Flexi-Sync

Flexible energy system integration using
concept development, demonstration and replication

FLEXIBILITY CHARACTERIZATION AND ASSESSMENT METHODOLOGIES

VERSION 1.0

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EXECUTIVE SUMMARY

The report at hand is the initial deliverable D1.1. of work package WP1 of the Flexi-Sync project which lays the foundation for the optimization strategy that will be developed to exploit the available flexibility in a district heating and cooling system. The deliverable summarizes the results from task T1.1 which is defined as follows:

> *Task 1.1 is "Flexibility characterization". A systematic characterization of flexibility which can be constrained from design, and can be used in control, optimization and quantification of the flexibility potential will be achieved. The characterization shall be generic in the sense that it can be applied to a large variety of components and can also consider the thermal comfort flexibility of humans residing in buildings, established as a comfort zone.*

Early in the project it was decided that thermal comfort flexibility of humans will not be considered in work package WP1 but instead be part of work package WP5.

The deliverable contains a review of the state of the art of characterizing and assessing the flexibility in a district heating and cooling system from the perspective of operational control and optimization. A generic characterization, quantification and assessment method is described and applied to a simulated test case. The test case is the district heating system of the city Luleå in northern Sweden. The reason for using the Luleå test case is that a complete dynamic model for production, distribution and buildings, including thermal storages is available and implemented in a co-simulation environment.

The results reported in D1.1 will be used with Task T1.2, T1.3, and in WP4. The work has been conducted starting in M1 and concluded in M15.

CONTRIBUTION

Main contributors to the deliverable are Riccardo Lucchese, Khalid Atta and Wolfgang Birk from LTU. Further Benedikt Leitner (AIT) provided insights regarding thermal energy storages and Jan-Henrik Sällström (RISE) contributed with additional state of the art articles and material.

Vahid Nik (Chalmers) and Érika Mata (IVL) served as reviewers for the report and the authors hereby thankfully acknowledge their comments and suggestions as they aided in improving the report.

1 INTRODUCTION

Flexibility in energy system has been studied for quite some time where concepts like demand response (DR) or automated demand response (ADR) are used to exploit the available energy flexibility to mitigate peak load events in the energy system. For a long time, the focus of study are electrical grids but more recently heating and cooling grids and the combination of both grid types have been studied.

Already in 2011, Denholm and Hand concluded that long term energy storage (several hours and up to one day) is strictly necessary for renewables to penetrate the largest share of generation in electrical grids, meaning that flexibility is needed to counteract the intermittence of renewable energy sources. The reasoning is similarly true for district heating and cooling system. Heat load variations in district heating systems are a source of flexibility if excess heat can be stored and heat load demands can be shifted. Gadd and Werner (2013) exemplify this by providing an insight on the daily variation of the heat loads in Swedish district heating systems. It has then further been shown that the heat load variation in the Gothenburg region can be largely mitigated using short-term heat storage in the building mass and thereby enabling more environmentally friendly and cost-efficient heat production, as concluded by Olsson-Ingvarsson & Werner (2008).

From this simple reasoning, one can conclude that exploiting flexibility on a control and optimization level (short-term) is highly beneficial. Due to the difference of heating and cooling grids compared to electrical grids in terms of the inertia and the heat or cold transport, heating and cooling grids have not been considered very often. Therefore, the primary focus has been the use of the inertia in buildings and thermal storages, as will be seen in the state-of-the-art section.

1.1 Scope - Control and optimization of operation

The Flexi-Sync project has a wide scope when it comes to flexibility in district heating and cooling systems considering levels from planning and design down to low-level operation and consumer thermal comfort aspects. In Figure 1, a typical hiearchy is depicted explaining the interdependencies of the levels, where methodologies on the higher level use aggregated information from the lower levels and imposing boundary conditions on the lower levels. For each of these levels the typical time scales are given and the associated model types to represent the system behaviour are given.

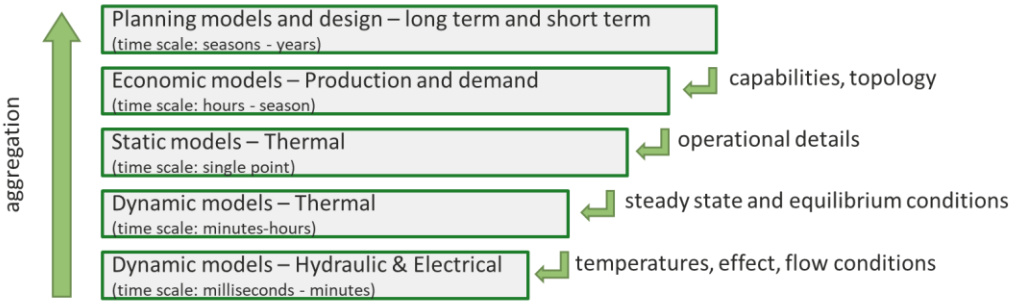

Figure 1: Hierarchical levels according to time scales and associated types of models used for representing the system, and for characterization and assessment of flexibility.

The scope of work package 1 is on control and optimization of operation, which is reflected in time scales up to hours and at most days, and thus only encompassing the lower levels. Moreover, the thermal grid, buildings and thermal storage are considered, alongside with wear and tear on components and economic aspects in terms of boundary conditions.

To characterize the available flexibility in a district heating/cooling system, models representing the system are needed. Depending on the time scale different types of models are used, as shown in Figure 1. Such a decomposition is also motivated by the established decomposition of hierarchical levels in the automation context as shown in Figure 2. Clearly, the time granularity and the primary source of information differ for the design, implementation, and operation of a solution that makes use of flexibility.

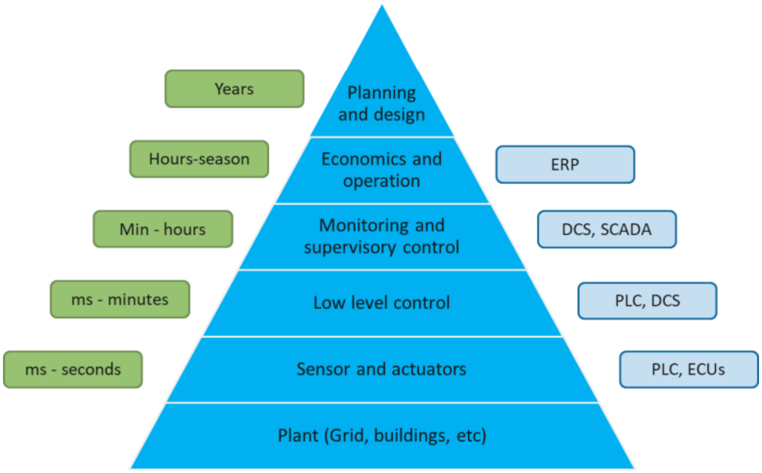

Figure 2: ISA-95 Automation pyramid with time scales and data sources for the association of modelling principles for flexibility.

1.2 Organization of the report

The report is organized as follows. First the state of the art is reviewed and current approaches for the characterization, assessment and exploitation of flexibility in the control and optimization context are discussed and assessed. The result from the state-of-the-art study are then used as a starting point for the following sections.

In the section *Flexibility characterization,* an approach to characterize flexibility is presented which is based on an optimization approach, enabling the joint use of flexibility on all parts in a district heating and cooling system. It is then followed by the description of a methodology to quantify flexibility in section *Flexibility quantification.* The section *Flexibility assessment* presents the methodologies that can be used for the assessment of flexibility either locally on one part of the district heating and cooling system or jointly on all parts.

Using a real-life test-case, the proposed approach is exemplified and discussed. Finally, some conclusions are given.

2 STATE OF THE ART

The aim of the state-of-the-art review was to understand what methodologies for the characterization and assessment of flexibility in the context of control and optimization of operation have been proposed so far and are in use. Most critical in the review is to get an understanding if there are methods in place which can consider all three major parts (production, distribution, consumption) jointly and what their limitations are.

2.1 Approach and overview

For the assessment of the state of the art on the characterization of flexibility and assessment methodologies the following approach was taken. First a set of keywords was chosen, and the premiere venues were selected from the resulting papers and their venues based on the impact factor (IF). The premiere venues are then used to get a grasp of the extend of publications in the field. To collect the gross list of publications *Google Scholar* and *SCOPUS* is used for publications search.

The keyword combinations used to collect the gross list of articles are as follows:

K1. “flexibility” AND “district heating”
K2. “flexibility” AND “district cooling”
K3. “flexibility” AND “building”
K4. “storage” AND “district heating”
K5. “storage” AND “district cooling”
K6. “storage” AND “building”

The resulting paper count for the primary venues is shown in Table 1 and is very high. The topic is thus under intense investigation for a longer period, meaning there is a substantial amount of research results that need to be considered.

Table 1: Number of papers published in the selected primary venues for the used keyword combinations

Keyword combination	**K1**	**K2**	**K3**	**K4**	**K5**	**K6**
Venue						
Applied Energy	654	495	2110	923	712	3364
Energy	759	525	1828	1168	827	3015
Renewable Energy	168	110	859	345	245	1865
Energy and Buildings	323	283	1874	639	575	3446
Energies	3	0	30	52	1	129
Energy Procedia	1169	1135	1896	2417	2348	4381

Clearly, the keyword combination K3 and K6 were too wide and discarded. To narrow down the number of articles considered in the review, the following criteria are used in the screening and needed to be fulfilled by assessing either title or abstract:

C1. Recent survey or review article with a focus on methodologies

C2. Either control, optimization of operation, scheduling or automation

C3. Neither design nor planning

C4. Not a pure case study

The criteria C1 was jointly used with C2 and C3, and only the most recent articles were considered. Criteria C3 had to be used with care, since there is often the terminology “design of a control scheme” or “design of an optimization strategy” leading to discarding of relevant articles. There are many articles that apply a methodology on a specific case which is of interest to understand the applicability and limitations of a methodology but does not propose a new method. Criteria C4 is used to discard these articles but needed to be used with care since most methodology articles use a case study or benchmark case to assess the feasibility of the proposed method.

The publications are then screened for their relevance for control and optimization where dynamic models and potentially economic models in accordance with Figure 1 are used. Thereafter, the short list is more carefully examined and their potential for re-use in the context of Flexi-Sync is assessed. For the most relevant papers, a summary and analysis are presented.

Three categories are used in line with the major parts of a district heating or cooling system: distribution, consumption side (buildings) and production side. After a short introduction of each category, the summary of the paper is given (an abridged version of the original abstract by the respective authors) and an assessment of the relevance and contribution to Flexi-Sync.

It should also be mentioned that thermal energy storages (TES) can be present in any of three categories, but there is a general focus on TES at the consumer side. TES are the natural means of introducing flexibility into a system by storing excess heat that can occur in any of the categories.

2.2 Articles focusing on the distribution

Using the distribution grid as a passive thermal energy storage unlocks additional flexibility but requires the use of more advanced control schemes for operation. There are relatively few papers published on that approach and most of them are very recent. A characterization of the flexibility is not given and, in all cases, embedded as the thermal inertia of system and a time delay of the transport phenomena, but instead there is a focus on exploiting the inertia by performing pre-heating or pre-cooling of the distribution grid. While Vandermeulen et. Al (2018) provide a nice introduction to the topic, the work in Atta & Birk (2018), Li et. al. (2020), and Zhou et. al. (2019) propose an optimization and control strategy that can exploit the thermal inertia to perform peak shaving and increase the economic efficiency of a district energy system. In the cases of Li et. al. (2020) and Zhou et. al. (2019), as sector coupling is also foreseen.

Article	Vandermeulen, A., van der Heijde, B., & Helsen, L. (2018). Controlling district heating and cooling networks to unlock flexibility: A review. Energy, 151, 103-115. Citation: 72

Summary	Investigates how to use the thermal capacity of the network, ad hoc thermal storages, and buildings to cope with intermittent Renewable Energy Sources (RES). Argues that Thermal Energy Storage (TES) units such as borehole TES or water tanks (up to 200’000 m^3) are necessary to achieve exploitable levels of flexibility. The TES systems can be either small and distributed across the network or larger and centralized. The authors moreover discuss how various actors (such as base load and peak load plants) can be connected to the network and controlled to implement peak shaving and valley filling in heating and cooling systems. A number of centralized and distributed control strategies are discussed, the description of which, however, are very high level.
Assessment	The paper provides a nice introduction to control issues for district heating and cooling networks but lacks depth. Most of the paper constitutes an interesting non-technical first read on the topic but, as a matter of fact, most of the discussion is just common-sense observations and pointers to various existing results, models, etc. that are to be pieced together.

Article	Atta, K., & Birk, W. (2018). Utilization of Generic Consumer Modeling in Planning and Optimization of District Heating and Cooling Systems. In 21st Nordic Process Control Workshop, Åbo Akademi University, 18-19 Jan. 2018.
Summary	This paper discusses the concept of utilizing a simplified static model of different types of consumers in the network to design a decision support system that will guide the operators of the DHC network to optimally operate the network with different operational scenarios that include but not limited to: (i) energy consumption minimization, (ii) economic operation, (iii) peak load reduction/shifting, and (iv) environmentally friendly operation. In its current form, the operator will be informed, while in the future these actions could be fully automated in a closed loop context.
Assessment	The paper makes use of a grid model and aggregated building models to perform peak load shaving by pre-heating and pre-cooling the grid and buildings. Flexibility is intrinsic and not explicitly characterized or assessed. The work is targeting optimization and control from a predictive perspective. The work is limited to a case and not generalized.

