EPC4SES

Digital Building Twins

EPC4SES - EPC based Digital Building Twins for Smart Energy Systems

Deliverable 4.1 Evaluation report comprising environmental performance

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Abbreviations

CA Consortium Agreement

CO2 eq Carbon dioxide equivalent

DSO District System Operator

EOS Energy monitoring system

EPC Energy Performance Certificate

ESC Energy Saving Contract

HVAC Heating, Ventilation and Air Conditioning

IP Intellectual Property

IoT Internet of Things

KER Key Exploitable Result

LCA Life Cycle Assessment

LCIA Life Cycle Impact Assessment

MPC Model Predictive Control

TRL Technology Readiness Level

TSO Transmission System Operator

Abstract

The project has developed methods for obtaining and using data from energy certificates (EPCs). In four pilots EPCs have been used as input data to a modelled optimisation of heating and electricity use in buildings, by use of multiple prediction modelling (MPC). The goal of the MPC design has been to optimise greenhouse gas emission savings. The four pilot cases are related to different infrastructure, namely: (1) an office building in Seville, (2) a university building in Salzburg, (3) a residential building in Vienna, and (4) an apartment complex in Berlin. Two cases have investigated the possibility to optimise in relation to use of renewable energy through electricity from grid, and the use of local production and storage of renewable energy when the grid produces fossil energy. The other two cases concern among other things optimisation of heating through improved integration between local heating based on renewables and district heating. The cases have aimed to implement smart control based on data on weather conditions and ambient/outdoor temperature. A key barrier for further implementation of the cases is access to EPC data and that EPC data quality shows variations between countries and regions. The evaluation shows that design of the optimisation algorithm for the MPC is a complex, but ultimately solvable task. The algorithm must make a decision that concerns the balance between different environmental impact categories. Care should be taken to alleviate future lock-in of decisions, and to minimise any potential for runaway use of internet servers. Higher greenhouse gas savings are associated with no increase in comfort level and that the solutions substitute fossil energy. Less savings are associated with cases in which district heating and grid electricity are already renewable, and where users increase comfort level. Large-scale implementation of these local solutions for heating and electricity use can under the right circumstances contribute to faster implentation of renewable energy both for heating and electricity, and can reduce the need for centralised solutions for energy production.

Sammendrag (in Norwegian)

Prosjektet har utviklet metoder for innhenting og bruk av data fra energisertifikater (EPC). I fire piloter er EPC-dokumenter benyttet som inndata for en modellert optimalisering av oppvarming og elektrisitetsforbruk i bygg, ved bruk av MPC (multiple prediction modellering). MPC-algoritmene har som intensjon å optimalisere besparelse i klimagassutslipp. Det er noe ulik infrastruktur knyttet til de fire case-områdene, som omhandler et kontorbygg i Sevilla, en universitetsbygning i Salzburg, et bolighus i Wien og et leilighetskompleks i Berlin. I to case er det sett på muligheter for å optimalisere i forhold til bruk av elektrisitet fra det tilknyttede elektrisitetsnettet når det produseres av fornybar energi, og å bruke lokal produksjon og lagring av fornybar energi når det tilknyttete nettet produserer fossil energi. De to øvrige casene omhandler blant annet optimalisering av oppvarming gjennom bedre samspill mellom lokal oppvarming basert på fornybar-løsninger og fjernvarmeanlegg. I alle casene er det lagt inn smart-styring etter værforhold og utetemperaturer. En sentral barriere for videre implementering av løsningene er at tilgangen til EPC-data og EPC-datakvalitet varierer mellom land og regioner. Evalueringen viser at design av optimeringsalgoritmen for MPC er en kompleks, men løsbar oppgave. Algoritmen krever en stillingstagen i balansegangen mellom ulike miljøbelastningskategorier. Man kan vurdere å designe systemet for å ta høyde for fremtidig lock-in av beslutninger samt potensialet for fremtidig overdreven bruk av internettservere. Størst effekt fra klimagassutslippene kommer i tilfeller der brukere ikke øker komfortnivå, og at løsningene erstatter bruk av fossile-kilder. Minst effekt kommer i tilfeller der fjernvarme og elektrisitetsnett allerede er fornybare, og der brukere øker komfortnivå. Storskala utbygging av lokale løsninger for MPC-kontroll av varme- og elektrisitetsbruk kan under rette forutsetninger bidra til raskere implementering av fornybar energi både til oppvarming og elektrisitet, og kan redusere behovet for utbygging av sentrale løsninger for energiproduksjon.

1. Introduction

The fundamental idea of the EPC4SES project is to use input data from Energy Performance Certificates (EPC) for optimal planning and operational control of smart energy systems for defining innovative applications. The EPC data may be used in processes, analysing demand for thermal networks, analysing possibilities to implement power-to-heat schemes in smart grids, and foreseeing virtual storage in smart energy systems. Combining model-based simulation of demand, using thermal capacity of buildings with models for consumer attitudes and behaviour models allows realistic predictions of demand and realistic interventions.

Work package 4 (WP4) has aimed at the evaluation of the implemented concepts in terms of environmental impacts and also potential wider impacts. The environmental assessment has been based on a simplified Life Cycle Assessment (LCA) approach.

The overarching question of the evaluation of the pilot applications assesses this issue:

Which environmental benefit can be achieved from the pilots?

More specifically, the benefits and risks of the innovative approaches has been evaluated by use of following criteria:

1. Potential global warming potential (GWP) of production and use phase
2. Potential side and rebound effects
3. Social and gender issues along the use cycle

For wider application of the results from EPC4SES the exploitation plan has been set up, which evaluates scenarios and define a roadmap for successful transition to higher technology readiness level (TRL). This may also alleviate further demonstration of the specified systems in the future. Set-up of the evaluation and analysis of the data has been performed by Western Norway Research Institute.

2. Specification of evaluation based on Life cycle Assessment

2.1. Introduction

Life cycle assessment (LCA) is a method for evaluating environmental impact indicators for products or processes (ISO 2006). The goal and scope of an LCA study can vary between different use cases, but there is a potential for evaluating all inputs and emissions from «cradle to grave» of the product. This means that emissions and other environmental impacts from a product are counted not only from, for instance, the on-site production of the product («gate to gate» scope). Typically, the extraction and production of raw materials and transport of these raw materials to the production site are also included («cradle to gate» scope). Emissions and impacts from each of these *life cycle stages* are then simply added to the LCA results, which means that a study with wider system boundaries typically will assign higher total emissions to the product. Use phase, waste phase and recycling/reuse can also be added to the life cycle stages, provided that specific data is available.

In the following chapter, an in-depth LCA study is used to illuminate the environmental performance of the four pilots in the project, which are further described in Appendices 1-4. The analysis serves to illuminate the potential climate effects, as well as potential side/rebound effects of the pilots. Potential social and gender impacts are also assessed.

2.2. Method

Although LCA studies are based on a comprehensive set of background data and may include a large set of indicators associated with the Life cycle impact assessment (LCIA) stage of LCA development, they should be interpreted with substantial care. For instance, as stated in ISO 14044, paragraph 4.5.5: *«An LCIA shall not provide the sole basis of comparative assertion intended to be disclosed to the public of overall environmental superiority or equivalence, as additional information will be necessary to overcome some of the inherent limitations in the LCIA. Value-choices, exclusion of spatial and temporal, threshold and doseresponse information, relative approach, and the variation in precision among impact categories are examples of such limitations. LCIA results do not predict impacts on category endpoints, exceeding thresholds, safety margins or risks.»* Thus LCA does not take into account health and safety, indoor air quality, social or economic issues, etc. LCA results should be regarded as generic and potential environmental information that must be carefully interpreted in an academic context. Moreover, the results could have limited relevance for the local environment, which in some cases could show substantial divergence from the generic modelling assumptions (ISO 2006; Potting & Hauschild 2006).

The main advantage of using LCA compared to an assessment of direct emissions is that life cycle environmental impacts from raw material production, energy use, transport, waste etc. will not be counted when only direct emissions are considered. Thus, what may seem like „zero emission" solutions when only considering direct emissions, can often or perhaps always be shown to be associated with some environmental effects across the life cycle, from the LCA perspective.

LCA has been standardized by ISO 14044 (ISO 2006). The study described in the following does not follow every recommendation from the standard, and should thus be considered a simplified LCA approach. Life cycle impact assessment (LCIA) refers to the module in LCA where the indicator results are calculated, based on selected LCIA methods.

2.3. Goal and scope

2.3.1. Goal

The goal of the simplified LCA study is to investigate environmental effects and side effects of the Berlin and Kuchl pilots.

2.3.2. Scope

The geographical scope of the two studies are four pilot buildings in Berlin, Germany; Kuchl, Austria; Stockerau, Austria; and Rota, Spain, respectively. Each pilot is thoroughly described in Appendices 1-4.

As the data is based on the pilot models, the temporal scope is not defined.

Table 2 shows the life cycles that are included in the assessment. Due to a lack of relevant life cycle inventory background data regarding EE waste, waste treatment has **not** been included in the LCA study.

Table 2.1. Life cycle stages in the simplified life cycle assessment

Life cycle stage	Comment	Included in the LCA study?
Raw materials incl. upstream activities	Includes upstream activities such as mining, etc.	Included

Transport of raw materials	Scenario for transport of raw materials to assembly site	Included
Assembly (production)	Assembly of raw materials into product.	Assumed no emissions for the electronic equipment
Transport from assembly to installation		Included
Installation		Assumed no emissions
Use phase		Included
Maintenance of infrastructure		Assumed no emissions
End of life/recycling of infrastructure	Could both increase and decrease actual emissions	Not included

2.3.3. Functional unit

The functional unit is 1 day of use of the infrastructure, with some figures using other units for illustration purposes.

2.3.4. Life cycle inventory

For the life cycle inventory phase, Ecoinvent v.3.9 was used as background database (Wernet et al. 2016).

For the Berlin case, relevant data was provided in 2022 by the developer of the pilot. For the energy use, a simple assumption was made that the apparatus has a direct energy use of 144 Wh/day, as estimated on Stackexchange (2022). There is, however, quite substantial uncertainty associated with this figure depending, among other things, on which physical setup is eventually used. The internet connection inventory data was provided by Ecoinvent 3.9. The substituted energy was assumed to be German district heating from hard coal.

For the Kuchl, Stockerau and Rota cases, relevant data was also provided in 2022 by the developers of the pilot.
For all cases, the energy savings have been estimated.

All pilots are modelled as an infrastructure which is installed with model predictive control (MPC). The MPC serves to lower the energy demand from an external source. Thus, there is an environmental trade-off between the infrastructure which has to be installed on one side, which would have a negative environmental effect, and the saved/substituted energy on the other side, which would have a positive environmental effect. For the case of Berlin, the external energy source is modelled as representing German based on coal, whereas in the Kuchl/Stockerau pilots the substituted external energy is modelled as representing Austrian district heating from biomass. German and Austrian energy mix, respectively, have been used for the pilot modelling.

2.3.5. Life cycle impact assessment

The software used for the LCA analyses was Simapro v.9.4.0.2. The Environmental Footprint 3.0 (EF 3.0) life cycle impact assessment method was applied (Fazio et al. 2018).

The life cycle impact assessment provides LCA results for several environmental impact indicators. For the case of EF 3.0, potential climate change (i.e., per functional unit) is one example of an indicator. The EF 3.0 method uses mainline climate footprint assumptions from the IPCC with a 100 year time horizon when recalculating greenhouse gas emissions into CO_2 equivalents.

2.4. Results and discussion

In the following, the LCA results for each pilot are presented.

2.4.1. Berlin pilot

For the purpose of illustrating the fundamental assumptions of the study, Table 2.2 shows the estimated potential global warming from the electronic technology involved in the Berlin pilot. Note that this only represents the use phase of the technology, i.e., it does not represent the full life cycle.

Table 2.2. Potential global warming from Berlin pilot technology

	Potential global warming	**Comment**
Infrastructure	406 kg CO2 eq/piece	Electronic equipment, etc.
Electricity and internet use	0.232 kg CO2 eq/day	From electricity and internet use associated with electronic equipment.

The numbers in Table 2.2 are associated with substantial uncertainty, and will in practical implementation show variation according to technological relevance, actual energy use, the setup of remote internet connected devices, and the energy mix used in the modelling. The energy use of daily online activity has been established on basis of the background database (Wernet et al. 2016) which is based on generic assumptions.

The type of energy which is saved by the technology is another key issue. Figure 2.1 shows the variation in potential global warming results for selected types of district heating, with geographical relevance for Germany.

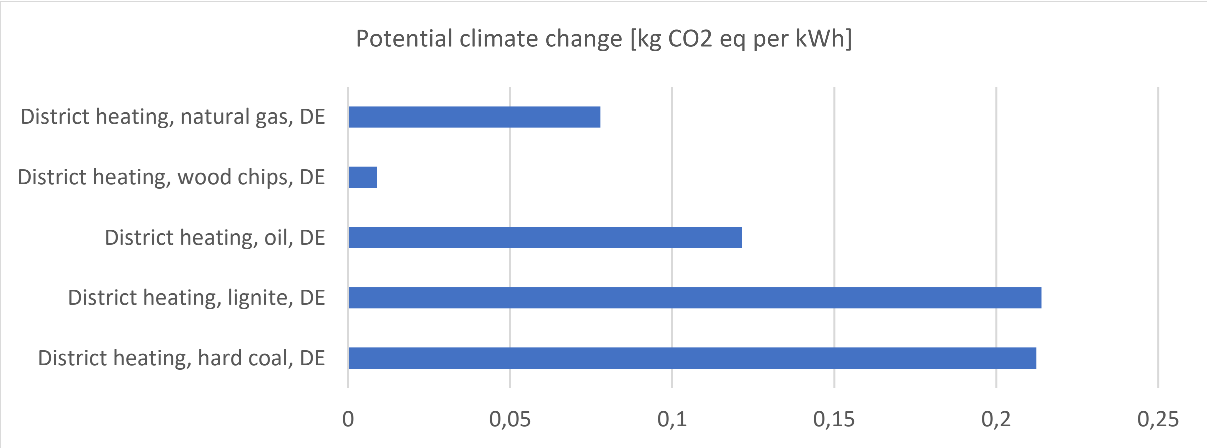

Figure 2.1. Assessed potential climate change from district heating

We can observe that hard coal has a much higher potential impact than wood chips – although an important discussion point would be that wood chips might be associated with higher land use impacts than coal, as well as other types of biodiversity impacts.

The Berlin pilot is assumed to substitute district heating. No precise data was found for the energy carriers used in the pilot's on-site district heating, and it was assumed to be from hard coal/lignite. There will be a payback time for the potential global warming of the control infrastructure and its associated energy use. Figure 2.2 shows the savings associated with the technology, based on different assumptions for energy use in the building. The green line shows the absolute potential global warming from the control infrastructure. For the highest energy use scenario = 1000 kWh/day, the break-even for potential climate change takes place after about 10 days. For 500 kWh/day, after about 30 days, etc.

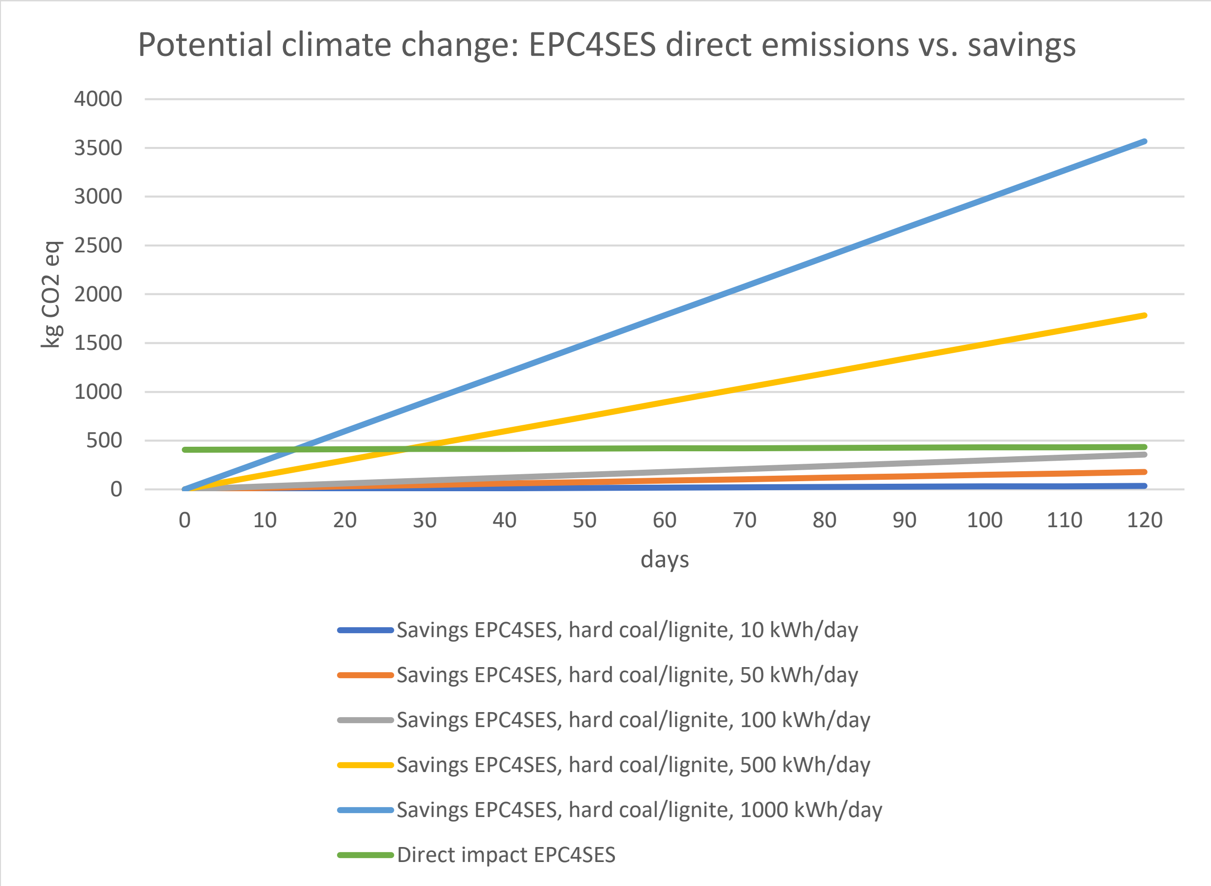

Figure 2.2. Potential climate change, control emissions vs. savings

It can be observed that the infrastructure – based on the assumptions of the LCA model – is thought to generate a limited increase in potential climate change over time. For buildings with particularly low energy use, the payback time is longer. It can be observed that in the case of escalating potential energy use from the control infrastructure the control infrastructure will be associated with a steeper slope, which would give higher potential payback times. Figure 2.3 shows the same information in a different way: The accumulated potential greenhouse gas savings after 10 years depend strongly on the energy use in the building. For a 10 kWh/day heating scenario, 10 years is not quite sufficient.

