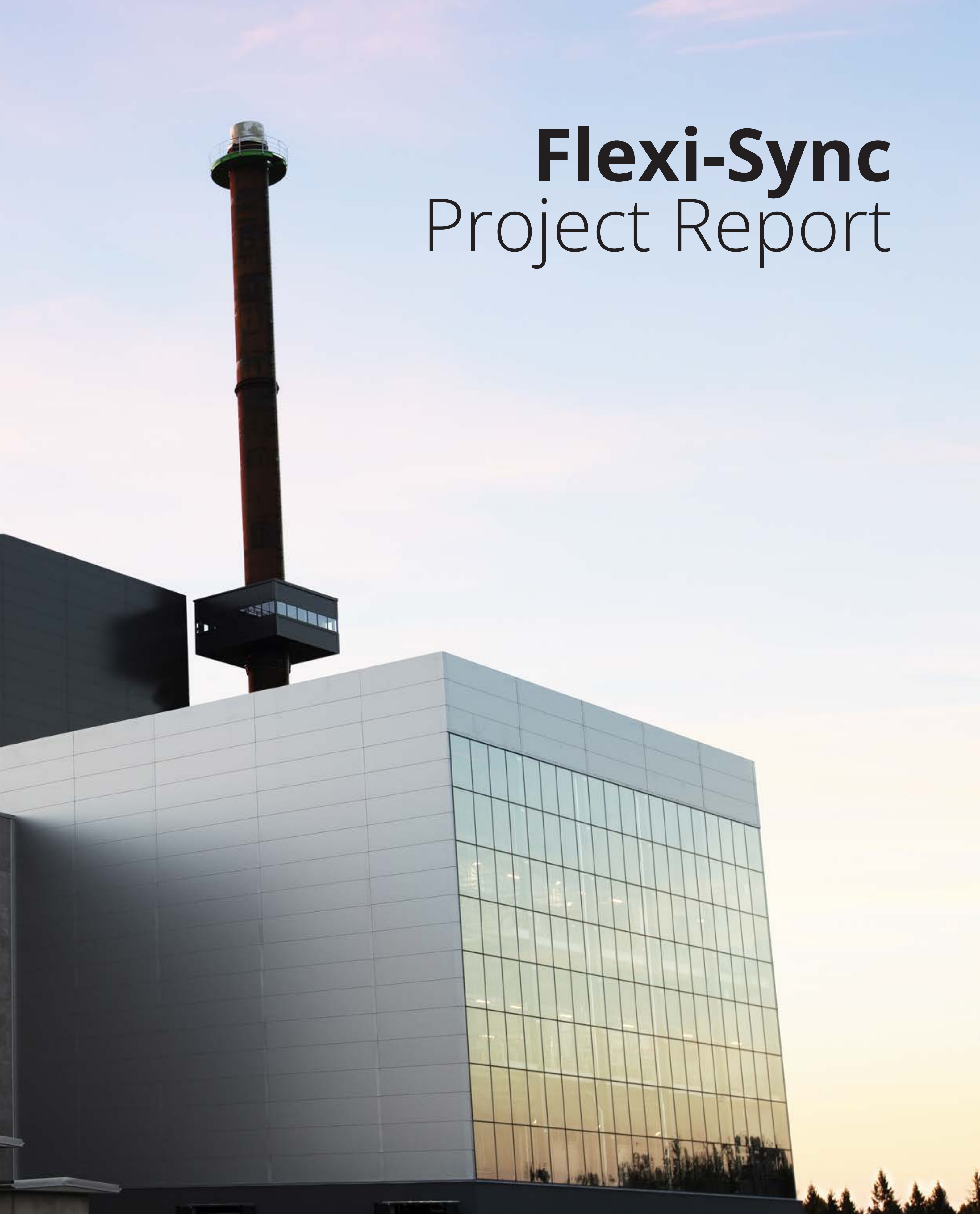

Flexi-Sync
Project Report

Flexi-Sync

Flexible energy system integration using concept development, demonstration and replication

Content

Website
www.flexisync.eu

This project has received funding in the framework of the joint programming initiative ERA-Net Smart Energy Systems' focus initiative Integrated, Regional Energy Systems, with support from the European Union's Horizon 2020 research and innovation programme under grant agreement No 775970.

Summary

The Flexi-Sync project has gathered academics and industry representatives with a shared vision to increase and optimise the use of both demand and supply side flexibility in district heating and cooling systems – an invaluable asset to attain energy system decarbonisation. The types of flexibility considered in the project are: i) combined heat and power plants, heat pumps, the district heating network, and centralized thermal energy storages on the supply side, and ii) individual heat pumps and thermal inertia of buildings serving as a storage on the demand side.

As there are few examples of optimisation with mutual benefits for district heating companies and their customers, the results from the demo sites participating in the project provide valuable insights into the system value of utilizing flexibility. Optimising the control of building flexibility together with the energy system adds great value compared to when optimisation is performed by each individual actor (energy company and building owner) within their system boundary. The technology for doing this is now available, and the project partners in the Flexi-Sync consortium together have all the know-how to enable the process for energy companies that want to realise the potential of flexibility.

The partners within Flexi-Sync have shown that the models and theories developed are actually viable in practice and have been used to set the actual limitations for the operational control of flexibility. There have also been advances in much more detailed models of flexibility than what can be used in the day-to-day optimisation software developed in the project. These models have proven to be very valuable for validating the more streamlined optimisation models.

Within the project, the partners have shown how the flexibility should be operated in the coming hours and days and how it could be deployed cost-efficiently in the energy systems in the coming decades. With energy system modelling, e.g., using TIMES, one can have a much longer time perspective than in day-to-day optimisation. It enables studies on long-term effects of flexibility technologies on the design of energy systems. In addition, the project has shown how climate resilience and the impact of climate change on energy systems could be taken into consideration by developing future climate data sets for regions.

To realise the potential of the day-to-day flexibility optimisation solutions developed in the project, there is a need for new business models and to ensure that end-users have good thermal comfort and accept the new services. These are aspects that also have been covered by the project: the output is valuable for energy companies to make good use of flexibility. Flexi-Sync also covers techno-economic aspects of district energy flexibility, such as the effects on network asset maintenance and durability - key for optimising flexibility utilization without negative impacts on the heating and cooling grids.

The project has disseminated some of the main results through project reports and peer-reviewed publications, online webinars, contributions to the IEA DHC Annex TS3 Hybrid Networks as well as the participation in industry networks and events such as the Celsius Initiative and the Euroheat and Power Congress 2021 and Euroheat and Power Conference 2022.

For energy companies to get started with demand flexibility together with their heating and cooling customers, the steps would be to: 1) build a viable business case based on their specific characteristics and flexibility potential; 2) create a win-win business model that can benefit both energy company and customer; 3) engage customers to make implementation viable; 4) implement solutions for operational optimisation that can integrate with flexibility providers and handle the new pricing models and business logics of flexibility; and 5) evaluate the operation and continuously improve on it. We, the 16 partners contributing to the progress of the Flexi-Sync project, are sure that the contributions from the Flexi-Sync project can provide valuable inputs into such a process.

Project background

The emerging challenge of balancing an increasingly variable electricity production with new electricity demand patterns is putting new requirements on the energy system. Without adding extensive amounts of flexibility that can support in balancing, there will be a costly transition to a decarbonized energy system. In the Flexi-Sync project, the need to balance volatility in the energy system is met by increasing and optimising the use of flexibility in district heating and cooling systems.

DISTRICT HEATING AND COOLING SYSTEMS offer large, unexploited potentials of cost-efficient flexibility. The district energy systems can store energy in the distribution grids themselves but also in thermal energy storages and in buildings connected to the networks. The networks are local or regional by nature, thus offering a possibility to supply energy system balancing and congestion management locally. In addition, the district energy networks offer several, centralised and decentralised, sector coupling points with the electricity systems: electric boilers, heat pumps, combined heat and power (CHP) plants, etc. Exploiting these resources' flexibility potentials can help increase energy systems' resilience.

To maximise the use of flexibility from both supply and demand side of district heating and cooling systems, competence from several areas of expertise and industries is needed. Flexi-Sync hase brought together academic researchers and practitioners such as energy service providers, district energy companies and housing companies. The mix of academic researchers and industry partners in the project has allowed for a better understanding of flexibility from different perspectives: such as how to define and quantify flexibility, the challenges and opportunities with actually implementing flexibility, possible implications on flexibility from future climate, the cost-optimal flexibility utilisation given different time perspectives, the district energy customer perspective on flexibility as well as other aspects impacting future business models incentivising flexibility.

The Flexi-Sync project has been running between 2019 and 2022 and received funding in the framework of the joint programming initiative ERA-Net Smart Energy Systems' focus initiative Integrated, Regional Energy Systems, with support from the European Union's Horizon 2020 research and innovation programme under grant agreement No 775970 (RegSys). IVL Swedish Environmental Research Institute has coordinated the project involving a consortium of 16 partners from four European countries: Austria, Germany, Spain and Sweden.

The project has been divided into different work packages (WPs), each led by a project partner. The methods, results, and discussion for each work package are presented in individual chapters of this project report. To test the optimisation of supply and demand side flexibility and to provide valuable input for all work packages, six demonstration sites represented by six individual district energy grids in four different countries have been involved: Borås, Eskilstuna, Mölndal (Sweden), Berlin (Germany), Palma de Mallorca (Spain) and Maria Laach (Austria). The demo sites, and the learnings from the flexibility implementations at these, are presented in individual chapters in this project report.

With this final report, the project consortia share the main findings from these past three years and give you the possibility to deep dive into further readings found in the list of publications. We hope that the results from Flexi-Sync can provide valuable insights into the value of district energy system flexibility and how to possibly unlock this potential to support the decarbonisation of the energy system.

The project has gathered researchers and industry partners to look at flexibility from different perspectives.

