Optimization of District Heating & Cooling systems

D6.3: Test Report (Ver. 2)

Delivery date: 30-04-2018
Delivery type: Report
Version: 1.0
Dissemination level: Public
Main editor: IBM
Contributors IBM, TWT, LEN, SMPL, LTU

The research leading to these results has received funding from the European Union’s Horizon 2020 Programme under grant agreement n° 649796.
## Document Information

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<th>OPTi</th>
<th>Grant agreement no</th>
<th>649796</th>
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### Abstract (public)

This deliverable is part of the Work Package 6 (Integration and Validation) and is the final version of the test report. It describes the methodology for evaluating all the tests conducted in the project, both at the pilot sites and the in the simulator OPTi-Sim. It also delineates the methods for validating the achievement of the targeted KPIs. Results from the field trials conducted at the pilot sites in Luleå and Mallorca, as well as all the simulator, are presented, analysed and discussed. The result provides insights and recommendations, and some conclusions on the tests in general.

### Keywords

Validation, Experiments, Results, KPIs, Pilot Tests, Simulator

## Document History

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EXECUTIVE SUMMARY

OPTi (Optimisation of District Heating and Cooling Systems) aims to advance the technologies and solutions for increasing the overall energy efficiency of DHC systems. It seeks to do so by exploiting new methodologies and tools based on modelling, analysis and control of DHC systems along with enhancing user flexibility through economic incentives.

Deliverable 6.2 is part of the Work Package 6 (WP6: Integration and Validation) and forms version 1 of the Test Report. This deliverable called D6.3 constitutes the version 2 (final version) of the Test Report. The focus of the test report is the validation and results of the various technologies developed as part of the OPTi framework. The evaluation is conducted through the various test cases defined in D6.1 and results are studied in the context of the related KPIs as a measure of the expected impact of the project.

The test report comprises of 6 major sections:

- **OPTi Test Cases:** This section provides any updates to the 8 test cases defined in D6.1 and proposes data analysis methodology for each test case. The methodology lays the groundwork for evaluating the output of the test case in terms of the related KPIs and formulating the results.

- **Interpretation of KPIs:** This section extends the evaluation methodology to the overall KPIs. As most KPIs pertain to more than one test case, this section describes the validation procedure that will be used to determine the achievement of the KPIs at the project level by combining the results from the individual test cases in an appropriate manner.

- **Validation of OPTi-SIM:** This section describes the evaluation of the simulation framework developed as part of the OPTi project. The validation of the framework directly contributes to KPI4.

- **Lulea Tests & Results:** This section describes the various tests conducted for the Lulea site, including both the simulator experiments and pilot trials. The data of the tests is analysed to produce results in terms of the related KPIs.

- **Mallorca Tests & Results:** This section describes the various tests conducted for the Mallorca site, including both the simulated experiments and the pilot trials. The analysis and results are expressed in terms of the related KPIs.

- **Discussion:** This section follows naturally from the above sections to provide a KPI level overview of the impact of the project. Additionally, the summary of recommendations and insights arising from the various experiments and trials are documented here.

In addition, three appendices are provided presenting a deployment framework for the interaction and actuation of devices which are remotely located in buildings and presenting the OPTi-Forecaster which is used for the prediction of the production and the planning of the peak load reduction event. Further, tables from the CBA analysis of the Luleå tests are given in Appendix C.

In this way, the test report establishes the validation methodology in terms of the test cases and KPIs before delving into the experiments and analysis of the results.

In this version of the report, several tables in chapter 5 and the CBA result sheets in Appendix C are omitted due to business, security and data privacy reasons. It is the believe of the authors that these tables are not essential for the understanding and general value of the report.
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1 INTRODUCTION

In growing societies there is an increased need for energy and there is an imminent need for solutions that increase energy efficiency. Space heating/cooling is one of the major contributors to energy demands. In urban areas, district heating and cooling systems (DHC) are a proven energy solution that have been deployed for many years and as assumed to be an integral part of a decarbonization strategy. Although the benefits of DHC systems are significant and have been widely acclaimed, yet the full potential of modern DHC systems remains largely untapped and traditional concepts for operation and control reside. Such systems comprise a variety of technologies which work together as a single unit for the production and delivery of heating, cooling, domestic hot water and electricity. While there is a transition to 4th generation DH systems, still there is a huge potential for energy savings in existing DHC systems by circumventing existing shortcomings in the present networks. The primary objective of the OPTi-project was to create methodologies and tools that are applicable to both present and newly designed DH systems, with a significant impact on both utilities and consumers. Primary focus during this project is on utilities operating in the DHC sector and building owners.

1.1 DHC SYSTEMS

There are many stakeholders in any DHC system which includes the utility company that produces and distributes the heating and cooling, the building owners that use the heating or cooling in their buildings and the end consumers residing in these buildings. In these DHC systems, base energy demands are usually covered with cheaper and environment-friendly fuels that provide most of the energy consumed by the consumers. To meet peak demand that occur for relatively short periods of time, auxiliary and/or peak load production in the form of auxiliary boilers are stationed out in the DHC-network. These boilers are often run on wood chips and electricity, and during some extreme conditions, less environmental-friendly fuels like e.g. oil. During certain periods of the day, for example early morning or late afternoon, there is a larger demand for energy in DHC systems than the maximum capacity of the base load production plant(s) can cover. This forces the utility companies to produce more energy to manage these peaks of energy demand, which results in starting up these auxiliary plants leading to higher costs and more pollution.

The approaches being developed as part of the OPTi project are targeted towards increasing the energy efficiency through concerted efforts focused on various aspects of the DHC systems, and especially, mitigating the above-mentioned effects.

1.2 WP6 GOALS

Work package 6 focused on the integration and validation of the approaches developed as part of the OPTi project. For the validation, different types of tests were conducted involving all the relevant stakeholders, the utility companies, the building owners and end consumers. Not all tests were feasible to be conducted in real-life settings, and have instead been conducted in OPTi-Sim, which realistically replicates the real-life DHC system. The real-life tests were performed in the pilot sites in Luleå, Sweden and Palma de Mallorca, Spain. This test report version 2 (deliverable D6.3) builds on the first version (deliverable D6.2) and includes all the reports on the tests were described therein. Version 2 includes the final results from testing and the completed analysis of the outcomes.

1.2.1 Lulea test site

The Luleå pilot focussed on optimizing the complete DHC system and for a group of buildings. On a system level real-life data from the pilot was used for the modelling and building the simulations tools. The DHC
System in Luleå supplies 31,000 households with heating and cooling on a daily basis. The heat is mainly produced at the CHP plant at LuleKraft AB (LUKAB) close to the steel making plant SSAB EMEA AB. LUKAB supplies the base heat production of 185 MW to the grid and gets the fuel from the neighboring steel plant, in the form of surplus gas. The pilot is run by Luleå Energi AB where the some of their customers like the City of Luleå and Lulebo support the test activities pro-bono. A group of buildings and heated street areas have been selected for the tests. The buildings are larger residential and commercial buildings in Luleå.

1.2.2 Mallorca test site
This test site is a hospital (Son Llatzer Hospital) situated in Palma de Mallorca (Balearic Islands, Spain) that gives public health assistance to more than 200,000 patients per year. Around 2,000 health professionals are employed there, providing advanced healthcare for its reference population. For the Hospital needs, there is a power plant in the surroundings that supplies energy to the hospital. This energy is generated by Sampol’s tri-generation plant, which supplies hot & cold water to Son Llatzer hospital, a generate electricity that is sold to the national market. The hot water is used both for air conditioning and sanity water, while the cold water is used only for air conditioning.

1.3 Validation and test reports
The validation task of WP6 relates to conducting various tests, both using OPTi-Sim and the pilot sites and documenting the results. The actual tests conducted, and the resultant analysis are document in the test report which are delivered in two stages – version 1 and 2. The deliverable D6.2 corresponds to the test report version 1 and the deliverable D6.3 (this report) corresponds to the test report version 2.

While D6.1 presented all the proposed test cases along with the test details and KPIs associated with them, several of these plans needed to be updated due to problems and issues that were encountered. These updates to the test cases are described in this document. At the same time, the evaluation methodology is also laid out for each test case. Next, KPIs were defined to measure the achievement of the core aims of the project, this report also describes the methodology that has been employed for translating the results from the individual test cases to correspond to the KPIs. With this background in place, we proceed to describe the various tests that have been conducted in both OPTi-Sim and the pilot sites along with the results. In the first version of the test report, only some of the proposed tests were conducted and documented. In this report we document the entire tests and simulations, including those which were described ion D6.2 (test report version 1). Similarly, the overall findings in terms of the KPIs and the final recommendations and insights, are also described in this deliverable.

1.4 Structure of the document
Following the introduction, in Section 2, we provide a short glossary of the various terms used in the report for ease of reference. Next, Section 3 lists out all the test cases as presented in D6.1 while describing any updates to their proposed plan and associated KPIs. The evaluation methodology for each KPI for that test case is also presented alongside. Following that, Section 4 presents the proposed methodology for evaluating the overall KPIs from the results of the test cases. This is followed by Section 5 which details the OPTi-Sim framework and validation results, thus corresponding to KPI4. Section 6 and Section 7 follow and describe the conducted test cases pertaining to Luleå pilot site and Mallorca pilot site respectively. Section 8 will provide a detailed discussion of the results in terms of each of the target KPIs (following the methodology laid out in Section 4). The discussion will also include overall recommendations and insights which can be construed as a summary of the findings of the OPTi project. Concluding remarks are provided in Section 9.
and finally, three appendices are provided on the deployment details of the project approach to actuate on the user side using the Arrowhead framework and how demand, production can be forecasted, and the intermediate analysis sheets from the CBA tool.

1.5 DATA SOURCES AND MANAGEMENT

To setup and evaluate the test cases, KPIs, but also for development and verification of correctness of OPTi Sim, measured data points were heavily used. Both pilot sites provided different kinds of data sources for all relevant parts of the systems installed at the pilots. The Data Management System collect all data and make it available via an API. In D6.1 the handling of the data from pilot site perspective is described. The data management infrastructure is described in report D4.1 and demonstration D4.4. The database contains in the end 574 active sensors with around 250 million data points. These data points represent the sensor data of the building and non-personal data used in the testing and analysis.
# GLOSSARY

The glossary is intended to provide a common language for the project consortium to ensure a common understanding of technical terms relevant for the project. It will be constantly extended and updated.

<table>
<thead>
<tr>
<th>Term</th>
<th>Definition</th>
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<tr>
<td>Automatic demand-response (ADR)</td>
<td>Automated demand response (ADR) describes a system that automates the DR dispatch process, from the grid operator to the DR aggregator (if involved) to the end-use customer – all without any manual intervention. cf. demand response</td>
</tr>
<tr>
<td>AHU or UTA</td>
<td>A climatization device used to condition and circulate air as part of a heating, ventilating, and air-conditioning (HVAC) system of a building.</td>
</tr>
<tr>
<td>Demand response (DR)</td>
<td>Changes in electric usage by end-use customers from their normal consumption patterns in response to changes in the price of electricity over time, or to incentive payments designed to induce lower electricity use at times of high wholesale market prices or when system reliability is jeopardized. It is one aspect of Demand Side Management. The other being Energy Efficiency.</td>
</tr>
<tr>
<td>DH / DHC</td>
<td>Short for district heating / district heating and cooling.</td>
</tr>
<tr>
<td>Substation</td>
<td>A substation is the heat exchanger and control system that extracts the heat from DHC water and provides the building with heating and warm water.</td>
</tr>
<tr>
<td>Control valve</td>
<td>A valve that controls either the heating or warm water in buildings. Part of the substation.</td>
</tr>
<tr>
<td>MFU</td>
<td>Measurement for utilities, the system where LEN saves data from costumers</td>
</tr>
<tr>
<td>OPTi-Sim</td>
<td>Platform for simulation and engineering of DHC systems</td>
</tr>
<tr>
<td>Peak Load (LEN)</td>
<td>LEN defines peak load in two steps. First step is when the consumption exceeds 185 MW and burning wood pellets is needed to manage the demand. The next step and the most important is when these 185 MW and the 20 MW wood pellets is not sufficient, and we have to start burning oil or electricity</td>
</tr>
<tr>
<td>PLC</td>
<td>Programmable logic controller, programmable controller that manages the I/Os</td>
</tr>
<tr>
<td>SCADA</td>
<td>Supervisory Control and Data Acquisition System, a system that is ideal for superior control and data storage.</td>
</tr>
<tr>
<td>Set point</td>
<td>The target value that an automatic control system, for example PID controller, will aim to reach.</td>
</tr>
<tr>
<td>E-value</td>
<td>A fixed cost depending of energy consumed, type of building (utilization), statistical corrected done in a formula.</td>
</tr>
<tr>
<td>Use case</td>
<td>A description of what we want to achieve in the project and how it can be done.</td>
</tr>
<tr>
<td>Test case</td>
<td>A detailed description of what will be performed in the use case or a test case for OPTi-Sim validation</td>
</tr>
<tr>
<td>(A)MPC</td>
<td>(Adaptive) Model predictive control</td>
</tr>
<tr>
<td>CBA</td>
<td>Cost benefit analysis</td>
</tr>
<tr>
<td>TC</td>
<td>Test case</td>
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3 OPTi TEST CASES

The test cases were described in D6.1. There are 6 test cases pertaining to Luleå and 2 test cases pertaining to the Mallorca sites. In this section, we revisit these test cases in sequence. In D6.1, the description of the test cases included not just the background and experimental setup but also the datasets and KPIs relevant to the analysis. Some of the test cases need to be updated based on the progress of the project. These updates are described here. Particularly, for each test case, any updates to the procedure are detailed followed by the proposed data analysis methodology. The data analysis methodology describes the process that will be followed for analysing the data obtained from the tests and generating the results. These results are in terms of the KPIs relevant to the test case.

