SENSE

SENSE: Semantic-based Explanation of
Cyber-physical Systems

Deliverable 6.3:
Results of sustainability evaluation

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Abstract

This report, Deliverable 6.3 of the SENSE project (Semantic-based Explanation of Cyber-physical Systems), presents the sustainability evaluation results in the area of Smart Grids and Smart Buildings. It analyses case studies including the Smart Grid Seehub, Local Energy Communities (LEC), and Smart Buildings, focusing on assessing the potential technical, economic, and environmental impacts of the SENSE system. The findings demonstrate improved grid efficiency, enhanced self-consumption, significant CO_2 emission reductions, and energy savings supported by anomaly detection. The report highlights the system's ability to foster user acceptance and transparency, emphasizing its role in sustainable energy management and offering insights for future research on intelligent control mechanisms and user investment willingness.

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Executive Summary

The SENSE project (Semantic-based Explanation of Cyber-physical Systems) aims to enhance the understanding and acceptance of complex energy systems, focusing on Smart Grids and Smart Buildings. Deliverable 6.3 presents the sustainability evaluation results of various case studies, including Smart Grid Seehub, Local Energy Communities (LEC), and Smart Buildings. The report analyses the potential technical, economic, and environmental impacts of the SENSE system using real-world data and simulations.

In the Smart Grid Seehub case, the SENSE system demonstrated improved grid efficiency through dynamic charging power limits, significantly reducing contractual penalties compared to static limits. The cost-benefit analysis highlighted the economic viability of the SENSE system in delaying or avoiding costly grid reinforcements while enhancing user transparency and trust.

For the LEC scenario, optimisation strategies increased self-consumption and reduced CO_2 emissions by up to 47.3%, with economic benefits scaling positively with precise forecasting and efficient energy management. The SENSE system's explainability feature plays a crucial role in fostering community acceptance of necessary technical measures such as load adjustments and curtailments.

In the Smart Building case, simulations assessed the energy impact of behavioural factors such as window positions and temperature settings. The SENSE system's ability to detect anomalies contributed to energy savings, with potential reductions of up to 10% in annual building energy consumption.

Overall, the SENSE system proves to be a valuable tool for sustainable energy management, offering economic advantages, operational efficiency, and ecological benefits. Future research should focus on user willingness to invest in such technologies and further development of feedback systems to maximise the potential of intelligent control mechanisms.

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1 Introduction

1.1 Purpose and Scope of the Document

The SENSE project provides users of complex systems in the field of Smart Grids and Smart Buildings (see [1]) with explanations of (abnormal) events. Such events can be, for example, a reduction in the charging power of electric vehicles, an active power limitation in the feed-in of photovoltaic systems or increased consumption in office buildings. The key question here is the impact of increased acceptance of complex systems, which can be achieved through improved user understanding (see [2]). The goal of significantly reducing greenhouse gas emissions through the introduction of these complex systems should be supported in this way. This report therefore looks at different use cases based on real and simulated data and analyses the potential impact of increased system acceptance and system efficiency.

1.2 Structure of the Document

This report is structured into several chapters, each addressing different aspects of the SENSE project. Chapter 1 introduces the purpose and scope of the report focusing on the SENSE project's role in enhancing user understanding of complex systems within Smart Grids and Smart Buildings to support greenhouse gas reduction objectives. Chapter 2 details the data and methodologies used, covering specific case studies in the Smart Grid and Smart Building area. It furthermore outlines the economic analysis and cost considerations related to the SENSE system.

Chapter 3 presents the evaluation results, providing in-depth analyses for each use case, including cost/benefit analyses and sustainability assessments. It highlights the impact of static and dynamic charging power limits, self-consumption optimizations, and smart building energy efficiency impacts of seasonal events such as opened windows or wrong room temperature settings. Finally, Chapter 4 summarizes the findings and offers an outlook on the potential of the SENSE system to contribute to sustainable energy system management, emphasizing the importance of continued research into user acceptance and intelligent control mechanisms.

2 Used Data and Methodology

This article examines various use cases based on innovative approaches to optimising and evaluating energy systems. The data basis of the respective cases reflects the specific challenges and potentials in the urban, rural and industrial context in the following chapters and serves as a basis for a cost-benefit analysis based on dynamic investment calculation (cf. e.g. [3]).

2.1 Smart Grid Seehub

The underlying data of the Seehub Case is based on measurement data collected in the Seehub Garage as part of the Aspern Smart City Research (ASCR - www.ascr.at) project. This testbed comprises an urban distribution grid environment with real and virtual loads. The analysed data includes measured values of energy consumption and feed-in as well as detailed information on the operating conditions of the components installed in the garage, including the charging infrastructure for electric vehicles (EVCS), a battery storage system (BESS) and a photovoltaic system (PV).

The measurement data was collected over a total period of four months, whereby the static and dynamic operating ranges were each evaluated over different periods of time. The static operating ranges were based on fixed maximum values, while the dynamic operating ranges were based on a continuous calculation of the available grid capacities, taking into account the current grid load status.

The data includes in particular:

- Charging infrastructure: Data was collected from eight charging points of different types and power classes, including AC chargers (11 kW, 22 kW) and DC fast chargers (30 kW, 75 kW).
- Battery storage system: The data includes charging and discharging profiles of the BESS (100 kW/200 kWh) for flexibility provision.
- PV system: Measured values of the electricity generation of a PV system with 11 kWp.
- Grid status: In addition, load data from other consumers within a virtual transformer was recorded, including around 100 flats, a supermarket and other commercial facilities.

Key performance indicators (KPIs) based on the measured data were defined to assess compliance with grid-related operating areas. These include the number of violations of the operating ranges, the average duration of the violations and the maximum power overrun (see Table 1). The data analysis showed significant differences in the violations especially between static and dynamic operating ranges. This is where the SENSE project comes in, firstly to recognise the above violations and secondly to explain the necessary technical measures to eliminate them (e.g. by reducing the charging power) to the users of the system.

Table 1: Data basis used for static and dynamic operating settings (see [4]).

	static	dynamic
Evaluated days	44	71
Number of envelope violations	1856	1446
Area of harm in [kWh]	118,03	29,78
Average violation in [kW]	1,56	0,55
Maximum violation in [kW]	62,93	29,16
Average violation duration in [min]	2,45	2,24
Total energy charged in [kWh]	15786	26737

2.2 Smart Grid LEC

The data basis for the second use case is based on a SimBench data set (see [5]), which serves as a reference for the dimensioning and parameters of a rural low-voltage grid settlement simulated in BIFROST (see [6]). The BIFROST co-simulation framework makes it possible to create a virtual testbed of a grid segment and to analyse various use cases through discrete simulation. On the one hand, physical processes (load flow, charging/discharging processes, etc.) are modelled according to the state of the art and, on the other hand, existing data sets (weather, load curves, etc.) are used. The specific SimBench data set used provides standardised data for the grid planning and operating environment in various scenarios, including a future scenario for the year 2034 that considers the extensive integration of photovoltaic (PV) systems and battery storage.

The following parameters were derived from the SimBench data set and integrated into the simulation for a local energy community (LEC):

1. grid topology and dimensioning: the simulated low-voltage grid settlement comprises 13 buildings that are connected to the medium-voltage grid via a 20/0.4 kV transformer station. The station has a rated power of 250 kVA, whereby 80% of the rated power (200 kW) is assumed for operation.
2. PV systems: The installed capacity of the PV systems totals 520 kWp.
3. battery storage systems: Battery storage systems with a total capacity of 421 kWh are available, whereby the CO2 emissions for the production of the battery storage systems are taken into account at 125 kg/kWh and distributed over a storage service life of 15 years[1].
4. e-charging stations: The charging infrastructure comprises five charging stations with different outputs (2 × 3.7 kW, 2 × 11 kW, 1 × 22 kW).
5. load profiles: The household load profiles are based on standardised data from SimBench and include typical consumption patterns that are characteristic of residential and agricultural buildings. The profiling also takes into account seasonal and daily fluctuations.