Article	Li, X., Li, W., Zhang, R., Jiang, T., Chen, H., & Li, G. (2020). Collaborative scheduling and flexibility assessment of integrated electricity and district heating systems utilizing thermal inertia of district heating network and aggregated buildings. Applied Energy, 258 Citation: 18

Summary	This paper proposes a collaborative scheduling model of integrated electricity and district heating systems considering the thermal inertia of district heating network and aggregated buildings and a flexibility assessment method of the integrated electricity and district heating systems. A detailed thermal model of the aggregated buildings and the transmission time delay characteristics of heating network pipelines, and a thermal inertia model of the district heating systems is proposed. Then, the scheduling model considering thermal inertia of district heating network and the aggregated buildings is formulated as a quadratic programming problem, the objective function of which is to minimize the operating cost of integrated electricity and district heating systems. Four scheduling cases based on whether to consider the transmission time delay characteristics of heating network pipelines or the adjustable indoor temperature of aggregated buildings are established, and a flexibility assessment method of different cases for the electricity system and coupling component is proposed.
Assessment	The article suggests a scheduling model of the integrated electricity and district heating system. The flexibility is related to the thermal inertia in the district heating system and the building stock. The operating costs of the integrated systems are optimized. The flexibility of the integrated system increases the possibility to integrate more wind power. The model for the transmission is simplified to time delays but might be sufficient. The results of the paper are very interesting and should be considered for the optimization and assessment.

Article	Zhou, C., Zheng, J., Liu, S., Liu, Y., Mei, F., Pan, Y., ... & Wu, J. (2019). Operation optimization of multi-district integrated energy system considering flexible demand response of electric and thermal loads. Energies, 12(20), 3831. Citation: 2
Summary	The paper considers a general energy transfer model of the district heating network (DHN), describes it by the basic equations of the heating network and nodes considering the characteristics of the transmission time delay and heat loss in pipelines. A coupling model of DHN and multi-district integrated energy system (IES) is established. Then a flexible demand response (FDR) model of electric and thermal loads is established. Considering the flexibility of the heat demand, a thermal load adjustment model based on the comfort constraint is constructed to make the thermal load elastic and controllable in time and space. Finally, a mixed integer linear programming (MILP) model for operation optimization of multi-district IES with the DHN considering the FDR of electric and thermal loads is established based on the supply and demand sides. The result shows that the proposed model makes full use of the complementary characteristics of electric and thermal loads in different districts. It realizes the coordinated distribution of thermal energy among different districts and improves the efficiency of thermal energy utilization through the DHN. FDR effectively reduces the peak-valley difference of loads. It further reduces the total operating cost by the coordinated operation of the DHN and multi-district IES.

Assessment	The paper proposes to optimize the operations costs of integrated energy systems including electricity, gas and district heating. There are also some costs for flexible demand response and the grid is considered using the time delays for the transport. The method can also consider the multiple energy sources that are integrated. Flexibility is not directly characterized or assessed but could be used for the optimization needed to be done in task T1.2.

2.3 Articles focusing on the consumer side

The bulk of material on exploiting flexibility is in focusing on the consumer side which target the thermal inertia of buildings in combination with TES and behavioural adaptation by the consumers, often referred to as demand response (DR). The aim is in all cases to use the local flexibility in the building or provided by the user to enable peak shaving and to reduce the energy consumption during pre-defined time-frames. The reduction in energy consumption is either defined in terms of room temperature or in terms of used energy (heat/cold).

Clauß et. al. (2017) summarize different characterization and assessment methods of flexibility from literature in terms of KPIs for control and optimization purposes, which is very valuable. Arroyo et. al. (2017) took an optimization approach to quantify the available flexibility on a building level, showing that the exploitation despite the few actuation points is difficult and might render conflicts with comfort requirements. How to assess the comfort issue and understanding the comfort flexibility of residents is discussed by Saurav et. al. (2017) which can be helpful in relaxing the comfort requirements in an optimization problem. From a mere understanding of the optimization problem already on a building level a multi-level optimization problem needs to be address. Broadening this beyond the building itself, yields additional levels in the optimization problem, where the question of degrees of freedom places an essential role. One need to ask the question: Is the problem controllable and observable?

The work by Dominković et. al. (2018) and the Powell et. al. (2016) be progress in that direction. Dominković and his co-authors argue that combined building and system level simulations can be used for optimization purposes but only uses static model, which is usually not a feasible assessment from a control perspective and to understand if the drawn conclusions are verifiable. Powell et. al. takes a similar approach and adds the electric market and economic factors, but also goes beyond the building level and uses multiple energy sources. In this respect Atta & Birk (2018), can confirm the later approach for a case but using dynamic models.

Article	Le Dréau, J., & Heiselberg, P. (2016). Energy flexibility of residential buildings using short term heat storage in the thermal mass. Energy, 111, 991-1002. Citation: 206

Summary	Focuses energy efficiency and Structural Thermal Energy Storage (STES) in prosumer buildings, proposing simple control strategies that either i) store heat (by increasing temp. set-points) temporarily, or ii) “conserve heat” (by decreasing the temp. set-points). The flexibility here is seen as the ability to manipulate the demand for thermal energy in time, within the limits set by considerations on the acceptable comfort. Three main indexes are considered to characterize the building structure as a storage medium: - The amount of heat charged/stored after an increase in temperature of 2K - The amount of heat discharged after a decrease in temperature of 2K - The ratio of the previous two quantities, which is referred to as shifting efficiency The conclusions are drawn from numerical simulations. Different scenarios are considered in which a charging phase is followed by a discharging one, and the effects on the overall power consumptions are quantified.
Assessment	The usefulness of these results for control is interesting although the work rather targets technological developments (such as the adoption of floor heating vs radiators). It should be stressed that the main proposal of the authors is that flexibility in adjusting the heating demand should be exploited to compensate fluctuations in the electrical grid. Overall, the results are not far reaching but the paper gives a basis of indications on which a feedback control strategy could be built.

Article	Saurav, K., Choudhury, A. R., Chandan, V., Lingman, P., & Linder, N. (2017, October). Building modelling methodologies for virtual district heating and cooling networks. In 2017 IEEE International Conference on Smart Grid Communications (SmartGridComm) (pp. 387-392). IEEE. Citation: 1
Summary	District heating and cooling systems (DHC) are a proven energy solution that has been deployed for many years in a growing number of urban areas worldwide. They comprise a variety of technologies responsible for the production and supply of heating, cooling, domestic hot water and electricity. Although the benefits of DHC systems are significant and have been widely acclaimed, yet the full potential of modern DHC systems remains largely untapped. There are several opportunities for improving the efficiency of DHC systems, which will enable the exploitation of renewable resources, waste heat recovery, etc., in order to facilitate the transition towards next generation of DHC systems. This motivated the need for modelling these complex systems. Large-scale modelling of DHC-networks is challenging, as it has several components interacting with each other. In this paper we present two methodologies to model the consumer buildings. These models will be further integrated with network model and the control system layer to create a virtual test bed for DHC system. The model is validated using data collected from the DHC system located at Lulea, Sweden. The test bed will be then used for simulating various test cases such as peak energy reduction, overall demand reduction etc. prior to real world testing.

Assessment	Consumer flexibility is assessed on a real-life pilot and used to determine the energy flexibility of a building by combining a model-based approach with real-life data from different climatic scenarios. The models are fully dynamic and can be used in a control context and the consumer flexibility is expressed as a temperature range which is determined from experimentation in the building. The ideas can be used for the assessment of flexibility.

Article	Reynders, G., Diriken, J., & Saelens, D. (2017). Generic characterization method for energy flexibility: Applied to structural thermal storage in residential buildings. Applied energy, 198, 192-202. Citation: 76
Summary	Focuses Structural Thermal Energy Storage (STES) in buildings and in the context of Active Demand Response (ADR) scenarios. Proposes three indexes to quantify the potential benefit toward ADR of STES: 1. Available storage capacity quantifies the amount of heat (in kWh) that can be stored within the STES. Energy is stored by, for example, temporarily increasing the STES temperature with respect to the nominal reference value. It is limited by comfort considerations. 2. The storage efficiency aims to quantify the energy losses that different STES temperature states or energy storage levels induce during operation. 3. The power shifting capability quantifies simultaneously the rate of heat that can be transferred to and from the STES and the length of time this rate can be maintained over a future horizon without violating comfort constraints. These indexes are mapped in function of the age and renovation level of detached, semi-detached, and terraced asset types for the typical Belgian building. The investigation and results are based on numerical simulations.
Assessment	The usefulness of these results for control is minor and rather targets technological developments (such as the adoption of floor heating circuits). The characterization of the flexibility is still somewhat interesting. I feel this is good material to build a background but not more than that.

Article	Finck, C., Li, R., Kramer, R., & Zeiler, W. (2018). Quantifying demand flexibility of power-to-heat and thermal energy storage in the control of building heating systems. Applied Energy, 209, 409-425. Citation: 75

Summary	The article investigates how to use optimal control to study how the thermal dynamics of the building, heat pump, electric heater, and Thermal Energy Storage (TES) tanks can be exploited to create demand flexibility. The authors suggest that "power-to-heat conversion using heat pumps is likely the most mature and favourable technology enabling flexibility in smart grid operations". The study builds on simulated results of a typical office building located in the Netherlands that are produced in MATLAB. Demand flexibility is characterized across its three different aspects of "size (energy), time (power), and costs": 1. For the size aspects, it considers the available storage capacity and storage efficiency. As in other works the ratio between the amount of heat that can be charged and consequently discharged is called storage efficiency or shifting efficiency. Section 2.3.1. 2. For the cost aspect, the authors consider the Flexibility factor (FF) which grades the usage of heating power in terms of the plausible low and high grid electricity costs. Section 2.3.2. 3. For the power aspect, they consider the power shifting capability, namely the difference between the power consumption during optimal control and nominal/reference control. The authors extend the index to systems with heat pumps, electric heaters, and TESs.
Assessment	An "optimal control" study is presented that analyses the power shifting capability of different TESs and the instantaneous power flexibility with respect to time and the length of the control time step. Probably not viable in practice, but the way the control strategy is presented and analysed graphically is highly interesting and could be re-used.

Article	Clauß, J., Finck, C., Vogler-Finck, P., & Beagon, P. (2017, August). Control strategies for building energy systems to unlock demand side flexibility–A review. In IBPSA Building Simulation 2017, San Francisco, 7-9 August 2017. IBPSA. Citation: 26
Summary	The paper is a survey of Demand Side Flexibility (DSF) KPIs in the context of building energy management. The paper recognizes that most existing flexibility metrics are defined in connection to some sort of "control scenario" in which changes in the energetic policy are applied and the effects are compared to the performance of a nominal or reference strategy. Broadly speaking, the paper defines flexibility at the building level as "the margin in which the building can be operated while respecting its functional requirements." The paper contains 1. An almost-two-page-long table (Table 1, p1752) listing a variety of flexibility indexes addressing different scenarios. 2. A one-page-long table (Table 2, p1754) listing building energy control strategies (mostly [seemingly] simple ones). 3. A mapping of which KPIs are used in each of the reviewed control strategies (Table 3, p1756).

Assessment	The information in the tables is highly interesting and of enormous value for the scope of understanding current KPIs and “control” strategies. Our opinion is that most of these KPIs are a bit artificial and difficult to generalize to different buildings.

Article	Stinner, S., Huchtemann, K., & Müller, D. (2016). Quantifying the operational flexibility of building energy systems with thermal energy storages. Applied Energy, 181, 140-154. Citation: 119
Summary	The paper addresses Building Energy Systems (BES) endowed with Thermal Energy Storages (TES). It is argued that flexibility must account for time, power, and energy aspects. The analysis is extended to the district level since the impact of unique buildings on the whole network is, per se, very small. The paper argues that the integration of sources of flexibility (heat pumps, TES, local CHPs) requires both the distribution of these resources across the network and their joint orchestration with smart electrical grids that are Renewable Energy Source (RES) aware. Different “types” of flexibility are considered: 1. Temporal: including forced and delayed flexibility. The first one quantifies the amount of time required to fully charge the TES at peek heat production capabilities. The second index, delayed flexibility, quantifies the amount of time the heating system can stay off while a fully charged TES is used to match the heat demand. By repeatedly evaluating these two indexes over a long period of time it is possible to understand when the overall Electrical grid coupled Heat Generators (EHGs; this refers to heat pumps and local CHPs) offer some flexibility. 2. Power: tries to quantify the amount of instantaneous power flexibility. For instance, some systems may be able to provide low power flexibility for long times or rather high-power flexibility but only for short times. Section 2.2. 3. Energy: are defined as integrals of the power flexibilities. Section 2.3. A quantification of these indexes is performed using numerical simulations. An interesting feature is that the authors normalize the KPIs using two dimensionless parameters that relate to the nominal heat load of the EHG and average daily heat demand of the building.
Assessment	The numerical results are interesting but are drawn considering a very simplified scenario with a yearly-constant heat demand.

Article	Arteconi, A., Hewitt, N. J., & Polonara, F. (2012). State of the art of thermal storage for demand-side management. Applied Energy, 93, 371-389. Citation: 442
Summary	The paper addresses TES systems to “shift electrical loads from high-peak to off-peak hours”. The emphasis is thus again Renewable Sources in the form of electricity, electrical districts, and electrical load management. An interesting point is made for pumped water storages in large hydroelectric plants and interstate high interconnectors as a high-level source of flexibility for the electrical grid. A brief breakdown analysis of the residential and tertiary sector electricity usage is given in Figures 1 and 2, highlighting the shares of the total usage that could be managed by TES (although the actual impact of managing the intrinsic flexibility would be necessarily smaller). A significant part of the paper proceeds to review TES technology (concrete, stratified water, latent heat systems, PCM, cold energy storages, thermochemical, etc.).
Assessment	the introduction to the subject and the review of the TES architectures is interesting as a first read but not particularly valuable for control.

