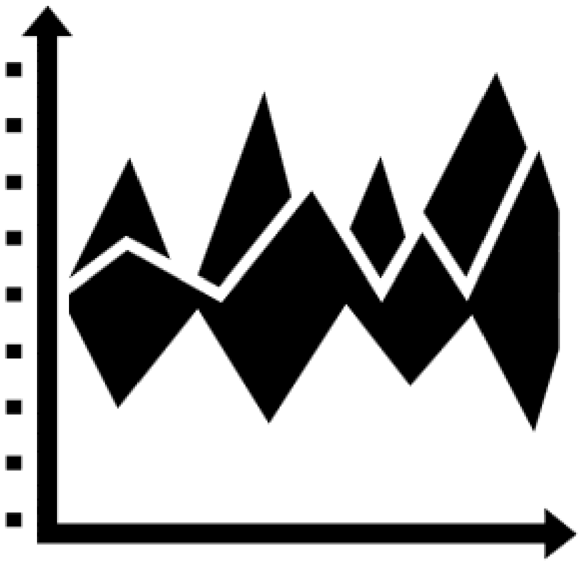
CRAVEzero

D4.3: Energy flexible building managing models



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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D4.3: Energy flexible building managing models

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FOREWORD

This report is under the Work Package 'WP04 – Cost reduction potentials for nZEB technologies', part of the Horizon2020 - CRAVEzero project.

This report summarises results of Work Package 'WP04 – Cost reduction potentials for nZEB technologies', task 4.3 'Adaptive and flexible energy building for a cost-effective operation'. 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 and for the market uptake of energy flexible building operation also adjustments in the energy market design. 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.

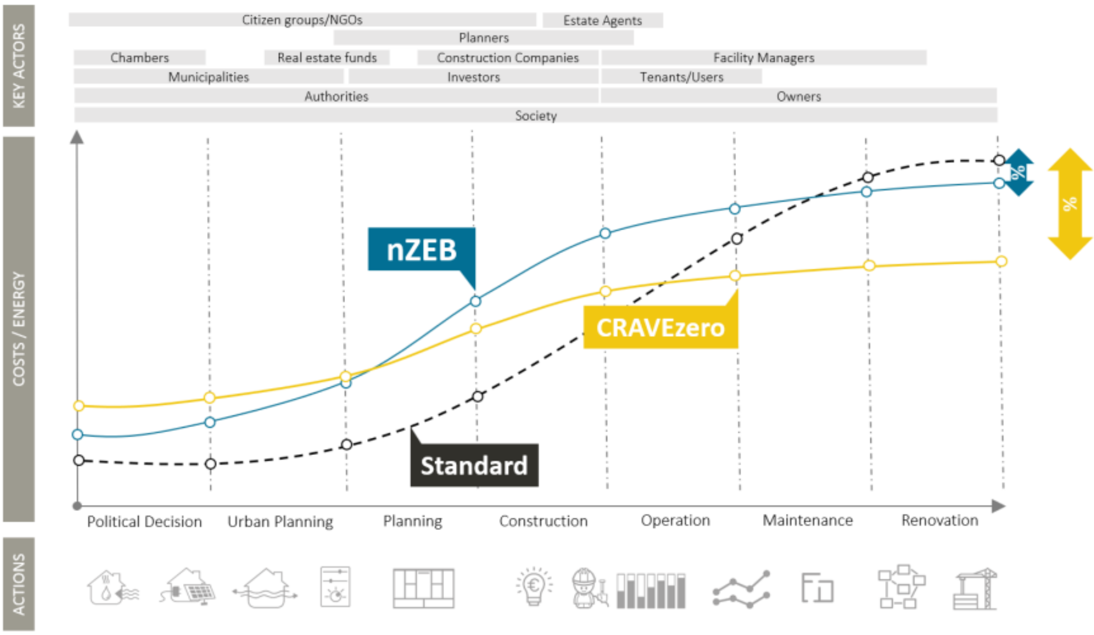

Figure 1: CRAVEzero approach for cost reductions in the life-cycle of nZEBs.

EXECUTIVE SUMMARY

Already today buildings can be realised in the nearly-zero and plus energy standard. These buildings achieve extremely low energy demands and low CO_2 emissions and can be operated economically. For this reason, the motivation in the CRAVEzero project is not only based on the energy characteristics of buildings, but also on their life-cycle costs and building operation, which is supporting the large-scale integration of fluctuating renewable energies in the building itself, but also in higher-level electricity grids. For the integration of fluctuating renewable energies (i) the integration and intelligent operation of storages (electric and thermal) as well as smart operation and management strategies are needed.

In the first part of the deliverable the theoretical background of the interaction between buildings and grids and flexibility options (technical, operational) are described. Furthermore, existing and new KPIs to analyse the flexibility of a building as well as the ability to integrate renewable energies in the building and higher-level grids are introduced. The assessed KPIs are:

- Self-consumption
- Autarky rate
- Grid-supportiveness coefficient (GSC)
- Smart readiness indicator (SRI)

In contrast to the first three KPIs, the latter is a based on a more qualitative approach compared to the others, which have a more quantitative character. In order to quantify the effect of different technology sets on the quantitative KPIs the two case studies “Brussels” located in Germany and “Moretti More” located in Italy are analysed in detail. Furthermore, the smart readiness of the buildings as they are built / planned is analysed based on a methodology currently discussed in Europe.

With an increasing complexity of the technology sets in buildings, but also of the requirements for the operation (support of grid stability, on-site integration of renewables, increased comfort requirements) a robust and reliable operation is essential. The process of continuous commissioning is one approach to increase the reliability and robustness of the planning, construction, commissioning and operation of buildings. As these factors are also essential for a flexible operation of a building the process of continuous commissioning is also described in this deliverable.

As a major goal of the CRAVEzero project is the cost reduction throughout the life-cycle of a building, possible cost savings are also assessed. As the building management models are mainly addressing the operational phase of a building, possible cost savings in this phase of the life-cycle are the focus of this deliverable. A detailed assessment of the investment and life-cycle costs of different technology sets are described in the publications of Work Package WP06.

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

- For the integration of renewable energies in buildings as well as a flexible building operation to support the integration of renewables in higher level grids different storage possibilities (thermal and electric) are needed in the building
- The technology concepts for increasing the self-consumption as well as the GSC with respect to electricity prices and the residual load are comparable and optimising / increasing one of the KPIs also positively influences the others. However, aspects / technologies increasing the autarky rate of a building are decreasing the other KPIs; one can conclude that an increasing autarky is negative for an improved / optimised building-grid interaction, especially when the goal is to support the broad scale integration of renewable energies on national / European level.
- If technologies for an improved building-grid interaction are installed in buildings, it is necessary to change the current operation mode (focus on heat demand) and proved possibilities to integrate additional (external) signals in control strategies
- For a market uptake of needed technologies, but especially for the broad implementation of the required control strategies adjustments in the energy markets are essential.

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LIST OF ABBREVIATIONS

BACS	Building Automation and Control Systems
BES	Building Energy System
BIM	Building Information Modelling
Cx	Commissioning
CCx	Continuous Commissioning
CHP	Combined Heat and Power
COP	Coefficient of Performance
DH	District Heat
DHW	Domestic Hot Water
DR	Demand Response
DSM	Demand Side Management
DSO	Distribution System Operators
EBC	Energy in Buildings and Communities
EE	Energy Efficiency
EEX	European Energy Exchange
EMD	Electricity Market Directive
EPBD	Energy Performance of Building Directive
EV	Electric Vehicle
GSC	Grid Support Coefficient
HP	Heat Pump
IAQ	Indoor Air Quality
I-Cx	Initial Commissioning
IEA	International Energy Agency
KPI	Key Performance Indicator
MBCC	Model-based Continuous Commissioning OR Monitoring-based continuous commissioning
nZEB	Nearly zero-energy building
NZEB	Net zero-energy building
On-Going-Cx	On-Going Commissioning
PH	Passive House
PHPP	Passive House Planning Package
PV	Photovoltaics
RES	Renewable Energy Sources
Re-Cx	Re-Commissioning
Retro-Cx	Retro-Commissioning
SR	Smart Readiness
SRI	Smart Readiness Indicator
TBS	Technical Building Systems

1. INTRODUCTION

The increasing share of fluctuating renewable energy generation in the electricity grids requires technical measures, new market designs and models to balance generation and demand for electricity on the demand and supply side. As buildings are major energy consumers in the energy system and electricity for heating, domestic hot water and cooling, as well as on-site electricity generation from renewables is increasing, the integration of building energy systems/ buildings in the energy system is gaining importance. Renewable electricity is generated on-site, stored in batteries, which could also be used for balancing the local distribution networks, heat-pumps and electrical vehicles are new electrical consumers in buildings with relatively high connected power,…there are many new and already established technologies, which have to be integrated in the system and operated in a way stabilizing the electricity grids.

In the first part of this document, the theoretical background of buildings and their interaction with the electricity grid, flexibility options in buildings as well as KPIs in the field of energy efficiency and flexibility are described. Furthermore, processes to improve the quality of buildings and the functionality of their technical installations are introduced.

In the second part, different options and the needed technologies to provide flexibility are described and applied in some of the CRAVEzero case study buildings. The options are then compared using three different approaches/ KPIs, namely:

- Self-sufficiency/ autarky rate based on Results of the tool PVopti
- Analysis of the Grid Support Coefficient GSC developed at Fraunhofer ISE
- Analysis of the Smart Readiness of the buildings based on the current status of the definition of the Smart Readiness Indicator, which might be introduced on the European level in the future.

Similarities, as well as contradictions of the approaches, are highlighted.

In the document at hand, the term "model" refers to the qualitative description of technological sets, operations strategies and characteristics of building-grid interactions. It does not include the development and description of mathematical/ physical models for the energy flexible building operation.

1.1. OBJECTIVE

The aim of the deliverable is the development and description of models and methodologies for (i) continuous commission of buildings and (ii) building-grid interaction with a focus on the on-site use of renewable energies. The deliverable thereby addresses two major challenges of the future, which are (i) the reduction of the energy use in buildings and avoidance of mal-functions in the building energy system and (ii) the integration of fluctuating renewable energies in the electricity grid by adjustments in the building operation.

The process of continuous commission is described based on a detailed literature review as well as on results from projects focusing on fault detection in large and complex building energy systems.

For the integration of renewable energies in the electricity grid by an adjusted building operation, the definitions and findings from the IEA EBC Annex 67 "Energy Flexible Buildings" are the basis. Possibilities for an improved building-grid interaction are described qualitatively and assessed quantitatively using different approaches/ tools and a comparison of the respective results. The quantitative analysis uses the PHPP-models of case studies as a starting point. With the tool PVopti[1], the self-consumption and autarky level of the base case and several other technology sets is assessed, and for each case hourly electricity profiles are generated. The hourly profiles are used in a second step to analyse the grid supportiveness of the building/ technology set using a methodology and indicator (Grid Support Coefficient GSC, see chapter 3) developed at Fraunhofer ISE. In addition, the case study buildings assessed in detail are rated using a

[1] http://annex67.org/publications/software/pvopti/

simplified method for rating the Smart Readiness of Building (Smart Readiness Indicator SRI) based on the proposed Simplified online quick–scan described in (Reynders, 2019).
The differences between the approaches and the respective results are compared, analysed and critically discussed. The aim is to identify different implications for the building technology sets from the different approaches resulting from the different focuses (self-consumption, grid-supportiveness,…).

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 development of guidance for continuous commissioning. Continuous commissioning in this context is understood as a process throughout the life-cycle of the building. Critical tasks and aspects of continuous commissioning are described. The focus thereby lies on the reliable and energy-efficient operation of a building.
The second task, which is also the main focus of the deliverable, is the development of building managing models and the building-grid interaction. The reason for focussing on this task is described above in the general introduction. The theory, KPIs and different (rating) schemes described and applied in this deliverable should enable facility managers, owners and users to exploit demand/response logics for a higher load matching and a better grid interaction of their buildings and technical installations. The focus thereby lies on the integration of fluctuating renewable electricity generation. Such models will be coupled with technology concepts, including needed hardware components.

2. THEORETICAL BACKGROUND

The integration of decentralized electricity production from renewable energy sources plays a key role in a sustainable energy system, mitigating fuel poverty and climate change. In many countries, the growing share of renewable energy sources (RES) goes in parallel with the extensive electrification of demand, e.g. replacement of traditional cars with electric vehicles or displacement of fossil fuel heating systems, such as gas or oil boilers, with energy-efficient heat pumps. At the same time renewables support the operation of low-temperature district heating grids. These changes in both the demand and supply side impose new challenges to the management of energy systems, such as the variability and limited controllability of energy supply from renewables or increasing load variations over the day (Denholm and Hand, 2011; Morales et al., 2014). Consequently, managing the energy transition following the traditional way would lead to a grid operation closer to its limits, with a possible consequent increase of the energy use at peak periods, requiring more complex control problems with shorter decision times and smaller error margins (Moslehi and Kumar, 2010).

Therefore, flexible energy systems are often named as an essential part of the solution. Flexible energy systems overcome the traditional centralized production-oriented approach, whereby the production follows the demand by integrating decentralized storage and demand response (DR) into the energy market. In this context, strategies to ensure the security and reliability of energy supply involve simultaneous coordination of distributed energy resources, energy storage and flexible schedulable loads connected to distribution networks (Baillieul et al., 2016).

As buildings account for approximately 40% of the annual energy use worldwide (United Nations Environment Programme, n.d.), they are likely to play a significant role in providing resilient and efficient operation of the future energy system. Hence, they may deliver significant flexibility services to the overall energy system by intelligent control of their energy loads, both thermal and electric. Therefore, it is acknowledged that the interactions between buildings and the energy infrastructure in time and scale should be fostered in order to fully benefit from the potential of renewables and mitigate CO_2-emissions on an aggregated level for achieving the intended de-carbonization of energy services until 2050. Consequently, building design and control goes beyond that of individual buildings.

To understand and integrate the potential of smart buildings in future energy systems, a holistic approach is needed harmonizing building and energy system engineering but also energy market design and even occupant interaction.

Within IEA EBC Annex 67 it was shown that a common terminology, methodology and labelling approach defining flexibility and smart readiness of buildings is currently missing, both at the single building and at the clusters of buildings level (Jensen et al., 2017). As building engineers are often not familiar with all technical aspects of energy networks and vice versa, the use of a set of flexibility indicators that are easy to understand by both parties should be targeted. These indicators should facilitate design and operational decisions on both building and energy system level, taking into account the complex interactions between building, energy system, occupants and other boundary conditions, e.g. RES availability, weather conditions (Junker et al., 2018).

2.1. BUILDINGS AND THEIR INTERACTION WITH GRIDS

Buildings interact with surrounding energy systems by importing and exporting energy (Salom et al., 2014). Usually, the focus is the **interaction** with the electricity grid. With the increasing usage and integration of fluctuating renewable energy technologies like wind and photovoltaic in buildings and electricity grids, the interaction between all participants (energy consumers and producers, as well as prosumers) is gaining importance. In order to support the integration of fluctuating renewables the import and export of buildings should be oriented on the current state of the superordinate power grid by increasing the flexibility of the energy supply and demand of the buildings. In (Weiß et al., 2019a) flexibility is described as the maximum time a power draw can be postponed or additionally consumed at a specific moment during the day.

In (Voss et al., 2010), the importance of building-grid interaction to realise net-zero-energy buildings (NZEBs) is emphasized. The interaction/ energy exchange with a grid infrastructure helps to overcome limitations of on-site seasonal energy storage. Grid interaction is defined in (Voss et al., 2010, p. 2) as "the temporal match of the energy transferred to a grid with the needs of a grid". In the following important terms and approaches to manage and optimise the interaction between energy grids and buildings as well as strategies to increase the intelligence of energy systems and buildings are described. Furthermore, approaches to quantify the ability and level to operate buildings in a way, which is helping to stabilize and manage the grids and thereby integrate an increasing share of fluctuating renewables are introduced.

Demand Side Management (DSM) can be used to manage the load curve of buildings, such as shift demand in time (load-shifting), reduce the peak in the energy demand (peak-clipping/load shaving) or temporally increase the load when the incentives are high, or the electricity prices are low (valley-filling) – see Figure 2. The relevance and possibilities for the different DSM approaches in several European countries and Alberta are shown in Figure 3, which illustrates the electric load in 2011 in January (winter), April (spring), July (summer) and October (autumn).

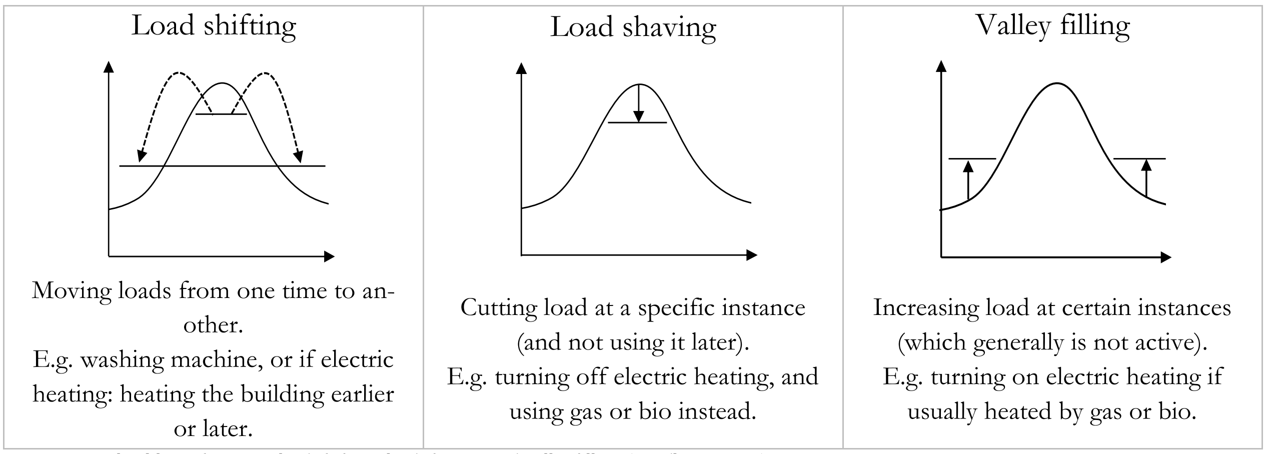

Figure 2: Flexible mechanisms: load shifting, load shaving and valley filling (Lindberg, 2017).

DSM is defined from a utility perspective as "the planning and implementation of those electric utility activities designed to influence customer uses of electricity in ways that will produce desired changes in the utility's load shape" (Gellings, 1985), and can be divided into two categories like energy efficiency (EE) and **demand response (DR)** (Palensky and Dietrich, 2011). The benefit of DR strongly depends on the available energy flexibility and successful implementation of DR programs. Hence, most state-of-the-art literature is focusing on demonstrating to what extent this can reduce energy cost, shift peak power, increase the use of local renewable electricity production, or achieve stability in the power grids by utilizing the flexibility of buildings.

In this context, the term "**grid-supportive**" operation of buildings is introduced and discussed in science, e.g. in (Klein, 2017). The goal of analysing and quantifying the grid supportiveness is to understand how and to what extent buildings can contribute to "efficient integration of a high share of intermittent renewable energy into the energy system" (Klein, 2017, p. 17). The focus is the support of the overall upstream energy system, not only local/ regional grids. "Grid-supportiveness" is defined by (Klein, 2017) as an operation of variable electrical loads in a way that they consume power predominantly in periods with low relative electricity demand in the system. Thereby, not only power load needs are considered, but also the availability of fluctuating renewable energies. On the other hand, a grid-supportive generator produces mainly when the relative electricity demand in the whole energy system is high (Klein, 2017). The contrary behaviour is termed **grid-adverse**. For measuring/ quantifying the grid-supportiveness, (Klein, 2017) developed the absolute Grid Support Coefficient GSC_{abs} and the relative GSC_{rel}, which are introduced in chapter 2.3.

One of the key barriers jeopardising the market uptake of smart technologies is the lack of clarity about the energy benefits. There are few studies about the impacts of implementing smart home devices in buildings, and there is a lack of independently verified empirical data on savings impacts (Urban et al., 2016), evaluated with a shared approach. The EPDB Recast 844/2018 (The European Parliament and the Council of the European Union, 2018) introduced the **Smart Readiness Indicator (SRI)**, in order to raise the awareness amongst building owners and occupants of the value behind smart devices and services, giving confidence to the occupants about the actual savings of those new enhanced-functionalities. It therefore measures the readiness of the building "to adapt the operation of buildings to the needs of the occupants and the grid and to improve the energy efficiency and overall performance of buildings" (The European Parliament and the Council of the European Union, 2018).