Real weather data from Vienna for the year 2021 was used to model PV generation, while the optimisation of battery and charging behaviour is based on physical models. This data basis enables a realistic depiction of the rural low-voltage grid and serves as the basis for the

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[1] See https://www.senergic.de/aktuelles/uebersicht-stromspeicher/

economic evaluation. The economic analysis primarily considers the realisable self-consumption values for the simulation results determined in Table 2.

Table 2: Data basis used for simulated scenarios of the LEC (see [7]).

Scenario	Electricity withdrawn from grid for LEC in **[MWh]**	Curtailment-PV in **[MWh]**
Reference with PV power restriction (without consumption optimisation)	163	0
Scenario 1 with optimisation	63,7	4,1
Scenario 2 with optimisation and ideal forecast	55,2	0,6

To calculate the resulting revenue for electricity exports, an average market price of € 70/MWh and an average tariff (energy, grid, taxes) of € 300/MWh for own consumption were assumed.

2.3 Smart Building

To validate the SENSE system with real building data, measurement data from the demonstration area in the Infineon building in Villach were collected. The measurement setup was built up in the finished ARROWHEAD (https://arrowhead.eu/) research project. The demonstration area consists of two large offices and two meeting rooms. The collected data consists of more than 200 sensor values related to energy, comfort and climate. For each room several temperature values, humidity, CO2, light, as well as the position of the shading (drawn or not drawn, tilt angle) and the window opening are collected. The heat transfer in the room for heating and cooling and the electricity consumption by light and electric devices are measured. At the top of the building a weather station including radiation sensor in all building directions are positioned. A three-month period (Feb to April) of data of one meeting room was used for the detailed evaluation. The most common issues (sensor outtakes, open windows, to high heating demand) are summarized in Table 3 .

Table 3: Observations during the measurement period

Observed values	**Values**
Evaluated days	89
Number of sensor outtakes	1
Number of open windows	16
Number of open window and open time > 7200 seconds	7
Number of high energy events	7

Beside the measured data, a simulation model in IDA ICE, created in the previous mentioned ARROWHEAD research project, was adapted to the usage in the SENSE project. IDA ICE (Indoor Climate and Energy) is a dynamic simulation software developed by EQUA Simulation AB, used for the detailed analysis of building energy performance and indoor climate. It allows for hourly and sub-hourly simulations of heating, cooling, ventilation, lighting, and occupant

comfort in complex building models. In this project, IDA ICE was employed to evaluate both energy consumption and indoor environmental quality under varying operational scenarios and specific mis-operation periods.
Three main operation scenarios were defined:

- Window Open
    - Standard Shading operation regardless of window opening
    - Shading off on windows, if window is open
    - Shading off on all windows and fixed glazing, if window is open
- Setpoint heating and cooling
- Shading mis-usage

Each operation scenarios were evaluated during winter, spring, summer and winter time (Table 4).

Table 4: Specified time-period of operation scenarios

Scenario	Start date	End Date
Winter	15.01.	28.01
Spring	13.05.	26.05.
Summer	15.07.	28.07.
Autumn	14.10.	27.10.

To allow a comparison between each case a reference scenario with a mis-operation period of 0 hours was used. The start-date and start-time of the specified mis-operation period is shown in Table 5.

Table 5: Specified mis-operation period

State	Scenario	Mis-operation time in hours	Start date of mis-operation period				
1	**Reference**	0	Winter	Spring	Summer	Autumn	Start Time
2	**3h**	3	24.01.	22.05.	24.07.	23.10.	08:00
3	**4h**	4					
4	**6h**	6					
5	**8h**	8					
6	**12h**	12					
7	**18h**	18					
8	**24h**	24					
9	48h	48					
10	**76h**	76	19.01.	17.05.	19.07.	18.10.	

To estimate the impacts of the mis-operation period on the overall building energy consumption, a reference simulation of the demonstration area (two offices and two meeting rooms) and a reference simulation of the whole building, are performed for a complete year (see Table 6).

Table 6: Overview reference simulation results

Name	Simulation period	Max Heating [kW]	Max Cooling [kW]	Energy Heating [kWh]	Energy Cooling [kWh]	PDH [h]
Building	1 year	-	-	1 338 358	265 231	7 557
Demo	1 year	2.25	7.86	22 108	9 255	5 166
Demo Winter	2 weeks	1.99	1.53	1604	0	89
Demo Spring	2 weeks	0.20	5.40	382	650	206
Demo Summer	2 weeks	0.03	5.83	128	952	257
Demo Autumn	2 weeks	0.02	3.57	919	175	187

The operation scenario of an open window showed the highest impact regarding to the increased heating demand during winter. Because of the climatic situation in Villach, an open window has during spring, summer and autumn lead to a lower cooling energy consumption, with the highest reduction in spring and autumn. The additional simulation runs, which consider, that the shading is also not drawn for the opened window and for all fixed glazing, showed only a minor decrease in cooling energy demand. The variation of the shading device, without an open window showed the assumed increase in cooling energy during spring, summer and autumn.

2.4 Cost of the SENSE system

The economic analysis of the SENSE system considers both initial investment costs (Capital Expenditures = CAPEX) and ongoing maintenance costs (Operational Expenditures = OPEX). The initial hardware investment is €2,000 (industrial computer), while setting up the system requires around 80 hours of labour. At an hourly rate of €100 net, this results in initial implementation costs of €8,000.

The annual maintenance costs amount to €500 (estimated effort of 5 hours per year). These costs form the basis for an economic cost/benefit comparison, the results of which are discussed in the following chapter.

3 Evaluation Results

3.1 Smart Grid Seehub

3.1.1 Static charging power limit

The case study focusses on the challenges of an urban electricity grid, in which grid reinforcements are often associated with high costs and/or very complex implementation. In the case of a static charging power limit, a maximum of 50 kW was set for the Seehub garage in this report to limit the grid load and only partially utilise existing grid reserves (especially for future load growth). Exceeding this limit (contractually permitted e.g. maximum 2% per year) leads to e.g. contractually regulated penalties (penalty of €1/kWh, gross), which are charged to the charging station operator instead of expensive grid reinforcement measures. The charging station operator is thus incentivised to further optimise charging behaviour and take appropriate measures (e.g. limiting the vehicle's charging capacity). The SENSE system recognises the necessity of such technical measures and can explain them to the system users.

The following figure illustrates resulting grid restriction violations based on measured data on the charging power of electric vehicles in the Seehub garage.