Article	De Coninck, R., & Helsen, L. (2016). Quantification of flexibility in buildings by cost curves–Methodology and application. Applied Energy, 162, 653-665. Citation: 114
Summary	The paper focuses thermal storage in building as a means to cope with the volatility of renewable sources. Results are presented showing the trade-off affecting flexibility and cost depending on time, weather, utility rates, building use, and comfort requirements (which are all obvious affecting factors). The focus on renewable electricity is stressed in the following definition: “the flexibility of a building is the ability to deviate from its reference electric load profile”. This flexibility is then an electrical power rate (for instance, kW), and the paper focuses a simulated building heating scenario in which the optimal “flexible” operations are compared to the “reference” minimum-cost operation. With this methodology the authors are able to define “cost curves” that link the available flexibility with its cost.
Assessment	The setup of the authors, while interesting, compares the optimal operation scenario with scenarios in which positive and negative flexibilities are exploited forcefully. This results in flexibility always inducing a non-negative cost compared to the optimal efficiency operations. We believe this kind of misses the point that the optimal operations are exploiting some degree of flexibility already since the underlying model is dynamical and thus accounts for thermal storage effects.

Article	Hedegaard, K., & Balyk, O. (2013). Energy system investment model incorporating heat pumps with thermal storage in buildings and buffer tanks. Energy, 63, 356-365. Citation: 86
Summary	This paper focuses flexibility by considering a thermal building manager that participates in demand response scenarios through a local heat pump system. This is a "more of the same" kind of paper, with so many similarities to other works in the literature. One of the main conclusions, although it seems that the authors do not stress it particularly, is that the overall acquisition and operation benefit-cost of exploiting passive flexibility induced by the ability of storing thermal energy in the building structure is larger than in scenarios in which ad hoc TES water thanks are deployed. This sort of contrasts other works in the literature but since the models are always linear and not necessarily fully specified (for example, the parameters are often unspecified), it is particularly difficult to draw definitive conclusions.
Assessment	Due to the limited report of details the paper is not directly useful. Still there is a minor contribution to be considered as mentioned where the deployment of TES is not necessarily an effective measure.

Article	Kensby, J., Trüschel, A., & Dalenbäck, J. O. (2015). Potential of residential buildings as thermal energy storage in district heating systems–Results from a pilot test. Applied Energy, 137, 773-781. Citation: 166
Summary	The paper evaluates the potential of utilizing buildings as a short-term thermal storage in a pilot involving five multifamily residential buildings in Gothenburg, Sweden (study length=52 weeks). On the basis of the observations, it proposes a "degrees hours" unit of measure to quantify the thermal storage capacity of residential buildings
Assessment	The pilot is carried out by feeding to the building substation controller an additive offset signal altering the measurement of the outside temperature. While this effectively offsets the control system behaviour, the control system would recover from the offset and after some time. The immediate question that arises is: Do the results reflect flexibility or the performance of the substation controller in rejecting unknown additive disturbances? The second option is the most likely scenario. The paper contains a number of good references that could help motivate the whole flexibility effort.

Article	Sun, Y., Wang, S., Xiao, F., & Gao, D. (2013). Peak load shifting control using different cold thermal energy storage facilities in commercial buildings: A review. Energy conversion and management, 71, 101-114. Citation: 219

Summary	The paper aims to review existing peak load shifting strategies using Building Thermal Mass (BTM), Thermal Energy Storage (TES), and Phase Change Material (PCM) systems. The review focuses on commercial buildings and culminates in a discussion about which research efforts are needed to develop both more efficient and more applicable load shifting controllers. The interest in peak load demand shifting is motivated on the basis that while peak load is typically serviced only for a short period, its cost may represent a sizeable (or even majority) part of the total heating cost. Peak load shifting strategies have three main ingredients: i) load prediction, 2) pre-charging control, 3) discharging control. The crux is then to understand how much of the heat-load or cooling-load should be pre-charged given the predictions and how to optimally discharge it. The paper then proceeds to list a large number of papers in which some more or less simple control strategy is applied.
Assessment	The review focuses largely papers that have adopted BTM, TES, and PCM technologies rather than how peak load shifting is done at a more abstract level (that is, in terms of a control and optimization strategy). Nevertheless, the basics of peak load shifting and how to address the problem are detailed and can be re-used.

Article	Seem, J. E. (1995). Adaptive demand limiting control using load shedding. HVAC&R Research, 1(1), 21-34. Citation: 27
Summary	The paper evaluates a load shedding control strategy that exploits predictions of the future loads based on a random walk model. In brief, a forecaster infers the amount of load shedding requirements over a time-discretize rolling horizon.
Assessment	Unfortunately, the analysis is limited to evaluating the particular forecasting model and a more concrete application is missing. Nevertheless, the basic intuition behind the forecaster and its simple structure are interesting. Since exploiting flexibility depends on forecasting the heat loads, an experimental analysis of the applicability of the random walk in a district network context could be interesting. While this is an older contribution, the ideas are more valuable values

Article	Johansson, C., Wernstedt, F., & Davidsson, P. (2010, May). Deployment of agent-based load control in district heating systems. In First International Workshop on Agent Technologies for Energy Systems, Canada. Citation: 37

Summary	The paper evaluates a control scheme in which a central authority supervises all substations in the network. The strategies are shown to have two benefits: peak load shaping and an overall reduction of the heating costs at the consumers. The paper presents experimental results from three different district heating systems in Sweden. Unfortunately, however, the exact control laws that are considered are not formalized.
Assessment	The paper is most likely one of the foundations of the NODA system that is nowadays fully commercialized.

Article	Powell, K. M., Kim, J. S., Cole, W. J., Kapoor, K., Mojica, J. L., Hedengren, J. D., & Edgar, T. F. (2016). Thermal energy storage to minimize cost and improve efficiency of a polygeneration district energy system in a real-time electricity market. Energy, 113, 52-63. Citation: 48
Summary	In this work, dynamic optimization exploits the flexibility of thermal energy storage by determining optimal times to store and extract excess energy. This concept is applied to a polygeneration distributed energy system with combined heat and power, district heating, district cooling, and chilled water thermal energy storage. The system is a university campus responsible for meeting the energy needs of tens of thousands of people. The objective for the dynamic optimization problem is to minimize cost over a 24-h period while meeting multiple loads in real time. The paper presents a novel algorithm to solve this dynamic optimization problem with energy storage by decomposing the problem into multiple static mixed-integer nonlinear programming (MINLP) problems. Another innovative feature of this work is the study of a large, complex energy network which includes the interrelations of a wide variety of energy technologies. Results indicate that a cost savings of 16.5% is realized when the system can participate in the wholesale electricity market.
Assessment	A district energy system including district heating and cooling, thermal storage and CHP is studied. The objective is to minimize the costs and solve the optimization problem. The issue is that the solution is tailored towards the studied case and that flexibility is not directly assessed. The value for the flexibility characterization and assessment is minor but could be of interest for the optimization problem in T1.2.

Article	Dominković, D. F., Gianniou, P., Münster, M., Heller, A., & Rode, C. (2018). Utilizing thermal building mass for storage in district heating systems: Combined building level simulations and system level optimization. Energy, 153, 949-966. Citation: 36

Summary	Higher shares of intermittent renewable energy in energy systems have raised the issue of the need for different energy storage solutions. The utilization of existing thermal building mass for storage is a cost-efficient solution. In order to investigate its potential, a detailed building simulation model was coupled with a linear optimization model of the energy system. Different building archetypes were modelled in detail, and their potential preheating and subsequent heat supply cut-off periods were assessed. Energy system optimization focused on the impact of thermal mass for storage on the energy supply of district heating. Results showed that longer preheating time increased the possible duration of cut-off events. System optimization showed that the thermal mass for storage was used as intra-day storage. Flexible load accounted for 5.5%–7.7% of the total district heating demand. Furthermore, thermal mass for storage enabled more solar thermal heating energy to be effectively utilized in the system. One of the sensitivity analyses showed that the large-scale pit thermal energy storage and thermal mass for storage are complimentary. The cut-off duration potential, which did not compromise thermal comfort, was longer in the newer, better insulated buildings, reaching 6 h among different building archetypes.
Assessment	The paper does consider flexibility from a load perspective by utilizing the thermal storage in the building. The problem is not treated as a control problem and only static models are considered, meaning the control and optimization objective on the lower levels is feasible. The study make use of a case and performs scenario-based simulations. The value is more from a guidance perspective and not for direct re-use.

Article	Arroyo, J., Gowri, S., De Ridder, F., & Helsen, L. (2017). Flexibility quantification in the context of flexible heat and power for buildings. The REHVA European HVAC Journal. Citation: 1
Summary	A framework that allows increasing the energy state of buildings during generation peaks and lowering their energy use when supply is scarce (and thus expensive), while respecting the indoor thermal comfort is proposed. For this end, a Dynamic Coalition Manager (DCM) architecture has been defined. To estimate the cost of changing the demand behaviour a measure for flexibility is required as well, i.e., the capacity of the load to behave differently compared to the baseline scenario. This flexibility quantification is needed to estimate the flexibility offer that the DCM can make to other market players such as the Distribution System Operators (DSOs) and Balance Responsible Parties (BRPs). Hence, the chosen flexibility indicator must be scalable since it has to be aggregated for a cluster of buildings. There already exist several ways of quantifying thermal flexibility of buildings. However, assessing and comparing the different definitions is a complicated task since the suitability of each indicator for its specific application is crucial. In this paper a flexibility quantification based on multiple Model Predictive Control (MPC) strategies is developed for an individual building, which is aggregated for a cluster of buildings. The flexibility indicator is demonstrated using grey-box models for the BAs.

Assessment	The proposed method is control and optimization oriented considering buildings as the primary focus. It also considers constraints and uses a predictive control perspective. The paper is highly relevant and interesting. It also shows the complexity of the task of characterizing and assessing flexibility.

Article	Arroyo, J., Spiessens, F., & Helsen, L. (2020). Identification of multi-zone grey-box building models for use in model predictive control. Journal of Building Performance Simulation, 13(4), 472-486. Citation: 0
Summary	Predictive controllers can greatly improve the performance of energy systems in buildings. An important challenge of these controllers is the need of a building model accurate and simple enough for optimization. Grey-box modelling stands as a popular approach, but the identification of reliable grey-box models is hampered by the complexity of the parameter estimation process, specifically for multi-zone models. Hence, single-zone models are commonly used, limiting the performance and applicability of the predictive controller. This paper investigates the feasibility of the identification of multi-zone grey-box building models and the benefits of using these models in predictive control. For this purpose, the parameter estimation process is split by individual zones to obtain an educated initial guess. A virtual test case from the BOPTEST framework is contemplated to assess the simulation and control performance. The results show the relevance of modelling thermal interactions between zones in the multi-zone building.
Assessment	Predictive controllers enable the consideration of constraints in their internal optimization, which means that the inertia can be considered and pre-heating and cooling for peak load shaving can be easily realized. Such controllers are model-based and depend on the model quality. The feasibility of such models is discussed in the study. It relates to flexibility through the model feasibility. Direct characterization and assessment is not given.

2.4 Articles focusing on the production side

In several works in the prior sections the production side is considered. Nevertheless, there is also a focus on integrating RES but also balancing the electricity market with the help of a district heating and cooling system where TES are considered. The general conclusion is similar, TES or thermal inertia can be exploited, but there are few results which could directly be used from a control and optimization perspective. The flexibility is generally not characterized and assessed directly, but used through the available storage capacity.

Article	Nuytten, T., Claessens, B., Paredis, K., Van Bael, J., & Six, D. (2013). Flexibility of a combined heat and power system with thermal energy storage for district heating. Applied energy, 104, 583-591. Citation: 287

Summary	The paper aims to study what is the maximum flexibility allowed by a system in which a CHP is coupled with a Thermal Energy Storage (TES). Points out nicely that “demand-side flexibility is a cost-effective means of enabling increased integration of renewable energy sources”. For a CHP with TES buffer one can think of “a system that can freely operate between maximal or minimal remaining buffer capacity, and the flexibility is defined in terms of the space between these two extremities”. Formal definitions in Section 2.1 and 2.1.1-2. Flexibility is here understood as a time-like quantity that measures the maximum delay in hours by which CHP operation can be postponed while the heat demand is serviced by the TES. as intuitively expected, flexibility is low or zero during winter and high (12 hours or more) during parts of the day in summer. An important conclusion is that while flexibility scales approximately with the size of the TES buffer, a larger TES is not particularly helpful during winter when flexibility is nearly zero. A similar numerical study is performed considering decentralized buffers leading to overlapping conclusions. Overall, the centralized buffer allows more flexibility.
Assessment	Interesting problem to formalize from a control theoretic perspective. The results of the paper are interesting, but we think mostly qualitative. Using time-like indexes to quantify flexibility seems to come short when the interesting quantities are energy/power/costs. This is nevertheless one of the approaches to consider seasonal TES connected to CHPs

Article	Pedersen, T. S., Andersen, P., Nielsen, K. M., Stærmose, H. L., & Pedersen, P. D. (2011, September). Using heat pump energy storages in the power grid. In 2011 IEEE International Conference on Control Applications (CCA) (pp. 1106-1111). IEEE. Citation: 69
Summary	The paper designs a linear MPC schemes by which the floating pricing of grid electricity due to renewables is considered to optimally provision heating to a group of simulated houses in Denmark. The electricity cost indirectly drives a heat pump based local heat generator. The strategy effectiveness leverages on the high thermal capacity of modern floor heated constructions.
Assessment	An interesting approach albeit very simplified analysis of the problem. These ideas might be relatively old, and one realizes that the ideas are already both thought of and should have achieved a realization at this point of time. The immediate question is to what are or have been the hinders thus far.

Article	Good, N., & Mancarella, P. (2017). Flexibility in multi-energy communities with electrical and thermal storage: A stochastic, robust approach for multi-service demand response. IEEE Transactions on Smart Grid, 10(1), 503-513.

	Citation: 66
Summary	The paper discusses a linear modelling and control strategy to capture opportunities in the interaction between the electrical energy grid and Demand Response (DR) mechanism that involve distributed Battery Energy Storage (BES) and Thermal Energy Storage (TES) units placed in correspondence to buildings or building districts. No link to district heating or cooling network is made. Numerical results performed using a linear model of 50 detached buildings located in England, show that scenarios in which buildings are endowed with TES and temperature flexibility produce the highest benefits in terms of cost reduction at the district level.
Assessment	The modelling is interesting albeit very abstract and not district heating + cooling related. The results are supportive of distributed TES and temperature flexibility at the building level.

