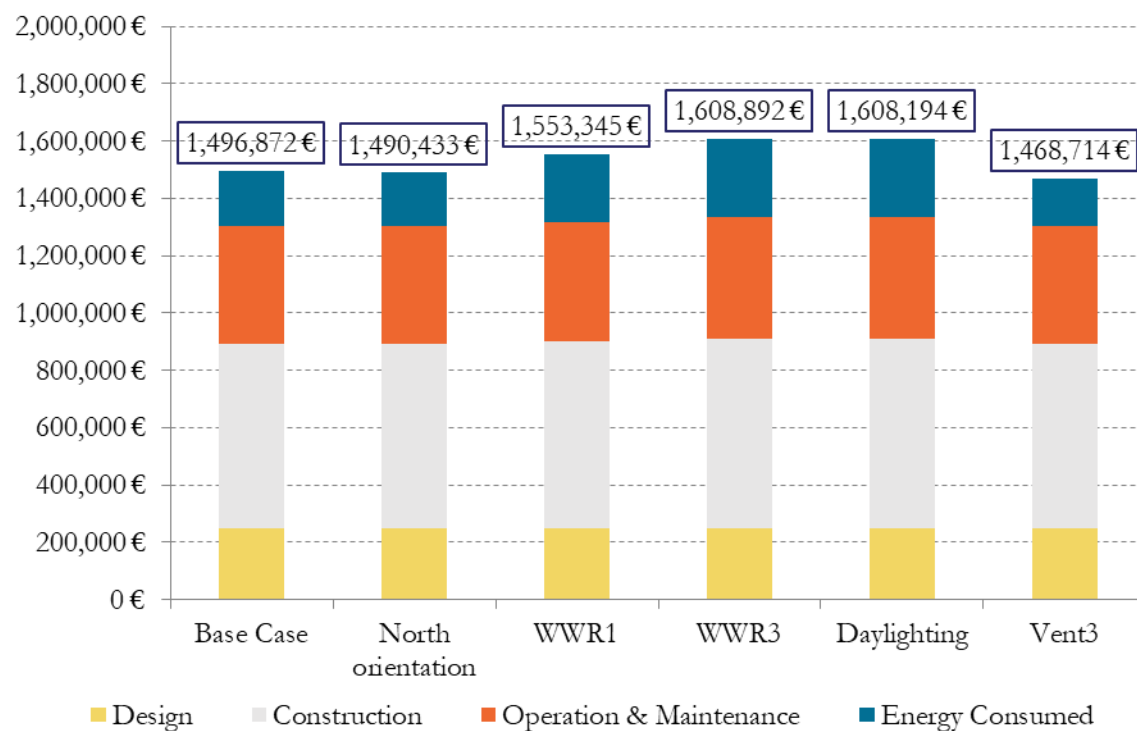
Figure 22: Life cycle costs of the building Parkcarré at the location Italy.
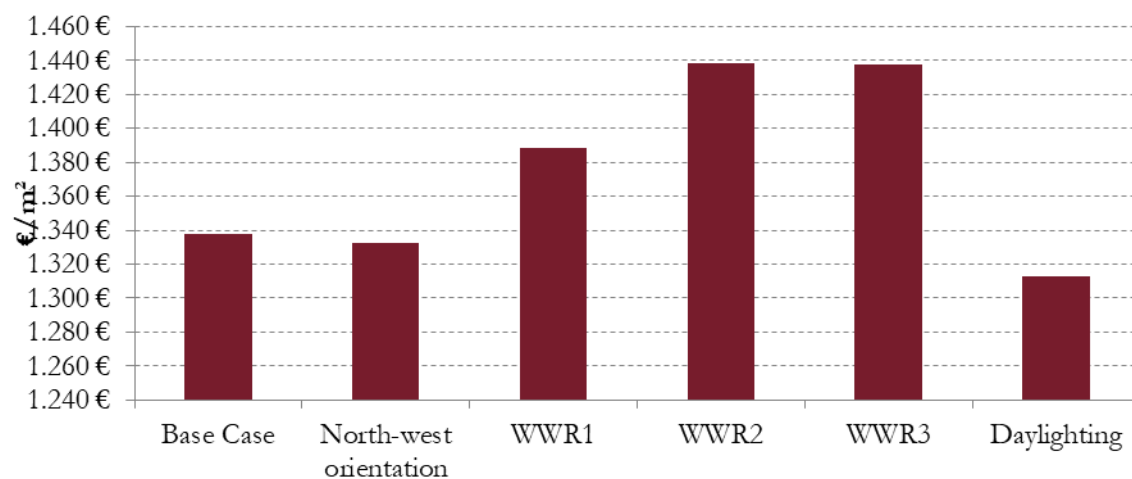
Figure 23: Specific overall Life cycle costs of the building Parkcarré at the location Italy.

Base Case
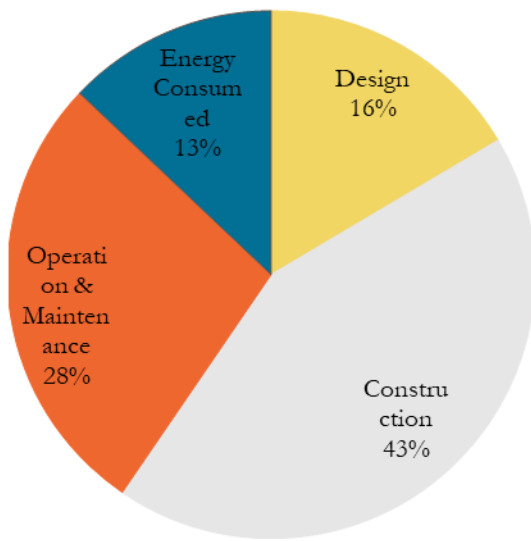
North orientation
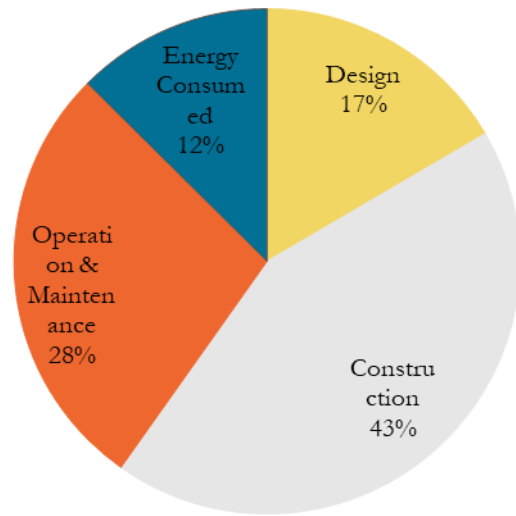
WWR1
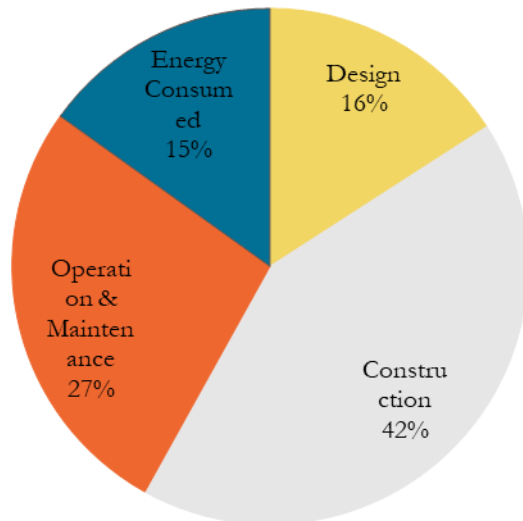
WWR3
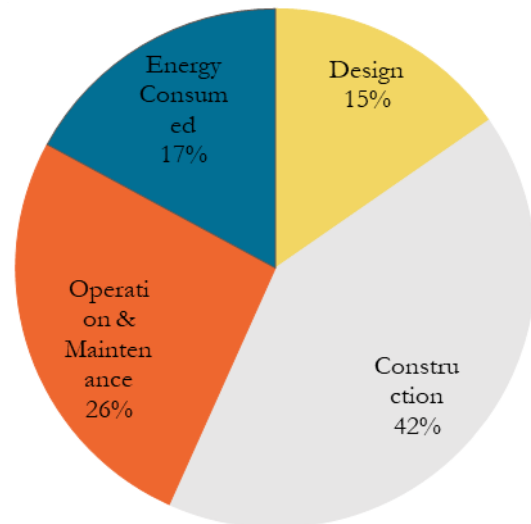
Daylighting
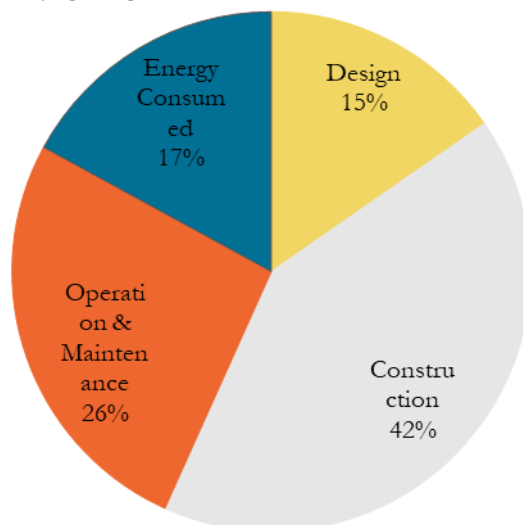
Vent3
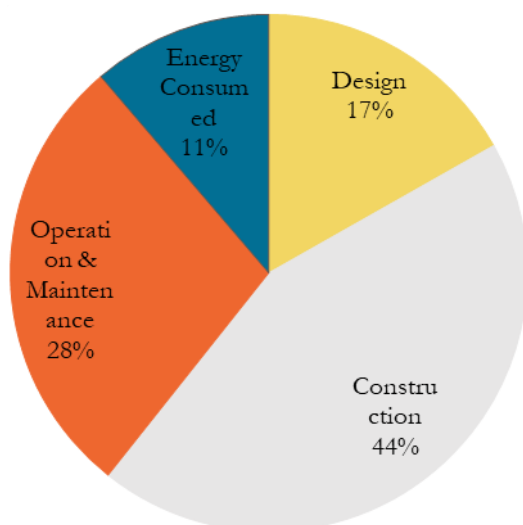
Figure 24: Life cycle costs of the building Parkcarré at the location Italy: share of the assessed cost groups in the overall LCC.

5. TECHNOLOGY SETS

The project CRAVEzero mainly builds on twelve case studies provided by the project partners. The case studies are located in Austria, Italy, France, Germany and Sweden. In the following the case studies are shortly described highlighting their most relevant features. The descriptions are taken from previous deliverables if available (D6.1 "Parametric models for buildings and building clusters: Building features and boundaries" (Weiß et al., 2019) and D6.2 "Results of optimised nZEB parametric models" (Venus et al., 2019)) or developed based on the case study information available on the projects website under http://www.cravezero.eu/cases-2/. Furthermore, variants with high and low costs (net present values) as well as low and high CO_2 emissions are described in detail.

In addition to the qualitative descriptions, simple visualisations of the technology sets were developed to provide a fast and easy overview of the major technologies used/ installed in the case studies. This allows an easy illustration of technology sets (i) as currently installed and (ii) for the improved/ optimised variants.

5.1. VISUALISATION OF TECHNOLOGY SETS

Figure 25 shows an example energy flow schema as used to illustrate the structure of the case study buildings in terms of (i) energy flows, (ii) installed technologies and thereby (iii) gives an overview of technology combinations used currently in the case studies and improved sets. The schematics are simple graphical illustrations of possible technology sets. The considered and illustrated (energy) flows in the building are:

- Yellow=   Electricity
- Red=   Hot water/ heating water
- Purple=   DHW
- Dark blue=   Water supply
- Light blue=   Supply air
- Green=   Exhaust air
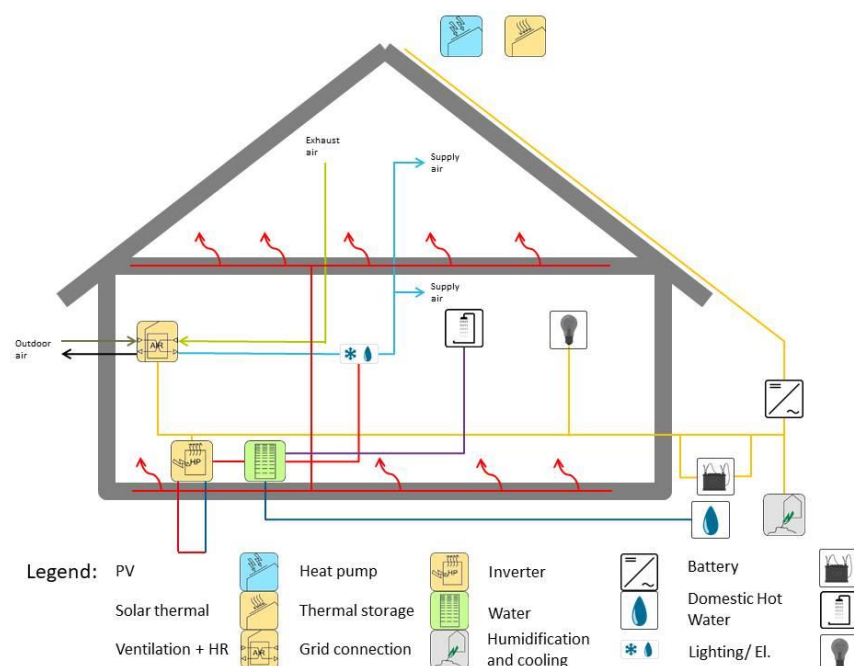
Figure 25: Exemplary visualisation of technology set

5.2. OVERVIEW OF COST STRUCTURE IN CASE STUDIES

In the deliverable D2.2 'Spreadsheet with LCCs' (Pernetti et al., 2018) of CRAVEzero, the cost structure of the case study buildings is described in detail. It contains the life cycle costs of all case studies. The overview in the following focuses on the investment costs for the building and especially the HVAC-system.

Figure 26 shows the cost shares of all phases in the total life cycle costs of the case studies. The costs for design, material, labour and other initial expenditures is around 56 %. The energy and maintenance costs account for approx. 43 %.

The energy costs only account for around 12 % during the life cycle of an nZEB.
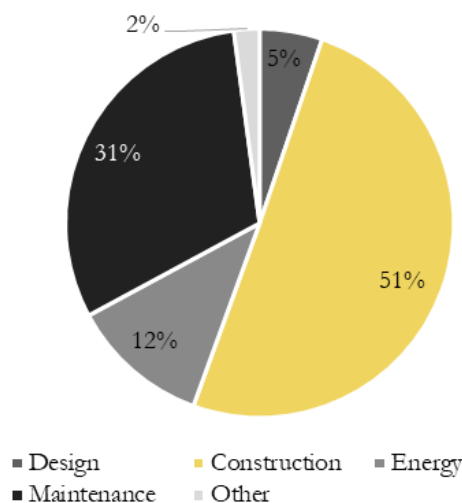
Figure 26: Life cycle cost breakdown – average share of the phases. Source (Pernetti et al., 2018)

Figure 27 shows the breakdown of the cost for building elements. It highlights the importance of the construction costs for each assessed case study. nZEB related technologies only have a minor impact on the overall construction costs. However, the technology costs (HVAC and on-site renewables (RES)) in nZEBs are – in absolute values – higher than in a standard building. The share of building services costs (which is mainly HVAC) ranges between 18 % and 35 %. The costs for RES have a share between 1 % and 8 % in the overall construction costs.
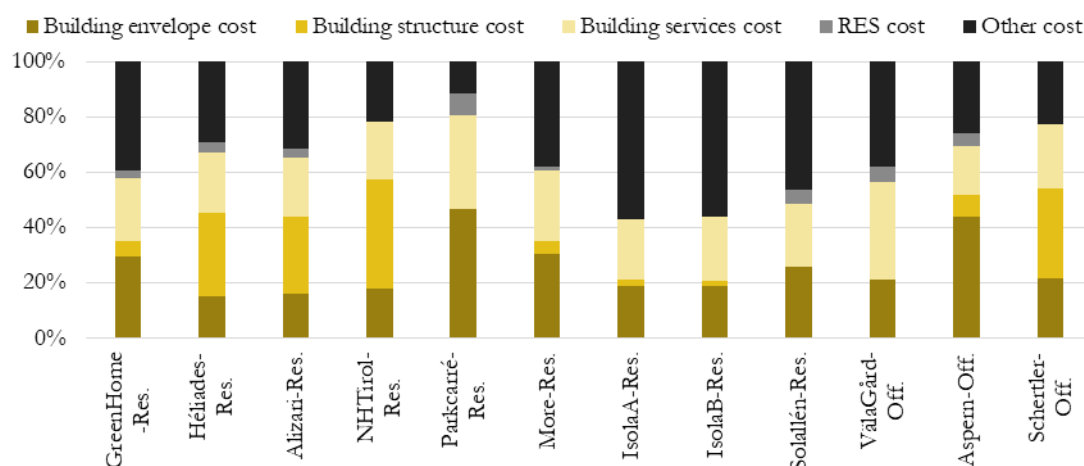
Figure 27: Construction cost breakdown. Source (Pernetti et al., 2018)

The specific costs show a high variation of approx. 120 €/m² – 600 €/m² for the building envelope and 80 – 300 €/m² for the technologies installed (HVAC and RES). The high variation shows that there is still a potential for cost reductions for the building envelope and the technologies in buildings.

Figure 28 shows the cost shares of the different building services and renewable energies. The figure is based on the LCC-spreadsheets developed in WP02. However, the cost information was not available in the desired level of detail for all case studies. This is very obvious for the service "Me-

chanical Ventilation". Almost all energy flow schematics presented in chapter 5.3 include mechanical ventilation, but costs are only available for one building.

Heating and domestic hot water (DHW) have the highest share in the total costs for building services ranging from 41 % to 73 %. The second largest share is associated with the hydraulic system and distribution, which have a share between 20 % and 64 %. Electric installations have a share of up to 41 %.

The costs for the heat supply and distribution have an increasingly high share with the increasing complexity of the system. The increasing complexity evolves from e.g. the integration of several heat generators and sources (boiler plus heat-pump, ambient air and ground as a heat source and sink

for (reversible) heat pumps, different temperature levels in distribution and other reasons. Designing highly efficient buildings with very low heat demands on the other hand can be operated without any heat generation and as a result without heat distribution systems minimizing the overall costs of the building (investment and operation; see e.g. the case study Green Home Nanterre). The opposite – i.e. a very complex system – is realised in Isola Nel Verde combining a CHP, heat pump and solar thermal collectors for the heat supply. This leads to comparably high specific costs and high shares of heating and DHW in the overall building services costs. Applying renewable energies on-site is in most cases not the cost driver for the building services; the share is only between 5 % and 21 %.
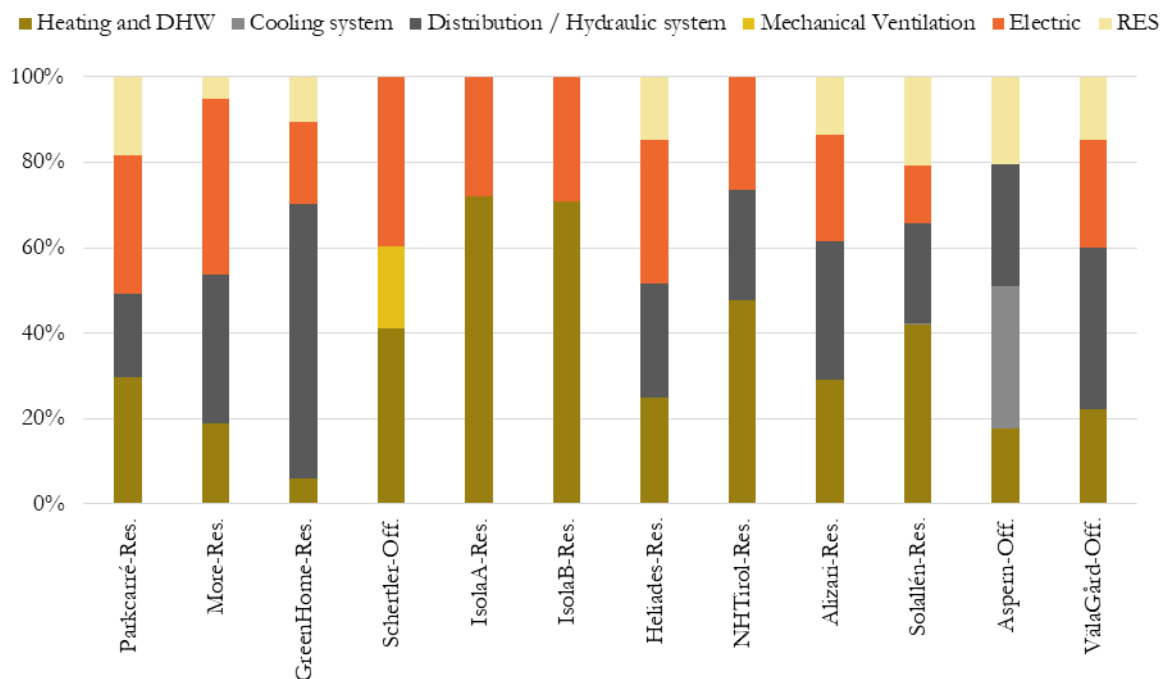
Figure 28: Breakdown of the building services and RES investment costs – relative values. Own illustration based on (Pernetti et al., 2018).

5.3. ANALYSIS OF TECHNOLOGY SETS

In the following, detailed descriptions of technology combinations from the parametric analysis conducted in WP06 are described. The described sets are the ones with the lowest and highest CO_2 emissions and costs. Furthermore, from the variants with the lowest costs the ones with low emissions were identified as possible best cases. The considered costs in the calculations in WP06 are planning and financing costs, (energy) consumption costs including PV own use and PV feed-in, operating costs, replacement investment and residual value. In the tables summarising the major parameters of the assessed variants, the variant number as it can be found in the CRAVEzero pinboard are given.

In (Weiß et al., 2019) the sum of these costs were named "net present value (NPV)". This expression is also used in the following for consistency reasons. In order to understand the results described in the following the main general definitions of the assessed variables in WP06 they are summarized in the following tables. Definitions about building technologies, building envelope and ventilation are described in the respective case study chapters.

Table 12: Description of the different assessed energy price and feed-in tariff increase ("sensitivity") according to (Venus et al., 2019)

Parameter	Level 1: Standard	Level 2: High	Level 3: Low	Level 4: Default
Energy price increase per year	1.0 %/a	2.0 %/a	0.5 %/a	-
Increase of PV feed-in tariff per year	1.7 %/a	2.7 %/a	0.7 %/a	-

Table 13: Description of the different assessed CO2 follow-up costs according to (Venus et al., 2019)

Parameter	Low	Standard	High	No
CO_2 follow-up costs	100 €/t_{CO2}*a	200 €/t_{CO2}*a	300 €/t_{CO2}*a	0 €/t_{CO2}*a

Table 14: Description of the different assessed user behaviours according to (Venus et al., 2019)

Parameter	Level 1: Efficient	Level 2: Standard	Level 3: Not Efficient	Level 4: PHPP Default
T_{room} during heating period	21°C	22°C	23°C	20°C
DHW-demand	29 l/d	33.3 l/d	48.5 l/d	33.3 l/d
Misuse external blinds in winter	0 %	+10 %	+20 %	0 %
Electrical loads	20 kWh/(m²a)	26.6 kWh/(m²a)	35 kWh/(m²a)	26.6 kWh/(m²a)
Additional window ventilation in winter:	+0.0 h^{-1}	+0.05 h^{-1}	+0.1 h^{-1}	+0.0 h^{-1}

5.3.1. RÉSIDENCE ALIZARI

5.3.1.1. BASE CASE

The following description of the case study is based on deliverable D6.2 (Venus et al., 2019).

The residential building has 31 apartments and one studio and was designed by "Atelier des Deux Anges". The gross heated floor area is 2,190 m². It is labelled Passivhaus and Promotelec RT 2012-20%. It is located in Malaunay, France. The design of the project was oriented to meet a high standard of energy performance, relying on the **compactness** of buildings and passive approaches like the **control of solar inputs** and an optimised building **orientation**. To achieve the high energetic quality, the envelope areas have very **low U-values**. The external wall against ambient air has an average U-value of 0.1 W/(m²K), the floor slab/ basement ceiling of 0.16 W/(m²K), the roof of 0.09 W/(m²K) and the windows between 0.91 and 0.99 W/(m²K). To further minimize the energy demand a double flux **ventilation system with heat recovery** is installed. The system has a specific power input of 0.45 Wh/m³ and a heat recovery rate of 82 %.

The heat is supplied by a **biomass boiler**, which is covering 92 % of the space heating demand.

For achieving the high energetic standard the **management of renewable energies** on-site and the interaction of all installed technologies (PV, heating system with ventilation) is a cornerstone. The installed **photovoltaic** panels have a peak power of approx. 33 kWp generating more than 29 MWh per year.