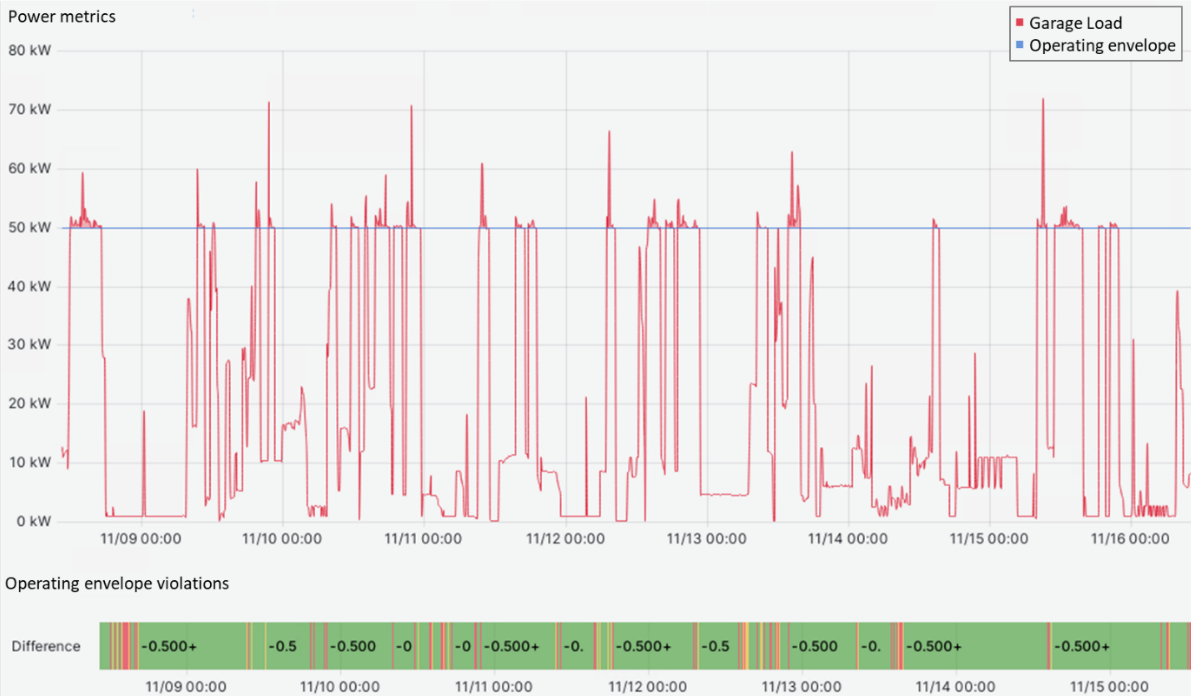

Figure 1: Overview of grid restriction violations based on measured data on charging power of electric vehicles in the event of a static charging power limitation.

3.1.2 Dynamic charging power limit

In the case of a more dynamic regulation, the existing grid reserves are further released by the grid operator and the charging power limit is increased to up to 85 kW depending on the load situation. As this measure further restricts the planned grid reserve, a breach of contract in this case is associated with an increased penalty (€2/kWh, gross). The following figure illustrates the resulting grid restriction violations based on the measured Seehub values.

Figure 2: Overview of grid restriction violations based on measured data on charging power of electric vehicles for dynamic charging power limitation.

During the investigation period of 77 days, the charging capacity limit was exceeded by around 30 kWh. These values were scaled to one year, resulting in an annual breach of contract of around 153 kWh. This results in an annual net penalty of €306.
Compared to a static limit, the dynamic regulation shows a significant reduction in breaches of contract and the resulting penalties. This is because the charging capacity limit can be increased at times of low grid load, which enables more efficient utilisation of the available grid capacity for fast charging.

However, the introduction of dynamic regulations requires close coordination between grid and charging station operators as well as the implementation of suitable technical measures for monitoring and controlling the charging infrastructure. The system developed in the SENSE project enables improved user integration in this respect. The following chapter analyses the extent to which the costs of this system would be in relation to any grid reinforcement costs.

3.1.3 Cost/benefit analysis

In the static scenario, the total annual costs (TOTEX = annuity (see e.g. [3]) of CAPEX + OPEX) of the SENSE system amount to €2,047, which, in combination with the contractual penalties, lead to total expenditure of €2,863 per year. The analysis shows that a break-even point is reached at around 90 metres for cable reinforcement alone (with installation costs of € 400 per metre, observation period 20 years, interest rate = 5% - see the following figure on the left). If additional transformer reinforcement costs in the range of € 10,000 to € 20,000 are taken into account, the break-even point shifts to approx. 40 to 60 metres of cable length.

In dynamic operation, the penalty is reduced as a result of flexible regulations, so that the total annual costs (TOTEX SENSE + penalty) are reduced to €2,353. This shifts the break-even point in favour of the SENSE system. With insulated cable reinforcement, this is around 80 metres, while values between 25 and 45 metres are achieved with simultaneous transformer reinforcement (see the following figure on the right).

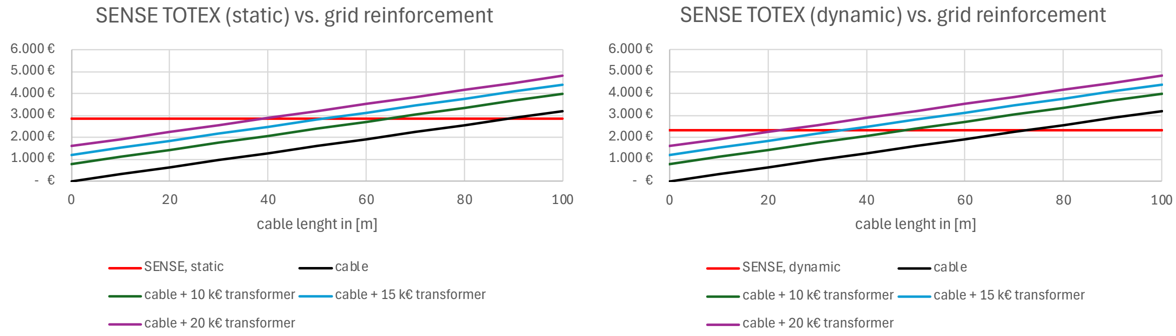

Figure 3: Results of the cost/benefit analysis, which compares the costs of the SENSE implementation with urban grid reinforcement costs.

The results of this case study show that the SENSE system can make a significant contribution to improving the utilisation of existing infrastructure. By using intelligent control algorithms, traditional grid reinforcement measures can be avoided or delayed, although a direct comparison broken down to a purely financial perspective is of course only of limited significance. There will be scenarios in which physical reinforcement is preferable due to its long-term effectiveness; in scenarios where construction measures need to be prioritised due to limited resources, an intelligent solution may often be the only possible short-term solution. Accordingly, the economic benefits outlined in the selected scenario are particularly relevant as they reduce capital expenditure and operating costs while promoting the sustainable development of urban energy systems.

The advantage, which is much more difficult to assess in monetary terms, lies in the general increase in the acceptance of smart grid solutions through the core aspect of the SENSE system, namely the user-centred explainability of the cyber-physical system itself. The SENSE system improves the information situation for both end customers and grid operators. Precise and timely data transmission and event explanation to the charging station operators and users increases transparency for those affected and creates trust in reliable control of the charging process, for example, considering the available grid capacity. At the same time, network operators benefit from detailed insights into the current network load. This supports forward-looking and optimised grid planning. Overall, the SENSE system thus contributes to a sustainable improvement in operational efficiency, economic benefits and ecological sustainability in urban energy systems.

3.2 Smart Grid LEC

3.2.1 Increase in self-consumption

The Local Energy Community (LEC) case investigated how self-consumption within a rural low-voltage grid settlement can be increased through appropriate optimisation strategies. The optimisation of the LEC's operational management was compared with the grid-side expansion restriction of PV systems. The focus of the optimisation was on maximising self-consumption with minimal grid violations or curtailment (=short-term reduction in PV production). The following results were determined (see Figure 4):

- **Expansion restriction vs. optimisation**: optimisation led to an **increase in self-consumption** of **99.3 MWh**, while **curtailment** was limited to 4.1 MWh.
- Expansion restriction vs. optimisation with optimal forecast: By including optimal forecasts, self-consumption was increased to **107.8 MWh** and curtailment was reduced to **0.6 MWh**.

The **economic revenue advantage** of the LEC results in:

- Expansion restriction vs. optimisation: The advantage is approx. **30 k€.**
- Expansion restriction vs. optimisation with optimal forecast: The advantage increases to around **32 k€.**

These results make it clear that the combination of optimised operational management and precise forecasting methodology can contribute to a significant increase in energy efficiency within the LEC. Nevertheless, it is essential to be able to explain to the LEC members why certain technical measures (e.g. curtailment, load/generation adjustment or storage management) were necessary. This is made possible by the feedback system developed in the SENSE project. A corresponding cost/benefit ratio is derived in the following chapter.