FLEXI SYNC IN NUMBERS

- 4 countries
- 16 partners
- Project length 2019-2022
- 6 demonstration sites
- 4.5 million Euros

Work packages

The partners in Flexi-Sync will bring their areas of expertise to the project. The combination of experts on district energy flexibility, district energy companies and their customers gives the project an unique approach in the context of district energy flexibility research.

WP1 Flexibility characterization and operational flexibility

- flexibility characterization
- operational flexibility enabled by optimization
- design for operational flexibility

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WP2 Cost-efficient flexibility potential in the demonstrations site areas

- definition of future scenarios
- characterization of flexibility potentials for energy system assessment
- future energy systems and flexibility

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WP3 Climate flexibility and resilience of the cost-efficient solutions

- representative future weather data sets for the demonstration sites
- energy demand and renewable generation potentials for future climate
- climate flexibility and climate resilience of the energy system

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WP4 Implementation of flexibility at the demonstration sites

- platform, service and application development
- platform integration
- input for demand optimization
- operation and output of operational co-optimization
- implementation of the flexibility services

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WP5 Business implications from increased flexibility

- price models
- network asset maintenance and durability
- end-user flexibility potential
- replicability of the new service

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WP6 Coordination and management and
WP7 Communication and dissemination

- management and quality assurance
- IPR management
- financial and technical reporting
- communication activities

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Flexibility characterisation and operational flexibility

The aim of the work package, led by researchers from LTU, was to identify the flexibility potential of different flexibility options available in the district energy systems in the demo sites of the project. Different issues to attain this aim were addressed from an optimisation and automatic control point of view.

Method

The work performed in this work package was governed by the idea of establishing a methodology to effectively define, characterise, quantify, and assess flexibility types of different nature, which are available in district energy systems.

At first, and in discussions with other work packages, the concept of flexibility from a control and optimisation point of view was defined and introduced. The approach originated from the fact that flexibility will be utilised in the design or operation of district energy systems. Thereafter, the methodology of characterising, quantifying, and assessing flexibility was introduced. The methodology was aligned with the objective that any flexibility type is to be integrated into an optimisation problem.

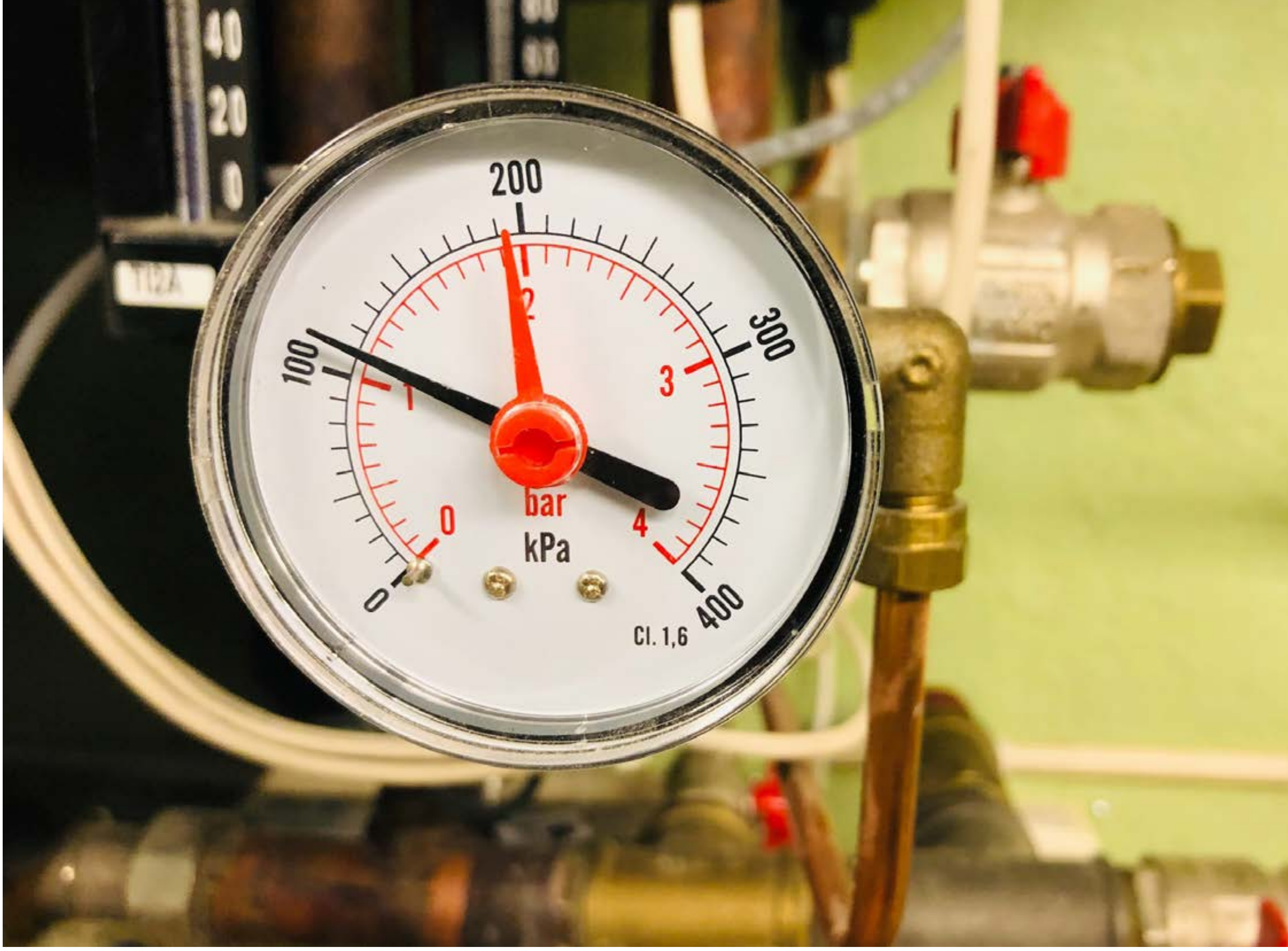
After that, a model predictive-based approach was adopted to formulate a generic optimisation problem. This was done with the aim of describing an approach to how design flexibility can be considered in the optimisation problem for operational flexibility.

Results

First, the concept of flexibility from the control and optimisation point of view was defined: flexibility is a crucial aspect in operation of any process or production system, including energy systems, which can be defined as the freedom available for changes in operation while complying to demands or targets. For example, the district heating system operator can use thermal energy stored in an accumulator tank to maintain a more even energy generation from the heat generation units and avoid the usage of the peaking generation units while still satisfying the demand. In this case, storage is a system component that provides flexibility and needs to be characterised and quantified for control and optimisation.

To characterise flexibility types of different nature, a common characterisation approach was introduced, and it included an identification of the:

- **Flexibility level:** The lowest applicable level of flexibility should be used to characterise a flexibility option.
- **Complexity:** The possibility of measuring or calculating the parameters of the flexibility option should be assessed as well as the complexity of performing this step.



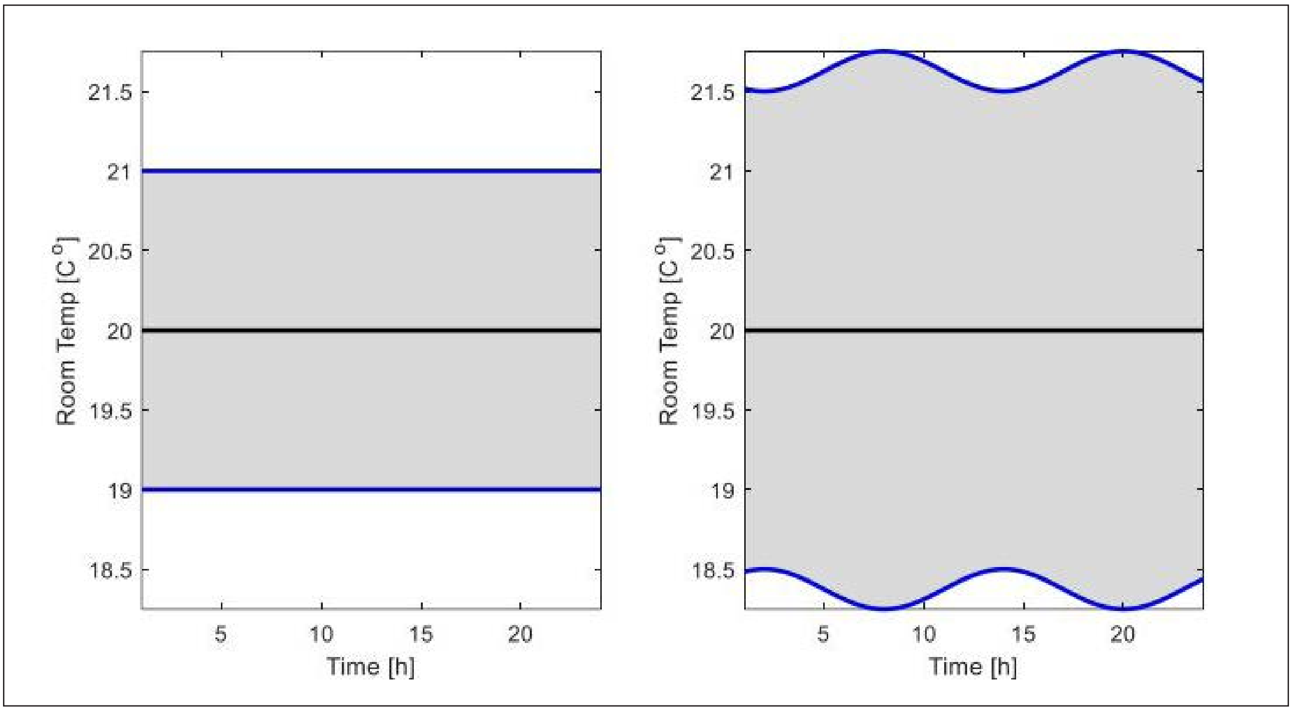
Flexibility was explored from an optimisation and automatic control point of view.