Special to the buildings are the large parts of **spaces and services shared** among the residents (local bicycles and strollers, optical fibre, local compost). Residential common laundry and a guest bedroom are also integrated into the new building.
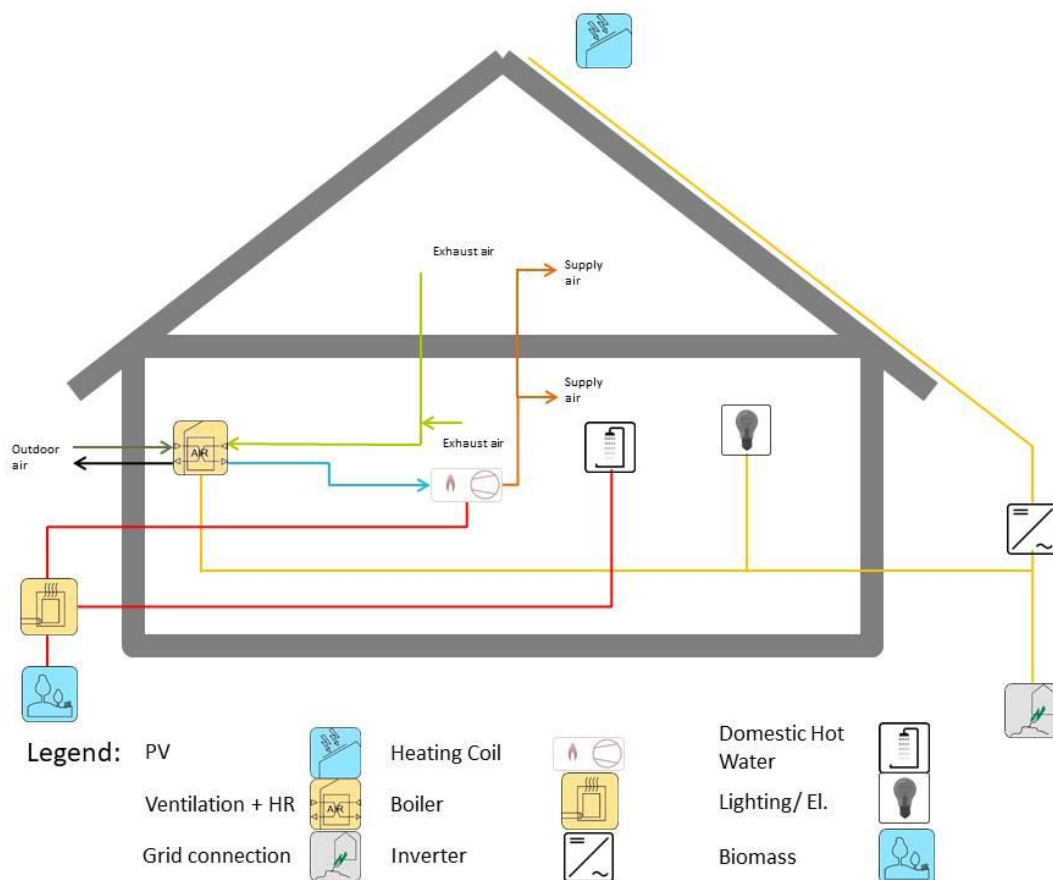
Figure 29: Visualisation of technology set of the case study Residence Alizari

5.3.1.2. LOW-ENERGY AND LOW-COST TECHNOLOGY SETS

The results presented in (Venus et al., 2019) show that among all calculated variants the ones without a PV system have the lowest investment and life cycle costs, but they are also amongst the variants with the highest CO_2 emissions. Furthermore, the results show that variants with a net present value of above 1,750 €/m² usually consider a substantial price increase of energy carriers and feed-in tariffs (parameter "sensitivity"), have high CO_2 follow up costs and are equipped with cogeneration units (CHPs). Besides, these variants also have comparably high CO_2 emissions of more than 24 kg_{CO2}/(m²a). Another finding from the analysis conducted in WP06 is that variants with large PV systems are amongst the variants with the lowest emissions. Other aspects with a large influence on the CO_2 emissions are the user behaviour and window ventilation instead of mechanical ventilation.

In Figure 30 the final energy demand for heating DHW, cooling and ventilation of the variants with highest and lowest NPV and CO_2 emissions is shown. It can be seen that DHW preparation is dominating the final energy demand in all cases, followed by heating. Mechanical ventilation only plays a minor role concerning energy demand (for the operation of the systems). Cooling systems are not installed in any variant. How the needed energy is provided and what the significant differences are is described in the following.
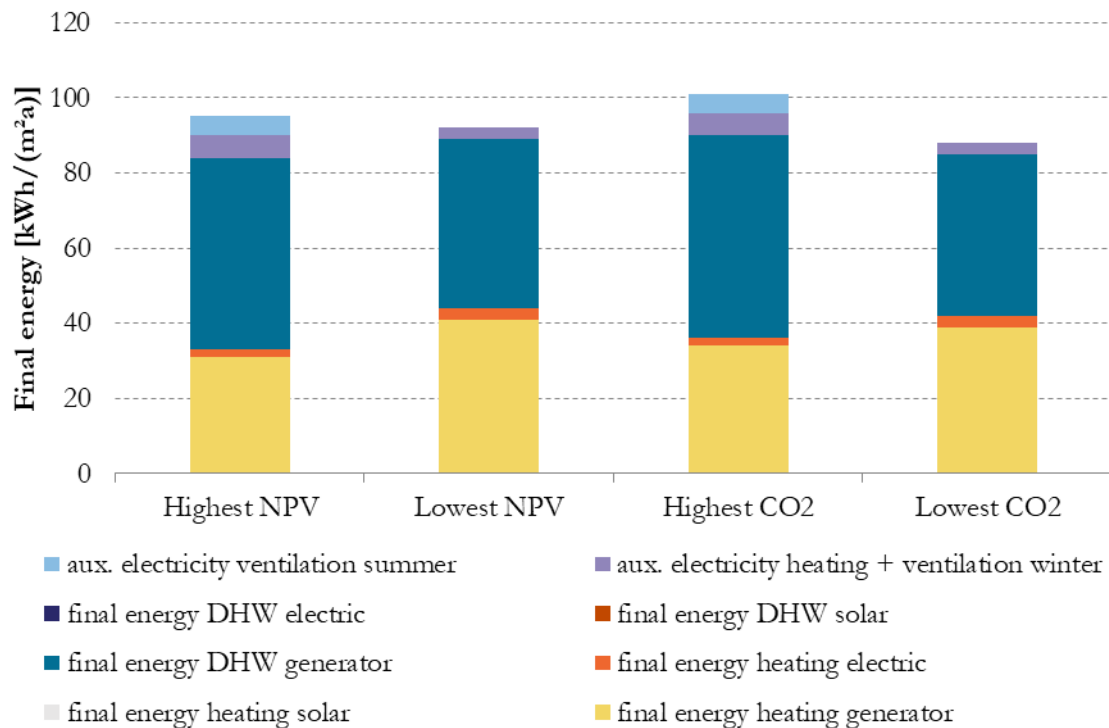
Figure 30: Final energy demand for heating, DHW, cooling and ventilation in the variants with the highest and lowest NPV and CO₂ emissions of the case study Résidence Alizari

Lowest and highest NPV

The basic characteristics of the variants with the highest and lowest NPV are summarized in Table 15. The main differences of the two variants are the type and thickness of the insulation of the envelope (external walls), the type of ventilation and the kind of heat generation. In the variant with the highest NPV there is internal and external insulation as well as a mechanical ventilation system installed. The cost difference of the insulation is approx. 22 €/m² and for the ventilation system about 8,000 €. The cost difference for the heating system is 820 €/kW and additional 1,000 € in the labour costs. With the installed capacity of 64 kW, the total cost difference for the heat generation system is 47,286 € (total cost boiler: 12,372 € vs. total cost CHP: 59,658 €).

The average heating load of the variant is 13.94 kW and the heating demand 30 kWh/(m²a). The share of heating, DHW, cooling and ventilation in the final energy demand of both variants is shown in Figure 31. Most energy is needed for DHW, followed by heating. The share of final energy for heating in the variant with the highest NPV is only 33 % compared to 45 % in the variant with the lowest NPV. The auxiliary electricity demand only plays a small role in both variants. The balanced CO_2 emissions of the variant with the highest NPV are 32.32 kg_{CO2}/(m²a) and of the variant with the lowest NPV 27.32 kg_{CO2}/(m²a). This shows that investing more money in a building does not necessarily lower the CO_2 emissions and that highly efficient and low emission buildings are possible with lower investments. In Figure 32 the technology set of the variant with the lowest NPV is shown visualising the major technologies for realising a low cost nZEB.

Table 15: Variants with the highest and lowest net present value (NPV) of the case study Résidence Alizari based on WP06; values for variables based on (Venus et al., 2019)

Variables	Highest NPV	Lowest NPV
Variant number	4765	12097
Sensitivity (Energy price increase)	High	PHPP
CO_2 follow-up costs	High	No
User behaviour	Not efficient	PHPP default
Envelope	External wall 200 mm external + 100 mm internal insulation	External wall 250 mm external insulation
Ventilation	Rotatech mechanical ventilation unit; heat recovery efficiency 68 %	Window ventilation
Heating	Pellet CHP-plant with efficiency of 109 %	ETA pellet boiler with thermal efficiency of 91 %
Climate	Real location	Real location
Cooling	No cooling	No cooling
Solar thermal	No solar thermal	No solar thermal
PV	No PV	No PV
Net present value	**1,790 €/m²**	**1,497 €/m²**
Balanced CO_2 emissions	**32.32 kg_{CO2}/(m²a)**	**27.32 kg_{CO2}/(m²a)**

Final energy demand highest NPV
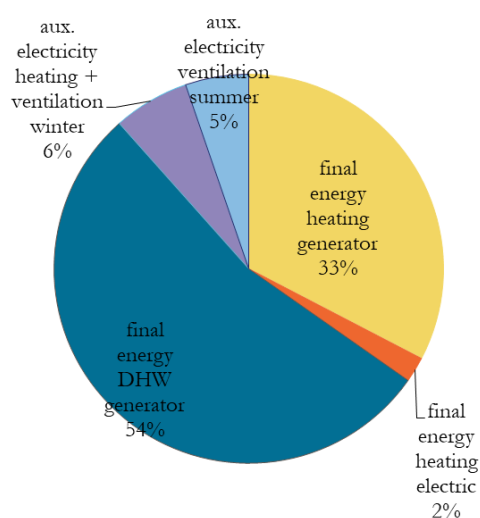
Final energy demand lowest NPV

Figure 31: Final energy demand for heating, DHW, cooling and ventilation in the variant with the highest NPV (left) and lowest NPV (right) of the case study Résidence Alizari
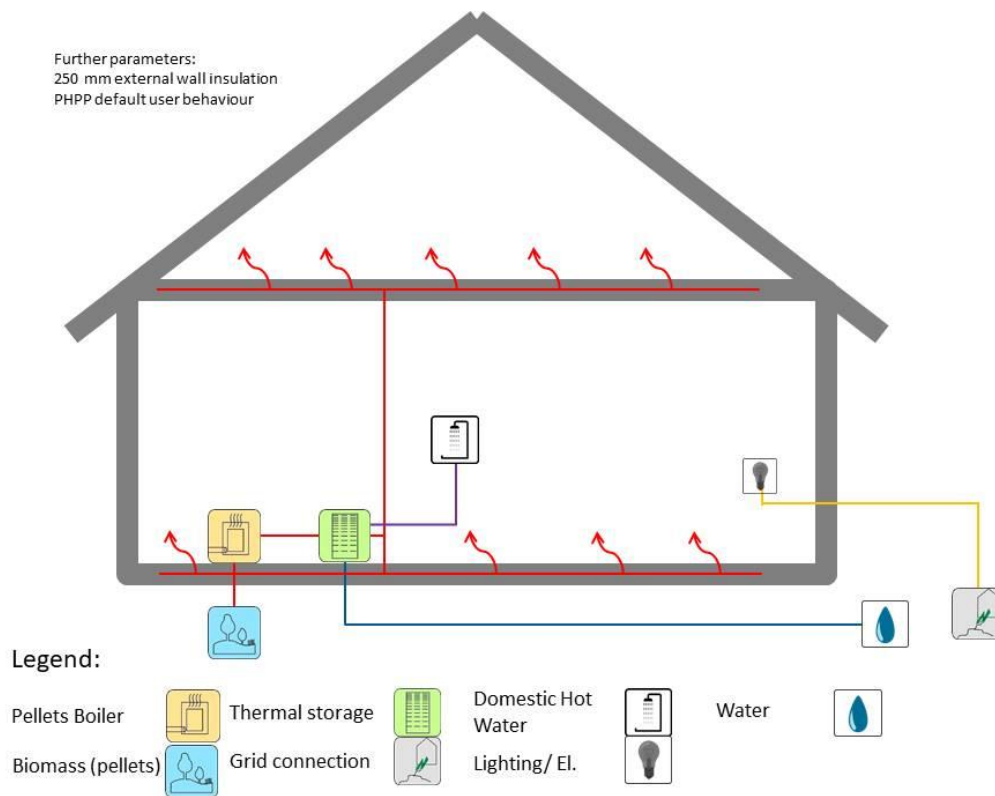
Figure 32: Visualisation of technology set of Alizari; variant with lowest NPV

Lowest and highest CO₂ emissions

The basic characteristics of the variants with the highest and lowest CO_2 emissions are summarized in Table 16. The balanced CO_2 emissions of the variant with the highest CO_2 emissions are 32.68 $kg_{CO2}/(m^2a)$ and of the variant with the lowest emissions 22.61 $kg_{CO2}/(m^2a)$. Like above (lowest and highest NPV) the main differences of the two variants are the thickness of the insulation of the envelope (external walls), the type of ventilation and the type of heat generation. In the variant with the highest CO_2 emissions, there is external insulation with a thickness of 250 mm as well as a mechanical ventilation system installed. The cost difference of the insulation compared with the variant with the lowest emissions (insulation thickness 300 mm) is approx. 6.3 €/m² and for the ventilation system about 8,000 €. The cost difference for the heating system is 820 €/kW and additional 1,000 € in the labour costs. With the installed capacity of 64 kW the total cost difference for the heat generation system is 47,286 € (total cost boiler: 12,372 € vs. total cost CHP: 59,658 €).

The relevant factors for the low CO_2 emissions are efficient user behaviour (PHPP default), the installation of a large PV system and the co-generation unit. The installed PV system has a capacity of 41 kWp with an efficiency of 21 % generating 33,948 kWh/a. The total cost for the system is 77,190 € (1,896 €/kWp).

The average heating load of the variant is 17.85 kW and the heating demand 37 kWh/(m²a). The share of heating, DHW, cooling and ventilation in the final energy demand of both variants is shown in Figure 33. Also here, DHW is the dominating factor followed by space heating. It highlights the importance of DHW for the overall final energy demand of the building.

The NPV of the variant with the highest CO_2 emissions is 1,531 €/m² and of the variant with the lowest emissions 1,601 €/m². In Figure 34 the technology set of the variant with the lowest CO_2 emissions is shown visualising the major technologies for realising a low cost nZEB.

Table 16: Variants with the highest and lowest CO₂ emissions of the case study Résidence Alizari based on WP06

Variable	Highest CO$_2$	Lowest CO$_2$
Variant number	11537	12176
Sensitivity (Energy price increase)	PHPP	PHPP
CO$_2$ follow-up costs	No	No
User behaviour	Not efficient	PHPP default
Envelope	External wall 250 mm external insulation	External wall 300 mm external insulation
Ventilation	Rotatech mechanical ventilation unit; heat recovery efficiency 68 %	Window ventilation
Heating	ETA pellet boiler with thermal efficiency of 91 %	Pellet CHP-plant with efficiency of 109 %
Climate	Real location	Real location
Cooling	No cooling	No cooling
Solar thermal	No solar thermal	No solar thermal
PV	No PV	41 kWp; efficiency 21 %
Net present value	**1,531 €/m²**	**1,601 €/m²**
Balanced CO$_2$ emissions	**32.68 kg$_{CO2}$/(m²a)**	**22.61 kg$_{CO2}$/(m²a)**

Final energy demand highest CO₂ emissions
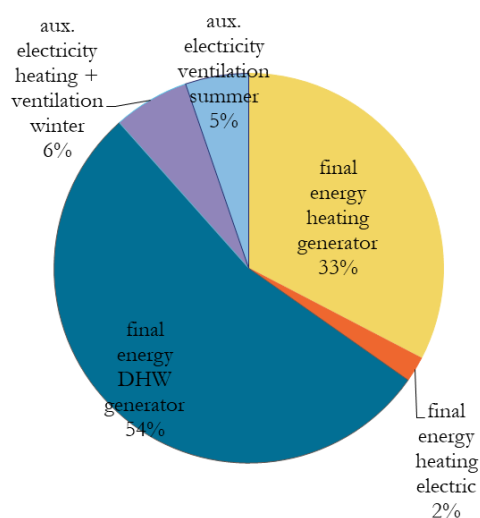
Final energy demand lowest CO₂ emissions

Figure 33: Final energy demand for heating, DHW, cooling and ventilation in the variant with the highest (left) and lowest CO₂ emissions (right) of the case study Résidence Alizari

Figure 34: Visualisation of technology set of Alizari; variant with lowest CO_2-emissions

Potential best cases

In Table 17 potential best cases are summarized. These variants have both comparably low CO_2 emissions and costs (NPVs). The balanced CO_2 emissions of the variants are between 23.05 $kg_{CO2}/(m^2a)$ and 23.61 $kg_{CO2}/(m^2a)$ and thereby only slightly higher than the variant with the lowest emissions. The NPV of all variants is between 1,512 and 1,521 €/m². In Table 17, only the differences between the variants are listed. The following parameters are the same for all variants:

- No CO_2 follow-up costs

- No price increase for energy carriers
- Efficient user behaviour (PHPP default or efficient user)
- Window ventilation
- Pellet boiler
- Real location
- No cooling
- No solar thermal

The differences between the variants are the thickness of the insulation (250 vs. 300 mm) and the size and efficiency of the PV system (30 vs. 34 kWp).

Table 17: Variants with low CO_2 emissions and comparably low costs of the case study Résidence Alizari based on WP06. The shown variable number is based on the results matrix of the parametric analysis and is equivalent to the number of the variant in the interactive case study dashboard in CRAVEzero-pinboard.

Variant Number	12098	12099	11907	12162	12163
Envelope	External wall 250 mm	External wall 250 mm	External wall 250 mm	External wall 300 mm	External wall 300 mm
PV	30 kWp; efficiency 15 %	34 kWp; efficiency 17 %	34 kWp; efficiency 17 %	30 kWp; efficiency 15 %	34 kWp; efficiency 17 %
NPV [€/m²]	**1,512**	**1,516**	**1,517**	**1,518**	**1,521**
CO_2 emissions [$kg_{CO2}/(m^2a)$]	**23.31**	**23.14**	**23.61**	**23.22**	**23.05**

5.3.2. SOLALLÉN

5.3.2.1. BASE CASE

Solallén consists of 21 dwellings in seven one-storey terraced houses, built in the southern part of Sweden (Växjö 56.837, 14.797). The net floor area is 1,778 m². The strategy for reaching a Net ZEB balance was a three-step approach. Firstly, the **thermal losses were reduced** in order to have a low heating demand. Secondly, a ground-source heat pump (GSHP) was chosen to lower the need for imported energy. Thirdly, the building was equipped with PV panels to generate renewable energy. The foundation is a concrete slab on ground with 300 mm of underlying expanded polystyrene (EPS), giving a U-value of 0.11 W/(m²K). The external walls are wood framework walls with 455 mm mineral wool insulation, giving a U-value of 0.09 W/(m²K). The roof is insulated with 500 – 600 mm of mineral wool, giving a U-value of 0.07 W/(m²K). Windows and doors were mounted with a U-value of 0.90 W/(m²K). The windows in the living rooms were given an external sunscreen. The combination of window and external sunscreen resulted in a g-value of 0.09.

The ventilation was designed with a **mechanical balanced ventilation system with heat recovery** of 90 %. The ventilation system has nominal ventilation, which gives the dwelling an air exchange rate of 0.5 air changes per hour (h⁻¹). The ventilation system has the capacity to increase the airflow to 1.0 h⁻¹, which may be done manually or programmed based on a chosen level of relative humidity or temperature.

A **ground source heat pump** was chosen to produce space heating and hot water. Heat for hot water is produced and supplied to a **hot water storage** tank. Space heating is distributed via **floor heating**. During the summer, the **boreholes** are used as a **natural heat sink**. The working fluid for the heat pump is circulated in the boreholes cooling the working fluid, which then is used to supply cooling via a cooling coil in the ventilation system. A circulation pump is used, but no compressors are used for cooling. Each building was designed with 40 **PV** panels measuring roughly 66 m², giving each building an installed capacity of 10 kWp.
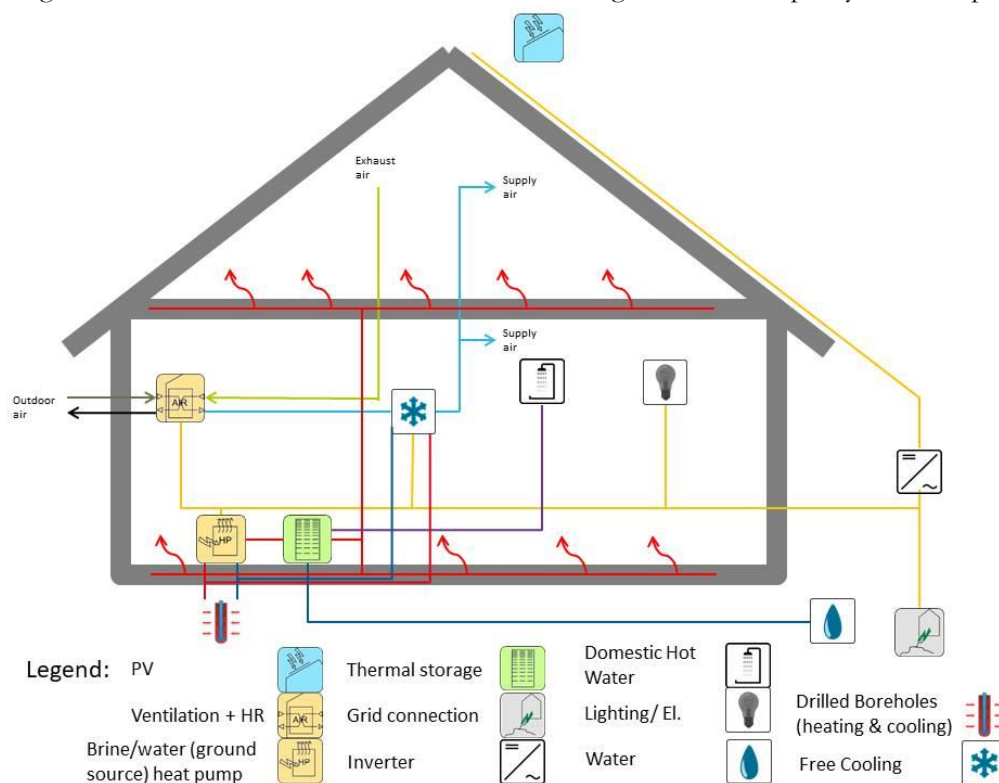
Figure 35: Visualisation of technology set of the case study Solallén

5.3.2.2. LOW-ENERGY AND LOW-COST TECHNOLOGY SETS

The results presented in (Weiß et al., 2019) and below show that the building envelope and size of the PV system have a strong influence on the net present value. The highest NPV is associated with a "Passive house" envelope and a large PV system (120 m²; 20 kWp). Furthermore, most variants with a NPV of more than 3,900 €/m² use a large ground source heat pump and free cooling. The specific CO_2 emissions of these variants vary between 18 and 31.4 kg/(m²a).

The highest emissions for Solallén occur in the cases without PV and solar thermal collectors and with inefficient user behaviour. The lowest emissions occur in the cases with large PV and solar thermal systems along with efficient user behaviour. In the cases with high emissions, the envelope quality does not play an important role; the most dominant factors are PV and solar thermal systems as well as the heating system (highest emissions in cases with an air source heat pump). The lowest emissions are associated with district heating.

In Figure 36 the final energy demand for heating DHW, cooling and ventilation of the variants with highest and lowest NPV and CO_2 emissions is shown. It can be seen that space heating is dominating the final energy demand in all cases, followed by DHW.
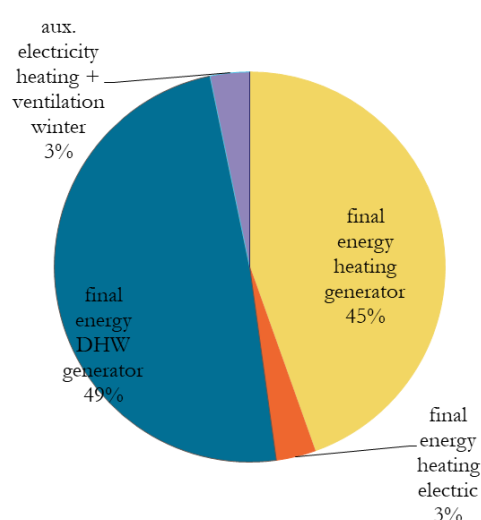

Figure 36: Final energy demand for heating, DHW, cooling and ventilation in the variants with the highest and lowest NPV and CO₂ emissions of the case study Solallén

Lowest and highest NPV

The basic characteristics of the variants with the highest and lowest NPV are summarized in Table 18. The main differences of the two variants are the type and thickness of the insulation of the envelope, the installation of PV and solar thermal as well as the user behaviour. In the variant with the highest NPV a "Passive house" insulation with very low U-values is realised. The cost difference for the insulation compared to the nZEB envelope (as built) is 14 €/m² (floor), 42.3 €/m² (wall), 10.4 €/m² (roof) and 2.4 €/m² for improved air tightness. The airtightness of the envelope and window quality (WinDoorAir) is between national

standard and passive house quality (nZEB level). The total cost for the heating system (extract air heat pump) is 27,070 €. The total cost for the solar thermal system in the variant with the lowest NPV is 54,600 €, and the cost for the PV system in the variant with the highest NPV is 260,000 €.