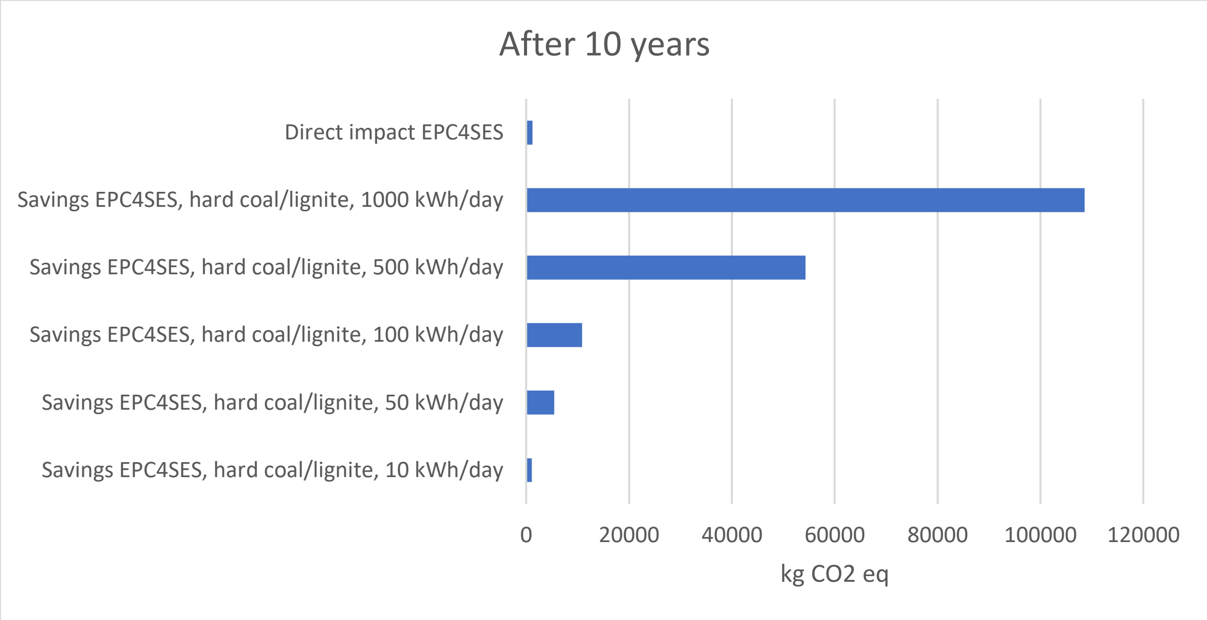

Figure 2.3. Accumulated potential global warming after 10 years. Control infrastructure vs. district heating savings

It should, however, be noted that potential climate change, notwithstanding its long-held importance, is one of many environmental impact indicators in LCA. Using the Environmental Footprint 3.0 weighting factors, it is possible to make a very rough comparison between impact categories – see figure 2.4, the unit is dimensionless. This analysis must be interpreted with substantial care due to its value-laden comparison of environmental apples, oranges and pears, and due to high value-based uncertainty. ISO 14044 generally does not recommend the use of weighting. Nevertheless the results may vaguely indicate that resource use and ecotoxicity are also important for the Berlin infrastructure, i.e., the electronic equipment. The payback time for potential resource use will likely be substantially longer than for potential climate change, particularly for minerals and metals. This potential resource depletion as well as the potential ecotoxicity could be mitigated and aggravated, respectively, through recycling or poor waste handling. There are many different practices for waste handling in use, and this issue is thus left open to interpretation. The table also serves as a reminder that other environmental impact categories than potential climate change may also be relevant.

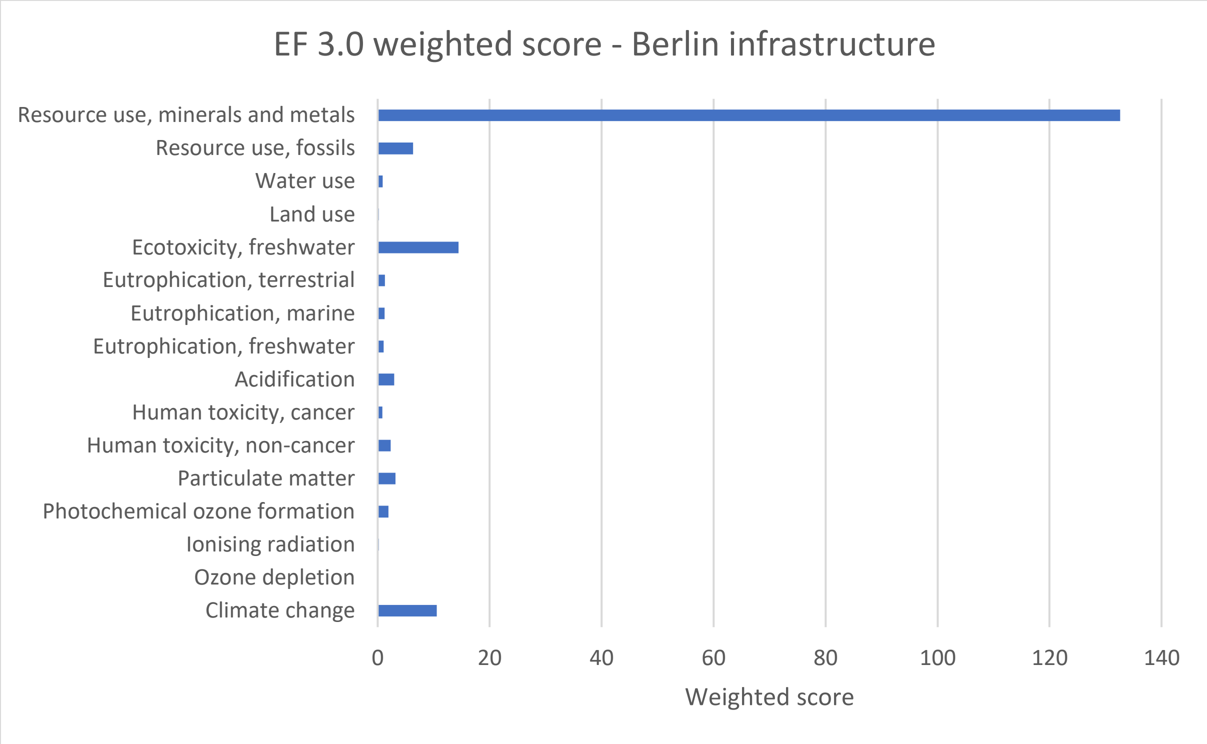

Figure 2.4. Weighted results, Berlin electronic equipment (use phase), 1d

Figure 2.5 shows the estimated share of the daily weighted potential environmental impact of the control infrastructure. The life cycle emissions of the internet operation appear to be more important than for the direct electricity use, and are also more uncertain and – one would assume – prone to future increase. Once again noting the substantial uncertainty involved in such analyses, the internet connectivity appears to be an important issue to watch for optimisation. Any future addition of further energy intensive software would in principle not be recommended from an environmental optimisation perspective.

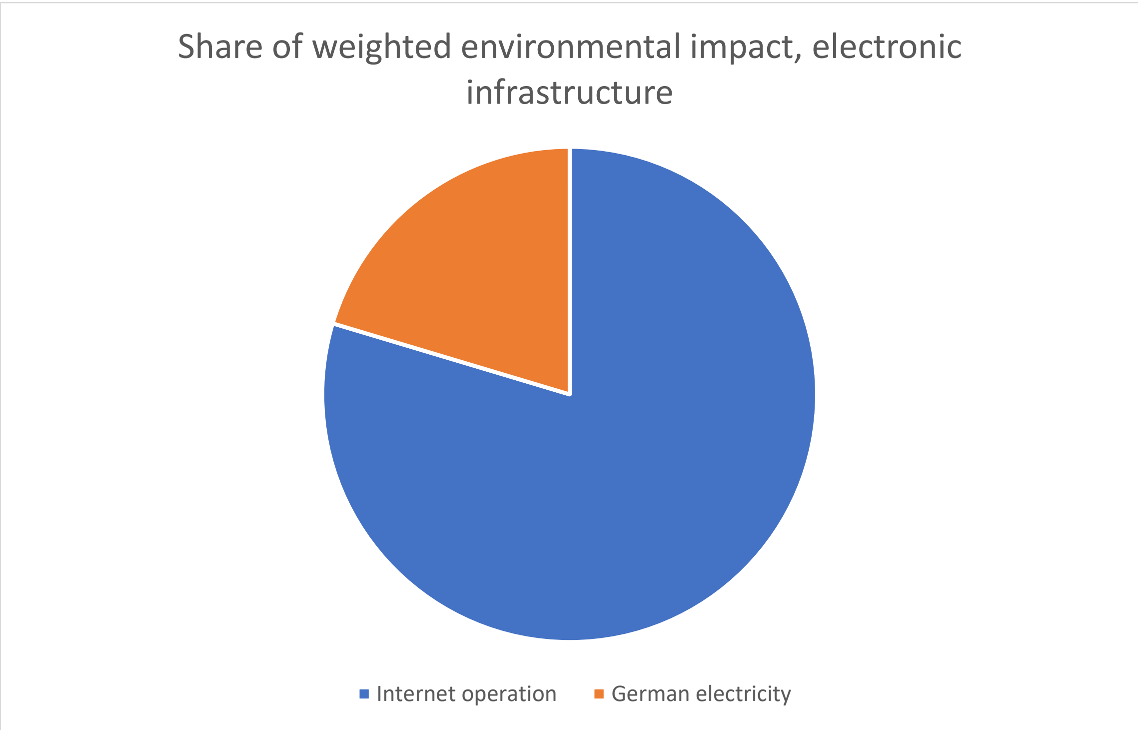

Figure 2.5. Share of potential environmental impact in the use phase (weighted environmental impact)- comparison between impact from local electricity and impact from internet (mostly remote activity)

2.4.2. Kuchl pilot

For the Kuchl pilot, the results for potential climate change before and after the intervention are shown in figure 2.6.

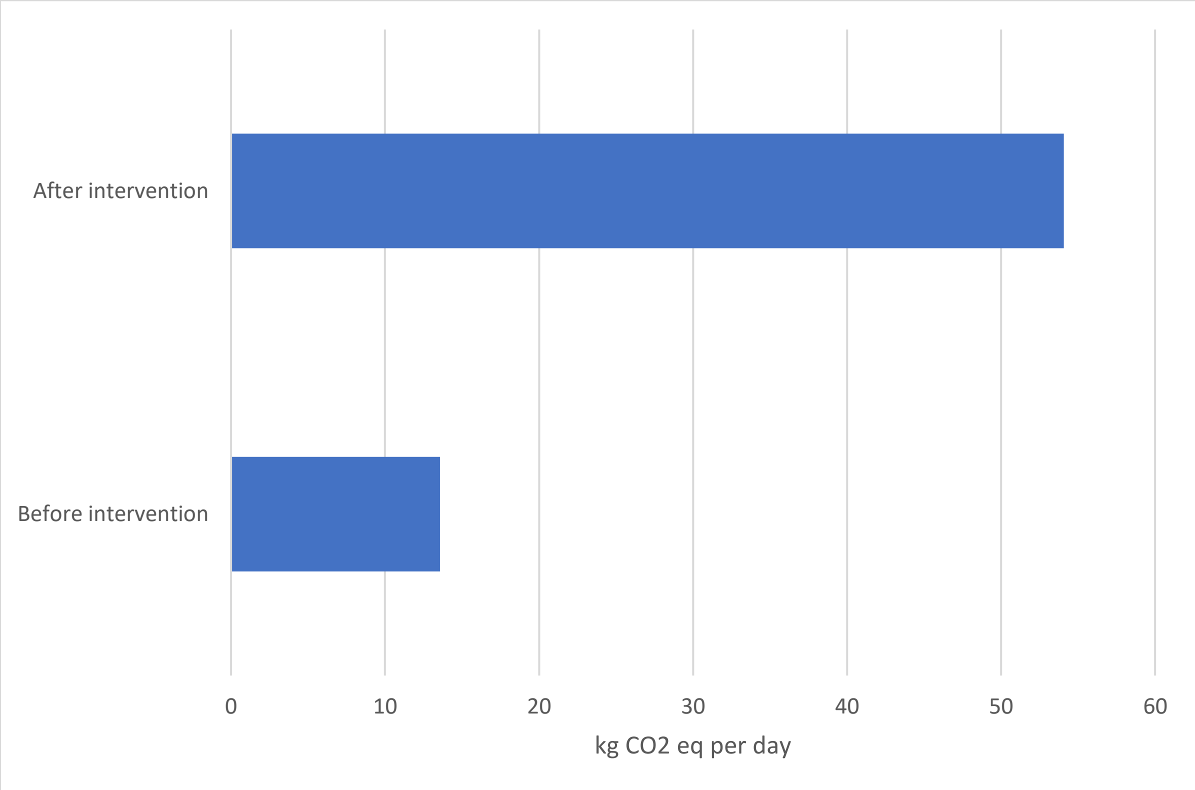

Figure 2.6. Potential climate change per day, before and after Kuchl MPC installment

Although the energy use has been reduced after installing the MPC, there still appears to be an increase in potential climate change impact. This result is due to the trade-off between a decrease in the use of district heating from biomass, and a smaller increase in electricity use. This is because the background database suggests higher potential global warming to the electricity than to the biomass. The MPC was optimised for potential climate change, but used other factors. This is quite informative, and can be attributed to the following:

- The difference between factors for direct emissions and factors for life cycle emissions;
- Comparatively high greenhouse gas emissions when the system is modelled according to life cycle emissions from Austrian electricity mix in the background database;
- Comparatively low life cycle greenhouse gas emissions assigned to life cycle emissions from Austrian district heating from biomass in the background database.

This quite clearly demonstrates how different assumptions and indicators for optimisation can give different results. While it can be recommended to use state of the art factors, any harmonisation of approaches has proven difficult due to the following reasons:

- Difference between assumptions in different coherent modelling approaches;
- Real difference in value perceptions on how to model.

Biomass and electricity are known to be particularly challenging to model both due to different assumptions/methodological approaches and an apparent lack of agreement (Faria et al. 2013; Tellnes et al. 2017; De Rosa et al. 2018). The uncertainty is thus substantial, and the pilot is informative in illuminating this point.

The results are further contextualised by Figure 2.7, in which more environmental impact indicators are shown.

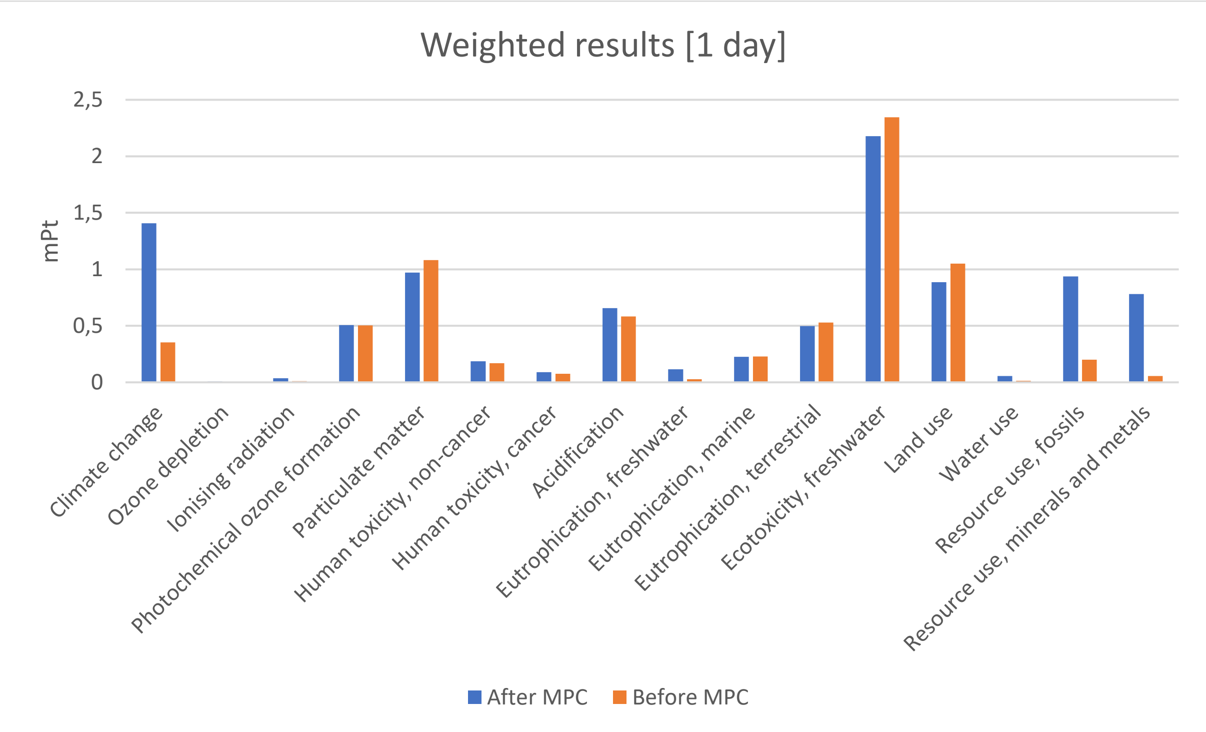

Figure 2.8. Potential enviromental impacts for the Kuchl pilot, dimensionless results

We can observe that several impact categories have been reduced through the introduction of the MPC, as would be expected when reducing the foreground total energy use.

These LCA results can be summarised by weighting them into one indicator by means of the EF 3.0 weighting factors – cf. figure 2.8. As mentioned in the above subsection on the Berlin pilot, weighted results must not be taken literally, as they are associated with substantial uncertainty.

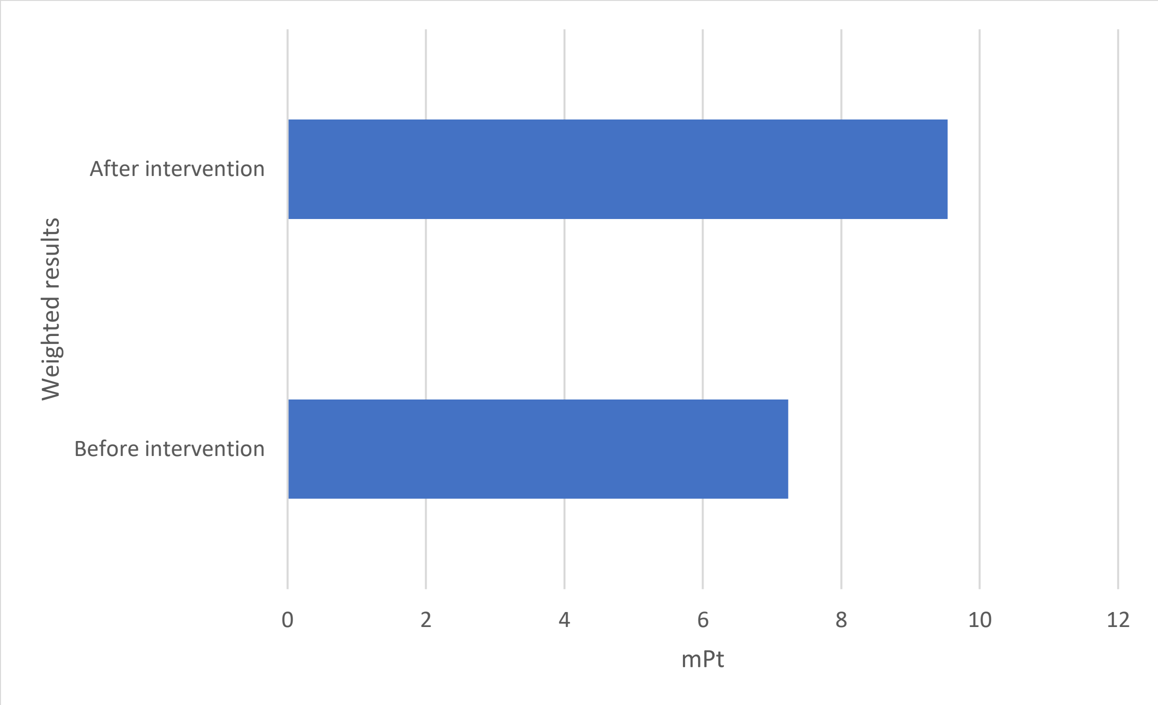

Figure 2.9. Weighted LCA result for Kuchl pilot. mPt is an aggregate unit („milli-points") that represents cumulative environmental impact.

The figure may indicate that the intervention is slightly worse off from an environmental viewpoint than the original setup. As shown in figure 2.8, this is primarily due to increased potential resource use and climate change. As pointed out in the above, however, this result is highly uncertain, and does not demonstrate conclusively that the introduction of the pilot in the building in question would be detrimental in environmental terms. However, it would be desireable that installing an MPC would more clearly make a positive contribution to the environment.

In order to make the environmental benefit of the relevant MPC installation more clear, it is recommended to:

- Substitute energy in a different location where the environmental benefit is more obvious, such as coal;
- Aim to reduce the increase in electricity use;
- And if relevant, aim for larger buildings where the energy savings would be higher.

2.4.3 Stockerau pilot

Like the other pilots, the Stockerau case has environmental trade-offs against this reduction in energy, such as the production of the PV plant, lithium-ion battery and storage tank. Notably, both photovoltaic elements and batteries represent advanced technology that will contribute to some extent to resource depletion. Figure 2.10 shows potential climate change for the infrastructure investment for case 2 of the Stockerau pilot; this infrastructure environmental cost is not included in the pilot description. Note that the unit is *g CO2 eq*, not kg CO2 eq as in the analyses above, in order to enhance comparability with the applicable pilot description.