From the view of a building, the logic behind this EPBD amendment is: It is intelligent only with minimum equipment of smart technologies and services. What might be missing, displaced or even able to generate resistance:

- These technologies and services do not guarantee that the building is intelligent in the context of the surrounding energy networks (electricity, heat and gas) or that it helps to lower the CO_2 emissions of the overall energy system. In the context of a neighbourhood or the surrounding network, however, the energy flexibility and "smartness" of buildings are essential resources for reducing CO_2 emissions at this level, in line with the IEA EBC Annex 67.
- Measured or achieved "smartness" could cause additional costs, which preclude the required affordability of housing. And there are fears that "grid-supportiveness" - if it is applied - would by no means be adequately remunerated by the utilities.

A consortium led by the Flemish Institute for Technological Research NV ("VITO") has been awarded the contract for the implementation respectively the concept of the SRI. If their proposal is accepted by the European Commission through parliament and council, the implementation respectively the ascertainment will be up to the individual states. The preparation of a possible national specification of the SRI as well as the possible integration in the process of energy performance calculation can still be influenced since the preparation process is on-going.

AEE INTEC is involved in the development of the calculation methodology, which is based on a technology and services rating system, weighting different services by their functionality level effecting predefined impact criteria (Reynders, 2019; Verbeke et al., 2018). Such effects are pre-calculated for the smart devices and services available on the market, but they are not associated either to physical nor to performance quantities. This should be noted and kept in background knowledge when new SRI developments are integrated into the work in CRAVEzero to assess the technologies' and building services' smartness found within CRAVEzero demonstration projects to learn from.

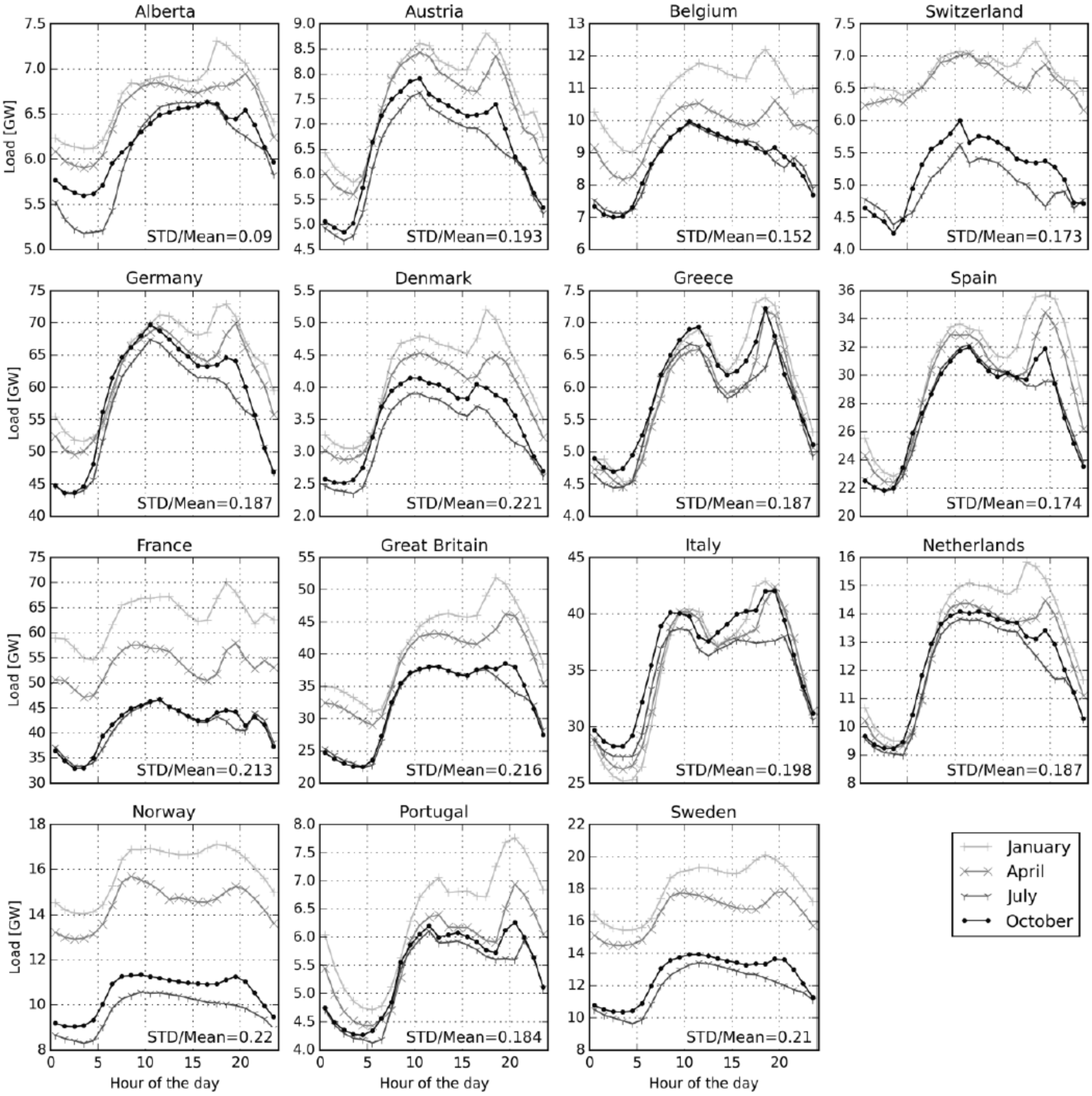

Figure 3: Aggregated daily profiles of the elctric load in several European countries and Alberta in 2011 for one month in winter, spring, summer and aurumn; source (Klein et al., 2016a).

2.2. FLEXIBILITY OPTIONS AND THEORETICAL POTENTIAL

In general, the potential flexibility is mostly used to minimize energy cost or procurement cost of purchasing electricity and heat from the energy networks, to increase the share of RES in the distribution networks, or to develop the ability of real-time matching of consumption and generation to keep the stability of the grid. So energy flexibility could be expressed as power [kW] and/or energy [kWh] that can be shifted - increased or decreased – in reaction to an external signal (within IEA EBC Annex 67 called "Penalty signal") without jeopardizing the indoor comfort over a specified time span. Consequently, the pivotal challenge in characterizing flexibility is to find a common language to describe the shape, these energy or power shifts can take, also considering the objectives (activations), the constraints, the time period (minute, hour, month or year) and the corresponding optimal control strategies. For instance, a storage system that can shift a certain amount of energy for a long period of time can be considered to be more flexible than another system, which can only shift the same amount of demand for a short period of time. And accordingly, a system shifting a high amount of energy has more flexibility compared to a system shifting a low amount of energy during the same period.

Within a building energy system (BES), there are several technical flexibility options as shown in Figure 4. According to Klein (2017) the central options are:

- Batteries: create a time shift between net power load and demand.
- Fuel switch: used to alter the relation between net power demand and thermal generation by switching between electric and fossil thermal generators.
- Thermal storage units: used to create time shift between heat generation and delivery.
- Thermal building mass: used for thermal storage by modifying heat delivery trajectory into a zone, respectively heat emission system.

Concerning the quantification of the technical potential for flexibility in buildings on international and national level more research is still needed. There were already several projects carried out to assess potentials in specific building types or industry / services sectors. However, an overall quantification is still missing.

For residential buildings in Germany, Lüking and Hauser (2011) calculated a theoretical load shifting potential of 1 TWh_{th}. Kohlhepp and Hagenmeyer (2017) calculated the existing technical potential of building energy systems in residential and non-residential buildings in Germany. They calculated a maximum potential of 20 GW_{el} during the heating season and 4 GW_{el} during the cooling season and a thermal shifting potential of 209 GWh_{th} mainly in residential buildings.

There are several more studies available. However, their results strongly differ in their findings and values. In Germany, the maximum shiftable electrical load in buildings is expected to be around 20 GW_{el} from which about 25 % can be economically be used in the future (mainly heat pumps and cooling units). Compared to the currently provided flexibility of large power plants (about 80 GW_{el}) this is a relatively low potential (compare (Jansen et al., 2015)). Furthermore, the expected increase of fluctuating renewable electricity generation form wind and PV requires large flexibility on the consumption side; according to Hartmann (2013) up to 139 GW_{el}. This large demand for flexibility shows that:

(i) All usable flexibility options have to be used in order to integrate large amounts of renewable electricity in the energy system, and
(ii) Other / additional technical flexibility options are needed in the future (e.g. central electricity storages, thermal storages with power-to-heat, curtailment of renewables).

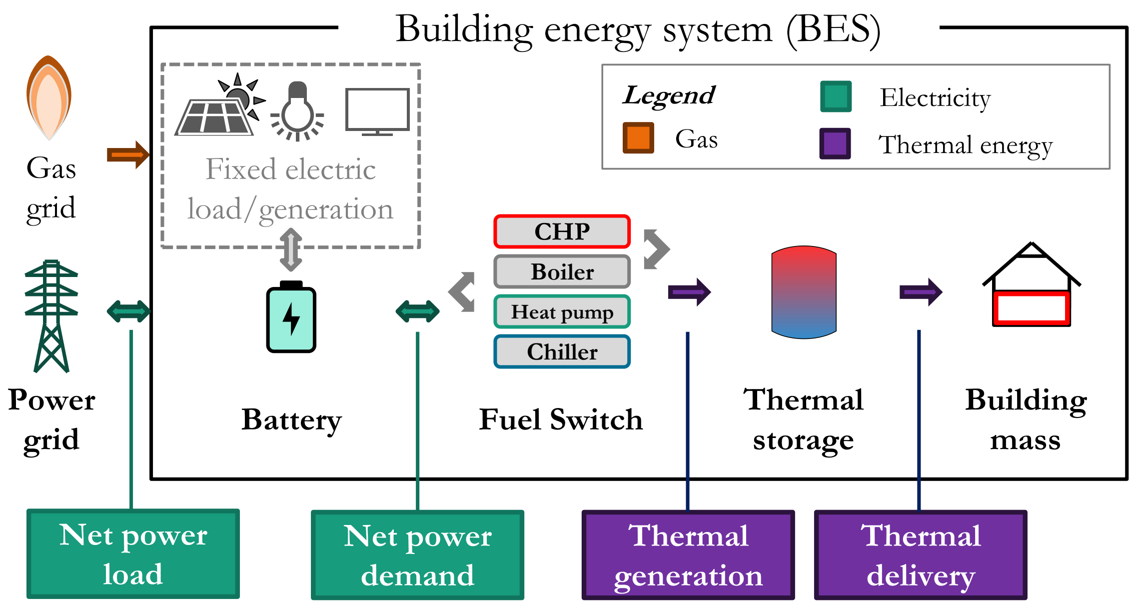

Figure 4: Flexibility and storage options within a building energy system (BES); (Klein, 2017)

2.3. KPIS TO MEASURE ENERGY PERFORMANCE

In the Clean Energy Package launched by the European Commission in November 2016 the need for Energy Flexibility in buildings is underlined. As described in Pernetti et al. (2017) Distribution System Operators (DSO) are challenged to actively take part in and exploit flexibility on a local level in order to use the existing grid more efficiently by proposed changes of the Electricity Market Directive (EMD). Moreover, the establishment of a flexibility market is expected. In (Pernetti et al., 2017) it is said that "*Buildings are expected to become "smart" and contribute to user comfort as well as in the flexibility market, which is underlined by the latest proposed amendment of the Energy Performance of Building Directive (EPBD) 2017. Nevertheless, the currently discussed Smart Readiness Indicator (SRI) differs from the IEA EBC Annex 67 approach. The study on SRI is defining a method for calculating affordably and efficiently a SRI, mainly rating different smart services integrated into buildings.*"

There are several indicators in literature for quantifying energy flexibility, dealing with the following three main levels: economic level, thermal level, grid control level, and there has been a lack of a unique and comparable quantification of energy flexibility in buildings.

By the IEA EBC Annex 67 a physical data- and simulation-based approach with quantitative indicators is proposed (Pernetti et al., 2017). "*As such, the method enables quantification and prediction of the building Energy Flexibility supporting decisions at both building and aggregated level during design and operation. In defining a quantitative and data-driven or simulation-based approach (that could also be based on simulations), IEA EBC Annex 67 acknowledges that Energy Flexibility is not only the result of the available technologies in a building but depends significantly on the way these technologies are used – i.e. controlled – and their interaction with the surrounding energy network, the occupants and other boundary conditions, such as local climate*" (see (Pernetti et al., 2017, p. 7).

The general methodological approach is based on the step-response function that characterizes a building under a so-called penalty signal (Junker et al., 2018), representing a variable boundary condition (e.g. electricity cost, CO_2 content of the energy) driving the control of a flexible building configuration. The amount of the consumed energy that can be shifted from the operation with a control not-aware of the penalty signal and the energy consumed from the building with the flexible operation (i.e. controlled considering the penalty signal) represent the amount of flexibility that can be offered by the building.

Going more in detail, the Figure 5 reports the step response function, describing the flexible behaviour of a building, in terms of:

- τ (Time): Delay from the penalty increase (or decrease) to initial response of the building.
- Δ (Power): Maximum change in the building response and it represents the maximum flexibility that a building can offer.
- α (Time): The time it takes from the start of the response to the maximum response.
- β (Time): time-interval of the consumption reduction following a penalty
- A (Energy): The amount of energy demand saving during the response
- B (Energy): The total amount of increased energy consumption due to the rebound effect.

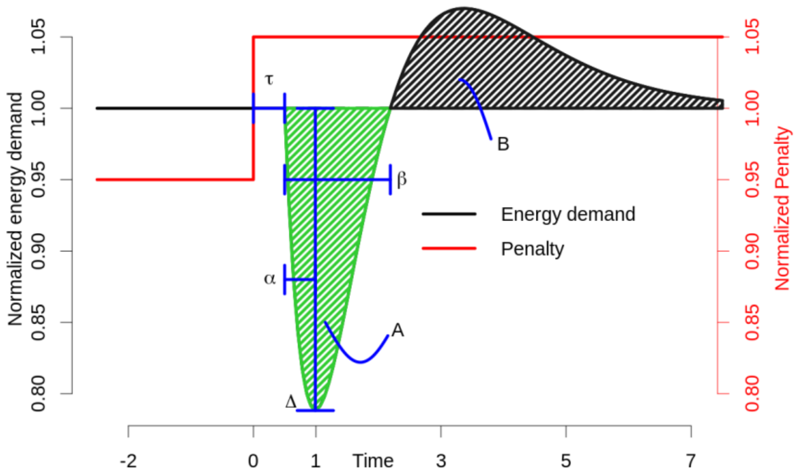

Figure 5: Description of the expected response of an energy flexible building exposed to a step increase in penalty signal, source (Pernetti et al., 2017)

For the analysis described in the following chapters, four KPIs/ approaches for describing the energy flexibility of a building are applied. These are:

- **Self-consumption rate**
- **Autarky rate**
- **Grid Support Coefficient (GSC)**
- An indicator based on the current development status of the **Smart Readiness Indicator (SRI)**

The KPIs / approaches are described in detail in chapter 4.

3. TECHNOLOGY CONCEPTS

The relevant technologies and technology sets for the energy flexibility of buildings can be derived from Figure 4. It shows the importance of renewable energy generation on-site, storage technologies (electrical and thermal) as well as heating and cooling technologies, which link the electricity with the thermal sector in the energy system as a whole, but also within single buildings (e.g. CHP, Heat-pump). In the following, the most relevant technologies are described based on Deliverable 4.1 (Köhler et al., 2018). Furthermore, promising technology sets providing different options for the energy flexibility in buildings are described briefly.

Renewable energy Generation:
The on-site generation of renewable electricity, as well as the self-consumption and feed-in patterns of these installations, have high relevance for the grid-supportiveness of a building. The primary source of renewable electricity on-site is PV. Another, not comprehensive source are small wind turbines, e.g. on roof-tops.

In (Köhler et al., 2018) the major economic parameters of PV (learning rates, investment costs, possible cost savings) are described. PV has a considerable cost reduction potential. In (Köhler et al., 2018) a decrease by about 49 % from 1,370 €/kW_p to approx. 700 €/kW_p (610 €/kW_p to 810 €/kW_p; -41 % to -56 %) is expected.

In (Bürger et al., 2015) three main technological fields are distinguished: silicon PV, thin-film and new technologies (III-V, organic PV). Currently, available silicon PV-modules achieve efficiency of 13 % to 18 % and an increase to up to 26 % is expected (compare (Bürger et al., 2015)). Thin-film technologies have slightly lower efficiencies (6 % to 13 %) but might achieve efficiencies of up to 25 % in the future. The highest possible efficiency is expected for III-V-concentrating PV modules with an efficiency of up to 45 %. However, the latter is most likely not applicable on/ at buildings.

Besides the installation on roof-tops, building-integrated PV as well PVT-collectors gain importance. They (i) can activate more areas for the on-site energy generation from renewables and (ii) allow more efficient usage of the solar irradiation. An additional advantage of building-integrated PV is that the modules can replace other building envelope elements, which can lead to overall cost savings.

Electricity storage/ batteries:
Stationary batteries are increasingly important, especially in combination with fluctuating renewable electricity generation on-site. In (Köhler et al., 2018) the focus of the analysis was on lithium-based batteries as they appear to be the most important technology for electrical storages in buildings in the near future (Taiyou Research, 2014). In 2016 the average cost of Li-batteries was approx. 860 €/kWh (Köhler et al., 2018). Until 2050 a cost decrease of 48 % to 78 % (average 64 %) to approx. 300 €/kWh is expected. In (Henning and Palzer, 2015) an electrical efficiency of stationary batteries in buildings of up to 95 % is expected.

At the interface between electrical and thermal energy, the so-called fuel switch is an essential possibility to react to e.g. grid signals and provide flexibility to the electricity grid. Of major importance are technologies which connect these types of energy (mainly heat-pumps and CHP), but also technologies which allow switching off electrical loads (heat-pump) or electricity generators (CHP) when needed while assuring the supply of the needed thermal energy (boilers).

Heat-pumps:
Heat-pumps (combined with thermal storage) are seen as the most essential heating technologies in future energy systems based on fluctuating renewable electricity (compare, e.g. (Bürger et al., 2015; Henning and Palzer, 2015)). The leading technologies, which also have the highest importance for the building-grid interaction, are electricity driven aerothermal and ground-source heat-pumps; gas-driven and other heat-pumps are not considered in the scope of this deliverable. Aerothermal heat pumps have slightly lower investment costs than ground-

source heat-pumps, but they also have lower efficiencies (COP of 2.9 to 4.3 compared to 3.1 to 5.7 for ground source heat-pumps; see (Bürger et al., 2015)). In (Köhler et al., 2018) a cost decrease from currently 1,190 €/kW_{th} to between 666 and 1,055 €/kW_{th} in 2050 is expected for aerothermal heat-pumps. In the same period the costs for ground source heat pumps are expected to decrease from 1,620 €/kW_{th} to between 1,080 and 1,496 €/kW_{th}.

Combined Heat and Power (CHP):

There are several technologies, which can generate electricity and heat simultaneously. They range from small Stirling engines, micro-gas turbines or fuel cells with an electrical power of just a few kW_{el} to large power plants up to 800 MW_{el} (Bürger et al., 2015). The most widespread CHP-technologies in buildings are small gas-driven cogeneration units. According to (Bürger et al., 2015) units with an electrical power of 1 to 10 kW_{el} cost between 3,200 and 9,300 €/kW_{el}. Generally, the specific costs sharply decrease with the installed electrical power. The overall efficiency ranges from 80 % to 90 %. In a mainly electrical energy system and buildings with a low heating energy demand, the electrical efficiency is increasingly important compared to the thermal efficiency of a CHP unit. Especially fuel cell CHPs have high electrical efficiencies of up to 65 % (compare (Bürger et al., 2015). However, the market is just starting to develop in Europe, and therefore the investment costs are still comparably high.

Boilers:

The most important boilers in Europe are gas boilers, which have a share of approx. 40 % in the heating technology stock (Fraunhofer Institute for Systems and Innovation Research et al., 2016). Gas boilers are an established technology and therefore it is not expected that the costs of currently approx. 170 €/kW_{th} will show a strong decrease in the future. Also the thermal efficiency will most likely not further decrease from currently approx. 95 % (based on calorific value).