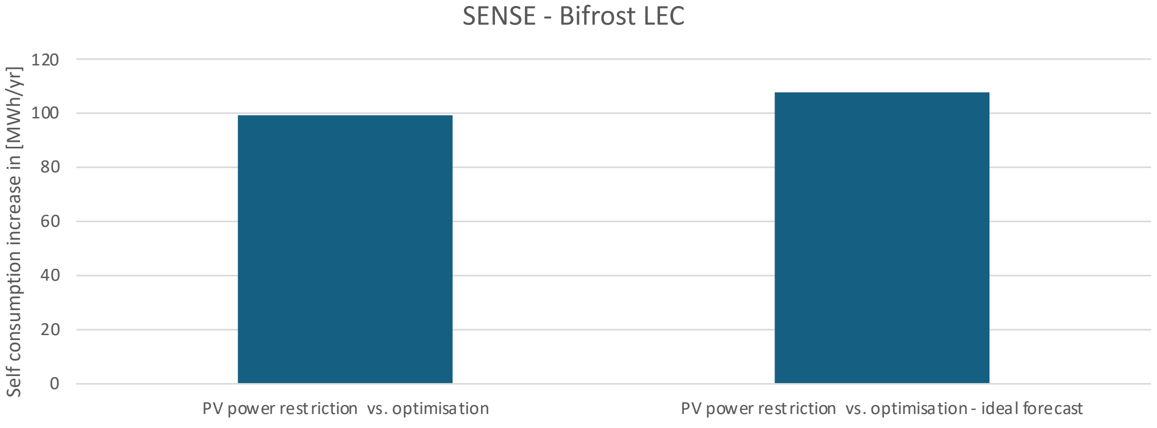

Figure 4: Calculated self-consumption increases of the LEC in comparison to a PV power restriction.

3.2.2 Cost/benefit analysis

The cost-benefit analysis of the LEC case shows that the extent to which the economic advantage of optimising self-consumption is taken into account has a significant influence on the economic efficiency of the SENSE system. The following figure illustrates that if 5% of the

LEC benefit is taken into account, the achievable income (€ 1,475 in the 'expansion restriction vs. optimisation' scenario and € 1,615 in the 'expansion restriction vs. optimisation ideal' scenario, see the following figure) is still below the total annual SENSE costs (TOTEX) of € 2,047. This means that the SENSE system would not yet be fully financed with this contribution.

However, if the recognised share of the LEC benefit is increased to 10 %, this results in annual revenues of around € 2,950 or € 3,229, which in both cases are higher than the SENSE TOTEX (see Figure 6). The break-even points are around 7% and 6.3% respectively.

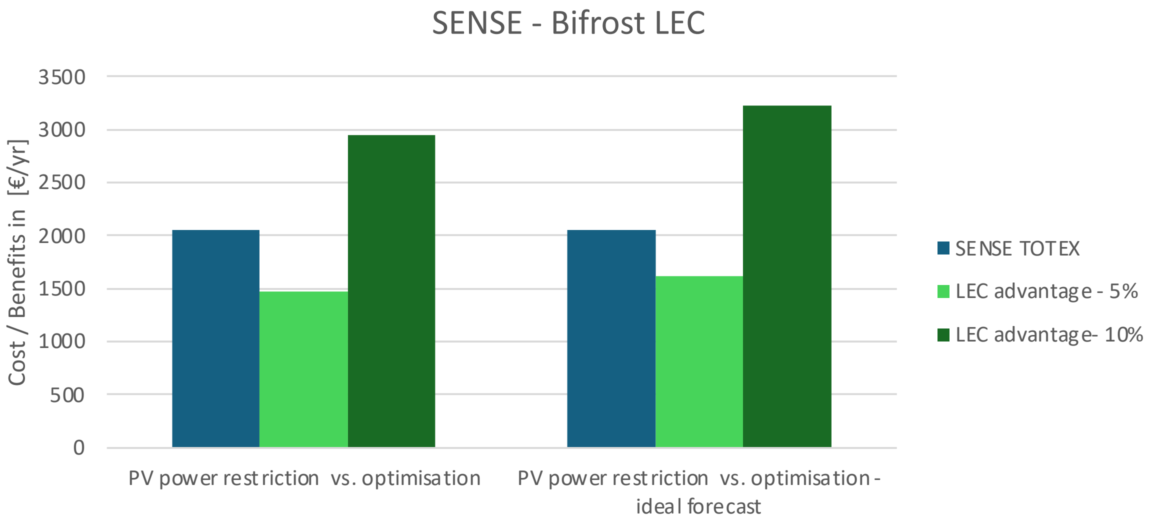

Figure 5: Cost/benefit ratio of the SENSE system compared to self-consumption benefits.

The improved provision of information by the SENSE system can therefore make a significant contribution to increasing user satisfaction by supporting the optimal use of self-generated energy and thus contributing directly to a reduction in CO_2 emissions. On the other hand, the system provides detailed insights into grid-driven active power limitation measures on photovoltaic systems, making it easier to understand both the causes and the effects of these feed-in limitations. Overall, this can result in a more sustainable integration of renewable energies into the existing grid.

In this respect, however, it is essential that in future research, the willingness to pay of energy communities is surveyed for a better understanding of active power limitations to be able to better categorise the calculated break-even points.

3.2.3 Sustainability evaluation

The investigation of CO_2 emissions as part of the Local Energy Community (LEC) Case illustrates the extent to which the climate impact of energy imports can be minimised through the optimisation strategies considered and the use of precise forecasts. Based on harmonised Austrian and European emission factors (see [8]), the reductions in CO_2 emissions through different scenarios were analysed as follows:

- EU average 2022: 255 g CO_2-eq / kWh
- Electricity generation in Austria: 226 g CO_2-eq / kWh
- Austrian power plant fleet: 170 g CO_2-eq / kWh
- Renewable energies: Values range from 5 g CO_2-eq / kWh (run-of-river power plants) to 40 g CO_2-eq / kWh (photovoltaics).

This data provides the basis for estimating the savings through optimised operational management in the LEC. The CO_2 emissions caused by electricity imports into the LEC vary as follows depending on the scenario:

1. **expansion restriction**
    - In this scenario, no additional optimisation or forecasting measures are used. Instead, the PV system output is limited on the grid side. The imported energy thus leads to reference CO_2 emissions.
    - Reference value: 42 to 28 tonnes of CO2 equivalent per year (see also Figure 6)
2. **optimisation**
    - By optimising self-consumption and reducing energy imports, emissions fall significantly:
        - EU average 2022: reduction of 42.9%
        - Electricity generation in Austria: reduction of 40.6%
        - Austrian power plant fleet: reduction of 33.9%
3. **optimisation with ideal forecast**
    - The additional integration of precise forecasts leads to further reductions, as energy imports are minimised even more efficiently:
        - EU average 2022: reduction of 47.3%
        - Electricity generation in Austria: reduction of 44.9%
        - Austrian power plant fleet: reduction of 37.9%

The results show that the combination of optimisation strategies and precise forecasts can achieve considerable savings in CO_2 emissions. The greatest reductions are achieved in the EU average scenario, as the specific emission factor is higher here. Even taking into account the already low emission values of the Austrian energy system, the optimised approaches show a clear advantage.