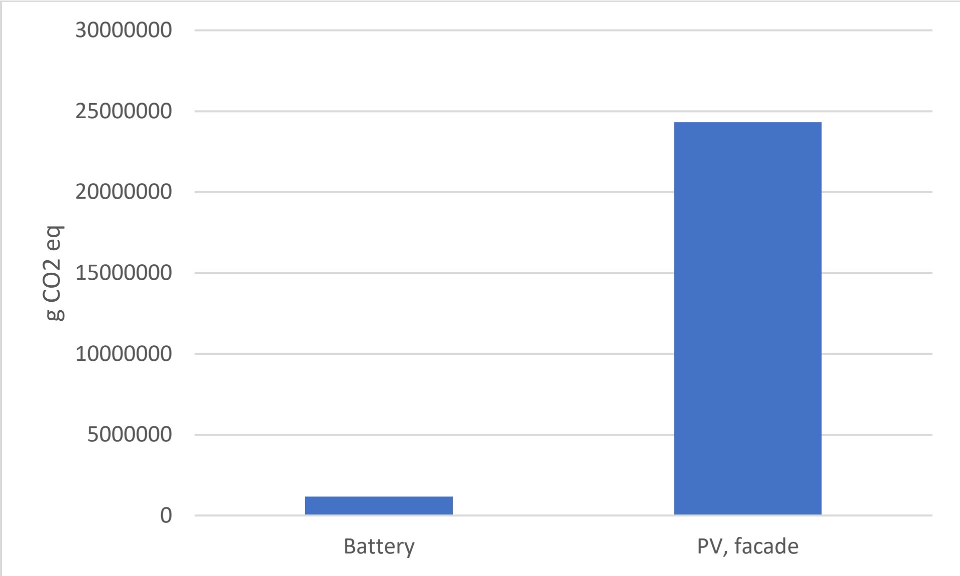

Figure 2.10 Potential climate change for the initial infrastructure installation for Stockerau case 2 (Battery + PV). Note that the unit is g CO2 eq, not kg CO2 eq

We can observe that the potential climate change involved for the battery and, in particular, facade-mounted PV is quite substantial. The figure only includes the initial installation of the infrastructure, and does not take into account any replacements over the lifetime. An important discussion point would be the lifetime of the batteries: In an extreme case where the battery has to be changed as much as 21 times more frequently than the PV panels, the greenhouse gas emissions associated with the battery will be larger than those of the PV (~24 million grams, or 24 tonnes of CO_2 eq). Another point is that the technology is evolving quite quickly, so that the background LCA database to some extent could lag behind in technological relevance. This would imply that the above results for the infrastructure would be somewhat overstated.

Weighted results are shown in figure 2.11. While weighting in LCA is not a recommended practice for several reasons, as mentioned previously, it might be instructive that the weighted results indicate that climate change is not the key impact category for the infrastructure, across the life cycle. Resource use, particularly of minerals/metals, is considered the most important environmental indicator from the vantage point of the weighted score. Ecotoxicity, acidification and several other impact categories are also relevant. Rinsing or cleaning of the photovoltaic panels may in some cases require substantial amounts of freshwater to prevent a deterioration of the function of the panels, and the water footprint will depending on local conditions and on how rinsing/cleaning is performed. These use phase impacts are not included in the figure.

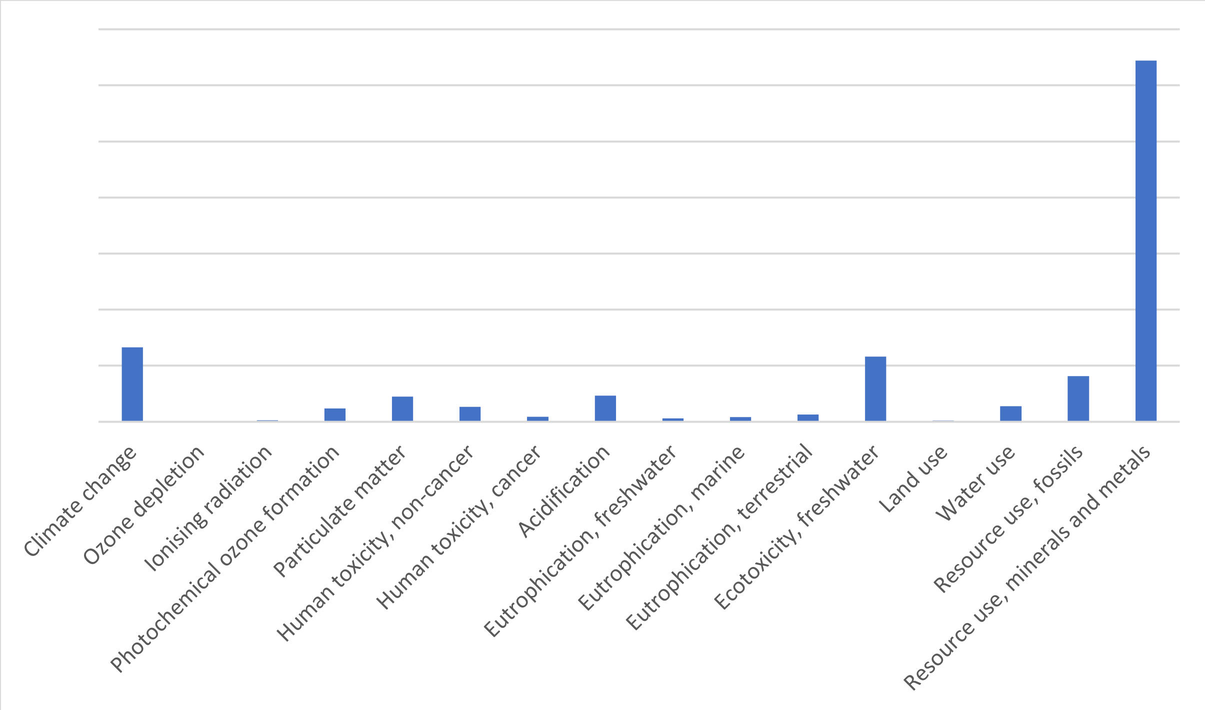

Figure 2.11. Weighted LCA results, Stockerau initial infrastructure (Battery + PV)

The possible further use of hydrogen suggested in the pilot description may also require mineral-intensive infrastructure. In addition, hydrogen fuel comes in many variations: The source and life-cycle emissions of the specific type of hydrogen used need to be considered before implementation to ensure acceptable emissions.

When assuming that the battery is changed every 2 years and that the PV system has a lifetime of 20 years, the results for potential climate change are as shown in Figure 2.12.

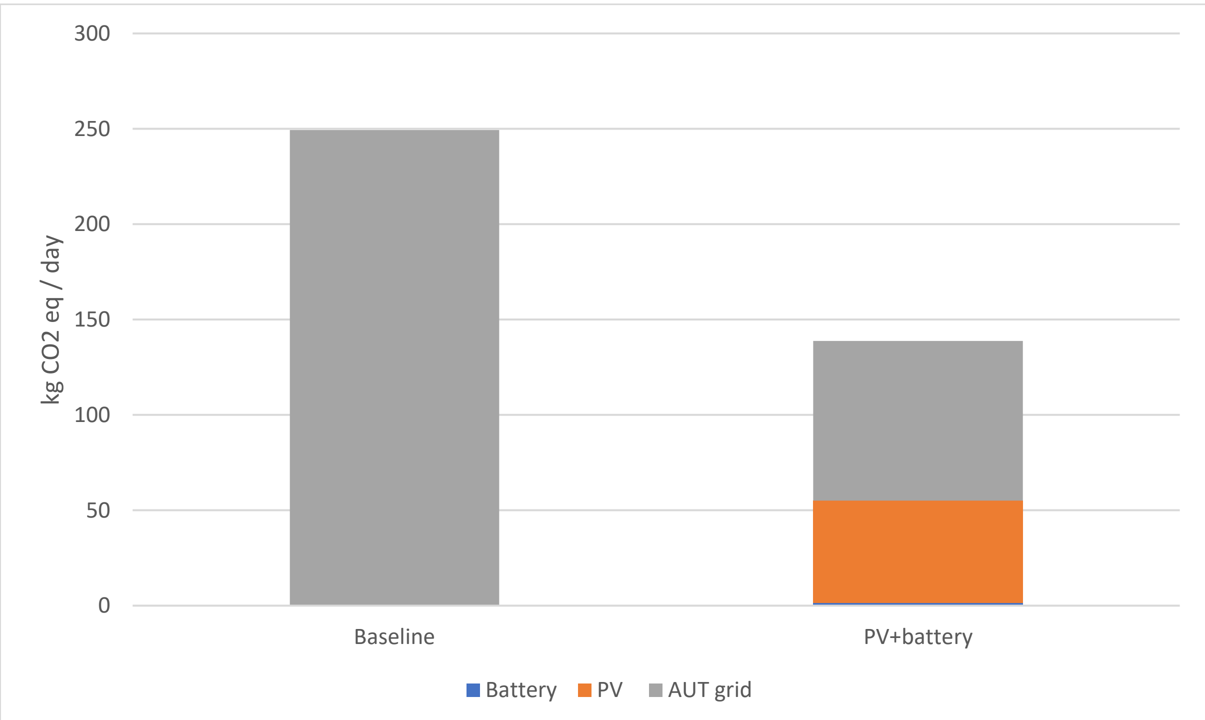

Figure 2.12. Potential climate change, Stockerau baseline case vs. case 2 with PV and battery

The assessment in figure 2.12 applies the generic use case assumptions for photovoltaic panels from the LCA background database. It can be observed that, of course provided that the data from Stockerau is accurate, this result may seem to roughly replicate the savings for case 2 suggested in the pilot description. Notably, the grid electricity is based on Austrian average/attributional electricity mix, and other results might ensue if other theoretical assumptions would be chosen, such as an European-wide electricity mix, a local or county-wide energy mix, or a marginal mix, or if electricity certificates are taken into account.

Figure 2.13 shows other environmental impact categories in addition to climate change, weighted as previously. Weighted results must be interpreted with immense care, but it might be instructive that substantial environmental side effects are suggested. The weighting scheme vaguely suggests that the two setups have more or less the same environmental profile when all impact categories are included and weighted. While Case 2 is strongly improved for climate change and fossil resource use, it notably has higher mineral/metal resource use, as well as a higher ecotoxicity score. It is important to remember that the European Commission weighting profile is generic in scope: Different value profiles (or, in fact, people) may emphasise the importance of different environmental impact categories. This may also fluctuate over time as different impact categories become more or less „fashionable“, and this diversity of opinion is important to consider both for the purpose of democratic inclusion and public acceptance.

Anyhow, as climate change is regarded as undesireable because if its general environmental impact, it does not seem logical to simply disregard other environmental impact categories. The case may suggest that particularly acidification, ecotoxicity and mineral/metal depletion will also need to be considered.

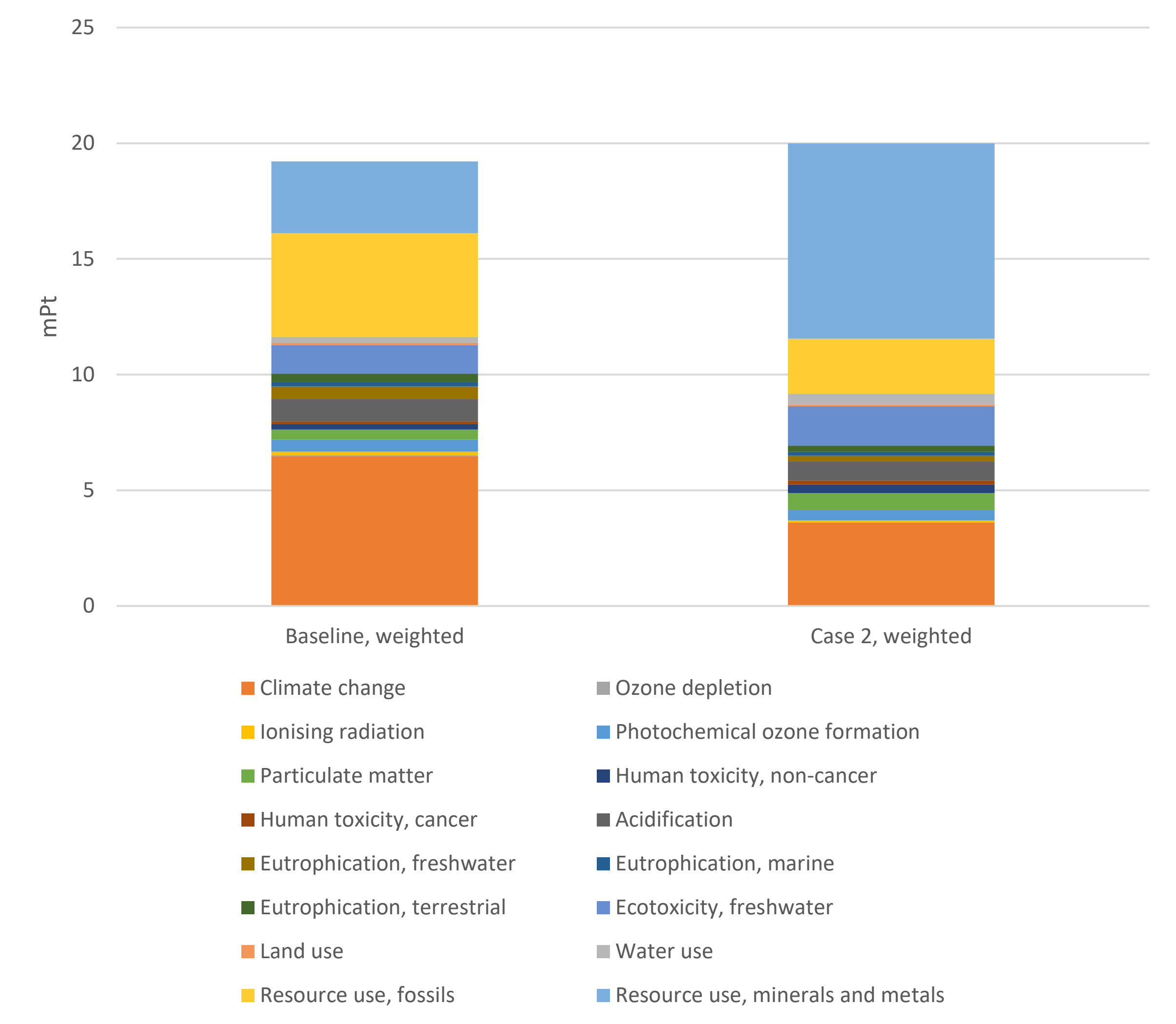

Figure 2.13. Weighted results for baseline vs. case 2

Of particular interest for the case of Stockerau is the use of live data from the Electricity Maps framework – cf. the current website at https://app.electricitymaps.com. This is a different calculation framework than the commonplace LCA assessment described in the above.

The Electricity Maps framework is based on flow tracing, and is documented by Tranberg et al. (2019) in the academic journal Energy Strategy Reviews. This framework is thus both recently developed and peer-reviewed, it is very frequently updated and also employs life cycle emissions. This framework may thus tentatively be considered to represent one particular branch of the state of the art with regard to this type of optimisation.

At the same time, an important discussion point is that yet other approaches might emphasise different geographic and temporal scopes, and might also consider a variety abstractions of the physical electricity, for instance market-based data such as green certificates and similar approaches (e.g., Raadal et al. 2012; Delardas and Giannos 2022). This challenge will, however, be relevant no matter which optimisation regime is chosen.

2.4.4. Rota pilot

The Rota pilot was designed quite similarly to the Berlin pilot, however as MPC for a building element rather than for a building. The pilot has reported slightly higher carbon savings than for the Berlin case, at about 10%.

The evaluation of the Berlin case above can be regarded as relevant for the Rota pilot as well, with a few differences. Energy savings is reported as higher, which is environmentally beneficial, but the electronic infrastructure is used for one room only, which gives somewhat higher environmental impact from the infrastructure.

2.5. Potential social impacts

- Privacy and transparency concerns. Could be mitigated by a strict opt-out policy and a physical power button.
- The energy security of households can be compromised if the technology is haphazardly designed, particularly in areas where temperatures can be cold – the technology must be failproof in this respect.
- More complex design may potentially increase the probability of downtime and lack of timely maintenance services.
- Waste from the EU is in some cases exported to locations with detrimental working conditions (Norsk Gjenvinning 2017). This problem appears to be difficult to eliminate completely.
- The MPC could make some choices between heat sources that some people will consider value-laden. It is possible that the user can be allowed to «tweak» the weighting factors. It may be difficult to determine in advance which priorities people currently hold, and not least which priorities they will hold in the future. This principle of dynamic user control can also be useful in future scenarios in which there are obvious drawbacks associated with a certain setup.
- Higher educational level among workers involved in heating installations. This could potentially be somewhat detrimental to equal opportunities, whereas it could provide benefits for the general educational level in society.

2.6. Potential gender impacts

- No relevant gender impacts were identified for the pilots.
- For equal opportunities in general, an increase in the complexity of the heating system would be associated with higher required expertise and/or educational level associated with heating. This could be slightly detrimental to equal opportunity when it comes to installing and maintaining the heating system. In particular, the use of remote communication risks associating heating with remote rather than user control. At the same time, of course, the user would potentially reap the benefits of what could be a more efficient heating system.

2.7. Rebound effects

Rebound effects (RE) are defined a behavioural or systemic responses mostly discussed in relation to energy efficiency improvements i.e., that the energy efficiency improvement reduces the price of energy and as result the demand for energy increases. RE is often expressed as the percentage differences between expected savings and actual energy use after implementation. An overall rebound effect of 100% means that the expected energy savings are entirely offset, leading to zero net savings. There is common to distinguish between three forms of rebound effects: (1) Direct use - the same service more due to a price reduction for example, when consumers purchase a heat pump, which is energy efficient and lowers total energy use, all else equal they might increase temperatures at home. (2) Indirect rebound effect involves money saved on reduced fuel consumption being spent on other energy-intensive goods and services. (3) Society/economy-wide - Commonly defined within mainstream economics as the sum of indirect and direct, but could also be structural effects that spurs energy demand.

In later years it has been accepted that RE could be understood beyond (energy) economics through other disciplines (industrial ecology, sociology, physics, phycology, urban planning) and that other dimensions such as time and space also could be applied for RE (Santarius et. al 2016). RE could be applied beyond energy for other natural resources and associated with other environmental categories. Some tend to conclude that the rebound effects are limited and therefore of minor importance (e.g., Lovins 2017). Others conclude that rebound effects are at least of some importance, but they need not make energy efficiency policy ineffective (Sorrell et al 2007). Others again state that the rebound effect is significant and challenge the belief that improving the efficiency of energy use will lead to a reduction in energy consumption, and hence be an effective policy for reducing GHG emissions (Saunders, 2013). These seemingly contradictory conclusions could stem from applying different definitions of what is meant by rebound effects and different system boundaries (Sorrell et al 2007).

The following RE could be relevant for EPC4SES:

1. If the MPC involves energy efficiency and subsequently that energy becomes cheaper than previous this can increase the demand of energy. This could lead to that people prioritise higher comfort level than previous i.e., a higher indoor temperature which could outweigh some of the gains from energy efficiency improvements. The direct RE of residential energy consumption, which includes heating, is found to be in the size of -9 to 127 percent. Excluding heating the RE could be lower (Cabeza et. al 2022).
2. Money saved from energy efficiency improvement could be used on buying other energy incentive goods and services, the indirect rebound effect is difficult to quantify but, in many cases, it is the most important one. According to the latest IPCC report chapter 9 (ibid.) the combined direct and indirect or the indirect only rebound effects were found to range between –2% and 80%, with a median at 12%.
3. For companies if the MPC lead to energy efficiency improvement this can be used to increase production or investment into new equipment that can increase production. It is stated by Cabeza et. al (2022) that the RE in non-residential buildings could be smaller because of two reasons: (1) The commercial sector have typically lower price elasticities of energy demand and (2) comfort levels ahead of renovation is likely to be better than in residential buildings (Qiu 2014 cited in Cabeza et. al 2022).
4. Indulgence effect, good environmental deed in one area by having lower GHG intensity from heating and power consumption can lead to omission in other parts of life, i.e., to spend money on energy consuming activities such as meat consumption and long-distance plane for holidays.
5. On a society level if there is an increase in living area per person or that the building envelopes have minor retrofitting and low energy standards this could create a “structural lock in” into a high demand for energy in buildings, thus outweighing potential gains from MPC at a societal level.

To sum up on the one hand RE in the building sector can be welcome where it enhances affordable energy and social well-being, on the other excess consumption above welfare levels should be avoided (ibid.). There is thus a need to find policies that balances these two perspectives. A key point to curb rebound effects are to secure that taxes (or similar) addresses excess consumption and luxuries consumption on the one hand while allowing less economically advantaged groups to afford energy thus avoiding energy poverty. In addition, policy packages for buildings and energy use should follow up with policies for retrofitting and energy standards, to avoid society wide rebound effect.