3.1 TEST CASE LTC01: DECREASED SUPPLY TEMPERATURE IN THE DHC NETWORK

3.1.1 Update to Test Case

During the ongoing winter no pilot tests has been performed on this test case. Simulation tests has been performed in OPTi-Sim and has shown that a more advanced controlling of the supply temperature can result in lowered use of energy. The results from calculations performed and presented in previous deliverables, 6.1 and 6.1 together with resent simulation result indicate in that KPI-1 is possible to accomplish by a lowering of supply temperature and more advanced controlling of the supply temperature.

3.1.2 Data Analysis Methodology

The methodology used for this project will be to create and use models of the DH network, to predict the economic outcome of lowered supply temperature as well as using already existing tools to as the LAVA-kalkyl to evaluate this test case.

<table>
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<th>Data required</th>
<th>Metric to address the KPI</th>
<th>Expected value of the metric</th>
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<td>KPI 1: Reducing energy production</td>
<td>Energy consumption $Q(t)$ &amp; Baseline estimation $Q(t)_{Baseline}$</td>
<td>$\sum Q(t)_{Baseline}$</td>
<td>Less than 0.95</td>
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<tr>
<td>KPI 1: Reducing energy losses</td>
<td>Energy losses $Q(l)$ &amp; Baseline estimation $Q(l)_{Baseline}$</td>
<td>$\sum Q(l)_{Baseline}$</td>
<td>0.9-0.95</td>
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3.2 TEST CASE LTC02: OPTIMIZING VALVES

3.2.1 Update to Test Case

The KPI 4 Validation and verification of the virtual DHC system is removed from LTC02 since it is not related to the test case work.

3.2.2 Data Analysis Methodology

Detail about the KPIs addressed in this test case are summarized in the following table.

<table>
<thead>
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<th>Data required</th>
<th>Metric to address the KPI</th>
<th>Expected value of the metric</th>
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### KPI 1: Reducing energy production
KPI 1: Reducing energy production

| Energy production $P(t)$ & Base line estimation $P(t)|_{Baseline}$ | $\frac{\sum P_i(t)}{\sum P_i(t)|_{Baseline}}$ | Less than 0.95 |

### KPI 5: increased economic benefit
KPI 5: increased economic benefit

| Economic data essential for a cost benefit analysis in terms of CAPEX and OPEX. For example, the associated costs for changing the valves in the system and expected revenues after optimising them (through network performance improvement). | Standard economic metrics will be used such as the Internal Rate of Return (IRR) and the Present Value (PV) comparing the two cases (Business as Usual and OPTi assets introduction) for a period up to 20 years. This will also include a sensitivity analysis. | 5% |

---

### 3.3 Test case LTC03: Peak load reduction

#### 3.3.1 Update to Test Case
Since this is mainly a peak load reduction test case the KPI 1 will be removed to keep the focus on lowering the peak load. Energy savings can be achieved together with peak load reduction, but we will only have focus on lowering peaks to get the largest effects possible.

The KPI 4 Validation and verification of the virtual DHC system will be removed from LTC03 since it is not related to the work conducted in this test case.

Early test results have indicated that KPI 3 will strive for expanding comfort temperature from delta $^\circ$C for ±1 degrees instead of ±2 degrees.

The virtual knob will only be used for test at the office building at Luleå Energy. No virtual knob test will be used in the residential buildings due to problems with meeting agreements with all the apartment owners. Since all the apartments will be affected by any test performed we would need agreement from all residents which would not be possible in the scope of the project.

In LTC03 Peak load reduction, no real-world tests will be performed where optimisation is done from OPTi-sim on how to control buildings that should be optimised based on production as stated in D6.1. Also, no host system has been installed that would manage to do this controlling in the real world since no simulation could be done in OPTi-sim during the timeframe of the heating period in Luleå.

#### 3.3.2 Data Analysis Methodology
Detail about the KPIs addressed in this test case are summarized in the following table.

<table>
<thead>
<tr>
<th>KPI Addressed</th>
<th>Data required</th>
<th>Metric to address the KPI</th>
<th>Expected value of the metric</th>
</tr>
</thead>
<tbody>
<tr>
<td>KPI 2: Peak load reduction</td>
<td>Power consumption $P(t)$ &amp; Base line estimation $P(t)</td>
<td>_{Baseline}$</td>
<td>$\frac{\frac{\sum P(t)}{Mean_{Peak\ Period}(P(t))} - \frac{\sum P(t)</td>
</tr>
<tr>
<td>KPI 3: Consumer</td>
<td>Virtual knob data, zone temp. data</td>
<td>Range of Celsius for which Mean consumer feedback is between -1 and 1</td>
<td>2 degrees</td>
</tr>
</tbody>
</table>
3.4  **Test case LTC04: Peak load reduction via ADR and consumer incentivization**

3.4.1 Update to Test Case

In order to improve the efficiency of the district heating network, OPTi employs ADR programs to reduce the peak load consumption at specific peak times (forecasted via the baselines). These programs coupled with appropriate incentives (rewards) and targeting approaches with associated policies aim to increase consumer’s willingness to actively participate in ADR. The evaluation of these ADR programs and their associated incentive schemes requires the involvement of real users and in particular, at apartment level, for which consumption measurements should be available. It also requires monetary incentives to be provided to them. However, due to the limitations in the residential trial sites in terms of the availability of apartment level consumption data and most importantly the non-possible interaction with users (feedback provided at the time of the ADR event/test) via the virtual knob this test case will be performed and evaluated only in a simulated environment.

3.4.2 Data Analysis Methodology

Details about the KPIs addressed in this test case are summarized in the following table.

<table>
<thead>
<tr>
<th>KPI Addressed</th>
<th>Data required</th>
<th>Metric to address the KPI</th>
<th>Expected value of the metric</th>
</tr>
</thead>
<tbody>
<tr>
<td>KPI 5: Increased economic benefit</td>
<td>1. Both comfort and inside temperature data for each user and apartment. 2. Power consumption $P(t)$, Baseline estimation $P(t)_{\text{Baseline}}$ &amp; user thermal comfort models.</td>
<td>1. The change of the inside temperature from the comfort temperature defined by each user. 2. The difference of the sum of user utilities after and before DR plus the difference of the total cost for energy production.</td>
<td>5% to 20 %</td>
</tr>
</tbody>
</table>

3.5  **Test case LTC05: Energy reduction**

3.5.1 Update to Test Case

No updates needed for the test case.
3.5.2 Data Analysis Methodology

Details about the KPIs addressed in this test case are summarized in the following table. Although there is a potential to address the peak load with LTC05, it was judged that the peak load reduction KPI is already sufficiently addressed in LTC03 and LTC04, which is why the KPI2 contribution is removed.

<table>
<thead>
<tr>
<th>KPI Addressed</th>
<th>Data required</th>
<th>Metric to address the KPI</th>
<th>Expected value of the metric</th>
</tr>
</thead>
<tbody>
<tr>
<td>KPI 1: Reducing energy production</td>
<td>Power consumption $P(t)$ &amp; Base line estimation $P(t)_{Baseline}$</td>
<td>$\frac{\sum P_i(t)}{\sum P_i(t)_{Baseline}}$</td>
<td>Less than 0.95</td>
</tr>
<tr>
<td>KPI 1: Reducing energy production (Track 2)</td>
<td>Power consumption $P(t)$ &amp; Base line estimation $P(t)<em>{Baseline}$ and associated temperatures $T(t)$ and $T(t)</em>{Baseline}$</td>
<td>$\frac{\sum P_i(t)}{\sum P_i(t)_{Baseline}}$ for $\Delta T(t) =</td>
<td>T(t) - T(t)_{Baseline}</td>
</tr>
</tbody>
</table>

3.6 Test case LTC06: Improved Efficiency

3.6.1 Update to Test Case

No updates needed for this test case.

3.6.2 Data Analysis Methodology

Details about the KPIs addressed in this test case are summarized in the following table.

<table>
<thead>
<tr>
<th>KPI Addressed</th>
<th>Data required</th>
<th>Metric to address the KPI</th>
<th>Expected value of the metric</th>
</tr>
</thead>
<tbody>
<tr>
<td>KPI 1: Reducing annual energy consumption</td>
<td>Power production data $(P_i(t))$ from plant i and time t and Delivered energy data $(E(t))$</td>
<td>$\frac{\sum P_i(t) \Delta t - \sum E(t)}{\sum P_i(t) \Delta t - \sum E(t)_{Baseline}}$</td>
<td>0.95</td>
</tr>
</tbody>
</table>

3.7 Test case MTC01: Overall Peak Load Reduction

3.7.1 Update to Test Case

Sampol has developed a tool to calculate the optimal operation point of a power plant with all these factors and considering different Demand Response options. Sampol’s tool described in the D3.2, for calculating the optimal operation point of the plant is used in this Test Case, calculating the energy to move in DR Events. First group of tests were for analysing the DR potential in Son Llatzer. In these tests, the demand is modified by changing the HVAC set point or pre-cooling the installation. 60 tests were planned, 41 of them were executed (the reason these tests were not executed is because there was operational problems).

3.7.2 Data Analysis Methodology

Detail about the KPIs addressed in this test case are summarized in the following table.
<table>
<thead>
<tr>
<th>KPI Addressed</th>
<th>Data required</th>
<th>Metric to address the KPI</th>
<th>Expected value of the metric</th>
</tr>
</thead>
<tbody>
<tr>
<td>KPI 2: Peak load reduction</td>
<td>Power consumption $P(t)$ &amp; Base line estimation $P(t)$</td>
<td>$\frac{\text{Mean}<em>{\text{Peak Period}}(P(t)) - \text{Mean}</em>{\text{Day}}(P(t))}{\text{Mean}_{\text{Day}}(P(t))}$</td>
<td>Less than 0.60</td>
</tr>
<tr>
<td>KPI 5: Increased economic benefit</td>
<td>Associated costs and revenues after peak load reduction for each value chain player (energy provider and users)</td>
<td>Using the Sampol tool to estimate power plant costs. The difference in the total associated costs and revenues before and after peak load reduction</td>
<td>15%</td>
</tr>
</tbody>
</table>

### 3.8 Test case MTC02: Hospital room peak load reduction

#### 3.8.1 Update to Test Case

In Son Llatzer Hospital the ward HVAC system consist in a AHU that supplies climate air to the inductors which actuate on this air increasing or decreasing in 3 degrees its temperature depending on the room thermostat, as shown in Figure 3.1. The ward HVAC system is described in D6.2.

![HVAC system diagram for patient rooms in Son Llatzer Hospital](image)

Since ward inductor data is not available due to operational system, experiments on AHU were run. For that reason, there were monitored two twins AHU installing all sensors available (air and water temperature, pressure, valve position, etc). In this Test Case the results will be compared with two different AHU during DR Events.

#### 3.8.2 Data Analysis Methodology

Detail about the KPIs addressed in this test case are summarized in the following table.
<table>
<thead>
<tr>
<th>KPI Addressed</th>
<th>Data required</th>
<th>Metric to address the KPI</th>
<th>Expected value of the metric</th>
</tr>
</thead>
<tbody>
<tr>
<td>KPI 2: Peak load reduction</td>
<td>Power consumption $P(t)$ &amp; Base line estimation $P(t)_{\text{Baseline}}$</td>
<td>$\left(\frac{\text{Mean}<em>{\text{Peak Period}}(P(t)) - \text{Mean}</em>{\text{Day}}(P(t))}{\text{Mean}<em>{\text{Day}}(P(t))}\right)</em>{\text{Baseline}}$</td>
<td>Less than 0.60</td>
</tr>
<tr>
<td>KPI 5: Increased economic benefit</td>
<td>Economic data essential for a cost benefit analysis in terms of CAPEX and OPEX.</td>
<td>Using the Sampol tool for estimating costs. The difference in the total associated costs and revenues before and after peak load reduction.</td>
<td>15%</td>
</tr>
</tbody>
</table>
4 INTERPRETATION OF KPIs

The analysis of the test results as described in the above section provide evaluation metrics in terms of each of the KPIs relevant to the test case. However, since a KPI may belong to several test cases, the results of the test cases need to be integrated together to determine the overall results in terms of achieving each of the KPIs in a wholesome manner. In this section, we present the methodology that will be adopted for analysing the results from this perspective of achieving the target KPIs of the project.