Air-conditioners:

Most air-conditioners use electricity from running compressors to provide cold for air-conditioning in buildings. The technology is of major importance in southern European countries and not widespread (at least not in residential buildings) in central and northern Europe. According to (Köhler et al., 2018) the costs for air-conditioners are likely to fall from currently 210 €/kW to between 120 and 170 €/kW. According to (Bürger et al., 2015) COPs of 2 to >4 can be achieved (with desirable boundary conditions and good ambient heat sinks also higher COPs are possible).

Thermal storage:

For the flexible operation of CHP units or heat-pumps thermal storages are essential. Buffer storages are already established in buildings and therefore only slight cost decreases from 3.5 €/l to approx. 2.5 €/l are expected in (Köhler et al., 2018). In order to provide flexibility, the storage volume per kW_{th} installed in buildings might increase.

Building mass:

Besides standard thermal storages, the thermal mass of buildings can be activated with adequate heat and cold emission systems like concrete core conditioning (CCC) and thermally activated building systems (TABS). The activation of the thermal mass of buildings can provide flexibility of the heat or cold generation and supply of several hours. However, both systems are mainly relevant for new constructions. General/ Average cost information is not available. Also, efficiency is highly dependent on operation modes and site conditions. Therefore, no explicit values are presented here.

Technology sets:

In order to provide flexibility on different levels in a building's energy systems, different storages, as well as electricity generating and using technologies, are needed. For the heat supply in buildings, heat-pumps or CHP units in combination with a boiler (fuel switch) and thermal storages are suitable sets and the activation of the thermal mass in new constructions increases the flexibility potential of a building (compare (Klein, 2017)). Combining heat-pumps with CHP-units could also provide additional flexibility as a shift from electricity consumption to generation (and vice-versa) would be possible. For additional flexibility, especially in combination with the generation of electricity from fluctuating renewable energy sources (i.e. PV), the integration of batteries, which are operated independently from the thermal load, is necessary (Klein, 2017).

4. METHODOLOGY

The applied methodology is illustrated in Figure 6. The analysis of the energy/ electricity flexibility of buildings builds upon the PHPP-spreadsheets developed early in the project. The spreadsheets provide detailed information about installed technologies in the CRAVEzero case study buildings as well as heating, domestic hot water, cooling, ventilation and lighting energy demand (useful and end energy, different energy carriers).

For the generation of hourly load electricity load profiles, the tool "PVopti" developed in connection with the IEA EBC Annex 67 "Energy Flexible Buildings". Based on simple input data, which can be taken from the PHPP spreadsheets, hourly profiles based on the Swiss Standard SIA 2024 (SIA 2024:2015, 2015)are generated and used for analysing the self-consumption rate and autarky rate of a building. It considers conventional heating systems, major energy demands (heating, domestic hot water, cooling, ventilation, appliances, lighting) and on-site electricity generation by PV and CHP. Furthermore, DSM and battery storages can be considered.

The PHPP files provided by the project partners are the base cases for each building. Several variations are calculated. Thereby, the effects on self-consumption and autarky rates of different flexibility options are assessed:

- Electricity storage/ battery
- Fuel-switch,
- Thermal storages

The detailed analysis has been performed for the two case study buildings "Brussels" located in southern Germany and "Moretti More" located in northern Italy. The variants for which the self-consumption rate, autarky rate and the GSC are analysed in the case study „Brussels“ are summarised in Table 2, for the case study More in Table 3.

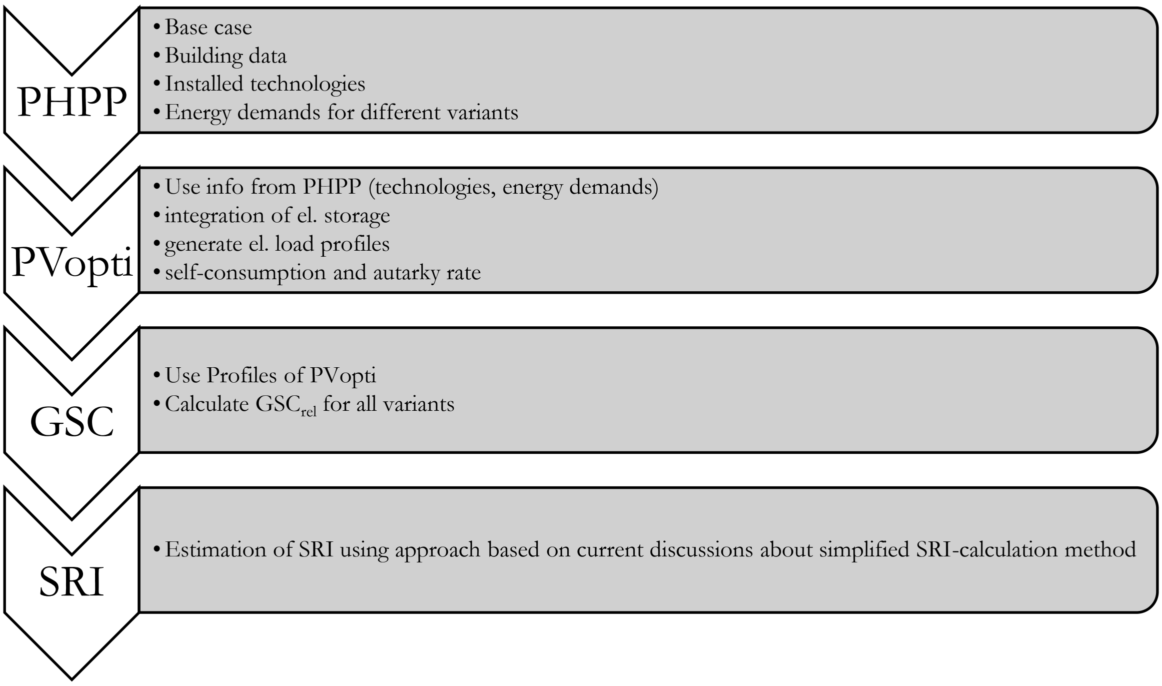

Figure 6: Illustration of applied methodology to analyse energy flexibility and building-grid interaction.

For the analysis described in the following chapters, four KPIs/ approaches for describing the energy flexibility of a building are applied. These are:

- **Self-consumption rate**
- **Autarky rate**
- **Grid Support Coefficient (GSC)**
- An indicator based on the current development status of the **Smart Readiness Indicator (SRI)**

The definition and calculation self-consumption rate and the autarky rate are based on the methodology applied in the tool PVopti, which is based on the Swiss building certification standard Minergie® and can be used for the proof of the respective rates within the framework of Minergie®.

The **self-consumption rate** is based on the hourly electricity demand and generation (if applicable) calculated with the tool PVopti. Based on the results, the hourly building-grid interaction is calculated and summarised on a monthly and annual level. The annual self-consumption rate is the quotient of electrical self-consumption (calculated for each hour and summed up for a whole year) and the annual on-site electricity generation.

Like the self-consumption rate, the **autarky rate** is based on the hourly electricity demand and generation (if applicable) calculated with the tool PVopti. It is calculated as the quotient of the self-consumption and the overall electricity demand of the building and presented in %.

With the methodology of the so-called **Grid Support Coefficient (GSC)** absolute and relative can be calculated (GSC_{abs}, GSC_{rel}). A detailed description of the methodology developed at Fraunhofer ISE can be found in (Klein et al., 2017; Klein, 2017; Klein et al., 2016b). The GSC "weights" the electricity consumption profile with a reference quantity (Klein et al., 2016b).

The reference value must express the electricity availability in the public grid. According to (Klein et al., 2016b), the stock price of electricity, residual load, cumulative energy consumption or share of PV and wind in the electricity mix can be used as reference values. The reference values for the analyses below are the stock price of electricity (EEX) and the residual load (Residual).

For calculating the GSC_{abs} a time-resolved electricity consumption profile is weighted with a time-resolved reference quantity. It is always calculated for at least two-time steps/ a time period and never for an instant of time. Usually, the considered period is either one day or one year with hourly or quarter-hourly steps. If for example the EEX electricity price is taken as reference quantity, for electricity consumers a GSC_{abs} value of 0.9 means that electricity is consumed at 90 % of the mean EEX price on weighted average, which is desirable (compare (Klein et al., 2016b)).

As shown in Figure 7, the operation of a building/ the building energy system can be either grid-supportive (desirable) or grid-adverse (non-desirable).

The value GSC_{rel} is used for comparing the GSC of different technical installations, different reference values, climate conditions etc. The attained GSC_{abs} is related on a scale of -100 to 100 representing the worst (lower potential boundary) and best (upper potential boundary) achievable GSC_{abs} in a given system. A positive value thereby is grid-supportive, a negative one grid-adverse and a value close to 0 is neutral.

The upper and lower potential boundaries are calculated by analysing the total electricity consumption and the required full load operation hours of the technical systems for each day of a year. Load shifting for the calculation of the boundaries is only possible within one day. The upper potential boundary (upperPB) thereby is the achieved GSC when the technical systems are operated during the hours with the most favourable external signal of a day, the lower potential boundary (lowerPB) is attained by operating the system in the hours with the least favourable external signal during one day.

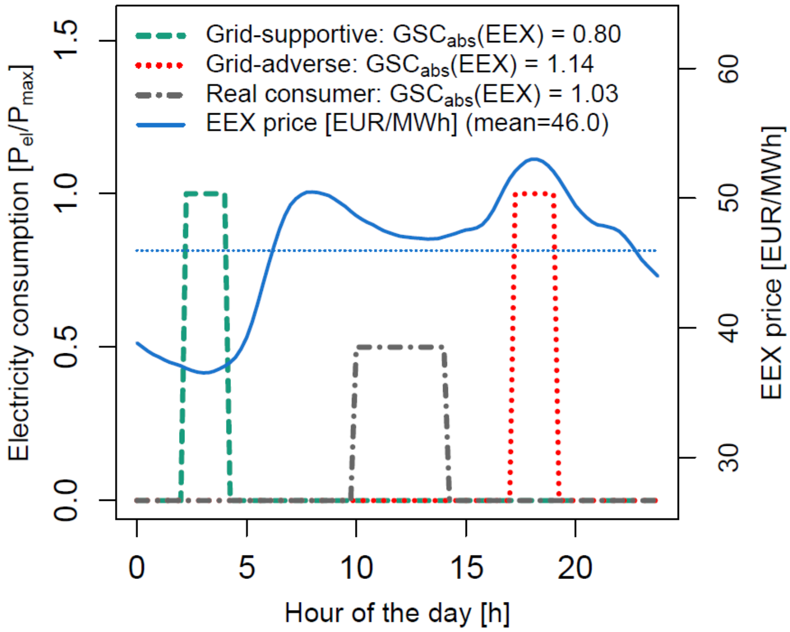

Figure 7: Grid supportive, grid adverse and grid neutral operation with respect to EEX price for an example da; source (Klein, 2017)

In addition to the quantitative approach described above, a more qualitative approach will be applied, and the results will be compared to the quantitative results.

In Europe, a **Smart Readiness Indicator (SRI)** is currently developed, and a first version of the calculation methodology is available. In this project, a simplified rating reducing the rated/ assessed services is used.

The background, methodology and detailed catalogue of services in buildings to be considered in the SRI are described in (Verbeke et al., 2019; Verbeke et al., 2018). The SRI should generally help to leverage the application of smart, energy-efficient technologies in buildings across Europe and increase investments in building renovation. It is expected that a broad uptake of smart technologies leads to significant energy saving in a cost-effective way and simultaneously help to improve indoor comfort (compare (Verbeke et al., 2019; Verbeke et al., 2018)). Additionally, the availability of smart technologies is seen as an essential part of a future energy system with a high share of fluctuating renewable electricity generation, which requires controllable loads in each consumption sector of the energy system including the building sector. The development of the SRI is defined in the last revision of the EPBD, which requires the development of a scheme to rate the smart readiness of buildings.

The aim of the SRI is to make the added value of smartness in buildings more concrete/ tangible for building owners, users, and service providers (see (Verbeke et al., 2018)).

The concept of the proposed methodology is based on smart ready services for the following domains (Verbeke et al., 2018):

- Heating
- Cooling
- Domestic hot water
- Controlled ventilation
- Lighting
- Dynamic building envelope
- On-site renewable energy generation
- Demand-side management
- Electric vehicle charging
- Monitoring and control

Overall, the service catalogue presented in Annex A of (Verbeke et al., 2018) comprises more than 100 services, which are rated according to defined functionality levels.

Current discussions were focussing on streamlining the methodology by reducing the domains and services to be assessed and thereby making the SRI easier to apply and use (compare (Reynders, 2019)).

Based on the results presented in (Reynders, 2019) and the detailed catalogue and methodology description in (Verbeke et al., 2018), a simplified rating of the smart readiness of the CRAVEzero Case studies was developed and tested (Verbeke et al., 2019). It comprises 26 services in the domains *heating*, *domestic hot water*, *cooling*, *controlled ventilation*, *lighting*, *dynamic envelope*, *electricity*, *electric vehicle charging* and *monitoring and control* as published in the file "sri2_annex-c_service-catalogue_simplified-method.xlsx" (VITO NV, 2019).

The SRI is exemplarily derived for the two case study buildings mentioned above. The importance of the different domains slightly differs between the two case studies as for example heating and lighting are more important in central/ northern Europe while cooling plays a more significant role in southern European countries. For each domain, weightings are defined representing the impact on *energy savings*, *flexibility for the grid and storage*, *comfort*, *convenience*, *health and well-being*, *maintenance and fault prediction, detection and diagnosis* as well as *user information* (Verbeke et al., 2018). Furthermore, the listed impacts have differing importance for the smartness/ energy flexibility of a building. For the analysis within this deliverable the most considerable significance is attributed to *flexibility for the grid and storage* followed by *energy savings* and *maintenance and fault detection*. All other impacts are attributed the same (and lowest) importance.

Table 1: Smart ready services to be applied in planned simplified SRI-methodology; Source (VITO NV, 2019).

Domain	**Theme**	**Smart ready service**
Heating	Heat control - demand side	Heat emission control
Heating	Control heat production facilities	Heat generator control (for combustion and district heating)
Heating	Control heat production facilities	Storage and shifting of thermal energy
Heating	Reporting	Report information regarding HEATING system performance
Domestic hot water	Control DHW production facilities	Control of DHW storage charging (with direct electric heating or integrated electric heat pump)
Domestic hot water	Flexibility DHW production facilities	Control of DHW storage charging
Domestic hot water	Information to occupants	Report information regarding domestic hot water performance
Cooling	Cooling control - demand side	Cooling emission control
Cooling	Control cooling production facilities	Generator control for cooling
Cooling	Control heat production facilities	Storage and shifting of thermal energy
Cooling	Reporting	Report information regarding cooling system performance
Controlled ventilation	Air flow control	Air flow control al the room level
Controlled ventilation	Feedback / Reporting	Reporting information regarding IAQ
Lighting	Artificial lighting control	Occupancy control for indoor lighting
Dynamic building envelope	Window control	Window solar shading control
Dynamic building envelope	Feedback / Reporting	Reporting information regarding performance
Electricity	Storage	Storage of locally generated energy
Electricity	Electricity Loads	Electricity Monitoring Systems
Electricity	Renewables	Reporting information regarding energy generation
Electricity	Storage	Reporting information regarding stored electricity
Electric vehicle charging	EV Charging presence&capacity	Number of charging spaces
Electric vehicle charging	EV Charging - Grid	EV Charging Grid balancing
Electric vehicle charging	EV Charging - connectivity	EV charging information and connectivity
Monitoring and control	TBS interaction control	Interaction between TBS and/or BACS
Monitoring and control	Smart Grid Integration	Smart Grid Integration
Monitoring and control	Feedback / Reporting	Central reporting of TBS performance and energy use

5. RESULTS

5.1. SCENARIOS OF OPTIMAL NZEB – ENERGY GRID INTERACTION

In the following, several KPIs described above are analysed for the two case study buildings "Brussels" and "Moretti More". For these two buildings, 37 variants are analysed according to:

1. Self-consumption and autarky rate
2. Grid-supportiveness (GSC)
3. Smart-readiness (SRI); only Base-Case

The self-consumption and autarky-rate are obtained from the tool PVopti. Additional results of the tool are hourly load and generation curves, which are the basis for the analysis of the grid-supportiveness according to the GSC developed at Fraunhofer ISE. For both case studies the smart-readiness is analysed based on interviews and a rating scheme based on the current discussions about a simplified SRI-rating.

The main drivers for the building-grid interaction are on-site electricity generation, electricity storages, the possibility for a fuel-switch and thermal storages. The sizes / presence of all technologies except thermal storages (focus is the electrical part) are varied for identified promising technology-sets / settings to increase the on-site renewable electricity generation and use as well as grid-supportive building operation. If a heat pump is installed in the variants, it is always considered to be an air-source heat pump.

5.1.1. CASE STUDIES

CASE 1: "Brussels/ Parkcarré" – Köhler & Meinzer (Parkcarré-Res.)

Figure 8: Illustration of the case study "Brussels";(c) Köhler & Meinzer GmbH & Co KG

General information

- Owner: Owner´s Association
- Architect: Alex Stern/Gerold Köhler
- Energy concept: Contracting model for the quarter energy supply (DHW, heating, and electricity) for all buildings with a local gas boiler and a PV-system
- Location: Eggenstein (Germany)
- Year of construction: 2014
- Net floor area: 1109 m²

Key technologies

- High level of thermal insulation
- Best quality heat-bridges optimization and an airtight envelope
- Decentralized ventilation system with heat recovery (2 systems/apartment)

The case study is a multi-family home, with four floors, ten dwellings, within a quarter of six buildings, each with four floors and overall 66 dwellings. This building consumes 40 % less than national standards requirements. The envelope is highly insulated and airtight. Decentralised ventilation systems (two for each dwelling) with heat recovery have been installed. DHW, heating and electric energy of all dwellings are supplied by a gas-fired heat and power plant (CHP) and a PV system on each building. Moreover, the social and economic sustainability has been taken into account by the project. On the one hand, one of the main objectives in developing this multi-family house was to create a type of building which can meet different demands. On the other hand, the designers focused on the cost-effectiveness of the construction to guarantee affordable costs of the dwellings. The analysed variants are summarised in Table 2.

Table 2: Analysed variants in PVopti for the case study "Brussels"; PH refers to passive house

Variant	Envelope	Heating	Cooling	PV	El. Storage
1		as built / Reference		38.9 kWp	no
2	as built	Heat-Pump	no	38.9 kWp	no
3	as built	Heat-Pump	no	19.3 kWp	no
4	as built	Heat-Pump	no	57.8 kWp	no
5	PH	Heat-Pump	no	38.9 kWp	no
6	PH	Heat-Pump	no	19.3 kWp	no
7	PH	Heat-Pump	no	57.8 kWp	no
8	as built	District Heat	no	38.9 kWp	no
9	as built	District Heat	no	19.3 kWp	no
10	as built	District Heat	no	57.8 kWp	no
11	PH	District Heat	no	38.9 kWp	no
12	PH	District Heat	no	19.3 kWp	no
13	PH	District Heat	no	57.8 kWp	no
14	as built	Heat-Pump	no	38.9 kWp	100 kWh
15	as built	Heat-Pump	no	19.3 kWp	100 kWh
16	as built	Heat-Pump	no	57.8 kWp	100 kWh
17	PH	Heat-Pump	no	38.9 kWp	100 kWh
18	PH	Heat-Pump	no	19.3 kWp	100 kWh
19	PH	Heat-Pump	no	57.8 kWp	100 kWh
20	as built	District Heat	no	38.9 kWp	100 kWh
21	as built	District Heat	no	19.3 kWp	100 kWh
22	as built	District Heat	no	57.8 kWp	100 kWh
23	PH	District Heat	no	38.9 kWp	100 kWh
24	PH	District Heat	no	19.3 kWp	100 kWh
25	PH	District Heat	no	57.8 kWp	100 kWh
26	as built	Heat-Pump	no	38.9 kWp	270 kWh
27	as built	Heat-Pump	no	19.3 kWp	270 kWh
28	as built	Heat-Pump	no	57.8 kWp	270 kWh
29	PH	Heat-Pump	no	38.9 kWp	270 kWh
30	PH	Heat-Pump	no	19.3 kWp	270 kWh
31	PH	Heat-Pump	no	57.8 kWp	270 kWh
32	as built	District Heat	no	38.9 kWp	270 kWh
33	as built	District Heat	no	19.3 kWp	270 kWh
34	as built	District Heat	no	57.8 kWp	270 kWh
35	PH	District Heat	no	38.9 kWp	270 kWh
36	PH	District Heat	no	19.3 kWp	270 kWh
37	PH	District Heat	no	57.8 kWp	270 kWh

CASE 2: “More” – Moretti (More-Res.)