Article	Johan Kensby, Linnea Johansson, Samuel Jansson, Jens Carlsson (2019). The value of flexible heat demand. Report 2019:565
Summary	The report aims at quantifying the value of flexibility in district heating systems that 1) use buildings as thermal storage, 2) adopt heat source shifting strategies, 3) are endowed with borehole storages connected to buildings. The benefits are demonstrated in terms of total reduction of the building heat demand, a reduction in the CO2e emissions, and the overall cost of supplying energy to the district heating system. These benefits are realized through: 1. Smoothing of the heat load profile and in particular a decreased dependence on expensive peak load Heat Only Boilers (HOBs). 2. Better optimization of CHP and heat pumps following the volatile price of electricity. A simulation study is developed that covers six different heat grid types (mainly characterized by their dependence on the fuels that are used; see Section 2.1) and considering a three years long production period.
Assessment	An interesting point made in the report is that Building Heat Pump systems should be prioritized since they incur a lower operating cost even when a district heating loop is present. The authors make use of an interesting notion of shallow and deep flexibility to address flexibilities in different parts of the building's heating system that may have different availability. One thing that is made very clear is that eventually leveraging the flexibility means having to take into consideration the connection with the electricity district grid.

Article	Bachmaier, A., Narmsara, S., Eggers, J. B., & Herkel, S. (2016). Spatial distribution of thermal energy storage systems in urban areas connected to district heating for grid balancing—A techno-economical optimization based on a case study. Journal of

	Energy Storage, 8, 349-357. Citation: 19
Summary	Spatial distribution of thermal energy storages in district heating networks (DHN) can increase flexibility options for the operation of central combined heat and power conversion units. The location, the size and the operation of thermal storage systems are determined with a techno-economical optimization tool. The optimization is driven by a cost minimization related to investment, maintenance and hourly fuel consumption. Simultaneously, the revenues for selling electricity at the electricity market are maximized. Technical and economical limitations are implemented in various scenarios in order to analyze the flexibility options with the spatial distribution and operation of thermal energy storage systems. Moreover, a bidirectional driven heating pipe system with spatially distributed entry points for heat is established in a further scenario and its advantage is discussed by the means of a case study.
Assessment	The paper addresses the issue of balancing the fluctuating renewable energy supplied to the electricity grid by integrating TES or operating CHPs differently. Costs for investments, maintenance and hourly fuel consumption are minimized and revenues for selling electricity at the electricity market are maximized. Flexibility is not characterized or assessed directly, and the optimization is performed on a higher level (economic and planning). The value for control and optimization purposes is limited.

Article	Zhang, X., Strbac, G., Shah, N., Teng, F., & Pudjianto, D. (2018). Whole-system assessment of the benefits of integrated electricity and heat system. IEEE Transactions on Smart Grid, 10(1), 1132-1145. Citation: 22
Summary	This paper presents a novel integrated electricity and heat system model in which, for the first time, operation and investment timescales are considered while covering both the local district and national level infrastructures. This model is applied to optimize decarbonization strategies of the U.K. integrated electricity and heat system, while quantifying the benefits of the interactions across the whole multi-energy system and revealing the trade-offs between portfolios of: 1) low carbon generation technologies (renewable energy, nuclear, and CCS) and 2) district heating systems based on heat networks and distributed heating based on end-use heating technologies. Overall, the proposed modelling demonstrates that the integration of the heat and electricity system (when compared with the decoupled approach) can bring significant benefits by increasing the investment in the heating infrastructure in order to enhance the system flexibility that in turn can deliver larger cost savings in the electricity system, thus meeting the carbon target at a lower whole-system cost.

Assessment	Zhang et al. study the integrated electricity and heat system in two timescales related to investment phase and the operational phase. The study does not consider control and optimization and the models are only intended for the design, planning and economic level, which have static character. Further, there is no direct characterization and assessment of the flexibility.

Article	Åberg, M., Lingfors, D., Olauson, J., & Widén, J. (2019). Can electricity market prices control power-to-heat production for peak shaving of renewable power generation? The case of Sweden. Energy, 176, 1-14. Citation: 6
Summary	100% renewable energy systems require high penetration of variable renewable electricity (VRE) generation. This causes the net load in the system to be more variable and could cause operational problems in local power grids. Demand side management (DSM), such as fuel or energy carrier switching in response to a price signal, can provide flexibility to meet the increased variability. This study investigates the impact of VRE production on electricity prices and their potential to act as an incentive to control district heating power-to-heat (P2H) production in order to shave VRE production peaks. Also, the potential to increase P2H production flexibility with additional heat storages is studied. Electricity prices are simulated by modification of historical electricity market supply curves. A heat storage component is implemented in an existing model for district heat production. The results show that P2H production is significantly increased (up to 98%) when electricity prices are influenced by VRE production. Thermal storages further increase the P2H production by up to 46%. The increased P2H production, however, does not necessarily coincide with the peaks of VRE. Thus, in conclusion, the pricing mechanism on the Nord pool electricity market is insufficient to control P2H production for shaving VRE production peaks.
Assessment	The paper investigates the influence of variable renewable energy on prices of electricity and their potential to be used for controlling power to heat in order to peak shave the variable electricity production. As such it is not aiming directly at control and optimization but studies the effect of pricing models. Flexibility is not directly considered or quantified and the outcomes can potentially be helpful in structuring the objective function for the optimization problem in T1.2 which should consider a market model.

2.5 Articles focusing on waste heat recovery from data centres

Data centers are a means to create additional flexibility in district heating as waste heat can be used at peak load hours if available. Complementing with TES can induce flexibility in the heating grid. This enables the concept of IT load to heat which can be spatially distributed depending on the heat load demand. Koronen, et.al. (2020) provides the motivation for such concepts.

The paper by Yaghmaie & Gustafsson (2019) uses a data centre as a case, but mainly proposes a method for model-free control that is based on a data driven approach which could be of interest for building control and exploiting flexibility while there are large uncertainties in building and comfort models.

Article	Koronen, C., Åhman, M., & Nilsson, L. J. (2020). Data centres in future European energy systems—energy efficiency, integration and policy. Energy Efficiency, 13(1), 129-144. Citation: 8
Summary	This paper investigates (among other things) the potential of waste heat utilization for data centres located near district heating systems. The authors provide a very interesting survey of recent developments (2018 and 2019), mentioning ongoing experiments in Scandinavia.
Assessment	Waste heat recovery from data centres can be seen as a means to increase the flexibility in district heating systems. The study can be used for motivation purposes, but not for method development. Flexibility methods are not discussed.

Article	Yaghmaie, F. A., & Gustafsson, F. (2019, December). Using Reinforcement Learning for Model-free Linear Quadratic Control with Process and Measurement Noises. In 2019 IEEE 58th Conference on Decision and Control (CDC) (pp. 6510-6517). IEEE. Citation: 1
Summary	This paper investigates a reinforcement learning strategy that applies to discrete-time linear systems subject to Gaussian process and measurement noises. A nearly optimal linear gain is recovered in a model-free fashion from input/output monitoring data. A data center example is treated/advertised but the modelling is too abstract and simplified to capture the intended application. There is no mention of flexibility.
Assessment	The control strategy is interesting and could find wider application in relevant building and district systems as long as linearized models can be tolerated (and I am sceptic about this point).

2.6 Current limitations and gap

Overall, most of flexibility measures described in literature are impractical for control or optimization of operation of the complete system, as only one of the main parts are targeted by the measure. Moreover, the measures have a local character which means they are applied locally at a component and then potentially aggregated.

While it is obvious that the measures or KPIs relate in some way to flexibility as thermal storages (passive or active) and the distribution system are assessed, but it is not clear at all how these indices can be exploited from a control and optimization perspective. Thus, the following question remains unanswered is: How is knowing the value for flexibility useful in an optimization and control context?

It is thus important to integrate the flexibility directly into control and optimization problem. An impactful development could be based on analysing the results of economic model predictive controllers (Hovgaard et. al. (2010)) in a real or realistic scenario and then drawing practical conclusions from those results.

Flexibility can be considered on the demand-side (at the building level), production-side (CHP plants, TES units as part of the district network) or the network itself. But it has usually been treated isolated for the different units. The difficulty that arises is the fact that flexibility is described in different quantities and tightly connected to the component that is assessed. It is therefore important to devise a methodology which harmonizes the definition of flexibility and provides a means to integrate flexibility present at different components.

For the characterization and assessment of flexibility, the literature is limited to the KPIs that have been derived for buildings. In all cases, there is also a high dependency on the availability of models that reflect the dynamic behaviour of the buildings and the surrounding system.

These limitations and gaps will be addressed now in the following sections to propose a more generic approach to flexibility.

The connection with the electricity grid is crucial since that appears to be the biggest source of energy that can be exploited to charge flexible storages. This aspect will though not be further explored here.

3 FLEXIBILITY CHARACTERIZATION

Flexibility is a crucial aspect in operation of any process or production system, including energy systems. It should be understood as the freedom available for changes in operation while complying to demands or targets. For example, what is the limit in the concentration of minerals in a water production unit, or the amounts of the impurities in a steel slab. These limitations represent the flexibility that provide the plants' operators with the ability to adapt operation of the plants. But the difficulty, now, is what is the definition of the flexibility. Our task in that context is given as follows

> *"… A systematic characterization of flexibility which can be constrained from design, and can be used in control, optimization and quantification of the flexibility potential will be achieved."*

We will therefore provide a generic way of defining flexibility being independent of the application. As already stated in the literature review, the most promising approaches for flexibility integrate flexibility to the optimization problem for operation or design, De Coninck et.al. (2014), Arroyo et.al. (2016) and Deng et.al. (2017). The main advantage is that the quantification is directly an integral part of the control and optimization of operation, while requiring a model representing the behaviour of the system. Here, the same outset is used.

3.1 Time and space granularity

Models of dynamic system are always purpose or use-case oriented meaning that the type of models and their complexity need to be aligned, Ljung & Glad (2016). For example, a model for simulation, what-if analysis and training purposes was a higher complexity and might use partial differential equations when representing the thermal grid, while a model for demand load forecasting might be a static nonlinear model. Usually, the complexity can be determined by understanding the needed granularity (resolution) of the dependent variable time and point in space.

Any district heating and cooling system is spatially distributed where multiple heat/cold production units feed into a distribution grid to supply heat/cold to a multitude of consumers. Controlling and optimizing the operation of such a distributed system requires a representation of the control or optimization targets and associated constraints in the appropriate time-scale and related to locations. As already depicted earlier in Figure 1, there are different hierarchical levels in the complete system and those have associated time scales. Further, to properly treat control and optimization aspects there is a need to consider associated model types to represent the system behaviour correctly. Thus, for the characterization and assessment of flexibility we need to determine the appropriate granularity in time and space associated with the control and optimization task.

3.2 Proposed Methodology

In general, optimization of a dynamic system can be described by the following formula, like Arroyo et.al. (2016):

$$\min_{u} Q(x, u, \theta_o, d_e)$$

$$
\begin{gathered}
s.t. \qquad x^{+} = f(x,u,\theta_s,d_e) \\
l_L \leq h_i(x,u,\theta_i,d_e) \leq l_U \\
g_i(x,u,\theta_e,d_e) = 0
\end{gathered}
$$

There, $d_e$represent the exogeneous inputs to the plant reflecting an external input to the problem, possibly measured or forecasted (e.g. outdoor temperature or energy prices), u respresent the control (actuation) signals, x denotes the states of the system (e.g. water or room temperature), $\theta_o, \theta_s, \theta_i$ and $\theta_e$represent the parameters describing the system (e.g. the dimensions of the storage tank or the limits of the allowed temperature). The parameters vectors l_L and l_U represent the lower and upper bounds for the constrained vector valued function $h_i(x,u,\theta_h,d_e)$. Note that, the inequality constraints sometimes can be written as $h_i(x,u,\theta_h,d_e) \leq 0$. We write it in the above format to make it clear to the reader how flexibility is interpreted.

The equation $x^{+} = f(x,u,\theta_s,d_e)$ is a representation of the system dynamics in discrete time state space form. Alternatively, it can be represented in continuous time as $\dot{x} = f(x,u,\theta_s,d_e)$.

Note, all variables and parameters are time dependent and thus might change over time but for the sake of readability and simplicity, we dropped the time argument.

The optimizer or controller will find the operational state that minimizes the objective function(s) $Q(x,u,\theta_o,d_e)$, either single or multi objective, while not violating the constraints. These objectives can be, for example, the operational cost, the consumed energy, or the environmental impact.

3.2.1 Definition of the flexibility from optimization point of view

From optimization point of view, introducing or exploiting flexibility can be interpreted as relaxing constraints, both equality and non-equality, as e.g. explained in Morales-Valdés et.al. (2014). In fact, the relaxation can be achieved mathematically in different ways as shown by the following approaches

A. Changing the constraints function,

$$
\begin{gathered}
l_L \leq \tilde{h}_i(x,u,\theta_i,d_e) \leq L_U \\
\tilde{g}_i(x,u,\theta_e,d_e) = 0
\end{gathered}
$$

Compared to the above case, $h_i(x,u,\theta_i,d_e)$ is replaced with $\widetilde{h_\iota}\left(x,u,\ \tilde{\theta}_i,d_e\right)$, requiring the change of the functions themselves in order to relax the problem. Moreover, it will be difficult to see the relaxation immediately.

B. Changing the parameter

$$
\begin{gathered}
l_L \leq h_i\left(x,u,\ \tilde{\theta}_i,d_e\right) \leq l_U \\
h_i\left(x,u,\tilde{\theta}_e,d_e\right) = 0
\end{gathered}
$$

In this case, the parameters θ_i is replaced with $\tilde{\theta}_i$, being more descriptive, but would not show the exact relaxation.