The average heating demand is 44 kWh/(m²a) (highest NPV) and 58 kWh/(m²a) (lowest NPV). The share of heating, DHW, cooling and ventilation in the final energy demand of both variants is shown in Figure 37. Most energy is needed for space heating followed by DHW. In the variant with the highest NPV, the high influence of the user behaviour on the final energy demand is clearly visible; in this case space heating has a share of more than 60 % in the overall energy demand of the building.

The balanced CO_2 emissions of the variant with the highest NPV are 45.34 kg_{CO2}/(m²a) and of the variant with the lowest NPV 23.17 kg_{CO2}/(m²a). This shows that investing more money in a building does not necessarily lower the CO_2 emissions and that highly efficient and low emission buildings are possible with lower investments if people using the building are behaving efficient. In Figure 38 the technology set of the variant with the lowest NPV is shown visualising the major technologies for realising a low cost nZEB.

Table 18: Variants with the highest and lowest net present value (NPV) of the case study Solallén based on WP06; values for variables based on (Venus et al., 2019)

Variables	**Highest NPV**	**Lowest NPV**
Variant number	4765	1051
Sensitivity (Energy price increase)	High	low
User behaviour	Not efficient	Efficient
Envelope	Passive house: Floor slab: 400 mm insulation Exterior walls: 600 mm insulation Roof: 750 mm insulation	nZEB: Floor slab: 300mm insulation Exterior walls: 455 mm insulation Roof: 600 mm insulation
WinDoorAir	National standard	National standard
Ventilation	Mechanical ventilation unit; heat recovery efficiency 80 %; SFP: 1.75	Mechanical ventilation unit; heat recovery efficiency 80 %; SFP: 1.75
Heating	Extract air heat pump: 1.8 kW SCOP: 2.5	Extract air heat pump: 1.8 kW SCOP: 2.5
Cooling	Compressor cooling: 3 kW SCOP: 3	Compressor cooling 3 kW SCOP: 3
Solar thermal	No solar thermal	20 m², vacuum tubes used for DHW and heating
PV	120 m²; 20 kWp	No PV
Net present value	**3,488 €/m²**	**2,686 €/m²**
Balanced CO_2 emissions	**45.34 kg_{CO2}/(m²a)**	**23.17 kg_{CO2}/(m²a)**

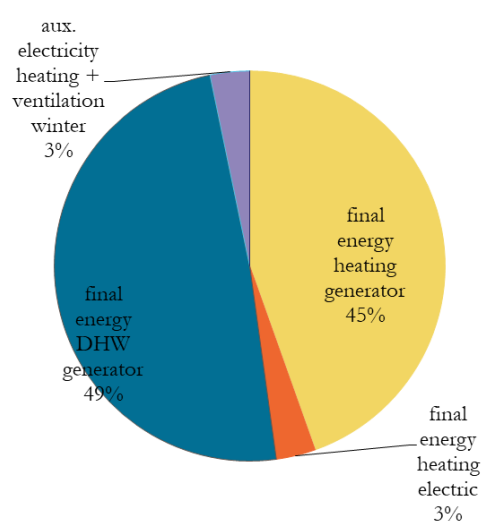Final energy demand highest NPV
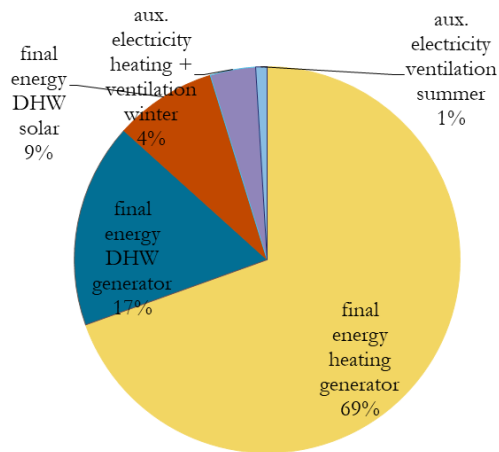
Final energy demand lowest NPV
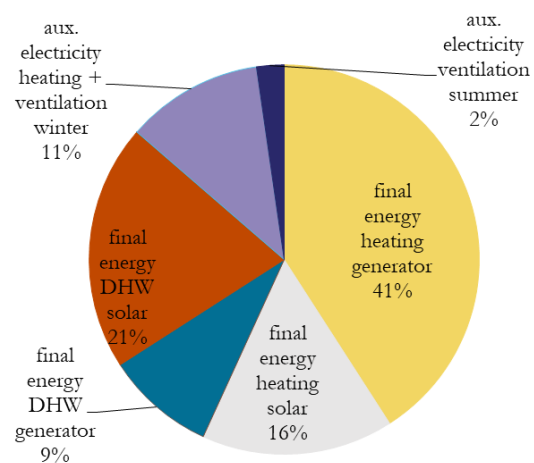
Figure 37: Final energy demand for heating, DHW, cooling and ventilation in the variant with the highest NPV (left) and lowest NPV (right) of the case study Solallén
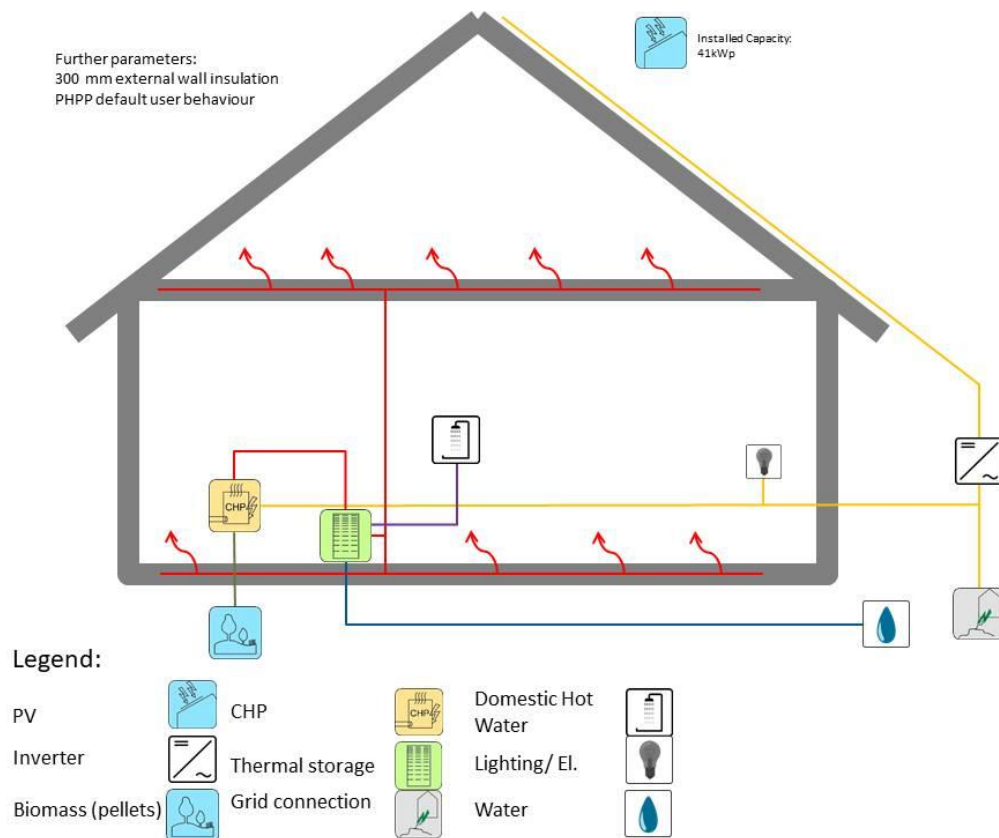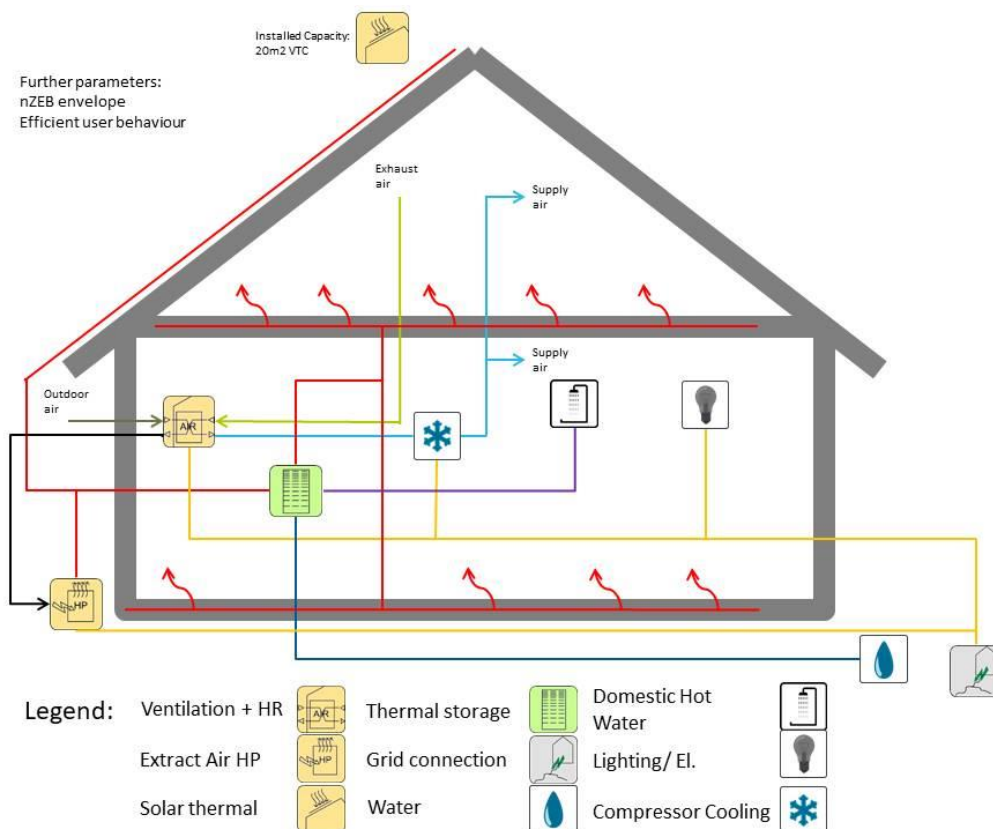

Figure 38: Visualisation of technology set of Solallén; variant with lowest NPV

Lowest and highest CO₂ emissions

The basic characteristics of the variants with the highest and lowest CO_2 emissions are summarized in Table 19. The balanced CO_2 emissions of the variant with the highest CO_2 emissions are 64.25 $kg_{CO2}/(m^2a)$ and of the variant with the low-est emissions 9.87 $kg_{CO2}/(m^2a)$. The variant with the highest emissions also has a higher NPV. The main differences of the two variants are the thickness of the insulation of the envelope, the type of ventilation, the installation of PV and solar thermal as well as the type of heat generation. In the variant

with the highest CO_2 emissions, there is no PV or solar thermal system installed.

The relevant factors for the low CO_2 emissions are efficient user behaviour, a highly efficient envelope, the use of district heating and the installation of a large PV and solar thermal system. The installed PV system in the variant with the lowest emissions has a capacity of 20 kWp generating 13,930 kWh/a. The total cost for the system is 190,000 € for all seven buildings (1,360 €/kWp; excluding labour cost). In addition to PV solar thermal collectors with a total area of 20 m² (vacuum tube) with total cost of 42,840 € (excluding labour) are installed. The final energy demand for heating of the variant is 23 kWh/(m²a). For the variant with the highest

emissions the final energy demand for heating is 70 kWh/(m²a). The share of heating, DHW, cooling and ventilation in the final energy demand of both variants is shown in Figure 39. Like above, space heating is dominating especially in the case with the highest CO_2 emissions. Reasons are on the hand the inefficient user behaviour, on the other hand the poorer quality of the building envelope.

The NPV of the variant with the highest CO_2 emissions is 3,362 €/m² and of the variant with the lowest emissions 3,162 €/m². In Figure 40 the technology set of the variant with the lowest CO_2 emissions is shown visualising the major technologies for realising a low cost nZEB.

Table 19: Variants with the highest and lowest CO₂ emissions of the case study Solallén based on WP06

Variable	Highest CO$_2$	Lowest CO$_2$
Variant number	1010	30091
Sensitivity (Energy price increase)	High	Low
User behaviour	Not efficient	Efficient
Envelope	nZEB: Floor slab: 300mm insulation Exterior walls: 455 mm insulation Roof: 600 mm insulation	Passive house: Floor slab: 400 mm insulation Exterior walls: 600 mm insulation Roof: 750 mm insulation
WinDoorAir	National standard	Passive house
Ventilation	Mechanical ventilation unit; heat recovery efficiency 80 %; SFP: 1.75	Mechanical ventilation unit; heat recovery efficiency 90 %; SFP: 1.25
Heating	Extract air heat pump kW: 1.8 SCOP: 2.5	District heating kW: ∞ SCOP: 1.0
Cooling	Compressor cooling 3 kW SCOP: 3	Compressor cooling 3 kW SCOP: 3
Solar thermal	No solar thermal	20 m², vacuum tubes used for DHW and heating
PV	No PV	120 m²; 20 kWp
Net present value	**3,362 €/m²**	**3,162 €/m²**
Balanced CO₂ emissions	**64.25 kg$_{CO2}$/(m²a)**	**9.87 kg$_{CO2}$/(m²a)**

Final energy demand highest CO$_2$ emissions
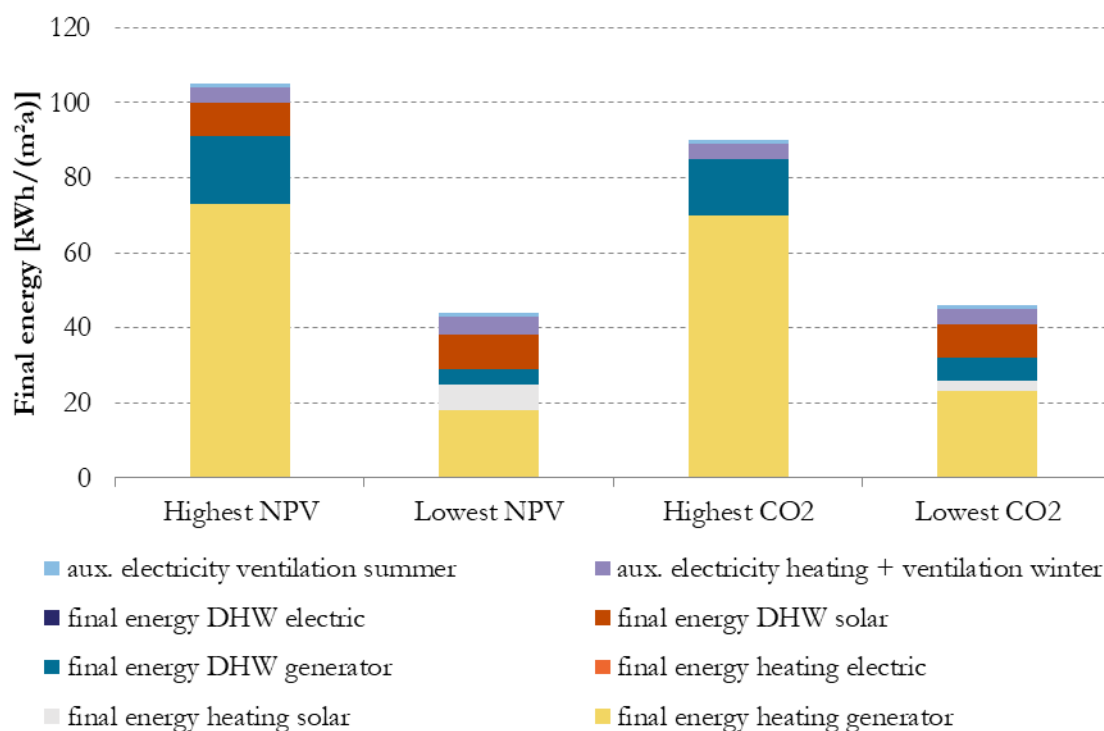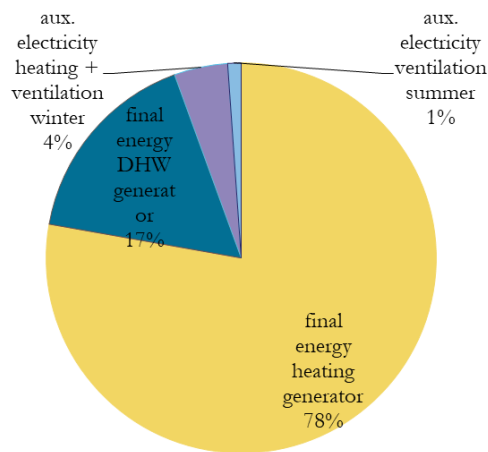

Final energy demand lowest CO$_2$ emissions

Figure 39: Final energy demand for heating, DHW, cooling and ventilation in the variant with the highest (left) and lowest CO$_2$ emissions (right) of the case study Solallén
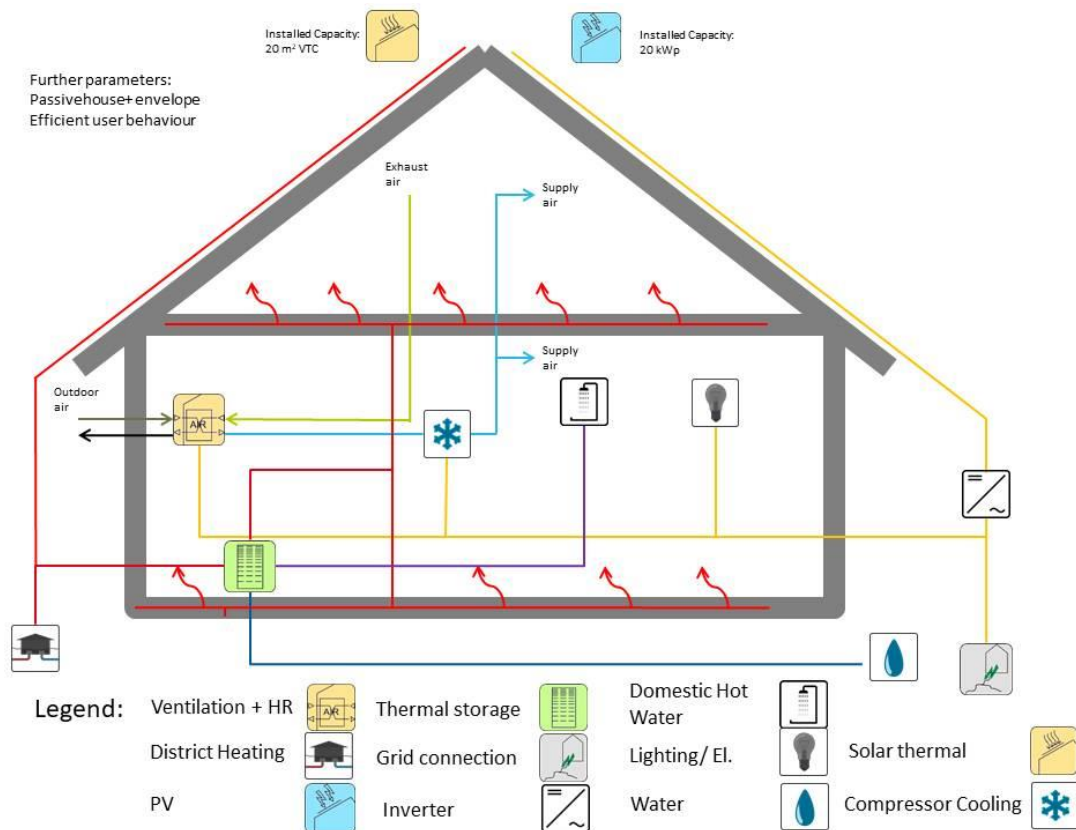
Figure 40: Visualisation of technology set of Solallén; variant with lowest CO$_2$-emissions

Potential best cases

In Table 20 potential best cases are summarized. These variants have both comparably low CO$_2$ emissions and costs (NPVs). The balanced CO$_2$ emissions of the variants are between 13.38 kg$_{CO2}$/(m²a) and 14.46 kg$_{CO2}$/(m²a) and thereby bout 45 % higher than the variant with the lowest emissions. The NPV of all variants is between 2,715 and 2,736 €/m², which is only slightly higher than in the variant with the lowest NPV. In

Table 20 only the differences between the variants are listed. The following parameters are the same for all variants:

- Low price increase for energy carriers
- Efficient user behaviour
- nZEB envelope
- District heating
- Compressor cooling
- No solar thermal
- No PV

The low emissions are mainly a result of the use of district heating with low emission factors. Ventilation is realised with a mechanical ventilation system with heat recovery. The efficiency of the system and the heat recovery rate differs. Besides differences in the ventilation systems, the variants differ in the quality of the envelope with regard to the airtightness and the quality of the windows (WinDoorAir).

Table 20: Variants with low CO_2 emissions and comparably low costs of the case study Solallén based on WP06. The shown variable number is based on the results matrix of the parametric analysis and is equivalent to the number of the variant in the interactive case study dashboard in CRAVEzero-pinboard.

Variant Number	12098	12099	11907	12162	12163
WinDoorAir	nZEB	National standard	nZEB	nZEB	Passive house
Ventilation	Mechanical ventilation unit; heat recovery efficiency 80 %; SFP: 1.75	Mechanical ventilation unit; heat recovery efficiency 85 %; SFP: 1.5	Mechanical ventilation unit; heat recovery efficiency 85 %; SFP: 1.5	Mechanical ventilation unit; heat recovery efficiency 90 %; SFP: 1.25	Mechanical ventilation unit; heat recovery efficiency 90 %; SFP: 1.25
NPV [€/m²]	2,715	2,720	2,720	2,725	2,736
CO_2 emissions [$kg_{CO_2}/(m^2a)$]	14.44	14.46	14.06	13.69	13.38

5.3.3. ASPERN IQ

5.3.3.1. BASE CASE

The following description of the case study is based on deliverable D6.2 (Venus et al., 2019).

Aspern IQ is located in Vienna's newly developed urban lakeside area "Aspern" – Austria's largest urban development project and one of the largest in Europe. The building was designed in line with Plus Energy standards and is conceived as a flagship project which shows the approach to create a **Plus Energy building** adapted to **locally available materials** and which offers the highest possible level of user comfort while meeting the demands of sustainability. The Technology Centre with a net floor area of 8,817 m² received a maximum number of points in its klimaaktiv declaration and had also

been awarded an ÖGNB Building Quality Certificate.

The energy demand of the building has actively been lowered by measures in the design of the building form (**compactness**), **orientation** and **envelope quality**.

A **balanced glazing percentage** (window-to-wall ratio of 50 %) and the **highly insulated thermal envelope** in passive house standard are the basis for the high performance of the building. The opaque envelope elements facing the ambient have very low U-values of 0.11 – 0.16 W/(m²K). Also the windows have a comparably low U-value of 0.91 – 0.96 W/(m²K). Furthermore, optimized details for reduced thermal bridges and an airtight

envelope (Blower Door Test=0.4 1/h) beating the Austrian building regulation OIB guideline 6 by 55 % reduce the energy demand of the building.

Heat is supplied by an **air-water heat pump** and from a **district heating** network.

To avoid overheating and guarantee high thermal comfort in summer several strategies are combined in the building. Essential are **external shading** strategies, which allow solar gains during the heating season in winter and avoid them during summer. This is achieved by external shading elements, which are also equipped with **PV panels**, and **plants**, which grow in summer and are cut in autumn/ winter. The remaining cooling demand is supplied by **panel cooling** and **supply air cooling** (254 kW). The panel cooling achieves a seasonal performance factor of 21.4.

PV panels are installed on the flat roofs and at the façade of the building. The capacity on the roof is 87 kWp and in the façade 61 kWp. The PV systems together generate more than 128 MWh/a (planned).
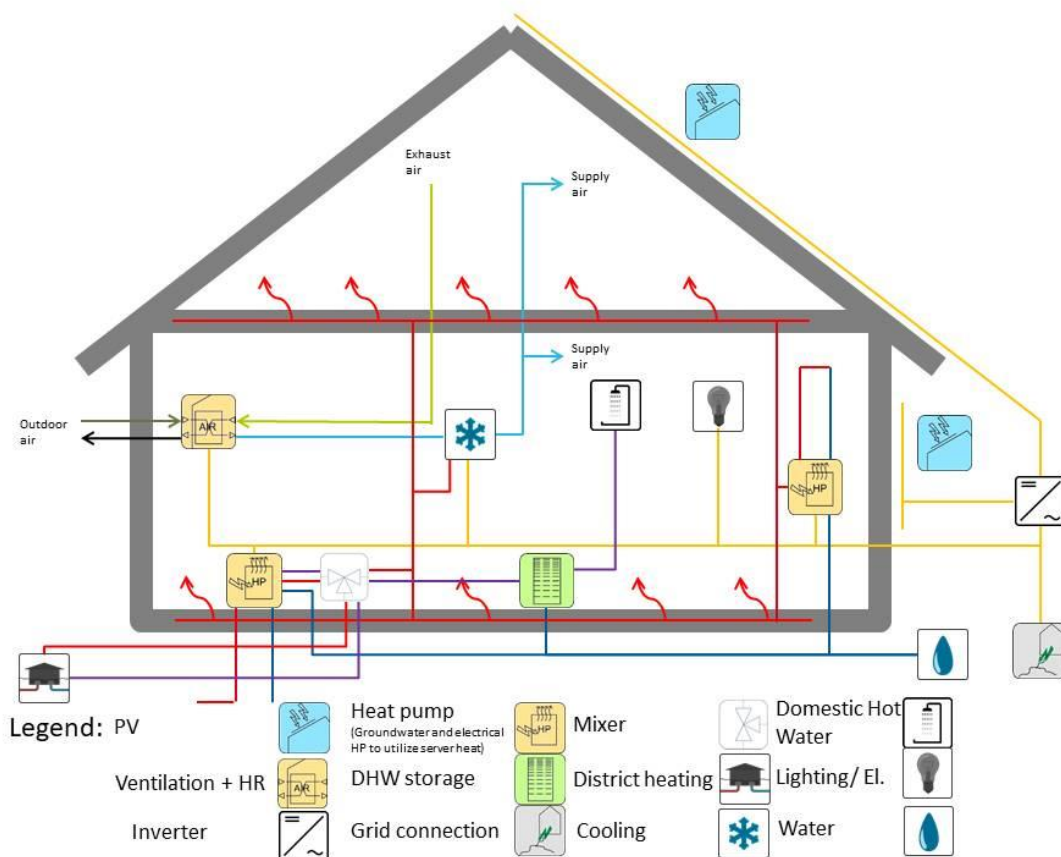
Figure 41: Visualisation of technology set of the case study Aspern IQ

5.3.3.2. LOW-ENERGY AND LOW-COST TECHNOLOGY SETS

The results presented in (Venus et al., 2019) show that in the variants with a NPV below 3,000 €/m² a building envelope according to national standard or maximum nZEB standard are dominating. Furthermore, in these variants ventilation is realised by window ventilation. The dominating heating technology is ground source heat pump and the dominating cooling technology a reversible air heat pump (in the variants with costs below 2,900 €/m² ground source heat pump for cooling is dominating). These variants have CO_2 emissions between 16.32 and 39.77 $kg_{CO2}/(m²a)$.