Figure 9: Illustration of the case study "Moretti More"; (c) Moretti S.p.A.

General information

- Owner: Groppi-Tacchinardi
- Architect: Valentina Moretti
- Energy concept: Heat pump and condensing boiler, solar heating panel
- Location: Lodi (Italy)
- Year of construction: 2014
- Net floor area: 128 m²

Key technologies

- Precast component
- Compact model home
- Central core
- Flexible and modular

Groppi / “Moretti More” represents one of the typologies of prefabricated single-family house produced by Moretti. The envelope and all the equipment have been designed with the aim to achieve high performances. The thermal equipment consists of an air-water heat pump, distribution through a floor heating system, balanced ventilation with heat recovery, electric system automation. In summer, a natural chimney activates air circulation inside the house, thus ensuring natural ventilation. In addition, the installation of special selective and low emissivity glasses ensures a low cooling demand. The analysed variants are summarised in Table 3.

Table 3: Analysed variants in PVopti for the case study "Moretti More"; PH refers to passive house and HP refers to Heat-Pump.

Variant	Envelope	Heating	Cooling	PV	El. Storage
1		as built / Reference		no	no
2	as built	Heat-Pump	Compr. cooling	no	no
3	as built	Heat-Pump	Compr. cooling	2.8 kWp	no
4	as built	Heat-Pump	Compr. cooling	5.5 kWp	no
5	PH	Heat-Pump	Compr. cooling	no	no
6	PH	Heat-Pump	Compr. cooling	2.8 kWp	no
7	PH	Heat-Pump	Compr. cooling	5.5 kWp	no
8	as built	HP + Boiler	Compr. cooling	no	no
9	as built	HP + Boiler	Compr. cooling	2.8 kWp	no
10	as built	HP + Boiler	Compr. cooling	5.5 kWp	no
11	PH	HP + Boiler	Compr. cooling	no	no
12	PH	HP + Boiler	Compr. cooling	2.8 kWp	no
13	PH	HP + Boiler	Compr. cooling	5.5 kWp	no
14	as built	Heat-Pump	Compr. cooling	no	10 kWh
15	as built	Heat-Pump	Compr. cooling	2.8 kWp	10 kWh
16	as built	Heat-Pump	Compr. cooling	5.5 kWp	10 kWh
17	PH	Heat-Pump	Compr. cooling	no	10 kWh
18	PH	Heat-Pump	Compr. cooling	2.8 kWp	10 kWh
19	PH	Heat-Pump	Compr. cooling	5.5 kWp	10 kWh
20	as built	HP + Boiler	Compr. cooling	no	10 kWh
21	as built	HP + Boiler	Compr. cooling	2.8 kWp	10 kWh
22	as built	HP + Boiler	Compr. cooling	5.5 kWp	10 kWh
23	PH	HP + Boiler	Compr. cooling	no	10 kWh
24	PH	HP + Boiler	Compr. cooling	2.8 kWp	10 kWh
25	PH	HP + Boiler	Compr. cooling	5.5 kWp	10 kWh
26	as built	Heat-Pump	Compr. cooling	no	20 kWh
27	as built	Heat-Pump	Compr. cooling	2.8 kWp	20 kWh
28	as built	Heat-Pump	Compr. cooling	5.5 kWp	20 kWh
29	PH	Heat-Pump	Compr. cooling	no	20 kWh
30	PH	Heat-Pump	Compr. cooling	2.8 kWp	20 kWh
31	PH	Heat-Pump	Compr. cooling	5.5 kWp	20 kWh
32	as built	HP + Boiler	Compr. cooling	no	20 kWh
33	as built	HP + Boiler	Compr. cooling	2.8 kWp	20 kWh
34	as built	HP + Boiler	Compr. cooling	5.5 kWp	20 kWh
35	PH	HP + Boiler	Compr. cooling	no	20 kWh
36	PH	HP + Boiler	Compr. cooling	2.8 kWp	20 kWh
37	PH	HP + Boiler	Compr. cooling	5.5 kWp	20 kWh

5.1.2.SELF-CONSUMPTION AND AUTARKY RATE

For the analysis of the self-consumption of on-site renewable electricity generation, the autarky rate and of the key factors/ technologies influencing these factors, 36 variants, as well as a base case, were analysed with the tool PVopti in the two case study buildings "Brussels" and "Moretti More". The base case reflects the building as it is built/ planned based on the PHPP-files developed earlier in the CRAVEzero.

Brussels:

Already in the base case, a PV system is planned. Therefore, all variants have on-site renewable electricity generation. The analysed variants are described in Table 2.

The **self-consumption** and feed-in rate of the electricity generated on-site (only PV) of the assessed variants is illustrated in Figure 10. The self-consumption rate varies between 19 % and 100 %. The lowest rate is achieved in Variant 10, which has a large PV-system, but no electricity storage and the heating is provided by the district heating system. Generally, it can be said that the self-consumption rate is the lowest in the variants with a large PV-system, no electricity storage and without a heat-pump for the heat-supply. The mentioned factors (presence and size of electricity storage, large electricity consumers (heat-pump) and the size of the PV-system) are key drivers for the self-consumption rate. The building envelope only plays a minor role in this building as the electricity generated during winter is more or less consumed on-site. In some variants with a self-consumption rate of around 70 %, which only differ in the envelope quality the self-consumption rate is even slightly higher in the variant with the worse building envelope (variants 16 and 19).

The highest self-consumption rate is obtained in the variants with a small PV-system and a battery. In these variants, the whole electricity can be consumed on-site even without a heat-pump.

The **autarky rate** ranges from 14.2 % to 77.2 % and is illustrated in Figure 11. Variants 34 and 37 have the highest rate. Both have a large PV-system and large battery storage and no heat-pump. The only difference is the building envelope, which does not influence the autarky rate. The main drivers for a high autarky rate are the size of the battery storage as well as the size of the PV-system. The presence of a heat pump only comes in the third place. The reason is that the heat-pump consumes the most electricity during winter when the PV generation is low. The lowest autarky rate is obtained in variant 3, which has a heat-pump, but no battery and only a small PV-system.

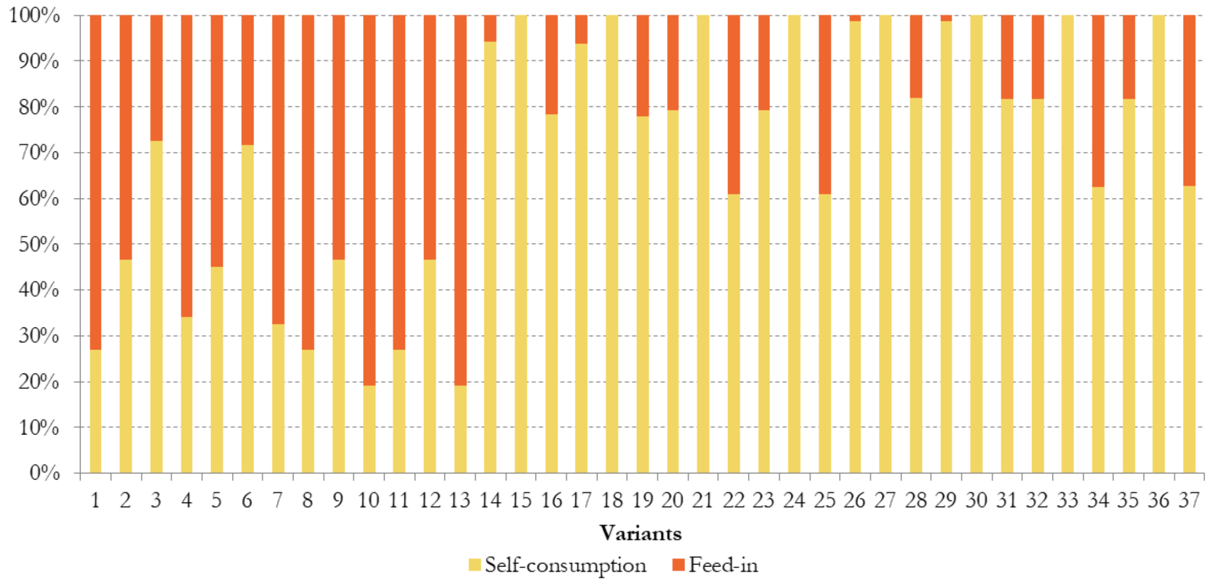

Figure 10: Relation of self-consumption and feed-in of the assessed variants of the case study „Brussels"; own illustration based on results obtained with PVopti

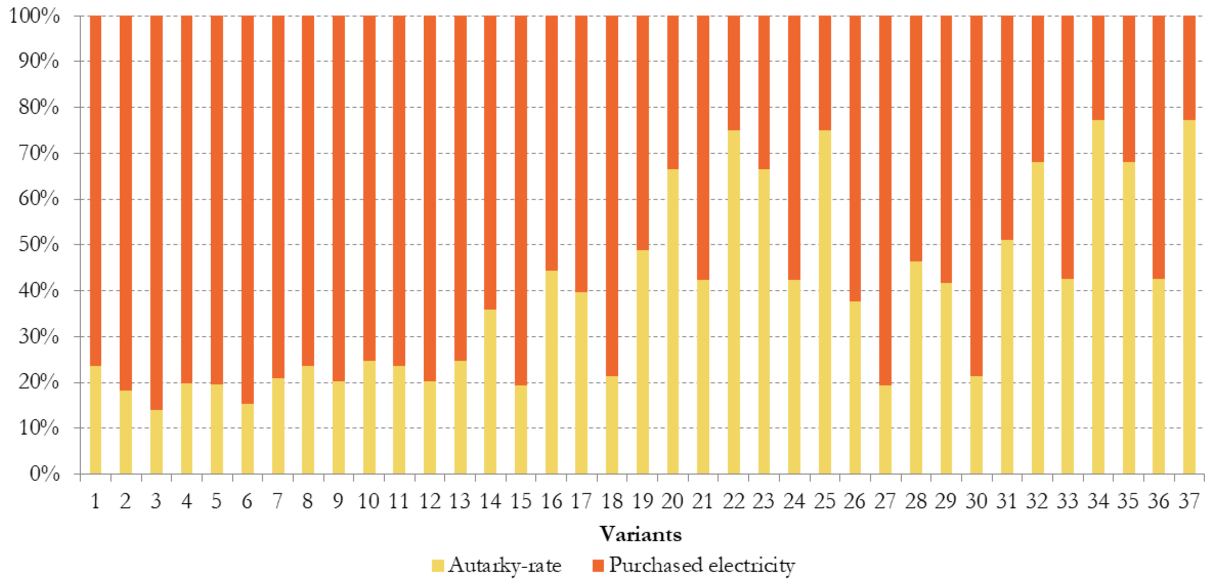

Figure 11: Autarky rate and share of purchased electricity of the assessed variants of the case study „Brussels"; own illustration based on results obtained with PVopti

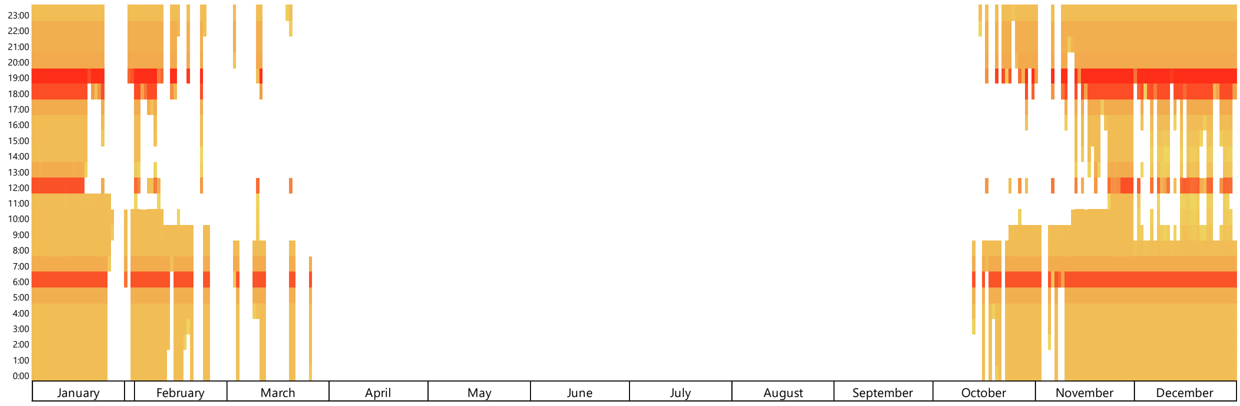

Figure 12: Carpet plot showing the electricity purchase from the grid of variant 34 (highest autarky rate) of the case study „Brussels" throughout a year. Light colours indicate a low purchase, red indicates a high purchase; own illustration based on results obtained with PVopti

Moretti More

In the base case, no PV system is planned / installed. Therefore, all variants where the PV-system was considered "as-built" / no PV) do not show a self-consumption and have an autarky of 0 %. The analysed variants are described in Table 3.

The **self-consumption** and feed-in rate of the electricity generated on-site (only PV) of all variants are illustrated in Figure 13. The self-consumption rate of the variants with a PV-system installed varies between 20 % and 92 %. The lowest rate is achieved in Variant 13, which has a large PV-system, but no electricity storage and the heating is provided by the heat-pump system in combination with gas boiler (as built). However, as the boiler only provides a small share of the needed heat and highest heat demand occurs when solar irradiation is low, the difference in the self-consumption rate between the case with heat-pump + boiler and the case, in which only a heat-pump is installed (variant 7), is negligible. Generally, it can be said that the self-consumption rate is the lowest in the variants with no electricity storage and a large PV-system. In the case study those two factors are the key drivers for the self-consumption rate. The building envelope only plays a minor role in this building and in most variants, which only differ in the envelope quality the self-consumption rate is slightly higher in the variants with the worse building envelope. The highest self-consumption rate is obtained in the variants with a small PV-system and a large battery.

The **autarky rate** of the variants with a PV-system ranges from 19.4 % to 69.6 % and is illustrated in Figure 14. Variant 37 has the highest rate. The four variants with the highest rate (37, 25, 31, 19) all have a highly efficient envelope (PH). The variants with a heating-system as it is built (Heat-pump + boiler) thereby have a higher autarky rate than the variants with only a heat-pump installed. In the variants with similar settings concerning the envelope, heating system and PV-system the size of the battery is – of course – the driving factor. In this case study the size of the PV-system is the most important driver for the autarky-rate; the eight variants with the highest rate all have a large PV-system. This parameter seems to be even more important than the size of the battery. The lowest autarky rates in buildings with PV are obtained in variants without a battery and only a small PV-system.

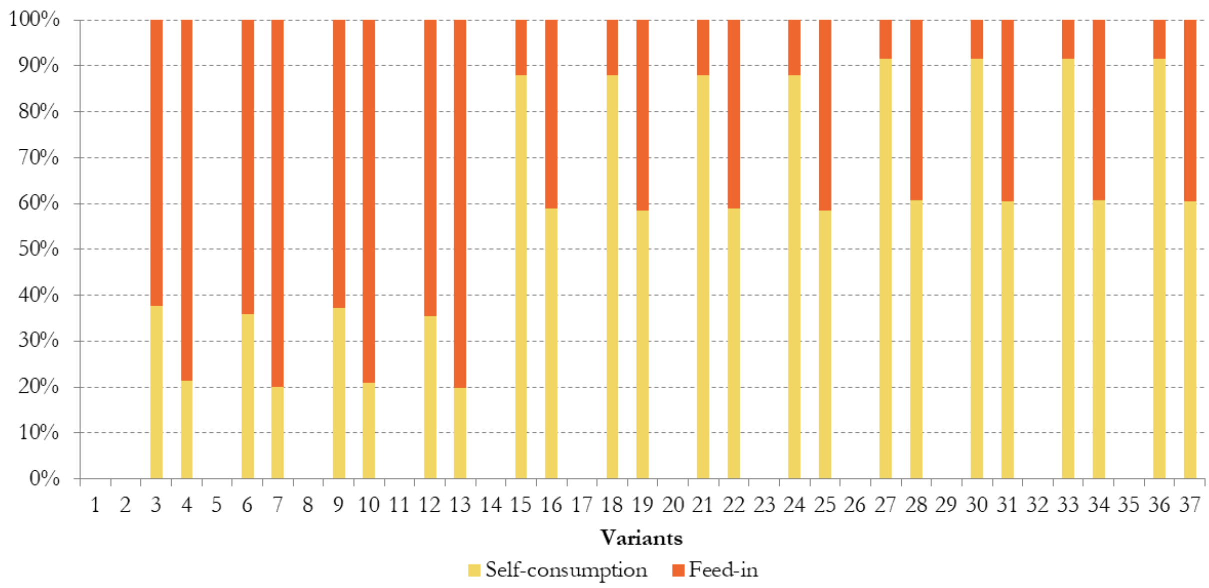

Figure 13: Relation of self-consumption and feed-in of the assessed variants of the case study „Moretti More"; own illustration based on results obtained with PVopti

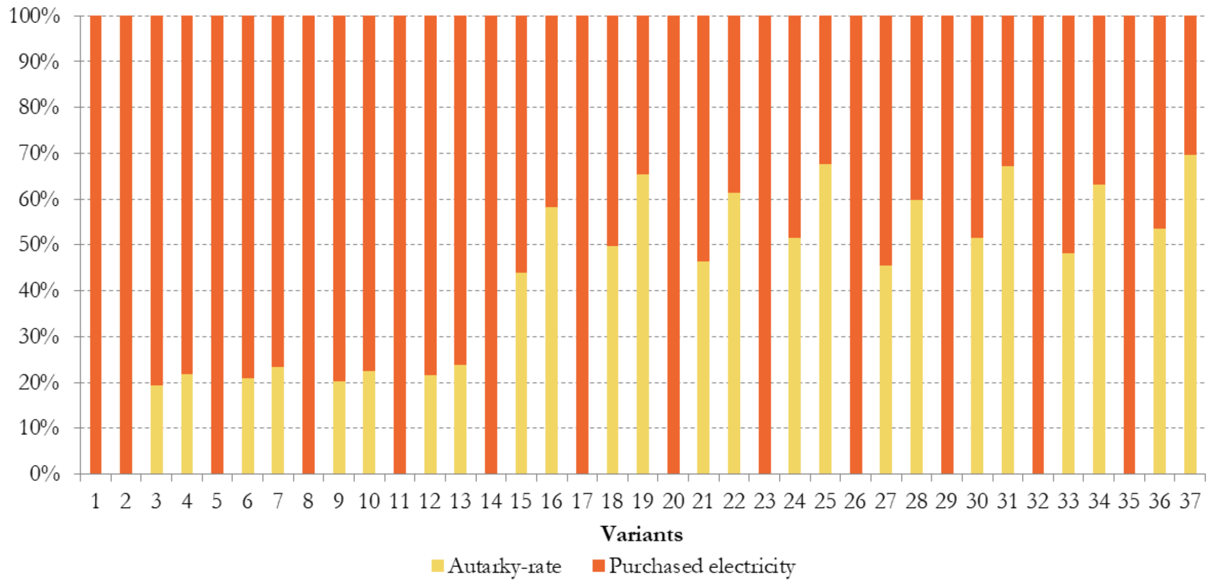

Figure 14: Autarky rate and share of purchased electricity of the assessed variants of the case study „Moretti More"; own illustration based on results obtained with PVopti

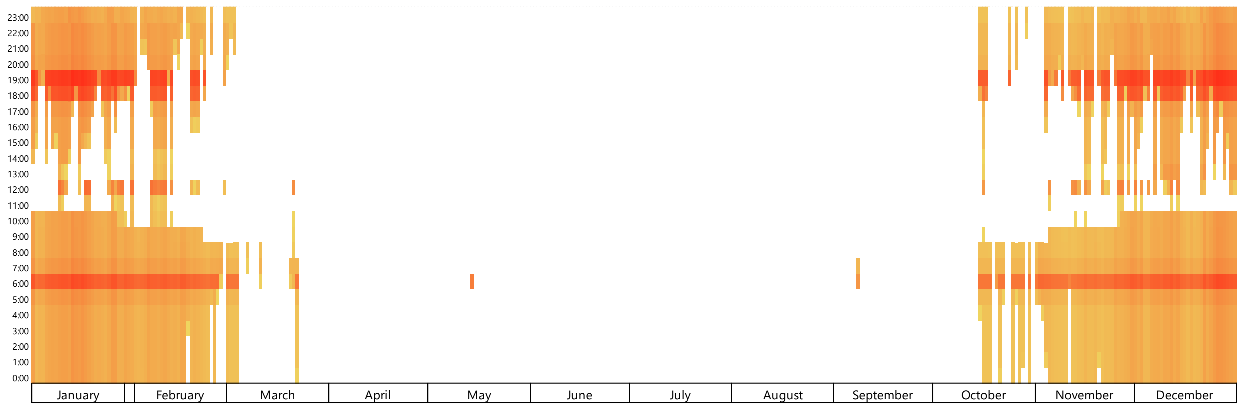

Figure 15: Carpet plot showing the electricity purchase from the grid of variant 37 (highest autarky rate) of the case study „Moretti More" throughout a year. Light colours indicate a low purchase, red indicates a high purchase; own illustration based on results obtained with PVopti

5.1.3. GRID-SUPPORTIVENESS

For the analysis of the grid-supportiveness and key factors therefor, 36 variations described in the previous chapter were analysed with the Grid-Support Coefficient (GSC) in the two case study buildings "Brussels" and "Moretti More". For the analysis of the GSC, hourly profiles from the tool PVopti are used. The GSC is obtained for the stock price of electricity (EEX) and the expected residual load in Italy and Germany in 2030 (Residual) based on (Klein et al., 2016a). The analysis focuses on the GSC_{abs} including the respective best and worst values for each variant. For the calculations the hourly profile of the electricity purchase is used. As the external signals (EEX-price, residual load can be negative also the upper boundaries can become negative when during one day all full load hours can be moved to a period with negative electricity prices or a negative residual load. The major differences between the case studies influencing the GSC results are the climate conditions (central vs. southern Europe) and the installation of a cooling unit in the case study more leading to different electricity consumption profiles especially during summer when PV generation is high. The EEX price is taken for both case studies and is illustrated in Figure 16. The expected residual load for Germany in 2030 is illustrated in Figure 17 and for Italy in Figure 22. An optimisation of the operation schedules/ control of the different building technologies and storages was not performed.