- **Impact:** An assessment of the influence of the flexibility option on different objectives of the optimisation problem, i.e., a sensitivity analysis, shall be performed.
- **Drawbacks:** Assessment of potential drawbacks caused by the utilisation of flexibility is to be performed.
- **Requirements:** Optimisation and control can only be developed or extended if the appropriate models are available, generating new requirements.
- **Flexibility nature (design or operational):** The nature of flexibility in determining how and when it can be used. Design flexibility will require the system to be simulated with different parameters, i.e., system dimensions.

After introducing the methods to define and characterise flexibility, we proposed an explorative and simulation-based approach to quantify flexibility options by simulating the operation of the complete system, e.g., a heat generation plant. To summarise, this work introduces a mechanism to convert the flexibility into a unified energy level to evaluate and find the designated flexibility's optimal operational and design utilisation.

Two cases were explored in-depth: thermal energy storage (TES) and the district heating (DH) grid as energy storage. For the TES case, its flexibility is identified physically by the storage dimensions, the maximum stored temperature, and the isolation of the tank. These parameters will be hard to incorporate into the optimisation problem. Thus, the introduced mechanism converted the TES flexibility into energy level flexibility, showing the maximum possible stored energy, the maximum in/out power, and the losses. This approach will enable the optimisation algorithms to incorporate additional flexibility and avoid mixing different parameters that characterise different types of flexibilities.

The second explored point was defining the flexibility parameters for the DH grid. This work has been conducted in collaboration with IVL and the TIMES energy system analysis performed within work package two (WP2). The grid is physically parameterised by some physical quantities, like the maximum allowed temperature, maximum energy



Flexibility, such as the possibility to vary the room temperature, is introducing a degree of freedom in a district heating system

inflow, water volumetric flow, and heat loss in the grid. Thus, after collecting all the data, it was converted to the level that the TIMES energy system analysis can process. The method was tested for the Eskilstuna district heating grid. The grid was parametrised as an energy storage, using parameters such as cycle efficiency, yearly losses, maximum inflow/outflow, maximum power capacity, annual hours of failure to deliver etc. Different values for these parameters were attained for different temperature increases, and the possible gains and losses were yielded.

To quantify the flexibility potential of buildings, i.e., the thermal inertia of buildings, IVL performed a separate assessment for the buildings in Eskilstuna (presented in the chapter related to WP2). AIT also assessed the demand response potential for the Austrian demo site, Maria Laach. The thermal inertia was simulated for six buildings accounting for 42% of the total district heating demand of Maria Laach in 2018. In the optimisation, the buildings considered flexible would shift their heat demand and provide demand response services, while the inflexible buildings had a static demand. The demo site partner, Agrar Plus, provided measured historical heat demand data, and with this data, heat load profiles for flexible and inflexible buildings could be attained. 5% of the total energy within the district heating system in Maria Laach could be shifted in time over the simulated year through peak shaving enabled by demand side measures.

After flexibility had been defined in general terms and specific terms for the heat grid and the thermal inertia and demand response of buildings, a generalised problem formulation for optimal operation and management of the district heating and cooling system was defined. The main of this was to assess the impact of identified flexibility options on the operation of district energy systems. The treated system consisted of different energy sources (generation units with different types of boilers), a distribution network (that could be treated as an energy storage by itself), energy storages, and different end-consumers. Starting from the Model-Predictive Control (MPC) point of view, the whole optimisation problem was stated as an energy/cost optimisation problem. In addition to the operational and physical constraints, the plant dynamics were also considered constraints. The main targeted features of the optimisation problem were:

- **Simple:** It should be feasible to run the optimisation algorithm with an extended time horizon.
- **Modular:** Integrating different components into the optimisation problem should be possible without structural changes.
- **Realistic:** The simplified and approximated models used in the optimisation algorithms should match the real parts of the DH system.

The developed algorithms were tested on the large-scale, already developed, digital twin of the Luleå city DH plant. The testing was done for five test cases, including four cases with the optimiser and a TES and one without them. The maximum cost reduction using the optimiser and the TES was about 22% compared to the current case.

Discussion

There are different interpretations of flexibility, which were noted early in the Flexi-Sync project. The optimisation and control-oriented approach adopted in this project enabled the definition of the basic parameters that characterise flexibilities. The unified level approach helped execute efficient optimisation algorithms, quantify flexibilities, and compare them accordingly.

Thus, the proposed mechanism to define, characterise, quantify, and unify different types of flexibility and the proposed optimisation schemes can have further usage in integrating various energy sources, and it can also be utilised in other use cases beyond the district heating where the methods were developed and tested in this project. For example, the sector integration of energy systems can use the same methodology. Accordingly, it will be easier to integrate and optimise small-scale renewable energy sources into larger-scale systems. A multi-sector integration is a logical next step. Integrating new energy-intensive industries (e.g., data centres), district heating, power sector, and hydrogen sectors is getting more attention, especially with an increasing need to accommodate renewable and fossil-free energy sources

WP1 CONCLUSIONS

- Flexibilities of different nature can be objectively compared and evaluated.
- Guided by digital twin, optimal design can be tested and verified, and operational procedures can be provided in advance.
- An approach was proposed to define, characterise, and quantify different flexibility options.
- Given the proposed approach and schemes, it is possible to integrate flexibility into a more extensive system optimally.

Cost-efficient flexibility potential in the demonstrator areas

The goal of the work package, led by IVL, was to estimate the long-term (2050) cost-efficient flexibility potential in the local or regional energy system given specific future scenarios. For the regions of Eskilstuna and Lower Austria, where the demo site Maria Laach is located, the aim was addressed by energy system modelling performed by researchers from IVL and AIT.

Method

The types of flexibility investigated included combined heat-and-power (CHP) plants, centralised and individual heat pumps (HPs), and thermal energy storages (TES), including TES in the district heating (DH) networks (both Lower Austria and Eskilstuna), the thermal inertia of buildings (both Eskilstuna and Lower Austria) and demand-side management (DSM, for Lower Austria).

For Eskilstuna, the method includes up-scaling the potential for TES in buildings from demo-scale to city/region scale by combining equations validated in WP1 and WP4 with the energy signature of the buildings obtained with the ECCABS model (explained more in this article). Dynamic energy system optimisation modelling using TIMES model generator was used to assess cost-efficient flexibility potential of DH systems in the long-term.

For Lower Austria, three different models (MILP, Balmorel and TIMES-HLA) were used to assess the impacts of flexibility measures: i) on the possibility to act on the electricity markets, ii) to project future electricity prices in Austria and iii) to project the future heating system of Lower Austria. The up-scaling of flexibility potential of demand-side management for Maria Laach to the Lower Austria region was conducted mainly by considering simulation results from AIT performed within WP1.

Results

The flexibility potentials of the demo sites were scaled up to the regions modelled. For Eskilstuna, the focus was on TES in buildings and on TES in the DH grid itself. These two storage types were described using the following parameters: i) maximum energy capacity, ii) maximum inflow and outflow, and iii) losses. The TES in the thermal mass of all the single-family houses in Eskilstuna is estimated to have 160 MWh of maximum capacity, 32 MW of maximum in- and outflow, and daily losses of 22%. For the multi-family houses the parameters are: 102 MWh – maximum capacity, 20 MW of in- and outflow, and daily losses of 14%. The TES in the grid can be characterized with 30 MWh of energy capacity, maximum in- and outflow of 13 MW and daily

The local energy system of Eskilstuna has been modelled to estimate the long-term cost-efficient flexibility potential.

losses of 24%. For Lower Austria, the task included data collection, assessment of current status, and upscaling DSM potentials obtained in the demo site. Accordingly, the maximum DSM potential for demand shifting was estimated at around 5% of the heating load.

The optimisation modelling results for both Eskilstuna and Lower Austria cases indicate that the heating sector of the future will be tightly connected to the power sector. HPs and/or CHP plants are likely to take the major share of the urban heating systems and hence, will increase the interdependency of the heating and electricity sectors by the consumption (heat pumps) and generation (CHP plants) of electricity.

Eskilstuna

The results obtained from the modelling indicate that the DH system of Eskilstuna will transform from a net electricity generator to a net electricity consumer. The existing biomass-fired CHP plant will be retired after 2035. To replace the retired capacity, the model invests in a centralised large-scale 137 MW air-based HP that becomes the primary heat generation unit in the DH system of Eskilstuna. One of the reasons for this shift from the CHP plant-dominated to the HP-dominated DH system is the assumed decrease in the electricity prices in Sweden in the future years, which makes CHP plants less profitable and HPs more profitable to run.

The modelling results show that the changes to the heat supply strategy of the city in the presence of a TES can lead to reduced heating costs, whereas the generation mix remains unchanged, i.e., dominated by air source-based HPs starting 2040. We show that the total cost of supplying heat over the modelling time horizon can be reduced by 0.5 % if there are TES options available in the system, i.e., existing grid, buildings, the storage tank, and the cost-optimal investment in a borehole TES. This indicates that, despite the investment cost required to invest in TES, the cost is paid off by reduced operational expenses of heat generation. The simulations also showed that the availability of a TES (the model invested in around 5.0-6.5 GWh of borehole storage capacity, depending on the modelled scenario) results in reduced peaks during the periods of the highest demand.

Lower Austria

For Lower Austria, the results from the simulation for a "100% renewables" scenario and "Maximized flexibility" scenario show that, in general, sector coupling points (CHP and heat pumps) will play a significant role as flexibility options supporting the decarbonisation of the heating system. The energy system model invests in additional district heating systems in urban as well as in rural zones, and biomass CHP (mainly wood), as well as air-sourced heat pumps, are expected to be the main options for the district heating network by 2050. The use of pellets and biogas in CHPs can be expected during the transition years, i.e., by 2035. In both scenarios explored, there is an improvement in the use of district heating generation to cover the winter peak demand. However, the installed capacity in 2050 is less than in 2017 because of an expected efficiency increase of future technologies and the use of demand-side management to reduce winter peaks. This is especially relevant in the "Maximised flexibility" scenario, where demand side management as a flexibility measure is assumed to have a higher acceptance.