The highest emissions occur in the variants without PV and solar thermal systems and inefficient user behaviour. The lowest emissions are achieved in variants with large PV and solar thermal systems, which are the dominating factors in the case study. The heating technologies associated with the lowest emissions are district heating and ground source heat pump.

In Figure 42 the final energy demand for heating DHW, cooling and ventilation of the variants with highest and lowest NPV and CO_2 emissions is shown. It can be seen that space heating is dominating the final energy demand in all cases followed by DHW. In some cases, mechanical ventilation also plays an important role. How the needed energy is provided and what the major differences are is described in the following.
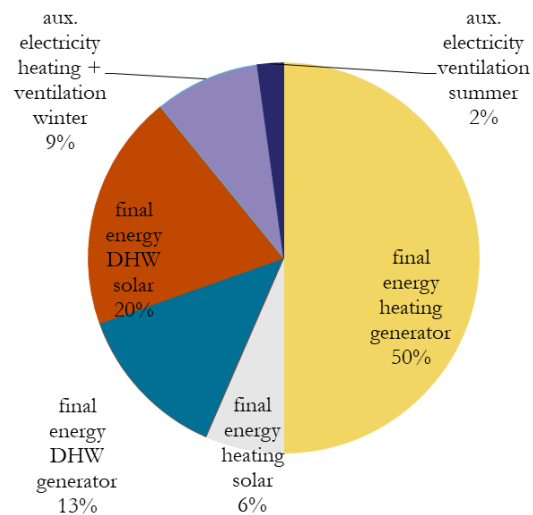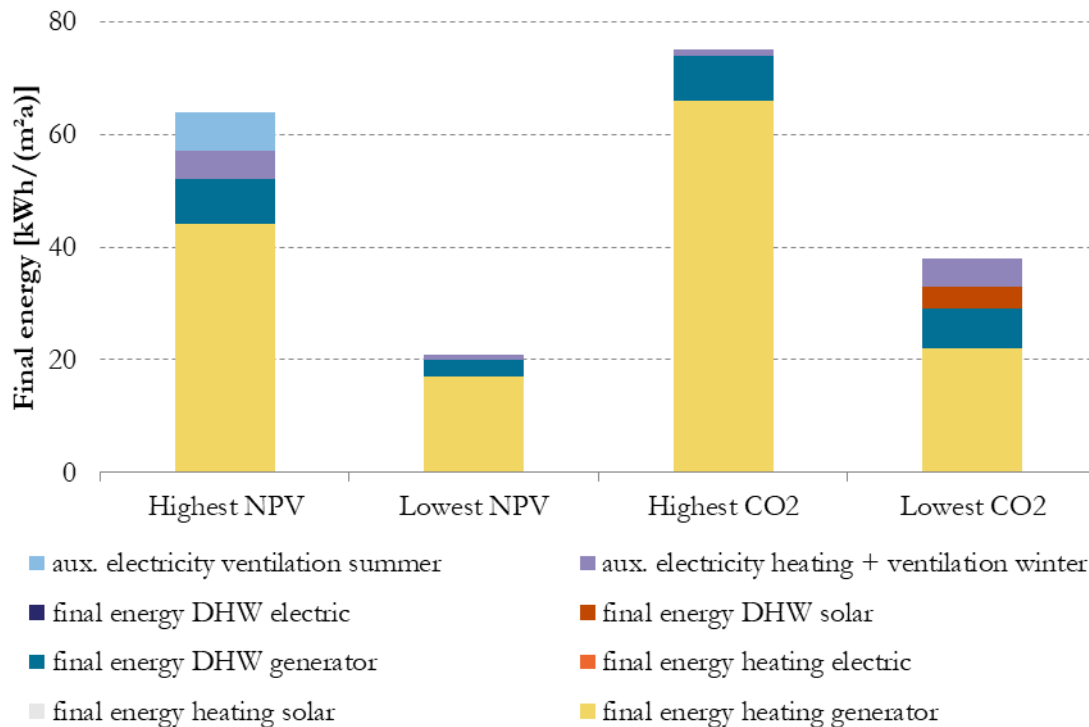

Figure 42: Final energy demand for heating, DHW, cooling and ventilation in the variants with the highest and lowest NPV and CO_2 emissions of the case study Aspern IQ

Lowest and highest NPV

The basic characteristics of the variants with the highest and lowest NPV are summarized in Table 21. General differences of the two variants are the CO_2 follow-up costs and user behaviour. Concerning HVAC and other technical systems the differences are the installation of mechanical ventilation, the heat and cold generation as well as the installation of battery storage. For the ventilation system additional investments in the variant with highest NPV compared to the one with the lowest NPV is about 480,000 €. The cost difference for the heating system is 111,000 € (total cost ground source heat pump including water well: 303,000 € vs. total cost air source heat pump: 192,000 €). The costs for the heating system do include the costs for cooling as

the heat pumps are also used for cooling purposes (reversible heat pumps).

The heating demand in the variant with the highest NPV is 69 kWh/(m²a) and in the variant with the lowest NPV 64 kWh/(m²a). The share of heating, DHW, cooling and ventilation in the final energy demand of both variants is shown in Figure 43. Most energy is needed for heating followed by DHW. The balanced CO_2 emissions of the variant with the highest NPV are 44.60 kg_{CO2}/(m²a) and of the variant with the lowest NPV 20.99 kg_{CO2}/(m²a). This shows that buildings with low CO_2 emissions are possible with lower life cycle costs. Essential is efficient user behaviour. In Figure 44 the technology set of the variant with the lowest NPV is shown visualising the major technologies for realising a low cost nZEB.

Table 21: Variants with the highest and lowest net present value (NPV) of the case study Aspern IQ based on WP06; values for variables based on (Venus et al., 2019)

Variables	Highest NPV	Lowest NPV
Variant number	23817	43849
Sensitivity (Energy price increase)	Standard	Standard
CO_2 follow-up costs	High	No
User behaviour	Not efficient	PHPP default
Envelope	National Standard: Floor slab: 0.4 W/(m²K) (earth touched); 0.2 W/(m²K) (outdoor air) Exterior walls: 0.35 W/(m²K) Roof: 0.2 W/(m²K)	National Standard: Floor slab: 0.4 W/(m²K) (earth touched); 0.2 W/(m²K) (outdoor air) Exterior walls: 0.35 W/(m²K) Roof: 0.2 W/(m²K)
Ventilation	Mechanical Ventilation with heat recovery; electric efficiency 0.153 Wh/m³	Window ventilation
Heating	Air source heat pump: 205 kW / COP 4.5	Ground source heat pump: 240 kW / COP 5.8
Climate	Vienna	Vienna
Cooling	Absorption cooling	Ground source heat pump cooling
Solar thermal	No solar thermal	No solar thermal
PV	No PV	No PV
Battery	Capacity 50 kWh	No Battery
Net present value	**3,671 €/m²**	**2,854 €/m²**
Balanced CO_2 emissions	**44.60 kg$_{CO2}$/(m²a)**	**20.99 kg$_{CO2}$/(m²a)**

Final energy demand highest NPV
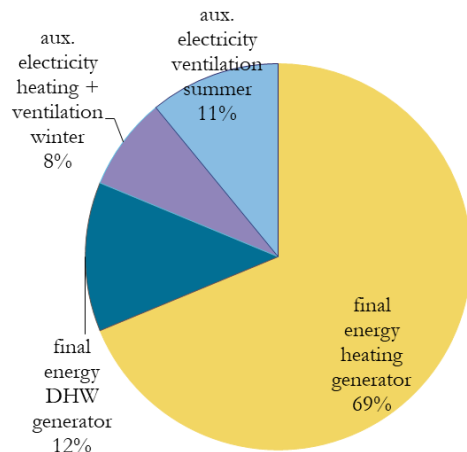
Final energy demand lowest NPV
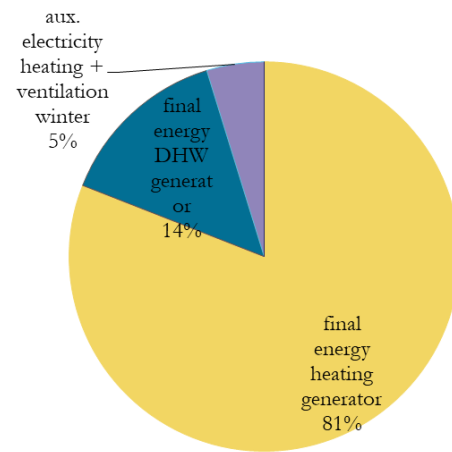
Figure 43: Final energy demand for heating, DHW, cooling and ventilation in the variant with the highest NPV (left) and lowest NPV (right) of the case study Aspern IQ
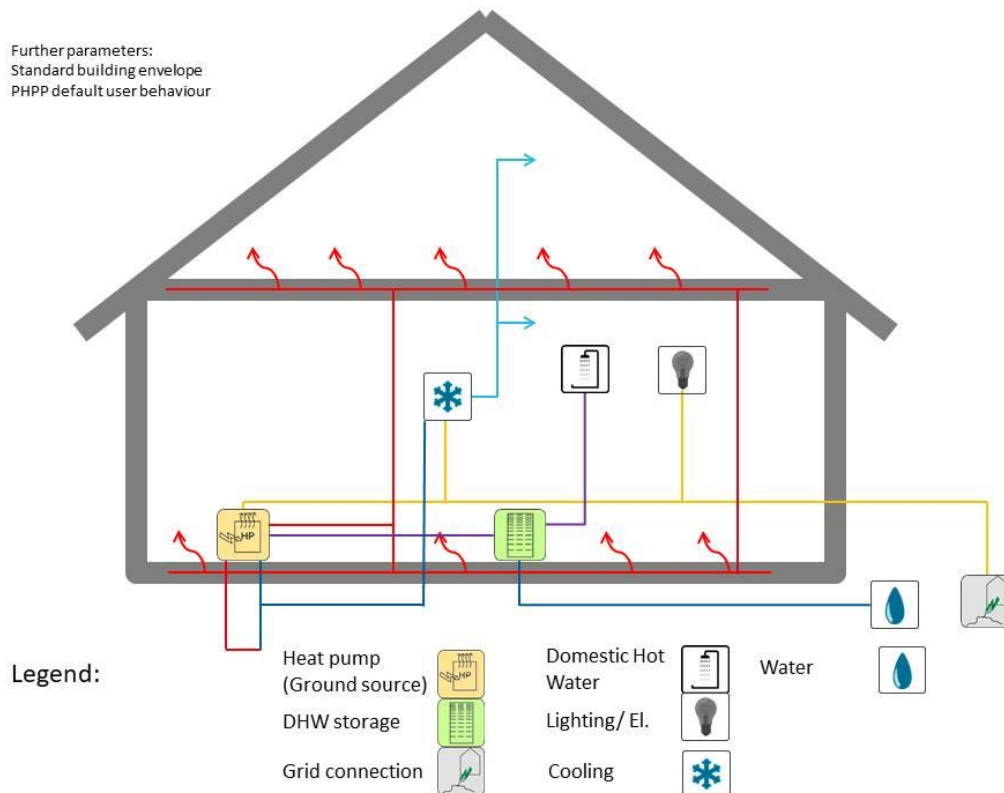
Figure 44: Visualisation of technology set of Aspern IQ; variant with lowest NPV

Lowest and highest CO₂ emissions

The basic characteristics of the variants with the highest and lowest CO_2 emissions are summarized in Table 22. The balanced CO_2 emissions of the variant with the highest CO_2 emissions are 50.27 $kg_{CO2}/(m^2a)$ and of the variant with the lowest emissions 10.99 $kg_{CO2}/(m^2a)$. The main differences of the two variants are the envelope quality, the type of ventilation and the type of heat and cold generation. Furthermore, the installation of PV and solar thermal systems are essential for achieving very low emissions. In the variant with the highest CO_2 emissions, the envelope is built according to national standard and in the variant with low emissions a nZEB envelope is realised. The cost difference of the insulation between the variants is 26.1 €/m² (external wall), 2.2 €/m² (floor), 28.3 €/m² and 69 €/m² (windows).

Ventilation is realised by window ventilation in the variant with high emissions and in the case of low emissions mechanical ventilation with heat recovery is installed. The cost for the ventilation system is 480,000 €.

The cost difference for the heating system is 48,000 € (total cost district heating: 240,000 € vs. total cost air source heat pump: 192,000 €).

The relevant factors for the low CO_2 emissions are efficient user behaviour (PHPP default vs. not efficient), the installation of a large PV and solar thermal system and the connection to the district heating network. The installed PV system has a capacity of 148 kWp with a calculated generation of approx. 128,260 kWh/a. The total cost for the system is 646,800 € (4,370 €/kWp including inverter and additional costs). Besides PV, a solar thermal system with 80 m² flat plate collectors for DHW preparation is installed in the variant with the lowest CO_2 emissions. The overall cost of the system is 76,960 €, including storage and other associated costs.

The average heating demand of the low emission variant is 21 kWh/(m²a) and in the high emission variant 102 kWh/(m²a). It has to be mentioned that a heating demand of 102 kWh/(m²a) would not be allowed by Austrian law. According to (Venus et al., 2020), national legal requirements are not taken into

account in the calculation and analysis of variants. Taking national requirement into account would have required using calculation tools according to national law. The share of heating, DHW, cooling and ventilation in the final energy demand of both variants is shown in Figure 45. It can be seen that space heating is the dominating factor in the building. However, an improved envelope, efficient user behaviour and ventilation with heat recovery decreases the share of space heating in the variant with the lowest emissions compared with the high emission variant.

The NPV of the variant with the highest CO_2 emissions is 3,590 €/m² and of the variant with the lowest emissions 3,334 €/m² and therefore lower than the costs for the high emission variant. In Figure 46 the technology set of the variant with the lowest CO_2 emissions is shown visualising the major technologies for realising a low-cost nZEB.

Table 22: Variants with the highest and lowest CO_2 emissions of the case study Aspern IQ based on WP06

Variable	Highest CO$_2$	Lowest CO$_2$
Variant number	23493	45360
Sensitivity (Energy price increase)	Standard	Standard
CO$_2$ follow-up costs	High	No
User behaviour	Not efficient	PHPP default
Envelope	National Standard: Floor slab: 0.4 W/(m²K) (earth touched); 0.2 W/(m²K) (outdoor air) Exterior walls: 0.35 W/(m²K) Roof: 0.2 W/(m²K)	nZEB (as built): Floor slab: 0.16 W/(m²K) Exterior walls: 0.15 W/(m²K) Roof: 0.112 W/(m²K)
Ventilation	Window ventilation	Mechanical Ventilation with heat recovery; electric efficiency 0.153 Wh/m³
Heating	Air source heat pump: 205 kW / COP 4.5	District Heating
Climate	Vienna	Vienna
Cooling	Absorption cooling	Air source heat pump cooling
Solar thermal	No solar thermal	80 m² flat plate collectors for DHW
PV	No PV	Capacity 148 kWp
	Capacity 50 kWh	Capacity 50 kWh
Net present value	**3,590 €/m²**	**3,334 €/m²**
Balanced CO$_2$ emissions	**50.27 kg$_{CO2}$/(m²a)**	**10.99 kg$_{CO2}$/(m²a)**

Final energy demand highest CO_2 emissions

final energy DHW generator 11%

aux. electricity heating + ventilation winter 1%

final energy heating generator 88%

Final energy demand lowest CO_2 emissions

aux. electricity heating + ventilation winter 13%

final energy DHW solar 11%

final energy DHW generator 18%

final energy heating generator 58%
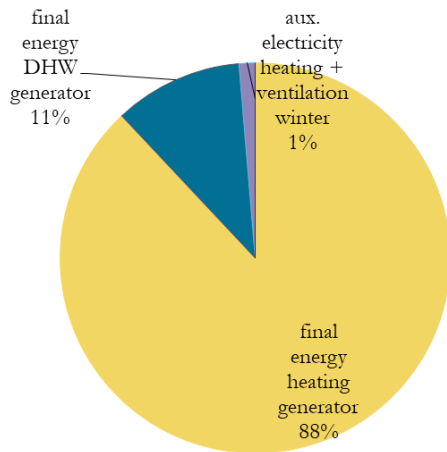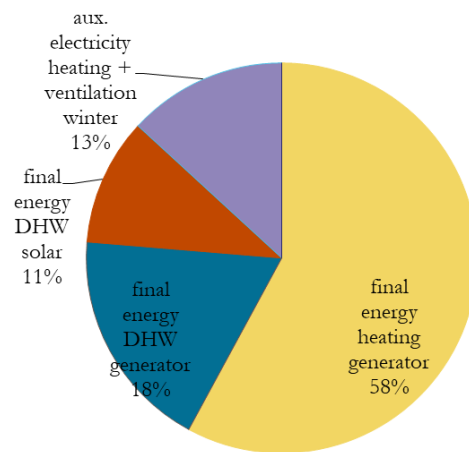
Figure 45: Final energy demand for heating, DHW, cooling and ventilation in the variant with the highest (left) and lowest CO_2 emissions (right) of the case study Aspern IQ
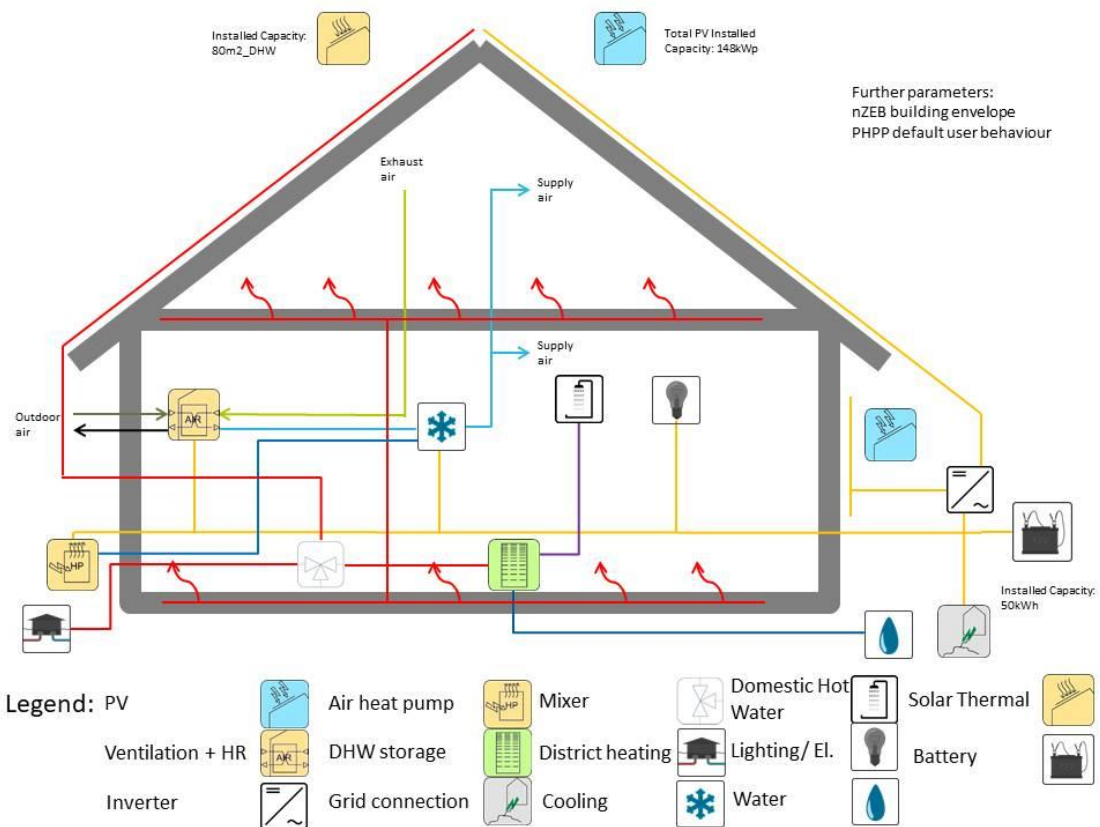
Figure 46: Visualisation of technology set of Aspern IQ; variant with lowest CO_2-emissions

Potential best cases

In Table 23, potential best cases are summarized. These variants have both comparably low CO_2 emissions and costs (NPVs). The balanced CO_2 emissions of the variants are between 14.76 and 17.32 $kg_{CO2}/(m^2 a)$. The NPV of all variants is between 2,855 and 2,882 €/m².

In Table 23 only the differences between the variants are listed. The following parameters are the same for all variants:

- Standard price increase for energy carriers
- No CO_2 follow-up costs
- Efficient user behaviour (PHPP)
- Envelope according to national standard
- Window ventilation
- Heating with ground source heat pump
- Climate: Vienna

- Cooling: Ground source heat pump cooling

The installation of a PV system is essential for realising low costs and low emissions. In some cases, an additional solar thermal system is installed. The differences between the variants are the installation of a solar thermal system, battery and the size and efficiency of the PV system (74 vs. 148 kWp).

Table 23: Variants with low CO_2 emissions and comparably low costs of the case study Aspern IQ based on WP06. The shown variable number is based on the results matrix of the parametric analysis and is equivalent to the number of the variant in the interactive case study dashboard in CRAVEzero-pinboard.

Variant Number	12098	12099	11907	12162	12163
Solar thermal	No solar thermal	No solar thermal	28 m² flat plate collectors for DHW	No solar thermal	28 m² flat plate collectors for DHW
PV	Capacity 74 kWp	Capacity 74 kWp	Capacity 74 kWp	Capacity 148 kWp	Capacity 148 kWp
Battery	No Battery	Capacity 25 kWh	Capacity 50 kWh	No Battery	Capacity 50 kWh
NPV [€/m²]	2,855	2,859	2,867	2,871	2,882
CO_2 emissions [$kg_{CO2}/(m^2a)$]	17.32	16.83	16.30	15.97	14.76

5.3.4. ISOLA NEL VERDE

5.3.4.1. BASE CASE

The following description of the case study is based on deliverable D6.2 (Venus et al., 2019).

The complex consists of two multifamily buildings, A and B, with a total net floor area of 3,154 m² and is located in Milano, Italy. The two buildings were constructed in 2012. The energy system is comparably complex combining different heating and renewable technologies. The average U-values are 0.49 W/(m²K) (building A) and 0.46 W/(m²K) (building B). In building A, the average U-value of the external walls is 0.24 W/(m²K). The roof and the floor slab/ basement ceiling have comparable U-values of 0.25 W/(m²K) and 0.24 W/(m²K) respectively. The windows have the highest U-values of all envelope elements (approx. 1.2 W/(m²K)). In building B the average U-value of the external walls is 0.24 W/(m²K), of the roof 0.28 W/(m²K) and of the floor slab 0.32 W/(m²K) respectively. The windows also have a U-value of approx. 1.2 W/(m²K). Beside the insulation of the roofs, they are also greened (**green roof**), which potentially also reduces the cooling demand of the buildings (effect is not visible in the calculations).

The apartments are heated by **radiant floor panels** with a supply temperature of 55°C. The conditioning is supplied by a **fan coil plant** with a supply temperature of 6°C (return flow temperature 12°C). Cooling is supplied by a **geothermal heat pump** with a maximum cooling capacity of 79.9 kW and a seasonal energy efficiency ratio of 3.6. The probes have a length of 20 m (depth of each borehole is 10 m) and there is a spacing/ distance between the probes of 10 m.

The **geothermal heat pump** is also used for heating and domestic hot water preparation (priority DHW). The heat pump provides 87 – 89 % of

heating and 70 – 72 % of DHW. The priority of DHW preparation of the heat pump leads to a comparably low seasonal performance factor of 1.4. Besides geothermal heat, **photovoltaic and solar thermal pane**ls as additional renewable energies are integrated in the system. The solar thermal collectors have a total area of 36 m² providing 8 – 10 % of the heating and domestic hot water demand. The PV systems on the buildings have an overall peak capacity of 7 kW_p.