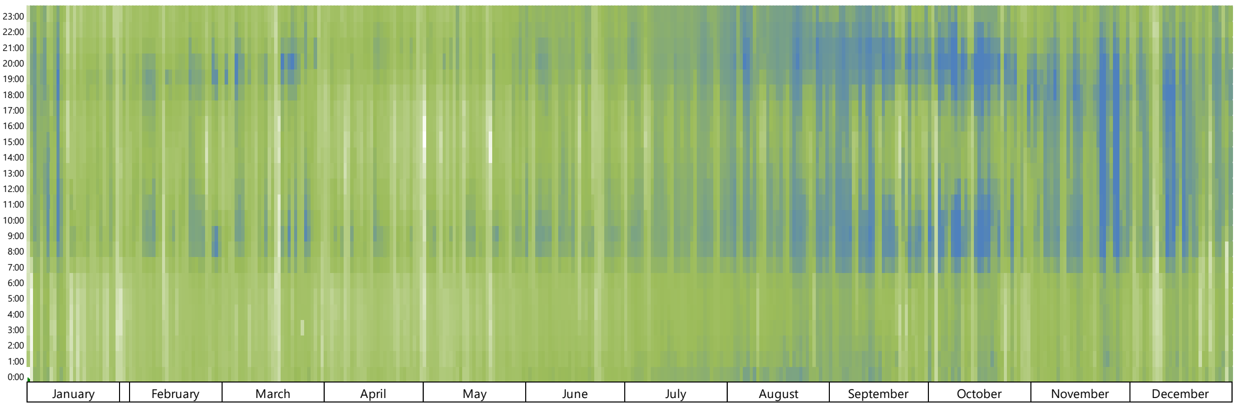

Figure 16: Carpet plot showing the EEX in 2018 throughout a year. White indicates times with a low electricity price, blue times with a high electricity price; own illustration based on (Klein et al., 2016a)

Brussels:

The GSC_{abs} with respect to **EEX** prices of the case study "Brussels" does not show high differences between the variants. It ranges from 0.99 to 1.08 (see Figure 18). A GSC_{abs} of ca. 1 can be considered as grid neutral, a $GSC_{abs} > 1$ as grid adverse and a $GSC_{abs} < 1$ as grid-supportive. The achieved GSC_{abs} are more or less grid-neutral with a tendency to be slightly grid-adverse.

The best (upperPB; most grid-supportive) and worst (lowerPB; most grid-adverse) achievable values calculated based on the technical constraints of the respective variant and taking into account the required daily operation time of the technical systems shows higher differences among the variants. The upper potential boundary varies between -0.1 and 0.5, the lower potential boundary between 1.48 and 1.88.

The best GSC_{abs} is achieved in variants in which the PV system is dimensioned like in the base case (38.8 kWp), heating with a heat pump system and the integration of a battery. The two variants with a $GSC_{abs} < 1$ have an envelope as built (slightly higher heat demand leading to a higher switching potential). The worst values are obtained in variants without a battery and with the use of district heat for heating and domestic hot water. Here, the envelope quality does not influence the absolute values. In the variants without the heat pump the shiftable electrical loads are limited leading to the comparably bad GSC_{abs}-values. The installation of the heat-pump is the driving factor increasing the GSC_{abs}. In the analysed cases the installation of a battery also increases the GSC_{abs}, but the size of the battery (100 or 270 kWh) only plays a minor role as a 100 kWh already provides a sufficient storage capacity for the size of the PV system and the daily electricity loads of the building even with a heat pump.

In Figure 21 the electricity purchase from the grid for variant 16, which has the best GSC_{abs} with respect to the EEX price, for each hour of the year is illustrated in a carpet plot. The main reason for the slightly better results compared with the other variants is the low electricity purchase in the evenings in September and October when the EEX prices are comparably high. However, during most of the time the purchase of the variant is still mainly during times with high prices and low during times with low prices.

The residual load of Germany in 2030 is illustrated in Figure 17. The GSC_{abs} with respect to the residual load (**Residual**; see Figure 19) is more grid-adverse and all values are above 1 (values between 1.07 and 1.24), while the upper potential boundary is below 0 in all variants (-0.05 to -0.90) increasing the gap between achieved GSC_{abs} and upper potential boundary. The best GSC_{abs} values are achieved in variants with a heat pump and a large PV system. In this case the energetic quality of the envelope is not influencing the achieved values. Like in the analyses of the GSC with respect to the EEX price the worst GSC_{abs} values are achieved in variants with the use of district heat for heating and domestic hot water and without a battery independent from the envelope quality. Slightly better results are obtained in the variants with a smaller PV system. The size of the battery system only plays a minor role for the achieved GSC_{abs} as the capacities considered are relatively high compared to the electrical load and PV generation.

The GSC_{rel} with respect to both external signals (EEX, Residual) is shown in Figure 20. As already described, most variants are slightly grid-adverse with better results with respect to the EEX price compared to the residual load. For improving the grid supportiveness of the building the installation of a heat-pump and a battery is essential. As the driving energy demand of the building is space heating, the integration of larger thermal storages and probably the installation of an additional heat generation using another energy carrier might be positive. Furthermore, the operation of the building systems has to be adjusted to the grid signals. As can be seen in Figure 17 heat pumps and other electricity consumers should be operated mainly during the day or in the early morning hours (the latter is, however, negative for the efficiency of the heat pump as the ambient temperature is usually low in these hours). Operation of electrical consumers between approx. 7 am until 10 am and between 5 pm and 8 pm should be avoided as much as possible.

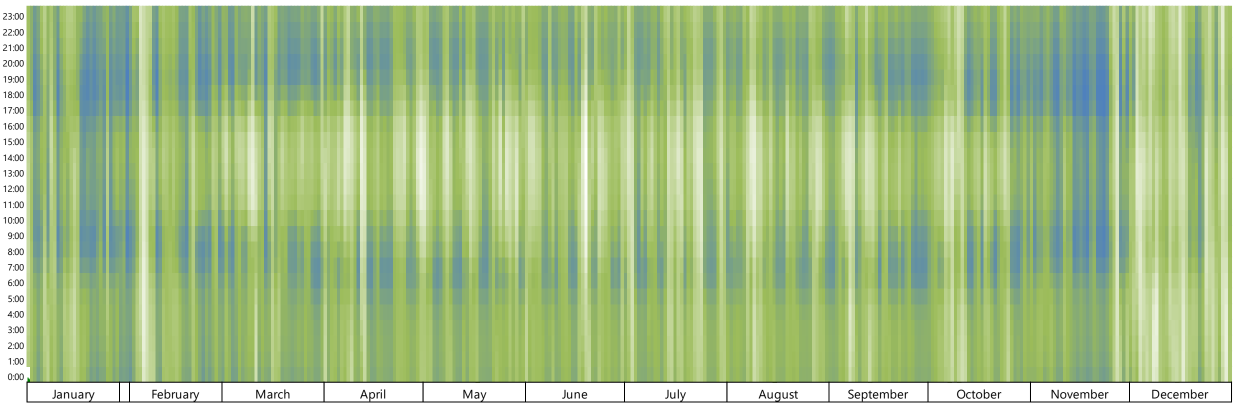

Figure 17: Carpet plot showing the residual load in Germany in 2030 throughout a year. White indicates times with a low residual load, blue times with a high residual load; own illustration based on (Klein et al., 2016a)

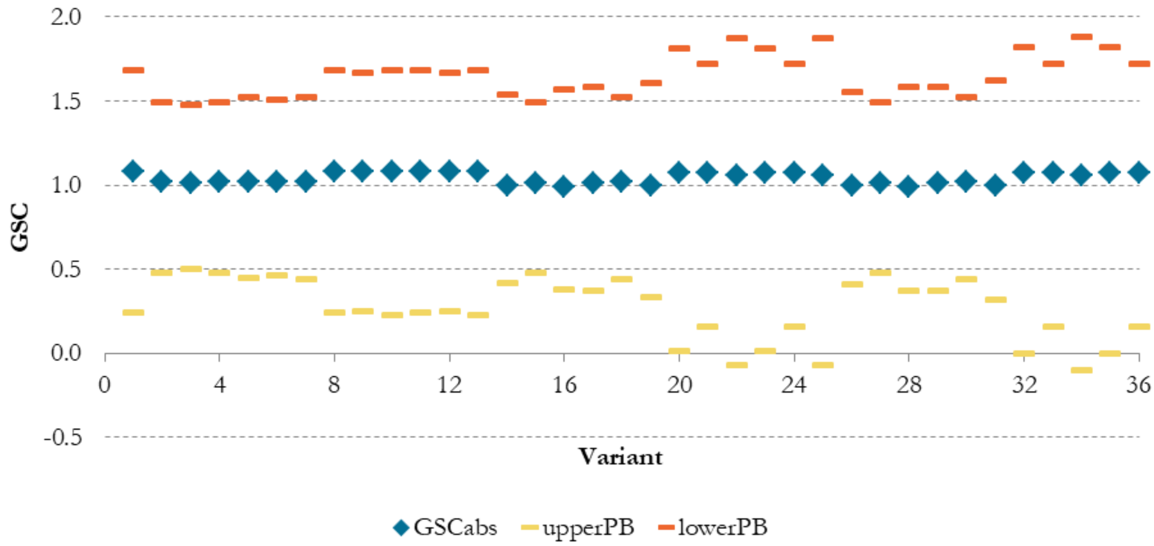

Figure 18: GSC_{abs} as well as upper (upperPB) and lower (lowerPB) boundaries with respect to EEX-prices for the case study "Brussels"

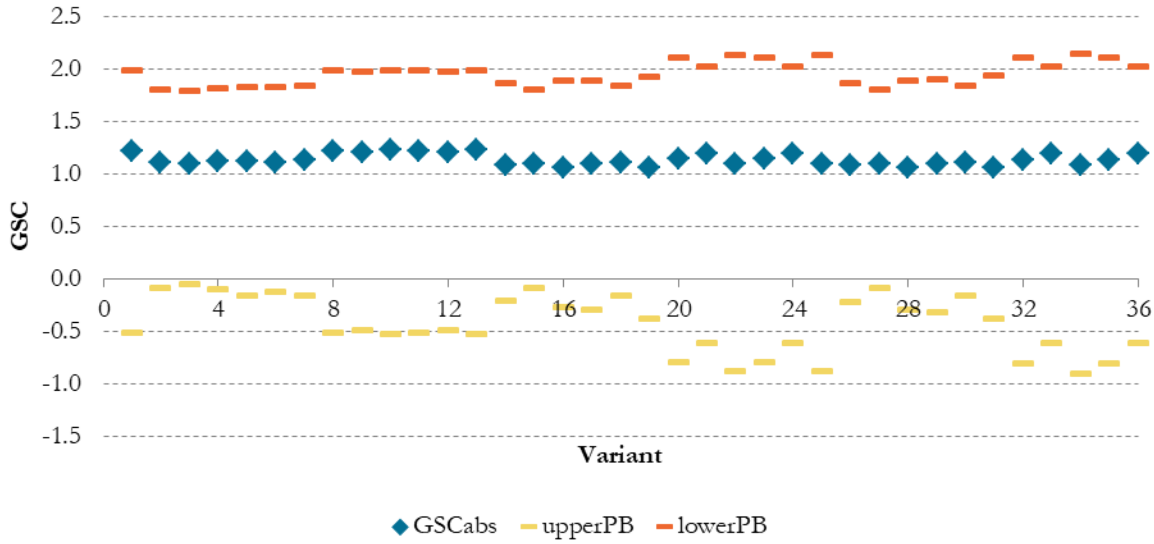

Figure 19: GSC_{abs} as well as upper (upperPB) and lower (lowerPB) boundaries with respect to expected Residual Load 2030 for the case study "Brussels"

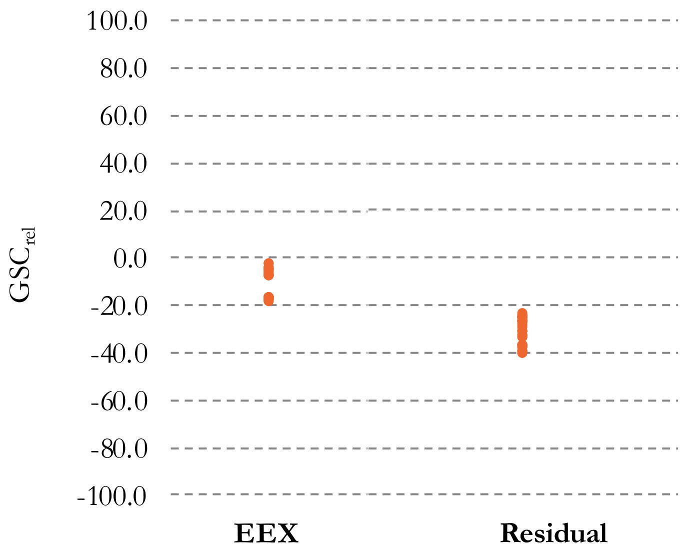

Figure 20: GSC$_{rel}$ of the case study "Brussels" with respect to EEX-prices (left) and expected residual load 2030 (right); positive values mean grid-supportive, negative values mean grid-adverse

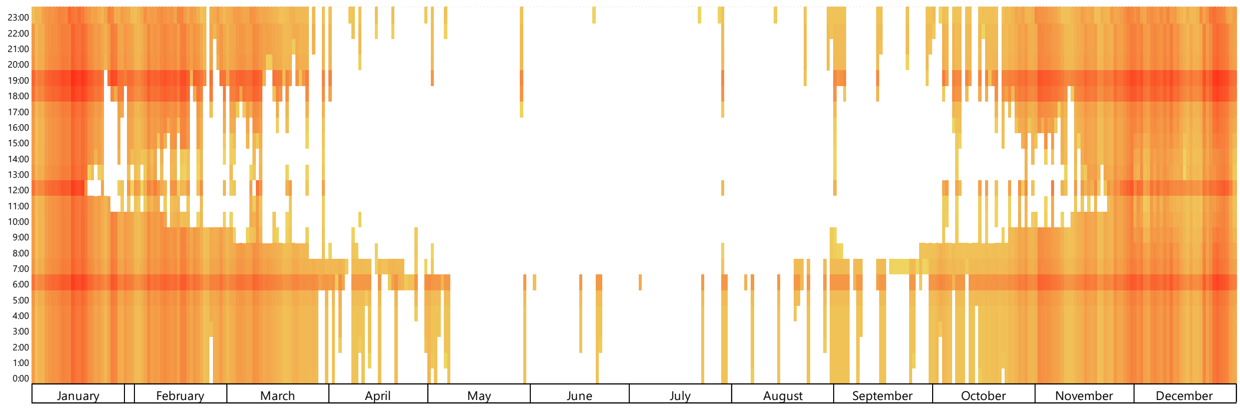

Figure 21: Carpet plot showing the electricity purchase from the grid of variant 16 (best achieved GSC with respect to EEX) of the case study „Brussels" throughout a year. Light colours indicate a low purchase, red indicates a high purchase; own illustration based on results obtained with PVopti

Moretti More

The GSC_{abs} with respect to **EEX** prices of the case study “Moretti More” does not show high differences among the variants. It ranges from 0.95 to 1.05 (see Figure 23). The achieved GSC_{abs} are more or less grid-neutral. The upper potential boundary varies between -0.04 and 0.32, the lower potential boundary between 1.62 and 1.84.

The best GSC_{abs} is achieved in variants with a large PV system and a battery. The installation of a PV system is the driving factor for a good GSC in all variants. However, when no battery is installed the installation of PV decreases the GSC. The size of the battery – if there is one – as well as the configuration of the heating (only heat pump or bivalent heat pump; slightly better results for heat pump only configurations) and the quality of the envelope only have a minor impact. The worst values are obtained in two variants with a PV system without a battery, a bivalent heat pump and a passive house envelope. There are several variants with only slightly better GSC_{abs} values all either without a PV system (then the variants without a battery show the worst values) or without a battery.

The residual load of Italy is illustrated in Figure 22. The GSC_{abs} with respect to the residual load (**Residual**; see Figure 24) is more grid-adverse. The values vary between 0.95 and 1.31). The upper potential boundary is between -0.34 to 0.01 and the lower potential boundary between 1.71 and 1.88. The best GSC_{abs} values are achieved in the variants without a PV system as they consume electricity from the grid in times when the residual load is low due to high PV generation in summer. The worst values are achieved in variants with a large PV system without a battery (high feed-in in times with already low residual load).

The GSC_{rel} with respect to both external signals (EEX, Residual) is shown in Figure 25. Most variants are slightly grid-adverse with better results with respect to the EEX price compared to the residual load. For improving the grid supportiveness of the building the installation of a battery is improving the performance of the buildings. Furthermore, the integration of larger thermal storages (especially cold storages to shift loads in summer) might be positive. Generally, the operation of the building must be optimised according to grid signals in order to improve the GSCs. The assessed technologies only have small improvement possibilities without an optimised operation (GSC with respect to Residual always grid adverse).