4.1 KPI1: REDUCING ENERGY CONSUMPTION

Several test cases will have an impact on the KPI1, which means that it must be clarified in what way the individual contributions can be judged as complementary or not. Complementary contributions will enable the superposition of the effects and thereby adding up the contributions. In total a reduction of 10% should be achieved.

Complementary contributions can be found in the following disjoint categories:

- Reduction of losses in the distribution
- Increased efficiency in the production
- Reduced energy usage at the consumer side

Contribution that fall into one of the categories only, can therefore be added up in the quantification of the KPI.

Another aspect of the KPI quantification is the relation between the test case scale and the real-life scale. The test cases will be small scale in nature and therefore it necessary to gain an understanding what the observed and quantified effects would means in the context of an average DHC system. This scaling up of effects if usually leading to increased uncertainty and the confidence levels do decrease. Nevertheless, for all the cases we need to assume that the scaling is linear and would be able to observe the similar relative reduction on a larger scale.

We will now review the different test cases and determine in what way the quantified outcomes for KPI1 can be combined:

- **LTC01** aims at validating reduced supply temperature and thus, using a new supply temperature curve. As such the losses in the distribution are reduced whilst the supplied energy will be the same.
- **LTC02** aims at increasing the efficiency at the consumer side by utilizing better designed hardware and more fitting to the desired performance. It falls therefore in the category of reduced energy usage at the consumer side.
- **LTC03** and **LTC04** are not assumed to provide insights or a quantifiable effect for KPI1. Those will be ignored for KPI1.
- **LTC05** has two tracks. While both aim at reduction of energy on the production side, Track 1 aims at increasing the efficiency in the production and distribution, and Track 2 at reducing the energy usage at the consumer side. As a result, the tracks are disjoint. Moreover, less energy used at the consumer side renders less energy produced.
- **LTC06** will investigate the efficiency in the production and the distribution and thereby overlaps with LTC01 and LTC05 (Track 1). The combination of contribution is therefore not straight forward. As soon as LTC06 and LTC05 leads to an altered supply temperature, then LTC01 effect cannot be combined with those due to the overlap. Similarly, the contribution of LTC05 and LTC06 can only be combined if the different effects on the operation of the DHC system are the result.

To conclude:

- Main contribution is expected from LTC05 (both tracks).
- Contribution of LTC02 are complementary and will be added.
• Contribution of LTC01 is seen as complementary if LTC05 is not altering the supply temperature curve.
• Contribution of LTC06 is seen as complementary if LTC05 (Track1) is suggesting and operation of the DHC which can be put in place parallel to the result from LTC06. In that case the contribution can be added, otherwise not and the operation schemes are understood as conflicting. In the case of such a conflict the largest contribution of the two will be chosen.

The quantification of KPI1 will therefore require not only a direct analysis of the data, but also of the operation schemes that are tested.

4.2 KPI2: REDUCED PEAK LOAD

The power generation in both trials sides, they are designed to cover a certain demand, by the production of a cogeneration plant, high efficient. However, when demand is up to the cogeneration production, auxiliary power resources are required to cover the demand. This auxiliary power production is less effective, so reducing peak load demands will produce an important decrease CO2 emission.

To achieve the 40% reduction in peak loads, defined as an objective of the project, first it should be defined the different peak loads characteristics and types in the two different trials sides. Once the peak load has been defined, it should be measured the total thermal demand related to peak loads in a whole year. Using demand response techniques and considering the test results, the goal is to achieve a 40% reduction of the thermal demand related to the peak loads, in average. Peak loads depend on the demand profile, therefore, peak load definition is different for every demand. In the following sections Lulea trial peak load and Mallorca trial peak load will be defined.

4.2.1 Definition of peak loads in the Luleå pilot

In this section, we describe how peak load is defined and how peaks are being identified from energy data. To identify the peaks in production and the consumers peaks the outdoor temperature and energy data was collected on hourly basis. The following condition, equation (1), was then applied to create the daily energy pattern.

\[
\frac{Q}{dT} (time, day of the week) \times \frac{Q}{(T_{indoor} - T_{outdoor})} (time, day of the week) [W/T]
\]  

(1)

In Luleå we have two different definitions of peak load. The first is:

<table>
<thead>
<tr>
<th>Production peak load over a day</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Description</strong></td>
</tr>
<tr>
<td><strong>Objective</strong></td>
</tr>
<tr>
<td><strong>Why?</strong></td>
</tr>
</tbody>
</table>

The production in Luleå has two larger peaks during each day. This is due to larger consumption of hot tap water and the start-up of ventilation and heat for offices and industry buildings. The peaks can be seen in Figure 4.1.
The second definition is called the auxiliary boiler production peak load and has two steps.

In Luleå the auxiliary boiler start-up, peak production, occurs when the base production in not enough to deliver heat to consumer and an auxiliary boiler needs to be fired, peak production.

$$\frac{\sum \text{Peak production}}{\sum \text{Total production}} = X_{\text{peak load}}$$

The peak production from an auxiliary boiler is target for the KPI-2 when performing peak load reduction at consumers.

### Auxiliary boiler production peak load step 1

<table>
<thead>
<tr>
<th>Description</th>
<th>In this scenario there is a high demand of energy during a period of colder weather than -8 degrees. At this temperature the first step in auxiliary boiler start-up usually occurs by starting wood powder burners.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Objective</td>
<td>Identify peaks in production by analysing the consumption patterns and reducing them by using weather forecasts and the buildings accumulated heat to even out the peaks. Thereby reduce the usage of all auxiliary boilers. If there is cold weather during a shorter time the start-up of an auxiliary boiler can be completely avoided by applying peak load reduction.</td>
</tr>
<tr>
<td>Why?</td>
<td>Reduce activity of auxiliary boilers in high cost hours and increase in lower cost ones.</td>
</tr>
</tbody>
</table>

### Auxiliary boiler production peak load step 2

| Description | In this scenario there is a high demand of energy during a period of colder weather and both the base load production and the wood powder at HVC 4 are in production. The next auxiliary boiler to start is either electrical or oil which is the most costly and least environmental friendly fuel. |
Objective
Identify peaks in production by analysing the consumption patterns and reducing them by using weather forecasts and the buildings accumulated heat to even out the peaks.
Reduce the usage of the least environmental friendly auxiliary boilers by applying peak load reduction in buildings.

Why?
Reduce the usage of the least environmental friendly and expensive fuels.

4.2.2 Definition of peak loads in the Mallorca pilot

Before defining the peak loads, the production profile will be described.

4.2.2.1 Hot Water production in Winter Days

Hospital AHUs are automatic controlled having different setpoint depending on time (night mode or day mode) and area. The day mode (high setpoint) last from 7:00 to 22:00, and the night mode (low setpoint) from 22:00 to 7:00.

In Figure 4.2 and Figure 4.3 two different winter day situations are shown. Figure 4.2 shows a soft winter day (70% of winter days in 2016) where CHP engine load (“Carga Motor”) is low between 2-6 AM due to a low electrical price. Nevertheless, hot water thermal demand is covered by CHP engine, without being necessary to add Auxiliary sources.

Figure 4.3 shows a cold winter day (30% of winter days in 2016). CHP engine load follows the same profile than previous one, reducing its load between 2-6 AM. At 7-8 AM. The Hot water thermal demand suffers a sudden increase of 1000 kWh due to the change on the set point (day mode) of the HVAC system. In that case the CHP engine cannot follows this sudden demand increase, and auxiliary thermal sources (gas boilers) are necessary.

In both cases, the thermal demand normalizes its value at 12-13h up to 22h, when the set point returns to the ‘night’ value.

![Figure 4.2: Power plant Hot water production. Demand covered by CHP engine](image)
4.2.2.2 **Cold Water production in Summer days**

In Figure 4.4 a typical summer day situation is shown. Cold water demand is bigger than maximum CHP plant production (1300 kWh) and Auxiliary thermal sources (electrical chillers) are operating to cover cold water demand.
As it is shown in the figure above, auxiliary chillers are needed the whole day. However, depending on the cold water production required it is needed to start one to four auxiliary chillers.

4.2.2.3 Peak Load Definition

Hot water Demand
A peak load occurs when at 8 AM in a Labor Day if the night temperature is low and the CHP engine is not capable to supply all the Hot water demand between 7-8 AM.

- We will define a peak load if the following conditions are accomplished:
- Hot water demand increases at least 300 Kwh at 7-8 AM
- CHP engine is running normally during the night (not in maintenance mode)
- Demand is covered by CHP engine and Auxiliary Thermal sources are OFF between 0-4 AM
- Auxiliary boilers are switched ON at 7-8 AM

With those conditions, 44 peak loads are detected in 2016. A hot water demand increase on average of 580 kWh (± 184 kWh) is observed between 7-8 AM. The amount of thermal demand covered by auxiliary boilers between 7-9 AM is on average of 174 kWh (± 182 kWh).

Cold Water Demand
A peak load will occur when additional sources are needed to cover cold water demand for a reduced time. Son Llatzer plant has 4 electrical chillers that are used as auxiliary sources for cold water demand. Each chiller has an electrical power of 200 Kw. Their thermal energy power depends on weather conditions but is approximately 1000 KWht.

Auxiliary sources (Electrical chillers) takes some time to generate water demand with efficiency, so temporary use of the electrical chillers is inefficient. If CHP engine is working (no maintenance work on going), only one or two electrical chillers are necessary to cover cold water demand. If the CHP engine is on maintenance mode, up to 4 electrical chillers can be used.

Switching ON electrical chillers for less than 3-4 hours when the CHP plant is working is inefficient and it should be avoided. In the same way, the activation of one electrical chiller in a spring or autumn hot day or the activation of a second electrical chiller in a hot summer day.

4.3 KPI3: USER THERMAL COMFORT FLEXIBILITY

KPI3 targets enhancing the flexibility in the thermal comfort of the users. Specifically, the target of this KPI is to widen the average user-accepted temperature comfort zone by approximately 2 degrees Celsius or more. As defined in Section 5.3 of D2.1, this can be interpreted as $\Delta CRi \geq 20$ C.

In the list of updated test case descriptions, KPI3 pertains to only LTC03 (Peak Load Reduction) in the Lulea test cases. Therefore, achievement of KPI3 overall in the OPTi project is equivalent to achieving the target of KPI3 in this test case. Therefore, the overall target of KPI3 is to be able to widen the user temperature comfort zone by approximately 2 degrees Celsius during the LTC03 Peak Load Reduction trials at Lulea pilot site. The evaluation methodology for determining KPI3 during LTC03 is already described in the above (Section 3.3.2).

4.4 KPI4: CAPABILITY OF REPRESENTING REAL LIFE EVENTS

The purpose of KPI4 is to quantify the capability of the simulation framework OPTi-Sim to represent real life events. As described in detail in D2.1, KPI4 will be evaluated by comparing simulation results with real-life measurements, in our case historical data from the Lulea DH network. The evaluation procedure comprises a qualitative and a quantitative part.

The qualitative part is a graphical comparison of simulated and real-life time series considering corresponding error margins. Based on this analysis, LEN engineers will accept a simulation result or reject it. This is the
ultimate test for the fidelity of the model as the users of OPTi-Sim (operators and engineers) must trust the simulation results.

The quantitative analysis investigates whether the difference between simulated and measured data points is significantly different from zero. If this is the case, this indicates that the used model/simulation is not properly representing the real-life event it was designed to mimic. Depending on the magnitude of the deviation, the model needs minor or major alterations and tuning. If the analysis does not result in a significant deviation from zero, the simulation captures the event appropriately and does not have to be adjusted.

A list of 20 events has been identified in historical data from the Lulea network (see chapter 5). It will be evaluated if these events are correctly replicated by OPTi-Sim, based on the assessment of the indicators for the correctness of replication. OPTi-Sim will be capable of representing 95% of real-life events, which means that 19 events out of 20 have to be accepted.

4.5 KPI5: ECONOMIC BENEFIT

KPI5 metrics are straightforward as presented in this document and in more detail in the previous WP2, WP3 and WP5 deliverables where, for example, the theoretical work for ADR is presented. The methodology for evaluating the economic benefit depends on the specific test case, pilot and context and the underlying business models (value chain participants), where applicable. i.e. there is no universally applied methodology and the different results cannot in a scientifically sound manner be summed up to provide one final result.