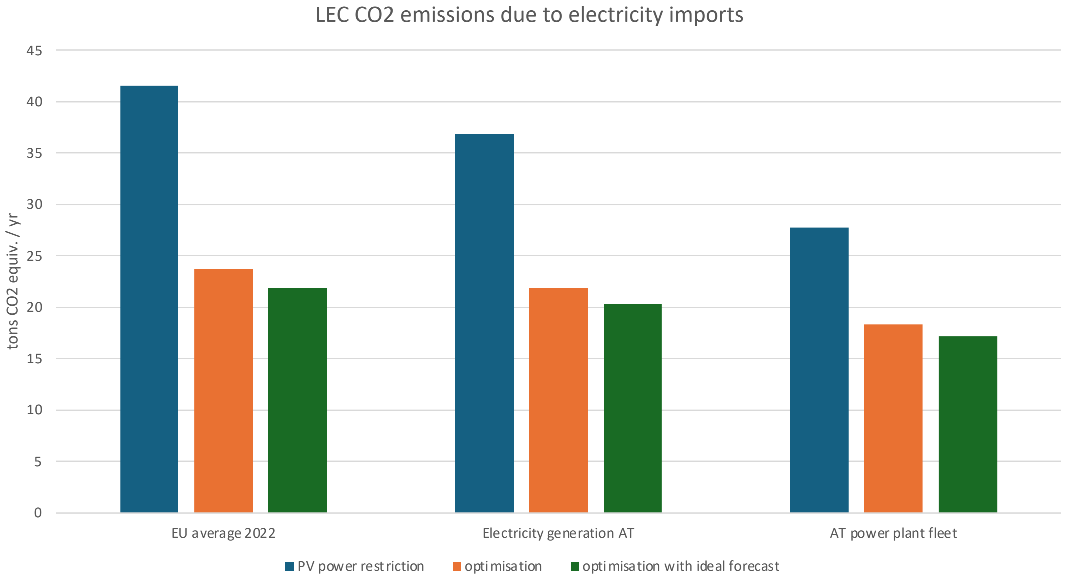

Figure 6: Calculated CO2 emissions of the LEC for different emission factors.

3.3 Smart Building

Based on the data presented in chapter 2.3, this chapter addresses the results of the sustainability evaluation of smart building simulations. For this purpose, various events, such as open or tilted windows, incorrect room temperature settings, or opened external shading, were randomly distributed (200 iterations for each season i.e spring, summer, autumn, and winter) for different durations (up to 72 hours).

Accordingly, the derived results regarding the impact on heating and cooling demand of the analysed demonstration area are discussed in the subsequent chapters.

3.3.1 Impact of opened and tilted windows in the Demo Area

This chapter examines the energetic impacts associated with open and/or tilted windows within the demonstration area. Variations in window positions can significantly influence both heating and cooling demand, contributing to energy efficiency considerations in building management.

The subsequent figures[2] present the results, illustrated through boxplot diagrams. The first diagram highlights the additional heating demand incurred due to open (median value = 1829 kWh/yr) or tilted (median value = 356 kWh/yr) windows, emphasizing the increased energy consumption during colder periods. The second diagram showcases potential savings in cooling requirements, predominantly achievable during the summer months (134 kWh/yr due to tilted and 437 kWh/yr for opened windows). These savings reflect the reduction in reliance on mechanical cooling systems facilitated by natural ventilation.

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[2] Both figures represent cases, where only one window is tilted or opened for different seasonal time periods.

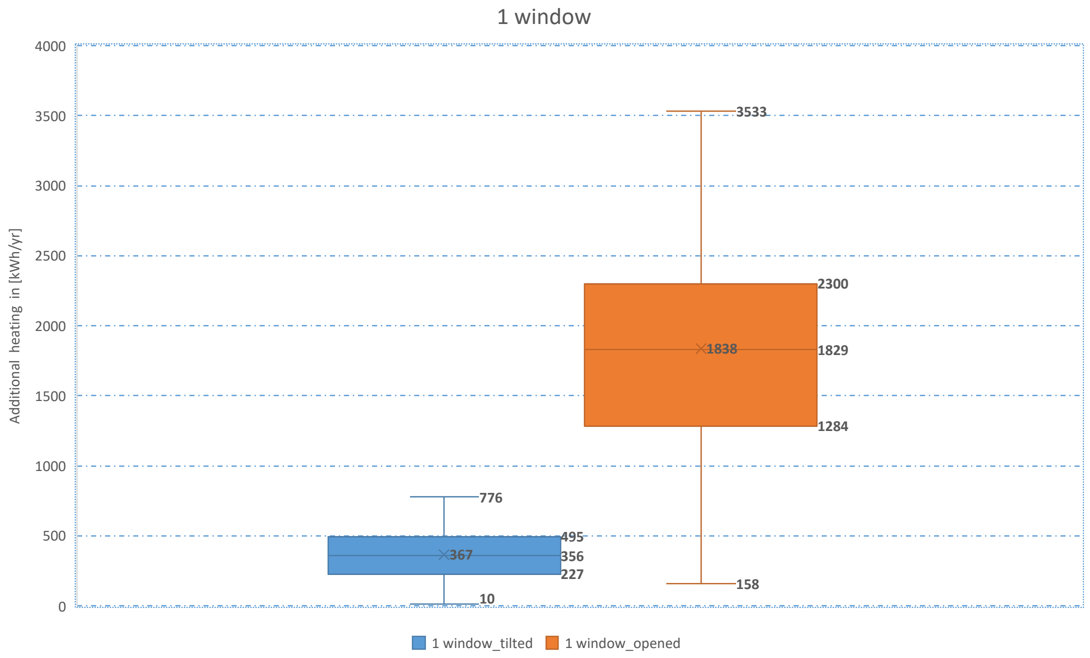

Figure 7: Evaluation results on additional heating demand for opened or tilted windows for several seasonal time periods.

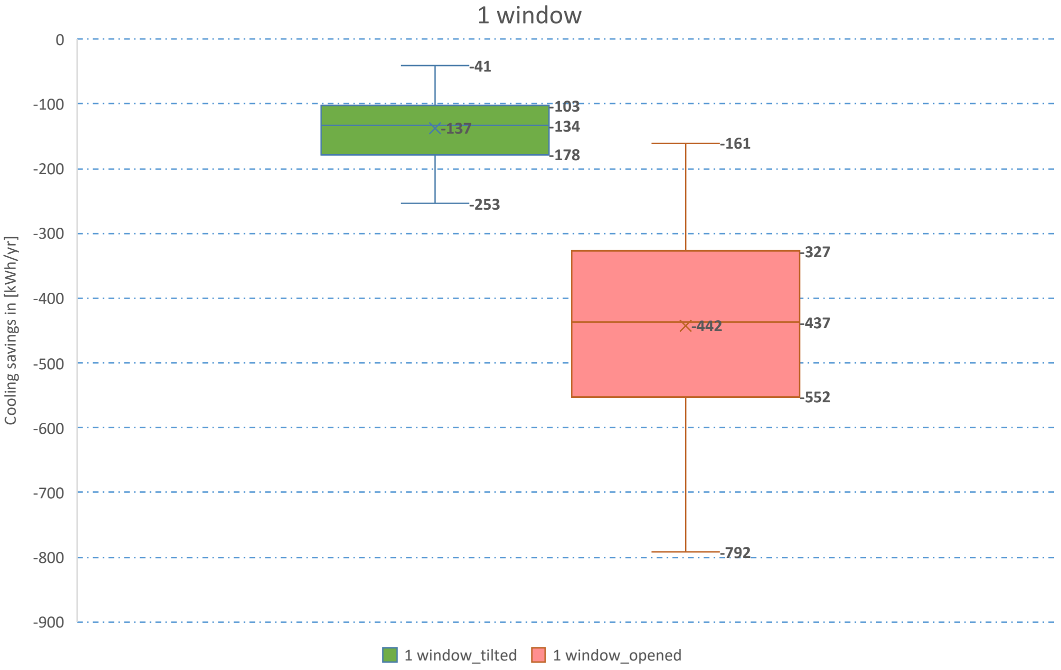

Figure 8: Evaluation results on savings in cooling demand for opened or tilted windows for several seasonal time periods.

When the heating and cooling generation costs are varied and compared to the costs of the SENSE system (assuming a higher implementation effort of 300 labour hours as well as an applicability of the SENSE system to the whole analysed building (scaling factor = 36)), the results are illustrated in the following figure. A break-even point is identified at generation costs of approximately €55/MWh for the case of open and tilted windows. For this analysis, median values of potential savings were aggregated for both opened and tilted windows.