In addition to the renewable energy technologies, a **CHP** plant for providing heat and electricity is installed in the building. The plant has an electrical efficiency of 29 % and a thermal efficiency of 66 %. Furthermore, a **hot water storage** with a volume of 4 m³ for heating and DHW as well as a DHW storage with a volume of 1.5 m³ are integrated in the system. Good air quality is assured by decentralised **mechanical extract air units** with a specific power input of 0.45 Wh/m³.
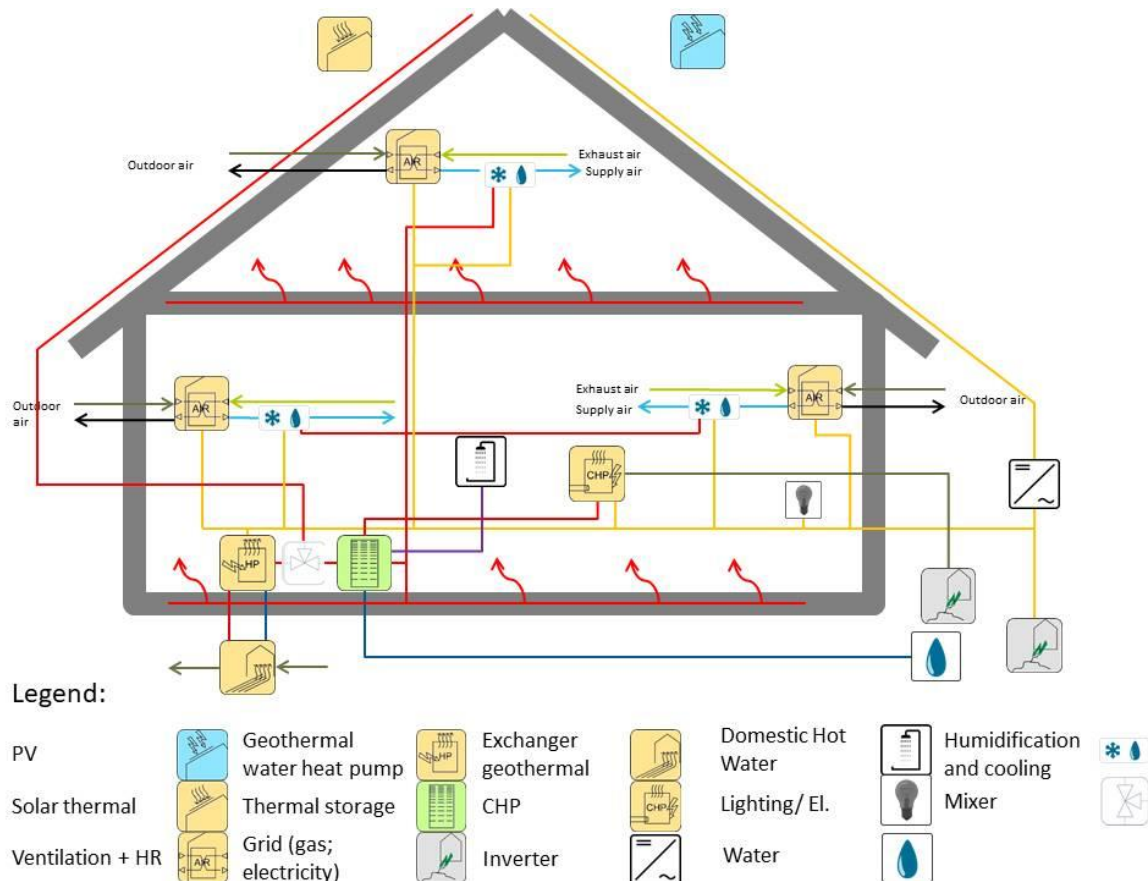
Figure 47: Visualisation of technology set of the case study Isola Nel Verde

5.3.4.2. LOW-ENERGY AND LOW-COST TECHNOLOGY SETS

The results presented in (Venus et al., 2019) show that among all calculated variants the ones without a PV and solar thermal system as well as inefficient user behaviour have the highest CO_2 emissions. The lowest emissions are achieved with large PV and solar thermal systems and with heat supply from ground source heat pump and/ or district heating combined with efficient user behaviour.

The variants with a net present value of above 3,500 €/m² are all equipped with a ground source heat pump and are connected with a district heating network. Furthermore, most of these variants have a passive house envelope, mechanical ventilation with heat recovery, a large solar thermal system and an air source heat pump for cooling. Almost 50 % of the variants with a high NPV do not have a PV system installed. The CO_2 emissions of the variants with the highest NPVs are between 24 and 33 $kg_{CO2}/(m^2a)$.

In Figure 48 the final energy demand for heating DHW, cooling and ventilation of the variants with highest and lowest NPV and CO_2 emissions is

shown. It can be seen that DHW preparation is dominating the final energy demand in the cases with the lowest NPV and highest CO_2 emissions, followed by DHW. In the variants with a high NPV and low emissions DHW preparation is dominating the final energy demand. Mechanical ventilation only plays a minor role with respect to energy demand. How the needed energy is provided and what the major differences are is described in the following.

Figure 48: Final energy demand for heating, DHW, cooling and ventilation in the variants with the highest and lowest NPV and CO₂ emissions of the case study Isola Nel Verde

Lowest and highest NPV

The basic characteristics of the variants with the highest and lowest NPV are summarized in Table 24. The main differences of the two variants are the envelope quality, the type of ventilation, heat and cold generation as well as the use of solar energy (solar thermal and PV). In the variant with the highest NPV a passive house envelope is realised and in the variant with the lowest NPV a nZEB envelope (as built). The cost of ventilation system with heat recovery is about 56,000 €. The major cost difference between the variants is associated with the heating and use of solar energy as well as cold generation. The heating system in the variant with the highest NPV is 414,577 € more expensive than in the variant with the lowest NPV. The cost difference for cold generation between the variants is 18,000 €. For using solar energy, the costs are 28,800 € in the highest NPV variant (solar thermal

collectors) and 20,800 € in the lowest NPV variant (PV).

The average heating demand in the highest NPV variant is 38 kWh/(m²a) and in the lowest NPV 46 kWh/(m²a) (final energy demand for heating is 6 kWh/(m²a) vs. 48 kWh/(m²a)). The share of heating, DHW, cooling and ventilation in the final energy demand of both variants is shown in Figure 49. Most energy is needed for DHW followed by heating in the high NPV variant. In the variant with the lowest NPV the shares are different. Here final energy demand for heating is dominating followed by DHW. The balanced CO_2 emissions of the variant with the highest NPV are 28.62 kg$_{CO2}$/(m²a) and of the variant with the lowest NPV 24.71 kg$_{CO2}$/(m²a). Also in this case study it can be seen that higher life cycle costs do not necessarily lower the CO_2 emissions and that a highly efficient and low emission building is possible with lower

costs. In Figure 50 the technology set of the variant with the lowest NPV is shown visualising the major technologies for realising a low cost nZEB.

Table 24: Variants with the highest and lowest net present value (NPV) of the case study Isola Nel Verde based on WP06; values for variables based on (Venus et al., 2019)

Variables	Highest NPV	Lowest NPV
Variant number	28024	61644
Sensitivity (Energy price increase)	High	PHPP
CO_2 follow-up costs	No	No
Envelope	Passive house: Floor slab: 0.15 W/(m²K) Exterior walls: 0.15 W/(m²K) Roof: 0.15 W/(m²K)	nZEB (as built): Floor slab: 0.25 – 0.32 W/(m²K) Exterior walls: 0.24 – 0.25 W/(m²K) Roof: 0.24 – 0.28 W/(m²K)
Ventilation	Mechanical Ventilation with heat recovery; electric efficiency 0.48 Wh/m³; heat recovery rate 83 %	Window ventilation
Heating	Geothermal heat pump + district heating: Heat pump: 86.82 kW / COP 4.38	District Heating
Climate	Milano	Milano
Cooling	Air source heat pump cooling	Compressor cooling
Solar thermal	72 m² flat plate collectors for DHW	No solar thermal
PV	No PV	Capacity: 14 kWp
Net present value	**3,691 €/m²**	**2,743 €/m²**
Balanced CO_2 emissions	**28.62 kg$_{CO2}$/(m²a)**	**24.71 kg$_{CO2}$/(m²a)**

Final energy demand highest NPV

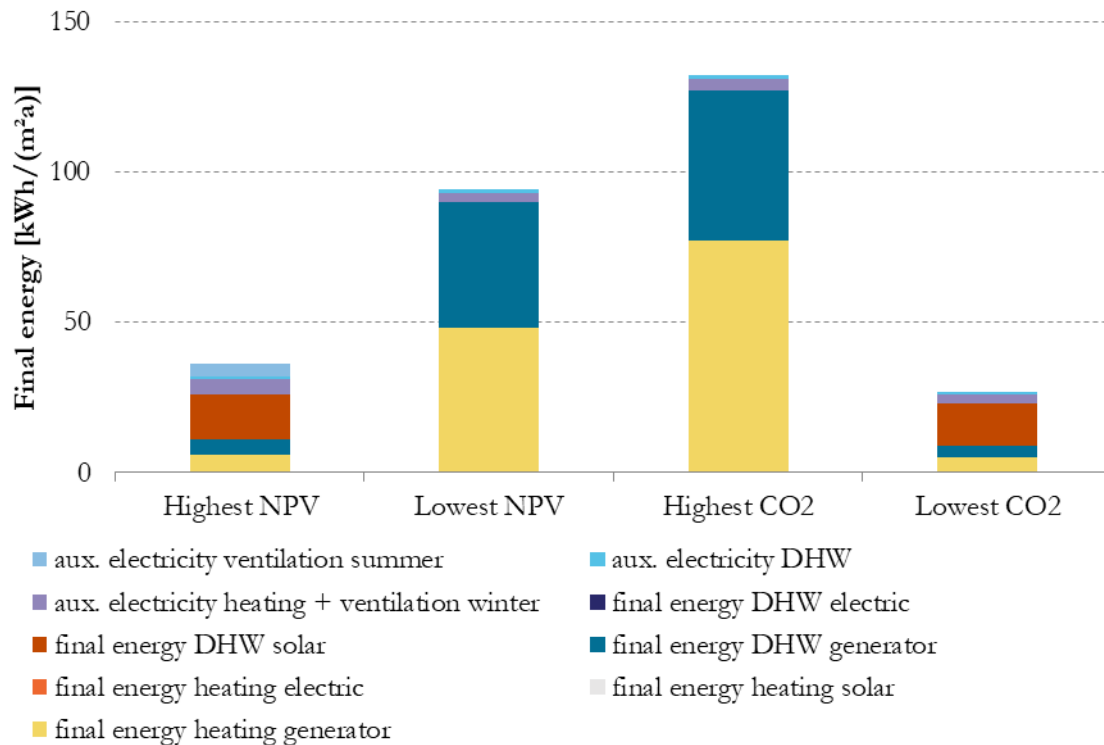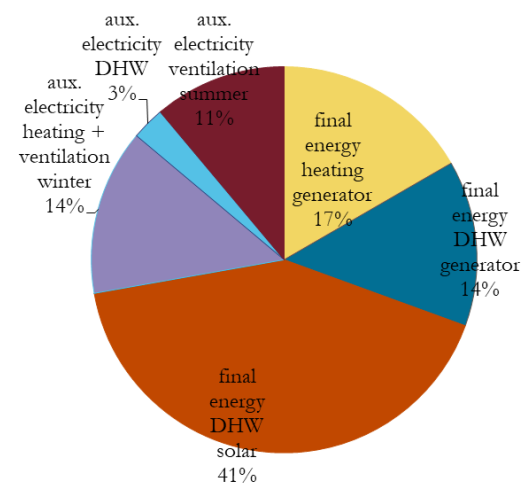Final energy demand lowest NPV
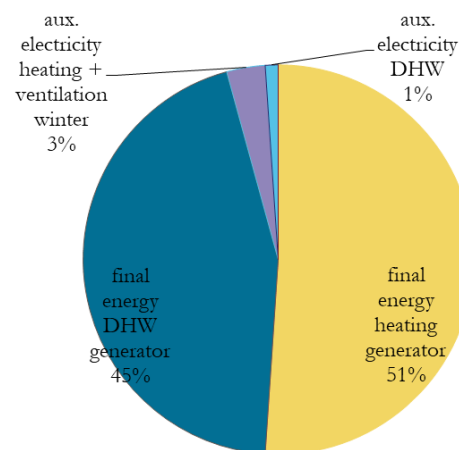
Figure 49: Final energy demand for heating, DHW, cooling and ventilation in the variant with the highest NPV (left) and lowest NPV (right) of the case study Isola Nel Verde

Figure 50: Visualisation of technology set of Isola Nel Verde; variant with lowest NPV

Lowest and highest CO₂ emissions

The basic characteristics of the variants with the highest and lowest CO_2 emissions are summarized in Table 25. The balanced CO_2 emissions of the variant with the highest emissions are 49.74 $kg_{CO2}/(m^2a)$ and of the variant with the lowest emissions 18.74 $kg_{CO2}/(m^2a)$. The main differences between the two variants are the envelope quality, the type of heat and cold generation and the use of solar energy. In the variant with the highest CO_2 emissions the envelope is built according to national standards, whereas the envelope in the variant with low emissions is a passive house envelope. The cost difference for the envelope is with less than 70,000 € comparably low. The cost difference for the heating system is more than 450,000 € and therefore a dominant factor for the upfront investment costs.

The relevant factors for the low CO_2 emissions are the installation of a large PV and large solar thermal system as well as the use of geothermal and district heat. The installed PV system has a capacity of 14 kWp generating 14,510 kWh/a. The total cost for the system is 20,800 € (1,486 €/kWp). The costs for the solar thermal collectors are 28,800 €.

The heating demand in the highest emission variant is 78 kWh/(m²a) and in the lowest emission 31 kWh/(m²a) (final energy demand for heating is 77 kWh/(m²a) vs. 5 kWh/(m²a)). The share of heating, DHW, cooling and ventilation in the final energy demand of both variants is shown in Figure 51. In the low emission variant, DHW is the dominating factor is the heating demand is minimized by a good thermal envelope and an efficient heating technology.

The NPV of the variant with the highest CO_2 emissions is 3,206 €/m² and of the variant with the lowest emissions 3,281 €/m². In Figure 52 the technology set of the variant with the lowest CO_2 emissions is shown visualising the major technologies for realising a low cost nZEB.

Table 25: Variants with the highest and lowest CO₂ emissions of the case study Isola Nel Verde based on WP06

| Variable	Highest CO$_2$	Lowest CO$_2$
Variant number	27235	61929
Sensitivity (Energy price increase)	High	PHPP
CO$_2$ follow-up costs	No	No
Envelope	National Standard: Floor slab: 0.26 W/(m²K) Exterior walls: 0.26 W/(m²K) Roof: 0.22 W/(m²K)	Passive house: Floor slab: 0.15 W/(m²K) Exterior walls: 0.15 W/(m²K) Roof: 0.15 W/(m²K)
Ventilation	Window ventilation	Window ventilation
Heating	Gas condensing boiler: 85 kW / η = 102 %	Geothermal heat pump + district heating: Heat pump: 86.82 kW / COP 4.38
Climate	Milano	Milano
Cooling	Air source heat pump cooling	Ground source heat pump cooling
Solar thermal	No solar thermal	72 m² flat plate collectors for DHW
PV	No PV	Capacity: 14 kWp
Net present value	**3,206 €/m²**	**3,281 €/m²**
Balanced CO$_2$ emissions	**49.74 kg$_{CO2}$/(m²a)**	**18.75 kg$_{CO2}$/(m²a)**
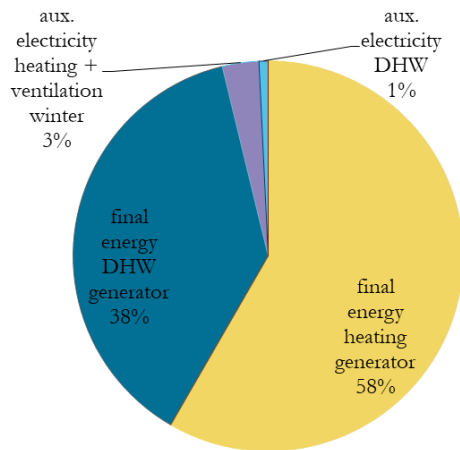
Figure 51: Final energy demand for heating, DHW, cooling and ventilation in the variant with the highest (left) and lowest CO₂ emissions (right) of the case study Isola Nel Verde
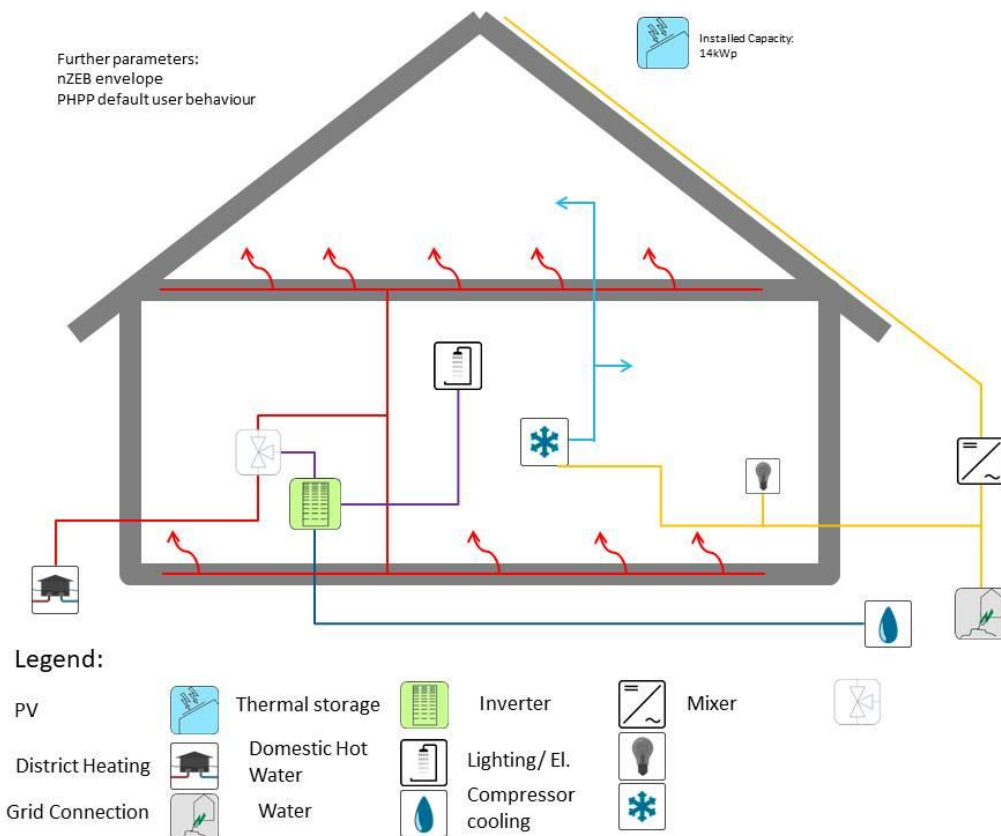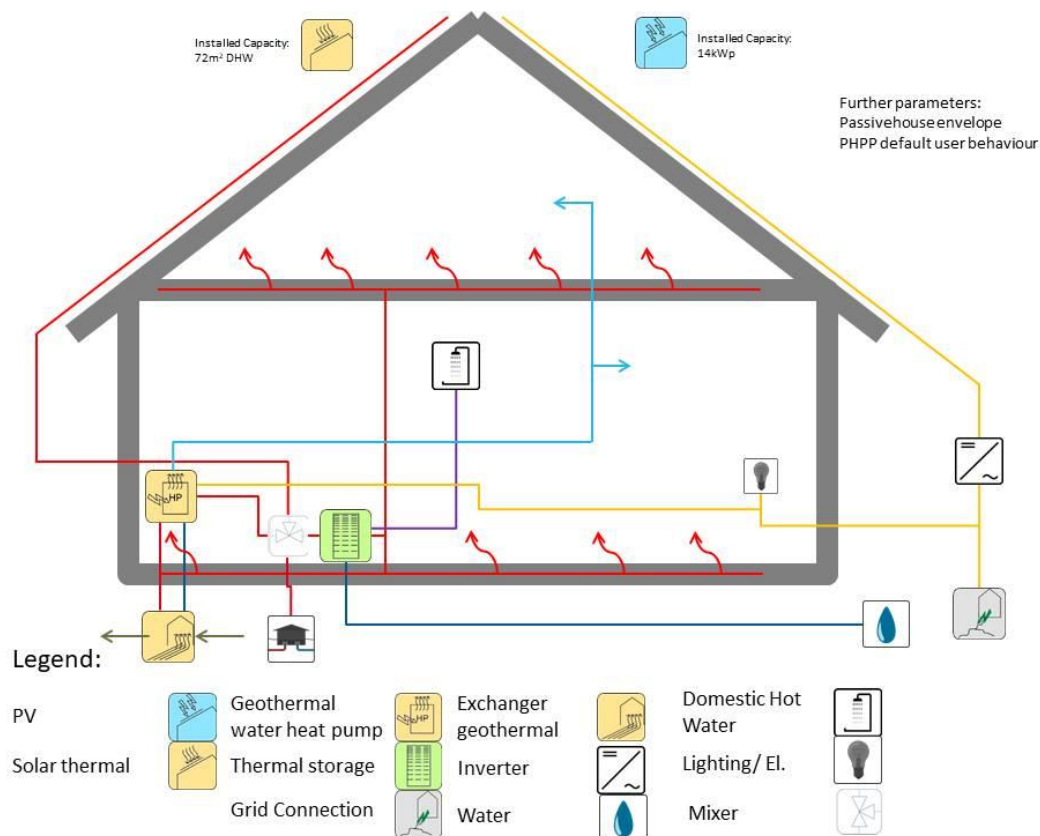
Figure 52: Visualisation of technology set of Isola Nel Verde; variant with lowest CO₂-emissions

Potential best cases

In Table 26, potential best cases are summarized. These variants have both comparably low CO$_2$ emissions and costs (NPVs). The balanced CO$_2$ emissions of the variants are 24.71 kg$_{CO2}$/(m²a) and thereby approx. 33 % higher than the variant with the lowest emissions. The NPV of all variants is between 2,743 and 2,763 €/m². In Table 26 only the differences between the variants are listed. The following parameters are the same for all variants:

- No CO$_2$ follow-up costs
- nZEB envelope (as built)
- Window ventilation
- District heating
- Climate/ location: Milano
- No solar thermal
- PV: 14 kWp

Differences are in the sensitivity of energy prices and the cooling technology installed.

Table 26: Variants with low CO$_2$ emissions and comparably low costs of the case study Isola Nel Verde based on WP06. The shown variable number is based on the results matrix of the parametric analysis and is equivalent to the number of the variant in the interactive case study dashboard in CRAVEzero-pinboard.

Variant Number	61644	61653	43863	46101	14988
Sensitivity (Energy price increase)	PHPP	PHPP	Low	Low	Standard
Cooling	Compressor	Ground source heat pump cooling	Compressor	Ground source heat pump cooling	Compressor
NPV [€/m²]	**2,743**	**2,744**	**2,753**	**2,754**	**2,763**
CO$_2$ emissions [kg$_{CO2}$/(m²a)]	**24.71**	**24.71**	**24.71**	**24.71**	**24.71**

5.3.5.LES HÉLIADES

5.3.5.1. BASE CASE

The following description of the case study is based on deliverable D6.2 (Venus et al., 2019).

Les Héliades is a multifamily building/ residence with 57 dwellings and a gross floor heated area of 9,265 m². It was completed in early 2017. It is designed as a Positive Energy Building (BEPOS) and located in Angers, France. It was designed by the architect Barré-Lambot and Bouygues Bâtiment Grand Ouest, with the goal to combine the comfort of the inhabitants and control of energy. The building has a **high shape compactness** and good U-values. The external wall has a U-value of 0.23 W/(m²K), the floor slab/ basement ceiling of 0.25 – 0.26 W/(m²K) and the roof of 0.14 W/(m²K). The windows have U-values between 1.14 – 1.61 W/(m²K), leading to an average value of the whole building envelope (opaque and transparent) of 0.5 W/(m²K).

A central element of the overall concept is the passive use of solar energy. **Solar gains** are favoured by a largely glazed façade, mainly facing south (the overall window-to-wall-ratio is 34 %). Thereby, the space heating demand is reduced.

Good air-quality is assured by a **central ventilation system**. The exhaust air system has assures an average air change rate of 0.23 h^{-1}. The fans have a specific power input of 0.2 Wh/m³.

The heat for space heating and DHW is provided by an **urban heat network** powered with **biomass.** The DHW production is complemented by **solar thermal** panels with an area of 42 m². The system provides approx. 24 MWh$_{th}$, which is about 22 % of the total DHW demand.

In addition a **photovoltaic** system is installed on the roof with a peak capacity of 56 kWp.

Two thermal storages for DHW are integrated in the system, mainly to maximize the use of the solar thermal energy generated on-site. Each storage has a volume of about 2 m³. The final energy consumption is 8.9 kWh/(m²a).