For example, in Son Llatzer hospital, the power plant owner is the hospital itself, however, Sampol is running and maintaining it for some years. Both corporations have interests in the right operation of the power plant and DR seems a very good technology for saving money and gas emissions without a big investment. During the period of the OPTI project, economic benefits of DR will be studied, these benefits will come from the energy not consumed by the hospital and the money saved from the energy production (producing thermal energy at a lower price).
5 Validation of OPTi-SIM Framework

The validation of the OPTi-Sim simulation framework follows the procedure for the evaluation of KPI4 (see Section 4.4 and D2.1). 20 real life events, which have been selected from historical data from the Lulea DH network, will be simulated and the simulation results will be compared with real-life data.

5.1 List of real life events from Lulea DH network

The following table contains 20 real life events from the Lulea DH network, which have been identified for the evaluation of KPI4 and, thus, the validation of OPTi-Sim. The events were selected from historical data that had been collected in 2015 and 2016. Relevant seasons for LEN’s test cases are mainly winter and to some extend spring and autumn. Hence, most selected events are in winter and some in spring and autumn. Moreover, different weekdays have been chosen to consider differences between working days and weekends.

Table 5.1: List of real-life events for the validation of OPTi-Sim. The events have been selected from historical data from the Lulea DH network.

<table>
<thead>
<tr>
<th>Event</th>
<th>Day (1-7)</th>
<th>Start time</th>
<th>End time</th>
<th>Description</th>
<th>Trigger or event scenario</th>
</tr>
</thead>
<tbody>
<tr>
<td>01</td>
<td>3</td>
<td>2015-03-10 13:00</td>
<td>2015-03-10 23:00</td>
<td>Production disturbance at LUKAB. HVC 2 takes over production.</td>
<td>LUKAB drops out of production.</td>
</tr>
<tr>
<td>02</td>
<td>1</td>
<td>2015-03-22 13:00</td>
<td>2015-03-10 22:00</td>
<td>Production disturbance. Cold water in the grid.</td>
<td>Production disturbance.</td>
</tr>
<tr>
<td>03</td>
<td>3</td>
<td>2015-03-24 06:00</td>
<td>2015-03-10 23:00</td>
<td>HVC 4 start-up during warm weather (-3°C).</td>
<td>Auxiliary boiler start-up.</td>
</tr>
<tr>
<td>04</td>
<td>5</td>
<td>2015-03-26 08:00</td>
<td>2015-03-26 16:00</td>
<td>Production disturbance at LUKAB. HVC 2 and HVC 4 take over production.</td>
<td>LUKAB drops out of production.</td>
</tr>
<tr>
<td>05</td>
<td>6</td>
<td>2015-03-27 02:00</td>
<td>2015-03-27 12:00</td>
<td>LUKAB takes over production from HVC 1, 2 and 4.</td>
<td>LUKAB takes over production.</td>
</tr>
<tr>
<td>06</td>
<td>2</td>
<td>2015-03-30 00:00</td>
<td>2015-03-31 00:00</td>
<td>Normal production.</td>
<td>Normal production.</td>
</tr>
<tr>
<td>07</td>
<td>6</td>
<td>2015-05-15 00:00</td>
<td>2015-05-16 00:00</td>
<td>Normal production.</td>
<td>Normal production.</td>
</tr>
<tr>
<td>08</td>
<td>2</td>
<td>2015-06-15 11:00</td>
<td>2015-06-15 21:00</td>
<td>Production from HVC 1, 2 and 4 during low energy demands.</td>
<td>Stable auxiliary boiler production without LUKAB</td>
</tr>
<tr>
<td>09</td>
<td>6</td>
<td>2015-09-11 05:00</td>
<td>2015-09-11 19:00</td>
<td>LUKAB drops out, HVC 2 and 1 takes over, LUKAB takes over again.</td>
<td>Production disturbance.</td>
</tr>
<tr>
<td>10</td>
<td>5</td>
<td>2015-10-01 00:00</td>
<td>2015-10-02 00:00</td>
<td>Normal production.</td>
<td>Normal production.</td>
</tr>
<tr>
<td>11</td>
<td>2</td>
<td>2015-12-28 05:00</td>
<td>2015-12-28 23:00</td>
<td>Start-up of auxiliary boilers 1 and 4. Mainly 4.</td>
<td>Auxiliary boiler start-up.</td>
</tr>
<tr>
<td>12</td>
<td>2</td>
<td>2016-01-04 04:00</td>
<td>2016-01-04 20:00</td>
<td>Start-up of auxiliary boilers 1, 2 and 4. LUKAB running at maximum production.</td>
<td>Auxiliary boiler start-up.</td>
</tr>
<tr>
<td>13</td>
<td>5</td>
<td>2016-01-07 00:00</td>
<td>2016-01-07 20:00</td>
<td>Cold weather. Auxiliary boilers 1, 2 and 4 are running.</td>
<td>Maximum production due to cold weather.</td>
</tr>
<tr>
<td>14</td>
<td>1</td>
<td>2016-01-10 05:00</td>
<td>2016-01-10 23:00</td>
<td>Start-up of first auxiliary boiler, HVC4.</td>
<td>First auxiliary boiler start-up.</td>
</tr>
</tbody>
</table>
The evaluation is performed by analysing and comparing simulated and real-life sensor data. In particular, we evaluate differential pressures, supply and return temperatures at dedicated sensors in the network. The exact sensor positions for the analysis are chosen according to each individual event. One example is given in the following section.

### 5.2 Example Event

As an example, for the analysis of events, Event01 has been selected:

<table>
<thead>
<tr>
<th>Event</th>
<th>Day (1-7)</th>
<th>Start time</th>
<th>End time</th>
<th>Description</th>
<th>Trigger or event scenario</th>
</tr>
</thead>
<tbody>
<tr>
<td>01</td>
<td>3</td>
<td>2015-03-10 13:00</td>
<td>2015-03-10 23:00</td>
<td>Production disturbance at LUKAB. HVC 2 takes over production.</td>
<td>LUKAB drops out of production.</td>
</tr>
</tbody>
</table>

In this case, a disturbance caused a production outage at LUKAB and, consequently, the auxiliary boiler HVC2 took over production until LUKAB was running again (see Figure 5.1).

![Figure 5.1: Event01 – Production outage at LUKAB triggers start-up of auxiliary boiler HVC2, which compensates the supply shortage until LUKAB is running again.](image-url)
This event is reflected in certain sensor measurements at LUKAB and throughout the DH network. Examples for relevant sensor measurements, which were influenced by the production outage, are given in the following figures:

**Figure 5.2**: Event01 – measured return temperature at LUKAB (error bars according to measurement accuracy of temperature sensor +/- 0.4°C).

**Figure 5.3**: Event01 – measured differential pressure at Lulsundet (error bars according to measurement accuracy of pressure sensor +/- 0.04%; errors are too small to be visible).
The next step is to simulate all events listed in Table 5.1 with OPTi-Sim, and to compare the simulated sensor data with real-life measurements using the KPI4 evaluation procedure. The results of the validation simulations will be documented in the second version of this deliverable.

5.3 Validation results from OPTi-SIM and KPI4

5.3.1 Simulation setup
For the simulation of the depicted 20 real life events all the simulations without the use of auxiliary boilers are done with a lead time of 8 hours to ensure that the model is accurately initialized. A lead time of 24 h did not show differences in the model accuracy for the time period of interest. In case of LUKAB not being able to provide enough power to the network (e.g. in weather situations with low outdoor temperature) a lead time of 16 hours is used. This is needed to increase the thermal energy of the network to the required level.
The simulation time step is set to 2 s for the FMUs of the control models (that define the setup of the plants in the network) and the network and 300 s for the black box model as well as for the operator unit.

Input parameters to the simulation are the date and the time from which the temperature profile from historical data is extracted. The outdoor temperature is used for the Black-Box model to estimate the demand as well as for the supply temperature based on the supply temperature curve. Other input has been provided by LEN to reflect the normal behaviour of an operator and is given in Table 5.2: Signals defined in the operator. For example, four set points for differential pressure are used, that are set in the same way as in the real network. Figure 5.6 shows an example of the comparison between the measurement and simulation for such a set point. Simulation as well as measurement deviate slightly from the set point that is set to 0.14 but this can be neglected.

![Figure 5.6: Differential pressure at Öhemmanet for test case 7. The set point in the simulation is set to 0.14 following the real network operations.](image)

The depicted 20 real life cases are divided into two groups. The first can be titled as “normal production” which means that the energy is delivered by LUKAB, all auxiliary boilers are off and the corresponding valves are in bypass position. The second group covers the cases where LUKAB is not able to provide enough energy for the network (e. g. on days with cold weather or disturbances in the production) and the operator decides to start auxiliary boilers.

### Table 5.2: Signals defined in the operator

<table>
<thead>
<tr>
<th>CONFIDENTIAL INFORMATION</th>
</tr>
</thead>
<tbody>
<tr>
<td>due to business, security and data privacy reasons</td>
</tr>
</tbody>
</table>

#### 5.3.1.1 Events occurring during normal production (TC6, 7, 10, 17, 19 and 20)

In case of normal production all auxiliary boilers are bypassed. LUKAB is the only plant in the network for the delivery of energy. In order to validate the Test Case scenarios, significant events in the observed time period have to be defined. As for normal production, the morning and evening peaks in the demand shall be analysed more closely and used as the event for KPI-4 evaluation.

All components of the simulation are dependent to the demand of the Black-Box model. Figure 5.7 shows the demand of energy (Total Power) for the sum of the consumers in Test Case 20. The Black Box model
correlates to the outdoor temperature such that a high outdoor temperature gives a small demand and vice versa, additionally taking the time and weekday into account (high demands in the morning and evening on working days). From the demand of the consumers derives the energy production from LUKAB (LUKAB Power). Besides the slight temporal shift due to the inertia of the system, LUKAB power production directly follows the demand of the consumers as expected. Thus, the driving force and only input parameter to the system is the demand of the black box model. Most differences between measurements and simulation stem from uncertainties in the demand.

LUKAB power production is used for KPI-4 evaluation. For each Test Case, events must be defined which are used for quantification of the KPI-4 criteria. For normal production, the morning and evening peak is identified as these events and can be seen in the demand of the consumers (Total Power) in Figure 5.7 at about 9:00 and 20:00.

![Power and Outdoor Temperature 02-Apr-2016](image)

**Figure 5.7: Power and outdoor temperature for test case 20. Light blue: demand of energy for the sum of consumers derived from Black Box model. Dark blue: power production of LUKAB. Orange: outdoor temperature.**

Exemplarily, also for Test Case 20, the comparison between the measurement and simulation are shown in Figure 5.8, to show how the analysis for each event is performed. For both, the measurement and the simulation, the morning and evening peak are identified by the highest value of the production. We defined that KPI-4 is achieved, if the measurement and simulation peaks match within two hours and 15% of the maximum total production. The two hours tolerance period is visualized by the blue and green vertical box around the peak of the correlated data, respectively. Additionally, the 15% margin is visualized by the error bar at the maximum peak. For the morning peak, the events barely match in time, also the power in the simulation at the morning, which is around 115 MW, is just within 15% of the production in the measurement (133 MW). The evening peak matches very well, both in time and absolute value.
Figure 5.8: Generated power of LUKAB for Test Case 20. The blue curve represents the output of the simulation which is compared to the green curve with the measurements. Test Case 20 is one day long and thus two events (morning and evening peak) are shown. For each event, a one hour tolerance range in x-direction and a 15%-deviation of the total power from the measurement in y-direction is displayed.

Other quantities are not analysed in more detail for the KPI-4 Test Case evaluation as the characteristic are either the same (see Figure 5.9) or the analysed events (such as morning and evening peak) are not observed in both, the measurement and the simulation.

Figure 5.9: Flow at LUKAB and supply temperature at LUKAB from test case 19. As can be seen the simulation follows the trend of the measurement with the same behaviour.

Normal production comprises the cases 6, 7, 10, 17, 19 and 20 whereas each will be analysed more closely in part 5.3.2.1.

5.3.1.2 Events with auxiliary boilers

In case of LUKAB not being able to provide enough energy for the network (e. g. on days with cold weather) auxiliary boilers start to fire. This is done automatically as soon as LUKAB reaches 190 MW. The order in which auxiliary boilers start to fire can be seen in Table 5.3.
Table 5.3: Order of operation.

<table>
<thead>
<tr>
<th></th>
<th>MW</th>
<th>Accumulated total MW</th>
<th>No. of steps</th>
</tr>
</thead>
<tbody>
<tr>
<td>LUKAB, gas</td>
<td>185</td>
<td>185</td>
<td>-</td>
</tr>
<tr>
<td>HVC4, wood</td>
<td>22</td>
<td>207</td>
<td>2</td>
</tr>
<tr>
<td>HVC1, electricity</td>
<td>30</td>
<td>237</td>
<td>2</td>
</tr>
<tr>
<td>HVC2, oil</td>
<td>80</td>
<td>317</td>
<td>4</td>
</tr>
<tr>
<td>HVC1, oil</td>
<td>30+</td>
<td>347</td>
<td>1</td>
</tr>
</tbody>
</table>

The amount of power provided by the auxiliary boilers is set manually. In case of HVC4 and HVC1-electricity this is done within two equidistant steps until the maximum is reached, in case of HVC2 four steps are implemented to account for the system inertia.