2.8. Economic effects

Economic data was only available for the Stockerau case. Here it was shown that several of the model predictive control scenarios would be associated with reduction in costs. The less complex interventions were associated with shorter pay-back times. PV and PV+battery were substantially less costly than the baseline alternative, whereas PV+battery+hydrogen was found to be more expensive than the baseline. The new technologies may serve to protect against indirect economic effects of power grid disruptions and electricity price fluctuations, but at the same time may require more complex and more frequent local maintenance, replacements, etc. than connection to the power grid.

Care should be taken so that economic drivers do not serve to invalidate life cycle environmental concerns.

2.9. Conclusion from the simplified LCA study

For the Berlin case, there is an environmental trade-off between the direct decrease in energy use from the functional benefit of the control mechanism, and the life cycle increase in energy use. An increase in technological complexity will in general terms increase the uncertainty of the inventory data. For instance, the software used and the internet activity are currently not feasible for the LCA practitioner to model in sufficient detail. In order to keep side effects under control, it is necessary to carefully implement the technology in a way that minimises or eliminates the risk of substantial or run-away use of energy online (i.e., ultimately from data centres) – currently, and also importantly, in the future.

For the Kuchl case, the pilot demonstrates a reduction in energy use, according to the LCA model, and provides an instructive case as it did not substitute a sufficiently «dirty» energy mix. The full environmental impact of biomass use is, however, under discussion, and it cannot be considered objectively incorrect to assign this energy source a higher environmental impact than the LCA study suggests, ref. for instance the methodological overview of Tellnes et al. (2017) on biogenic carbon, as well as considerations considering land use and indirect land use change. Nevertheless, it would be desireable to have a clear environmental benefit from the installation of MPC. For this purpose, the substitution of energy from fossil fuel could be considered.

For the purpose of minimising side effects, the technology could primarily be installed where the existing (substituted) energy mix is considered to be of concern and notably detrimental to the environment. A secondary consideration is that the control system appears to be a more effective intervention in buildings that consume more energy. A third consideration is that several environmental impact categories can be considered. A fourth consideration is that the MPC could be designed so that the local user can select an environmental profile, for instance based on perspectives, as in the ReCiPe 2016 LCA method (Huijbregts et al. 2016). The different perspectives in ReCiPe 2016 are based on different value profiles, called hierarchist, individualist and egalitarian. For instance, the individualist would typically prefer a shorter time horizon and to emphasise human health concern, whereas the egalitarian would prefer a longer time horizon with more focus on ecosystem damage. Allowing some degree of user interaction in the MPC could alleviate the problem of trend flucuations in societal perceptions of environmental concerns over time, and allow for a more democratic and less technocratic approach. A potential drawback is that this could be too advanced for the regular user to properly understand.

Specific results from the two remaining pilots from Vienna and Rota were not feasible to specify due to a lack of data at the time of writing. As suggested in the above, however, general considerations are as important as specific figures, and discussion in the above are relevant for these pilots as well.

3. Additional evaluation elements

3.1. General overview

The evaluation activities in this project include in addition to analyses of the pilots:

1. An overview of evaluation methodology
2. Conducting process evaluation of the project based on:
    - literature review regarding the processes in the project
    - interviews with the project partners
3. Analysing barriers for society wide use of project results:
    - review of literature and statistics regarding the project's topic
    - interviews with relevant stakeholders

3.1.1. Overview of evaluation methodology

Based on the diversity of the elements of work package 4 (WP4) presented above, we decided to implement a twofold evaluation of that project: firstly during its lifetime (process evaluation) and afterwards of its effects (outcome evaluation). The reason for this is that, as Bingham and Felbinger note, each evaluation is appropriate to a different set of research questions (2002, 4) and the different approaches are complementary. At the beginning of evaluation research there was only focus on measuring the effects of projects, and creating models based on those effects. Later the approach changed and the acceptance for process evaluation rose. It is not only interesting for the researchers but also useful for the stakeholders and projects owners to follow and understand the process that occurs when a project is conducted. Evaluation research had become more and more dialogue-oriented (Baklien 2000, 53-54).

Process evaluation focuses on following actions carried out in order to achieve a project's goals from the idea stage at the outset of the project, through its implementation, until the moment the results are received by the stakeholders (Tornes 2012, 117). The main questions in this evaluation approach include: Is the level of activity in the project satisfying? Are there any problems with the implementation of the project? (Tornes 2012, 111).

Baklien writes about three different types of process analyses: 1. describing which processes are initiated (effects, interventions, or actions), 2. describing processes that created the effects, 3. A combination of both (Baklien 2000, 54).

Process evaluation, according to Baklien, is about identification of barriers and 'push factors' that have a bearing on goal achievement. The connection between the action and its effect is as important as the effect itself (Baklien 2000, 54). That is why the description of which processes and effects that derive from an action, should be based on data collected from the beginning of the process to its end (Baklien 2000, 57). As commented by many authors, process evaluation is often one of the first activities to be cut out from the project in order to lower the budget and its importance is often not realized (Bingham & Felbinger 2002; Davidson 2005).

Outcome evaluation sometimes also called impact, summative (Bingham & Felbringer 2002, 5), result or effect evaluation (Tornes 2012, 111) focuses on the things that happen or are prevented from happening as a result of a project (Davidson 2005, 59). This category is connected directly to the goals and objectives of the project and it answers questions related to whether the goals were achieved, how effectively it was done, and what the effects are. Outcome evaluation, as well as process evaluation, is divided into two categories. Some authors suggest the following names: enumerating outcomes and measuring effectiveness (Bingham & Felbinger 2002, 5-7); others prefer to call them the goal-achievement model and the effect model (Tornes 2012, 111). The first approach, whichever name is used, focuses on the following questions: Are the goals achieved? If yes, to which extent? If not – why? The second approach, measuring effectiveness, asks: What are the effects of the project? Was the project effective? What would happen if it had not been implemented? (Tornes 2012, 111-112; Bingham & Felbinger 2002, 5-7). Bingham and Felbinger, who tend to call this type of evaluation 'impact evaluation', also explain that outcome evaluations are often quite objective and easy to use in empirical investigations, as the data can be extracted from records or from observation and testing, sparing the evaluator of reliance on clients or staff in data-gathering (Bingham & Felbinger 2002, 7).

Table 3.1. The Key Evaluation Checklist – part of it.

Process Evaluation	Outcome Evaluation
How good, valuable, or efficient is the evaluand's **content** (design) and **implementation** (delivery)?	How good or valuable are the **impacts** (intended or unintended) on immediate recipients and other impactees?

Source: Davidson 2005, 6.

The evaluation activities in this project include in addition to analyses gathering and analysing outcomes of the project pilots:

3.1.2. Literature review and interviews

Literature review on the evaluation methodology

The literature on evaluation methodology was analysed in the beginning of the project, in order to establish the plan and tasks as mentioned above. International papers and book chapters were analysed and the knowledge was adapted to the specific of this project. A summary of the knowledge has been given above, in the introduction to this report.

Data collection for process evaluation

- literature and document review regarding the processes in the project

The process of conducting the project has been closely follow throughout its entire lifetime. The evaluation team has had access to project documentation and literature gathered on a common digital platform. They have also been present during regular update meetings for all project partners, where they presented progress in their work packages, organized usually every two weeks. The outcomes of the pilots are presented below.

- partner interviews (participants feedback) and results

In project's first phase (first year) the evaluation team conducted interviews with project partners in order to learn about their experiences and expectations regarding the processes going on in the project. Gathered information was seen as important for successful conducting and accomplishing of the project. Due to Covid-19 pandemic, time and cost efficiency the interviews were conducted digitally by use of one of the globally known videoconference tools. The data has been treated with respect for the GDPR rules, and are presented below.

Data collection for effect evaluation
- literature review and statistics regarding project outcomes
The review has had its main focus on the literature regarding data driven energy efficiency, energy performance certificate (EPC) and its marked potential. International articles and reports has been analysed in order to learn about the current state-of-the-art and development possibilities for energy efficiency based on data and technology. These are further described in the next parts of this report, as well as in the conclusion chapter at the end.

- interviews with stakeholders
The evaluators conducted interviews with relevant international stakeholders who have expertise within data driven energy efficiency and represent different perspectives: national authorities, energy advisors and consulting companies, as well as technology developers. Semi-structured interviews were conducted based on a guide that focused on several topics: role and vision behind stakeholders' activities; opinions on the development of data driven energy efficiency and the EPC; experienced and expected barriers in introduction of different energy efficiency measures (including EPC). The results of these interviews are presented below, and contributed significantly to the conclusions in chapter 4.

3.1.3. Process evaluations: Partners' feedback on the process of the project
We present a short summary of the evaluation given by the partners on the topic of the project's process. (1) Communication within the project. Due to Covid-19 there were some challenges for project communication between partners in the start of the project, however adapting to more regular meetings and a physical gathering in Berlin helped to overcome communications barriers. (2) Another challenges mentioned by partners in an early phase was that national funding of ERA Net project with separate national parts was a barrier for coordination along with Covid-19. However, this were sorted out by the end of the project period. (3) Other obstacles was low funding in relation to an ambitious project and that there were some difficulties with data protection and different national and regional rules associated with access and quality of EPC data with utilization of EPC data.

3.2. Literature review to find effects and barriers for wider implementation
3.2.1. Articles
Literature studies show international interest in the topic, and different European cases, but at the same time the number of relevant articles is relatively low. Below we present examples of scientific papers, but also up to date documents and reports.

The first article was published in the Journal of Cleaner Production in 2019 by Pasichnyi, Levihn, Shahrokni, Wallin and Kordas, with title 'Data-driven strategic planning of building energy retrofitting: The case of Stockholm' (Pasichnyi et al., 2019) . Authors describe a data-driven urban building energy model (UBEM) based on EPC data obtained from the national building energy declarations database maintained by the Swedish Board of Housing, Building and Planning (Boverket). The paper presents high-resolution metered data in fact-based modelling of the energy performance of the building stock. It also refers to innovative heat recovery ventilation solution and energy-efficient windows for the retrofitting 'Million Programme' buildings in Stockholm. Results presented by Pasichnyi et al. show that the annual heat energy demand of the buildings stock in question was reduces by 18%. It has had variable impacts on the environmental performance of urban energy system and has only been partially economically viable. The results can be partially explained by the availability of an advances district heating (DH) system in Greater Stockholm, where the supply of energy has largely been decarbonised (Pasichnyi et al., 2019).

Another paper on the topic was also published in 2019, as an Environmental Research Letter by Gouveia and Palma (Gouveia & Palma, 2019) , taking as a topic the harvesting of big data from residential building energy performance certificates: retrofitting and climate change mitigation insights at a regional scale. This letter aims at regionally characterizing the Portuguese building stock, using the data from EPCs on the parameters of building and climatization equipment ownership. Authors point out that Energy Performance Certificates and a useful source of data, not only at the individual dwelling level but also for leveraging into bigger scale studies, encompassing a whole dwelling stock, namely for the assessment of its energy performance and GHG emissions. However, the results show that the Portuguese dwelling stock does not have the appropriate characteristics for adequate energy performance. Residential buildings in this country have very low energy performance, with windows and roofs being identified as the most energy inefficient elements. Gouveia and Palma describe that the roof is the element with the highest potential for reducing heating energy needs, particularly in the house typology from 1980-2005. Retrofitting of windows, on the other hand, can be effective in reducing cooling needs, particularly in house and apartment building typology from 1960-1980 (Gouveia & Palma, 2019).

Norwegian researchers, Kvålshaugen and Groskovs, published in 2020 a paper presenting a preproject called ‘Measuring the effects of digitalisation in the Norwegian construction industry’ (Kvålshaugen & Groskovs, 2020) . Initially, the authors say that the benefits of a fully digital construction process are estimated to reduce greenhouse gas emissions in the industry by 40%, lead to 50% faster project implementation, 25% cost reduction and 50% increased exports of goods and services. However, such fully digital process has not been created and taken into use yet. Their hypothesis is that analyses of the effects of digitalisation are needed across the actors in the core processes in construction and operation / maintenance of buildings and facilities. The conclusion from this preliminary study is that there is a great need to develop a method for measuring the effects of digitization both internally and between the actors in the construction process. A future main project will therefore focus on developing a method for analysing the benefits of digitization in close collaboration with actors in the entire construction process value chain as well as measuring the effects of digitization in selected core processes in construction and infrastructure projects (Kvålshaugen & Groskovs, 2020).

The fourth article (chronologically) was published in 2021 by Wenninger and Wiethe, with title ‘Benchmarking Energy Quantification Methods to Predict Heating Energy Performance of Residential Buildings in Germany’ (Wenninger & Wiethe, 2021) . Authors state that the methods to quantify building energy performance used most frequently and legally required nowadays show in fact low prediction accuracy. In order to enhance that accuracy, the research community introduced data-driven methods which obtained promising results. Different Energy Quantification Methods (EQM) has been benchmarked for residential buildings, applying a derived process based on the CRISP DM. The results presented in this paper show that firstly the focus should be in the interface of predicting heating Final Energy Performance for residential buildings, based on real-world data with annual energy predictions. Authors also proof that the data-driven EQMs outperform the engineering EQM by a large margin, reducing the prediction error by almost 50%. Hence, the conclusion that data-driven EQMs are in general more suitable for residential building energy quantification (Wenninger & Wiethe, 2021) .

3.2.2. Reports

The topic of EPC has been present on the international arena for several years. The EuropeanNetwork for Energy Performance Certification of Building worked on the ENFORCE project, conducted between 2009 and 2012, which helped the diffusion of energy certification, leading the way to energy-efficient buildings. Its aim was to give final consumers independent, qualified, information and assistance on Energy certification of their buildings, allowing them to make informed decisions. The project achieved impressive results (e.g., 6 national implementation reports; 5 national networks in each partner country and 1 European informal network of trained, qualified, independent and third-party energy audits; more than 70.000 units distributed of informative materials; first-time meetings for stakeholders from many countries) (European Network for the Energy Performance Certification of Buildings, 2014).

Project partners stands, among others, behind a report, published in 2010 on "Comparison of Building Certification and Energy Auditor Training in Europe" (European Network for Energy Performance Certification of Building, 2010). The starting point for this was the fact that residential and commercial buildings represent a potential source of energy savings, and that interventions aimed at achieving energy improvements in the residential field not only improve citizens' wellbeing, but also reduce energy needs, as well as reliance on other countries for energy supply. The authors refer to the 2002/91/CE Directive of the European Parliament and Council, related to energy performance of buildings (EPBD Directive), which complies with the European energy strategy and is a useful legal tool, on a European level, to improve the energy performance of buildings, in an effective way (European Network for Energy Performance Certification of Building, 2010, s. 4) . In conclusion to this comparison, the Network comes with several best practices and recommendations, such as Creation of a well-structured network platform of independent energy certification assessors and a proper training for them; Regulation on EPC elaboration costs and linking financial instruments to EPC; Creation of a central EPC data collection managed by a national official entity; Organised awareness building campaign properly targeting the various actors (European Network for Energy Performance Certification of Building, 2010, s. 42–47).

Another example is a report created for the "Transparense" project ("Increasing Transparency of Energy Service Markets" supported by the EU program "Intelligent Energy Europe") in 2013 focusing on the European EPC market overview (Garnier, 2013) . It presents results of an EU-wide market survey across 20 EU countries. Surveys were created to gather information for a comprehensive overview of the existing EPC market in European Union, and it was addressed to EPC providers, banks and finance houses. In conclusions of this report, the author summarize drivers and barriers for the development of EPC market in EU. The main barriers are of regulatory ("regulation / lack of support from the government", "subsidy / policy uncertainty"), structural ("lack of trust in the ESCO industry", "complexity of the concept / lack of information") and financial ("financial crisis", "raising affordable finance") character. While the main drivers are "overwhelmingly financial", with "increasing energy prices" and "pressure to reduce costs" being the two most chosen responses, and "government policy", "customer demand" and "financial crisis" also as popular answers (Garnier, 2013, s. 36).

When it comes to more regional studies, an interesting report was written in 2015 by Liv Randi Lindseth, presenting an overview of the EPC in the Nordic Countries, with focus on the public sector (Lindseth, 2016). The author describes the state-of-the-art on this topic in Denmark, Sweden, Norway, Finland and Iceland, at the end creates a comparison and suggests preliminary recommendations. What is interesting, by the time this report was written, all these countries, beside Iceland, have had EPC projects in both public and private sector. Summarizing, the author underlines that in Denmark and Norway, the EPC market is already strong, and provided that the current framework is maintained, further growth is expected. Sweden, on the other hand, was, in the first years of 2000, one of the pioneers and leading countries on EPC, but in the last few years, the EPC market in this country has been week, due to “issues of knowledge, trust and uncertainties around public procurements”. In Finland, the market experienced interest in public sector, even though it has been slow and small. Based on the mentioned comparison of successes and failures in each country, the author recommends implementation of several elements, taking the best from each country and working for adapting it in the others: governmental promotion strategies for information and training for all relevant stakeholders; financial support schemes; development of National Standards for EPC; EPC website(s); increased number of EPC facilitators (Lindseth, 2016, s. 8).

On the national level, there are two interesting reports from Norway, from 2017 and 2019, published by, respectively, Zero Emission Resource Organisation (ZERO) and Enova. The first of them “How we cut the energy use in buildings” (Østby Stub & Antonsen Brenna, 2017) presents instruments for energy efficiency. The starting point for this work is the broad political agreement on a goal of a 10 TWh reduction in energy supplied to existing building stock by 2030. For comparison, in 2015 the total energy consumption in the building stock in Norway was 83 TWh. To achieve this goal, the use of several instruments must be strengthened, and measures must be implemented in both private homes and commercial buildings. Those measures suggested by ZERO are, among others: improve and adapt the requirements for rehabilitation, in order to increase the number of rehabilitations; to introduce component requirements for passive house windows; subsidy managed by the Directorate for Building Quality; tightening of the building regulations for new buildings in line with technology development and revised regularly; development of energy label scheme to improve the information between the authorities and building owners about energy efficiency (Østby Stub & Antonsen Brenna, 2017, s. 4).

Somehow responding to the last suggestion, the Norwegian Ministry of Petroleum and Energy ordered a report from Enova on the existing EPC and development of a new one. This report was published in 2019 as a result of a pilot project (Forprosjekt Ny energimerkeordning - Hovedrapport, 2019) . In Norway energy labelling of homes and commercial buildings was adopted in 2010, and in 2016 the responsibility for it was transferred from NVE to Enova. Since the energy label scheme was established, a ban on heating with fossil oil has been passed to heat buildings. There is currently little greenhouse gas emissions from energy use in buildings in Norway. In addition, the Energy Report published in 2016 clarified a need for increased consideration of power load in the power grid. On the basis of this, Enova proposes that the energy label scheme information on energy status in the future places more emphasis on power load in the power grid and less on renewable energy sources. In recent years, several surveys, and input meetings have been conducted to evaluate the energy label scheme. Based on the analysis and input, Enova shows in this pilot project how the energy label scheme can be further developed. Proposals have been made for a new design of the energy label and energy certificate, as well as for a new calculation model that includes power use. The pilot project shows that several of the proposed changes in the energy label scheme will require changes in the energy label regulations on the national government level (Forprosjekt Ny energimerkeordning - Hovedrapport, 2019).

SINTEF – Norwegian organisation for applied research, technology and innovation has recently worked on a project called “Energy services, energy use and effect use in buildings”, and expects publishing results in the beginning of 2022. One of the starting points was a potential and barriers study written together by Enova and SINTEF in 2020. Some of the conclusions are that there is a theoretical potential of approximately 14 TWh in industrial buildings in 2050 (all is rehabilitated to TEK10), but only 2 TWh are triggered through rehabilitation. Researchers present also four different types of barriers: administrative and systematic; competence and knowledge of building owners; market barriers of suppliers; practical, technical and economic barriers. The conclusion is that the potential in building stock is big for both energy saving and harvesting (Krekling Lien, 2021).