Discussion

The integrated approach, e.g., using models to assess flexibility potentials (done by AIT, IVL and LTU) and then scale the potentials to be used in energy system modelling (performed by AIT and IVL), is proven effective and can provide insights to the scientific community, policy and industry; i) the integrated methodology can be replicated and used by academia in other regions to highlight and quantify flexible measures; ii) the results can support policymakers to identify decarbonisation pathways and set necessary policies for a more effective and efficient energy policy, and iii) the results can support the energy industry to prioritise technologies that can contribute to the decarbonisation of the heating sector.

In this WP, the analysis of the economic viability of flexibility potentials in DH systems is performed using optimisation models. As is the case for any modelling, the results obtained depend on the assumed input data. The assumed electricity prices, changes in heating demand, and investment costs in technology and infrastructure, among others, significantly impact the results. Different fuel and electricity price assumptions are one of the main reasons why the modelling results for Eskilstuna and Maria Laach differ from each other. In the case of Eskilstuna, the prices were extracted from the Balmorel modelling for the so-called "Climate Neutral Nordics" storyline of the Nordic Clean Energy Scenarios project. In the case of Lower Austria, the electricity prices were extracted from the national power system model by using Balmorel modelling tool. The simulated storyline is based on the national electricity targets, namely 100 % renewable electricity supply by 2030. Contrary to lower electricity prices expected for Sweden, electricity prices are expected to increase in Austria by 37 % by 2030 and 62 % by 2050 compared to the 2017 level. Such differences in the assumed electricity prices result in the fact that the applied optimisation models suggest investing in centralised air-based HPs (electricity consuming) in Eskilstuna and in CHP plants (electricity generating) in the region of Lower Austria.

In the case of Eskilstuna, strong dependency on the electricity-consuming technologies in the heating sector, i.e., heat pumps and electric boilers, will lead to the lock-in effect of the entire sector to one technology type and hence jeopardise the security of supply and increase the pressure on the power sector. And yet, country- and continental-scale energy models often show that the electricity prices will generally get lower in the future (because of high shares of renewables such as wind and solar), naturally leading to significant investments in HPs. This discrepancy between 1) the recently observed high electricity prices and a common belief (at least in Sweden) that future DH systems should contain CHP plants and be able to support the electric power sector, and 2) the modelling results pointing towards high shares of HPs should be addressed in detail, e.g., in future research projects and in business-governmental discussions

WP2 CONCLUSIONS

- The availability of thermal energy storage options could benefit the operation of district heating systems by lowering the cost of heat generation and reducing peaks in heat generation.
- The thermal and power sectors will be tightly connected in the future via the use of heat pumps and CHP plants.
- The future electricity prices will significantly affect the development of the investigated DH systems, in particular the investment in heat pumps and CHP plants.
- Techno-economic optimisation models applied at regional or city scales can provide valuable insights for the development of energy systems.

Climate flexibility and resilience of the cost-efficient solutions

The goal of the work package, led by researchers from Chalmers, has been to understand the adjustments needed for energy systems to be climate resilient – an important aspect to make future energy systems sustainable.

Method

The method for assessing climate flexibility or resilience is based on approaches that researchers from Chalmers have specifically developed and which are mentioned in previous works published in Applied Energy and Nature Energy, and in publications made within the scope of the Flexi-Sync project (see items 5 and 6 in the list of publications). In short, the approach is based on developing future climate data sets and using them to project future energy demand and supply scenarios considering typical and extreme climate scenarios, and then assessing the energy system's performance considering its climate flexibility/resilience.

To apply this approach to the demo site regions of Flexi-Sync, the work package received energy-related data and information from the demo sites through Utilifeed and some additional data from IVL. Several future climate projections for the demo site regions were then investigated to synthesise future weather data sets representing typical, extreme cold and extreme warm conditions. The considered climate projections include different climate models and greenhouse gas concentrations, enabling us to consider a wide range of future climate scenarios.

Results

Based on downscaling climate models and synthesising future climate data sets for typical and extreme conditions, it is obvious that by climate change the average heating demand for a building will decrease in the future. However, the impacts of extreme climate events can become more significant due to stronger extreme events, which will be more critical for cooling seasons. There will be a need for higher climate flexibility and resilience of the energy systems, including both the demand and supply sides. Increasing the share of renewable generation, both in terms of centralised and decentralised energy resources, will increase the flexibility and resilience of the energy systems.

The developed methods and data for generating representative weather data sets to be used in energy system analysis and assessing their climate resilience can be interesting for the scientific community, industry, and policymakers. The methods allow to efficiently quantify the performance of a system while considering probable future conditions and uncertainties.

Discussion

In public debate there is much focus on how the transition to a renewable energy system is one of the keys to tackle climate change. Less is being said about the impact of climate change on the energy system, and in particular energy demand and renewable generation. The fact is that climate change can affect both energy demand and renewable generation. This becomes challenging for the sustainable energy transition of societies, especially due to extreme climate events and weather variations. Climate change can induce unprecedented weather extremes and variations that our buildings and energy systems are not necessarily designed for. To avoid energy system failures in the future, we should account for the climate change adaptation of energy solutions.

Climate change can induce unprecedented weather extremes and variations that need to be considered in the design of energy systems.

The climate resilience assessment of energy systems in connection to future climate models is a very new concept. The work done in Flexi-Sync is pioneering, suggesting novel methods for the analysis to the scientific community and industry. The result has addressed the need for conducting a scientifically valid climate resilience assessment using the most recent and advanced data and knowledge available on climate change.

The generated results and future weather data sets can help both energy utilities and housing companies to estimate future needs and plan better for the required adjustments in the coming years. For example, it might be the case that the average annual heating demand decreases in the future while the peak demand increases due to climate variations. Such an insight, while it is quantified using scientific analysis based on high spatiotemporal resolution future climate scenarios, can become very valuable for the companies and stakeholders to develop the energy system towards higher flexibility.

For the future climate, there is no sustainability without resilience. Any system should perform and sustain extreme events. In this regard, this work contributes to the sustainability of the energy systems. More importantly, it opens new doors toward considering sustainability and resilience when discussing future sustainable energy systems.

The next step is to adopt a multidisciplinary approach when assessing the climate resilience of urban energy systems. By adopting innovative control approaches, accounting for multiple factors in complex systems, further gains for energy system resilience could also be attained

WP3 CONCLUSIONS

- On average, there will be a lower heating demand and higher cooling demand for buildings compared to past and current conditions.
- Extreme climate events can become more frequent and substantial, putting considerable pressure on energy systems.
- To have a reliable resilience assessment, proper future weather data sets (accounting for extreme events) should be used, and suitable methods and KPIs should be developed.
- Adding renewable energy sources and enhancing the decentralised generation can considerably enhance energy flexibility and climate resilience at the urban scale.
- Energy flexibility will contribute to climate resilience.

Implementation of flexibility at the demo sites

The goal of the work package was to demonstrate implementations of optimized flexibility at the demo sites in the project. The primary method for achieving this has been to develop a cloud-based solution that handles the end-to-end (end-user to energy company) optimisation and utilise it in the tests at the demo sites. The work was mainly performed by project partners Utilifeed and NODA in close collaboration with the demo site partners.

Method

The method used can be broken down into several parts:

1. **Data management and integrations:** Data from all demo sites has been validated, standardised, and integrated into the Utilifeed platform. This enables all services that have been developed in the project to access the data in a standardised format for all sites and that the services work without specific adjustments to each demo site. Interactions have also been set up between the Utilifeed platform and the NODA system, which executes the control in the buildings providing flexibility.

2. **Development of operational co-optimisation:** Software for optimising the energy system with an expanded system boundary has been developed in an agile development process where a product owner, a UX expert, a data science team, and frontend and backend development teams have collaborated.

3. **Live testing:** The solution has been tested in all six demo sites. For five of the sites, the testing has been in the actual day-to-day operation of the district heating system. Production planners have used the tool to optimise the production and distribution together with the flexibility in the buildings by sending a control signal from the tool. The production planners have logged their experiences with using the tool and validated that it works. All six sites have also been evaluated for more extended periods through simulation where the optimal dispatches, with and without the flexibility measures, have been compared.

Results

The results confirm that operational optimisation of flexibility utilization is viable in actual operation. There was a successful integration of a complete system optimisation (supply, distribution, and demand flexibility) developed by Utilifeed together with the building optimisation developed by NODA. Through the integration, a flexibility potential of the flexibility-enabled buildings for the upcoming hours

One of the houses in Borås where the solutions have been tested.

and days has been sent from the NODA system. These forecasts have been utilised in the system optimisation in the Utilifeed platform. The optimised flexibility plan has then been sent back to NODA, which has executed the plan while at the same time guaranteeing the indoor climate in the buildings providing flexibility.