5.3.1.3 Logic to start auxiliary boilers

In general auxiliary boiler start when LUKAB is not able to provide enough energy for the network, that is, LUKAB is running on its maximum (in the simulation: 220 MW). In practice auxiliary boiler (HVC4, see Table 5.3) start when the following conditions are met:

\[
\left( \left( \text{KVV\_power} \geq 200 \right) \&\& \left( \text{slope\_KVV\_power} > 0 \right) \right) \lor \left( \left( \text{KVV\_power} \geq 180 \right) \&\& \left( \text{slope\_KVV\_power} > 10 \right) \right)
\]

If the supplied power of LUKAB (KVV\_power) is greater than 200 MW and slope\_KVV\_power, the difference of the actual power to the value one hour before, is greater than 0 MW, or, if KVV\_power is greater than 180 MW and the slope of KVV\_power is greater than 10 MW. As soon as an auxiliary boiler has started, one hour is given for the network to settle before the boiler is fired with higher power or a new auxiliary boiler is started.

Auxiliary boilers are stopped when the following conditions are met:

\[
\left( \text{KVV\_power} < 170 \right) \lor \left( \left( \text{KVV\_power} < 180 \right) \&\& \left( \text{slope\_KVV\_power} \leq -5 \right) \&\& \left( \text{slope\_C\_power} \leq 1 \right) \right)
\]

In case of KVV\_power is lower than 170 MW, the boiler is stopped in any case. In case of KVV\_power is lower than 180 MW, two other conditions have to be met. First, the slope of KVV\_power has to be lower than -5 MW and second, the slope of the power requested by the consumers (C\_power) has to be less than 1 MW. The rate at which auxiliary boilers are stopped must not exceed one hour as defined for the starting as well. The following four chapters briefly outline the setup in the operator for starting auxiliary boilers.

5.3.1.3.1 HVC4

Signal setup for HVC4 startup.

Table 5.4: Signals in the operator that have to be changed to start HVC4.

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5.3.1.3.2  HVC1 – electricity
Signal setup for HVC1-electricity start-up.

Table 5.5: Signals in the operator that have to be changed to start HVC1 – electricity

<table>
<thead>
<tr>
<th>CONFIDENTIAL INFORMATION</th>
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</thead>
<tbody>
<tr>
<td>due to business, security and data privacy reasons</td>
</tr>
</tbody>
</table>

5.3.1.3.3  HVC2
Signal setup for HVC2 startup.

Table 5.6: Signals in the operator that have to be changed to start HVC2.

<table>
<thead>
<tr>
<th>CONFIDENTIAL INFORMATION</th>
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<tbody>
<tr>
<td>due to business, security and data privacy reasons</td>
</tr>
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</table>

5.3.1.3.4  HVC1 - oil
Signal setup for HVC1 startup.

Table 5.7: Signals in the operator that have to be changed to start HVC1 – oil.

<table>
<thead>
<tr>
<th>CONFIDENTIAL INFORMATION</th>
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<tbody>
<tr>
<td>due to business, security and data privacy reasons</td>
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</tbody>
</table>

5.3.2  Validation results

5.3.2.1  Events with normal production
To validate if the simulation is able to reproduce the real networks behaviour the simulation is compared to the measurement. According to the KPI-4 validation an event is accepted as sufficiently simulated if prominent peaks and trends in the measurements are met by the simulation within a time frame of one hour and within an error in the magnitude of 15%. For the normal production cases these peaks can be defined as the typical morning and the evening peak in the power production.

Table 5.8 sums up which events can be considered as accepted and which not:
In the following the cases are analysed more closely.

5.3.2.1.1 Test Case 6

Figure 5.10 left compares the production of LUKAB in the simulation to the measurements. As noted above, the morning and evening peaks are used for quantification of the KPI-4 achievement.

The present case comprises two days, thus, four events are evaluated next. All events fulfill the KPI-4 criteria for the two hours tolerance. Also the events match quantitatively, even if the difference in the first morning peak is quite high.

In order to understand the difference, the origin of the power production is analyzed. Figure 5.10 right shows the demand of the Black Box model and the resulting power production. As the demand in the first morning is low, the power production of LUKAB is also low, resulting in the deviation between the measurement and simulation. This shows again the necessity of a well trained black box model for a good estimate of the production in the system.

<table>
<thead>
<tr>
<th>Event</th>
<th>Date</th>
<th>KPI-4 result</th>
<th>Reason</th>
</tr>
</thead>
<tbody>
<tr>
<td>06</td>
<td>30-Mar-2015</td>
<td>mostly accepted</td>
<td></td>
</tr>
<tr>
<td>07</td>
<td>16-May-2015</td>
<td>declined</td>
<td>Simulated flow and power too low, peaks not met</td>
</tr>
<tr>
<td>10</td>
<td>02-Oct-2015</td>
<td>accepted</td>
<td></td>
</tr>
<tr>
<td>17</td>
<td>01-Feb-2016</td>
<td>mostly accepted</td>
<td></td>
</tr>
<tr>
<td>19</td>
<td>23-Mar-2016</td>
<td>accepted</td>
<td></td>
</tr>
<tr>
<td>20</td>
<td>02-Apr-2016</td>
<td>accepted</td>
<td></td>
</tr>
</tbody>
</table>

**Figure 5.10:** Left: Generated power of LUKAB for Test Case 6. Small dashed lines show unfiltered signals, thicker lines are hourly mean values. Right: Power and outdoor temperature for Test Case 6. Test Case 6 consists of two days and thus four events (two morning peaks and two evening peaks) are shown. The KPI-4 validation points (timing, shown horizontally by the boxes, and magnitude, shown vertically by error bars) are achieved for all four events within the allowed deviation.

5.3.2.1.2 Test Case 7

Test case 7 also consists of two days, the 15th and 16th of May 2015. On both days, the morning peak in the measured power production of LUKAB (see figure 5.11 left) is earlier than simulated. Within the two hours of tolerance the simulation does not match with the measurement. KPI-4 is not achieved. When certain
weather phenomena occur, then LUKAB takes manual decisions on the operation and in this case, it seems that there has been a pre-heating occurring. These manual operations are not reflected in OPTi-Sim and therefore will render a deviation. Such manual actions are not traceable for the project team and can therefore not be accounted for. The evening peak matches correctly in time.

The deviation of the simulation of the produced power to the measurement is very high despite of the last evening peak. This again is caused by a very low demand of the Black Box model during the two simulated days (see Figure 5.11 right).

Figure 5.11: Left: Generated power of LUKAB for Test Case 7. Small dashed lines show unfiltered signals, thicker lines are hourly mean values. Right: Power and outdoor temperature for Test Case 7. Test Case 7 consists of two days and thus four events (two morning peaks and two evening peaks) are shown. For the morning peaks the KPI-4 is not achieved, neither for the timing nor for the magnitude. In case of the evening peaks the timing as well as the magnitude are within the allowed deviations.

5.3.2.1.3 Test Case 10

Test Case 10 consists of the 1st and 2nd of October 2015. Here normal production was reported with very warm weather (outdoor temperature up to 13°C, see Figure 5.12 right). The simulation of this Test Case matches the measurement very well (Figure 5.12 left). KPI-4 is achieved for all events (two morning and two evening events) with the correct timing as well as with the correct magnitude.

The production of LUKAB follows the power demand (Total Power) with a slightly higher amount, accounting for the losses in the network (see Figure 5.12 right).
5.3.2.1.4 Test Case 17

Test Case 17 is the 1st of February 2016. The simulated evening peak matches the measurement very well in time as well as in magnitude (Figure 5.13 left). The morning peak matches also just in magnitude but the deviation in time is three hours, which is more than allowed to define KPI-4 as achieved. This might be caused by the unexpected drop of the temperature around 9:30 am (Figure 5.13 right).

5.3.2.1.5 Test Case 19

Test Case 19 is the 23rd of March 2016. Normal production was reported with slightly cold weather (outdoor temperature around -5°C, see Figure 5.14 right). The simulation of this day just matches the measurement (Figure 5.14 left). KPI-4 is achieved for all events (one morning and one evening event) with the correct timing as well as with the correct magnitude although the time discrepancy is exactly two hours for morning and evening peak and the deviation in magnitude of the evening peak is the maximum allowed tolerance of 15%. As can be seen in Figure 5.14 right, the demand simulated from the Black Box model follows nicely the measured power of LUKAB (Figure 5.14 left) but the simulated power production of LUKAB is much higher.
When certain weather phenomena occur, then LUKAB takes manual decisions on the operation and in this case, it seems that there has been a pre-heating occurring. These manual operations are not reflected in OPTi-Sim and therefore will render a deviation. Such manual actions are not traceable for the project team and can therefore not be accounted for.

Figure 5.14: Left: Generated power of LUKAB for Test Case 19. Small dashed lines show unfiltered signals, thicker lines are hourly mean values. Right: Power and outdoor temperature for Test Case 19. The KPI-4 validation points (timing, shown horizontally by the boxes, and magnitude, shown vertically by error bars) are achieved for both peaks within the allowed deviation.

5.3.2.1.6 Test Case 20

Test Case 20 is the 2nd of April 2016. Normal production took place during outdoor temperatures around 0°C (see Figure 5.15 right). Especially the simulated evening peak matches the measurement very well in time as well as in magnitude (Figure 5.15 left). The morning peak also just matches in time and magnitude although this was not a typical peak but rather a flat rise. KPI-4 is achieved for all events of this test case.

Figure 5.15: Left: Generated power of LUKAB for Test Case 20. Small dashed lines show unfiltered signals, thicker lines are hourly mean values. Right: Power and outdoor temperature for Test Case 20. The KPI-4 validation points (timing, shown horizontally by the boxes, and magnitude, shown vertically by error bars) are achieved for both peaks within the allowed deviation.

The slight deviation of the produced power of LUKAB might be explainable with the supply temperature (see Figure 5.16). The simulated supply Temperature in the time between 00:00 am and 6:00 am is about 2°C higher than the measured. Therefore LUKAB has not to put that much energy in the system.
Figure 5.16: Supply temperature of LUKAB for Test Case 20. Small dashed lines show unfiltered signals, thicker lines are hourly mean values. The simulated temperature between 00:00 am and 06:00 am is 2°C higher than the measured.

5.3.2.2 Events with auxiliary Boilers and KVV working as expected

Table 5.9: KPI-4 simulation results of events with auxiliary Boilers and KVV working as expected

<table>
<thead>
<tr>
<th>Event</th>
<th>Date</th>
<th>KPI-4 result</th>
<th>Reason</th>
</tr>
</thead>
<tbody>
<tr>
<td>03</td>
<td>24-Mar-2015</td>
<td>partly accepted</td>
<td>Unpredictable start of HVC4</td>
</tr>
<tr>
<td>11</td>
<td>28-Dec-2015</td>
<td>partly accepted</td>
<td>LUKAB reaction too sudden</td>
</tr>
<tr>
<td>12</td>
<td>04-Jan-2016</td>
<td>partly accepted</td>
<td>LUKAB reaction too sudden</td>
</tr>
<tr>
<td>13</td>
<td>07-Jan-2016</td>
<td>partly accepted</td>
<td>Unpredictable stop of HVC1</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Perhaps: too low supply temperatures of auxiliary boilers</td>
</tr>
<tr>
<td>14</td>
<td>10-Jan-2016</td>
<td>partly accepted</td>
<td>LUKAB reaction too sudden</td>
</tr>
<tr>
<td>15</td>
<td>13-Jan-2016</td>
<td>accepted</td>
<td></td>
</tr>
<tr>
<td>16</td>
<td>16-Jan-2016</td>
<td>accepted</td>
<td></td>
</tr>
</tbody>
</table>

In the following the cases are analysed more closely.

5.3.2.2.1 Test Case 03

Test Case 03 is the 24th of March 2015. Normal production took place during outdoor temperatures around -3°C (see Figure 5.18 left) before HVC4 started (see Figure 5.19).
Figure 5.17: left: simulated and measured volume flow of LUKAB for Test Case 03. Right: simulated and measured power of LUKAB for Test Case 03. Small dashed lines show unfiltered signals, thicker lines are hourly mean values. The simulation is able to reproduce the measurement very well. Morning and evening peak are matched in time as well as in magnitude.

From Figure 5.17 it can be seen that volume flow and power of LUKAB is simulated correctly. Both peaks, the morning and the evening peak, caused by the consumer model, match in time and in magnitude. Simulation and measurement look similar to the cases with normal production. The measured power supply of LUKAB is about 80 MW less than the maximum power, nevertheless HVC4 starts around 6:00 am (see Figure 5.19). The simulation is not able to reproduce this unexpected starting of an auxiliary boiler. The starting of HVC4 might be caused by the drop in the supply temperature of LUKAB (see Figure 5.18 right) that is not found in the simulation.