3.3. Feedback from stakeholders

3.3.1. Method

Qualitative interviews were conducted with project partners and selected stakeholders representatives relevant for the scope of EPC4SES. The purpose of the qualitative interviews was to collect data that makes it possible to better understand a phenomenon. In other words, the qualitative method answers questions ‘What?’, ‘Why?’, ‘How?’, But not ‘How much?’ (Kvale et al., 2015) . The latter characterizes quantitative surveys. Kvale and Brinkmann describe qualitative research interviews as a tool for the purpose of understanding aspects of the interviewee‘s daily life, from his or her own perspective. The structure of the research interview is similar to the everyday conversation, but as a professional interview it also involves a specific method and questioning technique (Kvale et al., 2015, s. 42). Qualitative interviews, in a broad phenomenological approach, are used as a research tool and what the respondent or informant says is treated as a ‚report‘ on experiences. Some approaches look more at ‘what’ people have experienced, while others at ‘how’ they express themselves through the interview situation (Kvale et al., 2015) . Open individual interviews are chosen when relatively few units are examined, and when the desire is to get a deep and thorough description of the phenomenon. Transparency in this case means questions without fixed answer options, but with a guide that includes topics of interest to this research. Such interviews are usually time-consuming, especially in the follow-up work where the researcher reviews the recording, transcribes and systematises answers (Kvale et al., 2015) . Due to the corona situation and in order to save both time and financial resources, the interviews were conducted in the form of digital meetings. Disadvantages of such meetings in relation to ‘physical’ ones are that in the second case the researcher can observe the informant's body language better, and that the person can be more relaxed and focused on the interview. However, there are many benefits to digital meetings, including: economic and related to climate change, since the researchers do not travel to meet informants. The time perspective is also different, where the researchers can conduct several interviews with informants from different places on the same day. Thanks to the choice of digital meetings, this study was conducted cheaper, faster and more environmentally friendly.

In this report, we use the word ‘researcher’ when we talk about the person who conducted interviews on behalf of the Western Norway Research Institute. „Informants“, on the other hand, is the name of the stakeholder representatives who were interviewed. The choice of the word „informant“ is not random and separates that person from a „respondent“. The respondent interview is conducted with people who themselves have experience with the phenomenon (self-experienced). The informant interview, on the other hand, is conducted with people who know a lot about the phenomenon (experts), as it is with project partners and stakeholders (Jacobsen, 2005).

3.3.2. Selection of informants

As mentioned before the interviews were conducted with two groups of informants for two separate purposes. The first part of the conversations took place at the end of 2020 with project partners and the questions focus on evaluating the process of conducting the project and the obstacles emerging on the way. Interviews in this part were conducted with all the six project partners (Effiziente, Senercon, SUoAS, WTG, AICO, Cleopa). The second part of the interviews took place at the end of 2021 and in the first half of 2022. The informants' group included those of project partners who were responsible for the pilot cases. It was in total four pilot partners and stakeholders that were interviewed. The stakeholders were chosen based on the institution they work at and their role, as well as the expertise of project partners, whose recommendations were essential for the choice of informants. In order to maintain the GDPR rules for data collection, the names of informants (pilot partners and stakeholders) are anonymized, and only their role and workplace are presented in table 3.2.

3.3.3. Stakeholders' feedback on data driven energy efficiency

The stakeholders' representatives who became informants represent different interests and perspectives on the EPC and data-driven energy efficiency: national agencies, technology developers, service providers and advisors. Below, we present the interview guide that was used and the results of this part of the data collection.

Interview guide

The interview guide consists of five main thematic areas: general information, data-driven energy efficiency, savings potential, barriers, market potential. The questions are open, but the
guide also describes suggestions (sub-questions) that can be helpful for the interviewer in leading the conversation and further explaining details for the informants.

General

•What is the main task/goal of your company/institution?
•What is your role in the company? What is your role in the project?
•How long have you had that role?

Data-driven energy efficiency

•How is your company/institution involved with/using data-driven energy efficiency?
•What do you think about the future of data-driven energy efficiency?
•What kind of data-driven energy efficiency? (Based on EPC/MPC measurements?)

Savings potential

•What do you think is the energy savings potential from data driven energy optimisation based on EPC/MPC improvements in the building sector in Europe?

Barriers

•What are the practical barriers for implementation of data driven energy optimisation efficiency based on EPC/MPC measurements?
•Financial? (e.g., lack of profitability and high-investment requirements)
•Attitude barriers? (e.g., lack of commitment and the preference of comfort over energy-efficient buildings)
•Knowledge barriers? (Lack of information about products and services and the benefits and profitability of energy efficiency and lack of competence about building operations)
•Public framework? (Systematic policy analysis at different levels of governance—business, sector, local, regional, national, and EU levels—that directly and indirectly affect the possibility of change towards large-scale improvements of existing building mass)
•What are the technical barriers for implementation of data driven energy optimisation

efficiency based on EPC/MPC measurements?
•Metadata available for machine learning and modelling?

Market potential
•What is the marked potential of data driven energy optimisation efficiency based on EPC/MPC measurements?
•Looking at the EPC4SES project and its use cases, what would be the scenario giving the best CO2 savings within 5 years from implementation?

3.4. Results

1. National agencies in Norway, such as Enova and NVE use data actively to work on energy efficiency. Enova is a government enterprise responsible for promotion of environmentally friendly production and consumption of energy. The last years they have been working on the development of a new Energy Performance Certificate (EPC) system, a task that was ordered by the Ministry of Petroleum and Energy of Norway. They have analysed the previous system and in a report from 2019 suggested a new setup (Forprosjekt Ny energimerkeordning - Hovedrapport, 2019) . Their current focus is on finding well-functioning solutions, such as more flexible power grid. Within data driven energy efficiency they are developing an IT system to handle EPC. One of the main obstacles for it are the GDPR rules regulating access to data. Enova has a agreement with Norwegian banks working with green finance, but data flow between buildings owners and suppliers is a challenge, as there is a need for a management system where the owner accepts that the energy supplier has access to data. As per now Enova can therefore only share information about energy grade and heating grade. The situation is easier for single households, where the owners can log into a website with all the necessary data, and Enova can, based on that, conduct simulation of energy savings potential.

There are also existing private companies in Norway, which, despite the lacking access to real time data, can create a theoretical calculation of energy consumption and saving opportunities, based on the address given by the building owner.

One of Enova's main tasks is offering grants for hiring an energy consultant and upgrades of buildings for better energy efficiency (up to 150 000 NOK), as well as giving a background for lower interests from a bank loan taken in connection to that. An important factor for using EPC is the fact that in Norway there is a duty of presenting it due to sales of buildings. This is connected to banks requiring those certificates, as they themselves can get better terms if they prove that they give money to 'green projects'. Enova estimates that 40% of private buildings in the country that are on the market have an actual EPC. However the number is much lower for industrial building stock. At the same time, there have been conducted potential studies for energy efficiency, but they have not looked at how much of the savings can come from the EPC.

Enova also works with energy saving contracts (ESC), which are characterised by a significant investing risk, but give great results. Enova has helped nearly 80 municipalities in Norway by supporting such contracts, and their hope is that this trend will spread from public to other sectors.

An important observation is that, according to Enova representative, the EU standard factors for EPC do not suit Norway, and that this is a political exercises, with different considerations of those factors.

What is interesting, before 2015, there was no comprehensive energy efficiency upgrade system for building stock in Norway. Nowadays, Enova provides support for up to 6000 buildings a year, at the same time estimating that there are between 10000 and 20000 that could be upgraded.

2. NVE (Norwegian Water Resources and Energy Directorate) uses data to learn about energy use in building development. They have divided building stock into 13 categories (e.g., blocks, small houses, etc.) and identified 13 types of measures. Thanks to that system NVE can look at what it takes for each category of building to be lifted to a higher standard of energy efficiency. They base their work, among others on simulations provided by a consultancy company called Multiconsult who apply the software Simien (Simein, 2022) which let them estimate the cost and saving that can be gained from the upgrade.

NVE uses data in many different ways, among others to analyse energy consumption per m2, person, household. Their main line of work is assignments, and they search for data according to problems that they need to solve. They also have created a model that they can improve every time they get access to new data sets. A challenge is connected to the difficulty in getting the data, due to GDPR, and NVE cooperates with a company called Elhub (Elhub, 2022) which gather data from electricity generators from all households. However, they only have the data for a limited time (3 years), which means that also NVE cannot access them for a longer period. Another challenge is that the building owners, who have the data, need to know what data they have and how to use it.

NVE representative points out the importance of different instruments which can influence the energy efficiency development in a country. Those are information campaigns, grants from Enova, tax deduction for rehabilitation and rebuilding, and certificates, such as EPC. However, government must want to implement it as a requirement for all in order to make it works. The more information the user has, the more they are triggered to do something. Also electricity prices trigger interest in change for more energy efficiency in building stock. According to the representative of NVE, media coverage and attention to the topic plays a role in this process, not only the profitability. Significant barriers can prevent building owners from investing in upgrades for better energy efficiency, since people see the process as too complicated and often have trouble to orientate themselves in this market.

It seems that the greatest potential in Norway now is in better heating technology, and there should be information available about where there is free heat from industrial and commercial processes, and ventilation.

3. Norwegian technology developers, such as Intin (Intin, 2022) , who works with smart house points out that the interest in development within energy efficiency in Norway is great. The systems are easy to use for individuals and allow controlling the energy use, while the price for a simple smart house system does not exceed a few thousands NOK. At the same time, they observe that such systems are still mostly purchased by specially interested people for private or company use. Intin works on developing smart house solution for tourism (mainly cabins and smaller hotels). What is interesting, the main reason for interest in their systems seems to not be energy efficiency but time saving, as the technology provides a key solution that makes it easier and less time consuming for the owners to give guests access to their rooms. However, more and more tourism companies has focus on following Sustainable Development Goals (United Nations, 2015) and are therefore turning their attention towards heating and electricity control.

Also for technology developers, the GDPR rules for data access are one of the main challenges. As well as the fact, that the system must be easy and practical to use for each and every individual, with as little training as possible.

4. Representatives for advisors and service providers within energy labelling present a different perspective from national agencies. Enøk-senteret (Enøk-senteret AS, 2022) works with interdisciplinary energy efficiency in Norway since 1989. They work mainly with energy monitoring and mapping of industry, and notice that EPC is used by few except the biggest companies. The EPC labelling is also not always of good quality, as the information on areal for the building stock is missing and only the year of construction is used in the simulation, which isn't enough to create a valuable certificate. Access and quality of data is also pointed out as a challenge here, mainly due to the lack of sufficient information on older buildings (e.g. often impossible to find drawings of buildings from 1970's). Enøk experiences the importance of different actions for owners to get more engaged in upgrading their buildings to more energy efficient. Here both incentives and punishments seem to work, especially for small and medium sized businesses. In their work with different customers, they focus firstly on low-hanging-energy saving-fruit, and it is not always EPC, as they see it as a useful tool but not a must. The impression is that possible cost saving plays a major role for building owners deciding on implementing energy efficiency systems, but at the same time, if the costs of the upgrade are too big, the interest is falling down rapidly. Also SDG's seem to play a bigger and bigger role in making decisions.

There is a potential for energy saving in small and medium businesses but for them the incentives offered by Enova are not actual, it is too expensive to renew the buildings otherwise, and that is why they often chose cheap solutions that do not capture this saving potential. There is then a need for different kinds of support in order to unleash the potential, and it must be a predictable development (more than one year of prediction). Enøk-senteret also organises courses for companies in managing the Energy monitoring system (EOS). This system gives the opportunity to follow the status of energy use, with current reporting regarding e.g. the cost and CO_2 created.

Insufficient consciousness of individuals is mentioned as a challenge, and example was given of application that seem often to be bought but not properly used. Enøk-senteret has also experience in international projects and their experience in that field shows that measures cannot be generalized on international level and must be adapted to countries (e.g. there is no point of using Norwegian solutions in Bulgaria, as the energy efficiency development in this country is on a significantly lower level). Another known challenge is the utilization of data, in which the customer (as the data owner) must be involved. Some of the companies deny giving access to data on their improvements as it is a competitive advantage.

Regarding data driven system, the question arises whether it always gives savings (e.g. if the temperature is set on 21 degrees all year round, even though the price differs within 24-hours, then then there will be savings sometimes but some not). It seems that data driven system technologies need more maturing.

The representative of Enøk-senteret point out that there is another very interesting topic appearing in that field in Norway, next to energy efficiency, and it is energy production (e.g. in Norway: solar panels, solar collectors, wave power, etc.) and the possibilities of its storage for further use e.g. for charging of cars).

5. Another Norwegian advising company is Segel (Segel AS, 2022). Their experience is that the business economic criteria play a major role for customers and that the financial benefits of a building rehabilitation project must be clearly communicated. However, they see not only significance of clean energy benefits, but also of non-energy benefits (e.g. cost reduction), and look at energy efficiency as a process, which both reduces energy costs and provides better quality of the end product. A very important factor for Segel's work is the type of customer, which directly influences the subsidy opportunities. At the same time they notice that in most of the cases the building owner, who in practice manages the upgrade, project is an amateur, without expertise, and that the rehabilitation often has an ad hoc character. The owner is exposed to several professional actors who convey their message, not always consistent with each other, and then the amateur is the one making the decision. In order to avoid such confusions, Segel created a one stop shop solution.

In the representatives opinion it is not sustainable to heat houses with electrical energy, something that is common in Norway.

The representative of Segel points out that the reduction of power peaks is most the important in energy systems. Also the challenge of energy storage is mentioned. Another important element is better interaction and collaboration between different energy suppliers, so that building owner who e.g. has access to both fjord heating and solar panels can use the source which is more efficient in particular moment. Still manual control is used in such cases, and there is a flat use of one energy source, possible topped with different type when needed. A data driven system can be created with chosen parameters in order to increase the efficiency (e.g. system that controls current prices of energy from different sources and says: 'fjord heating is expensive now, better to use solar panels'). Also the quality and accuracy of theoretical simulations of energy saving potential can be seen as a barrier. The reason for it is that people attitudes and actions regarding use of energy differ significantly even if the building type is the same. That is why one simulation for a single house will not bring the same kind of savings for different families owning such a house.

There is therefore a need for a map of the value chain of the different suppliers, different types of building owners and a reflection on gains and pains for each individual player. This in turn should be connected to economic perspective: What must a single player invest? How will this affect costs: direct energy costs for building owners, and operating costs? Will it reduce them? What about maintenance? Does it have positive or negative effects? How will this affect revenue for individual companies? What are other non-energy benefits that affect it? Energy efficiency upgrades must give benefits. Who has to take the lead and implement them? It can be government actors, the policy instruments, etc. If the upgrade turns out to be unprofitable, then the question is how much subsidies from Enova are needed to do it anyway. There is a need for regulations ('carrot and whip'), and some countries in Europe have required energy companies to make commitments and take action for energy efficiency and usage reduction.

Segel also refers to network companies struggling with business models. Tibber (Tibber Norge AS, 2022) , a newly developed Norwegian company, is an exception and an interesting case globally, as they challenge energy companies, not selling energy directly but services around it.

4. The potential role of MPC in decarbonisation

4.1. Basic/Theory

Generally speaking, flexibility in grids/network is able to absorb fluctuating renewable energy supporting decarbonisation. This refers to energy in thermal networks and energy in storage, either thermal or electric storage. The assets in the electric grid to be considered are (Drax, 2022):

- Ventilation systems
- Air conditioning
- Heating
- Lighting
- Pumps
- Batteries/electric storage
- Industrial and manufacturing processes

Cross-energy vector flexibility (Strbac, et al., 2020) is including electricity, heat and gas.

With Model Predictive Control (MPC) a virtual storage approach can be applied. This may be applied on the building level modulating the heating and DHW demand (Finck et al. 2019).

But also in district heating networks Model Predictive Control-based optimal operation is possible (Verrilli, et al., 2016) (Quaggiotto, Vivian, & Zarrella, 2021). Figure 4.1 shows the asset in an district heating system with distrusted energy conversion.

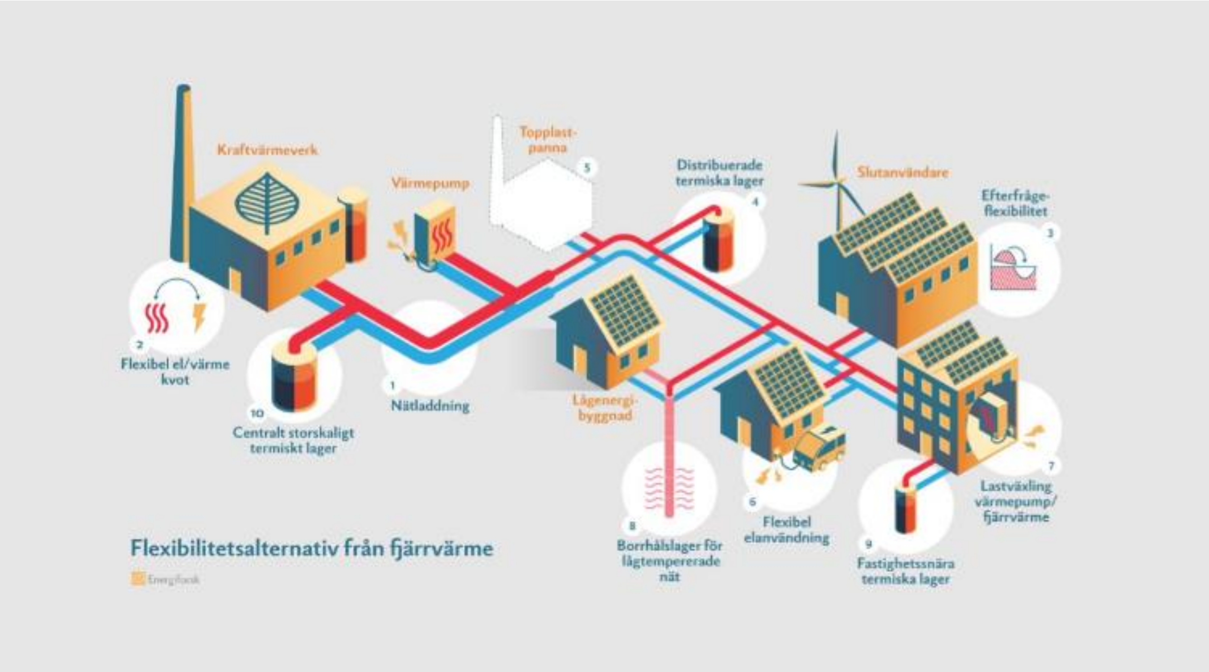

Figure 4.1. Flexibility options from district heating (courtesy Energiforsk Sweden, 2019)

4.2. Implementation

Within the project both approaches were implemented, MPC on the building level and MPC at the network level.

4.2.1. Building level: Berlin and Rota

A thermal storage in the subnetwork was modelled additionally and simulation with and without heuristic MPC made. The results showed a small improvement, which when scaled up for large buildings, for instance municipal buildings, may contribute to decarbonisation. Environmental side effects from the Berlin case were found to be quite moderate, at least as long as energy use associated with remote data centres can be minimised.

4.2.2. Network level: Kuchl and Stockerau

Both the Kuchl and the Stockerau cases showed some promise for decarbonisation. In particular, the Stockerau case seems to have demonstrated that state of the art renewable technology with model predictive control can contribute to substantial decarbonisation, although not without environmental side effects.

The Kuchl case was instructive in illustrating that the substituted energy in the grid should be as environmentally detrimental as possible.

The Stockerau case served to illustrate how there may be substantial environmental side effects from infrastructure investments, when more high-tech solutions are used for decarbonisation. This illustrates a general point that successful technology for decarbonisation is not necessarily synonymous with advanced or complex technology. Simple technologies that do not require complex infrastructure may be investigated further.

4.3. Assessment/Outlook

The improvement of the CO2 emission of ~3% in the Berlin pilot (from simulation of the year 2016) shows the limited impact of MPC, but also it has to be accounted for the small investment, in the best case only adding software and retrieving weather forecasts. The improvement is reduced if the CO2 intensity of the energy from district heating is lowered. But TES control helps to bring more renewable energy into the system. In a 100% RE system the effect is that MPC can result in smaller buffer tanks and solar thermal – 9,5 m² aperture and 95l buffer Volume instead of 10m² aperture and 100l per building for the Berlin example. In general, the use of simple MPC designs at the building level appears to be viable from an environmental point of view, and careful planning of the implementation is recommended for better results. The effect will be greater for larger buildings that use more power for heating. Municipal buildings would perhaps be an interesting use case.