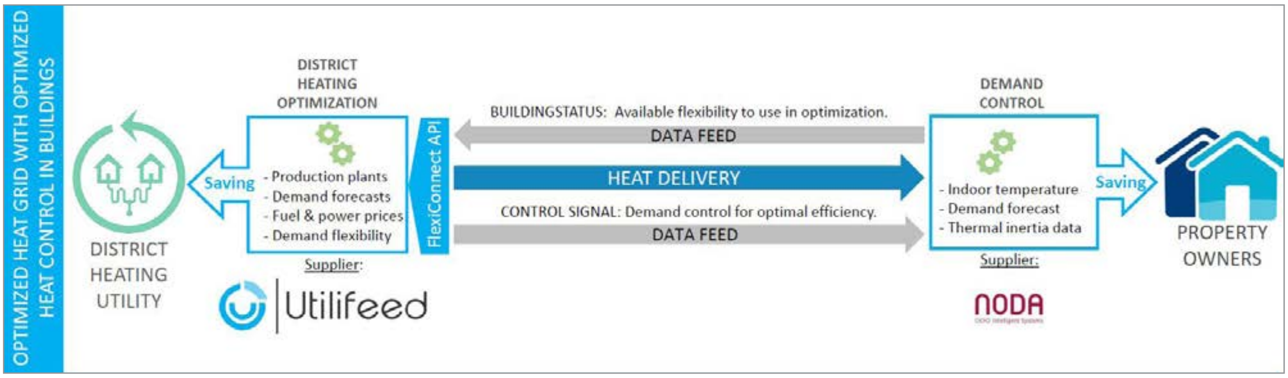
Practical tests at five of six demo sites have confirmed that the workflow of this optimisation is viable for use in a real operational scenario at an energy company. The practical tests have also confirmed that the output dispatch plans of the optimisation are viable and that the results help the energy companies to operate their systems more efficiently.

Long-time simulations of the systems, using the same models as in the practical tests with and without the added flexibility resources, have confirmed that this type of optimisation achieves both economic and environmental benefits. The conclusion that operational optimization is viable applies to all types of flexibility tested in this project. You can read more about the different types of flexibility tested at the demo site in the individual chapters about the demo sites.

The housing companies at the Swedish demo sites have confirmed that there has not been an increase in complaints from tenants about the thermal comfort in the buildings utilised as flexibility during the operational tests. This indicates that the flexible control of the buildings is also viable from a thermal comfort perspective. This is further supported by the measurements of the indoor temperature in the buildings; these did not show any significant effects from the flexible control.

Discussion

When in place, it is easy to use flexibility as a part of the optimisation, on a day-to-day basis. The project's experience is that there were no complaints from the tenants of the buildings that were flexibility-enabled, which makes it easier for the property owners to let the energy companies use the flexibility in the buildings. There might be some problems with integrating a specific building, so that more testing could be needed during the initial phase. It would



The service tested combines district heating optimization with demand side control.

also be good to follow up after a couple of weeks on how the control of the specific building has been, to see if any of the limit values need to be changed to use the right amount of flexibility from each building. This could not be done within this project since the testing period was too short.

By using demand-side flexibility as a part of the production optimisation, the energy company can reduce their operational costs and make savings. In the long run, this should also lower the customers' prices. Also, if the energy company knows how much demand side flexibility it has available at certain times, they can count on it when calculating their design load. If the design load is low, the energy company could also lower its investments. The investments can be reduced both in terms of production and distribution capacity.

When an energy company controls demand side flexibility, it is easy to calculate the effects on the CO_2 emissions. The load can be shifted to hours with lower emissions, and production units with high emissions could be utilised less. During the live testing in this project, we did not have any actual emission data available. Still, since the district heating marginal price primarily correlates with its emissions, most probably, the control has lowered the system's emissions.

The more flexibility there is in a district heating and cooling grid, the easier it is to lower the operational costs and increase revenues. As an example, electricity production from CHP plants can be used to balance the electric grid when electricity demand is high, and when electricity demand (and prices) are low, it might be better to use electricity for heating, i.e., by controlling the demand side heat pumps to be fully on.

The work addressed the need to enable the transition to a carbon neutral and cost-efficient energy system. Flexibility is a major enabler of this transition since it makes it easier to match demand with the supply of renewable energy. The main benefit of flexibility is that it makes this transition much more economically viable and faster. Some types of flexibility can be enabled at a relatively lower cost, e.g., thermal mass of the water in the DH grid and of the buildings connected to DH, than traditional investments in infrastructure that would otherwise be needed to achieve the same reduction in climate impact. This means we can accelerate the transition and reach climate targets faster.

The unique aspect of the methodology described and applied in this project is how it enables scalability. Thanks to using an IT infrastructure that can be applied to almost any energy company without costly adjustments, the results from the project can be scaled very rapidly to many energy companies. The scalability of the solution and the cost-effectiveness of demand flexibility means that the results from the project have the potential to significantly impact the energy industry transition towards significantly lower carbon emissions

WP4 CONCLUSIONS

- Operational optimisation with demand flexibility is proven to work in practice, it is economically viable and can significantly reduce CO_2 emissions.
- The next step in developing these types of services targeting energy companies and housing companies is to improve the solution based on feedback from the practical testing, develop a commercial service offer and scale up the solution.

Business implications from increased flexibility

RISE has led the work to explore the business implications of increased flexibility by targeting questions regarding new price and business models to capture flexibility, effects on network asset maintenance and durability from a more flexible operation of the district energy networks and the flexibility potentials from the end-users.

Method

Different price models that district energy companies could apply were identified through a survey and a literature review. A price modelling and optimisation was done through a case study, using demand-side data from the demo sites of Borås and Eskilstuna, where different price models were analysed to assess how well they could capture flexibility in buildings with both heat pump and district heating as a heat supply. The results were compared to a baseline where a heat pump was used as a baseload for the building's heating demand. Based on that, and the Business Model Canvas methodology, two representative business models were proposed for the flexibility optimisation service developed within Flexi-Sync.

To align maintenance activities with operational optimization of the heat networks, different types of damages and costs for maintenance and replacement were reviewed for district heating system operation and then implemented in the Utilifeed optimisation model to reduce the total system cost.

To investigate end-users' attitudes towards flexibility provision, a comprehensive survey was conducted presenting three plausible flexibility scenarios for residential buildings. This was combined with a stakeholder workshop. The scenarios were explored through with a questionnaire distributed to tenants in a Swedish demo site. The result was analysed, and the findings were compared with reviewed literature. Insights from a stakeholder workshop in Austria complemented the predominantly Swedish perspective in the survey findings.

To analyse the profitability from delivering electricity to the power market (demand side management and market participation of centralised CHP and heat pump in day-ahead and balancing markets), a Net Present Value (NPV) calculation was conducted by AIT. Furthermore, the state-of-the-art business model of Maria Laach district heating was investigated and validated. Following stakeholder interviews and based on the developed new services in the project, the business model was adapted and innovated using the Business Model Canvas and the Odyssey

Control over temperature is desirable to residents.

3.14 approach. Additionally, an analysis of the EU and national policy framework was conducted, and barriers were derived to validate the developed business models.

Results

The results from the four parts of the work packages are presented here

Price models capturing flexibility

Conclusions made from the case study were that, to enable flexibility by load shifting between district heating and heat pump, an energy price component in district heating needs to be competitive against the cost of operating a heat pump. Return temperature and flow components could be used to incentivise energy efficiency and secure revenue for the district heating company with higher independence of the weather year. Higher temporal resolution in both district heating and electricity prices creates better incentives for end-users with smart heating systems to be more flexible in their heating use. Using prices that better reflect the cost of producing heat, load shifting between individual heat pumps (electricity) and district heating can be incentivised. Savings for an end-user can be obtained by operating a load-shifting heating system more efficiently by following price signals. In most cases, the customer could decrease its heating costs and the district energy companies could also increase their profits by using competitive price models against the cost of operating a heat pump. Carbon emissions could also be decreased by switching between a heat pump and district heating depending on what kind of fuel the marginal heat production unit uses.

Flexibility potentials from the end-users

Results from the project showed that it is essential that occupants understand the flexibility setup but that it is difficult to inform them in an understandable and accessible way. To complicate matters, people often have specific and individual preferences regarding heating, for example, acceptance of high variations during the night but not in the morning or differences between bathroom and bedroom. Some residents also have very energy-intensive expectations on heating, e.g., wanting between 23 and 27°C. Furthermore, there are more aspects than the range in which the temperature is allowed to vary that are important for the acceptance of varying indoor temperatures. Control over temperature is desirable to residents.

The survey conducted in the project showed that the respondents prefer a flexibility setup in which they have control over the flexibility and are compensated economically for temperature ranges larger than ±0.5°C, over flexibility setups with the same variation and no control or more considerable variations without control. But interestingly, some respondents showed a willingness to accept a deterioration of the heating service without any compensation. In the survey, younger residents (aged 18 to 34) showed the highest acceptance of a heating service deterioration without compensation. The survey respondents' satisfaction with their current heating seemed to influence the extent to which they accepted higher variations in indoor temperature. Finally, the survey indicated that if you spend more time at home, you will have higher demands on thermal comfort. Future pricing models incentivise indoor temperature variation could enhance the acceptance rate of minor comfort losses.

Maintenance effects of flexibility

The operating temperature peaks must be limited to certain given design values or levels already used for the system for several years. For the demonstration sites in Flexi-Sync, the actual overall maintenance costs of the district heating network, based on the average during a few recent years, could be used as a baseline. It is assumed that the operating temperature will affect only a small portion of the maintenance costs. Here, the proposed levels are 5% of the maintenance costs related to fatigue of the service pipes, and 5% of the maintenance costs are related to the degradation of the polyurethane foam. There are no statistics to confirm these levels, which probably vary between energy companies, but these levels can be used as a starting point until more data is collected.

For the costs related to fatigue of service pipes, temperature cycles must be counted for at least a year when the network is run without introducing additional flexibility. A suitable resolution may be 5-10 K. Furthermore, the number of cycles must be counted or estimated in advance when the increased flexibility is introduced. For the costs related to the degradation of polyurethane foam, the time at selected temperature levels must be registered for at least a year when the network is run without introducing additional flexibility. Here a suitable resolution may be 5-10 K. Furthermore, the time at the same levels must be registered or estimated in advance when the increased flexibility is introduced.