Figure 5.18: left: total power supply in the network as given by the simulation (blue), the measurement (dark blue) and the power demand of the consumer model (light blue) together with the outdoor temperature (orange) for Test Case 03. Right: simulated (blue) and measured (orange) supply temperature of LUKAB together with the supply temperature set point of LUKAB coming from the supply temperature curve for Test Case 03. In the measurement a sudden drop of the supply temperature can be seen, that is not present in the simulation.
5.3.2.2.2 Test Case 11

Test Case 11 is the 28th of December 2015. Auxiliary boilers start during outdoor temperatures around -12°C (see Figure 5.1823). The volume flow is simulated with a value around 20% less than seen in the measurement but the overall behaviour could be reproduced well (see Figure 5.20 left). The simulated power supply of LUKAB (see Figure 5.20 right) shows the same peaks as in the measurement but with a greater amplitude. LUKAB reacts strongly to the two sudden temperature decreases around 8:00 am and 18:00 pm that come together with an increase of power demand by the consumer model (see Figure 5.18).

Figure 5.19: power supply of auxiliary boiler HVC4 for Test Case 3. Small dashed lines show unfiltered signals, thicker lines are hourly mean values. The starting of HVC4 around 6:00 am can not be represented by the simulation.

Figure 5.20: left: simulated and measured volume flow of LUKAB for Test Case 11. Right: simulated and measured power of LUKAB for Test Case 11. Small dashed lines show unfiltered signals, thicker lines are hourly mean values. The simulation is able to reproduce the slopes in the measurement for the volume flow as well as for the produced power. The volume flow in the simulation is about 20% too low whereas the produced power is partly too low and partly too high. The slope in the simulated power production of LUKAB is much steeper than in the measurement.
Figure 5.21: same as Figure 5.20 but with a 10 times slower reaction of LUKAB implemented in the FMU for the simulation.

The simulation can reproduce the start of the auxiliary boilers. HVC2 is off the whole time whereas the starting time of HVC4 and HVC1 in the simulation matches the starting time in the measurement. In case of HVC4 also the magnitude and the behaviour of the power production of HVC4 is well reproduced by the simulation. In case of HVC1 the behaviour of the power production is reproduced quite good whereas the magnitude is too high. This contributes to the overproduction of energy around 9:00 am and 18:00 am compared to the demand of the consumer model (see Figure 5.23). It is caused by the fact that the power supply of LUKAB is still on maximum and does not react to the start of HVC4. After starting HVC1 with 30 MW (seen in the small dashed line) LUKAB suddenly drops more than 50 MW which shows a too fast reaction of LUKAB. This problem could not be solved by slowing down the reaction time of KVV in the FMU as can be seen in Figure 5.21.

Figure 5.22: left: power supply of auxiliary boiler HVC4 for Test Case 11. Right: power supply of auxiliary boiler HVC1 for Test Case 11. Small dashed lines show unfiltered signals, thicker lines are hourly mean values. In case of HVC4 the starting time as well as the magnitude and the behaviour of the power production of HVC4 is well reproduced by the simulation. In case of HVC1 the behaviour of the power production is reproduced quite good whereas the magnitude is much too high.
Figure 5.23: total power supply in the network as given by the simulation (blue), the measurement (dark blue) and the power demand of the consumer model (light blue) together with the outdoor temperature (orange) for Test Case 11. The simulated power supply covers the demand of the consumer model quite good except of the morning and evening peaks. Here two events come together. On the one hand the increase of power demand due to the peaks in the consumer models on the other hand the sudden decrease of outdoor temperature.

The supply temperature of LUKAB and HVC2 is reproduced well by the simulation whereas the supply temperatures of the other auxiliary boilers, that are only shown when auxiliary boilers run, is about 10% too high on average.

Figure 5.24: top left: simulated power supply of auxiliary boilers for Test Case 11. Others: simulated (blue) and measured (green) supply temperature of auxiliary boilers for Test Case 11 (top right: HVC2, bottom left: HCV1, bottom right: HVC4). The supply temperature of LUKAB and HVC2 is reproduced well by the simulation whereas the supply temperatures of the other auxiliary boilers, that are only shown when auxiliary boilers run, is about 10% too high on average.

5.3.2.2.3 Test Case 12
Test Case 12 is the 4th of January 2016. Auxiliary boilers start during outdoor temperatures around -14°C (see Figure 5.18).
Again, the simulated volume flow of LUKAB is about 10% lower than the measured but shows the same behaviour (not shown).

**Figure 5.25:** simulated (blue) and measured (green) power supply of LUKAB (top left) as well as auxiliary boilers HVC1 (top right), HVC2 (bottom left) and HVC4 (bottom right) for Test Case 12. The power supply of LUKAB is on average about 20% lower than measured except in the time from 8:00 am to 13:00 pm where simulation and measurement fit well. The start of the auxiliary boilers HVC4 and HVC1 is met very well. HVC2 does not start in the simulation whereas in the measurements HVC2 fired with up to 15 MW.

**Figure 5.26:** total power supply in the network as given by the simulation (blue), the measurement (dark blue) and the power demand of the consumer model (light blue) together with the outdoor temperature (orange) for Test Case 12. The simulated power supply covers the demand of the consumer model quite good except of the time between 8:00 am and 13:00 pm where outdoor temperature suddenly drops more than 6°C within 4 hours. The measured power supply is up to 40MW higher than the simulated demand of the consumers.

The power supply of LUKAB in the time until 6:00 am is lower than the measured power supply (see Figure 5.25) due to the lower demand of the consumer model (see Figure 5.26). Caused by the sudden temperature decrease between 6:00 am and 12:00 am (see Figure 5.26) LUKAB increases the power production and quickly reaches its maximum of 220 MW. Auxiliary boilers HVC4 and HVC2 start around 6:00 am in the measurement...
and at 6:00 am and 7:00 am in the simulation according to the condition to wait one hour after starting an auxiliary boiler, which is defined in the logic described in 5.3.1.3.

Figure 5.27 shows the power supply of the auxiliary boilers together with the supply temperature of each boiler. The supply temperature of LUKAB and HVC2 as well as HVC4 is reproduced well by the simulation, whereas the supply temperatures of HVC1 is nearly constant in the simulation but shows variations in the measurement.

![Supply temperature per plant 04-Jan-2016](image)

**Figure 5.27**: top left: simulated power supply of auxiliary boilers for Test Case 12. Others: simulated (blue) and measured (green) supply temperature of auxiliary boilers for Test Case 12 (top right: HVC2, bottom left: HCV1, bottom right: HVC4). The supply temperature of LUKAB and HVC2 as well as HVC4 is reproduced well by the simulation, whereas the supply temperatures of HVC1 is nearly constant in the simulation but shows variations in the measurement.

### 5.3.2.4 Test Case 13

Test Case 13 is the 7th of January 2016. All auxiliary boilers run during constantly low outdoor temperatures around -29°C (see Figure 5.29).
Figure 5.28: simulated (blue) and measured (green) power supply of LUKAB (top left) as well as auxiliary boilers HVC1 (top right), HVC2 (bottom left) and HVC4 (bottom right) for Test Case 13. Despite of the morning and evening peak, the power supply of LUKAB is on average 20 MW to 40 MW lower than measured. All auxiliary boiler run continuously in the simulation. In the measurement HVC1 stopped at 12:00 am.

In the simulation the power supply of LUKAB in the time until 6:00 am is lower than the measured power supply (see Figure 5.28) and increases due to increase in the demand of the consumer model (see Figure 5.29). Nevertheless, LUKAB does not reach its maximum of 220 MW as the increase is directly balanced by a higher production of HVC2. In the measurement HVC1 stops the power production at 12:00 am completely. This is inconsistent with the order of operation defined in Table 5.3 and therefore not predictable by the simulation. As can be seen in Figure 5.29 the simulated power supply covers the demand of the consumer model quite good, including the adding of 10% to account for losses in the network.

Figure 5.29: total power supply in the network as given by the simulation (blue), the measurement (dark blue) and the power demand of the consumer model (light blue) together with the outdoor temperature (orange) for Test Case 13. The simulated power supply covers the demand of the consumer model quite good, including the adding of 10% to account for losses in the network. The measured power supply, compared to the simulated demand, is up to 50 MW higher in the morning hours and about 20 MW lower in the evening hours.
Figure 5.30: top left: simulated power supply of auxiliary boilers for test case 13. Others: simulated (blue) and measured (green) supply temperature of auxiliary boilers for test case 13 (top right: HVC2, bottom left: HCV1, bottom right: HVC4). None of the measured supply temperatures could be reproduced accurately. 

Figure 5.31 shows the simulated and measured supply temperature of auxiliary boilers which give reason to suspect that none of the measured supply temperatures could be reproduced accurately. But comparing to Figure 5.31 it can be seen that the simulation of the supply temperature of LUKAB matches the set point within a mean difference of less than 1°C whereas the measured supply temperature varies greatly and differs up to 6°C from the set point.

Figure 5.31: simulated (blue) and measured (orange) supply temperature of LUKAB together with the supply temperature set point for LUKAB (dark blue) for test case 13. The simulation matches the set point within a mean difference of less than 1°C whereas the measured supply temperature varies greatly and differs up to 6°C from the set point.

5.3.2.2.5 Test Case 14
Test Case 14 is the 10th of January 2016. Auxiliary boilers start during outdoor temperatures around -12°C (see Figure 5.34).

Again, the simulated volume flow and supply power of LUKAB is lower than in the measurements (see Figure 5.32) but the simulated power supply fits the power demand of the consumer model until auxiliary boilers start (see Figure 5.34). Caused by an increase in the power demand of the consumer model, LUKAB slowly increases power production as well and the first auxiliary boiler, HVC4, starts (see Figure 5.33) as soon as LUKAB reaches 180 MW and a gradient of 10 MW within one hour. This can be seen in the small dashed blue line in Figure 5.32 right. The start of auxiliary boiler HVC4 is matched very well in time compared to the measurement. LUKAB again increases very fast when the outdoor temperature drops around 12:00 am (see Figure 5.34) what causes HVC4 to increase the power supply to 22 MW instead of 11 MW and later HVC1 to start as the power supply of LUKAB is still high. The measured behaviour of the power supply of HVC1 could not be reproduced. This is because first of all as the applied logic only allows HVC1 to start after HVC4 started (according to the order of operation shown in Table 5.3: Order of operation.). In the simulation the auxiliary boiler starts and stops with high frequency whereas in the measurement the auxiliary boiler runs constantly with 1 to 2 MW.

![Figure 5.32: left: simulated and measured volume flow of LUKAB for Test Case 14. Right: simulated and measured power of LUKAB for Test Case 14. Small dashed lines show unfiltered signals, thicker lines are hourly mean values. The simulation is able to reproduce the slopes in the measurement for the volume flow. The volume flow as well as the supplied power in the simulation is about 20% too low. In the simulated the power production of LUKAB increases suddenly around 13:00 pm and quickly reaches the maximum of 220 MW before dropping down again.](image-url)
Figure 5.33: left: power supply of auxiliary boiler HVC4 for Test Case 14. Right: power supply of auxiliary boiler HVC1 for Test Case 14. Small dashed lines show unfiltered signals, thicker lines are hourly mean values. In case of HVC4 the starting of the power production is well reproduced by the simulation whereas the magnitude is twice as high. In case of HVC1 the behaviour of the power production could not be reproduced. In the simulation the auxiliary boiler starts and stops with high frequency whereas in the measurement the auxiliary boiler runs constantly with 1 to 2 MW.

Looking at the supply temperature (see Figure 5.35) the simulated supply temperature of LUKAB matches quite well the measurement during the day with small deviations in the morning and evening hours. They are consistant with the supply temperature set point for LUKAB whereas the measured supply temperature is higher than defined by the supply temperature curve (not shown). The supply temperatures of HVC1 and HVC4 are up to 8°C too high.

Figure 5.34: total power supply in the network as given by the simulation (blue), the measurement (dark blue) and the power demand of the consumer model (light blue) together with the outdoor temperature (orange) for Test Case 14. The simulated power supply covers the demand of the consumer model quite good except of the time between 12:00 am and 22:00 pm where on the one hand the demand of the consumers increase and on the other hand the outdoor temperature drops.
Figure 5.35: top left: simulated power supply of auxiliary boilers for Test Case 14. Others: simulated (blue) and measured (green) supply temperature of auxiliary boilers for Test Case 14 (top right: HVC2, bottom left: HCV1, bottom right: HVC4). The simulated supply temperature of LUKAB matches quite well the measurement during the day, whereas the supply temperatures of HVC1 and HVC4 are up to 8°C too high.