C. Changing the bounds

$$\tilde{l}_L(t) \leq h_i\big(x, u,\, \tilde{\theta}_i, d_e\big) \leq \tilde{l}_U$$
$$-\epsilon_i \leq h_i\big(x, u, \tilde{\theta}_e, d_e\big) \leq \epsilon_i$$

In this approach, we relax the boundaries of the constraints directly being readable and easily interpreted. Moreover, the equality constraints can be relaxed into smaller boundaries (ϵ_i is a small positive value). In Figure 3, an example for extending the thermal comfort temperature of a building from a fixed value range into time varying and more relaxed one is depicted.

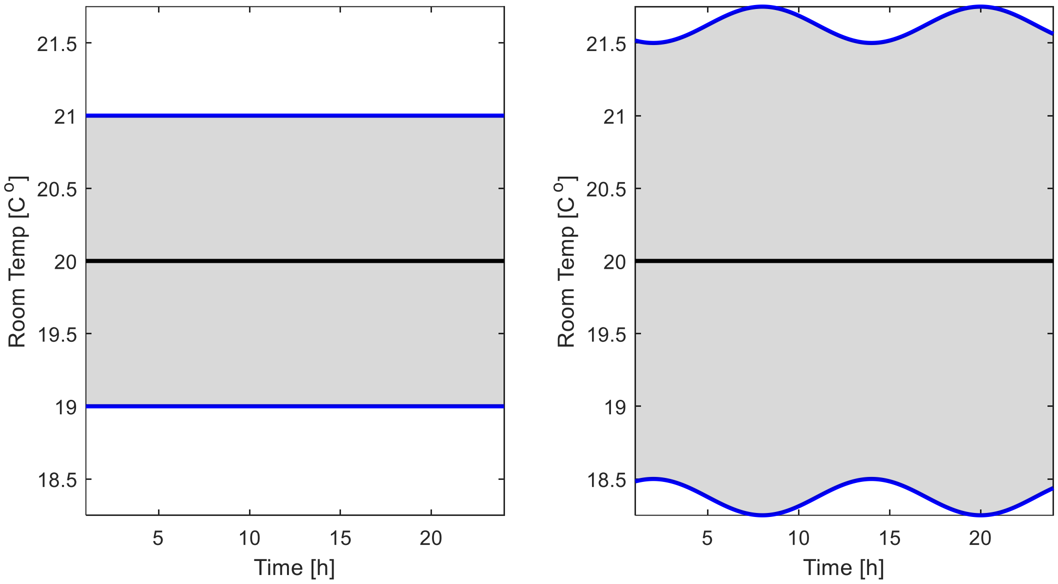

Figure 3: Relaxation of the temperature comfort constraints by introducing a time dependency.

Clearly, these different relaxation approaches can be combined.

3.2.2 Levels of Flexibility

During the review of literature, we came across different understandings or even definitions of “flexibility”. We are now trying to clarify and provide a more generic definition of “flexibility” and will introduce the term of “level of flexibility”.

Just to give an example. Some authors suggest the change in the generated power in the CHP plant as flexibility, while others understand the change in provided energy to buildings as flexibility. Thus, interpreting the control actions as flexibility which is only the consequence of exploiting flexibility being a property of the system or its operational characteristics. Therefore, we will discuss the problem from an abstract point of view.

In order to understand the problem including the objectives and the constraints, we need to understand the plant under optimization. In general, the problem can be divided into three stages (like any energy provider): energy generation, transmission and distribution, and consumption. The main goal of this operation is to provide the required energy to a different location, mainly to provide the required comfort to the residents of buildings and to some industrial applications, e.g. de-icing operation at a metro station.

Depending on the point of interest, different levels of flexibility can be defined. The lowest (or highest depend on the perspective on the problem) is the flexibility in the provided service.

In the building case, the building residents will be interested in their perception of comfort. Accordingly, the comfort is not a defined temperature but rather some range (i.e. instead of a constant temperature, a -/+ range around an average can be defined). Moreover, the range is not constant over time, it might vary over time depending on the time of the day, the day of the year, etc. In this case, the *temperature range is the flexibility* and can be used by the optimizer and leading to actuations by the controller. Instead of keeping a constant temperature inside the buildings, the controller will start to control the energy provided in order to keep the temperature within these limits and at the same time trying to minimize the energy cost.

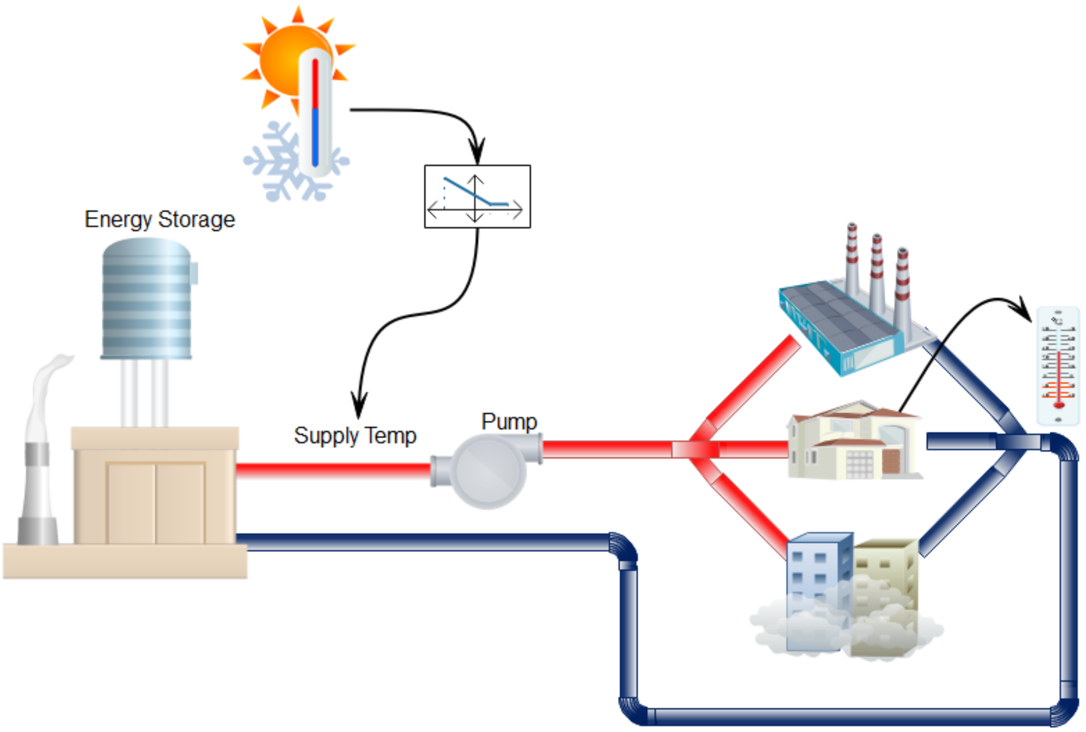

Figure 4: Sketch of a simplified DHC system with typical base components.

Now, if we look one level up, we can ask ourselves what opportunities this temperature range will give us? The answer is that the building in general has thermal storage capabilities through its thermal inertia, and thus, the system does not need to continuously provide a fixed temperature, instead the optimizer will be able to over-charge/ under-charge the building, also referred to as pre-heating and pre-cooling. Consequently, the stored energy can be used maintain a more even energy production and avoid the usage of the axillary energy sources, like peak load plants. In this case, the *accumulated deviation from the nominal energy is the flexibility*.

Another example of the flexibility, from a heat or cold generation point of view is the management of the supplied water temperature, where we use the simplified setup in Figure 4 for the sake of reasoning. It is well noted that the temperature of the medium (usually water) can be adjusted over time in order to ensure the required level of the service. But in addition to that, the medium can be pre-heated to some temperature in order to avoid the expected or forecasted rise in demands. Now, the increase of the stored energy in the water can be understood as flexibility in this case, and again the optimizer can store more energy in order to avoid using some auxiliary sources. If we look at it from one step ahead perspective, we can see that in some plants, the human operator has some tolerance in increasing the generation power for a short time in advance to overcome the very same problem. In the latter case, the increase or decrease in the used power be the flexibility.

Note that the two cases are connected and we can derive one from the other, but in general and following the classic control approach, it might be difficult to use the temperature flexibility due the fact that the buildings do not have sufficiently many indoor temperature sensors centrally connected.

To conclude, the level of flexibility is reflecting the accessibility of the flexibility to the optimizer and the service provisioning.

3.2.3 Flexibility characterization and classification

Flexibility in general is a positive property of a system and can be used to introduce additional performance improvements. But this gain comes usually at a cost, it might introduce some new deterioration to other objectives. For example, the increase/decrease in the water temperature to shift the load and to prevent the use of auxiliary boilers, might lead to a higher energy loss, higher return temperatures might reduce the efficiency of CHP plants, or might reduce the remaining useful life of pipes and pumps. Thus, we need to identify any of the above aspects when flexibility is characterized by collecting the following information:

- **Level of the flexibility**. Identifying if it is the lowest level and if not connecting it to the lower levels of flexibility.

- **Complexity of evaluation**. Indicate the possibility to measure/calculate it and assess the complexity of performing it.

- **Impact**. Assess the influence of the flexibility on different objectives in the optimization problem (sensitivity analysis.)

- **Drawbacks**. Exploiting flexibility will generate a positive impact on the optimized objectives, but it might lead to drawbacks in other factors.

- **Requirements**. Optimization 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 is determining how and when it can be used. Design flexibility will require the system to be simulated with different parameters (i.e. dimensions of the system for example).

4 FLEXIBILITY QUANTIFICATION

As we stated earlier, the main objective of modelling the flexibility is to be able to use it in different optimization scenarios. The difficulty that might arise is the complexity of different models to interpret the flexibility at different levels making the usage of these models in optimization algorithms impractical or difficult. Thus, it is better to convert different types of the flexibilities into a higher common level that enable a faster optimization of the process from an engineering perspective.

4.1 Methodology

The different levels of flexibility can be transformed using approximation techniques. The main idea of the approximation is not to convert the description of the system from set of variables into the another set of variables. Note, conversion into a new set of variables can be explained by describing the flexibility of building in terms of energy instead of room temperatures. Instead, it is about reducing the time granularity (resolution) and going to a different scale.

As an example, instead of having a model that describes the change of temperature at a time scale of seconds, an energy model at the time scale of 15 minutes can be used. Such an approximation needs to take into consideration the process nature and dynamics. The conversion can be done by fitting the flexible component data into another level model and identifying/learning its parameters. The component data can be acquired from a real plant or from simulations of the model (surrogate data). In the following, the approximation using simulation data is explained.

4.2 Flexibility quantification through simulation

Current advances of simulation tools can lead to an advanced approach supporting optimization problems by simulating the plant in order to optimize decisions. These decisions can be at design time (when system dimensions are the desired result) or at the operation time (when operational characteristics and decisions are the desired result).

Even though simulation tools are getting faster, it is still hard to have a realistic tool that will simulate a complete DHC system at rates meeting engineering requirements on the execution times of the optimization problems. For example, a full-scale DH system simulator of a small city can run at 3 times of real-time when an exact first principle approach is used. Meaning, 3 days of operation need one day of simulation time, preventing proper engineering activities. It is thus required to simplify the simulator and represent flexibility in a simpler form.

The main idea is to convert all the flexibilities that come from a low level into a higher level (i.e. converting the temperature boundaries into an energy boundary in a storage tank or building). This conversion can be done by model reduction and conversion tools, but often suffer from limitations when it comes to the conversion of complex models, i.e. models with multi-phase flows like in heat pumps. Alternatively, a simplified approach based on simulation can be used where a variety of operational scenarios can be simulated and the approximated by simplified models using system identification or machine learning techniques. Monte Carlo simulations have also proven to be a good approach to generate the surrogate data.

5 FLEXIBILITY ASSESSMENT

One of the most important aspects in the context of flexibility, is the capability of evaluating the impact of the flexibility. This assessment is important during the different life cycles of any process/plant. It is important for the designers to introduce flexibilities in a system and to decide which one is best to implement and integrate. Further, it is important for plant operators to select the optimal operation scenario given ambient conditions or operational circumstances, and for the maintenance and planning engineers when to schedule maintenance and to perform upgrades.

Thus, it is important to define a set of indices that aid in assessing flexibility. Following the trends in process and production industry, there are many ways to perform this task. In this report will explain two major approaches, flexibility indices and key performance indicators (KPIs).

5.1 Flexibility metrics

Inspired by the metrics in manufacturing and process control, a metric called flexibility metric can be used to assess any flexibility. In Eltohamy et.al. (2019)**,** flexibility was defined *as the ratio of the largest variation range of uncertainty system can accommodate to the target variation range of uncertainty the system aims to accommodate*. In this case, the target flexibility is known, and it is required to measure how the introduced flexibility will be exploited. In manufacturing context, Kazmer, et.al. (2003) defines flexibility as *the ratio of the likelihood of operating the process within its feasible region to the likelihood of operating the process within the specification limits*. It defines how much increase the flexibility will render.

From these two examples we can see that the flexibility metrics has a different interpretation to what it originally was based on, namely the requirement of flexibility. In the first example case, the required improvements are known, and the index will tell how each flexibility can contribute, while in the second case, the problem is more like an exploratory case to find the influence of each flexibility on the process outcome. Both cases do have their own place.