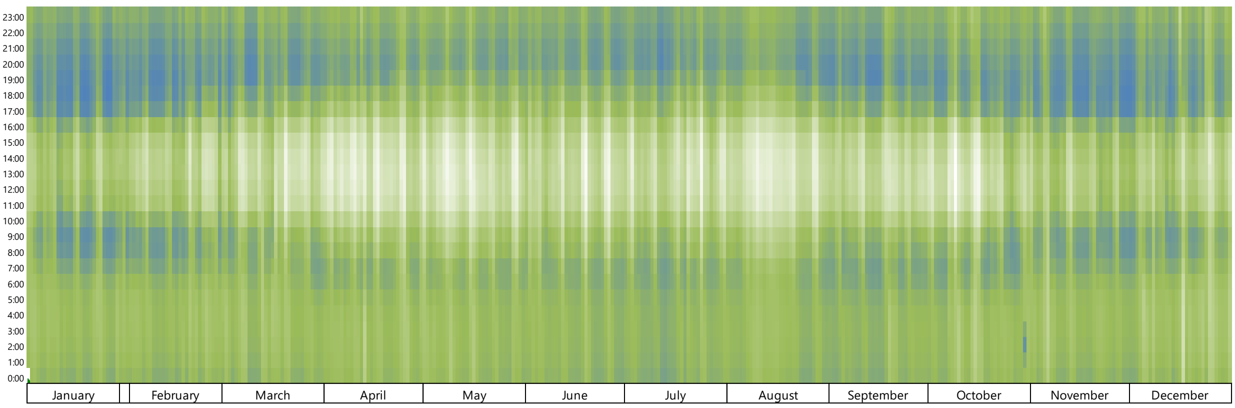

Figure 22: Carpet plot showing the residual load in Italy in 2030 throughout a year. White indicates times with a low residual load, blue times with a high residual load; own illustration based on (Klein et al., 2016a)

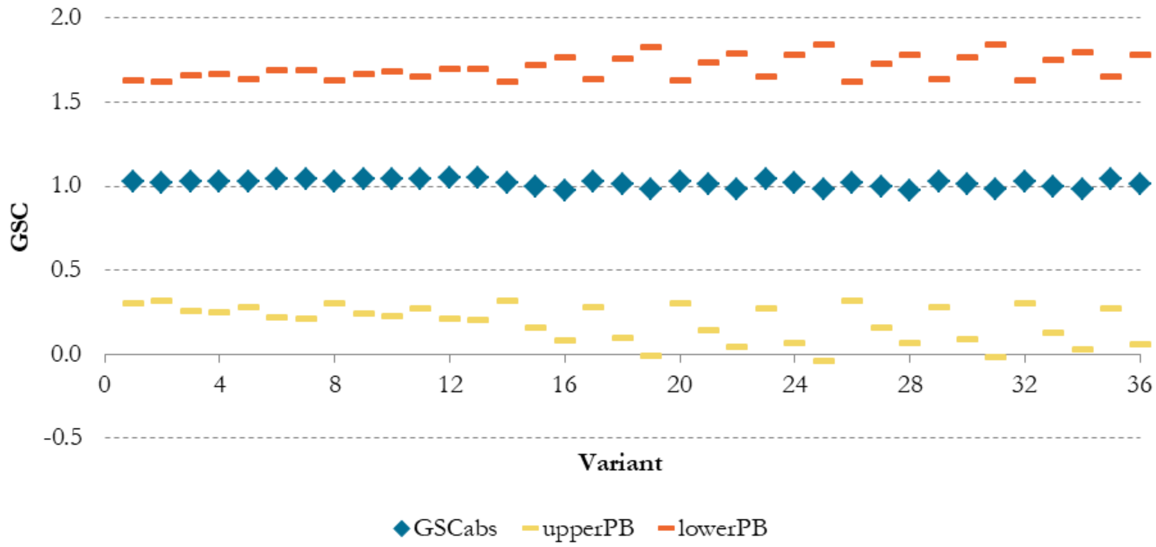

Figure 23: GSC_{abs} as well as upper (upperPB) and lower (lowerPB) boundaries with respect to EEX-prices for the case study "Moretti More"

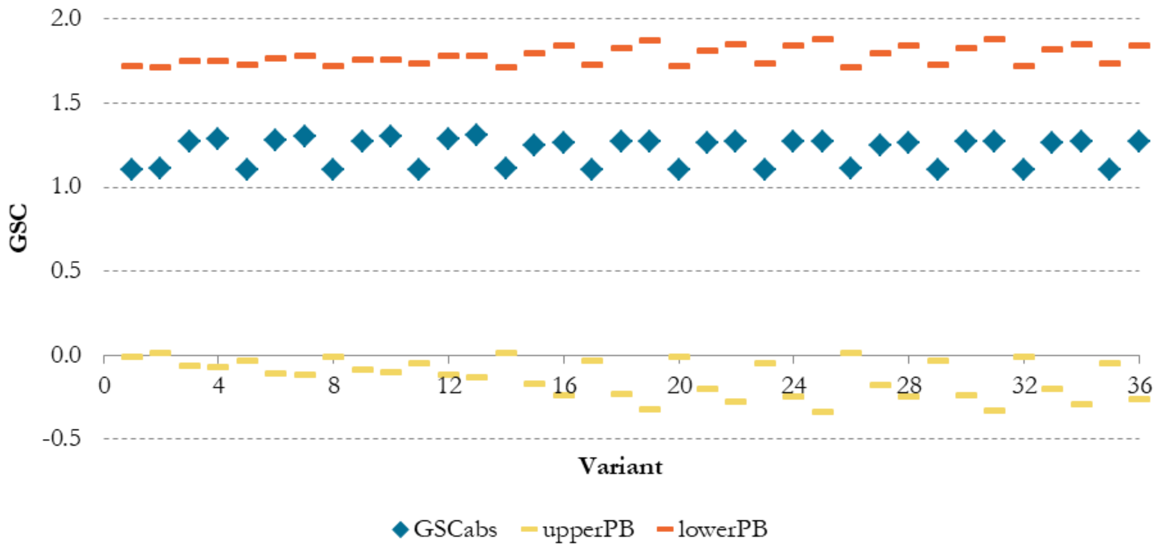

Figure 24: GSC_{abs} as well as upper (upperPB) and lower (lowerPB) boundaries with respect to expected Residual Load 2030 for the case study "Moretti More"

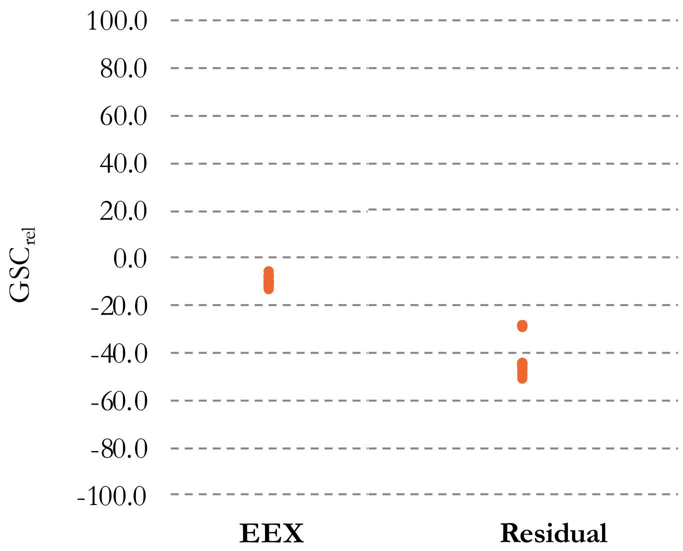

Figure 25: GSC_{rel} of the case study "Moretti More" with respect to EEX-prices (left) and expected residual load 2030 (right); positive values mean grid-supportive, negative values mean grid-adverse

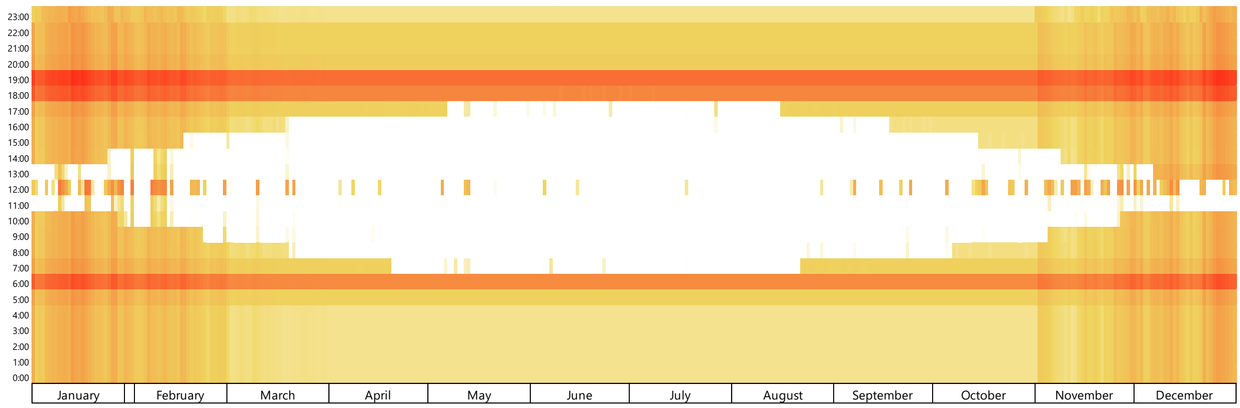

Figure 26: Carpet plot showing the electricity purchase from the grid of variant 16 (best achieved GSC with respect to EEX) of the case study „Brussels" throughout a year. Light colours indicate a low purchase, red indicates a high purchase; own illustration based on results obtained with PVopti

5.1.4.SMART READINESS

For the analysis of the smart-readiness (SR) of the two case study buildings "Brussels" and "Moretti More" the buildings as they are built/ planned (base case) are assessed. For the analysis, a matrix and a calculation method have been derived based on the current discussion about the development of the Smart-Readiness Indicator (SRI) on European level. In the discussion, a simplified rating based on a view services only is currently under development, and the approach discussed in this context is followed in this deliverable as well (compare (Verbeke et al., 2019) and services published in (VITO NV, 2019)).

Brussels:
The case study "Brussels" achieves an overall Smart Readiness of 43 %.
The Scores of the rated impact criteria varies between 25 % (Health and well-being) and 55 % (On-site energy savings). The comparable low rating for Health and well-being is mainly due to the control of the ventilation and shading systems, which are both not operated depending on presence and need due to e.g. bad air-quality or high irradiation. The high scores in the field of energy savings, comfort, flexibility and user information result from the high efforts especially in the areas energy efficiency, heating and domestic hot water. There are comfortable and efficient control possibilities for the users, thermal storages and there is a detailed monitoring, providing actual and historic data on heat and hot water consumption.
As there is no cooling system and no lighting control installed the scores for these domains are 0 %. As already mentioned, high emphasis is placed on the heat and hot water supply, which are efficient, monitored, equipped with storages and especially concerning the heating comfortable and efficient to control leading to the highest score for the domain Heating (67 %) and second highest for Domestic Hot Water (45 %). As the other domains do not comprise special services/ intelligence, the scores are comparably low; e.g. possibility to charge electric vehicles, but no control for the charging process and time.

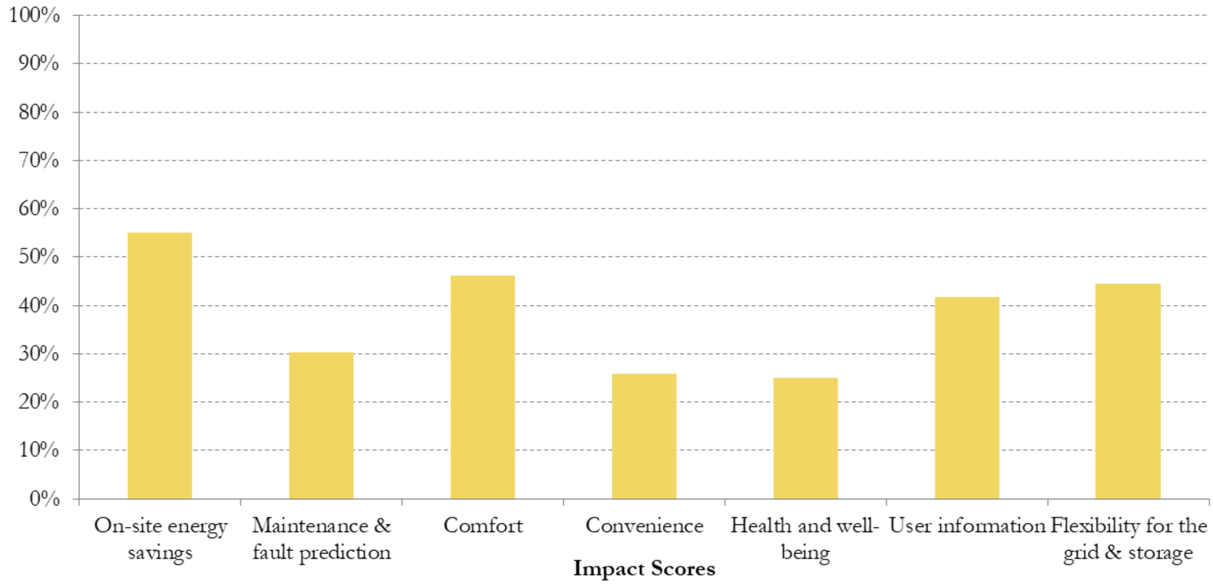

Figure 27: Scores of the Smart Readiness Rating of the assessed impact criterions of the case study "Brussels".

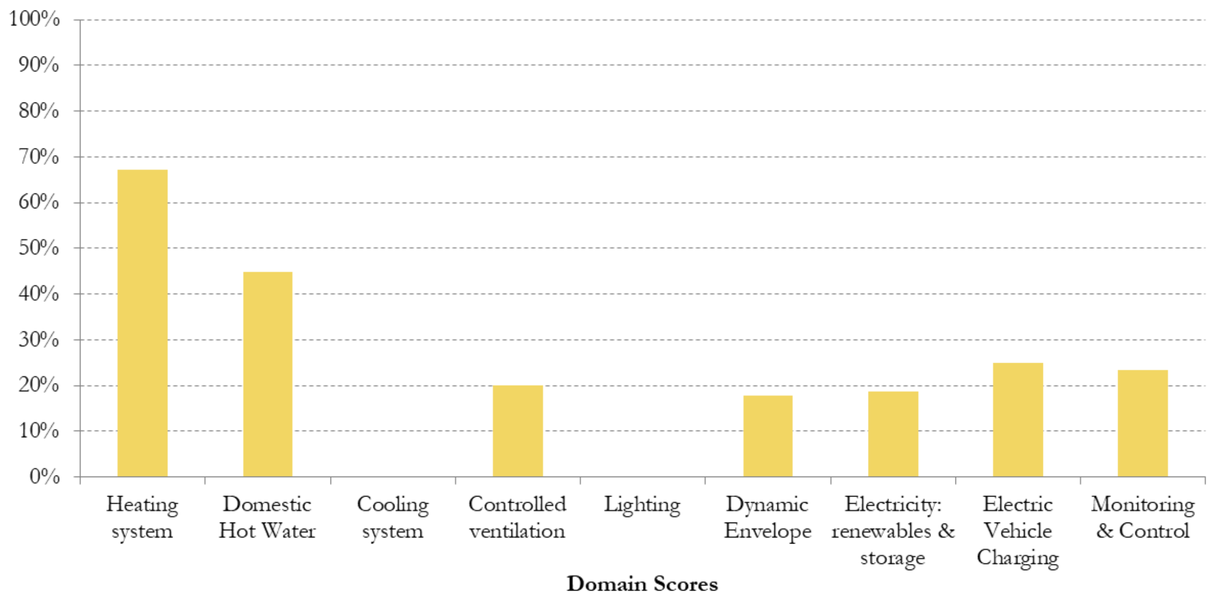

Figure 28: Scores of the Smart Readiness Rating of the assessed domains of the case study "Brussels."

Moretti More:
The case study "Moretti More" achieves an overall Smart Readiness of 31 %.
The Scores of the rated impact criteria vary between 29 % (Information for occupants) and 59 % (Comfort). As there is no thermal or electricity storage and no controlled ventilation, the scores for the impacts "Health and well-being" as well as "Flexibility for the grid and storage" are 0 %. The high score for comfort results from the good controllability of the heating and cooling system (individual room control, communication between controllers).

There are several domains with a score of 0 % (Domestic hot water, Controlled ventilation, Dynamic envelope, Renewable electricity and storage, Electric vehicle charging). The reason is either that there are no installations (renewable energies, electric vehicle charging) present, or there are only manual control (on/ off) possibilities without storages and/ or "intelligence" (hot water, ventilation, shading/ envelope). The highest score is obtained for the lighting (presence control, automatic dimming) followed by the cooling system (individual room control with communication between controllers).

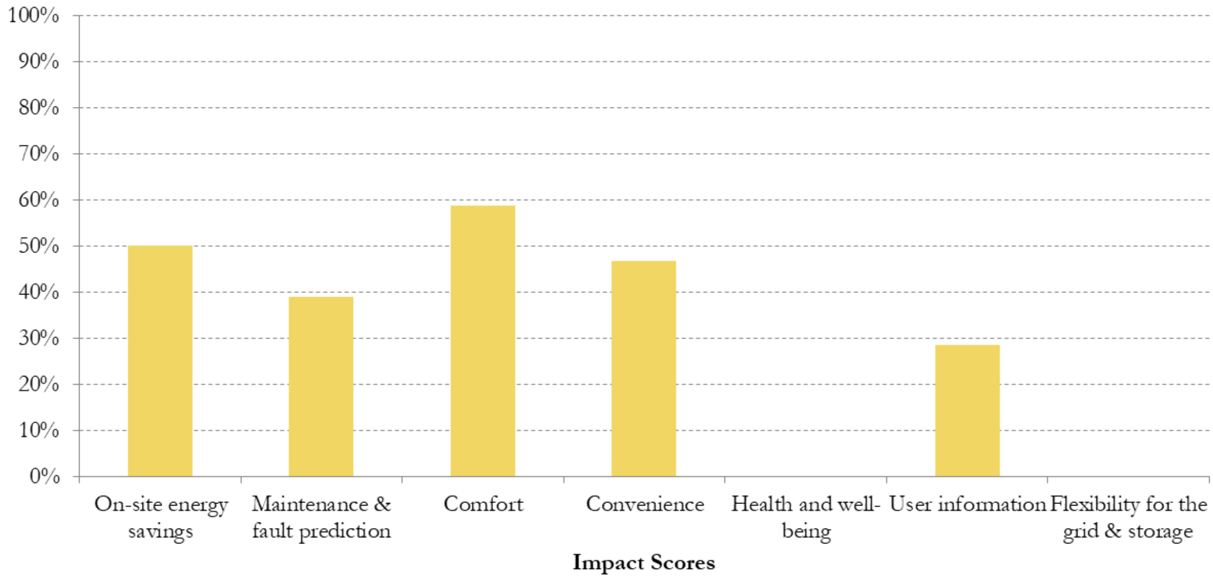

Figure 29: Scores of the Smart Readiness Rating of the assessed impact criterions of the case study "Moretti More"

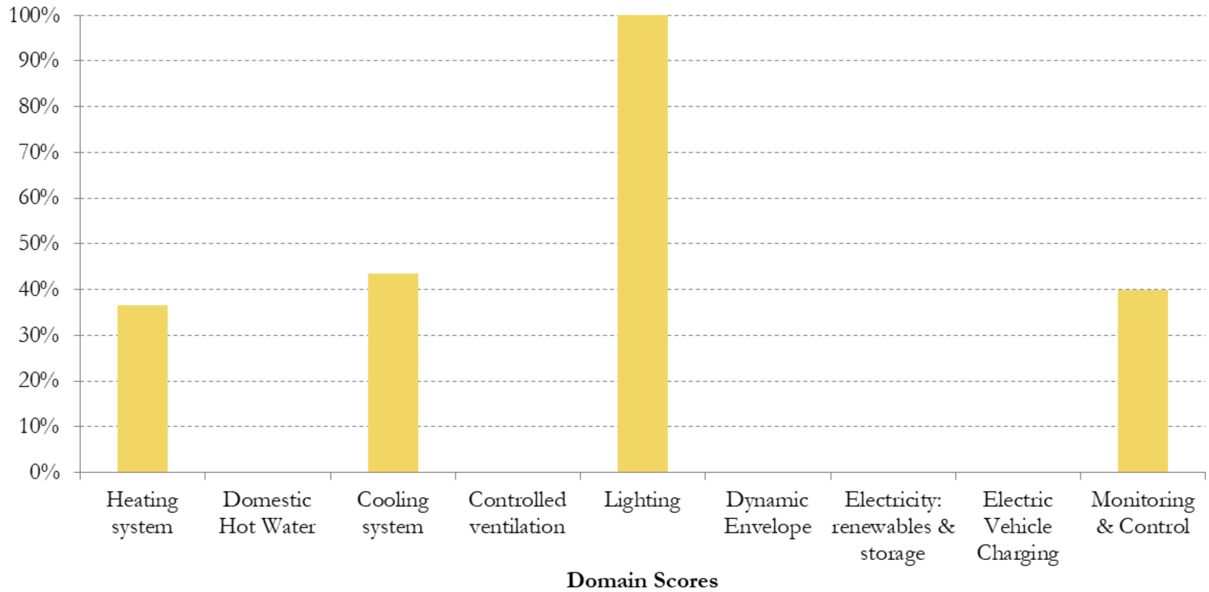

Figure 30: Scores of the Smart Readiness Rating of the assessed domains of the case study "Moretti More"

The driving parameters for a high smart readiness score are the presence of storage systems, detailed monitoring/ data availability and user information as well as intelligence in the control and operation of the building. Depending on the location of a building, different systems/ domains are more important which should be represented in weighting factors for the smart readiness (in moderate/ colder climates the focus is on heating, in southern countries on cooling).