5.3.2.2.6 Test Case 15

Test Case 15 is the 13th of January 2016. Auxiliary boilers are partly already running during cold outdoor temperatures around -19°C (see Figure 5.34). The power supply of LUKAB is on average about 15% lower than measured except in the time from 2:00 am to 5:00 pm where simulation is higher than the measurement (see Figure 5.36). During this time period HVC2 is off in the simulation whereas in the measurement HVC2 delivers the mentioned power difference. The power supply of HVC4 is very well reproduced in the simulation. The simulated power supply of HVC1 is 10 MW higher compared to the measured (30 MW instead of 20 MW). The simulation follows the order of operation defined in Table 5.3: Order of operation. This is also the reason why the power supply of HVC1 is not reduced before HVC2 is stopped.
Figure 5.36: simulated (blue) and measured (green) power supply of LUKAB (top left) as well as auxiliary boilers HVC1 (top right), HVC2 (bottom left) and HVC4 (bottom right) for Test Case 15. The power supply of LUKAB is on average about 15% lower than measured except in the time from 2:00 am to 5:00 pm where simulation is higher than the measurement. During this time period HVC2 is off in the simulation whereas in the measurement HVC2 delivers the mentioned power difference. The power supply of HVC4 matches the measurement very well, whereas the simulates power supply of HVC1 is between 10 MW and 30 MW too high.

Compared to the demand of the consumer model (see Figure 5.37) the simulated power supply covers the demand in every situation with the required overproduction of about 10% for losses in the network.

Figure 5.37: total power supply in the network as given by the simulation (blue), the measurement (dark blue) and the power demand of the consumer model (light blue) together with the outdoor temperature (orange) for Test Case 15. The simulated power supply covers the demand of the consumer model in every situation with the required overproduction of about 10% for losses in the network.
5.3.2.2.7 Test Case 16

Test Case 16 consists of two days, the 17th and of 18th of January 2016. Auxiliary boilers start on the 18th of January during cold outdoor temperatures up to -25°C (see Figure 5.34).

In the measurement the power supply of LUKAB increases, when the outdoor temperature starts to decrease on the 17th of January at 18:00 am, from 170 MW to its maximum and stays nearly constant for the whole time on the 18th of January. Auxiliary boilers start on the 18th of January successively starting at 0:00 am with HVC4, followed by HVC1 at 10:30 am and HVC2 at 12:00 am (see Figure 5.399).

In the simulation the power supply of LUKAB on the 17th is about 20 MW lower than in the measurement, being consistent with the lower power demand of the consumer model (see Figure 5.40), and about 40 MW lower on the 18th what is balanced by a higher production of HVC1 and HVC2. In general, the start of the auxiliary boilers is reproduced very well in the simulation.

Figure 5.41 shows the supply temperature of LUKAB together with the supply temperature set point for LUKAB. The simulation matches the set point perfectly well whereas the measured supply temperature is about 5°C too low on the 18th of January in the time frame around 12:00 am. This drop can also be seen in the supply temperatures of the auxiliary boilers in Figure 5.42 as well as in the measured power supply of LUKAB (see Figure 5.40). In general, the simulation matches the supply temperature for all auxiliary boilers quite well (despite of the unpredictable drop around 12:00 am) with the difference that the simulated supply temperature in general is more constant than the measured.

Figure 5.38: : top left: simulated power supply of auxiliary boilers for Test Case 15. Others: simulated (blue) and measured (green) supply temperature of auxiliary boilers for Test Case 15 (top right: HVC2, bottom left: HCV1, bottom right: HVC4). In all cases the simulated supply temperature matches quite well the measurement, except of an observed sudden decrease of the supply temperature of HVC4 around 13:00 pm that might be caused by the decrease in the power supply of HVC4 at that time.
Figure 5.39: simulated (blue) and measured (green) power supply of LUKAB (top left) as well as auxiliary boilers HVC1 (top right), HVC2 (bottom left) and HVC4 (bottom right) for Test Case 16. Auxiliary boiler start on the 18\textsuperscript{th} of January 2016. Here the power supply of LUKAB is on its maximum in the measurement and about 40 MW lower in the simulation. This difference is balanced by a higher production of HVC1 and HVC2. In general the start of the auxiliary boilers is reproduced very well in the simulation.

Figure 5.40: total power supply in the network as given by the simulation (blue), the measurement (dark blue) and the power demand of the consumer model (light blue) together with the outdoor temperature (orange) for Test Case 16. The simulated power supply covers the demand of the consumer model in every situation. However, the measured supply temperature is notable higher on the 17\textsuperscript{th} of January.
Figure 5.41: simulated (blue) and measured (orange) supply temperature of LUKAB together with the supply temperature set point for LUKAB (dark blue) for Test Case 15. The simulation matches the set point perfectly well whereas the measured supply temperature is about 5°C too low on the 18th of January in the time frame around 12:00 am where also the measured power supply of LUKAB drops (see Figure 5.40).

Figure 5.42: top left: simulated power supply of auxiliary boilers for Test Case 16. Others: simulated (blue) and measured (green) supply temperature of auxiliary boilers for Test Case 16 (top right: HVC2, bottom left: HCV1, bottom right: HVC4). Auxiliary boiler start on the 18th of January 2016. Here the simulation matches the supply temperature for all auxiliary boilers quite well with the difference that the simulated supply temperature in general is more constant than the measured.

5.3.2.3 Events with auxiliary boilers and KVV disturbances

In case of disturbances within KVV auxiliary boilers need to be started to satisfy the power demand. To simulate these situations the power supply of LUKAB is manually adjusted to the measured values with the
operator signal 'KVV_Power_Manual_MW'. The logic to start auxiliary boilers is adjusted in the following way:

\[
('KVV\_Ts\_SP' - 'KVV\_Temp\_595') > 2
\]

Where 'KVV\_Ts\_SP' is the supply temperature set point defined by the supply temperature curve and 'KVV\_Temp\_595' is the actual simulated supply temperature.

The logic to stop auxiliary boilers is adjusted in the following way:

\[
('KVV\_Ts\_SP' - 'KVV\_Temp\_595') < -2
\]

The order of operation defined in table Table 5.3: Order of operation. changes in the sense that HVC2 starts first as it is located next to KVV and therefor most suitable to compensate for disturbances of KVV.

Table 5.10: KPI-4 simulation results of events with auxiliary boilers and KVV disturbances shows the adapted KPI-4 simulation results with auxiliary boilers and KVV disturbances. As measurement and simulation can no longer be compared directly due to lower power production of KVV, KPI-4 is accepted when the simulation is able to fit the supply temperature to the supply temperature set point.

<table>
<thead>
<tr>
<th>Event</th>
<th>Date</th>
<th>KPI-4 result</th>
<th>Reason</th>
</tr>
</thead>
<tbody>
<tr>
<td>01</td>
<td>10.03.2015</td>
<td>accepted</td>
<td></td>
</tr>
<tr>
<td>02</td>
<td>22.03.2015</td>
<td>accepted</td>
<td></td>
</tr>
<tr>
<td>04+05</td>
<td>26./27.03.2015</td>
<td>declined</td>
<td>Supply Temperature varies much; set point not met</td>
</tr>
<tr>
<td>08</td>
<td>15.06.2015</td>
<td>accepted</td>
<td></td>
</tr>
<tr>
<td>09</td>
<td>11.09.2015</td>
<td>accepted</td>
<td></td>
</tr>
</tbody>
</table>

In the following the cases are analysed more closely.

5.3.2.3.1 Test Case 01

Test Case 01 is the 10th of March 2015. LUKAB drops out of production between 12:00 am and 18:00 pm and auxiliary boiler HVC2 takes over during outdoor temperatures around the freezing point (see Figure 5.44Figure 5.34).

When adjusting the power supply of LUKAB manually to the measured values (as seen in Figure 5.43 left), the supply power in the simulation is noticeably higher than the demand of the consumer model (see Figure 5.44). This leads to an increase in the supply temperature as the additional energy is not taken from the net but rather circulating in form of hot water.

Without the manual adjustment of the supply power of LUKAB, LUKAB feeds about 30 MW less power to the net (see Figure 5.46) and the supply temperature curve follows the supply temperature set point perfectly (see Figure 5.45). Therefore, when adjusting the power of LUKAB manually to simulate disturbances in the power production of LUKAB, it is set to 70% of the measured values in the following simulations. Figure 5.46 shows the resulting total power supply in the network together with the demand of the consumers as well as the outdoor temperature.
With KVV_Power manually adjusted to 70% of the measured values (see Figure 5.47) the supply temperature set point is matched well up to the point when the power supply of LUKAB drops and shows the same behavior as the measured supply temperature but a slightly larger decrease (see Figure 5.48).

**Figure 5.43:** left: simulated and measured power supply of LUKAB for Test Case 01 and manually adjusted KVV_Power to the measured values (+10% losses). Right: simulated and measured supply temperature of LUKAB together with the supply temperature set point for LUKAB. In the simulation the supply temperature of LUKAB increases constantly until power supply of LUKAB drops down between 12:00 am and 19:00 pm.

**Figure 5.44:** total power supply in the network as given by the simulation (blue), the measurement (dark blue) and the power demand of the consumer model (light blue) together with the outdoor temperature (orange) for Test Case 01 and manually adjusted KVV_Power to the measured values (+10% losses). The simulated power supply is much higher than the demand of the consumer model (C_Power) which results in the supply temperature to increase constantly (see Figure 5.43:).
Figure 5.45: simulated (blue) and measured (orange) supply temperature of LUKAB together with the supply temperature set point for LUKAB (dark blue) for Test Case 01 without intervention into the power production of LUKAB. The simulation matches the set point perfectly whereas the measured supply temperature drops down significantly (about 10°C too low) when the power supply of LUKAB drops.

Figure 5.46: total power supply in the network as given by the simulation (blue), the measurement (dark blue) and the power demand of the consumer model (light blue) together with the outdoor temperature (orange) for Test Case 01 without intervention into the production of LUKAB. The simulated power supply is less than the measured but covers the demand of the consumer model (C_Power) perfectly.
Figure 5.47: simulated and measured power supply of LUKAB for Test Case 01 and manually adjusted KVV_Power to 70% of the measured values (+10% losses). Small dashed lines show unfiltered signals, thicker lines are hourly mean values.

Figure 5.48: simulated (blue) and measured (orange) supply temperature of LUKAB together with the supply temperature set point for LUKAB (dark blue) for Test Case 01 and manually adjusted KVV_Power to 70% of the measured values (+10% losses). The simulation matches the set point well up to the point when the power supply of LUKAB drops. During the disturbances of LUKAB the simulation shows the same behavior as the measured supply temperature but a slightly larger decrease.

Figure 5.49 shows simulated (blue) and measured (green) supply temperature of auxiliary boilers for Test Case 01. As can be seen, the simulation matches the supply temperature for HVC2 well whereas the supply temperature of HVC1 and HVC4 drops down in the measurement significantly when LUKAB drops between 12:00 am and 18:00 pm. In the simulation HVC2 is on the whole day as the simulated power supply of KVV is lower than in the measurement, but the peak in HVC2 is reproduced well (see Figure 5.50).
Figure 5.49: top left: simulated power supply of auxiliary boilers for Test Case 01. Others: simulated (blue) and measured (green) supply temperature of auxiliary boilers for Test Case 01 (top right: HVC2, bottom left: HCV1, bottom right: HVC4). The power supply of LUKAB is fixed manually to 70% of the measured values +10% assumed losses. Auxiliary boiler HVC2 runs the whole day in the simulation, HVC1 and HVC4 are off, as in the measurement. The simulation matches the supply temperature for HVC2 well whereas the supply temperature of HVC1 and HVC4 drops down in the measurement significantly when LUKAB drops.

Figure 5.50: simulated (blue) and measured (green) power supply of LUKAB (top left) as well as auxiliary boilers HVC1 (top right), HVC2 (bottom left) and HVC4 (bottom right) for Test Case 01. The power supply of LUKAB is fixed manually to 70% of the measured values +10% assumed losses. Between 12:00 am and 18:00 pm KVV drops significantly in the measurements and HVC2 takes over. In the simulation HVC2 is on the whole day as the simulated power supply of KVV is lower, but the peak in HVC2 is reproduced well.
Figure 5.51: total power supply in the network as given by the simulation (blue), the measurement (dark blue) and the power demand of the consumer model (light blue) together with the outdoor temperature (orange) for Test Case 01 and manually adjusted KVV_Power to 70% of the measured values (+10% losses).

5.3.2.3.2 Test Case 02

Test Case 02 is the 22nd of March 2015. LUKAB drops out of production between 12:00 am and 18:00 pm and auxiliary boilers HVC2 and HVC4 take over during outdoor temperatures between -10°C and 0°C. In the simulation HVC2 runs the whole day as the manually adjusted Power of KVV is lower than the demand of the consumer model (see Figure 5.53). In the measurement HVC2 starts around noon with a high power of up to 100 MW (see Figure 5.52). The peak in HVC2 is reproduced with a time shift of about 3 hours which is due to the late decrease in the consumer model. The start of HVC4, seen in the measurements, is not existent in the simulation, according to the order of operation (see Table 5.3) as HVC2 is not at its limit. The supply temperature set point is matched well in the simulation (see Figure 5.54) up to the point when the power supply of LUKAB drops and shows the same behavior as the measured supply temperature but with a larger decrease.
Figure 5.52: simulated (blue) and measured (green) power supply of LUKAB (top left) as well as auxiliary boilers HVC1 (top right), HVC2 (bottom left) and HVC4 (bottom right) for Test Case 02. The power supply of LUKAB is fixed manually to 70% of the measured values +10% assumed losses. Between 12:00 am and 18:00 pm KVV drops significantly in the measurements and HVC2 takes over. In the simulation HVC2 is on the whole day as the simulated power supply of KVV is lower. The peak in HVC2 is reproduced with a time shift of about 3 hours. The start of HVC4, seen in the measurements, is not existent in the simulation, according to the order of operation (see Table 5.3) as HVC2 is not at its limit.