Business model design to utilise flexibility

Two business models, the connected product and the performance contract, were created based on the new service developed in the Flexi-Sync project. For the connected product business solution, district energy companies install an optimisation product and operate the demand side flexibility either by an aggregator or individual customers. For this business model, the new price models presented above could play an important role in incentivising flexibility. For the performance contract business solution, it can be possible for district energy companies to provide heat as a packaged service. District energy companies offer a heating contract or a heat plan, and consumers buy an agreed level of warmth rather than kilowatt-hours of energy. The packaged service sets a heating schedule for homes hour-by-hour and room-by-room using a smart heating control system. Meanwhile, district energy companies capture the flexibility potential and optimise the whole system by adopting demand-side response mechanisms (such as the service developed in Flexi-Sync). In any regard, a good and close customer relationship is the most important factor in increasing customers' willingness to engage.

Flexibility measures on the supply side, such as heat pumps and CHP plants in district heating networks, are seen as profitable investments that can stabilise the electricity grid and generate additional revenues for the case of Maria Laach in Austria. Funding for such installations is still an essential requirement to guarantee economic viability. District heating could profit from knowledge transfer from conventional electricity supply companies concerning subsidies, feed-in and market participation possibilities.

Furthermore, the policy framework in the EU and the member states of the demos is highly relevant for business models. Some of the main barriers are the lack of transparency in pricing and billing and the lack of consumer protection regulations, which lead to lower trust in district heating companies. There are also changing legal requirements, slow processes, and difficult planning that hamper the application of flexibility measures within district heating networks. In addition, flexibility measures that include sector coupling with the electricity sector mean that additional, in some cases extensive, provisions of electricity law must be complied with. In some countries, the long-term nature of local heating supply contracts makes it difficult to forward flexibility incentives to existing end users.

Discussion

Understanding current price models could be an invaluable input in decision-making for district energy companies, especially in the context of increased flexibility. Most district energy grids are slow to recognise and capture flexibility that can be catalysed through end-users and current price and business models cannot transparently convey the value of flexibility. However, district energy companies have a big potential to further capitalise on flexibility in the energy system. Including flexibility incentives in price models can create a win-win by cutting operational costs for the district energy provider and the energy consumption of the end-user. District energy companies are suggested to deploy easily understandable price models to be able to convey incentives to customers.

The proposed maintenance cost function is considered to, in a general perspective, estimate how the costs of both maintenance and reduced durability develop relative to the present costs due to a more flexible operation. The purpose of including these costs in the overall optimisation of district energy companies is to decrease the incentive to run the heat network with a degrading operational strategy. District energy companies could verify the cost function by applying it in the operational optimisation of the complete energy system. More data on maintenance activities and costs could be continuously collected for heat networks to update model parameters and verify the model presented.

By utilising the results dealing with heat end-users, the housing companies and district energy companies could apply different occupant-related flexibility measurements for different groups of end-users, different preferences of them, different locations, and different home adaptations and equipment, corresponding to different flexibility scenarios. These could serve as important information for their design of business and price models. The district energy and housing companies should further notice that comfort losses within the buildings are not desired. However, innovative price models that incentivise flexibility could enhance approval of possible comfort losses.
The emerging concept of "heat-as-a-service" could serve as an inspiration for both district energy companies and housing companies. It calls for their business model innovation to catalyse further exploitation of flexibility in the sector. In doing this, district energy and housing companies should pay attention to the barriers, such as their own institutional inertia and resistance to change, to adapt to different flexibility-emerging technologies. When coupling the flexibility services with the electricity market, the flexibility measures that combine demand side management and sector coupling (e.g., electricity market participation) can generate profits and benefits for both the district heating company and its customers. The results of the work package show the profitability of flexibility in district heating networks, with current business models needing to evolve to offer enhanced services and to take advantage of flexibility

WP5 CONCLUSIONS

- Innovative price models can transparently convey the value of flexibility that not only benefits the district energy company but also motivates the end-users to provide flexibility.
- The usability of the maintenance cost function could be verified by applying it in the operational optimisation of the complete energy system.
- Flexibility is difficult to explain to, and to be understand by, the end-users, but it is essential to do so.
- Flexibility potential from the end-users is not fully exploited, and the potential should be considered based on individual preferences.
- Existing business models for district heating companies must be developed to exploit flexibility.
- It is possible to create win-win business models for a service, bridging the supply and demand sides in district heating systems. However, financial risks regarding investment and return, social risks regarding customers' trust and acceptance, technical risks regarding response to the control signal, and legal barriers should be carefully considered when applying new business models.

Demonstration sites

Six demosites are at the heart of the project. Four of the demo sites have district heating and cooling companies that are active in mature heat markets (Germany and Sweden), making the interconnection with electricity essential. Two of the demosites (Austria and Spain) to electricity operate on less mature heat markets, making the interconnection important for future efficiency in the energy system.

Maria Laach, Austria

- A district heating system with a heat plant, fuelled with biomass from agricultural and forest residues, and a district heating grid.
- **Annual demand:** 1.6 GWh district heating.
- **Flexibility used in project:** central storage tank, distributed storage tanks and future CHP.

Palma de Mallorca, Spain

- A district heating system with a district heating and cooling grid and a combined heating, cooling and power plant (CCHP), fuelled with natural gas, diesel, biomass and solar thermal.
- **Annual demand:** 9 GWh district heating and 3 GWh district cooling.
- **Flexibility used in project**: district heating and demand side swimming pool.

Mölndal, Sweden

• A district heating system with a district heating grid and a CHP and multiple heat boilers mainly fuelled with biomass from forest residues and liquid biofuel (RME).

• **Annual demand:** 300 GWh district heating.

• **Flexibility used in project**: building thermal inertia. Three multi-family residential buildings are part of the demonstration.

Borås, Sweden

• A district heating system with a district heating grid, multiple CHPs and HWBs mainly fuelled with biomass, municipal waste and bio-oil. A 1.8 GWh thermal heat storage is used to balance the heat demand of the district heating system.

• **Annual demand:** 600 GWh district heating.

• **Flexibility used in project:** building heat pumps in combination with district heating. Two multi-family residential buildings are part of the demonstration.

Eskilstuna, Sweden

• A district heating system with one CHP and a heat only boiler, both fuelled by wood chips. Four bio-oil fuelled boilers used as peak capacity and four oil-fired boilers for reserve capacity.

• **Annual demand**: 700 GWh district heating.

• **Flexibility used in project**: building heat pumps and building thermal inertia. Two multi-family residential buildings are part of the demonstration.

Berlin, Germany

• A neighbourhood with residential buildings is part of the demonstration.

• **Annual demand of neighbourhood:** 618 MWh.

• **Flexibility used in project:** Thermal storages coupled with PV, waste heat integration and a CHP. Heat pumps in combination with district heating.

Borås, Sweden

Borås Energi och Miljö supplies district heating and cooling to the citizens of Borås. Together with one of their heat customers, the housing company Willhem, they have formed the Borås demo site where demand side flexibility from alternating between district heating and building heat pumps was investigated.

The NODA system, including indoor climate sensors and a control system, were installed in two of Willhem's residential buildings and connected to the existing Web Port system. The buildings were two multi-family residential buildings equipped with both district heating and a local ground source heat pump. Magnus Åkerskog, Willhem, explained that during this integration process they identified the need for clear descriptions of technical capabilities in the buildings' energy systems to successfully connect overriding control systems, such as the NODA system, in a transparent way and without major investments in the facilities. He highlights the need for standards enabling different suppliers and district heating networks to prepare their systems for this type of integration.

Borås Energi och Miljö used Utilifeed's Optimization software to optimise supply and demand side flexibility and automatically control the flexibility of the two buildings via the NODA system. The live testing was ongoing for about one week. Before that, the energy company had time to learn how to use the tool and all demo site partners did some tests together.

The intention was to test flexibility from the thermal inertia of the buildings, but due to the limited time for live testing, a decision was made to only test switching between heat pumps and district heating. Everything worked as intended when tests were made before the live control, but during the live control week, the control of the heat pumps did not work. The optimisation software worked and calculated when the heat pumps should be on and off (high electricity prices led to them being shut off), and the signal was sent to NODA. Unfortunately, there were problems with the connection from NODA to the buildings' control system, and the heat pumps were never switched off. The primary learning from this is that it would be good with standardised protocols on how to send external signals to the buildings and also that it is crucial to test each individual integration.

In addition to the implementation done at the demo site, both demo site partners have been keen to learn from the business model work done within the project. Stefan Hjärtstam, Borås Energi och Miljö, explained that their current district heating price models do not take changing marginal production costs or electricity prices into account, which means that individual heat pumps often become more economical than district heating for heat customers. Therefore, it is common in Sweden that housing companies to run their heat pumps as base load and use district heating only for peak demand or redundancy. These types of customer behaviours are rarely beneficial for district heating companies. Magnus Åkerskog, Willhem, explains that the design of new business models will also be crucial for a major rollout of flexibility services,

The thermal heat storage connected to the district heating grid of Borås is visible all over town.

especially for commercial housing companies such as Willhem. Since heating is included in the rent in most of Sweden's multi-family residential buildings, there are no existing incentives for the tenants to accept any discomfort or variation in their indoor climate today. If we can create this incentive for our customers and allow more significant variations in temperature, the effect of this kind of functionality can probably be higher, Magnus Åkerskog concludes

FACTS AND FIGURES

District heating units:

- Combined heat and power plant (120 MW_{th}, wood chips + 36 MW, FGC)
- Combined heat and power plant (2x20 MW_{th}, waste + 9MW, FGC + 2x45MW_{th}, wood chips)
- Heat only boiler (15 MW, wood pellets)
- Heat only boiler (45 MW, bio oil)
- Heat only boiler (2x24 MW, bio oil)
- Heat storage (1.8 GWh)

Supply/return temperature: 80-95°C/40-45°C

Network length: 235 km

Annual district heating demand: 600 GWh

Eskilstuna, Sweden

The Swedish municipal energy company Eskilstuna Energi och Miljö teamed up with their heating customer, the municipal housing company KFast and formed the demo site of Eskilstuna. In the demo site, thermal inertia of buildings, as well as a combination of individual heat pumps and district heating, were tested.