In the following, we will discuss the flexibility index as the ratio of change in the objective function to the change in the flexibility, drawing similarities from a sensitivity measure.

$$Flexibility\ index = \frac{change\ in\ the\ objective\ function}{change\ in\ the\ feasibility\ (constraints)}$$

Following the mathematical definition presented in section 3.2, the problem was shown as a relaxed optimization problem:

$$\begin{aligned}&\min_{u} Q(x, u, \theta_o, d_e)\\ &s.t. \quad x^{+} = f(x, u, \theta_s, d_e)\end{aligned}$$

$$\begin{gathered} l_L \le h_i(x,u,\theta_i,d_e) \le l_U \\ h_i(x,u,\theta_e,d_e) = 0 \end{gathered} \quad \Longrightarrow \quad \begin{gathered} \tilde{l}_L(t) \le h_i\big(x,u,\, \tilde{\theta}_i, d_e\big) \le \tilde{l}_U \\ -\epsilon_i \le h_i\big(x,u,\tilde{\theta}_e,d_e\big) \le \epsilon_i \end{gathered}$$

The relaxation of the problem will render a general gain in an improvement in the objective function which is illustrated by Figure 5 in a simplified way.

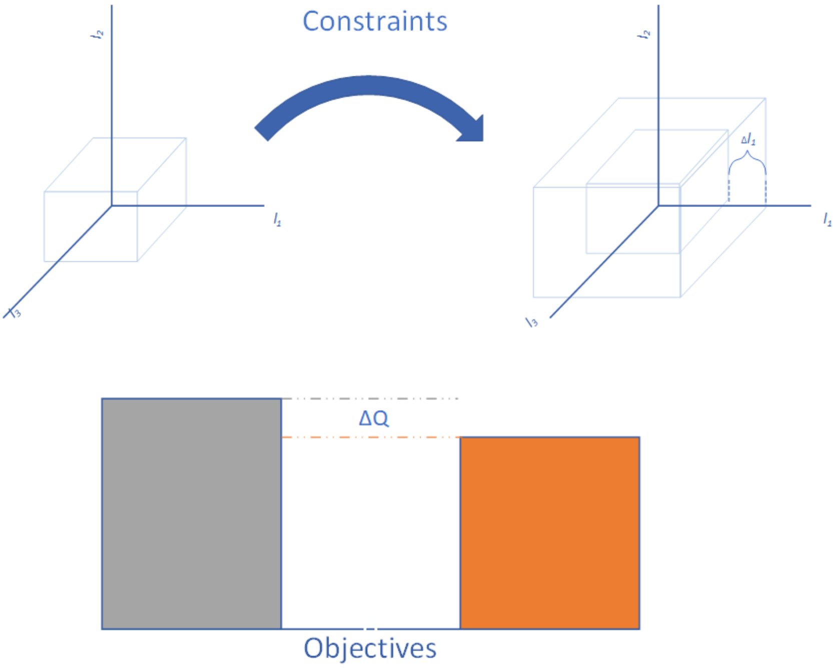

Figure 5: An illustrative figure shows the improvements in the objective when the optimization problem was relaxed

If we will use a similar definition, then the index will be given as

$$Flexibility\ index = \frac{\Delta Q(x,u,\theta_o,d_e)}{|l_i - \bar{l}_i|}$$

and

$$Flexibility\ index = \frac{\Delta Q(x,u,\theta_o,d_e)}{\epsilon}$$

The main drawback of this approach is that the ratio and the comparison between the different indices is hard to compare, i.e. the ranges to implement flexibility is using different contiguities. For example, compare the increase in the range of the thermal comfort temperature in a building to the installation of a larger heat storage tank. This issue can be managed by using a normalization like

$$Flexibility\ index = \frac{\dfrac{\Delta Q(x,u,\theta_o,d_e)}{Q(x,u,\theta_o,d_e)}}{\dfrac{|l_i - \bar{l}_i|}{|l_i|}}$$

in which the index is a measure of the sensitivity for the relaxation of the optimization problem.

Another solution for the mismatch is to use a conversion of the objective’s improvement and the constraints increments into a measurable quantity (like energy, or cost) and then compare them, for example as

$$Flexibility\ index = \frac{\mathrm{Profit}(\Delta Q(x, u, \theta_o, d_e))}{\mathrm{Cost}(|l_i - \bar{l}_i|)}$$

This approach can enable the interpretation and the comparison of the different flexibilities in the operation and the design of the plant.

Note that the comparison can be done on different time scales and might lead to different results for a given time horizon. For example, including the life cycle of different components.

5.2 KPIs for assessment

Key performance indicators are good approach for the assessment of the impact of the flexibility, and the table presented in Clauß et. al. (2017) is an excellent summary to start from. It is an efficient tool widely used to monitor subprocesses and the plant wide performances and can be used for benchmarking purposes. Thereby, enabling to evaluate the different actions taken in a plant including but not limited to, control and operation, maintenance, environmental impact, energy consumption, and profit (Lindberg et.al. (2015)).

KPIs can be generally defined the following different objectives/interests. Kourkoumpas et.al. (2018) classified KPIs into four major categories depending on the requirements and the intended outcomes of the evaluation process as follows

1. Social
2. Economic
3. Environmental
4. Technical.

It is important to notice that defining multiple KPIs might lead to a conflict in the process of improving the plant. As it is known in any multi-objective optimization problem, the improvements of one KPI might lead to a deterioration in another one, the so-called pareto front. Figure 6 shows an example of a multi KPI optimization problem.

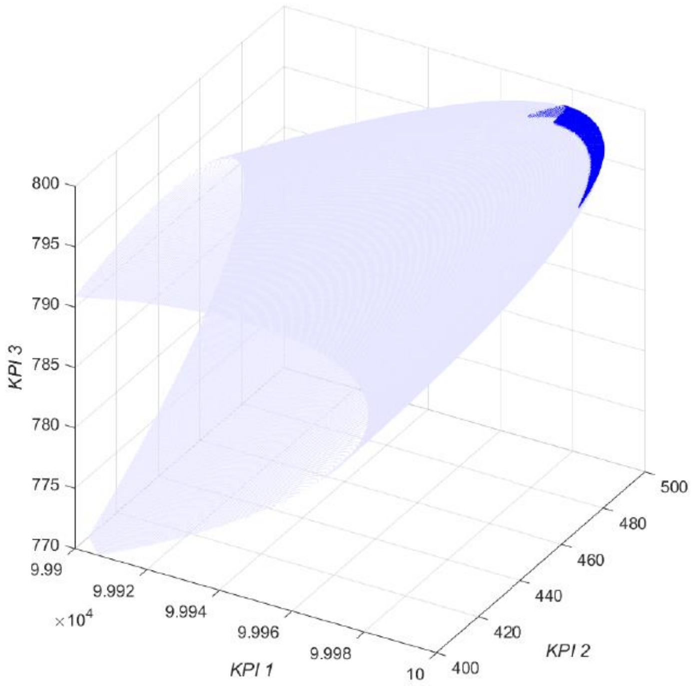

Figure 6: An illustrative example showing the possibility of having a pareto front when using different KPIs for evaluation of a plant

Similarly, the initially introduced flexibility metrics as the KPIs might change when considering different aspects, for example the time horizon. In this case, it is important to define the required time frame and the main interest in order to facilitate making the appropriate decision based on the selected KPIs.

In ANNEX I, a KPI definition is presented which is based on the state of the art and that facilitates the quantification of the project impacts.

6 REAL LIFE TEST-CASE

We will now use a real-life city test-case to evaluate the introduction of flexibility using a thermal energy storage (TES). Since the models for Spanish demo site ParcBit were not ready at the time of conducting this work an alternative city-scale case was used.

The district heating system in Luleå has been studied and analysed in the EU H2020 project OPTi and will be used as a test case here, as a complete dynamic model of the district heating system is available and implemented in a simulation environment. The simulator replicates all three main parts as a combination of physics-based models, machine learning models (black box), namely the generation, the distribution and the consumer side (end users). Since the city is geographically quite large, several generation units are distributed over the city and connected to the same thermal grid. Figure 7 shows an overview of the thermal grid, with a distance of close to 20 km main generation unit and the farthest point of consumption.

The main generation unit uses a combined heat and power (CHP) plant that is located near the steel factory and utilizes the surplus gas from the blast furnace at the steel mill as its primary energy source. The power/heat generation ratio is determined based on the demand and the electricity price on the market. In addition to the CHP, four other heat generation units are geographically distributed over the city, and one close-by to the CHP plant. Moreover, a large heat storage tank (30,000 m^3) has been installed as a thermal energy storage.

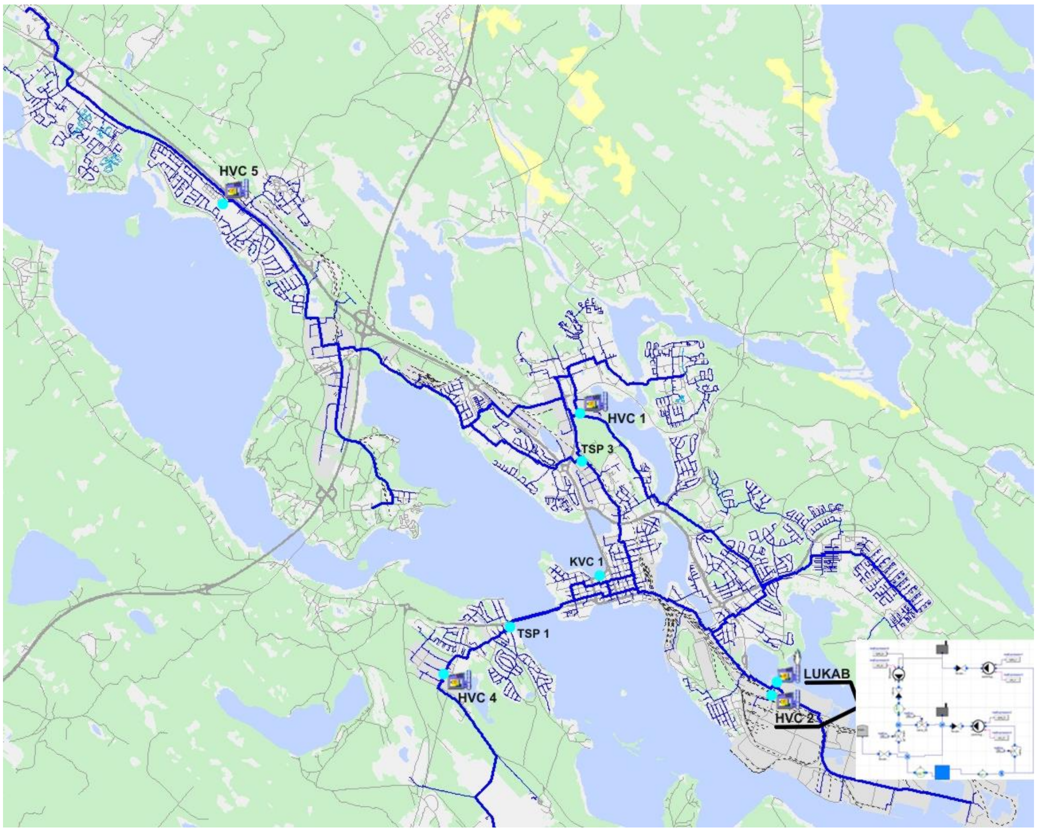

Figure 7: Luleå DH system sketch. Abbreviations for components in the picture: auxiliary boilers (HVC), CHP (LUKAB), pumping stations (TSP)

The distribution network consists of a large network of double pipes (2 x 22376 pipes for supply and return) that deliver the heat energy to Luleå City. Pumping stations will ensure optimal flow in the network such that an optimal energy transfer to all the consumers in the city is guaranteed. Each heat generation unit is also complemented with a pumping station, for addition pressure increase. Further, three additional pumping stations aid to boost the energy transfer place at strategical points in the grid. The third part are the 9533 end consumers, which are commercial buildings or residential buildings, everything from larger complexes down to one family houses. Those consumers have variable and different loads as well as consumption profiles.

The scenario for the test case is about the simulation of the usage of the storage tank in a cold winter day, when the outdoor temperature falls rapidly. Figure 8 shows the outdoor temperature.

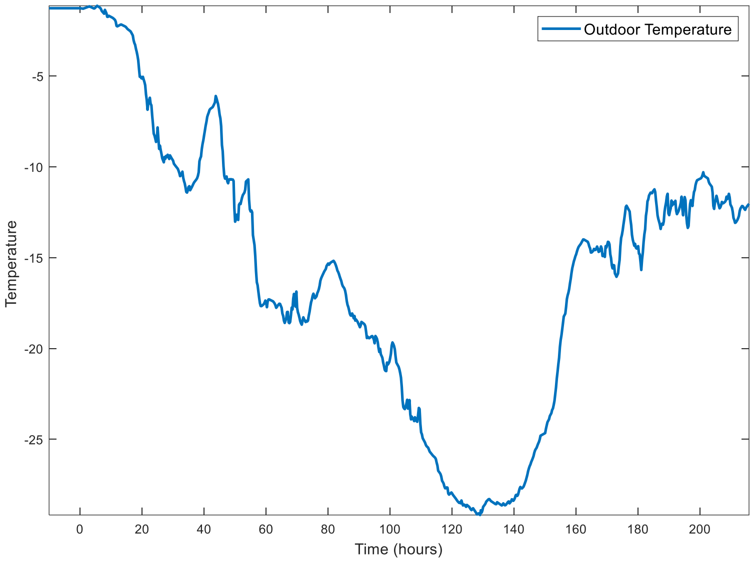

Figure 8: Outdoor Temperature during cold days at Luleå city

The model representing the behaviour of the TES considers a tank with two layers, hot at top and cold in the bottom. The model considers a loss of energy to the outside weather and a transfer of energy between the 2 layers and could be extended to a multi-layer model. In order to not slow down simulations too much, this simplistic case is used for the test case. The Tank was charged automatically with water when the forecasted outdoor temperature is cold and when the main CHP plant power generation is below a certain level. The heat was extracted from the tank when the main CHP plant power was close to its maximum limits. The flow volumes and temperature of the hot and cold side of the TES are shown in Figure 9, showing this behaviour.