For MPC at the network level, a higher infrastructure impact may be expected, but also a higher potential for decarbonisation. Novel energy technologies such as PV panels, batteries and hydrogen may be associated with lower life cycle carbon emissions, but also with apparently severe environmental side effects that should not be underestimated. Notably, PV panels, batteries and hydrogen technologies may be associated with life-cycle impacts of ecotoxicity and mineral/metal resource depletion. Hydrogen emissions should be considered in a life-cycle perspective rather than as „zero emission" by default. Technologies with more obvious enviornmental benefit can also be considered. If scaling up the different MPC approaches is successful, the impact can potentially become very large due to the substantial amount of energy consumed in buildings. MPC will also contribute to evening out peak loads in the grid, which will have a further beneficial effect on the energy system as a whole.

It can be assumed that the existence of further assets which might be controlled will bring more arguments for the application of MPC:

Asset to be controlled	Now	Near Future	Distant future
DH pipes (grid storage)	X	X	X
Buffer Tank	X	X	X
Thermal Mass Building (Building integrated Storage)		X	X
Central Heat pump	X	X	X
Decentral DHW Tanks		X	X
Decentral Heat Pump with buffer tank			X
Borehole Thermal Storage			X
Cooling/heating integration			X

The simplified LCA study refers to a somewhat generic technological model for the MPC infrastructure, and there may be opportunities for more fine-grained refining of the environmental performance of the infrastructure in question, and of improving the technological relevance in future LCA studies. How to limit, optimise and assess the use of non-local computing power may be of particular research interest. For the LCA part in particular, state of the art background databases were employed, but questions surrounding system boundaries and data completeness that were pointed out by Andrae & Andersen (2010) still remain poignant, and further research is still needed in this field.

5. Conclusion

Data-driven and EPC generated efficiency tools can in general terms be labelled technology optimistic. They deviate from absolute energy saving in that they aim to increase technological complexity while simultaneously reducing energy consumption. Technology pessimists will typically be careful with applying such an approach. The pilots show how MPCs can provide society with improvements in grid distribution and greenhouse gas savings based on a comparatively small technological investment, and with a minimalist and careful approach it is thought that the demands of both groups can be met.

The simplified LCA study shows that there can be certain drawbacks to the model predictive control approach, that some precautions should be made, and that use cases should be carefully selected. As pointed out in the above, for the purpose of minimising side effects, the technology could primarily be installed where the existing (substituted) energy mix is considered to be of concern, i.e., detrimental to the environment. A secondary consideration is that the building-control system appears to be a more effective intervention in buildings or other on-site locations that consume more energy. A third consideration is that several environmental impact categories can be considered. A fourth consideration from the LCA study is that the MPC could be designed so that the local user can select an individual environmental profile. It should be noted that an unreasonably maximalistic design of the MPCs with regard to indirect energy use and infrastructure production can pose a potential risk of a net negative impact on the environment, and a parsimonious and careful approach is thus recommended, both in present and future implementations.

There are privacy arguments against the introduction of smarter private houses, connected to remote monitoring and remote control of heating. Public acceptance concerns can be alleviated if the technology is introduced in private homes with a possibility for opt-out. Larger buildings, for instance office or educational/municipal buildings, will likely not be associated with similar concerns, and will give more pronounced benefit and thus show shorter payback times.

A fundamental challenge addressed by the project is the current lack of interaction between energy production and energy use. The use cases can empower users to utilise cheaper electricity, and provide the societal benefit of better harmonisation of production and use of electricity. When there is a market design of power consumption, however, there might eventually be economic winners and losers of such an approach. The societal and environmental problem of power peaks and troughs introduced by variable power sources such as wind power can seemingly be alleviated by MPC systems. If carefully implemented, by mindfully taking into acount the observations of this report, both types of MPC systems can also improve the environmental performance of buildings, reduce user energy costs, and reduce greenhouse gas emissions in general.

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Appendix 1. Berlin pilot description

[Confidential]

Appendix 2. Kuchl pilot description

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1. The building

Research pilot in Kuchl (State Salzburg) is a university building built in 2003. It has a gross floor area of 4374m^2 and a gross volume of 18,182m^3. The construction type of the building is “medium weight”, meaning a combination of heavy (e.g. reinforced concrete) and light construction system (e.g. timber frame with insulation). The building has 4 floors and a basement. All floors and the basement are conditioned. The existing heating system in the pilot building is solely supplied by biomass district heating

2. Simplified model of the building

2.1 Model structure

Heat dynamics of the building is represented by a thermal resistance-capacitance network model (RC-model). This modelling technique has been deemed to be an appropriate approach for building energy simulation (De Rosa, Bianco, Scarpa, & Tagliafico, 2014) (Reynders, Diriken, & Saelens, 2014). The model is mathematically represented by a set of differential equations (Bacher & Madsen, 2010).

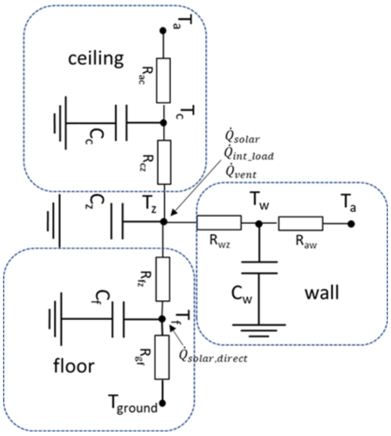

Figure 1 RC network model of a building

$$C_w \frac{dT_w}{dt} = \frac{1}{R_{aw}}(T_a - T_w) + \frac{1}{R_{wz}}(T_z - T_w)$$

$$C_c \frac{dT_c}{dt} = \frac{1}{R_{ac}}(T_a - T_c) + \frac{1}{R_{cz}}(T_z - T_c)$$

$$C_f \frac{dT_f}{dt} = \frac{1}{R_{gf}}(T_g - T_f) + \frac{1}{R_{fz}}(T_z - T_f) + 0.5 * \dot{q}_{solar,direct}$$

$$C_z \frac{dT_z}{dt} = \frac{1}{R_{cz}}(T_c - T_z) + \frac{1}{R_{wz}}(T_w - T_z) + \frac{1}{R_{fz}}(T_f - T_z) + \dot{q}_{heat} + \dot{q}_{solar,diffuse} + 0.5 * \dot{q}_{solar,direct} + \dot{q}_{vent} + \dot{q}_{int\_load}$$

It is assumed that 50% of the incoming direct solar radiation is absorbed by the floor, the remaining 50% is reflected to the indoor space.

Parameter	Description
R_{aw} [m^{2}K/W]	Thermal resistance between ambient air and external wall
R_{wz} [m^{2}K/W]	Thermal resistance between external wall and indoor air
R_{ac} [m^{2}K/W]	Thermal resistance between ambient air and roof
R_{cz} [m^{2}K/W]	Thermal resistance between roof and indoor air
R_{gf} [m^{2}K/W]	Thermal resistance between the ground and ground-contacting floor
R_{fz} [m^{2}K/W]	Thermal resistance between ground-contacting floor and indoor air
C_w [J/m^{2}K]	Thermal capacitance of external wall
C_c [J/m^{2}K]	Thermal capacitance of roof
C_f [J/m^{2}K]	Thermal capacitance of ground-contacting floor
C_z [J/m^{2}K]	Thermal capacitance of indoor air
T_a [°C]	Ambient temperature
T_w [°C]	Temperature of external wall
T_c [°C]	Temperature of roof
T_f [°C]	Temperature of ground-contacting floor
T_g [°C]	Ground temperature
T_z [°C]	Indoor temperature
$\dot{q}_{heat}$ [W]	Heat from heater
$\dot{q}_{solar,direct}$ [W]	Heat from direct solar radiation
$\dot{q}_{solar,diffuse}$ [W]	Heat from diffuse solar radiation
$\dot{q}_{vent}$ [W]	Heat from forced/free ventilation
$\dot{q}_{int\_load}$ [W]	Heat from internal loads

Table 1 Model parameters and variables

2.2 Input data

2.2.1 Building-related data

Instead of obtaining model parameters from construction drawings or parameter estimation from measurement data, the model parameters were obtained from an EPC XML file, a data transfer file generated during EPC issuance process.

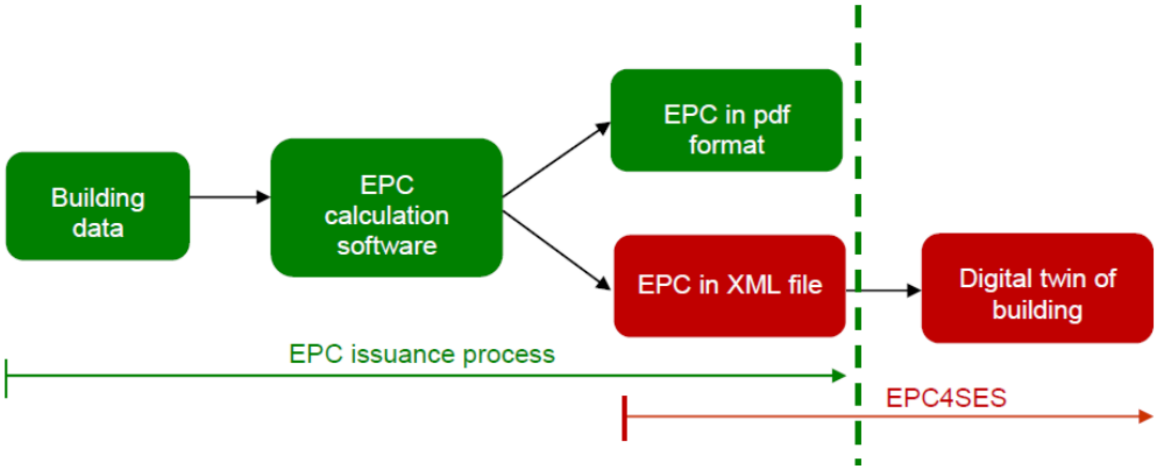

Figure 2 EPC issuance process

```
<bauteile>
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    <bezeichnung>Außenwand Stahlbeton mit WDVS</bezeichnung>
    <flaeche einheit="m2">737.88</flaeche>
    <uwert einheit="W/m2K">0.26</uwert>
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    <waermekapazitaet einheit="J/m2K">163545</waermekapazitaet>
    <temperaturkorrekturfaktor>1</temperaturkorrekturfaktor>
    <neigungswinkel einheit="°">90</neigungswinkel>
  </bauteil>
```
Figure 3 Example of EPC XML file

The XML files contains data of the building which can be used as or translated to model parameters

	Parameters required for modelling	Available in EPC XML (ZEUS) file?
Geographic data	-Latitude and longitude	-location*
Occupancy data	-Hourly internal loads	-type of buildings*
Geometric data	- conditioned volume	yes
Building component properties	-Area of external wall, roof, ground floor and window	yes
	-thermal resistance (R-value)	yes, can be calculated from aggregated U-value
	-thermal capacitance (C-value)	no
	-inclination angle	yes
	-solar heat gain coefficient (g-value)	yes
	-orientation of window	no

Table 2 Data related to building energy modelling in XML file

Items marked with * means the data cannot be used directly as model parameters. The XML file only contains qualitative data of the location (e.g. "Kuchl") and the category of the building (e.g. "educational building"). These two pieces of information have to be translated to quantitative information so that they can be used as model parameters and inputs. The location was translated to latitude and longitude by using Google Map. The building type was translated to internal loads according to Austrian Standards. The internal load schedule was slightly adjusted based on the author's knowledge of the building usage.

Opaque building components mostly include multiple layers and materials. However, the XML file only provides a single aggregated U-value for a multi-layer component. The U-value can be used to calculate the R-value by the below equation:

$$U = \frac{1}{R_{si} + R_{wall} + R_{se}}$$

R_{si} : thermal resistance of internal surface
R_{se} : thermal resistance of external surface
R_{wall}: thermal resistance of wall/opaque component

The value of R_{si} and R_{se} are obtained from Austrian Standards (Kunze, et al., 2008).

C-values of opaque building components and orientation of windows are not available in the XML file, although they are the required input data for EPC calculation. There are two ways to obtain the aggregated C-values of opaque building components:
manual calculation based on the information in the EPC pdf file of the considered building. The pdf file contains details of material layers, layer thickness and thermal conductivity but no information of specific heat and density. Specific heat and density of the materials have to be acquired from other databases for building materials. For the Kuchl pilot, information from "baubook" (baubook GmbH, kein Datum) was used.
approximation by using the data of gross volume and construction type from XML file, and the corresponding factors (f_{BW}) provided by Austria Standards (Kunze, et al., 2008) :

$$C = f_{BW} * V$$

V: gross volume of building [m^3]

f_{BW} [Wh/m^{3}K]	Construction type
10	Light weight
20	Medium weight
30	Heavy weight

Table 3 Factors for approximation of thermal capacitance

The C value is then divided by the sum of areas of opaque building components in order to obtain a C value per area.

Orientation of windows can be obtained directly from the information in the EPC pdf file of the considered building.

2.2.2 Other input data

Weather forecast of hourly ambient temperature, direct and diffuse solar radiation were acquired from weather service provider.
Ground temperature is assumed to be constant at 10°C.
Infiltration rate is assumed to be 0.4h^{-1} .
Internal load is assumed to be 300W/room according to Austrian Standards B 8110-3 (Austrian Standards International, 2020). The most popular occupancy hour is assumed to span between 10 a.m. and 8 p.m during weekdays. From 8 a.m. to 10 a.m. and from 8 p.m. to 10 p.m. the occupancy is assumed to be halved.

2.3 Validation of the simplified model

Since the solar radiation measured by the on-site weather station contained global radiation only (not divided into direct and diffuse radiation), simulations using real-time measured weather could not be implemented. Simulations by the simplified model and meter readings are not comparable.
The simplified model was therefore validated by comparing its calculated space heating demand with that obtained from the detailed model (benchmark model) created in commercial building simulation software IDA ICE.
In order to identify the most suitable parameter set, the simplified RC model was parameterized by four different sets of parameters. The differences between the four parameter sets lie in the R and C values.

Parameter set (“Para”)	R_w	C_w, C_f, C_c
1	Equivalent thermal resistance (assume resistance of all external walls are connected in parallel)	According to Austrian Standards
2	Equivalent thermal resistance (assume resistance of all external walls are connected in parallel)	According to detailed data of building components
3	Average thermal resistance	According to Austrian Standards
4	Average thermal resistance	According to detailed data of building components

Table 4 Four parameter sets for simplified model

The simulation was run for a 5-day period from 14-Feb to 18-Feb. Weather data, internal loads and indoor setpoint temperature (22°C) remained the same in all four cases.

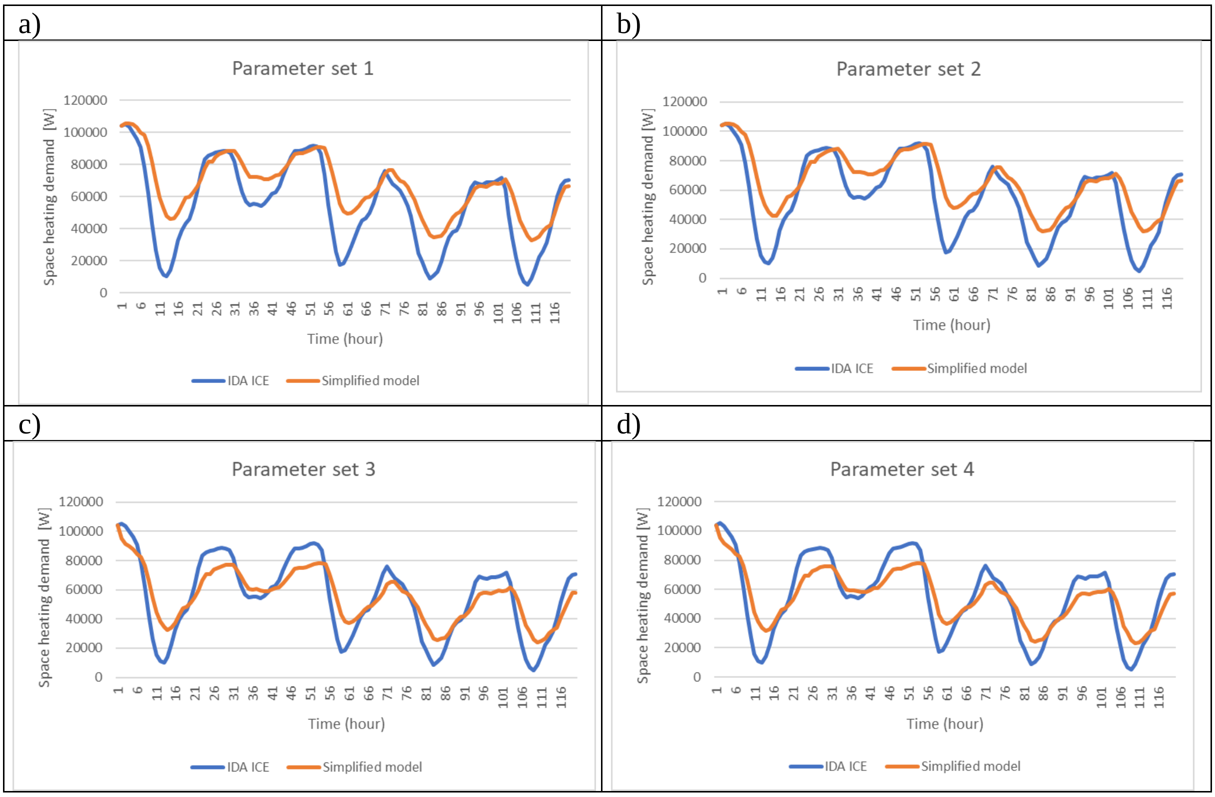

Figure 4 a)-d) Comparison of hourly demand profile of space heating between simulation with simplified model and simulation with benchmark (IDA ICE) model

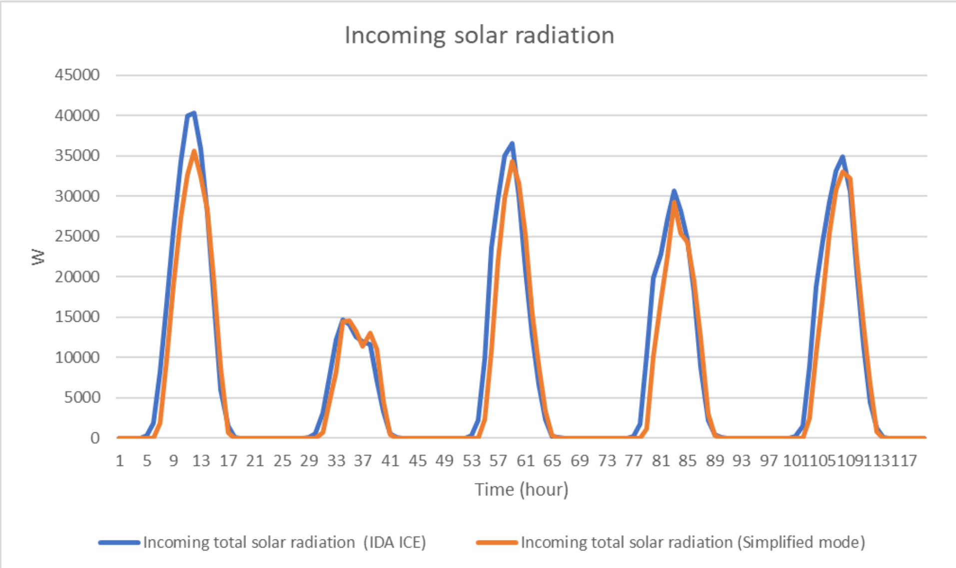

Figure 5 Comparison of solar radiation entering indoor between simulation with simplified model and simulation of benchmark model

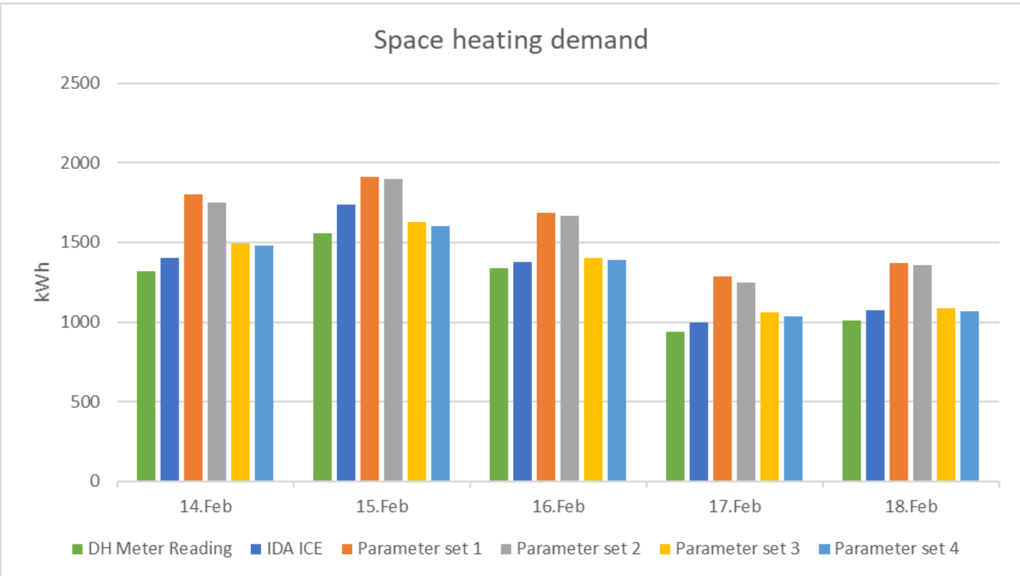

Figure 6 Comparison of daily demand for space heating

Figure 4a) and b) shows that simplified model Para 1 and Para 2 overestimated space heating demand most of the time throughout the 5-day period, while figure 4c) and d) shows that simplified model Para 3 and Para 4 overestimated the demand during the daytime and underestimated it at night time.