The flexibility of two apartment buildings with rental apartments was part of the demo site: a newly constructed, low-energy student housing building and an older multi-family building with an exhaust air heat pump. The buildings are located in an area undergoing a transition process. As part of this, KFast is testing new products and services that tackle issues related to energy consumption, such as the Flexi-Sync concept. By participating in the project, KFast wanted to explore how the integration between different types of building management systems can be set up to operate smoothly, gain practical experience from flexibility and learn what the tenants would say about potential changes in indoor temperature.

The NODA system was installed in the two Eskilstuna demo site buildings. In one building the focus was on how the thermal inertia of the building could help to move the heat demand in time. In the other building, the partners had the ability to control both the heat pump and the district heating connection and therefore use both flexibility from thermal inertia and switch between a heat pump and district heating as the heat supply. During a major part of the testing period, due to problems with the heat pump control, the demo site tested flexibility from the thermal inertia of the building. During the last week of testing, the switch between the heat pump and district heating could be tested.

Eskilstuna Energi och Miljö used Utilifeed's Optimization software to perform optimisations with flexibility and automatically control the buildings via the NODA system. The live testing was ongoing for about one and a half month, and before that the energy company had time to learn how to use the tool, and all partners did some tests together. Some new testing was also done before the switch between the heat pump and district heating could be tested live.

Everything worked as intended, and the partners managed to control the buildings to react when the optimisation software suggested it was the most profitable. The building thermal inertia shifted heat demand to hours with lower heat production costs. The building heat pump enabled a shift between a heat pump and district heating, given the lowest cost from a system perspective for each point in time. No indoor climate changes in the buildings were registered, and KFast did not have any complaints from the tenants during the testing period. The tenants did not know when the live testing was ongoing.

Per Örvind, Eskilstuna Energi och Miljö, says that the energy company has been keen to explore how flexibility can work and what future business models in the heating sector could look like, but also to learn about the total economic potential for the entire district energy system in using flexibility. There are a lot of

Eskilstuna's district heating plant with the characteristic white and red colours.

discussions in Sweden on the possibilities of using different kinds of demand-side flexibility, he explains. Still, so far, mainly the prominent players in the district energy market in Sweden have experimented with demand side flexibility. Flexi-Sync has given smaller players the resources to participate in the development of the future district energy landscape. As the district heating grid in Eskilstuna is representative of the systems in many mid-sized Swedish towns, the Flexi-Sync experiences could also benefit other regions

FACTS AND FIGURES

District heating units:

- Combined heat and power plant (92 MW_{th}/560 GWh, 38 MW_{el}/180 GWh)
- Heat only boiler (67 MW_{th}/170 GWh)
- Four heat only boilers (50 MW_{th}/10 GWh, bio oil), peak capacity
- Four heat only boilers (250 MW_{th}, oil), reserve capacity
- Heat storage (1.2 GWh)

Supply/return temperature: 75-100/40-50°C

Network length: 33 km

Annual district heating demand: 700 GWh

Main fuel: Wood chips

Mölndal, Sweden

The energy company Mölndal Energi joined the Flexi-Sync project together with one of their major heat customers, the housing company Mölndalsbostäder and formed to demo site of Mölndal in the west of Sweden.

The demo site has aimed to study how the district heating production is affected when the customer uses the thermal inertia of their building stock to optimise and reduce heat production costs. Mölndal Energi has been keen to see how a demand-side management system in district heating and cooling could reduce primary energy demand as well as heat production costs. Another aspect is the security of supply and the possibility to distribute the energy in case of a major incident in the production or distribution. If the overall heat demand in the district heating system during peak load hours can be reduced, it is possible that expensive peak fuels can be avoided. It was also of interest to study to what extent the thermal capacity of buildings can be used in optimising electricity production in the combined heat and power plant, as well as how the trading with the neighbouring grid (Gothenburg) could be optimised.

NODA connected three buildings owned by Mölndalsbostäder to the demand side management system, these three buildings were intended to be used for flexibility from the buildings' thermal inertia. The connection to the NODA system was done via the existing KTC control system of the buildings. At the beginning of 2022, tests were carried out to see how the flexibility of the buildings could be utilised. During the live testing, only two buildings were used, the third one was under renovation.

Mölndal Energi used Utilifeed's Optimization software to optimise flexibility and automatically control Mölndalsbostäder's buildings via the NODA system. The live testing was ongoing for about a month, and before that, Mölndal Energi had time to learn the tool, and all partners did some tests together.

Everything worked as intended, and the partners managed to control the buildings to react when the optimisation software suggested it was the most profitable. The building thermal inertia shifted heat demand to hours with lower heat production costs. Some features were missing in the Optimization software to represent Mölndal Energis grid completely, but it was close enough to still make it valuable for the energy company. The NODA system registered no changes in indoor climate in the buildings. Mölndalsbostäder did not have any complaints from the tenants during the testing period. The tenants did not know when the live testing was ongoing.

Charlotta Brolin, Mölndalsbostäder, sees potential in the technology used in the Flexi-Sync project and

The district heating plant of Mölndal produces 290 GWh of heat each year.

believes that the company will use the technology more in the future. Their buildings are moving away from being a sole consumer of energy. As a housing company they are becoming more of an integrated part of the urban energy system, and the Flexi-Sync concept could be a first step in the right direction

FACTS AND FIGURES

District heating units:

- Combined heat and power plant (80 MW_{th} + 25 MW FGC, 27 MW_{el}, solid biofuels)
- Heat only boiler (35 MW_{th} + 7 MW FGC, solid bio-fuels)
- Two heat only boilers (50 MW_{th} and 2x10 MW_{th}, liquid bio fuels)

Supply/return temperature: 72-85/40-45

Network length: 150 km

District heating demand: 290 GWh + 150 GWh (Gothenburg connection)

Main fuels: Forest residues and wood waste

Berlin, Germany

In the residential district Grüne Aue in Berlin, the German project partner and energy company Vattenfall has tested the optimisation of flexibility from building thermal inertia and building heat pumps supplied with excess heat from a sewage system and in combination with photovoltaics. Other energy concepts have also been developed at the demo site and are now getting ready to be commercialised.

By utilising the thermal inertia of buildings, one can periodically overheat and underheat the buildings, hence allowing for the heat demand to be flexible in time. In combination with photovoltaics, building heat pumps and a connection to a small heating network supplied with excess heat, will enable a building to change the heat supply to either district heating or heat pumps supplied by electricity from the photovoltaics or the power grid.

The flexibility was tested using a combination of the NODA system and the Utilifeed Optimization software. In contrast to the other demo sites, there was no live testing, but simulations were made in the Flexi-Sync system based on forecasts and data from the demo site. A grid flexibility forecast was used as an input to the operational optimisation. The purpose was that the local system operators should build an understanding of how the optimisation worked, perform a sanity check and find an optimised production plan. Data was transferred from the demo site to the NODA system and the Utilifeed Optimization software. As there was no real installation of photovoltaics at the demo site yet, the solar electricity production was calculated based on a forecast of solar irradiation. The calculated electricity production from the photovoltaics was used to assess how much additional electricity was needed for the heat pump, for charging electric cars or for direct other use in the buildings.

It was found that between 4-11% of the heating time over a day, the flexibility option to increase the indoor temperature by 2K could be applied by using the thermal inertia of the building. This would not negatively impact the comfort within the buildings, and almost the same heating demand could be expected. This option should be used in periods with high excess heat volumes combined with high solar irradiation during the day.

Diana Adam, Vattenfall, explains that the concept developed in Flexi-Sync will be exploited further in other projects by Vattenfall, and two main exploitable results from the project will be taken to the next step by the German project partner. First, Vattenfall took the initiative to form alliances with the Berlin Public Transport company (BVG) and the Berlin Water Treatment company (BWB) to exploit excess heat from the subway grid and the sewage lines all over Berlin. This will form the base for a new energy service based on flexibility for business-to-business (B2B) customers in Berlin. The excess heat recovery from subway and sewage pipes will supply nearby B2B customers with heat. Vattenfall will unite the heat source (BWB and BVG) and the heat sink (real estate owners). Second, Vattenfall explored the potential to harvest excess heat from cooling processes, made a standardised technical concept and turned this into a product (Kühlung Smart, or Smart Cooling). The concept builds on that

Grüne Aue, the German demo site, is located in the city of Berlin.

cooling process heat is recovered and fed into the district heating system, leading to a more careful use of the primary energy resources and the reduction of urban hotspots in Berlin. In addition, no re-cooler needs to be set up at the customer's facility, meaning that space is freed up for other purposes. The German Property Federation ZIA awarded this concept an "Outstanding innovation 2021"

FACTS AND FIGURES

Local heating units:

- Heat pump (99 kW_{th}, excess heat from sewage system)
- Combined heat and power plant (99 kW_{th}, 50 kW_{el}, natural gas)
- Heat only boiler (570 kW_{th}, natural gas)

Supply/return temperature: 75°C/40°C

Network length: 1 km

Annual heating and cooling demand: 2.9 GWh heating and 1.2 GWh cooling (estimated)

Main fuel: Natural gas and excess heat

Palma de Mallorca, Spain

The Spanish project partner Sampol operates and maintains a tri-generation plant producing electricity and hot and cold water distributed to customers in the science and technology park Parc Bit close to Palma de Mallorca. Several types of flexibility have been explored at the demo site: storage flexibility, grid flexibility and individual customer flexibility from the thermal inertia of a heated swimming pool.

The flexibility of the district energy network in Parc Bit was explored by implementing a control system for smart substations. The aim was to improve the efficiency in the energy distribution and the ability to store energy in the network. By using the water of the district network as an inertia tank, the grid can be used as a large thermal storage. On the customer side, the flexibility was optimised by installing controllable valves and a smart control system for the customers' energy meters. These new solutions will allow the operator to change the temperature of the district heating and cooling depending on the needs of the tri-generation plant and without affecting the quality of the energy supplied to the customers.