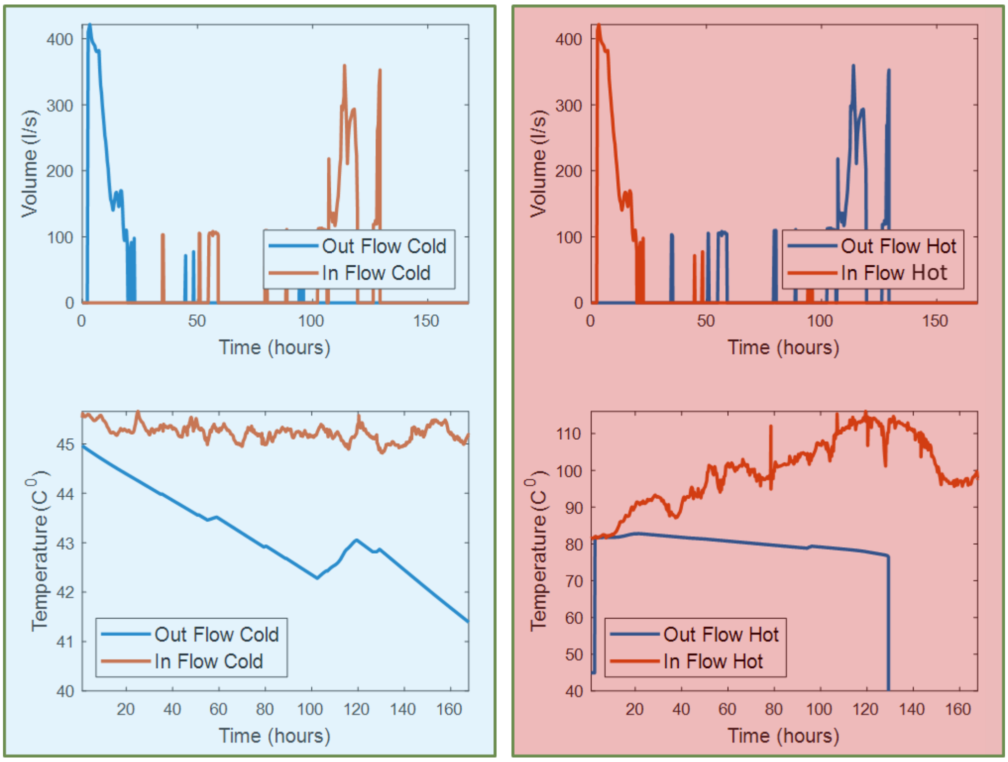

Figure 9: The volumes and temperatures of the flow into and out of the tank. Blue shaded area represents the cold-side and red shaded area represents the hot-side.

The simulated volumes and energy of the two layers are show in Figure 10, where the pre-charging of the tank can be seen whilst maintaining the correct level.

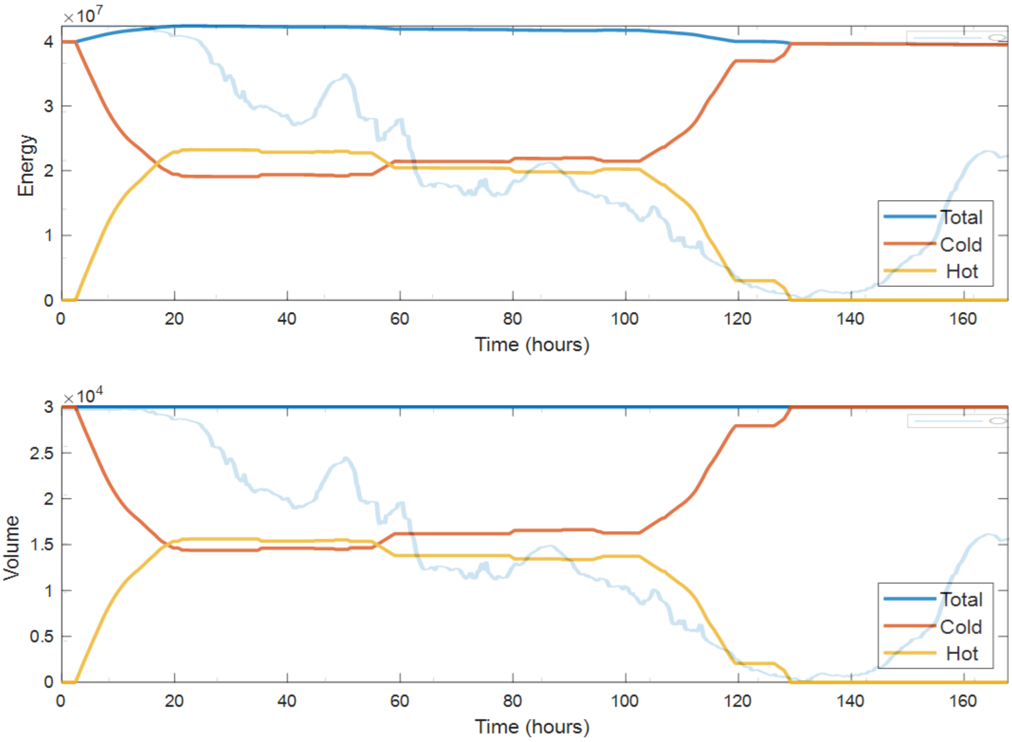

Figure 10:Energy and volumes of the 2 layers of the tanks with an overlaid temperature curve (light blue).

The simulated values of the input, output and the tank were fed into the next stage. The simplified model of the task is given by

$$\begin{aligned}
&\Delta Q = \lambda(Q - Q_0) + \eta_{in} Q_{in} - \frac{1}{\eta_{out}} Q_{out} \\
&Q_{min} \ \leq Q \leq Q_{max} \\
&0 \leq Q_{in} \leq \bar{Q}_{in} \\
&0 \leq Q_{out} \leq \bar{Q}_{out}
\end{aligned}$$

Where Q represents the total energy of the tank, λ represents the los factor, Q_0 the Energy that at which the tank will not lose energy, η_{in} the energy losses during the energy charge the tank and η_out the losses factor when discharging the Tank. In this case, the charging and the discharging losses where assumed to be equal. The data were fed to the identification tool and the values of the parameters $[\lambda, Q_0, \eta_{in}, \eta_{out}, Q_{min}, Q_{max}, \bar{Q}_{in}, \bar{Q}_{out}]$ were identified. Figure 11 shows the energy of the tank in the simulated case and the result of the approximated model.

As a final remark on this test case, the set of the original parameters $[V_{tank}, T_{max}, \lambda_{isolation}, V_{in\_max}, V_{out\ max,,}]$ were converted into another set of parameters $[\lambda, Q_0, \eta_{in}, \eta_{out}, Q_{min}, Q_{max}, \bar{Q}_{in}, \bar{Q}_{out}]$ with a 15 minutes time resolution. This can simplify the optimization algorithm to operate and combine the storage tanks model with other models (production, network, and consumers).

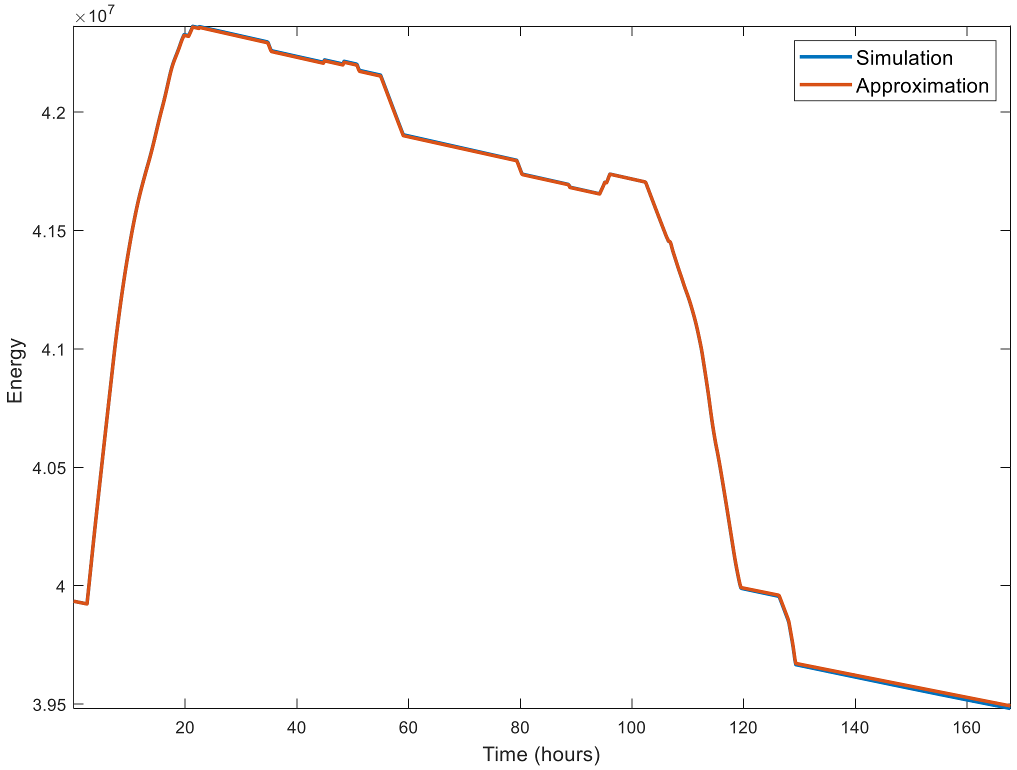

Figure 11: The Energy of the simulation and the approximated model.

7 CONCLUSIONS

This report provides a summary of the results achieved in Task 1.1 of the Flexi-Sync project which had the aim to provide a systematic approach for the characterization and assessment of flexibility in district heating and cooling system for control and optimization of operation purposes.

The state of the art in relation to methods and approaches for flexibility in DHC systems was reviewed, complementing the review that was available in the proposal. Using the identified limitations and gaps, the characterisation, quantification and assessment are presented. As a result, the following procedure oriented to control and optimization of operation exploiting flexibility is suggested

1. Collect information on the DHC system in terms of physical properties of components of the system and time series data of the system aligned with the time scale for the modelling.
2. Derive a dynamic model of the system where production units, distribution, consumption-side components, storages, and other energy sources like RES are represented.
3. State the optimization problem with objective function(s) and constraints. There, the system model is part of the constraints.
4. Collect information on the components offering flexibility according to section 3.2.3.
5. Model the flexibility in terms of constraints and assess how the optimization problem can be relaxed.
6. Translate the flexibilities in the system into a unified level which can be used jointly in the optimization problem. Make use of model approximations where needed for the translation.
7. Perform the optimization either for operation or for design purposes. If the results are feasible an implementation of an optimization-based control scheme for online use can be considered.
8. Assess the flexibility using the metrics from section 5 if needed.

The proposed procedure was then applied to the DH system for the city of Luleå, Sweden, where a full-scale dynamic model and simulation environment is readily available. For the test an additional component, a 30.000 cubic meter TES was introduced into the system.

The results indicate that the procedure is applicable in real-life cases but need to be further benchmarked on the Flexi-Sync pilot cases.

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ANNEX I

KPI DEFINITIONS

2020-12-18

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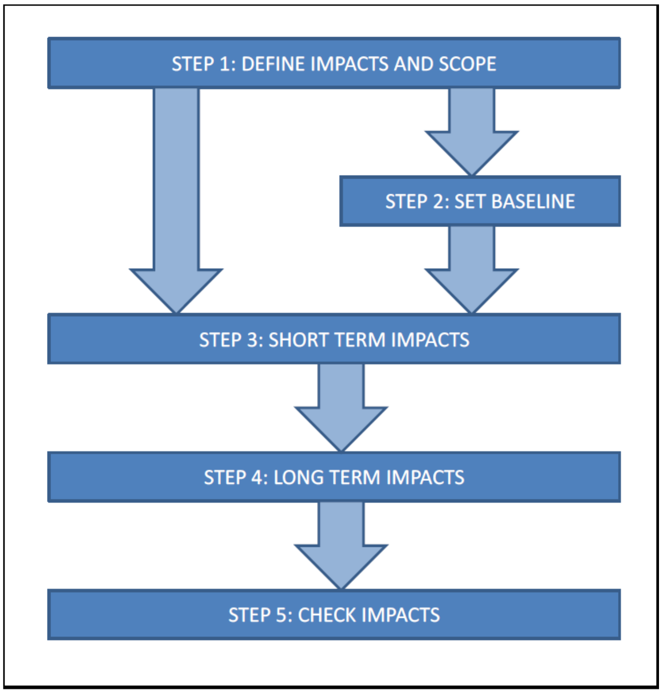
1 BACKGROUND

This document is created for tracking the KPI definition of the project. In the definition process, the European Commission document: Guidelines for the Calculation of Project Performance Indicators (v2.0) has been used as a reference document. The methodology described in this method follows 5 steps which are the following:

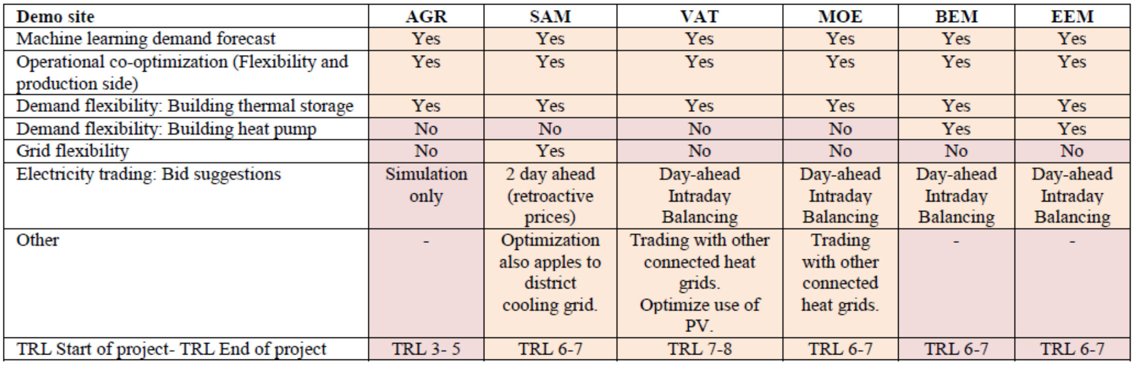


2 PROJECT INFORMATION

The objectives of the project are the following

1. Identify the current flexibility potential in the six demo sites
2. Assess the cost-efficient flexibility potential in the local or regional energy system
3. Understand the adjustments needed to the cost-efficient solutions to be climate resilient
4. Six demo site implementations of optimized flexibility
5. Understand the business implications of increased flexibility and development of business model and market uptake analysis of the new service
6. Stimulate the need owners of the project to adopt the flexibility options in multiple locations in their district energy system (beyond the installation in the demo site).