Legend: PV | Thermal storage | Lighting/ El.
Solar thermal | Grid connection | Domestic Hot Water
Ventilation + HR | District heating | Inverter | Fan Coil
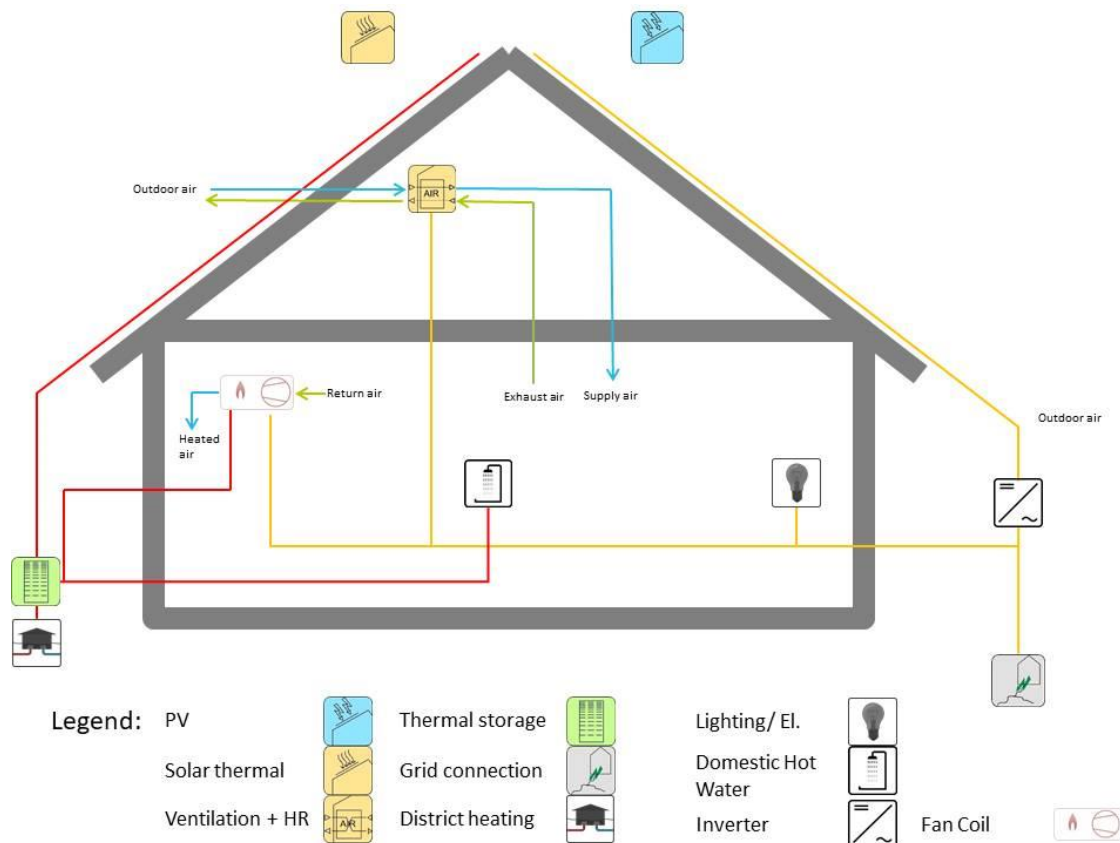
Figure 53: Visualisation of technology set of the case study Les Heliades

5.3.5.2. LOW-ENERGY AND LOW-COST TECHNOLOGY SETS

The results presented in (Venus et al., 2019) show that among all calculated variants the ones with a building envelope according to national standard have the lowest investment and life cycle costs, but they are also amongst the variants with the highest CO_2 emissions. Variants with district heating have on the one hand high investment costs, on the other hand comparable life cycle costs to the variants with a building envelope according to national standard and they are amongst the ones with the lowest CO_2 emissions. Furthermore, the results show that variants with a net present value of above 3,000 €/m² have a passive house envelope and use an air source heat pump for heating. These variants also have CO_2 emissions between 17.58 and 33.99 $kg_{CO2}/(m^2a)$. Another finding from the analysis conducted in WP06 is that variants without PV and solar systems and with inefficient user behaviour are amongst the variants with the highest emis-

sions. Another aspect with a large influence on the CO_2 emissions is the use of district heating.

In Figure 54 the final energy demand for heating DHW, cooling and ventilation of the variants with highest and lowest NPV and CO_2 emissions is shown. It can be seen that DHW preparation and space heating are dominating the final energy demand. In the variants with the highest NPV and CO_2 emissions, heating is dominating, in the ones with the lowest NPV and emissions DHW is dominating. As heating is a dominant factor, the climate conditions also have a large influence on the energy demand and emissions; climate data from southern France lead to low emissions. Mechanical ventilation only plays a minor role with respect to energy demand. How the needed energy is provided and what the major differences are is described in the following.
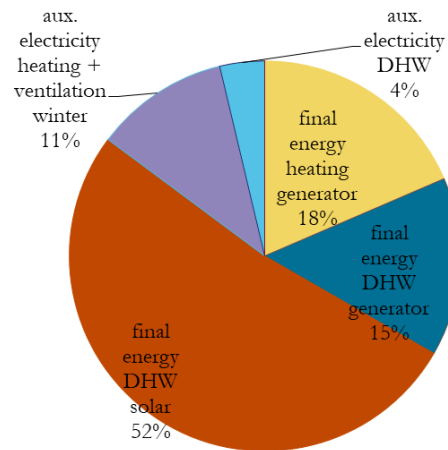

Figure 54: Final energy demand for heating, DHW, cooling and ventilation in the variants with the highest and lowest NPV and CO_2 emissions of the case study Les Héliades

Lowest and highest NPV

The basic characteristics of the variants with the highest and lowest NPV are summarized in Table

27. The main differences of the two variants are the envelope quality, the type of heat generation, sensitivity and CO_2 follow-up costs and the climate con-

ditions. In the variant with the highest NPV a passive house envelope is built. Compared to the variant with the lowest NPV (envelope according to national standard) the additional cost of the insulation is 52 €/m² (external wall), 37 €/m² (floor), 20 €/m² and 400 €/m² (windows) higher for the passive house envelope.

The heating demand in the highest NPV variant is 48 kWh/(m²a) and in the lowest NPV 19 kWh/(m²a) (final energy demand for heating is 28 kWh/(m²a) vs. 21 kWh/(m²a)). The share of heating, DHW, cooling and ventilation in the final energy demand of both variants is shown in Figure 55. Most energy is needed for heating followed by DHW in the variant with the highest NPV. In the variant with the lowest NPV it is the other way around. The balanced CO_2 emissions of the variant with the highest NPV are 32.45 kg_{CO2}/(m²a) and of the variant with the lowest NPV 10.88 kg_{CO2}/(m²a). The low emissions in the latter are mainly caused by the use of district heating, efficient user behaviour and climate conditions. In Figure 56 the technology set of the variant with the lowest NPV is shown visualising the major technologies for realising a low cost nZEB.

Table 27: Variants with the highest and lowest net present value (NPV) of the case study Les Héliades based on WP06; values for variables based on (Venus et al., 2019)

Variables	Highest NPV	Lowest NPV
Variant number	24049	61291
Sensitivity (Energy price increase)	High	PHPP
CO_2 follow-up costs	High	No
User behaviour	Not efficient	PHPP default
Envelope	Passive house: Floor: 0.18 W/(m²K) Exterior walls: 0.23 W/(m²K) Roof: 0.14 W/(m²K) Windows: 1.38 – 1.61 W/(m²K)	National Standard: Floor: 0.25 – 0.29 W/(m²K) Exterior walls: 0.39 W/(m²K) Roof: 0.18 W/(m²K) Windows: 1.85 – 2.04 W/(m²K)
Ventilation	Window ventilation	Window ventilation
Heating	Air source heat pump: 220 kW / COP 3.5	District Heating
Climate	Northern France	Southern France
Cooling	No cooling	No cooling
Solar thermal	No solar thermal	No solar thermal
PV	No PV	No PV
Net present value	**3,146 €/m²**	**2,347 €/m²**
Balanced CO_2 emissions	**32.45 kg_{CO2}/(m²a)**	**10.88 kg_{CO2}/(m²a)**

Final energy demand highest NPV

Final energy demand lowest NPV

Figure 55: Final energy demand for heating, DHW, cooling and ventilation in the variant with the highest NPV (left) and lowest NPV (right) of the case study Les Héliades

Figure 56: Visualisation of technology set of Les Héliades; variant with lowest NPV

Lowest and highest CO_2 emissions

The basic characteristics of the variants with the highest and lowest CO_2 emissions are summarized in Table 28. The balanced CO_2 emissions of the variant with the highest CO_2 emissions are 36.25 $kg_{CO2}/(m^2a)$ and of the variant with the low-est emissions 5.68 $kg_{CO2}/(m^2a)$. The main differences of the two variants are the climate conditions, user behaviour heating system and the use of solar energy. In the variant with the highest CO_2 emissions the building is located in northern France

while the one with the lowest emissions is located in southern France.

In the variant with the lowest emissions a PV and a solar thermal system are installed. The associated costs for the installed PV system with a capacity of 82 kWp is 229,600 € (2,800 €/kWp). The system generates 66,376 kWh/a. The total cost for the solar thermal system is 84,260 € (excl. heat storage). The heating demand in the highest emissions variant is 60 kWh/(m²a) and in the lowest emissions 31 kWh/(m²a) (final energy demand for heating is 35 kWh/(m²a) vs. 32 kWh/(m²a)). The share of

heating, DHW, cooling and ventilation in the final energy demand of both variants is shown in Figure 57. Most energy is needed for heating followed by DHW. Auxiliary electricity demand only plays a minor role in both variants.

The NPV of the variant with the highest CO_2 emissions is 2,952 €/m² and of the variant with the lowest emissions 2,409 €/m². In Figure 58 the technology set of the variant with the lowest CO_2 emissions is shown visualising the major technologies for realising a low cost nZEB.

Table 28: Variants with the highest and lowest CO_2 emissions of the case study Les Héliades based on WP06

Variable	Highest CO$_2$	Lowest CO$_2$
Variant number	23401	61929
Sensitivity (Energy price increase)	High	PHPP
CO$_2$ follow-up costs	High	No
User behaviour	Not efficient	PHPP default
Envelope	National Standard:	National Standard:
	Floor: 0.25 – 0.29 W/(m²K)	Floor: 0.25 – 0.29 W/(m²K)
	Exterior walls: 0.39 W/(m²K)	Exterior walls: 0.39 W/(m²K)
	Roof: 0.18 W/(m²K)	Roof: 0.18 W/(m²K)
	Windows: 1.85 – 2.04 W/(m²K)	Windows: 1.85 – 2.04 W/(m²K)
Ventilation	Window ventilation	Window ventilation
Heating	Air source heat pump:	District Heating
	220 kW / COP 3.5	
Climate	Northern France	Southern France
Cooling	No cooling	No cooling
Solar thermal	No solar thermal	110m² flat plate collectors for DHW
PV	No PV	Capacity: 82 kWp
Net present value	**2,952 €/m²**	**2,409 €/m²**
Balanced CO$_2$ emissions	**36.25 kg$_{CO2}$/(m²a)**	**5.68 kg$_{CO2}$/(m²a)**

Final energy demand highest CO_2 emissions
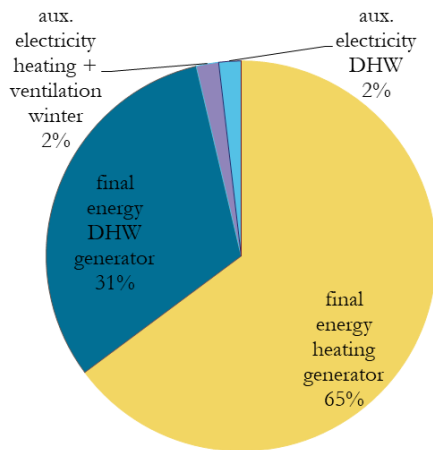
Final energy demand lowest CO_2 emissions
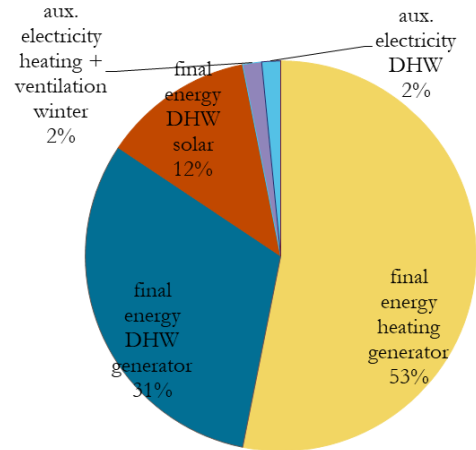
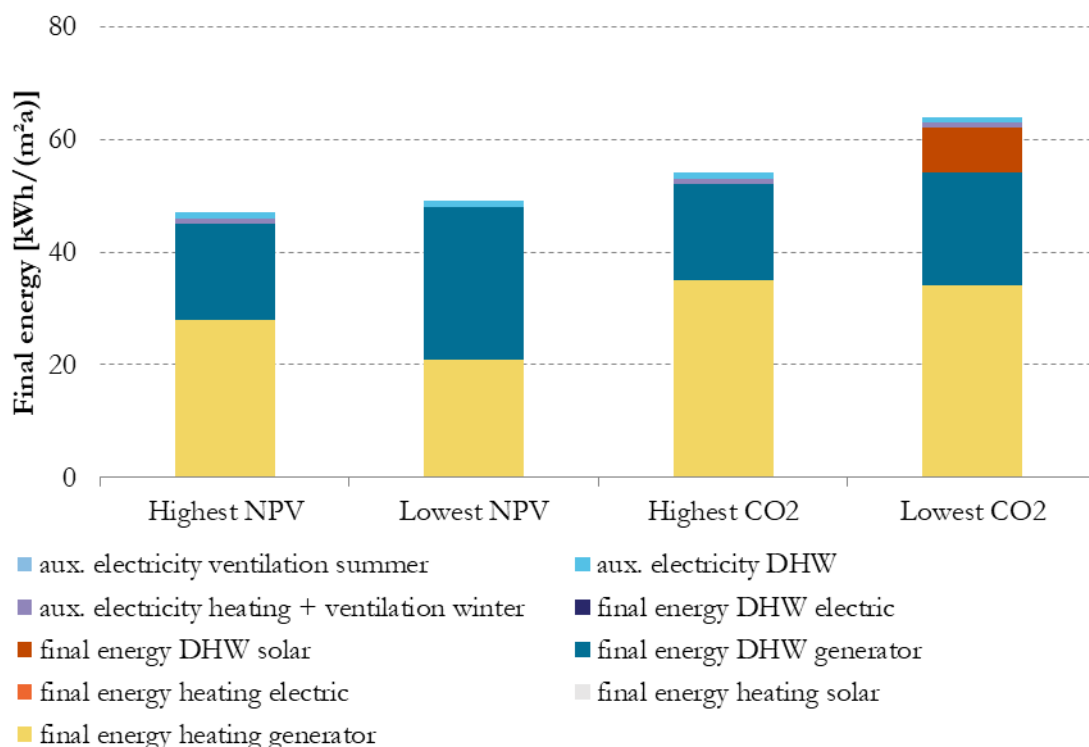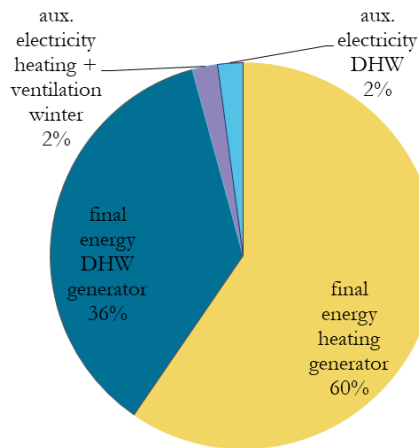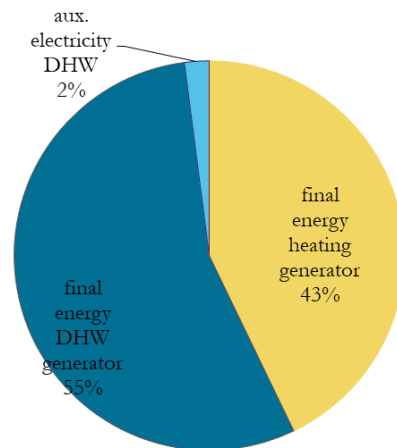*Figure 57: Final energy demand for heating, DHW, cooling and ventilation in the variant with the highest (left) and lowest CO_2 emissions (right) of the case study Les Héliades*
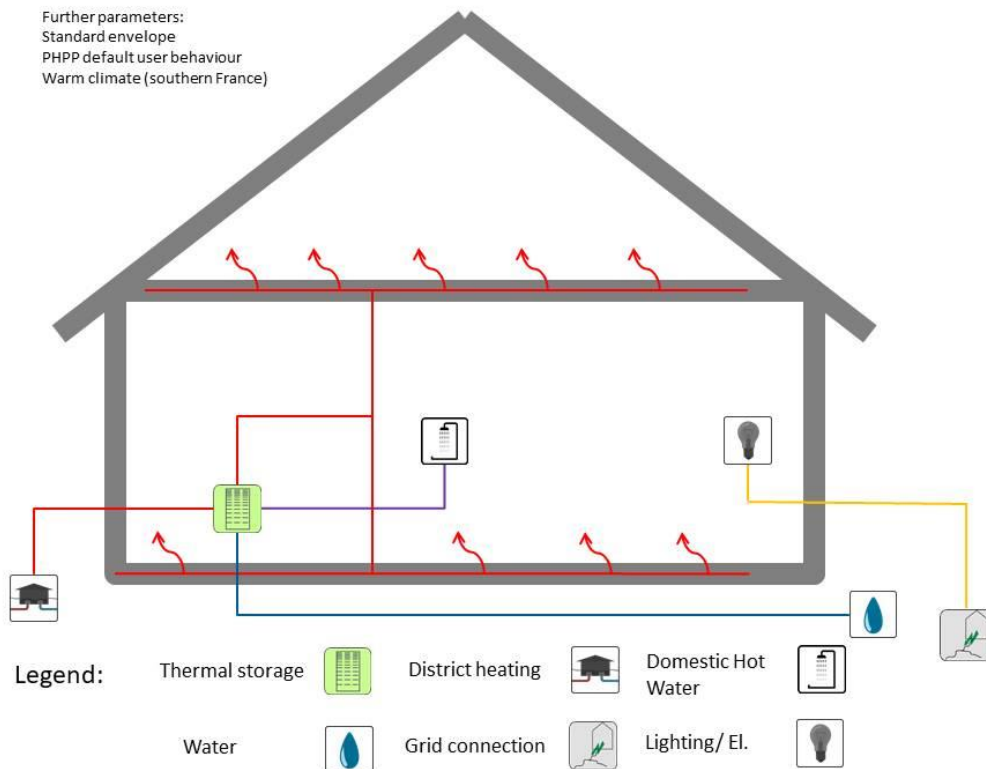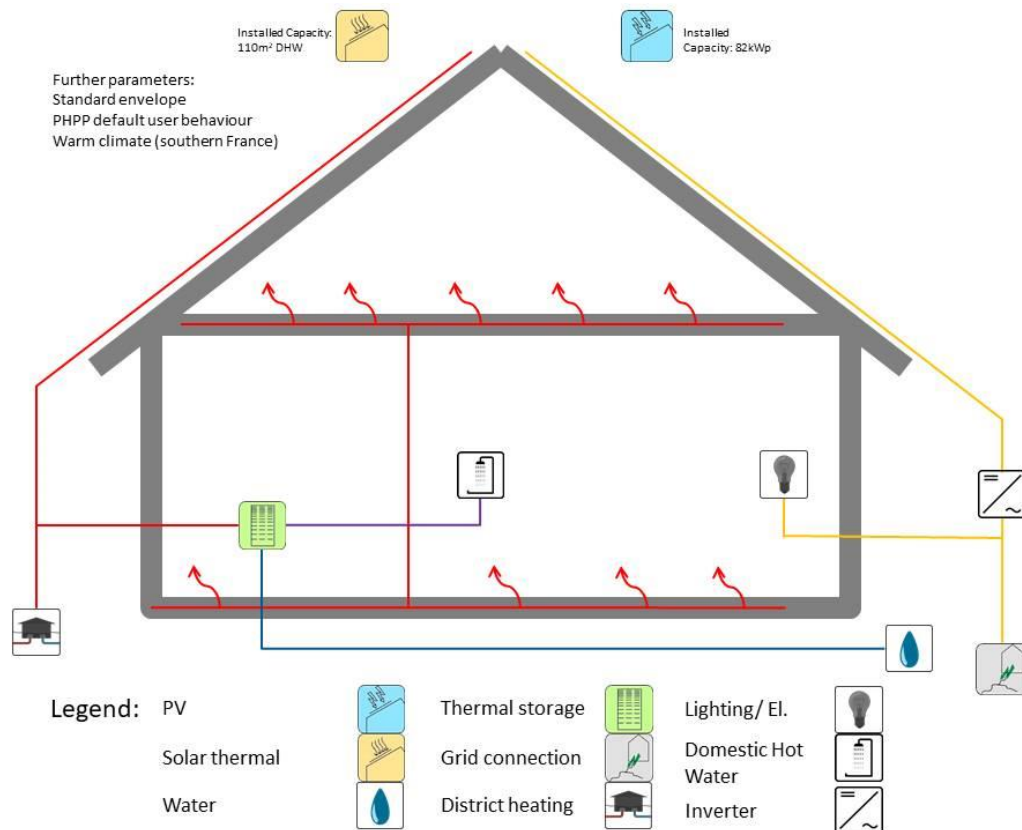

Figure 58: Visualisation of technology set of Les Héliades; variant with lowest CO_2-emissions

Potential best cases

In Table 29 potential best cases are summarized. These variants have both comparably low CO_2 emissions and costs (NPVs). The balanced CO_2 emissions of the variants are between 6.53 $kg_{CO2}/(m^2a)$ and 10.90 $kg_{CO2}/(m^2a)$. The NPV of all variants is between 2,347 and 2,369 €/m². The variants only have a minor cost difference while the emissions show a variation of approx. 40 %. In Table 29 only the differences between the

variants are listed. The following parameters are the same for all variants:

- No CO_2 follow-up costs
- Envelope according to national standard
- Window ventilation
- District heating
- Climate: Southern France

- No cooling

The variants differ in the sensitivity and user behaviour (PHPP default or efficient user). Furthermore, the use of solar energy (PV or solar thermal systems) is different. However, one of the two solar technologies is installed in most cases.

Table 29: Variants with low CO_2 emissions and comparably low costs of the case study Les Héliades based on WP06. The shown variable number is based on the results matrix of the parametric analysis and is equivalent to the number of the variant in the interactive case study dashboard in CRAVEzero-pinboard.

Variant Number	61291	61294	45742	61292	60320
Sensitivity (Energy price increase)	PHPP	PHPP	Low	PHPP	PHPP
User behaviour	PHPP default	PHPP default	PHPP default	PHPP default	Efficient user
Solar thermal	No solar thermal	42m² flat plate collectors for DHW	42m² flat plate collectors for DHW	No solar thermal	No solar thermal
PV	No PV	No PV	No PV	Capacity 56 kWp	Capacity 56 kWp
NPV [€/m²]	**2,347**	**2,358**	**2,365**	**2,367**	**2,369**
CO_2 emissions [$kg_{CO2}/(m^2a)$]	**10.88**	**10.90**	**10.90**	**6.53**	**6.59**

5.3.6. MORETTI MORE

5.3.6.1. BASE CASE

The following description of the case study is mainly taken from deliverable D6.2 (Venus et al., 2019). Groppi represents one of the typologies of the prefabricated single-family houses produced by Moretti in Italy. The building has a net floor area of 128 m². The **envelope and all the equipment** have been designed with the aim to achieve **high performances**. The external walls have U-values of 0.16 to 0.36 W/(m²K) with an average of 0.22 W/(m²K). The roof has an average U-value of 0.15 W/(m²K), the floor slab 0.23 W/(m²K) and the windows between 1.13 and 1.25 W/(m²K). The windows have special **selective and low emissivity glasses** ensuring a low cooling demand.

The heat for the building is generated by an **air-water heat pump** (space heating) and a **solar thermal collector** (domestic hot water). In addition, a gas boiler with 15 kW_{th} is installed, which covers around 20 % of space heating and 25 % of the DHW demand. The efficiency at nominal output is 95 %. The solar thermal collectors (flat collectors) have an area of 5.14 m² and generate approx. 3,500 kWh/a, which is 75 % of the total DHW demand.

The heat is distributed by a **low temperature system** (35°C supply temperature) supplying a **floor heating** system. The nominal power of the system is 12 kW and the system is divided in three loops. The system can also be used for cooling in summer.

The domestic hot water is distributed in one loop and there is a **DHW heat storage** with a volume of 300 l integrated in the system. The storage is also needed for the integration of all different heat sources.

There is a **balanced mechanical ventilation system with heat recovery** installed. The average air change rate is 0.4 h⁻¹ (128 m³/h). The nominal effi-ciency of the heat recovery is 88 % and the efficiency of the humidity recovery is 20 %. The electric efficiency of the mechanical ventilation is 0.34 Wh/m³.