Furthermore, it is assumed, that the SENSE system can enable 100% of all savings due to the proposed feedback system. A variation of this factor will be performed in chapter 0

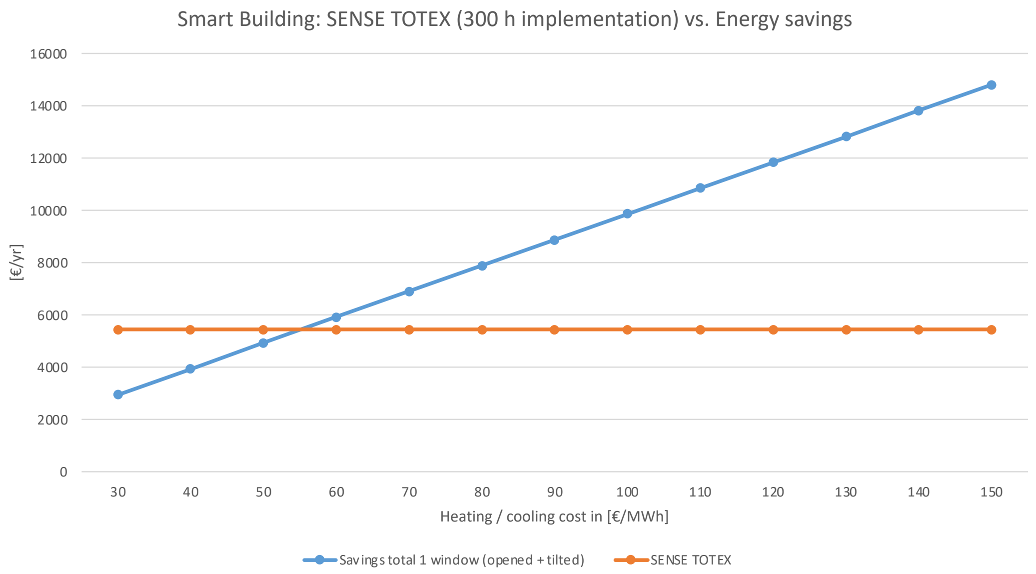

Figure 9: Break even analysis of heating/cooling generation cost compared to SENSE implementation cost.

When the shading system is additionally turned off for opened or tilted windows, the results alter as depicted in the following figures. The heating demand changes to 1897 kWh/year (increase of approx. 4%) for tilted windows and to 270 kWh/year (decrease of approx. 25%) for opened windows. Cooling savings rise to 448 kWh/year (almost tripling the savings) for tilted windows and 814 kWh/year (doubling the savings) for opened windows. As a result, the break-even point shifts to approximately 45 €/MWh as shown in Figure 12.

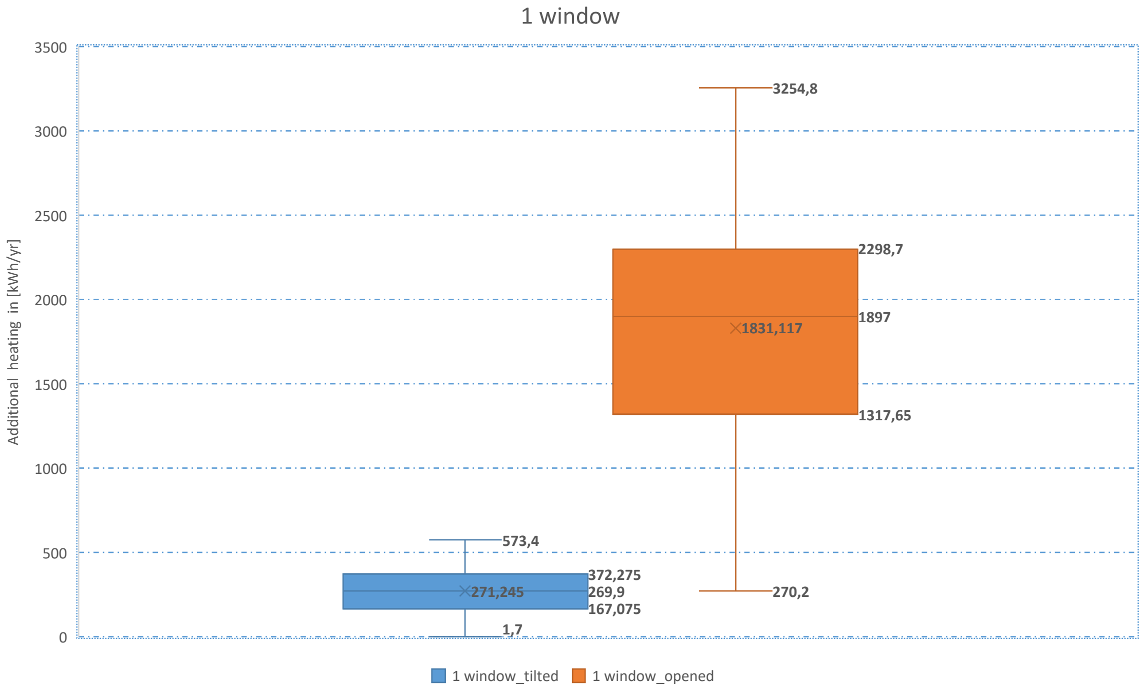

Figure 10: Evaluation results on additional heating demand for opened or tilted windows with deactivated shading.

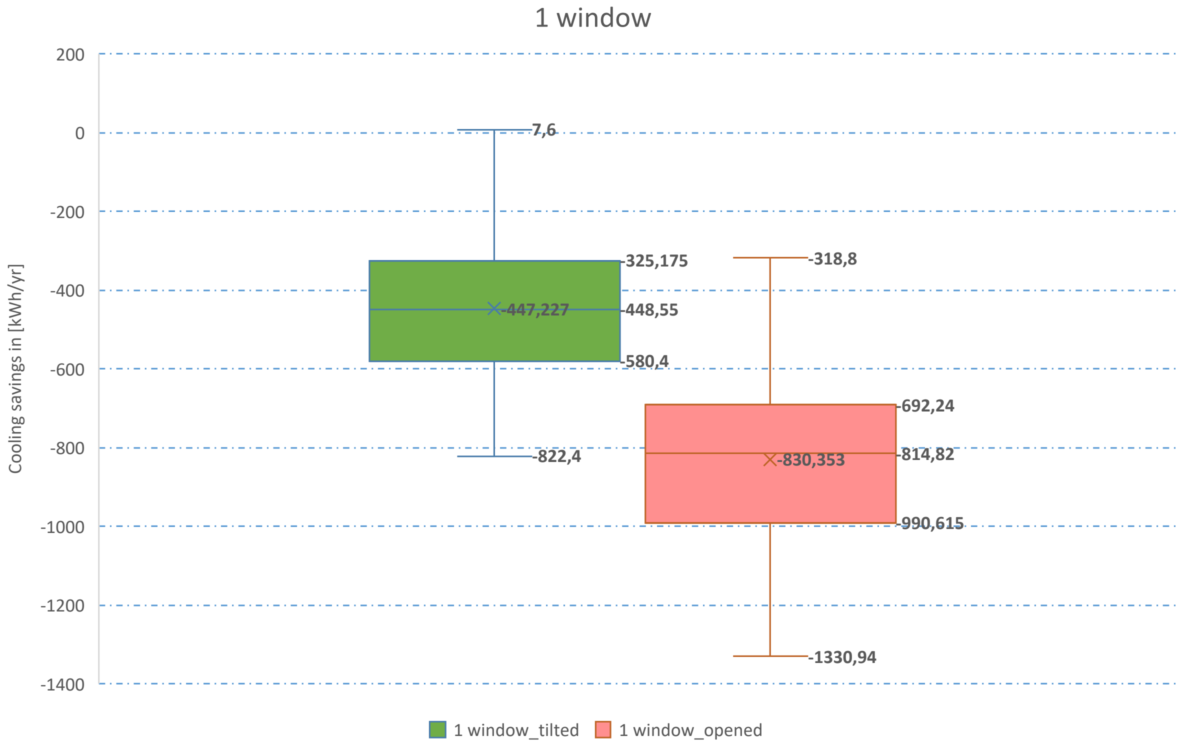

Figure 11: Evaluation results on savings in cooling demand for opened or tilted windows with deactivated shading.