The expected implementations at the demo sites are the following, although minor changes might happen throughout the project.



Demo site	AGR	SAM	VAT	MOE	BEM	EEM
Machine learning demand forecast	Yes	Yes	Yes	Yes	Yes	Yes
Operational co-optimization (Flexibility and production side)	Yes	Yes	Yes	Yes	Yes	Yes
Demand flexibility: Building thermal storage	Yes	Yes	Yes	Yes	Yes	Yes
Demand flexibility: Building heat pump	No	No	No	No	Yes	Yes
Grid flexibility	No	Yes	No	No	No	No
Electricity trading: Bid suggestions	Simulation only	2 day ahead (retroactive prices)	Day-ahead Intraday Balancing	Day-ahead Intraday Balancing	Day-ahead Intraday Balancing	Day-ahead Intraday Balancing
Other	-	Optimization also apples to district cooling grid.	Trading with other connected heat grids. Optimize use of PV.	Trading with other connected heat grids.	-	-
TRL Start of project- TRL End of project	TRL 3- 5	TRL 6-7	TRL 7-8	TRL 6-7	TRL 6-7	TRL 6-7

3 KPI DEFINITION

The methodology KPI group agreed to use is a bottom up approach to develop KPI:s, hence Step 2 Baseline is not needed. However, there is still a need to have a reference value for most of the KPI:s. The KPI's will be categorised by Economic, Environmental, Technical or Social impact.

3.1 Step 1: Defining scope and impacts

The activities within the project:

- Machine Learning (ML) demand forecast
- Operational co-optimization
- Building thermal storage
- Heat pumps in building and grid
- Grid flexibility

Impact expected in trials (short term):

- Increase flexibility (including building storage).
- Increase renewable and excess heat integration
- Manage demand in relation to dynamic pricing and costs at supply side
- Decrease GHG emissions
- Replicability
- Comfort of the end-user

Impact expected in science (long term):

- Better ML techniques in demand forecast
- Flexibility guidelines (either in science or industrial dissemination)

3.2 Step 2: Estimate the short-term impacts (expected in trials)

When we talk about increasing flexibility in a system, it can be seen from two points of views: the actions taken (Operation and optimization) or the actual results obtained (Evaluation), see Figure 1. But not all flexibility available in a system is ready to be used. First, there is the flexibility inherent to the system limited by system design (HVAC design temperature, storage and so on) and then restrictions related to the user satisfaction allowed by the tenants (KPI-5). After considering design and comfort restrictions, there is the flexibility available to use in the system which has an impact that can be measured by evaluation KPIs.

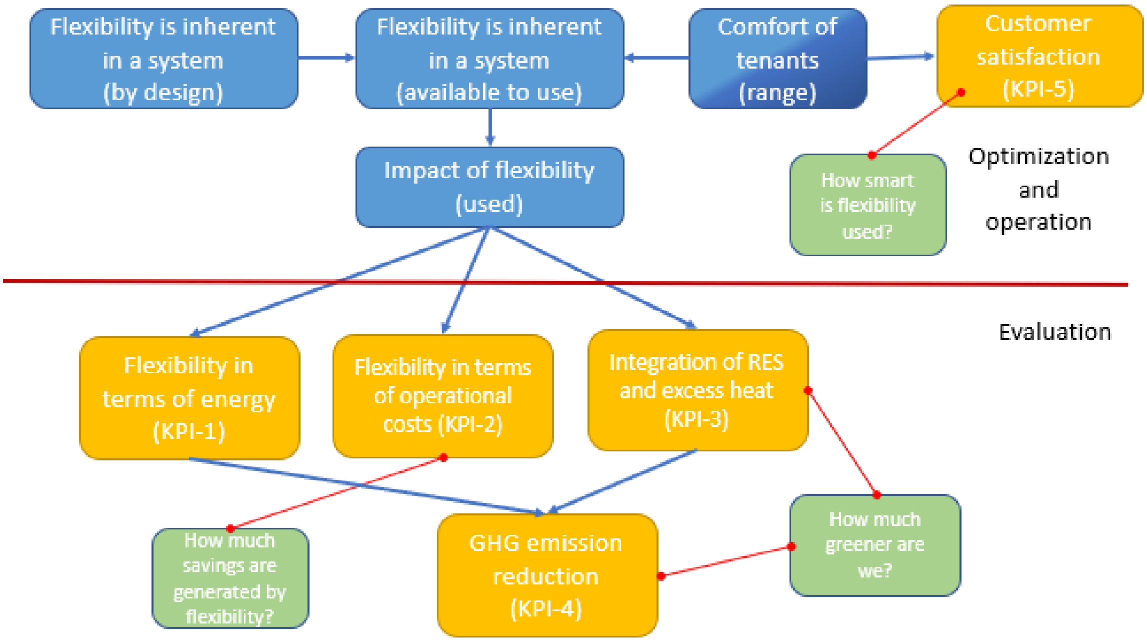


Figure 1 KPI:s evaluating flexibility

In this part, there are some suggestions of KPI as a beginning point. After defining the KPI, the time frame and scope of the KPIs needs to be defined.

KPI 1: Flexibility in terms of energy (Technical impact)

Two different time scopes are defined for flexibility: one to analyse the flexibility of a facility (e.g. a building, city or area of a district heating system) and another to analyse a single event in a certain place.

The flexibility in a DH or a building depends on the demand and environmental conditions, therefore the depending on seasons. For this reason, in order to calculate an overall perspective of the flexibility, a whole year must be analysed (defining flexibility in winter, summer and mid-seasons).

Furthermore, regarding flexibility in a single event depends of temperature sensitivity of the facility to study, for example, temperature changes in a room is normally measured per quarter of hour, so it makes no sense to have a smaller event time. Flexibility can be defined in the using the same time of the event, but in order to compare different events it is necessary to define the same time scope. So, considering outside temperature varies in a cycle of 24 hours, one day (24h) can be defined as flexibility time. This measurement actually relates to the impact memory of the underlying thermal process, which can vary depending on dynamic and static circumstances. However, 24 hours is an appropriate approximation for the purpose of formalising a KPI.

Here the definitions refer to the heating in buildings, but it could also be applied for an entire system. The definition may be used for energy shifted in time, but also for energy shifted between energy sources.

Available storage (Coc): the energy shifted during optimal control is

$$C_{OC} = \int_{0}^{Ioc} (Q_{OC} - Q_{Ref})dt$$

Where Q_{OC} is the heating power, Ioc the duration of the optimal control and Q_{Ref} the heating demand during reference control, e.g. the baseline.

Flexibility factor (FF): amount of cost shifts, being -1 inflexible and 1 flexible, is:

$$FF = \frac{\int_{0}^{I_{lowprice}} (Q_{heating})dt - \int_{0}^{I_{highprice}} (Q_{heating})dt}{\int_{0}^{I_{lowprice}} (Q_{heating})dt + \int_{0}^{I_{highprice}} (Q_{heating})dt}$$

Where $Q_{heating}$ is the amount of heating power over low and high price periods I.

After defining the KPI the time and the scope must be defined.

KPI 2: Flexibility in terms of operational costs (Economic impact)

Expected Flexibility Savings Index: (EFSI): This index is related to actual costs savings due to flexibility in a system, for example meaning that an EFSI equal to 0.10 implies that the expected savings for flexibility actions compared to the baseline is 10%. The actual costs refer to the costs for heating/cooling the system on a system level (incl. the electricity system) which implies that the costs need to be allocated from the system level to an individual building level.

1. Let λ_t be the actual cost on the energy consumption at time t.
2. Simulate the control of the original system, and let u_t^0 be the energy consumption at time t.
3. Simulate the control of the system, and let u_t^1 be the energy consumption at time t.
4. The total operational cost of the original system is given by

$$C^0 = \sum_{t=0}^{N} \lambda_t u_t^0$$

5. Similarly, the operational cost in the system is given by

$$C^1 = \sum_{t=0}^{N} \lambda_t \, u_t^1$$

6. Then $EFSI$ is given by

$$EFSI = 1 - \frac{C^1}{C^0}$$

KPI 3: Integration of RES and excess heat (Environmental impact)

This KPI will quantify the effect of the energy shifted during optimal control (C_{oc} from KPI 1) on the increase of produced energy (the final energy multiplied with the primary energy factor) based on renewables and excess heat sources (RES).

The change in RES and excess heat integration, I_{RES}, is

$$I_{RES} = \int_0^{Ioc} \left(SH_{RES_{oc}} - SH_{RES_{ref}} \right) dt$$

where $SH_{RES_{oc}}$ is the RES and excess heat share during optimal control compared and $SH_{RES_{ref}}$ the RES and excess heat share in the baseline during the specific period of time, Ioc. $SH_{RES_{oc}}$ and $SH_{RES_{ref}}$ are calculated for each time step by allocating RES and excess heat share from a system level to the flexible part of the heat demand at the demo site.

The RES share is normally measured from the consumer side (share of renewable energy in gross final energy consumption), however, since the project is focused on energy production the RES share of the produced energy is much easier calculated. The RES energy share, SH_{RES}, is:

$$SH_{RES} = \frac{E_{RES}}{E_{Total}}$$

Where E_{RES} is the energy production from renewables and excess heat, and E_{Total} is the total production of energy.

KPI 4: GHG emission reduction (Environmental impact)

For evaluating the GHG emissions saved, comparing emissions expected with no changes (baseline) and the actual emissions for a year.

A way of calculating KPI-4 will be considering only GHG emissions saved of RES integration and peak shifting. The GHG emission reduction, ER, is:

$$ER = I_{RES} * f_{GHG} + C_{OC} * f_{GHG,\mathrm{peak}}$$

Where I_{RES} is the change in RES and excess heat energy production from optimal control (assuming E_{Total} not changed by the control) and f_{GHG} is the GHG emission factor for the energy production in the baseline (kg emissions per kWh in the baseline). C_{OC} is the thermal energy shifted from peak loads (taken from KPI-1) and $f_{GHG,peak}$ the emission factor for the peak load production in the baseline.

For calculating this KPI the same method and time period that is used for KPI-2 and KPI-3 could be applied.

KPI 5: Social acceptance of flexibility (Social impact)

As WP5 will perform a survey on the customers' perceived control and social acceptance connected to flexibility in heating, this social indicator will be developed when the result of this survey has been made public. This KPI will primarily be linked to the Swedish housing companies.

However, a few ideas have been discussed so far. One way to measure the social performance of the project is to assess any changes in the customer satisfaction for the tenants living in the buildings where flexibility will be tested. The customer satisfaction, meaning the tenants residing in the houses where flexibility will be tested, can be measured in different ways. One way could be to assess the number of complaints about indoor temperature, e.g. taken from the CRM databases of the housing companies or heating companies, or the customer satisfaction score for indoor temperature in annual customer satisfaction surveys that are performed by the housing companies. Another way is to simply measure any deviations in indoor temperature with sensors.

Please note that the buildings owners' social acceptance of flexibility could also be assessed.

3.3 Step 3: Estimate the long-term impacts

The long-term impacts are impacts that goes beyond the project lifetime. Long term impacts up to 5 years after the project may be considered. This step will be developed after by extrapolating short term impact making some assumptions. The most important assumption made is that instead of using only the practically available flexibility that can be made available during the project lifetime, all potential flexibility during a year is being used.

KPI 2.L: Potential cost reduction (Economic impact)

The cost efficiency is related to the efficiency in reducing the costs as there might be more cost reductions available that could be made if all potential flexibility resources would be utilized. Hence, instead of calculating the cost savings during optimal control as in KPI-2, the EFSI when all available flexibility is utilized is calculated using the formulas presented in KPI-2.

KPI 3.L: Potential RES and excess heat integration (Environmental impact)

The efficiency of using RES is related to the question "How good are we at green?". Even though the RES integration may be high, there might be more RES available that could be utilized if all potential flexibility resources would be utilized. For calculating this KPI, the formula presented in KPI 3 is utilized, but the potential maximum share of RES and excess heat due to flexibility is utilized instead of the share during optimal control.

KPI 4.L: Potential GHG reductions GHG efficiency (Environmental impact)

The GHG efficiency is related to the efficiency in reducing the emissions as there might be more GHG reductions available that could be made if all potential flexibility resources would be utilized. Similar to KPI-2.L and KPI-3.L, the GHG emissions reduction efficiency will be calculated when all potential flexibility is utilized using the formula from KPI-4.

4 REFERENCES

Guidelines for the Calculation of Project Performance Indicators, v2.0 05 December 2017; Executive Agency for Small and Medium-sized Enterprises (EASME), Unit B1 Energy.

Reynders G, Diriken J, Saelens D. Generic characterization method for energy flexibility: Applied to structural thermal storage in residential buildings. Appl Energy 2017;198:192–202. http://dx.doi.org/10.1016/j.apenergy.2017.04.061

Characterizing the energy flexibility of buildings and districts Rune Grønborg Junkera,∗, Armin Ghasem Azara, Rui Amaral Lopesc,d, Karen Byskov Lindbergb, Glenn Reynderse, Rishi Relana, Henrik Madsena,b

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