The Flexi-Sync project partners Sampol, Utilifeed and LTU worked jointly on simulation models of the Parc Bit power plant, the heating and cooling grid and the customer demand to optimise the energy production planning and the operation of the network. During 2020 and 2021, all the control systems were installed, and data were collected to develop the models. In 2022 the Flexi-Sync solution was validated in live operation.

To increase flexibility, three pillars have been essential at the demo site. First, an energy production baseline was established as it is crucial to know how the energy production will behave if there is a change in the production plan due to flexibility. The first pillar was developed by Utilifeed, who used their optimisation software to calculate the optimal operation of the Parc Bit plant. Second, a demand forecast determined the margin of energy to be stored or the flexibility required for an optimal energy production. Sampol worked on this second pillar using data analytics. Last, a modelling tool of the district heating and cooling grid and the available grid storage was crucial. This third pillar was developed by LTU, using data from distribution grid blueprints and geographical data to create a model of the network in Parc Bit.

For the Spanish demo site, the practical learnings were that simulations are key to unlock flexibility; simulations of the system, including production baseline, demand forecast and grid model, could significantly increase the savings. Energy companies are frequently using energy production simulations in their day-to-day operations, but an entire system simulation is very useful to make use of flexibility. It was also noted that some end-users could be integrated as energy storages due to their large flexibility potential; knowing their needs, one can create a win-win business. Finally, to study flexibility using network inertia requires accurate data and

Parc Bit has an advanced tri-generation plant that supplies the area with heating, cooling and electricity.

there are many factors which might influence the results. Further studies are required to obtain actual gains from grid flexibility.

Pau Cortés, Sampol, concludes that flexibility is a key aspect in the energy transition; however, it is difficult to exploit since it is not intuitive to predict consequences such as rebound effects on efficiency from demand response or efficiency losses with using energy storages. But, by studying flexibility in a real case, one can gather valuable findings which cannot be found in books

FACTS AND FIGURES

District heating and cooling units:

- Internal combustion engine (2 x 1.45 MW_{el}, natural gas)
- Heat only boiler (1 MWh, biomass)
- Solar thermal (864 m^2)
- Absorption chillers (1.258 + 0.432 + 1.318 MW_c)
- Electric chillers (1.2 MW_c compressor and 1.3 MW_c screw)

Supply/return temperature: 80-90°C/55-65°C

Network length: 4.6 km

Annual thermal demand: 9 GWh heat/3 GWh cold

Main fuels: Natural gas and wood chips

Maria Laach, Austria

The district heating grid of Maria Laach, represented by the project partner Agrar Plus, is a rural district heating grid. In contrast to the other demo sites of Flexi-Sync it does not yet have a combined heat and power plant in operation. The flexibility tested was building thermal inertia controlled by remotely making alternative settings of the substation controllers.

Five buildings connected to the heating grid, representing 50% of the total energy demand in the network, were prepared for live testing: a primary school with kindergarten, a municipal office, restaurants, hotels and a multi-family apartment building. To unlock the flexibility potential of the buildings it was necessary to install new substation controllers, update the SCADA software and install a software interface between the existing Schneid SCADA system and NODA. After a stability test of the data connection and data transfer between the demo site and NODA, NODA performed response tests to determine the buildings' responses to control measures and changes. This also made it possible to quantify the thermal inertia of the buildings.

The live tests were done in Utilifeed's Optimization software. Settings made it possible to consider the weather forecast and the building flexibility. After optimising the operation parameters, the optimisation generated a two-day operation plan. With the optimisation the peak load could be reduced by about 80 kW, or about 6% of the contracted load compared to regular operation. Live tests were made for one month and saved about 6 MWh, or 7% of the energy demand.

Key learnings from the flexibility integration was that preparation of historical operational data takes time and the optimisation planning needs regular plant personnel; there could be efficiency gains from automating these processes. Positively, the heat end-users involved in the testing did not notice when the buildings were controlled. The consumers were informed about the project and that some testing would be done, but they were unaware of when and how. This shows that the controlling measures were very soft, and there could be further potential.

Additional optimisation possibilities were identified in discussion with project partners. The contracted load limit of the substations could be overridden to overheat buildings, i.e., use the thermal inertia of the buildings to pre-heat them before the heat demand increases. The same could be done with domestic hot water boilers. Additional measures that could be explored further are a more active control of the buffer storage tanks in the grid, e.g., a forced load or blocking of buffer storage tanks and active management of central buffer storage tank coupled with demand side management.

Josef Petschko, Agrar Plus, mentions that the cost for flexibility integration, licencing, and operation (estimated to be about 12% of the raw material feedstock costs) is possibly too high for small rural

The district heating plant of Maria Laach is the smallest in the project and located in a rural area.

grids like Maria Laach. Hence, finding a low-cost solution, e.g., automating the optimisation process to reduce operational costs is necessary. Another solution would be to combine several small- and mid-sized heat plants to spread the costs for optimisation measures. In the future, with a combined heat and power plant in Maria Laach, excess electricity could also be used for load compensation and stabilising the power grid.

To further build on the results from the Flexi-Sync project, a project called DigiCiti was started in mid-June 2022. In the project Agrar Plus, together with NODA and Schneid, will take the next steps in developing the demand side management and flexibility optimisation

FACTS AND FIGURES

District heating units:

- Two heat only boilers (2 x 600 kW, biomass)
- Heat storage (8 m^3)

Supply/return temperature: 81-87/65-67°C

Network length: 1.5 km

Annual heat demand: 1.6 GWh

Main fuel: Agricultural and forest residues

List of publications

Project reports

- Deliverable 1.1: Flexibility characterization and assessment methodologies. Wolfgang Birk and Khalid Atta, LTU. https://doi.org/10.5281/zenodo.4911876
- Deliverable 1.2: Design flexibility and flexibility constraints for optimization. Wolfgang Birk, Khalid Atta and Maryam Razi, LTU. https://doi.org/10.5281/zenodo.4911649
- Deliverable 1.3: Operational and design optimization methodologies for flexibility. Wolfgang Birk, Khalid Atta, Maryam Razi, Andre Yamashita, LTU. https://doi.org/10.5281/zenodo.5797821
- Deliverable 2.1: Definition of future scenarios. Akram Sandvall, Érika Mata, Johanna Nilsson and Anna Nilsson (IVL) and Nicolás Pardo García, Demet Suna and Ralf-Roman Schmidt (AIT). https://doi.org/10.5281/zenodo.5797831
- Deliverable 2.3: Energy system cost-optimization of flexibility potentials. Érika Mata, Dmytro Romanchenko, Anton Jacobson, Burcu Unluturk, Musbau Adeoye Bello and Veronika Kronnäs (IVL), Nicolas Pardo Garcia, Demet Suna, Ralf-Roman Schmidt, Sarah Wimmeder (AIT). https://doi.org/10.5281/zenodo.7060011
- Deliverable 3.1: Report on representative future weather data sets for selected demosite areas. Vahid M. Nik, Chalmers. https://doi.org/10.5281/zenodo.4911957
- Deliverable 3.2 and 3.3: Report on energy demand, climate flexibility and resilience of energy solutions for future climate. Vahid M. Nik, Chalmers. https://doi.org/10.5281/zenodo.7157270
- Deliverable 4.1: Platform integration. Jared Peacock and Johan Kensby, Utilifeed. https://doi.org/10.5281/zenodo.4627731
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- Deliverable 4.4: Feature complete operational co-optimization. Johan Kensby, Utilifeed. https://doi.org/10.5281/zenodo.6925036
- Deliverable 5.1: Analysis of price models. Tobias Gunneberg, Sujeetha Selvakkumaran, Lina Eriksson and Ying Yang, RISE. https://doi.org/10.5281/zenodo.6925107
- Deliverable 5.2: Report on maintenance effects of flexibility installed in demosites. Jan Henrik Sällström, RISE. https://doi.org/10.5281/zenodo.4911939
- Deliverable 5.3: End-user flexibility potential. Sara Renström and Sofie Nyström (RISE), Burcu Ünlütürk (IVL) and Carolin Monsberger (AIT). https://doi.org/10.5281/zenodo.4911762
- Deliverable 5.3: End-user flexibility potential. Sara Renström and Sofie Nyström, RISE, Burcu Ünlütürk, IVL and Carolin Monsberger, AIT. https://doi.org/10.5281/zenodo.4911762
- Deliverable 5.4: Business model and market analysis for the new service. Ying Yang, RISE, Carolin Monsberger, Klara Maggauer and Demet Suna, AIT. https://doi.org/10.5281/zenodo.7157277

Peer-reviewed publications

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2. Javanroodi, K., Nik, V. M., Giometto, M. G and Scartezzini, J-L., ”Combining computational fluid dynamics and neural networks to characterize microclimate extremes: Learning the complex interactions between meso-climate and urban morphology”. Science of The Total Environment 2022;829: 154223. https://doi.org/10.1016/j.scitotenv.2022.154223
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7. Pardo Garcia, N. and Suna, D., "Future energy transformation of the heating sector in Lower Austria Region" EEM22/18th European Energy Market Conference. Ljubljana, Slovenia, 2022, pp. https://www.eem22.eu/wp-content/uploads/EEM_Booklet_FIN-web_4.pdf

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14. Yang, Y. and Lygnerud, K., "Innovative price models and business models to capture flexibility for district heating and heat pump integrated systems" [Manuscript under preparation]

Other

- Flexi-Sync annual report 2020, https://doi.org/10.5281/zenodo.7185231
- Flexi-Sync annual report 2021, https://doi.org/10.5281/zenodo.7185239
- Decision Support Tool (developed by AIT): https://flexi-sync-tool.ait.ac.at/

Project partners

Flexi-Sync

Flexible energy system integration using concept development, demonstration and replication