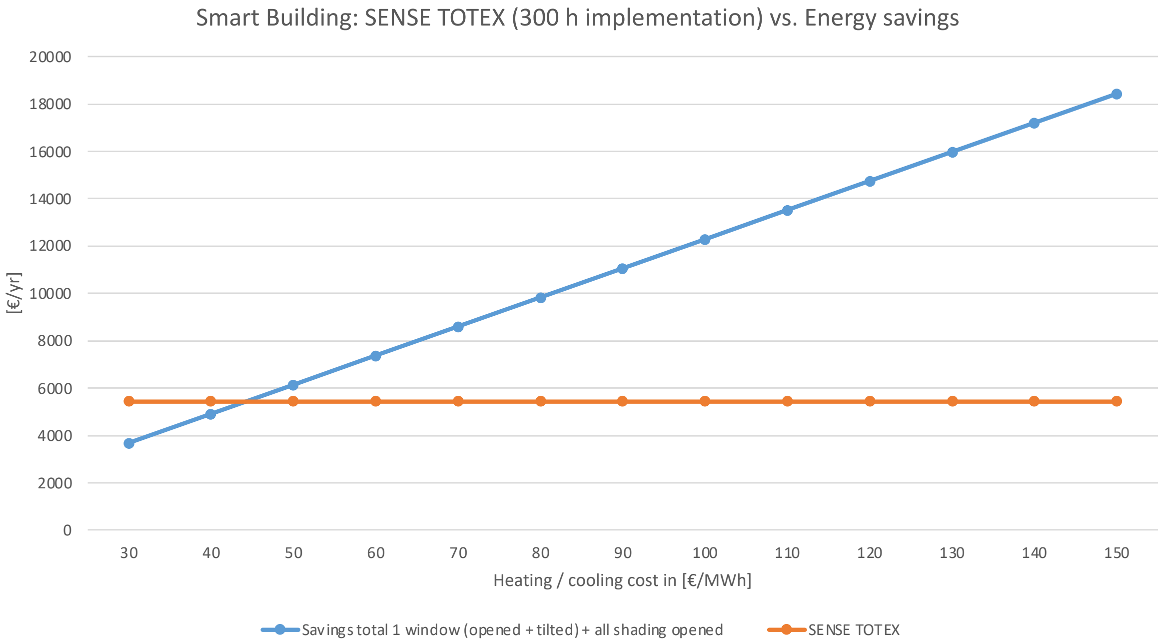

Figure 12: Break even analysis of heating/cooling generation cost compared to SENSE implementation cost with deactivated shading.

3.3.2 Impact of opened shading in the Demo Area

If only the shading system is deactivated while the windows remain closed, the following figure illustrates an additional cooling energy demand of approximately 650 kWh/year (median value) and minor heating savings of around 60 kWh/year. Due to these reduced effects, a break-even point of approximately 215 €/MWh would be required as can be seen in Figure 13.

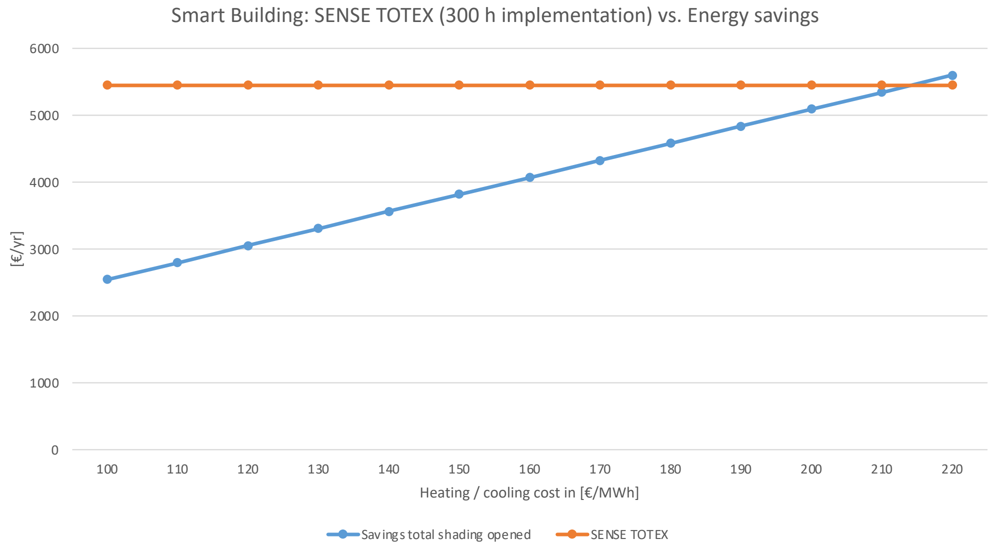

Figure 13: Break even analysis of heating/cooling generation cost compared to SENSE implementation cost with deactivated shading and closed windows.

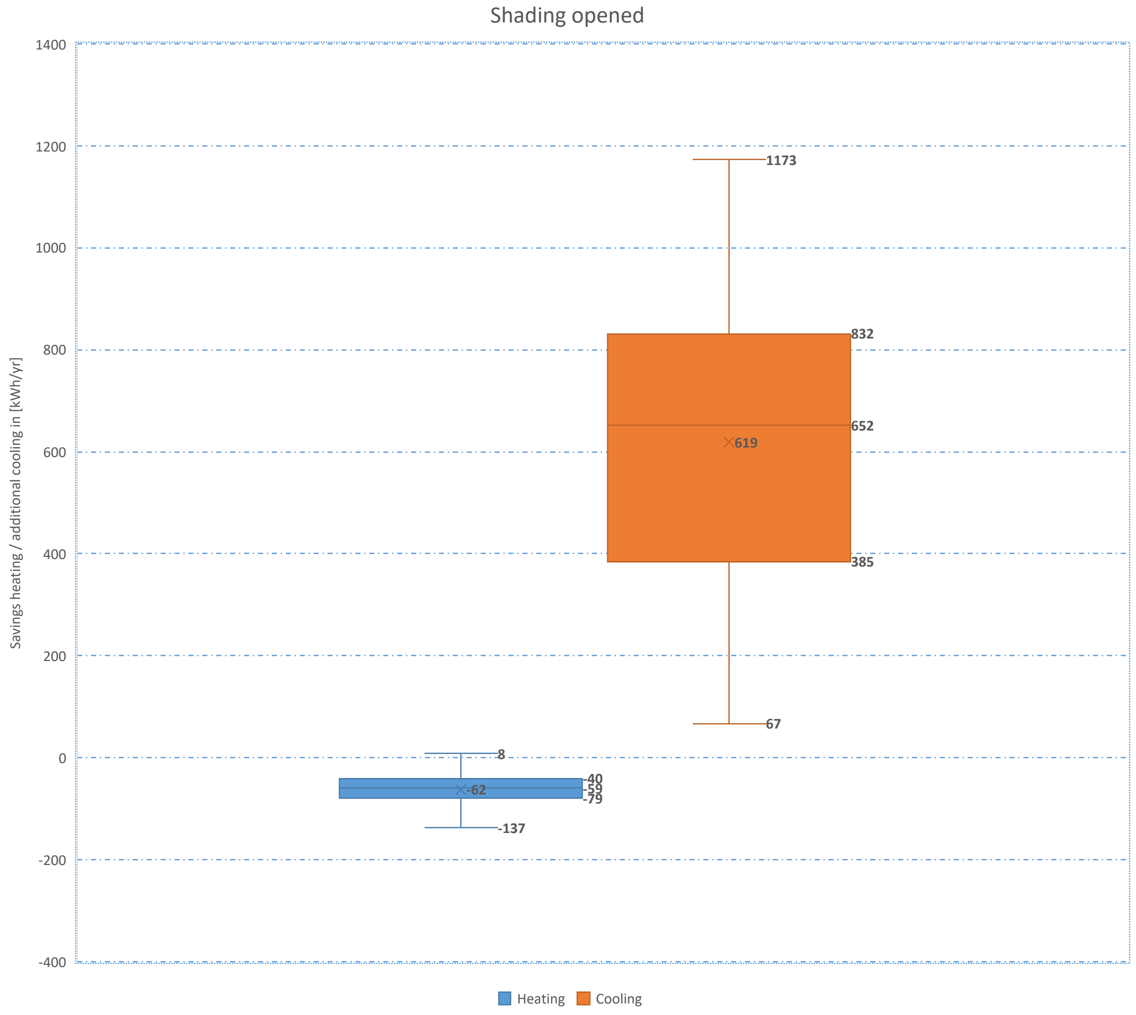

Figure 14: Evaluation results on impacts on cooling and heating for deactivated shading with closed windows.