In current standards and regulations, the focus is on the energy demand and supply of a building. Factors concerning well-being and health often only play a minor role. Therefore, it is to be welcomed that this is considered in the SRI as it is currently discussed (Verbeke et al., 2019). This also addresses Co-benefits, which can influence the economic feasibility of a building and which are discussed in Work Packages 6 and 7 of CRAVEzero.

5.2. GUIDANCE FOR CONTINUOUS COMMISSIONING

As described in (Weiß et al., 2019b), commissioning is a process to prove the full functionality of all systems installed in the building. The result is a functional building. In many cases, commissioning is seen as a process between the construction and beginning of the operational phase, probably including detailed monitoring during warranty times. Beyond that, continuous commissioning (CCx) comprises a continuous performance evaluation of the building (including all technical installations) throughout the building life-cycle in order to maintain, improve and optimise the building operation (Verhelst et al., 2017).

Already in (Visier and Jandon, 2004) it is stated that the process of commissioning should be performed throughout the building's life-cycle and not just in the beginning of the operation period to verify the system enables a proper building operation and that all systems work as planned and intended as it is often understood and performed. In (Visier and Jandon, 2004) it is described that in practice, four different types of commission are applied:

- Initial Commissioning (I-Cx)
- Retro-Commissioning (Retro-Cx)
- Re-Commissioning (Re-Cx)
- On-Going Commissioning (On-Going Cx)

The process of commission as well as continuous commissioning gained importance in the past decade and will most likely gain importance and develop in the coming years due to three central drivers/ reasons (compare (Visier and Jandon, 2004)):

- *Energy and environment*: increased pressure on all sectors including buildings to reduce greenhouse gas emissions and mitigate climate change
- *Business*: diversification of services in the building and energy sector; commissioning a way to develop new business for the benefit of customers
- *Technological*: Installation of building automation and monitoring systems in many new buildings already provide data for innovative (continuous) commission services

Besides cost, energy and emission savings, the continuous commission can increase the reliability of the building operation as well as the comfort and health of a building's occupants, which gains importance as comfort requirements of people increase.

The broader view on commission as described in (Visier and Jandon, 2004) consists of several actions to bridge the gap between the expectations of the owner, designer, built system of the contractor and the running system of the operator:

- Clarify the owner's project requirements/ expectations → common understanding of project goals
- Translation of design into understandable specifications for the contractor
- Functional performance testing to verify that the system operates as expected
- Production of system manuals
- Production of regular reports by the operator throughout the building's life-cycle

The actions described in (Visier and Jandon, 2004) can be supported by BIM-methods (BIM: Building Information Modelling); making information available for all stakeholders involved in the building life-cycle in a way, which is understood by all stakeholders at any time. Furthermore, it becomes clear that commissioning should start in a very early phase of the life-cycle (predesign-phase).

(Verhelst et al., 2017) describes two advanced and more detailed approaches of continuous commissioning:

- Model-based Continuous Commissioning (MBCC)
- Monitoring-based continuous commissioning (MBCC)

The difference is that the latter uses measurement data from sensors in the building to analyse and compare the current and past performance of the building, while model-based CCx uses a reference model, which is built either by using historical measurement data or based on expert knowledge and design data. Model-based CCx, therefore, is slightly broader than monitoring-based CCx. However, monitoring-based CCx allows the application of model-free algorithms such as Artificial Neural Networks (ANN) (compare (Verhelst et al., 2017)).

5.3. POSSIBLE COST SAVINGS

For the calculation of possible cost savings the total energy costs of each variant calculated with PVopti are compared. The applied energy costs are taken from Work Package 2 and 6 of the CRAVEzero project, in which also detailed assessments of the investment and life-cycle costs of the technologies applied within this deliverable can be found. They are summarised in Table 4. Besides the overall annual costs for energy cost savings through the on-site usage of renewable energies are assessed (PV self-consumption, solar thermal).

Table 4: Energy prices considered for Germany and Italy

	Germany [€/kWh]	**Italy [€/kWh]**
Natural gas		0.095
District Heat	0.10	
Electricity	0.25	0.216
PV feed-in (< 40 kWp)	0.12	0.07
PV feed-in (> 40 kWp)	0.11	

Brussels:
The different variants show a high variation of the overall energy costs of 3,492 €/a to 15,365 €/a (see Figure 31). The lowest energy costs are achieved in the variants with the connection to the district heating as the costs for district heat are very low compared to the electricity costs, which are relevant for all variants with a heat pump for heating and domestic hot water. The lowest costs are achieved in variants with a passive house envelope (variant 37 and 25). Besides the building envelope the size of the PV system and the size of the battery are major drivers concerning the energy costs as a larger PV system and battery increase the own-consumption on-site as well as the revenues from feed-in. The highest annual energy costs are in variants with a heat pump, a building envelope as built and a small PV system (highest costs in variant 3).
Concerning the achieved cost savings due to the on-site use renewable energies (Figure 32) the size of the PV system as well as the battery and the installation of a heat pump are the driving factors. Furthermore, the heating energy demand slightly influences the energy cost savings; the higher the heating demand, the more electricity from the PV-system can be used on-site by the heat pump. The highest savings are realised in variant 28, the lowest in variant 9, which only has a small PV system, no battery and is connected to the district heating system.
The differences of the annual energy costs in comparison to the base case are illustrated in Figure 33. Therein, negative values indicate higher annual energy costs and positive values lower costs. The highest savings are achieved in buildings connected to the district heating system and a large PV system (variants 22, 25, 34, 37). If all other parameters are the same, the size of the battery has an influence; the higher the capacity, the higher the achieved savings. The highest cost increases are – of course – observed in the variants with the highest energy costs (variants 3, 15, 27). Only in 12 out of the 36 variations the energy costs are below the base case, in the remaining 24 they are higher.

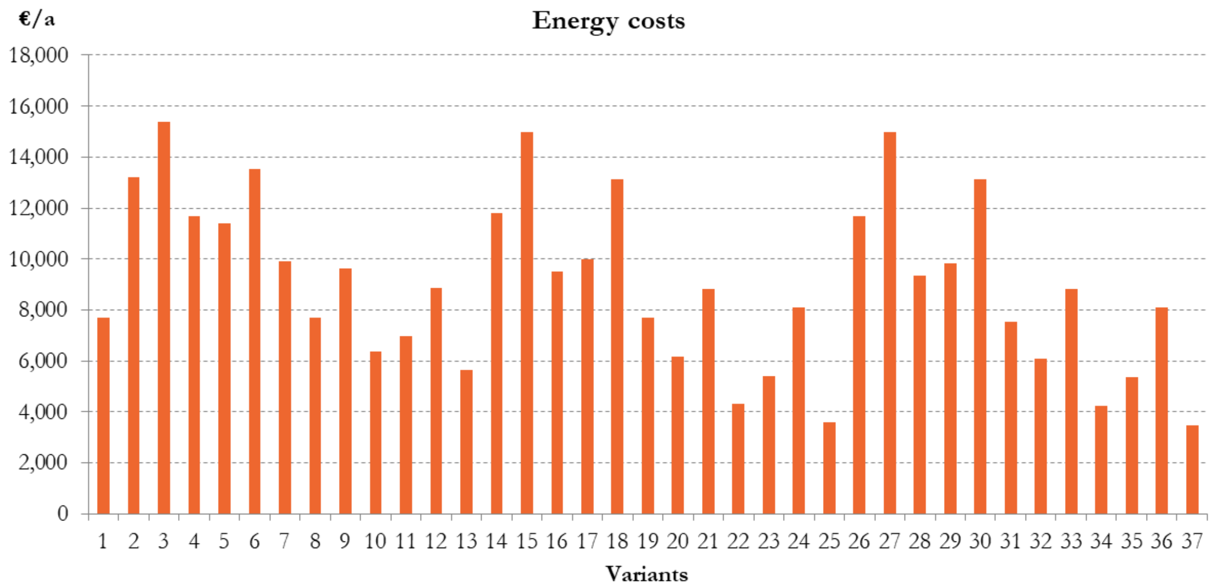

Figure 31: Energy costs of the case study "Brussels"; energy savings due to on-site use of renewable energies and feed-in already considered; own illustration based on results obtained with PVopti

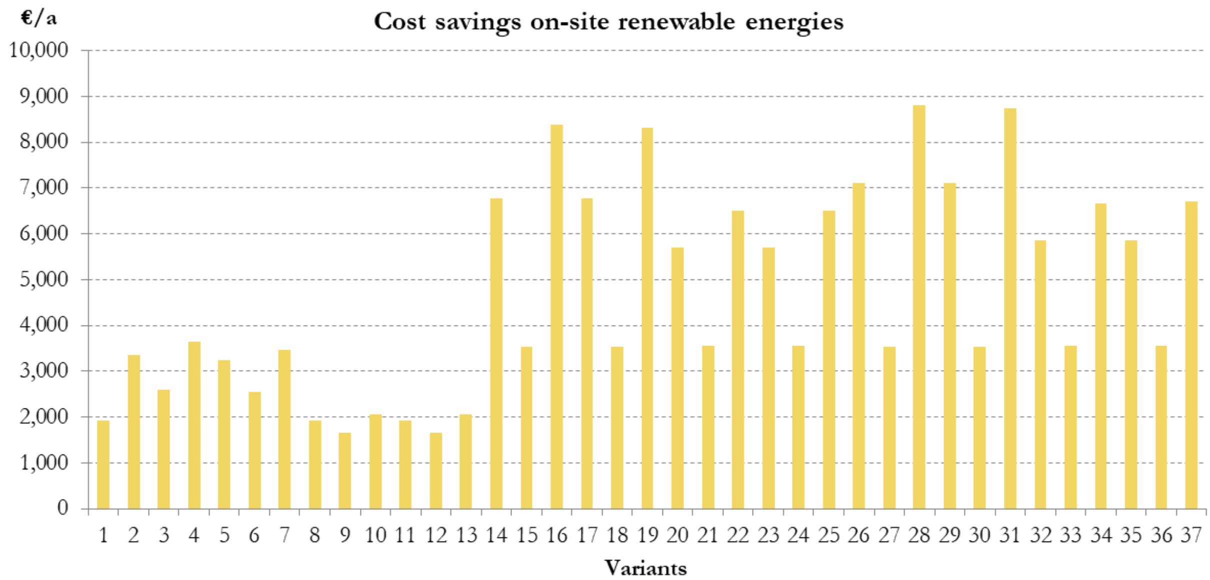

Figure 32: Energy cost savings due to on-site use of renewable energies of the case study "Brussels"; own illustration based on results obtained with PVopti

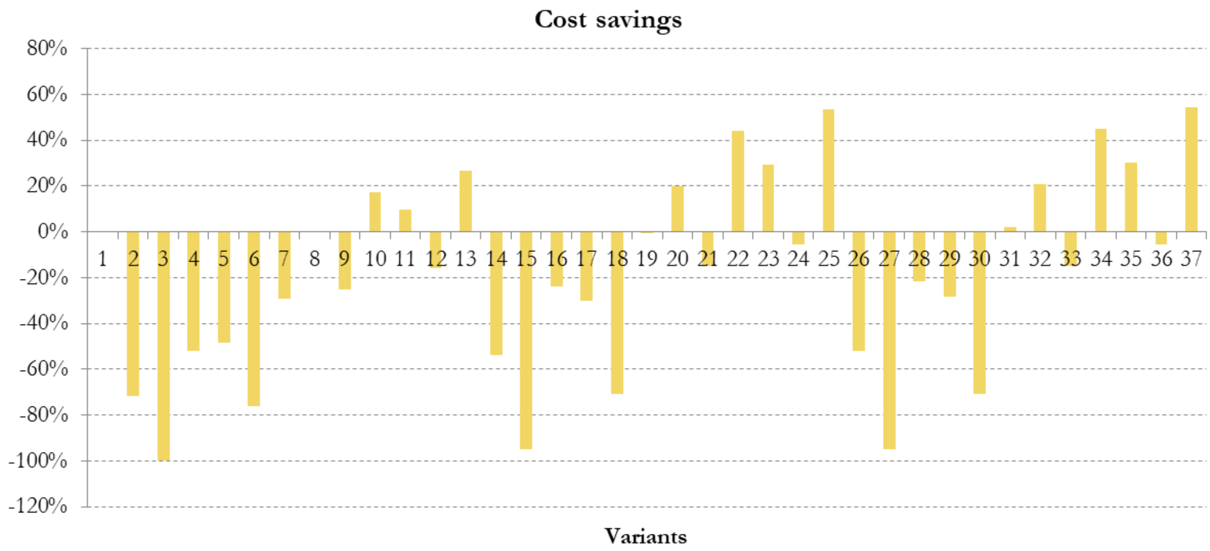

Figure 33: Cost savings compared to the base case of the case study "Brussels"; own illustration based on results obtained with PV opti

Moretti More
The different variants show a comparably small variation of the overall energy costs of 367 €/a to 1,295 €/a (see Figure 34). The lowest energy costs are achieved in the variants which only use a heat pump for heat generation, have a passive house envelope and a large PV system (variants 19 and 31) followed by two variants with same configuration but with the bivalent heat pump installed. The building envelope quality and the size of the PV system are the major factors influencing the annual energy costs followed by the battery storage. The highest annual energy costs are observed in the base case followed by the variants without a PV system.
Concerning the achieved cost savings due to the on-site use renewable energies (Figure 35) the size of the PV system followed by the battery are the driving factors. Furthermore, the heating energy demand slightly influences the energy cost savings; the higher the heating demand, the more electricity from the PV-system can be used on-site. The highest savings are realised in variant 28, the lowest in the variants 1, 8, 20 and 32 (as built no PV, no influence of battery storage in these cases).
The differences of the annual energy costs in comparison to the base case are illustrated in Figure 36. The highest savings are achieved in buildings with a large PV system (variants 19, 25, 31, 37). If all other parameters are the same, the size of the battery followed by the installed heat pump (mono- or bivalent with higher savings in variants with monovalent heat pumps) are the parameters with the highest influence.

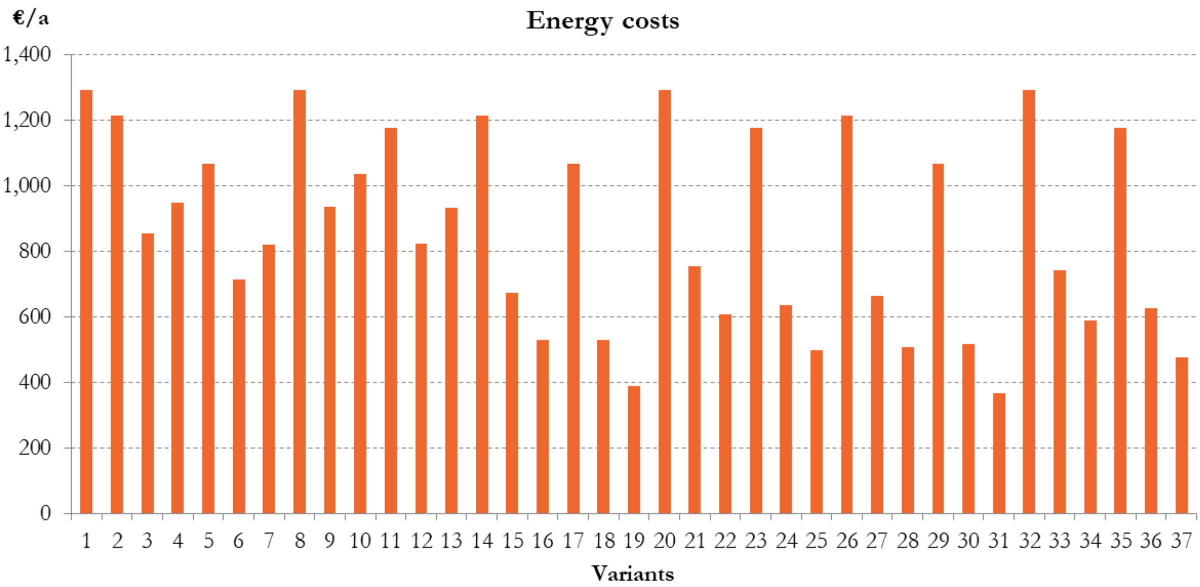

Figure 34: Energy costs of the case study "Moretti More"; energy savings due to on-site use of renewable energies and feed-in already considered; own illustration based on results obtained with PVopti

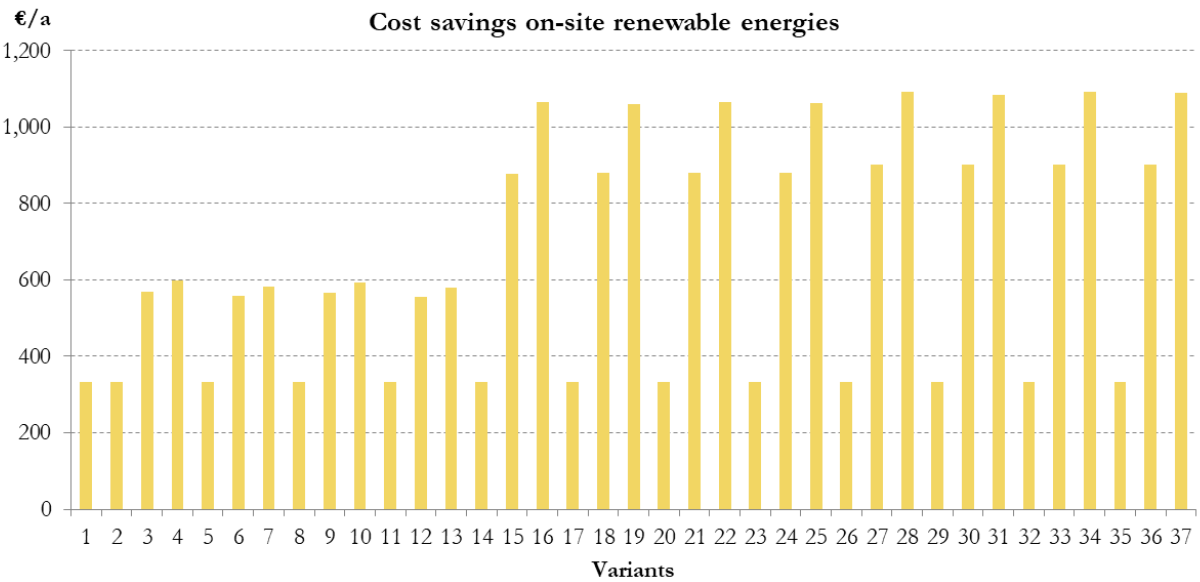

Figure 35: Energy cost savings due to on-site use of renewable energies of the case study "Moretti More"; own illustration based on results obtained with PVopti

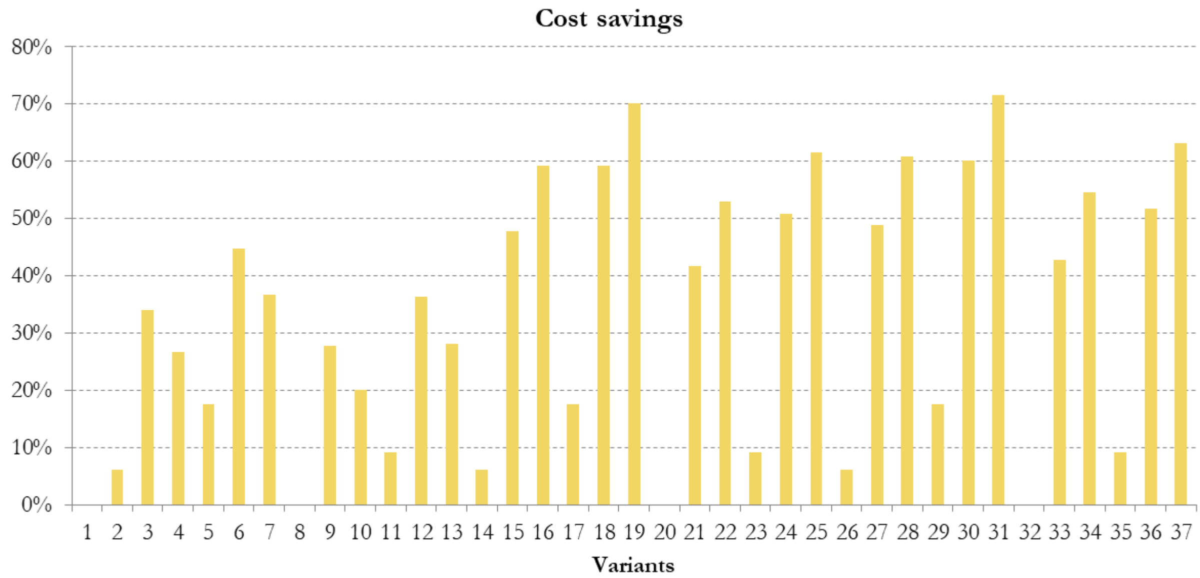

Figure 36: Cost savings compared to the base case of the case study "Moretti More"; own illustration based on results obtained with PVopti

Concerning the energy costs, the end energy used in the building and the respective price is the major factor. As electricity prices are still high compared to other end energy carriers (district heat, gas, fuel oil) energy costs in variants using electricity for heating are higher than in variants without electricity using heating technologies. Besides that, the on-site generation and self-consumption of renewable energies (mainly PV and solar thermal) are decreasing the energy costs if it is assumed that electricity directly used on-site compensates electricity, which otherwise would have been purchased from the grid. Costs associated with the on-site renewable energy generation (i.e. levelised costs of electricity from PV and levelised costs of heat for solar thermal heat) are not considered here; they are considered through the investment and operational costs within the economic analysis and LCC assessment in Work Package 6.