In addition to parameters, underestimation of incident solar radiation entering the building (figure 5) accounts for overestimation of space heating demand during the daytime in all 4 cases.

Figure 6 shows that simplified model Para 3 and Para 4 had closer estimates (+1.28% and +0.2% respectively) to that of the benchmark model in terms of daily demand for space heating. Difference between model Para 3 and Para 4 was minor. Since the data sources of parameter set 3 are EPC XML file and Austrian Standards, which fits better the purpose of the project, it was selected as the prediction model of model predictive controller.

DH Meter Reading in Figure 6 is the meter reading of district heating use of the campus building during the same period. In addition to the model accuracy, difference between the simulation results and the actual energy use are caused by the accuracy of forecast weather data (figure 7) and internal loads.

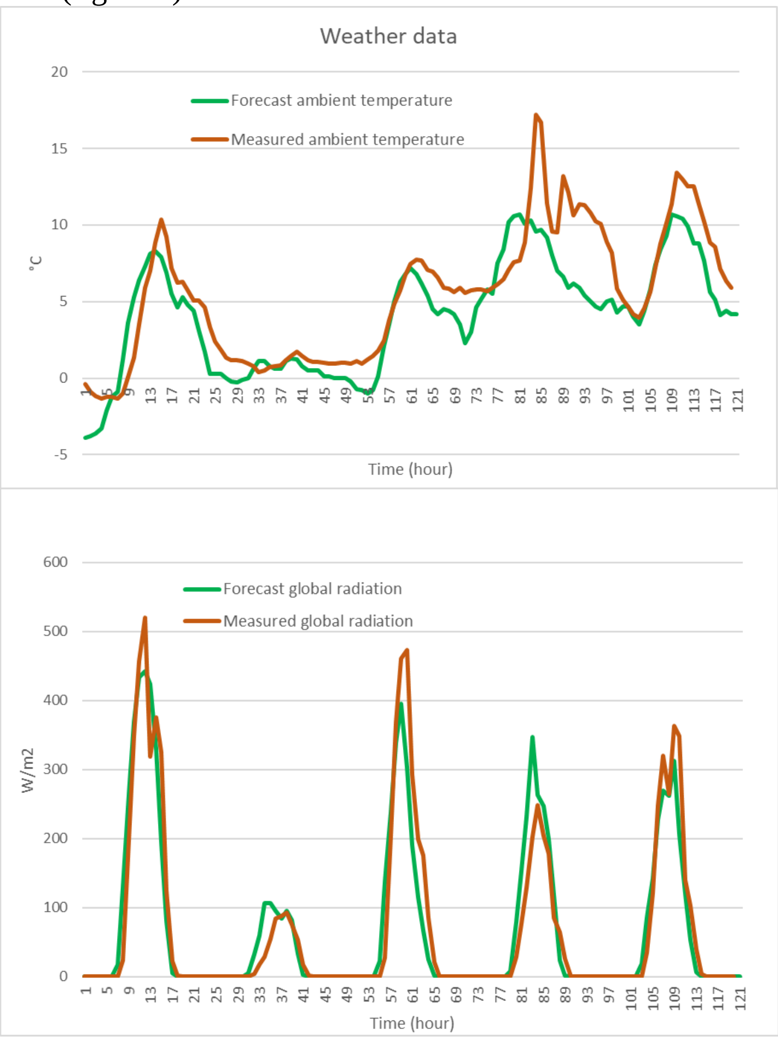

Figure 7 Comparison of forecasted and measured weather

3. Optimisation through demand response and supply scheduling

The existing heating system in the pilot building is solely supplied by biomass district heating. The optimisation potential under the current setting is very little due to

i) CO_2 emission intensity of biomass is already low.
ii) CO_2 emission intensity of energy consumption remains nearly constant over time because there is only a single energy source. Optimisation not only depends on control algorithms but also objects that can be manipulated.

In order to demonstrate the influence of MPC optimisation, a simulation study in which a 1000L solar-assisted thermal storage tank is integrated into the system was carried out. The goal of MPC optimisation is to utilize solar energy and low CO_2 energy from grid.

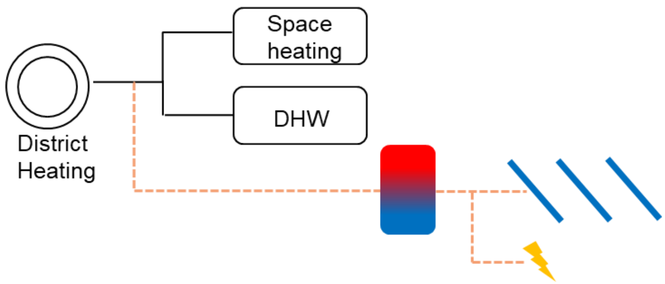

Figure 8 System setup for optimisation study

3.1 Other input data for optimisation

In addition to the input data mentioned in 2.2, the following data are needed for optimisation purpose.
Real-time data of CO_2 intensity of electricity on an arbitrary day were extracted from Electricity Maps for testing purpose (The leading resource for 24/7 electricity CO2 data, 2022). The data were used as a forecasted CO_2 signal (i.e. perfect forecast was assumed). It was assumed that this 24-hour CO2 signal repeats everyday within the simulation period.
Past PV production data was used as an ideal PV production forecast to reduce the complexity of the study.

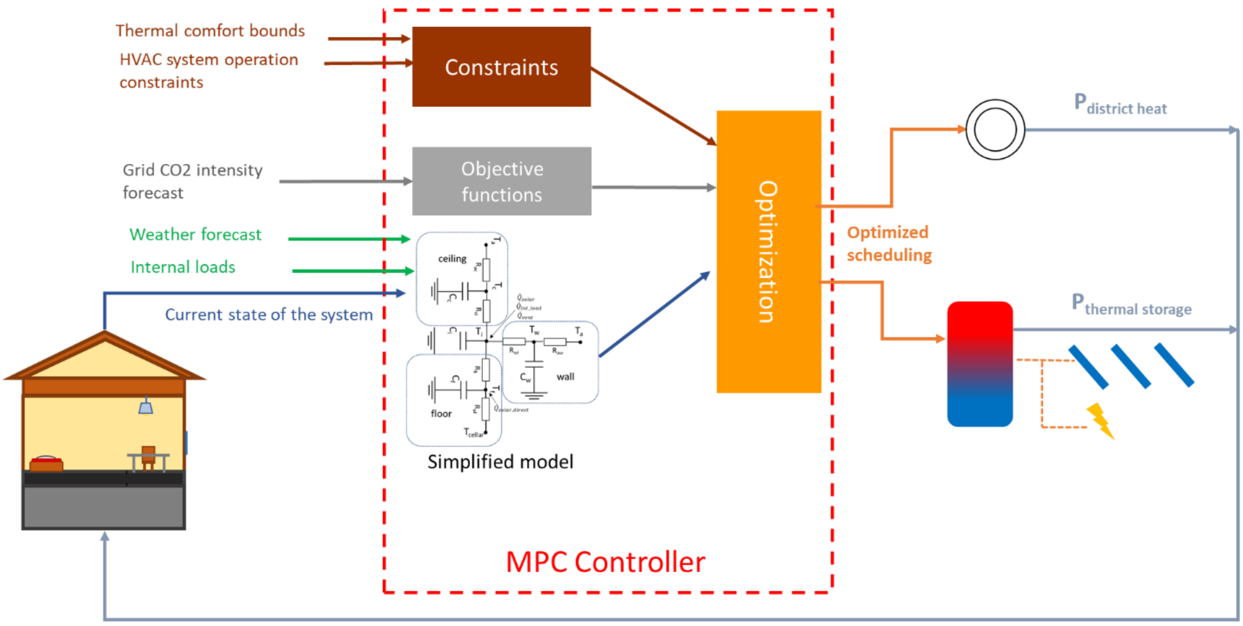

Figure 9 MPC for building heating system

3.2 Objective function

Two groups of objective functions were formulated in this study. One group handles demand response and the other group handles operational scheduling of energy supply units in the building.
The objective function for demand response decides the optimal value for input heating power and the zone setpoint temperature at time t considering the CO_2 intensity at time t and the reference temperature (user's preferred temperature, 22°C).

$$\min \sum_{t=1}^{24} c(t) * u(t) + \sum_{t=1}^{24} (T_z(t) - T_{ref})^2 + \sum_{t=1}^{24} e^2$$

where
c: CO_2 intensity in grid

u(t): input power to zone
T_{ref}: reference room temperature (22°C)
e: slack variable

The objective function for operational scheduling decides the optimal schedule of taking electricity from the grid for the heat pump according to the CO_2 intensity within the prediction horizon.

$$\min \sum_{t=1}^{24} c(t) * P\_grid(t) + \sum_{t=1}^{24} c\_DH(t) * P\_DH(t)$$

where
P_grid: power from grid
P_DH: power from biomass district heating
c_DH: CO_2 intensity of biomass district heating (supposed to be constant all the time)

3.3 Constraints

Constraints are occupant thermal comfort and operational limits. The optimized setpoint temperatures should be within ±1.5°C from the reference temperature. To increase the optimisation feasibility, a slack variable is added to the temperature constraint and it is penalised in the objective function shown in 3.2. The operational constraints are the capacity of energy storage, maximum and minimum power output of heating system installations and the energy balance within the system boundary.

3.4 Results

The impact of MPC was evaluated by 2 cases:

Case baseline: biomass district heating is the only energy source; indoor temperature is maintained at 22°C

Case CO_2-optimising MPC: in addition to biomass district heating, a thermal energy storage connected to PV and electric grid also supplies heating to the building; CO2 emission forecasts is considered in the control algorithm; Indoor temperature is allowed to vary between ±1.5°C.

Simulation for a 5-day period was conducted. Heating load with and without application of MPC (keeping temperature at 22°C) were compared. After MPC intervention the heating load was reduced by 6.02% (Figure 10). Lower indoor set point temperature accounts for the reduced energy use. Within the 120-hour period, the indoor temperature oscillated between 22°C and 23.5°C for 25% of the time, and between 20.5°C and 22°C for 75% of the time (Figure 11).

Not only the heating load was reduced, but also the CO_2 intensity of energy use was kept below 230g/kWh throughout the considered period (Figure 12).

In figure 13 it is shown that electricity was consumed and the power-to-heat element operated at full load to charge the thermal storage tank during times of lower CO_2 intensities. The plant did not take electricity from grid when the intensity was over 233g CO_2/kWh.

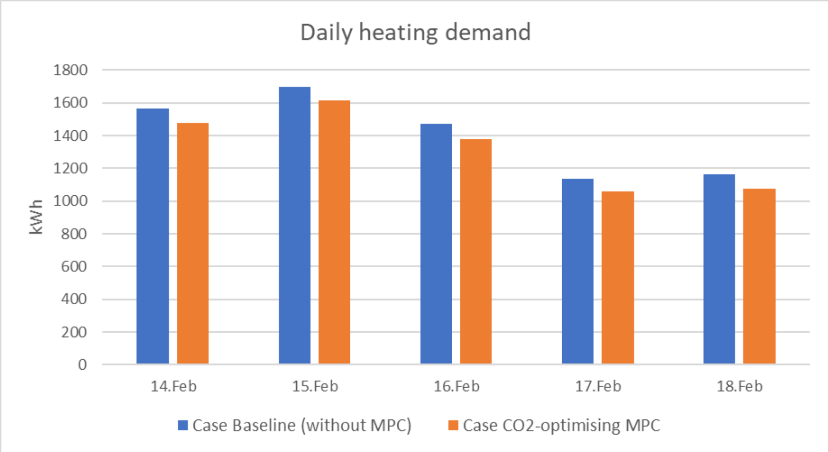

Figure 10 Daily heating demand for both cases

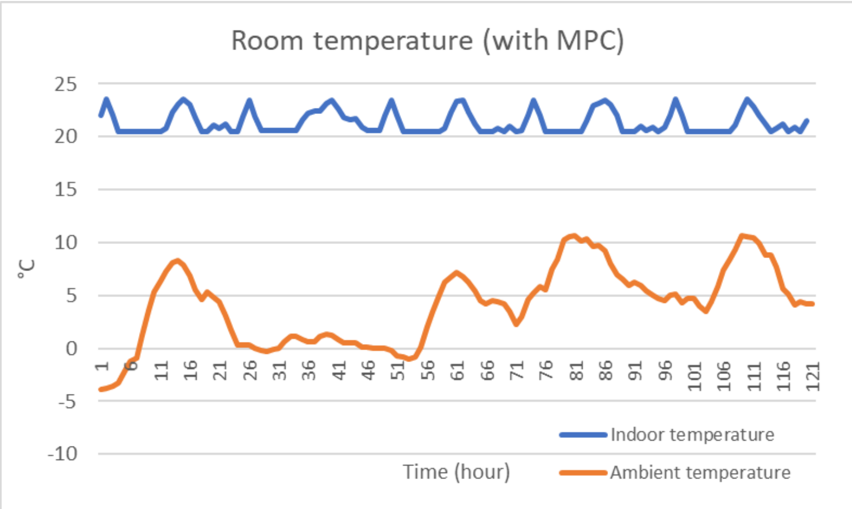

Figure 11 Varying indoor temperature in Case CO2-optimising MPC

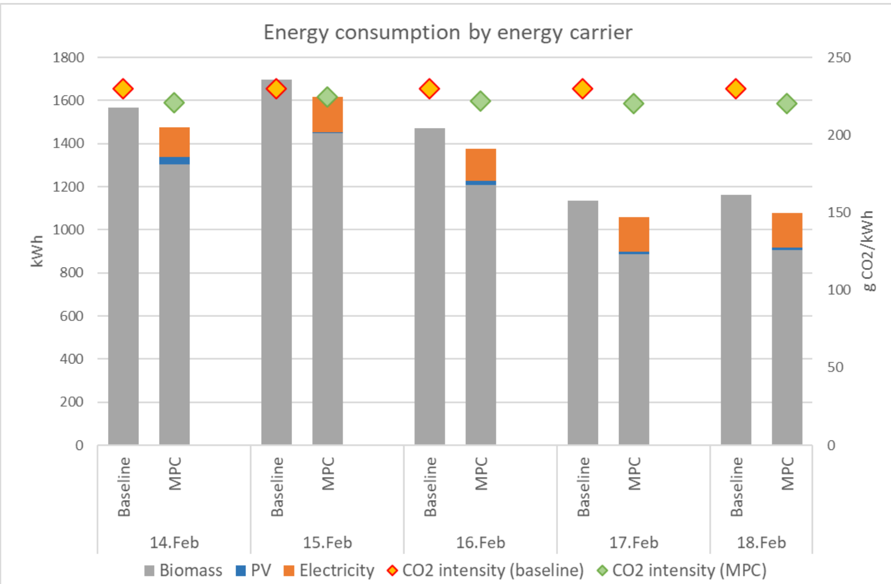

Figure 12 Energy consumption by carrier

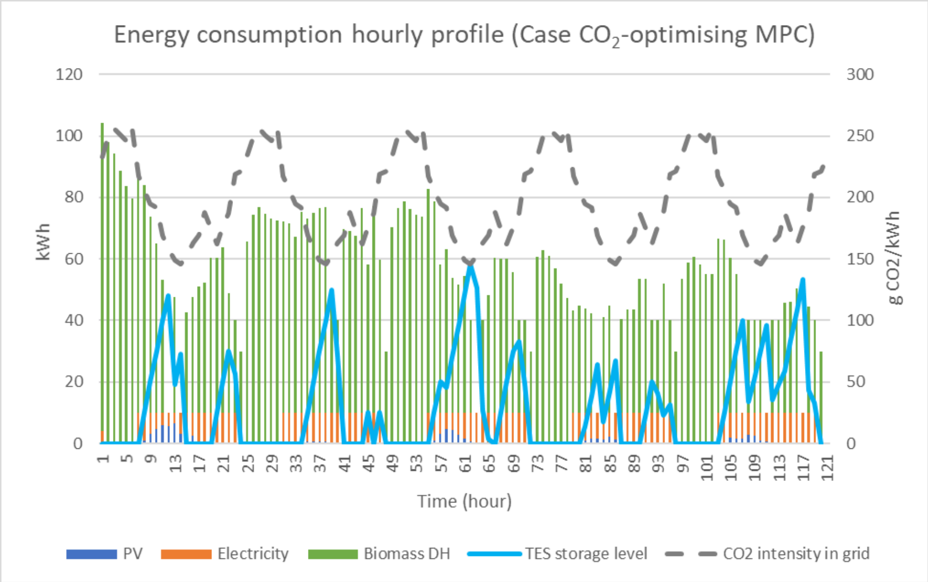

Figure 13 Energy consumption hourly profile in Case CO2-optimising MPC

*In this study, CO_2 intensity was calculated based on the data provided by Electricity Maps (The leading resource for 24/7 electricity CO2 data, 2022). CO_2 intensity of biomass is 230g CO_2 / kWh.

4. References

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Appendix 3. Stockerau pilot description

Author: Shuk King Stephanie Chan, Georg Brunauer/ Salzburg University of Applied Sciences

1. The building and microgrid

Research pilot in Stockerau (State Lower Austria, near Vienna) consists of two parts:

i) a single family house built in 1950 and renovated in 2014. It has a gross floor area of 202m^2 and a gross volume of 609m^3. The construction type of the building is "medium weight", meaning a combination of heavy (e.g. reinforced concrete, brick) and light construction system (e.g. timber frame with insulation). The building has 2 floors and a basement. All floors and the basement are conditioned. The house is classified as low energy house with annual heating demand of 75.75 kWh/m^2 under reference climate. A PV system without battery storage is installed on site.

ii) a microgrid comprised of 20 residential buildings

Three experiments were demonstrated: i) short-term operational optimisation for home energy system, ii) energy design and planning for home energy system and iii) microgrid sector coupling and decarbonisation in long-term timescale

2. Optimisation through demand response and supply scheduling for single family house

A simulation study demonstrating MPC application in home energy system utilising PV, heat pump, battery storage and electric vehicle charging was carried out. The model of the house shares the same model structure as the Kuchl pilot, therefore the details of modelling will not be described again here. Only the part of optimisation for home energy system will be presented in this section.
The goal of MPC optimisation is to utilize solar energy and low CO_2 energy from grid to fulfil household energy demand (thermal and electrical).

2.1 Other input data for optimisation

In addition to the model parameters mentioned in the document of Kuchl Pilot, the following data are needed for optimisation purpose.
Real-time data of CO_2 intensity of electricity on an arbitrary day were extracted from Electricity Maps for testing purpose (The leading resource for 24/7 electricity CO2 data, 2022). The data were used as a forecasted CO_2 signal (i.e. perfect forecast was assumed). It was assumed that this 24-hour CO_2 signal repeats everyday within the simulation period.
Past PV production data was used as an ideal PV production forecast to reduce the complexity of the study.