3.3.3 Impact of changed room temperature settings

The following table presents seasonal simulation results on heating and cooling energy consumption, highlighting both energy savings and increased usage across different temperature settings for spring, summer, autumn, and winter in the demonstration area. Again, the duration of the wrong set-points and seasonal distribution was randomly varied in 200 iterations.

Table 7: Overview of wrong set-point and corresponding median impacts on cooling and heating consumption

Season	Heating Threshold	Cooling Threshold	Heating Change	Cooling Change
Spring	Up to 23°C	From 24°C	-13 kWh (savings)	+69 kWh (increase)
Summer	Up to 20°C	From 22°C	-11 kWh (savings)	+201 kWh (increase)
Autumn	Up to 24°C	From 23°C	+51 kWh (increase)	+47 kWh (increase)
Winter	Up to 24°C	From 26°C	+308 kWh (increase)	—

As a result, the break-even point for the SENSE system calculates to approximately 200 €/MWh if the SENSE system would be applied only for this specific case (see Figure 15).

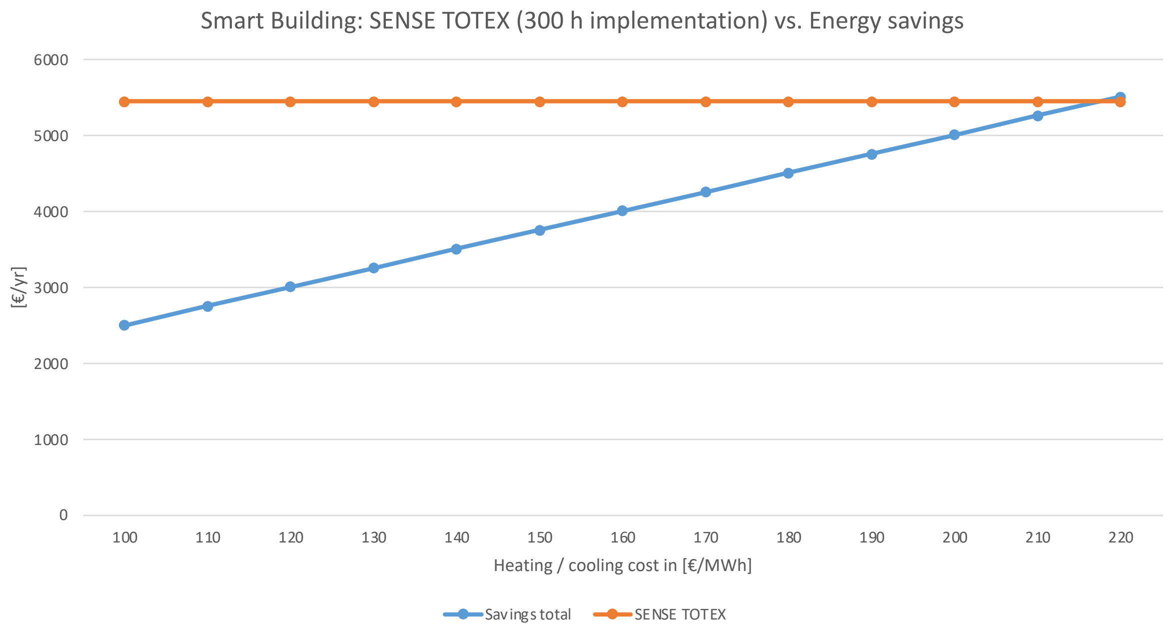

Figure 15: Evaluation results on impacts on cooling and heating for wrong room temperature settings

3.3.4 Sensitivity of implementation cost and SENSE success rate

In the previous chapters, it was examined that the SENSE system is installed and initialized for each individual case, successfully detecting all anomalies and deriving the corresponding contribution margins. This chapter, therefore, investigates how the combination of all analysed use cases influences the break-even point and how variations in the success rate of the SENSE system affect its economic viability.

As depicted in the accompanying figure, the break-even point is substantially influenced by the success rate of the SENSE system, which refers to the number of events detected and subsequently leading to a reduction in energy consumption. Consequently, the break-even point falls within the approximate range of 35 to 75 €/MWh for heating or cooling generation costs.

Figure 16: Evaluation results for a combination of use cases with varying SENSE success rate (50% to 100%)

If the SENSE implementation costs are varied for 80 to 300 labour hours (i.e. the implementation of an improved User Interface could reduce the necessary labour efforts for implementing and scaling the SENSE system), the break-even point range increases even further to approx. 15 to 75 €/MWh.

3.3.5 Sustainability evaluation

Considering all evaluated use cases, a potential energy savings of approximately 150 MWh per year (based on median values) can be achieved for the entire studied building, provided that the SENSE success rate is 100%. This corresponds to a reduction of about 10% of the building's total annual energy consumption. Should the SENSE success rate decrease, the reduction in energy consumption will diminish proportionally.

4 Summary and Outlook

The results of the case studies carried out in the Smart Grid Domain show that the SENSE system could potentially make a significant contribution to the optimisation and control of modern energy systems. Both in the urban context of the Seehub case and in the rural Local Energy Community, the positive effect of more efficient utilisation of existing grid resources and, depending on the application, a contribution to avoiding costly grid reinforcement measures is evident. The actual core aspect of the SENSE system, the improved, user-centred provision of information to increase user acceptance, is naturally difficult to evaluate in monetary terms. However, AI-supported analyses of abnormal events - such as reduced charging power or active power limitations - allow technical measures to be implemented in a targeted manner and made comprehensible. This is an important contribution to promoting the spread of smart energy systems, as negative consequences can be avoided due to a lack of understanding of system interventions (e.g. ‘dimming’ of generation or consumption systems). As a result, further significant reductions in CO_2 emissions can then be supported through the intensified integration of renewable energies.

In the Smart Building domain, the SENSE system demonstrated its capability to enhance sustainability through anomaly detection related to energy consumption behaviours. The findings highlight that behavioural factors such as incorrect room temperature settings, open or tilted windows, and improperly managed shading systems can significantly influence both heating and cooling demand. The SENSE system’s detection of such anomalies contributes to potential energy savings of up to 10% of a building’s annual energy consumption. Furthermore, the break-even analyses for various scenarios indicate that the implementation of the SENSE system can be economically viable when the system success rates are optimised. The system’s ability to provide actionable insights into energy-saving opportunities thus can foster operational efficiency and reduce ecological impacts.

The cost-benefit analysis carried out also underlines that the SENSE system could support the realisation of economic benefits, particularly in dynamic control approaches. The possibility of realising economic benefits through increased self-consumption optimisation (primarily through increased PV output) also makes the system an attractive instrument for future smart grid applications.

Further research should focus on the willingness to pay for improved information provision and the further development of feedback systems to better assess the potential of intelligent control. Additionally, exploring advanced integration with building management systems and enhancing user engagement strategies can maximise the benefits of the SENSE system in both Smart Grids and Smart Buildings domains, ultimately supporting the transition to more sustainable energy systems.

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