For the operation of the building with its diverse heating, cooling and ventilation elements, electric **system automation** is installed.
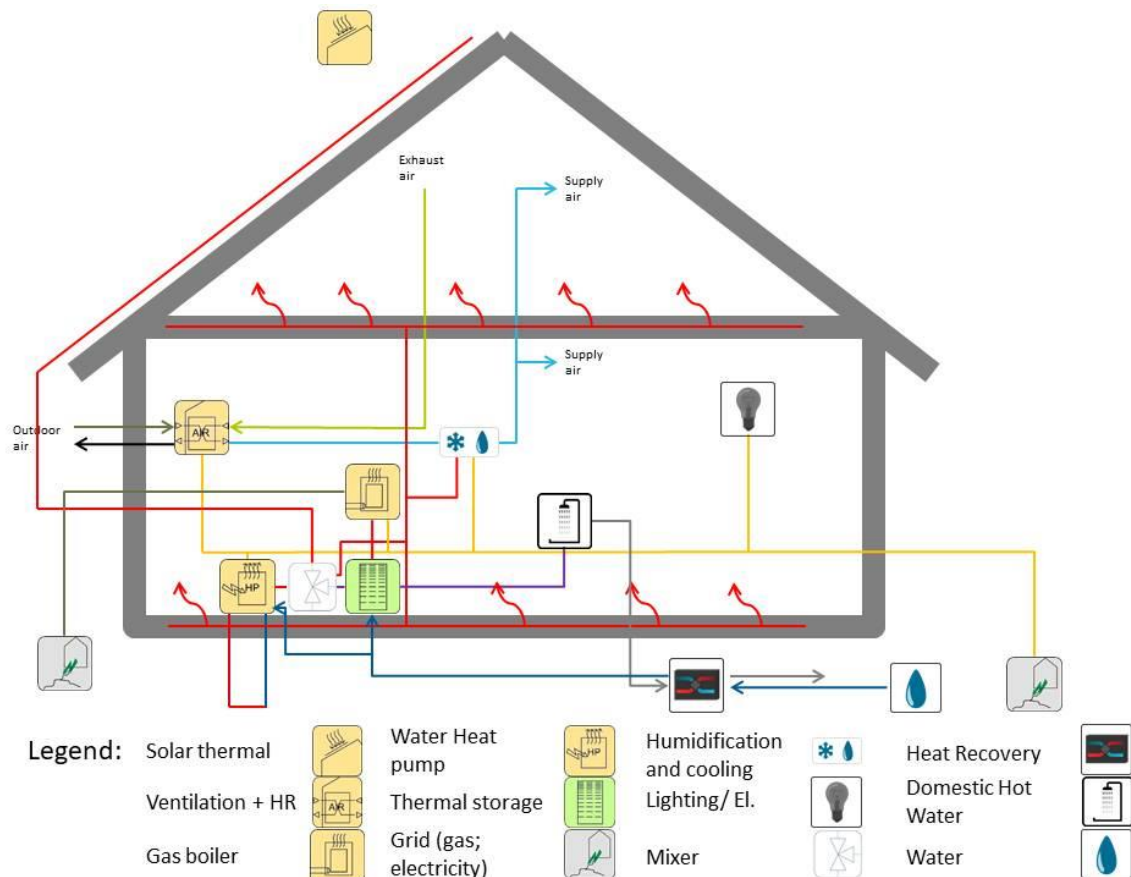
Figure 59: Visualisation of technology set of the case study Moretti More

5.3.6.2. LOW-ENERGY AND LOW-COST TECHNOLOGY SETS

The results presented in (Venus et al., 2019) show that among all calculated variants with an envelope according to national standard have the lowest investment and life cycle costs. However, a nZEB envelope only has slightly higher costs, but much lower CO_2 emissions. The results show that variants with a net present value of above 5,500 €/m² usually have a passive house envelope, air source heat pump for heating, no PV system, but a solar system for DHW. These variants also have CO_2 emissions between 24.11 and 44.57 $kg_{CO2}/(m²a)$. Another finding from the analysis conducted in WP06 is that the PV and heating system as well as the envelope quality have the highest influence on the net present value. For the case study Moretti More, also different climate conditions were assessed, which also have a strong influence especially on the CO_2 emissions. Furthermore, user behaviour and the installation of solar thermal systems have an impact on the emissions. The highest emissions are calculated for variants without PV or solar thermal systems and with inefficient user behaviour. In Figure 60 the final energy demand for heating DHW, cooling and ventilation of the variants with highest and lowest NPV and CO_2 emissions is shown. DHW preparation is dominating the final

energy demand in most cases. In the variant with the lowest NPV heating only plays a negligible role (located in southern Italy). In the variant with the highest emissions heating is dominating the final

energy demand. How the needed energy is provided and what the major differences are is described in the following.

Figure 60: Final energy demand for heating, DHW, cooling and ventilation in the variants with the highest and lowest NPV and CO₂ emissions of the case study Moretti More

Lowest and highest NPV

The basic characteristics of the variants with the highest and lowest NPV are summarized in Table 30. The main differences of the two variants are the quality of the envelope, the type of ventilation, the type of heat and cold generation and the use of solar energy. Furthermore, the variants have different climate conditions and user behaviour. In the variant with the highest NPV a passive house envelope is realised, whereas the envelope in the variant with the lowest NPV is as built (nZEB). Furthermore, a mechanical ventilation system with heat recovery is installed in the highest NPV variant with extra costs of 6,000 € compared to manual window ventilation. The cost difference for the heating system is approx. 3,850 € (total cost air source heat pump: 11,000 € vs. total cost air source heat pump + condensing boiler: 7,150 €). In the highest NPV variant a large solar thermal system (10 m²) is installed for space heating and DHW. The system

costs are 7,500 € vs. 3,700 € for smaller system in the lowest NPV variant, which is only for DHW preparation. In the variant with the lowest NPV there is also a PV system with 10 kWp installed costing 13,750 € (1,350 €/kWp).

The heating demand in the highest NPV variant is 56 kWh/(m²a) and in the lowest NPV 11 kWh/(m²a) (final energy demand for heating is 30 kWh/(m²a) vs. 1 kWh/(m²a)). The share of heating, DHW, cooling and ventilation in the final energy demand of both variants is shown in Figure 61. DHW plays a major role in the final energy demand of both variants; heating is only important in the variant with a high NPV due to the climate conditions in this variant. The balanced CO_2 emissions of the variant with the highest NPV are 32.53 kg_{CO2}/(m²a) and of the variant with the lowest NPV 2.05 kg_{CO2}/(m²a). Main reasons for the low costs in low emissions in the variant with the lowest NPV are the climate conditions (almost no

heating demand in southern Italy) and the efficient user behaviour. In Figure 62 the technology set of the variant with the lowest NPV is shown visualising the major technologies for realising a low cost nZEB.

Table 30: Variants with the highest and lowest net present value (NPV) of the case study Moretti More based on WP06; values for variables based on (Venus et al., 2019)

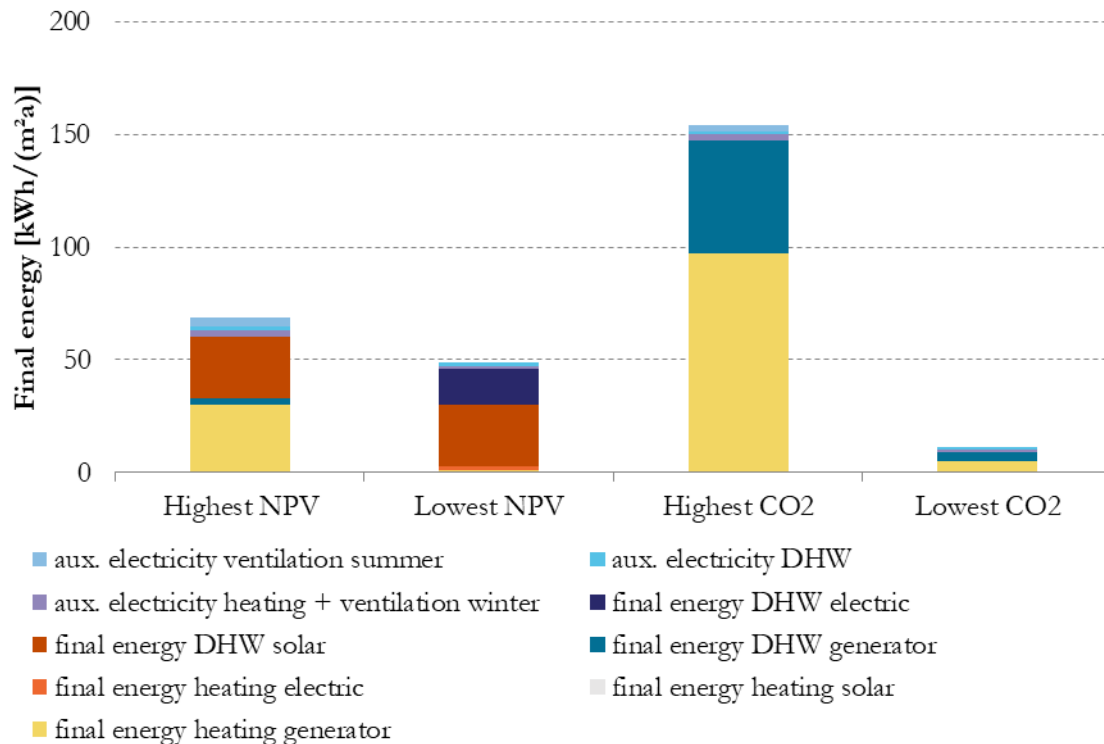| Variables	Highest NPV	Lowest NPV
Variant number	26611	42981
Sensitivity (Energy price increase)	Standard	Standard
CO₂ follow-up costs	High	No
User behaviour	Not efficient	Efficient
Envelope	Passive house: Floor slab: 0.15 W/(m²K) Exterior walls: 0.15 W/(m²K) Roof: 0.15 W/(m²K)	nZEB (as built): Floor slab: 0.23 W/(m²K) Exterior walls: 0.22 W/(m²K) Roof: 0.15 W/(m²K)
Ventilation	Mechanical Ventilation with heat recovery; electric efficiency 0.196 Wh/m³	Window ventilation
Heating	Air source heat pump: 45 kW / COP 4.07 / EER 3.12	Air source heat pump + gas condensing boiler: HP: 15 kW / COP 4.2 Boiler: 33.74 kW / η = 97.3 %
Climate	Lodi	Palermo
Cooling	No cooling	Air source heat pump cooling
Solar thermal	10 m² flat plate collectors for DHW and space heating	5 m² flat plate collectors for DHW
PV	No PV	Capacity: 10 kWp
Net present value	**5,644 €/m²**	**4,167 €/m²**
Balanced CO₂ emissions	**32.53 kg_{CO2}/(m²a)**	**2.05 kg_{CO2}/(m²a)**
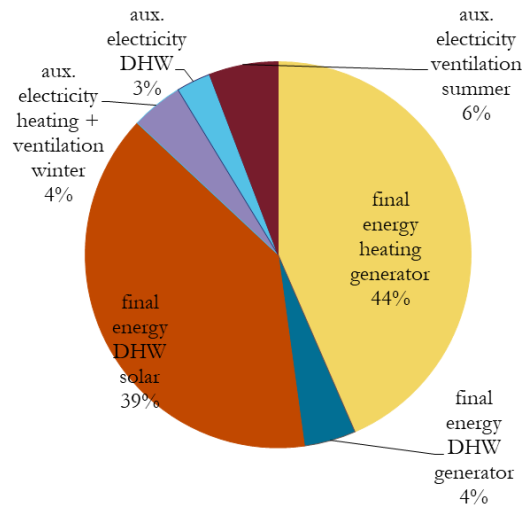
Figure 61: Final energy demand for heating, DHW, cooling and ventilation in the variant with the highest NPV (left) and lowest NPV (right) of the case study Moretti More

Figure 62: Visualisation of technology set of Moretti More; variant with lowest NPV

Lowest and highest CO_2 emissions

The basic characteristics of the variants with the highest and lowest CO_2 emissions are summarized in Table 31. The balanced CO_2 emissions of the variant with the highest CO_2 emissions are 50.07 $kg_{CO2}/(m^2a)$ and of the variant with the lowest emissions -5.40 $kg_{CO2}/(m^2a)$. The negative emissions are a result of the low emissions of the building as a whole and the balancing of the PV generation on-site. The building generates more than it needs and therefore receives credits. The main differences of the two variants are the type of ventilation and the type of heat generation, the climate conditions, user behaviour and use of solar energy. In the variant with the highest CO_2 emissions an extract air unit is installed. Heat is generated by a gas condensing boiler, which on the one hand is 7,500 € cheaper than the air source heat pump in the low emission variant, on the other hand causes high emissions. Besides the heating system, the major factors are the climate conditions (lowest CO_2 variant is located in southern Italy) and the

installation of a 10 kWp PV system generating 16,762 kWh/a.

The heating demand in the highest CO_2 emissions variant is 102 kWh/(m²a) and in the lowest CO_2 emissions 11 kWh/(m²a) (final energy demand for heating is 97 kWh/(m²a) vs. 5 kWh/(m²a)). The share of heating, DHW, cooling and ventilation in the final energy demand of both variants is shown in Figure 63. In both cases, heating is dominating the final energy demand of the building followed by DHW. In the low emission variant the auxiliary electricity demand is comparably high due to the heating technology installed and mainly due to the low overall energy demand, which increases the share of the auxiliary energy demand even though it is still low in absolute numbers.

The NPV of the variant with the highest CO_2 emissions is 4,914 €/m² and of the variant with the lowest emissions 4,365 €/m². In Figure 64 the technology set of the variant with the lowest CO_2 emissions is shown visualising the major technologies for realising a low cost nZEB.

Table 31: Variants with the highest and lowest CO₂ emissions of the case study Moretti More based on WP06

Variable	Highest CO$_2$	Lowest CO$_2$
Variant number	35902	43086
Sensitivity (Energy price increase)	Standard	Standard
CO$_2$ follow-up costs	No	No
User behaviour	Not efficient	Efficient
Envelope	National standard: Floor slab: 0.26 W/(m²K) Exterior walls: 0.26 W/(m²K) Roof: 0.22 W/(m²K)	National standard: Floor slab: 0.26 W/(m²K) Exterior walls: 0.26 W/(m²K) Roof: 0.22 W/(m²K)
Ventilation	Extract air unit; electric efficiency 0.712 Wh/m³	Window ventilation
Heating	Gas condensing boiler: 45 kW / η = 104 %	Air source heat pump: 45 kW / COP 4.07 / EER 3.12
Climate	Lodi	Palermo
Cooling	Air source heat pump cooling	Air source heat pump cooling
Solar thermal	No solar thermal	No solar thermal
PV	No PV	Capacity: 10 kWp
Net present value	**4,914 €/m²**	**4,365 €/m²**
Balanced CO$_2$ emissions	**50.07 kg$_{CO2}$/(m²a)**	**-5,40 kg$_{CO2}$/(m²a)**

Final energy demand highest CO$_2$ emissions
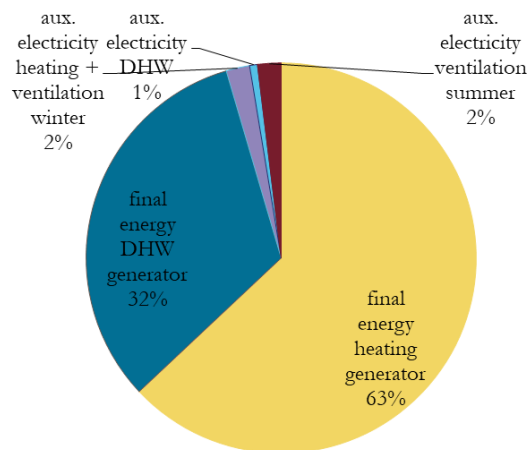
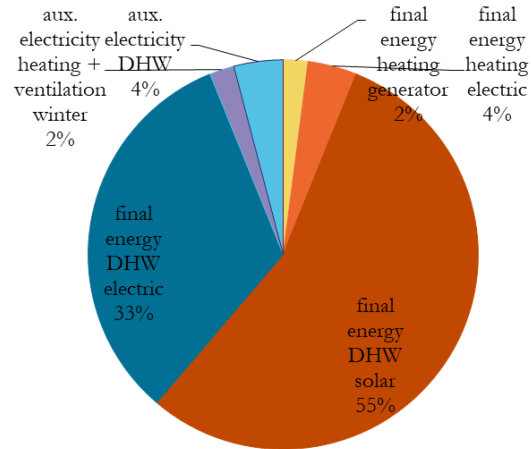Final energy demand lowest CO$_2$ emissions
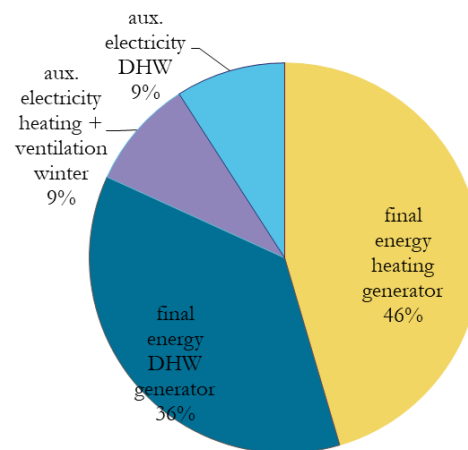
Figure 63: Final energy demand for heating, DHW, cooling and ventilation in the variant with the highest (left) and lowest CO$_2$ emissions (right) of the case study Moretti More
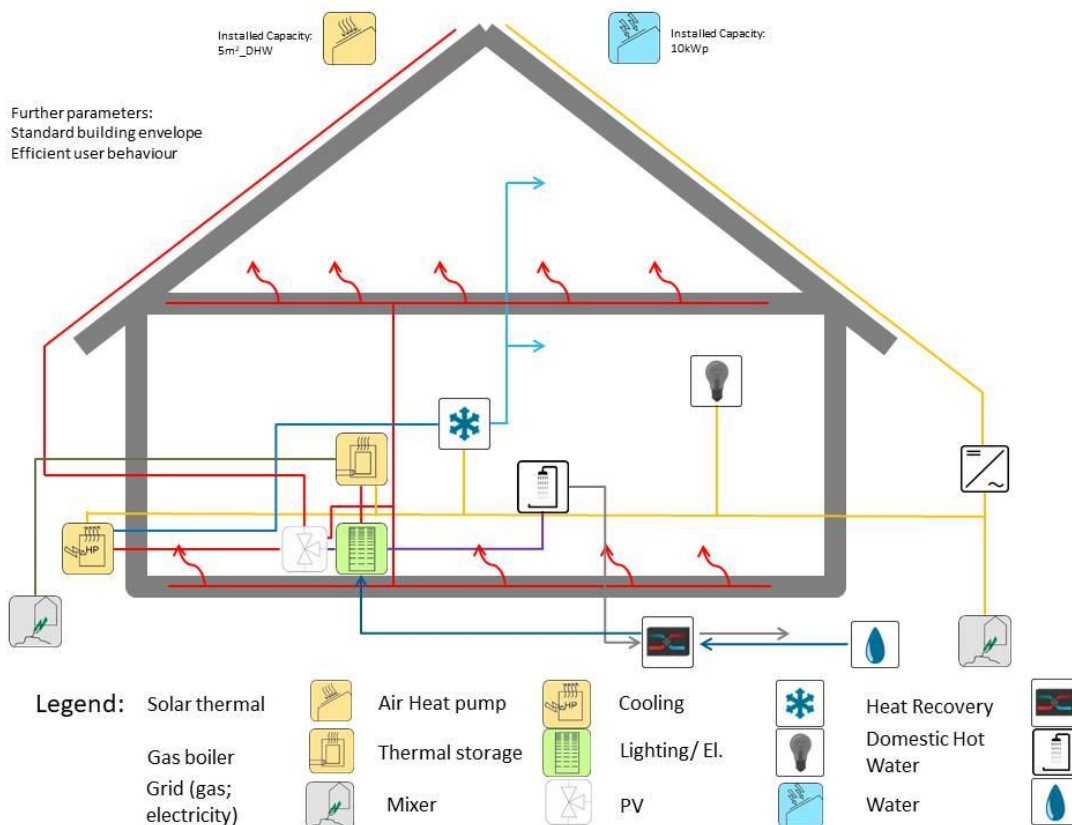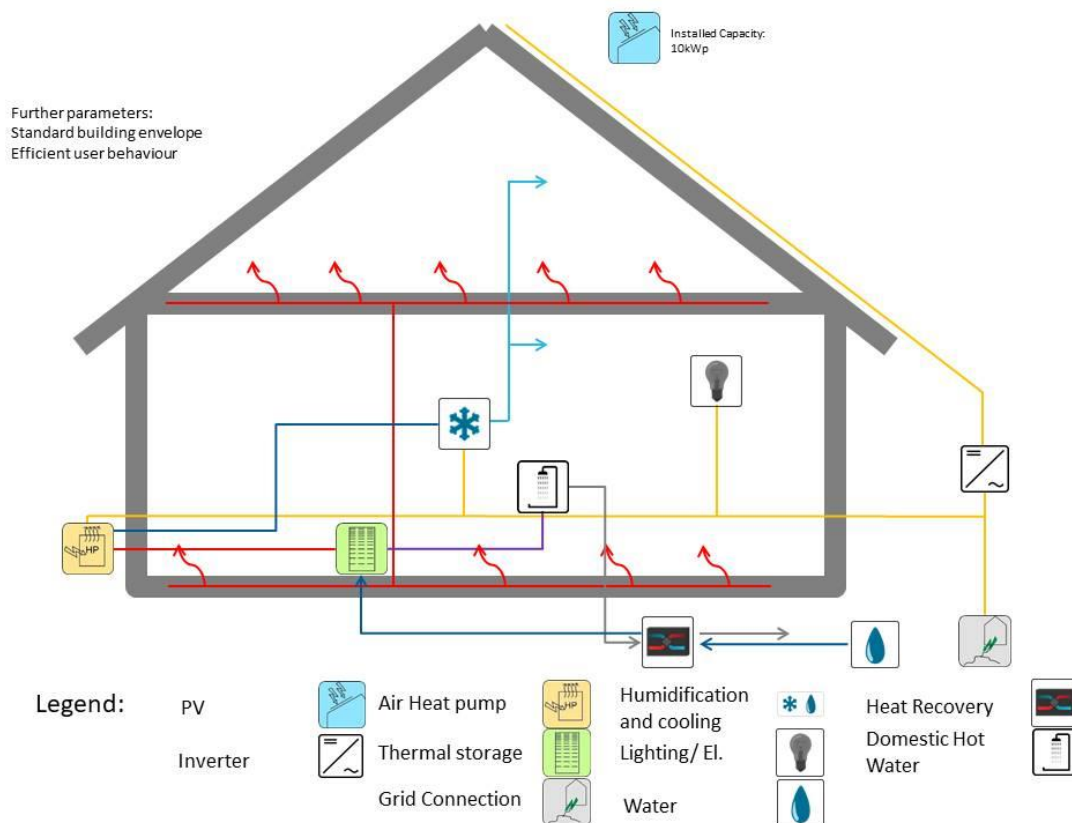
Figure 64: Visualisation of technology set of Moretti More; variant with lowest CO₂-emissions

Potential best cases

In Table 32 potential best cases are summarized. These variants have both comparably low CO_2 emissions and costs (NPVs). The variants 8187, 19851, 31515 and 43179 only differ in the CO2 follow up cost which in this case does not influence the NPV and CO_2 emissions. The balanced CO_2 emissions of the variants are between $0.48 \text{ kg}_{CO2}/(\text{m}^2\text{a})$ and $2.05 \text{ kg}_{CO2}/(\text{m}^2\text{a})$, which is comparably low. The NPV of all variants is between 4,167 and 4,177 €/m². In Table 29 only the differences between the variants are listed. The following parameters are the same for all variants:

- Standard energy price sensitivity

- Efficient user behaviour
- Envelope according to national standard
- Window ventilation
- Climate: Southern Italy (Palermo)
- Solar thermal: 5 m² flat plate collectors for DHW
- 10 kWp PV

The CO_2 follow-up costs differ amongst the variants. Heating is supplied by an air source heat pump or district heating. Cooling is supplied by compression cooling in the cases of a district heating connection. In the case with an air source heat also cooling is provided by this technology.

Table 32: Variants with low CO$_2$ emissions and comparably low costs of the case study Moretti More based on WP06. The shown variable number is based on the results matrix of the parametric analysis and is equivalent to the number of the variant in the interactive case study dashboard in CRAVEzero-pinboard.

Variant Number	42981	8187	19851	31515	43179
CO$_2$ follow-up costs	No	Low	Standard	High	No
Heating	Air source heat pump + gas condensing boiler	District Heating	District Heating	District Heating	District Heating
Cooling	Air source heat pump cooling	Compressor cooling	Compressor cooling	Compressor cooling	Compressor cooling
NPV [€/m²]	**4,167**	**4,177**	**4,177**	**4,177**	**4,177**
CO$_2$ emissions [kg$_{CO2}$/(m²a)]	**2.05**	**0.48**	**0.48**	**0.48**	**0.48**

5.3.7. VISUALISATION OF TECHNOLOGY SETS OF THE OTHER CASE STUDIES

1. Parkcarré

Parkcarré is a multi-family apartment building with a treated floor area of 1,189 m², which was built in several variations in the South-West of Germany. The assessed case study building is located in Eggenstein-Leopoldshafen, Germany. It is built as a KfW-Efficiency House 55, which implies a **highly efficient envelope** (U-values: external wall: 0.19 W/m²K, windows: 0.6 W/m²K, roof: 0.194 W/m²K).

The apartments are equipped with decentralized mechanical **ventilation systems with heat recovery**. The maximum heat recovery rate is 0.89 (average during operation 0.82 – 0.84). The exhaust air flow rate per unit is between 27 and 56 m³/h and a power consumption of 0.09 – 0.1 Wh/m³. All devices together have a design air flow rate (maximum) of 1,299 m³/h and the average air change rate is 0.3 h^{-1}.

Heat for space heating and domestic hot water is provided by a local heat network from a gas-fired

CHP (gas-condensing boiler as back-up). The district heating system has a thermal efficiency of 85 %. The thermal efficiency of the CHP is 50 % and the electrical efficiency 40 %.

The heat distribution in the building is hydraulically separated from the district heating network. There are two distribution systems inside the building: a **low temperature system** for heating and one for domestic hot water. In the DHW system, **stratified heat storage tank** is integrated. The apartments are equipped with heat exchange modules for hygienic water heating supplying 60°C at all taps.