6. DISCUSSION

The case studies "Brussels" and "Moretti More" were analysed with respect to different KPIs, namely self-consumption, autarky GSC with respect to EEX prices, GSC with respect to residual load and the smart readiness of the buildings. For all KPIs except the smart readiness several variants were assessed to identify the driving (technical) factors. However, a positive factor for increasing e.g. the self-consumption is not necessarily positive for the GSC and vice versa. The main positive and negative factors identified for the case study "Brussels" are summarised in Table 5 and for "Moretti More" in Table 6.

The main drivers for a high self-consumption are the installation of electricity storage and the size of the PV-system in relation to the electricity consumers. Thereby, the presence of large electricity consumers especially in summer (cooling units, heat pump) is a crucial factor as well. Generally one can say the smaller the PV-system compared to the electricity demand, the higher the self-consumption as (almost) all electricity is used on-site throughout the year. The challenge in buildings without high electrical demands in summer (high PV generation) is the usage of the generated electricity in the summer months. For a high autarky rate as well as good GSC values however large PV systems are positive.

For good GSC values the installation of battery storages as well as the use of electricity using heating systems is positive, especially when a PV system installed. In climate regions with mainly heating demands a large PV system in combination with heat-pumps is increasing the GSC with respect to EEX prices.

The absence of large electricity consumers, especially the absence of heat pumps with thermal storages, is a crucial part for the self-consumption and GSC as this is (i) affecting the possibility to use PV electricity generated on-site and (ii) affecting the load-shifting possibilities, which are necessary to operate a building grid-supportive. Bivalent heat-pumps thereby even offer higher shifting/ switching potentials and are also positive for the autarky rate.

Especially concerning the self-consumption and autarky, the followed strategy strongly affects the technical installation needed; to increase the self-consumption by trend small PV systems are positive, for a high autarky large systems are necessary. Furthermore, it is crucial that the PV system is sized accurately to the demands of a respective building and sufficient storage possibilities are available.

As the analysis of the smart readiness is based on a more qualitative approach positive and negative factors for the SRI are not included in the summarising tables below. The dimensioning of renewable energy technologies on-site is not influencing the SRI result, but the presence of these technologies. However, what is more important is the availability of storages and the controllability / usability of these storages based on external (grid) demands. Thereby, the installation of batteries, which is positively influencing all other KPIs, has also a positive effect on the smart readiness. For a high SRI-score the controllability and control strategies supporting the stability and management of higher level grids are positive. Implementing these strategies in buildings is also supporting the increase of the self-consumption, autarky as well as the GSC. The quantitative effects were not assessed in this study as detailed buildings models and optimisations would be needed for the analysis, which was not part of the project. It can be concluded however that considering the high level services described in the SRI services catalogue is positively affecting all other quantitative KPIs assessed in the frame of this study.

Table 5: Comparison of factors positively and negatively affecting the assessed KPIs in the case study "Brussels"

	Self-consumption	Autarky	GSC_EEX	GSC_Residual
Positive	• Battery storage • Accurate dimensioning of PV in relation to el. demand (by trend smaller PV) • Installation of heat-pump	• Large PV-system • Large battery storage • No big el. consumer like heat-pump during winter (bivalent heat pumps achieve better results)	• Medium – large PV system in combination with heat pump and battery storage	• Heat pump + Large PV system • If no heat pump and Battery installed, smaller PV-system positive
Negative	• No big el. consumers in summer • No battery storage • Too large PV system	• No Battery storage • Small PV system • Heating system only using electricity → bivalent heat-pumps better	• Non-electric heat generation / district heat → only low shifting potential • No Battery storage	• Non-electric heat generation / district heat → only low shifting potential • No Battery storage

Table 6: Comparison of factors positively and negatively affecting the assessed KPIs in the case study "Moretti More"

	Self-consumption	Autarky	GSC_EEX	GSC_Residual
Positive	• Battery storage • Accurate dimensioning of PV in relation to el. demand especially in summer	• Bivalent heat pump • Large PV system • Battery storage	• Installation of battery + large PV	• Battery • Optimisation of operation
Negative	• Large PV-system • No battery storage	• No battery storage • Small PV system	• Large PV without battery	• Installation of PV

7. CONSLUSION

The aim of the deliverable was to develop and description models and methodologies for continuous commission of buildings and building-grid interaction with a focus on the on-site use of renewable energies. The deliverable thereby addresses two major challenges of the future:

- Reduction of energy use in buildings and avoidance of mal-functions in building energy systems
- Integration of fluctuating renewable energies in electricity grids by adjustments in the building operation

The process of continuous commission is described based on a detailed literature review as well as on results from projects focusing on fault detection in large and complex building energy systems. The importance for a reliable and robust operation of a building is highlighted and suggestions for the integration of continuous commission in the building life-cycle are provided.

For the integration of renewable energies in the electricity grid by an adjusted building operation, definitions and findings from the IEA EBC Annex 67 “Energy Flexible Buildings” are the basis. Possibilities for an improved building-grid interaction are described qualitatively and assessed quantitatively. Therefore, PHPP-models of case studies and the tool PVopti are used to assess the self-consumption and autarky level of several technology sets are assessed. The results show that an adequate sizing of on-site renewable energy technologies in combination with electrical and thermal storages is essential. A difference between the goal of increasing the self-consumption and increasing the autarky is the size of the on-site renewable generation. While for a high autarky rate a high generation capacity is needed to provide the needed electricity also in times with low specific on-site generation this approach reduces the self-consumption in times with high specific on-site generation. In the case study “Brussels” self-consumption rates between 19 % and 100 % and autarky rates of 14 % to 77 % are achieved. The variants with a high autarky always have a relatively low self-consumption compared with similar technology sets and vice versa. Variants with a large PV system and battery but no heat pump (see e.g. variants 22, 25, 34, 37 in Figure 10 and Figure 11) have a high autarky rate (large part of the electricity demand during winter can be provided by on-site PV generation). On the other hand variants with a small PV system and a heat pump (27 and 30) have high self-consumptions but a very low autarky. Similar results are obtained in the case study “Moretti More”. However, due to a more constant electricity demand throughout the year due to the electrical cooling units installed, the importance of a battery for both, the self-consumption and autarky, is lower than for the case study “Brussels”, in which the electricity demand fluctuates more throughout the year. The right dimensioning of the PV system is of major importance in this case.

With the tool PVopti, also hourly profiles for the electricity purchase from the grid were generated, which are used to analyse the grid-supportiveness with respect to two external grid signals:

- EEX-prices
- Residual load

Almost all analysed technology sets are grid-adverse and no set is really grid-supportive. However, the technologies installed and combined offer the possibility to operate the buildings grid-supportive. In order to increase the grid-supportiveness (GSC) the control strategies of single technologies as well as the whole building energy system have to be adjusted. Especially the use of storages and the operational times of large electricity consumers like heat pumps and cooling units are crucial. To quantify the effects of different control strategies, detailed simulations and optimisations are required, which were not part of this study.

In addition to the quantitative assessment, the smart readiness of two case study buildings is rated using a simplified method based on the proposed simplified online quick–scan for the SRI. Here, only the base case (as built / as planned) is rated. Both buildings achieve an SRI below 50 %. Especially concerning on-site energy savings and comfort, both buildings show a good performance, which can be explained with the focus on energy demand reductions and a high comfort in buildings in the past years. The flexibility and smartness of building operation is just starting to gain importance and the current energy markets are still not offering promising business cases for a smart and flexible operation. However, the topic will gain importance in the future and many technologies currently installed in buildings already offer an increased flexibility with some adjustments in control strategies (thermal storages, heat pumps).

Besides the technical implementation, the market design including sufficient incentives to provide flexibility in / of the building for the operation and management of higher-level electricity grids has to be adjusted. Currently, only large switchable and shiftable loads can participate in the electricity market. However, the required power for participation is much higher than the power most buildings can provide. Different approaches to close the gap are currently assessed in different projects. Possibilities are e.g. pooling of many small loads to reach the required load size, lowering the required size or new ways of trading amongst participants in the energy markets.

Summing up, the addressed KPI strongly influences the technologies needed. Especially the autarky rate has very different needs compared to the other KPIs. Furthermore, most technologies needed for a flexible building operation are already available. However, some are still comparably expensive and therefore not wide spread. The main challenge is the operation and management of buildings in way that renewable energy can be integrated in the energy system on different levels (on-site, regional, national, European). Therefore, on the one hand control strategies in buildings have to be adjusted and optimised, on the other hand adequate grid signals have to be available for building management and control systems.

8. REFERENCES

2019. Annex C - simplified service catalogue (excel sheet): Part of the deliverables of the study "Support for setting up a Smart Readiness Indicator for buildings and related impact assessment". https://smartreadinessindicator.eu/sites/smartreadinessindicator.eu/files/sri2_annex-c_service-catalogue_simplified-method.xlsx. Accessed 22 August 2019.

Baillieul, J., Caramanis, M.C., Ilic, M.D., 2016. Control Challenges in Microgrids and the Role of Energy-Efficient Buildings [Scanning the Issue]. Proc. IEEE 104 (4), 692–696. 10.1109/JPROC.2016.2532241.

Bürger, V., Hesse, T., Palzer, A., Köhler, B., Herkel, S., Engelmann, P., 2015. Klimaneutraler Gebäudebestand 2050. Öko-Institut e.V., Institut für angewandte Ökologie; Fraunhofer Institut für Solare Energiesysteme, 291 pp. https://www.umweltbundesamt.de/sites/default/files/medien/378/publikationen/climate_change_06_2016_klimaneutraler_gebaeudebestand_2050.pdf. Accessed 7 March 2018.

2004. Commissioning tools for improved energy performance: Results of IEA ECBCS ANNEX 40, 201 pp. https://www.ecbcs.org/Data/publications/EBC_Annex_40_Commissioning_Tools_for_Improved_Energy_Performance.pdf. Accessed 6 August 2019.

Denholm, P., Hand, M., 2011. Grid flexibility and storage required to achieve very high penetration of variable renewable electricity. Energy Policy 39 (3), 1817–1830. 10.1016/j.enpol.2011.01.019.

Fraunhofer Institute for Systems and Innovation Research, Fraunhofer Institute for Solar Energy Systems, Institute for Resource Efficiency and Energy Strategies GmbH, Observ'ER, TU Wien - Energy Economics Group, TEP Energy GmbH, 2016. Mapping and analyses of the current and future (2020 - 2030) heating/cooling fuel deployment (fossil/renewables): Work package 2: Assessment of the technologies for the year 2012, 215 pp. Accessed 7 March 2018.

Gellings, C.W., 1985. The concept of demand-side management for electric utilities. Proc. IEEE 73 (10), 1468–1470. 10.1109/PROC.1985.13318.

Hartmann, N., 2013. Rolle und Bedeutung der Stromspeicher bei hohen Anteilen erneuerbarer Energien in Deutschland : Speichersimulation und Betriebsoptimierung. Doctoral Thesis. Universität Stuttgart, Stuttgart.

Henning, H.-M., Palzer, A., 2015. Was kostet die Energiewende? – Wege zur Transformation des deutschen Energiesystems bis 2050: Die modellbasierte Studie untersucht sektor- und energieträgerübergreifend die System- und Kostenentwicklung einer klimaschutzkompatiblen Transformation des deutschen Energiesystems., Freiburg, 90 pp. https://www.ise.fraunhofer.de/content/dam/ise/de/documents/publications/studies/Fraunhofer-ISE-Studie-Was-kostet-die-Energiewende.pdf. Accessed 24 April 2018.

Jansen, M., Richts, C., Gerhardt, N., Lenck, T., Heddrich, M.-L., 2015. Strommarkt-Flexibilisierung: Hemnisse und Lösungskonzepte. Eine Studie im Auftrag des BEE e.V., Bochum, 65 pp. https://www.bee-ev.de/fileadmin/Publikationen/Studien/20150216BEE_Strommarkt_Flexibilisierung.pdf. Accessed 29 August 2019.

Jensen, S.Ø., Marszal-Pomianowska, A., Lollini, R., Pasut, W., Knotzer, A., Engelmann, P., Stafford, A., Reynders, G., 2017. IEA EBC Annex 67 Energy Flexible Buildings. Energy and Buildings 155, 25–34. 10.1016/j.enbuild.2017.08.044.

Junker, R.G., Azar, A.G., Lopes, R.A., Lindberg, K.B., Reynders, G., Relan, R., Madsen, H., 2018. Characterizing the energy flexibility of buildings and districts. Applied Energy 225, 175–182. 10.1016/j.apenergy.2018.05.037.

Klein, K., 2017. Quantifying the energy flexibility of building energy systems: Evaluation of grid-supportive concepts for space heating and cooling in non-residential buildings. Doctoral Thesis. Fraunhofer Verlag, Karlsruhe, 206 Seiten.

Klein, K., Herkel, S., Henning, H.-M., Felsmann, C., 2017. Load shifting using the heating and cooling system of an office building: Quantitative potential evaluation for different flexibility and storage options. Applied Energy 203, 917–937. 10.1016/j.apenergy.2017.06.073.

Klein, K., Killinger, S., Fischer, D., Streuling, C., Salom, J., Cubi, E., 2016a. Comparison of the future residual load in fifteen countries and requirements to grid-supportive building operation. EuroSun Conference Proceedings.

Klein, K., Langner, R., Kalz, D., Herkel, S., Henning, H.-M., 2016b. Grid support coefficients for electricity-based heating and cooling and field data analysis of present-day installations in Germany. Applied Energy 162, 853–867. 10.1016/j.apenergy.2015.10.107.

Köhler, B., Stobbe, M., Moser, C., Garzia, F., 2018. Guideline II: nZEB Technologies: Report on cost reduction potentials for technical NZEB solution sets. Fraunhofer Institute for Solar Energy Systems; AEE - Institute for Sustainable Technologies; Eurac Research, Freiburg, Gleisdorf, Bolzano, 74 pp. Accessed 20 August 2019.

Kohlhepp, P., Hagenmeyer, V., 2017. Technical Potential of Buildings in Germany as Flexible Power-to-Heat Storage for Smart-Grid Operation. Energy Technol. 5 (7), 1084–1104. 10.1002/ente.201600655.

Lindberg, K.B., 2017. Impact of Zero Energy Buildings on the Power System - A study of load profiles, flexibility and system investments. Doctoral Thesis. Trondheim, 192 pp.

Lüking, R.-M., Hauser, G., 2011. Die thermische Konditionierung von Gebäuden im Kontext eines zukünftigen Energieversorgungssystems: Studie des Fraunhofer-Instituts für Bauphysik. Fraunhofer IRB-Verl., Stuttgart, 72 pp.

Morales, J.M., Conejo, A.J., Madsen, H., Pinson, P., Zugno, M., 2014. Integrating Renewables in Electricity Markets: Operational Problems. Springer US, Boston, MA, s.l., 429 pp.

Moslehi, K., Kumar, R., 2010. A Reliability Perspective of the Smart Grid. IEEE Trans. Smart Grid 1 (1), 57–64. 10.1109/TSG.2010.2046346.

Palensky, P., Dietrich, D., 2011. Demand Side Management: Demand Response, Intelligent Energy Systems, and Smart Loads. IEEE Trans. Ind. Inf. 7 (3), 381–388. 10.1109/TII.2011.2158841.

Pernetti, R., Reynders, G., Knotzer, A., 2017. Annex 67: Energy Flexible Buildings - Energy Flexibility as a key asset in a smart building future: Contribution of Annex 67 to the European Smart Building Initiatives. Position Paper of the IEA Energy in Buildings and Communities Program (EBC) Annex 67 "Energy Flexible Buildings", 16 pp. http://www.annex67.org/media/1470/position-paper-energy-flexibility-as-a-key-asset-i-a-smart-building-future.pdf. Accessed 29 August 2019.

Reynders, G., 2019. Second Technical Study to support the establishment of a common European scheme for rating the Smart Readiness of Buildings. Energy Ville; VITO; Waide Strategic Efficiency. Third topical group B meeting, 11 June 2019, online.

Salom, J., Marszal, A.J., Widén, J., Candanedo, J., Lindberg, K.B., 2014. Analysis of load match and grid interaction indicators in net zero energy buildings with simulated and monitored data. Applied Energy 136, 119–131. 10.1016/j.apenergy.2014.09.018.

SIA - Schweizer Ingenieur- und Architektenverein, 2015. Raumnutzungsdaten für Energie- und Gebäudetechnik. SIA, Zürich, Switzerland.

Taiyou Research, 2014. Global Market for Lithium-Ion Batteries - Forecast, Trends & Opportunities, 2014-2020. https://www.marketresearch.com/product/sample-8323376.pdf. Accessed 25 June 2018.

The European Parliament and the Council of the European Union, 2018. DIRECTIVE (EU) 2018/844 OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL of 30 May 2018 amending Directive 2010/31/EU on the energy performance of buildings and Directive 2012/27/EU on energy efficiency, 17 pp.

UN Environment, n.d. Sustainable buildings. https://www.unenvironment.org/explore-topics/resource-efficiency/what-we-do/cities/sustainable-buildings. Accessed 16 August 2019.

Urban, B., Roth, K., Harbor, D., 2016. Energy Savings from Five Home Automation Technologies: A Scoping Study of Technical Potential. Final Report to the Consumer Technology Association, Boston, 67 pp. Accessed 16 August 2019.

Verbeke, S., Aerts, D., Rynders, G., Ma, Y., Waide, P., 2019. Interim Report July 2019 of the 2nd Technical Support Study on the Smart Readiness Indicator for Buildings, Mol, 281 pp. https://smartreadinessindicator.eu/sites/smartreadinessindicator.eu/files/sri2-_second_interim_report.pdf. Accessed 22 August 2019.

Verbeke, S., Ma, Y., van Tichelen, P., Bogaert, S., Gómez Oñate, V., Waide, P., Bettgenhäuser, K., Ashok, J., Hermelink, A., Offermann, M., Groezinger, J., Uslar, M., Schulte, J., 2018. Support for setting up a Smart Readiness Indicator for buildings and related impact assessment - final report, Brussels, 288 pp. https://smartreadinessindicator.eu/sites/smartreadinessindicator.eu/files/sri_1st_technical_study_-_final_report.pdf. Accessed 12 June 2018.

Verhelst, J., van Ham, G., Saelens, D., Helsen, L., 2017. Model selection for continuous commissioning of HVAC-systems in office buildings: A review. Renewable and Sustainable Energy Reviews 76, 673–686. 10.1016/j.rser.2017.01.119.

Voss, K., Sartori, I., Napolitano, A., Geier, S., Gonçalves, H., Hall, M., Heiselberg, P., Widén, J., Candanedo, J.A., Musall, E., Karlsson, B., Torcellini, P., 2010. Load Matching and Grid Interaction of Net Zero Energy Buildings, in: Conference proceedings / EuroSun 2010, International Conference on Solar Heating, Cooling and Buildings: 28 September - 1 October 2010, Graz, Austria. EuroSun 2010, Graz, Austria. 9/28/2010 - 10/1/2010. International Solar Energy Society, Graz, pp. 1–8.

Weiß, T., Fulterer, A.M., Knotzer, A., 2019a. Energy flexibility of domestic thermal loads a building typology approach of the residential building stock in Austria. Advances in Building Energy Research 13 (Issue 1), 122–137.

Weiß, T., Meier, K., Knotzer, A., Höfler, R., 2019b. D3.1: Guideline I - nZEB Processes, Gleisdorf, München, 186 pp. www.cravezero.eu/wp-content/uploads/2019/03/CRAVEzero_D31_nZEBProcesses.pdf. Accessed 6 August 2019.