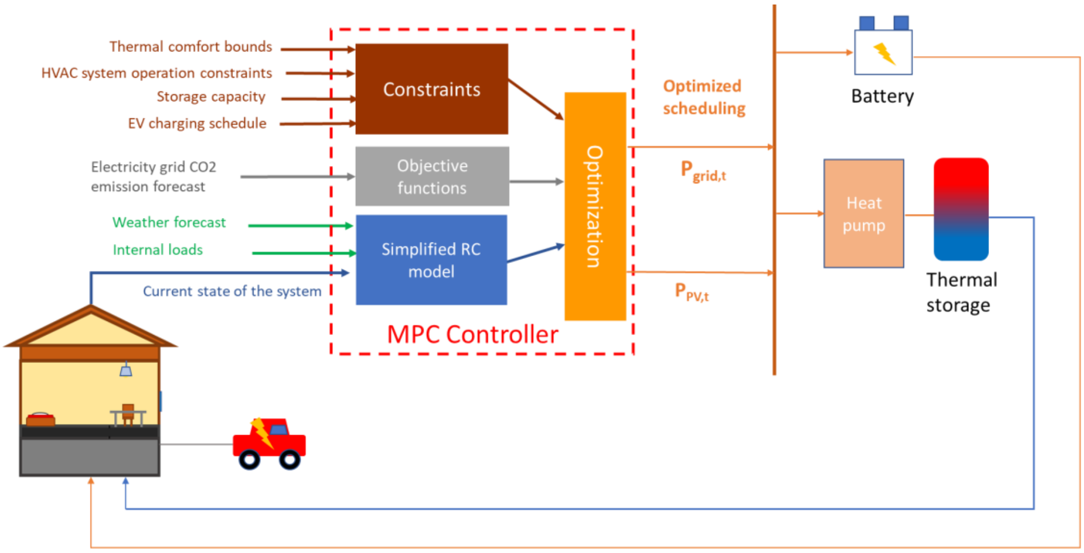

Figure 14 MPC for home energy system

2.2 Objective function

Two groups of objective functions were formulated in this study. One group handles demand response and the other group handles operational scheduling of energy supply units in the building.

The objective function for demand response decides the optimal value for input heating power and the zone setpoint temperature at time t considering the CO_2 intensity at time t and the reference temperature (user's preferred temperature, 22°C). A slack variable is included in the objective function to ensure the feasibility of the MPC controller by allowing the optimal range of indoor temperature being violated.

$$\min \sum_{t=1}^{24} c(t) * u(t) + \sum_{t=1}^{24} (T_z(t) - T_{ref})^2 + \sum_{t=1}^{24} e^2$$

Where

c: CO_2 intensity in grid
u(t): input power to zone
T_{ref}: reference room temperature (22°C)
e: slack variable

The objective function for operational scheduling decides the optimal schedule of taking electricity from the grid for the heat pump according to the CO_2 intensity within the prediction horizon.

$$\min \sum_{t=1}^{24} c(t) * P\_grid(t)$$

where
P_grid: power from grid

2.3 Constraints

Constraints are occupant thermal comfort and operational limits. The optimized setpoint temperatures should be within ±1.5°C from the reference temperature. To increase the optimisation feasibility, a slack variable is added to the temperature constraint and it is penalised in the objective function shown in 2.2. The operational constraints are the capacity of energy storage, maximum and minimum power output of appliances and the energy balance within the system boundary.

2.4 Results

The impact of MPC was evaluated based on comparison with case baseline.
Case baseline: Indoor temperature is maintained at 22°C. Thermal storage temperature is maintained at 60°C. Heat pump utilises solar energy and electricity from grid. Battery storage is not available.
Case CO_2-optimising MPC: PV and electric grid are connected to heat pump and battery; emission forecasts is considered in the control algorithm; Indoor temperature is allowed to vary between ±1.5°C.
Simulation for a 5-day period was conducted. Heating load with and without application of MPC (maintaining indoor temperature at 22°C) were compared. After MPC intervention the heating load was reduced by 12.1% (Figure 2). Lower indoor set point temperature accounts for the reduced energy use. Within the 5-day period, the indoor temperature oscillated between 22°C and 23.56°C for 30.8% of the time, and between 20.44°C and 22°C for 69.2% of the time (Figure 3).
Not only the heating load was reduced, but also the CO_2 intensity* of energy use was lowered by 20.7% at a minimum and 44.7% at a maximum (Figure 4). Share of solar energy in energy use was increased by 5 times due to energy storage and energy scheduling. The degree of reduction in CO_2 intensity of energy use was influenced by the amount of energy consumption and the share of solar energy in the consumption. Higher energy consumption did not necessarily lead to increased CO_2 intensity of energy use.
In figure 5 it is shown that **the energy storage was charged up during times of low CO_2 intensities and discharged during the times of high CO_2 intensities, proving that the MPC controller performed the intended goal**. Up to the end of the 5-day period, total energy consumption was increased by 4.9% compared with case baseline, which was due to higher storage level (temperature) in thermal energy storage (Figure 5).

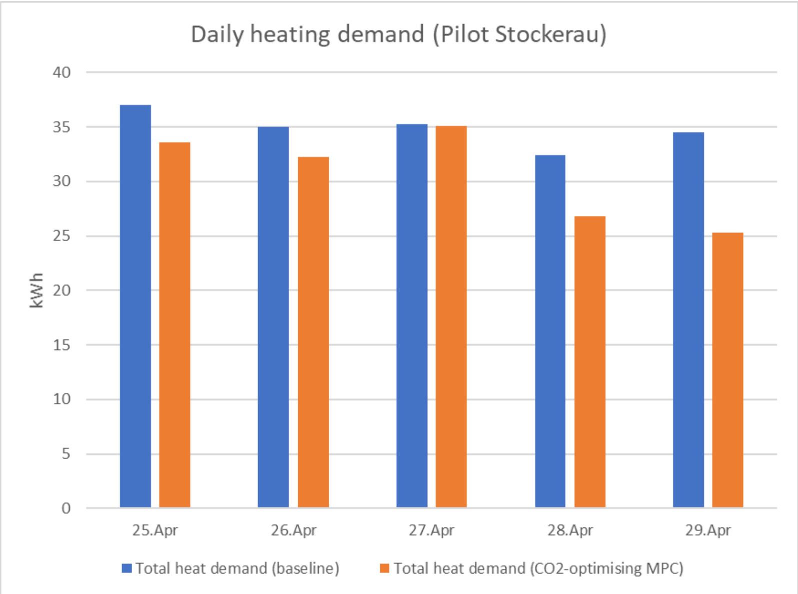

Figure 15 Daily heating demand for both cases

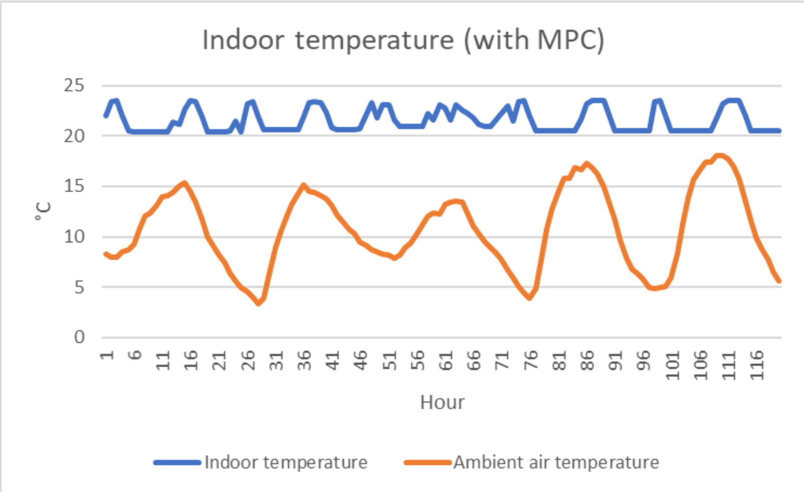

Figure 16 Varying indoor temperature in Case CO2-optimising MPC

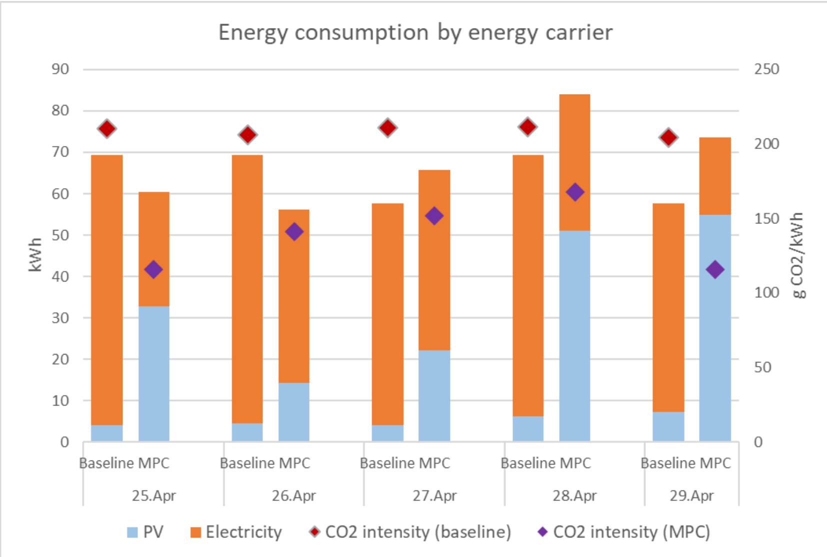

Figure 17 Energy consumption by carrier in both cases

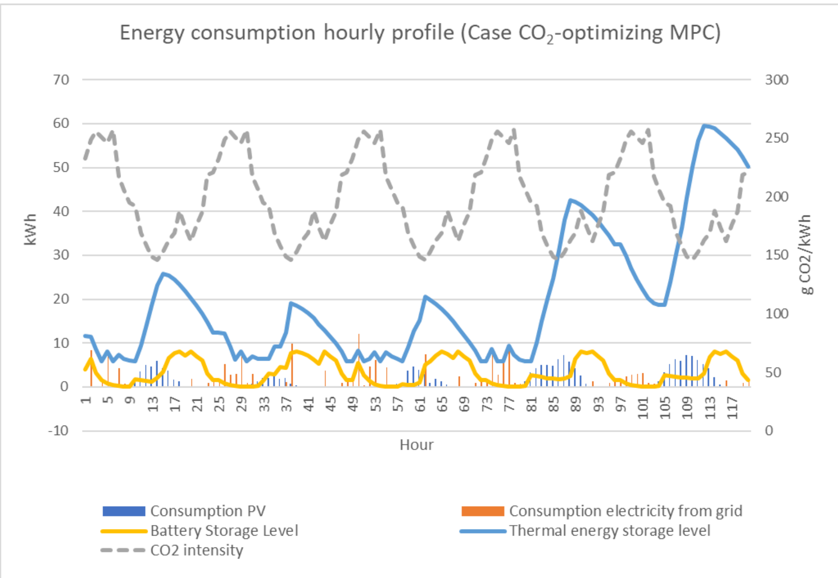

Figure 18 Energy consumption hourly profile (Case CO2 optimising-MPC)

*In this study, CO2 intensity was calculated based on the data provided by Electricity Maps (The leading resource for 24/7 electricity CO2 data, 2022).

2. Decarbonisation of building energy system

A simulation study on energy design targeting low-CO_2 emission and energy independence was carried out. Two scenarios were set up in the study:
Base case: Electrical energy and heating energy is supplied by power grid and gas respectively.
Best case: Electrical energy is supplied by a PV plant of 10kWp and power grid. A battery of 19.3 kWh storage capacity is included. Heating energy is supplied through a 13 kW heat pump.

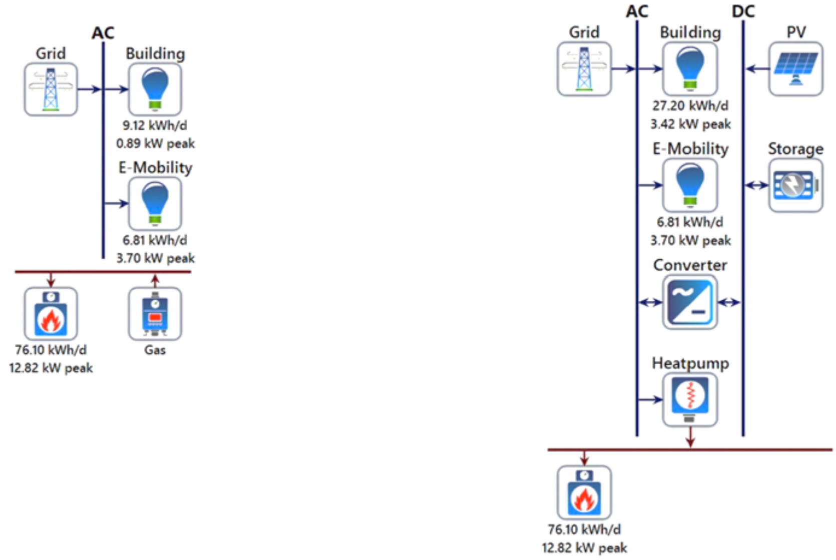

Figure 19 System configuration in HOMER ® PRO (left: base case; right: best base)

Load profiles were estimated based on the annual energy consumption data provided in EPC. Simulation for 1-year period was carried out for both cases. Annual energy consumption by source and its associated CO_2 emission were calculated and compared. In best case, the CO_2 emission was reduced by 98% (from 8073 kg/annum to 190 kg/annum) compared with base case, and reached 96% of energy self-sufficiency thanks to PV plant and battery storage.

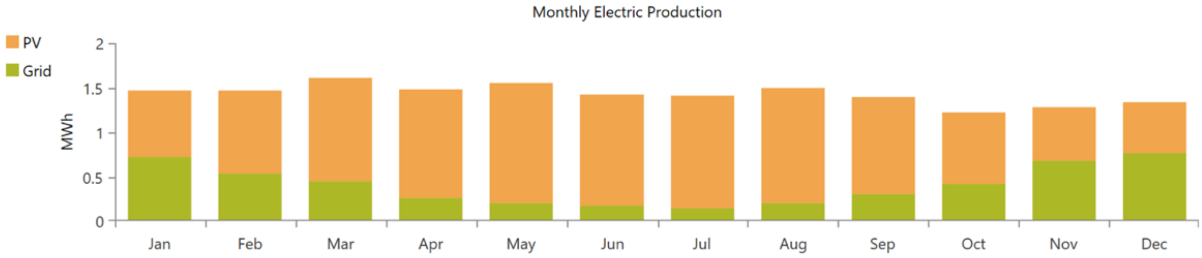

Figure 20 Electricity supply by source

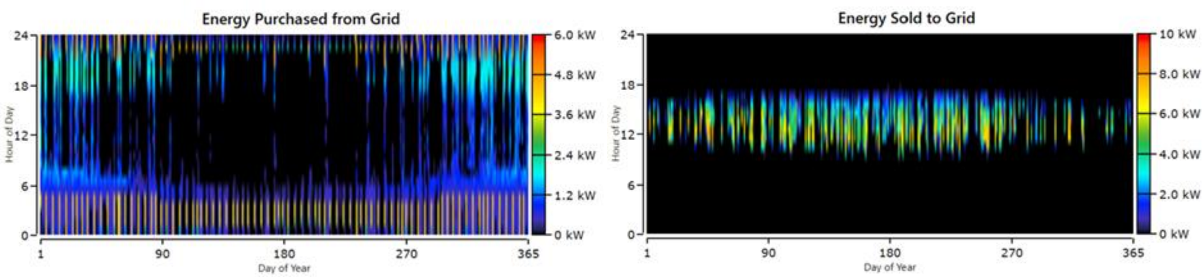

Figure 21 Electricity purchased from and sold to grid

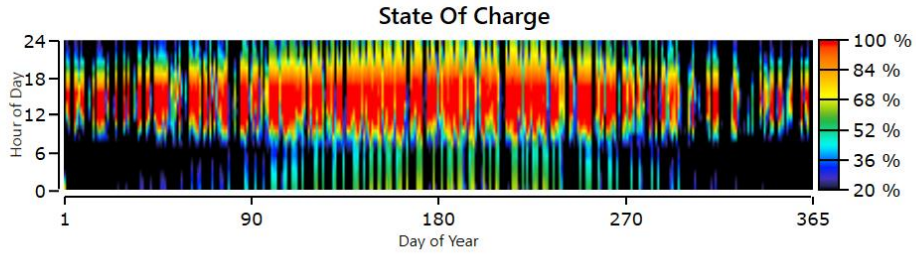

Figure 22 State of charge of battery

3. Microgrid sector coupling and decarbonisation

A microgrid simulation for a residential quarter consisted of 20 buildings was conducted to demonstrate the potential of using EPC data for energy transition planning. Load profiles were estimated based on EPC data of the buildings. Three different system combinations involving heat pump, electric grid, PV, battery and hydrogen plant were investigated.

- Case Baseline — ONLY Network related power consumption
- Case Study 1 — Network power consumption + PV
- Case Study 2 — Network power consumption + PV + Battery
- Case Study 3 — Network power consumption + PV + Battery + Hydrogen

Plot No.	Building Typology	Plot Size [m²]	Residential Units	Plot No.	Building Typology	Plot Size [m²]	Residential Units
01	SFH	800	1	11	MFD	812	4
02	SFH	800	1	12	MFD	756	4
03	SFH	706	1	13	MFD	756	4
04	SFH	784	1	14	MFD	770	4
05	MFD	968	4	15	MFD	896	5
06	SFH	740	1	16	MFD	906	5
07	SFH	900	1	17	MFD	914	5
08	SFH	750	1	18	MFD	981	5
09	SFH	750	1	19	*under develop*	105	-
10	MFD	903	4	20	SFH	900	1

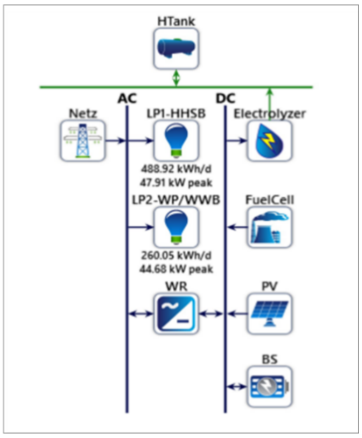

Figure 23 Simulation setting in HOMER ® PRO

*SFH = single family house, MFD = multi-family dwelling

		Baseline	Case 1	Case 2	Case 3
ECONOMIC EFFICIENCY					
Net Present Cost	[€]	3.641.000	2.158.000	1.831.000	3.254.000
Additional Costs	[€]	-	337.800	637.000	2.330.000
Cost of Energy	[€/kWh]	0,50	0,16	0,15	0,44
Simple Payback	[a]	-	4,9	6,4	24,4
ENERGY DATA					
Electrical power consumption	[kWh/a]	273.372	273.372	273.372	273.372
Network related power consumption	[kWh/a]	273.372	160.958	91.658	34.524
Supplied energy	[kWh/a]	-	247.952	172.355	1.532
Peak load	[kW]	78	78	78	58
PV production Gesamt	[kWh/a]	-	383.295	383.295	383.295
Self-consumption PV plant	[kWh/a]	-	135.343	210.940	381.772
Self-consumption rate PV plant	[%]	-	35	55	99,6
Degree of self-sufficiency (conventionel)	[%]	-	50	77	140
Degree of self-sufficiency (hourly)	[%]	-	33	66	80
Hours of autarchic operation	[h]	-	2.874	5.805	6.983
Isolated operation	[h];[d]	-	-	12 h	47 d
EMISSION DATA					
CO2 annual	[t/a]	62,1	36,5	20,8	7,8
CO2 project duration (25 years)	[t]	1551,4	913,4	520,2	195,9
Annual CO2 per unit (SFH)	**[t/WEa]**	**1,85**	**1,09**	**0,62**	**0,23**
Annual CO2 per unit (MFD)	**[t/WEa]**	**1,03**	**0,61**	**0,35**	**0,13**
CO2 per unit (SFH) – over project duration	**[t/WE]**	**46,21**	**27,21**	**15,50**	**5,84**
CO2 per unit – over project duration	**[t/WE]**	**25,81**	**15,19**	**8,65**	**3,26**
DATA (H2 –Energy system)					
Output battery storage	[kWh/a]			69.433	69.433
Input electrolyser	[kWh/a]	-	-	-	198.168
Output fuel cell	[kWh/a]	-	-	-	67.914
Max. tank level	[kg]	-	-	-	2.842

Compared with case baseline (without on-site renewable energy generation and storage system), in a 25-year period CO_2 saving per annum attained by different variants ranged from 40.8% to 87.6%.

The degree of savings in CO_2 emissions is correlated with the variety of renewable energy source. The case that achieves the maximum CO_2 saving and highest self-sufficiency has the longest payback period and the least reduction in energy cost, since capital costs increase with system complexity.

Appendix 4. Rota pilot description

[Confidential]