The pent roof of the building is maximally occupied by **PV**. The plant consists of mono-silicon modules with a nominal power of 275 W each. The installed capacity is 33.14 kW$_p$. The applied business model for the energy supply and plant operation is a contracting model. The plant is operated by a local contractor.
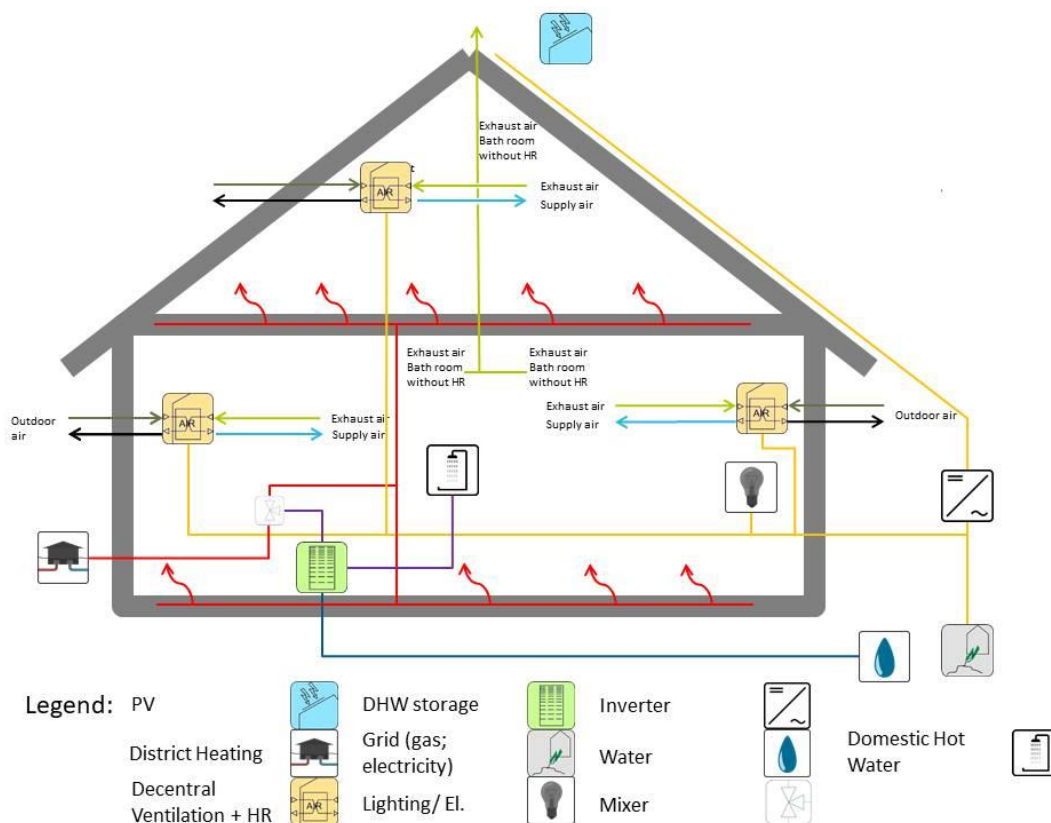

Figure 65: Visualisation of technology set of the case study Parkcarré

2. Green Home Nanterre

The building is located in Nanterre in the Paris metropolitan area, France. It is a plus-energy residential building with a net floor area of 9,267 m², designed by "Atelier Zündel Cristea" and constructed in 2016 by Bouygues Construction. It has a **highly efficient envelope** to minimize the heating demand. The average U-value of the external walls is 0.21 W/(m²K). The roof and the floor slab/basement ceiling have extremely low U-values of 0.078 W/(m²K) and 0.077 W/(m²K) respectively. As the window-to-wall ratio is relatively high the U-values of the windows also have to be very low in order to achieve a high energetic standard. It is 0.83 W/(m²K) on average. Due to the good thermal quality of the envelope, the building has very low energy needs (80 % less than a standard building).

The special feature is that it operates without heating and cooling systems (Pernetti et al., 2018). It can be considered as a low-tech building (compare chapter 2.4) as the needed technical installations (HVAC) are reduced to a minimum.

The heat for domestic hot water is provided by a **heat pump** using **heat recovered from the greywater**. Due to the high source temperature, the heat pump achieves a seasonal performance factor of 5 even though also the sink temperature is high (DHW). In the domestic hot water system a **thermal storage** with a volume of 6 m³ is integrated.

The building is equipped with **decentralised mechanical ventilation with heat recovery**, which is additionally equipped with el. heaters in case the internal loads are not sufficient to provide the desired indoor temperatures during the heating season. The heat recovery is enough to meat almost 100 % of the building's heat demand. It has an efficiency of 84 % and a specific efficiency of 0.29 Wh/m³.

Furthermore, a 730 m² **PV** system is installed on the roof top to locally generate renewable electricity. The system has a peak capacity of almost 134 kW$_p$.
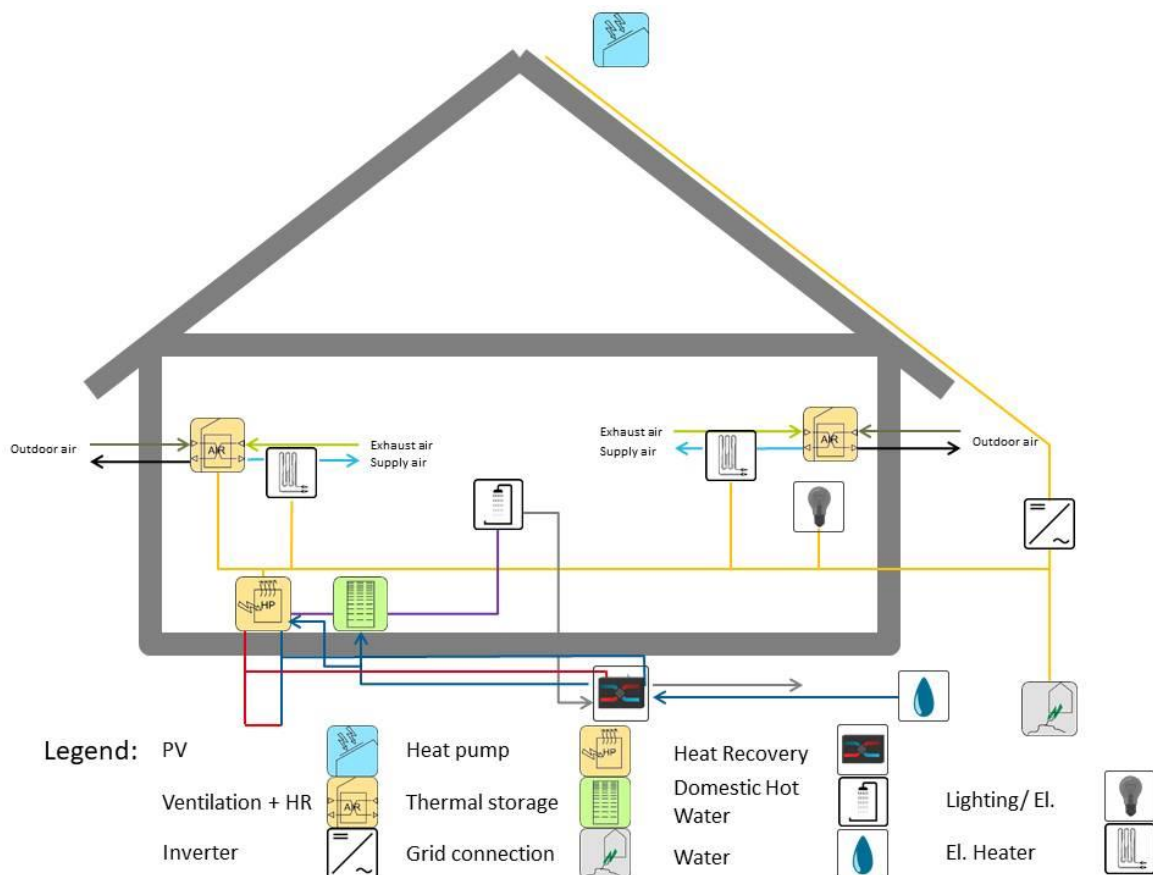

Figure 66: Visualisation of technology set of the case study Green Home Nanterre

3. i+R-Headquarter

The building is located in Lauterbach, Austria. It is a non-residential building (mainly offices) with a net floor area of 2,759 m². The concept is based on the use of natural materials and renewable energy. The **thermal envelope** has a low average U-value of 0.32 W/(m²K). The external walls (to ambient) and the floor slab have a U-value of 0.22 W/(m²K), the roof of 0.12 W/(m²K) and the windows of 0.73 – 0.75 W/(m²K).

To further reduce the heating demand, a **central ventilation system with heat recovery** is installed. The system has a heat recovery rate of approx. 75 % and a specific power input of 0.45 Wh/m³. The average air change rate is 0.57 h⁻¹.

The heat is mainly supplied by a **reversible geothermal heat pump**, which also cools the building in summer. The cooling capacity in summer is 115.6 kW. The seasonal energy efficiency ratio for cooling is 15 and for heating 2.2. There are four **probes** with a depth of 150 m each. The average annual extraction rate is 7 W/m and the pump power for the probes is 1.1 kW.

In order to operate the heat pump efficiently the building is equipped with a **low temperature heating system** (flow heating) with a supply temperature of 35°C. Cooling is provided by supply air cooling **and panel cooling**.

Domestic hot water is provided by **electric instantaneous water heaters**.

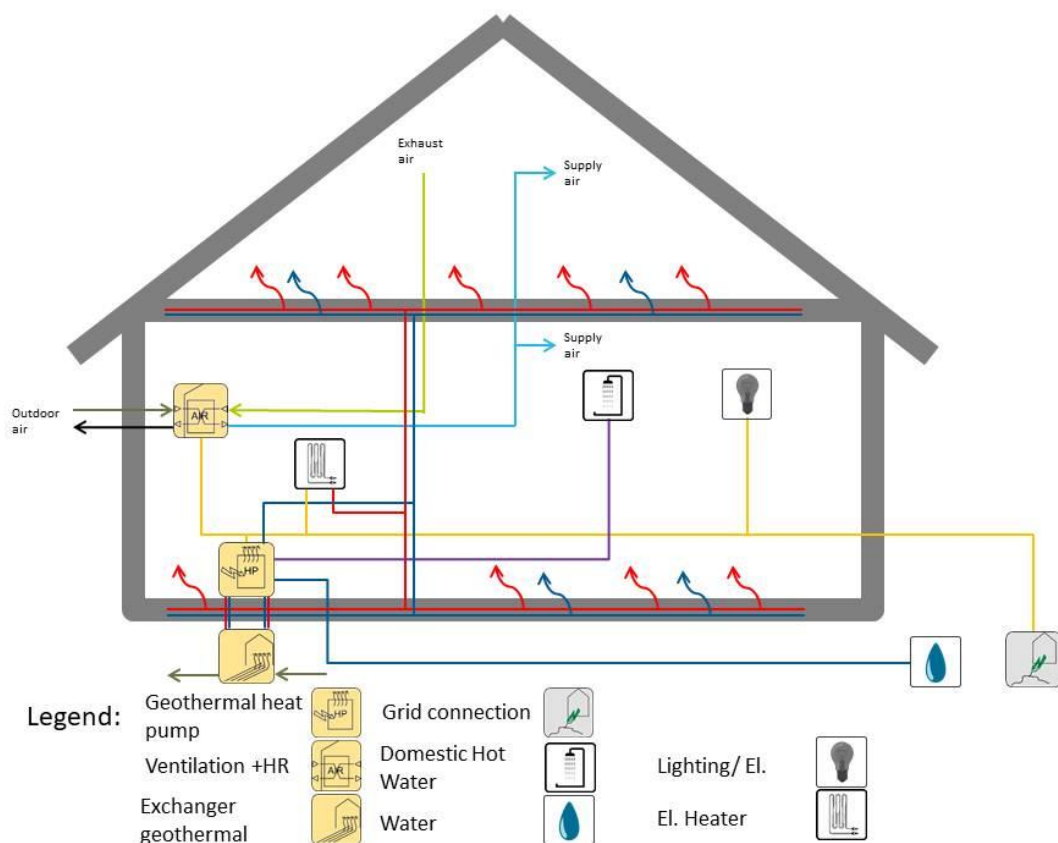Renewable electricity is partly generated on-site by a roof-top **PV** system.

Figure 67: Visualisation of technology set of the case study i+R-Headquarter

4. NH Tirol

The building is located in Innsbruck, Austria. It is a multi-story apartment building with a net floor area of 7,493 m² planned as a passive house. An **efficient building envelope** with an average U-value of 0.28 W/m²K to reduce the heating demand is the central element of the building. The single envelope components have U-values of 0.11 W/(m²K) (external wall against ambient air), 0.21 W/(m²K) (floor slab/ basement ceiling), 0.08 W/(m²K) (roof) and 0.72 – 0.75 W/(m²K) (windows).

The heat demand is further reduced by a **central mechanical ventilation system with heat recovery**, which also assures good indoor air quality. The installed system has a specific efficiency of 0.66 Wh/m³ and is designed for an average air change rate of 0.36 h⁻¹. The effective heat recovery rate is 81 %. In the ventilation system, a subsoil heat exchanger with an efficiency of 25 % is integrated.

The heat is mainly supplied by a district heating system based on a gas-fired CHP covering about 70 % of the space heating and 40 % of the DHW demand. Furthermore, a **wood-fired boiler** plant is installed inside the building. The system is amended by **solar thermal collectors** with an area of 279 m² covering 42 % of the DHW demand. For connecting and managing all different supply technologies a **heat storage** with a volume of 2.5 m³ is integrated in the system. The overall efficiency of the system is supported by the low supply temperature (36°C) of the heating system.
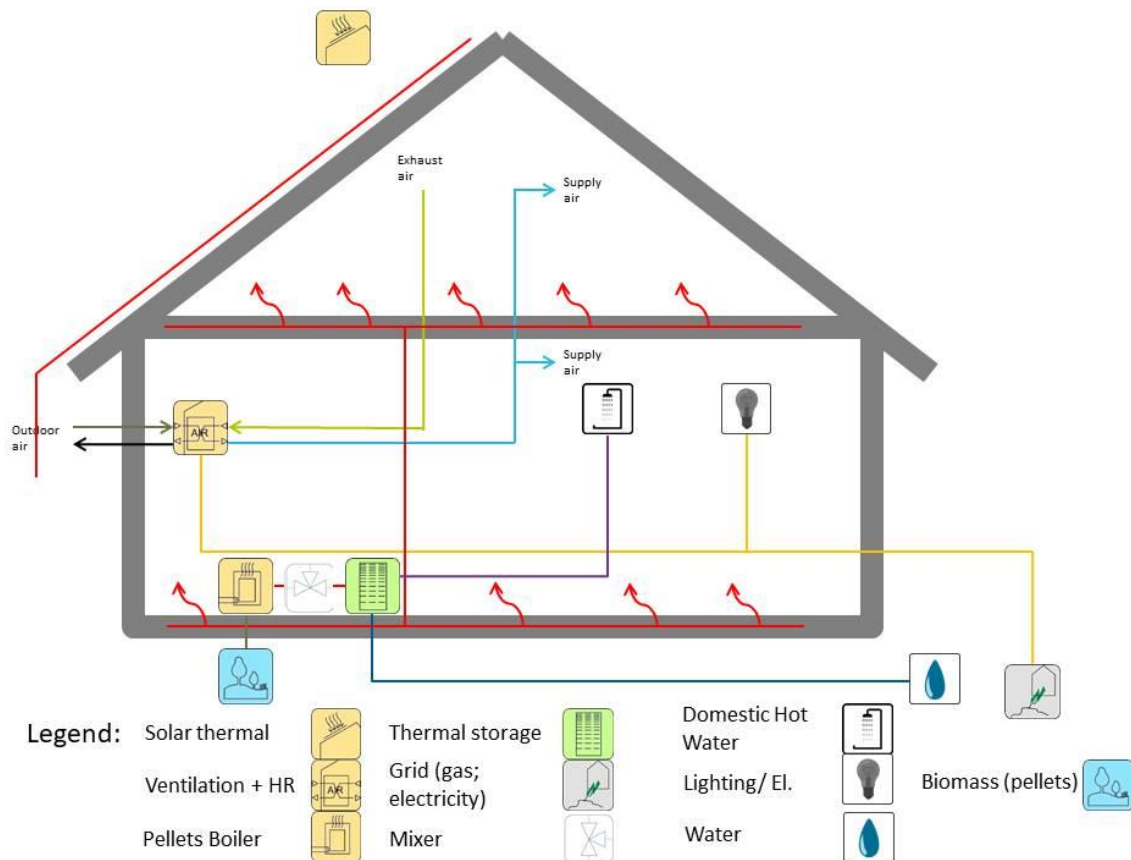

Figure 68: Visualisation of technology set of the case study NH Tirol

5. Väla Gård

Väla Gård is a two-storey office building with a net floor area of 1,670 m², built in the southern part of Sweden (Helsingborg). The strategy for reaching a Net ZEB balance was a three-step approach. Firstly, the **thermal losses and heat gains were reduced** in order to have a low heating and cooling demand. Secondly, a GSHP was chosen in order to lower the need for imported energy. Thirdly, the building was equipped with PV panels to generate renewable energy.

The foundation is a concrete slab on ground with 350 mm of underlying expanded polystyrene (EPS), giving a U-value of 0.08 W/m²K. The external walls are concrete walls with 295 mm external insulation, giving a U-value of 0.11 W/m²K. The roof is insulated with 370-520 mm insulation, giving a U-value of 0.08-0.10 W/m²K. Windows were mounted with a U-value of 0.90 W/m²K. The glazed entrance has a U-value of 1.00 W/m²K. Windows towards southeast and southwest have solar shading.

The ventilation was designed with a **mechanical balanced ventilation system with heat recovery** of 84 % with variable air volume (VAV). The ventilation is controlled by presence, temperature and CO_2. The ventilation operates Mon-Fri 6-18.

A **ground source heat pump** was chosen to produce space heating and hot water. Space heating is distributed via radiators. If there is a cooling demand, the airflow increases with cooled air in the room. If the supply air temperature is too high, the cooling coil lowers the supply air temperature using free **cooling from the boreholes** in the ground source heat system.

The lighting system consists of **energy efficient light fixtures**, which can be **dimmed and controlled by presence and daylight**. To minimize tenant electricity (reducing standby losses), the main part of the electrical outlets, plug loads, are turned off when the building alarm is switched on.

The building is designed with 288 **PV** panels with five inverters, giving the building an installed capacity of 70 kWp.
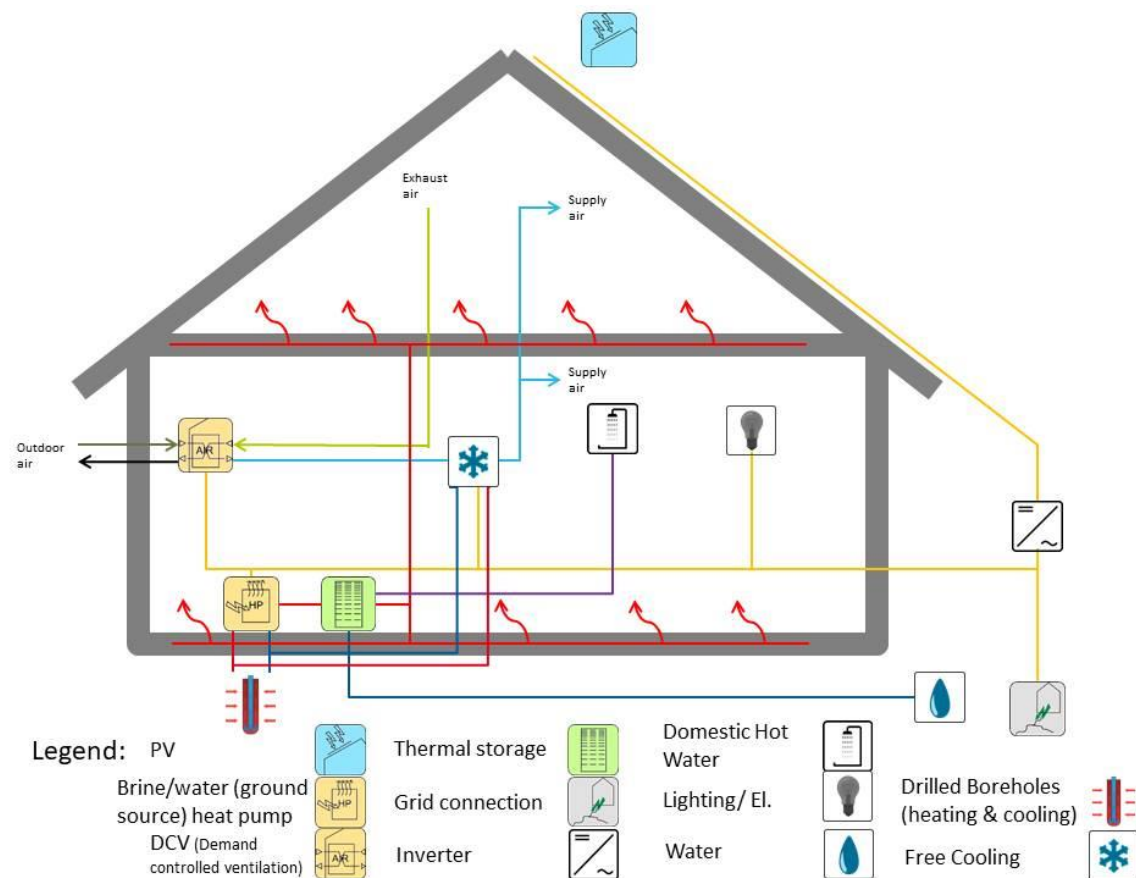

Figure 69: Visualisation of technology set of the case study Väla Gård

6. SUMMARY AND CONCLUSION

Several passive approaches to minimize the energy demand of a building under different climate conditions were assessed. The analysed factors were the building orientation, window-to-wall ratio, daylighting control and free ventilation. In the climate regions with a high heating demand (Germany and Sweden) the variation of the named factors lead to an increase in the heating energy demand and thereby also have a negative effect on the LCC of the building. A reason is that the base case is oriented to the south, which is the best orientation under these climate conditions, and every deviation from that reduces the solar gains and increases the heating demand. Concerning the window-to-wall ratio further increasing it decreases the heating demand in most cases (exception is increasing the WWR only on the west side of the building). The most significant effects concerning the heating energy demand are achieved when the WWR on the east and west side of the building are increased (WWR3; decrease of the heating energy demand of 12 % in Germany and 2 % in Sweden). However, an increase of the WWR increases the LCC as the specific costs of windows is higher than the specific costs of an excellent insulated external wall. The reduced heating demand is not refinancing the increased costs in the considered 40 years.

Using daylighting control strategies however do decrease the electricity demand for lighting by 3 – 6 %. Though, the effect on the overall energy demand and the energy costs is low as the electricity demand for lighting only has a share of 4 – 5 % in Germany and 1 – 2 % in Sweden.

The effects of the assessed passive approaches have a higher effect in climate regions with high cooling demand (southern Italy). With rising global temperatures due to climate change designing buildings to minimize cooling demands gains importance also in moderate climates as cooling demands might rise there. Orienting the case study building north instead of south can reduce the cooling energy demand by 5 %. An even higher effect on the cooling demand is achieved by free ventilation. The analysed strategies reduce the cooling energy demand by 18 – 22 % compared to the base case (south orientation).

Increasing the WWR has a strong negative effect on the cooling energy demand; without adding additional external shading, the cooling demand is increased by 64 % when the WWR is increased on the east and west side of the building. Generally one can say that large window areas should be avoided in hot climates as the high solar gains in summer (i) negatively influence the comfort and (ii) lead to very high cooling energy demands (and loads).

Applying daylighting control in southern regions has a higher effect than in northern climates as more daylight is available. Daylighting control can reduce the electricity demand for lighting in Italy by up to 9 %.

The best variations of the different parameters for the different climate regions are summarized in Table 33.

The analysis of the variants with the highest and lowest NPV as well as the ones with the highest and lowest CO_2 emissions based on the parametric analysis conducted in WP06 shows that non-technical factors have a strong influence on the energy demand, emissions and NPV of a building. These are (amongst others) the user behaviour and climate conditions. Furthermore, a building envelope at least having an nZEB standard – in many cases even a higher standard – is an important component of low emission and low-cost buildings. In these buildings, DHW is in most cases dominating the final energy demand. An interesting finding of analysing the variants with the lowest NPV and lowest emissions is that in most cases these variants have less technical installations than the base cases and can be considered as low tech buildings. Minimising the technical installations is, on the one hand, reducing the investment as well as operation and maintenance cost and on the other hand minimises the auxiliary energy demand. Furthermore, an active use of solar energy (mainly PV, in several cases, also solar thermal) is essential for achieving minimal CO_2 emissions. Solar technologies are often competitive with other technologies and es-

pecially in the case of PV have positive effects on the costs/ NPV. The analyses of the passive approaches and also of the results of the parametric analysis show that there is not one optimal solution for every setting and side conditions. Furthermore, the goal (minimal costs, minimal emissions) of a design team/ building owner is strongly influencing the technology set and building concept.

Focus on own simulations: energy and costs

The results used for the analysis of the low cost and low emission technology sets can be accessed in the CRAVEzero pinboard: https://www.cravezero.eu/pinboard/Dashboard/DBInfo.htm

Table 33: Best variations of the assessed passive approaches in the different climate regions. The achieved energy demand reduction is presented in brackets.

	Building orientation	Window-to-wall ratio	Daylighting	Natural ventilation
Germany	South (Base case)	WWR3 (heating demand -12 %)	WWR3 with daylighting control (electricity demand for lighting -6 %)	-
Sweden	South (Base case)	WWR3 (heating demand -2 %)	WWR3 with daylighting control (electricity demand for lighting -5 %)	-
Italy	North (cooling demand -5 %)	Base case	WWR3 with daylighting control (electricity demand for lighting -9 %)	Vent3 (cooling demand -22 %)

7. REFERENCES

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