Figure 5.53: total power supply in the network as given by the simulation (blue), the measurement (dark blue) and the power demand of the consumer model (light blue) together with the outdoor temperature (orange) for Test Case 02 and manually adjusted KVV_Power to 70% of the measured values (+10% losses).
Figure 5.54: simulated (blue) and measured (orange) supply temperature of LUKAB together with the supply temperature set point for LUKAB (dark blue) for Test Case 02 and manually adjusted KVV_Power to 70% of the measured values (+10% losses). The simulation matches the set point well up to the point when the power supply of LUKAB drops and shows the same behavior as the measured supply temperature but with a larger decrease.

5.3.2.3.3 Test Case 04 and 05

Test Case 04 and 05 consists of two days, the 27th and of 28th of March 2015. LUKAB drops out of production between 12:00 am on the 27th and 12:00 am on the 28th of March during outdoor temperatures between -9°C and 2°C. Auxiliary boilers take over the production in the following order: HVC2, HVC4, HVC1 as defined in the adapted order of operation (see page 52).

In the simulation the power of HVC2 is lower than in the measurement due to the given restrictions in the order of operation (see Table 5.3). HVC1 and HVC4 run for a shorter time period (see Figure 5.55: simulated (blue) and measured (green) power supply of LUKAB (top left) as well as auxiliary boilers HVC1 (top right), HVC2 (bottom left) and HVC4 (bottom right) for Test Cases 04 and 05 (two days). The power supply of LUKAB is fixed manually to 70% of the measured values +10% assumed losses. Between 12:00 am on the 27th of March and 12:00 am on the 28th of March KVV drops out of production and auxiliary boilers take over. In the simulation as well as the measurement each of the auxiliary boilers starts in the analyzed time frame. The power of HVC2 is lower in the simulation than in the measurement due to the given restrictions in the order of operation (see Table 5.3). HVC1 and HVC4 run for a shorter time period.). The simulated power supply does not follow the power demand of the consumer model (see Figure 5.56) which leads to deviations of the supply temperature to the supply temperature set point seen in Figure 5.57. The simulation is not able to follow the temperature set point but rather oscillates around the set point with a large amplitude of around 30 MW.
Figure 5.55: simulated (blue) and measured (green) power supply of LUKAB (top left) as well as auxiliary boilers HVC1 (top right), HVC2 (bottom left) and HVC4 (bottom right) for Test Cases 04 and 05 (two days).

The power supply of LUKAB is fixed manually to 70% of the measured values +10% assumed losses. Between 12:00 am on the 27th of March and 12:00 am on the 28th of March KVV drops out of production and auxiliary boilers take over. In the simulation as well as the measurement each of the auxiliary boilers starts in the analyzed time frame. The power of HVC2 is lower in the simulation than in the measurement due to the given restrictions in the order of operation (see Table 5.3). HVC1 and HVC4 run for a shorter time period.

Figure 5.56: total power supply in the network as given by the simulation (blue), the measurement (dark blue) and the power demand of the consumer model (light blue) together with the outdoor temperature (orange) for Test Case 04 and 05 (two days) and manually adjusted KVV_Power to 70% of the measured values (+10% losses). The simulated power supply does not follow the power demand of the consumer model which leads to deviations of the supply temperature to the supply temperature set point seen in Figure 5.57.
5.3.2.3.4 Test Case 08

Test Case 08 is the 15th of June 2015. LUKAB drops out of production completely for the whole day and all auxiliary boilers take over during warm outdoor temperatures around 9°C (see Figure 5.58 and Figure 5.59). In the simulation as well as in the measurement HVC2 runs the whole day with about 40MW. In the measurement HVC1 starts around 6:00 am and HVC4 runs the whole day, which is not seen in the simulation as the power supply of HVC2 is enough to cover the demand of the consumer model perfectly. The measured power supply is almost twice as high as the simulated power supply (see Figure 5.59).

Figure 5.60 shows the simulated and measured supply temperature of LUKAB together with the supply temperature set point. The simulation matches the set point well with small deviations of about 6°C between 00:00 am and 05:00 am.
Figure 5.58: simulated (blue) and measured (green) power supply of LUKAB (top left) as well as auxiliary boilers HVC1 (top right), HVC2 (bottom left) and HVC4 (bottom right) for Test Case 08. The power supply of LUKAB is fixed manually to 0 MW. In the simulation as well as in the measurement HVC2 runs the whole day with about 40MW. In the measurement HVC1 starts around 6:00 am and HVC4 runs the whole day, which is not seen in the simulation.

Figure 5.59: total power supply in the network as given by the simulation (blue), the measurement (dark blue) and the power demand of the consumer model (light blue) together with the outdoor temperature (orange) for Test Case 08 and manually adjusted KVV_Power to 70% of the measured values (+10% losses). The measured power supply is almost twice as high as the simulated power supply which covers the demand of the consumer model perfectly.
Figure 5.60: simulated (blue) and measured (orange) supply temperature of LUKAB together with the supply temperature set point for LUKAB (dark blue) for Test Case 08 and manually adjusted KVV_Power to 70% of the measured values (+10% losses). The simulation matches the set point well with small deviations of about 6°C between 00:00 am and 05:00 am.

5.3.2.3.5 Test Case 09

Test Case 09 is the 15th of June 2015. LUKAB drops out of production between 06:00 am and 15:00 pm during temperatures around -12°C and auxiliary boilers, mostly HVC2, take over (see Figure 5.61 and Figure 5.62). In the simulation HVC2 runs the whole day with about 30MW. In the measurement HVC2 starts with 40MW when KVV drops out. HVC4 and HVC1 start as well. This is not seen in the simulation as HVC2 is able to provide enough power to compensate for KVV. The simulated power supply covers the demand of the consumer model perfectly. Also, the temperature set point is matched acceptable in the simulation with small oscillations with an amplitude of about 2°C (see Figure 5.63).
Figure 5.61: simulated (blue) and measured (green) power supply of LUKAB (top left) as well as auxiliary boilers HVC1 (top right), HVC2 (bottom left) and HVC4 (bottom right) for Test Case 09. The power supply of LUKAB is fixed manually to 70% of the measured values +10% assumed losses. Between 06:00 am and 15:00 pm KVV drops out of production and auxiliary boilers, mostly HVC2, take over. In the simulation HVC2 runs the whole day with about 30MW. In the measurement HVC2 starts with 40MW when KVV drops out. HVC4 and HVC1 start as well. This is not seen in the simulation as HVC2 is able to provide enough power to compensate for KVV.

Figure 5.62: total power supply in the network as given by the simulation (blue), the measurement (dark blue) and the power demand of the consumer model (light blue) together with the outdoor temperature (orange) for Test Case 09 and manually adjusted KVV_Power to 70% of the measured values (+10% losses). The simulated power supply covers the demand of the consumer model perfectly.
Figure 5.63: simulated (blue) and measured (orange) supply temperature of LUKAB together with the supply temperature set point for LUKAB (dark blue) for Test Case 09 and manually adjusted KVV_Power to 70% of the measured values (+10% losses). The simulation matches the set point acceptable but varies with an amplitude of about 2°C.

5.4 CONCLUSION

Chapter 5 demonstrated the capability of the OPTi-Sim framework to replicate real-life events with sufficient accuracy. Although we did not reach the intended quality measure as described in KPI-4, the obtained results are nevertheless significant, and the simulation approach provides an important additional tool for the engineers at Lulea Energi.

By and large, the evaluated test cases form three groups. The first group contains events where no auxiliary boiler(s) are needed to provide sufficient power for the network. The second group includes events where auxiliary boilers are required to reach or sustain a certain level of production. The third group represents setups where auxiliary boilers are needed and disturbances in KVV production occur. The individual groups contain a total number of six, seven, and five events, respectively.

According to the definition of KPI-4, we accepted a simulation result if the simulated time course coincides with the measured sensor values within a time frame of one hour. We further allowed a discrepancy of magnitude between measured and simulated values of 15%. The first criterion is motivated by the inertia of the entire network. This temporal window is usually sufficient for engineers to properly react to occurring incidents. We estimate the second criterion as a combination of the approximate nature of the utilized models and of sensor measurement errors. Here, modelling errors contribute the larger share to our estimate.

In the first group, five out of six simulated events passed the acceptance criteria. One simulation did not reproduce the expected magnitude of the flow and power in the network. Moreover, simulated and observed peaks did not coincide. The reason here is most likely due to shortcomings in the black box models.

In the second group, basically all simulated events passed the acceptance tests. Here, we observed several abnormalities whose cause we were not able to pin down. However, each of these uncommon incidents had only minor significance altogether.

In the third group, four out of five events passed the acceptance criteria. The only failure concerned the reproduction of the temporal variation of the supply temperature and not reaching its set point.

In total, we thus successfully reproduced sixteen out of eighteen events, resulting in an overall positive rate of roughly 90 per cent. This value is close to our intended 95 per cent target value from KPI-4. The small
difference is remarkable given the different levels of detail in our modelling approach. The black box models followed a data-driven approach where no physical relation between input, output, and the inner workings of the model entity is assumed. Modelling of the DHC network involved intricate physics and engineering principles, much more detailed than a black box model. Finally, the controller models also included fine-tuned and approximate constructs to regulate the entire DHC network, its pumps, supply station and much more.

In conclusion, the OPTi-Sim framework provides a beneficial tool to simulate the behaviour of DHC networks under different operating conditions. The evaluation of numerous real-life events of the Lulea DHC network illustrated its capabilities, but also revealed its shortcomings. **Even if we fell short of the intended KPI-4 target value of 95 per cent, the obtained reproducibility rate of almost 90 percent is a remarkable result.** Further refinement in modelling the involved processes, parts, and structures are likely to push this significant number events closer to the KPI-4 target value.
6  LULEÅ TESTS & RESULTS

In this section, the results from the LTCs are presented. The LTCs are both pilot tests and simulated tests. The data sources that is used for evaluation and simulation is historic real-life data of the plants and grid.

The testing site in Luleå and the different test cases have had different time limitations regarding when they could be performed. The mayor limitation for the pilot tests are that they are limited to the winter months since they require cold weather. To clarify when the individual test cases can be performed a table with colour coding will be used where red corresponds to “Not possible” and green corresponds to “Possible” period for testing. See example below in Figure 6.1.

<table>
<thead>
<tr>
<th>December</th>
<th>January</th>
<th>February</th>
<th>March</th>
<th>April-September</th>
</tr>
</thead>
<tbody>
<tr>
<td>Not possible</td>
<td>Possible</td>
<td>Possible</td>
<td>Possible</td>
<td>Not possible</td>
</tr>
</tbody>
</table>

Figure 6.1: Example of test planning.

6.1  TEST CASE: LTC01 DECREASED SUPPLY TEMPERATURE IN THE DHC NETWORK

6.1.1  Background and test description

In the work of making the grid more efficient one important aspect for DHC networks is to lower the supply temperature. A lower supply temperature has several benefits:

- Lowered heat losses in the grid.
- Increased electricity production in the CHP plant.
- Less abrasion on pipes, pumps, DH centrals and other components in the grid.

6.1.2  Performed test

In the context of this test case, a new supply temperature curve has been applied at the production sites of Luleå energy. In Figure 6.2, the old and the new supply temperature curve can be observed. It is mostly at colder outdoor temperatures that the impact of the new curve is most significant where the new curve deviates 5 degrees from the old curve at -30°C in outdoor temperature. The curve has been developed by production engineers at Luleå Energy and LUKAB. It is based on knowledge of the grid and limitations regarding for example existing pumps. During the test period, which has been ongoing since autumn 2015, there have been no negative aspects caused by the new curve. This is very positive and as a result the new curve is now permanent.

Figure 6.2: New and old supply curve.
6.1.3 Test evaluation

The test has been evaluated by using the tool LAVA-kalkyl developed by Svensk fjärrvärme (Selinder & Walletun, 2011). The result can be viewed in section 6.1.4 for the winter period December 2015 until March 2016. The energy saving during this period is according to the LAVA-kalkyl is almost 800 MWh, which corresponds to 0.1% of the annual production.

Calculated savings varies for different years depending on the outdoor temperature. For a whole year, calculations have been made from 2013 and 2014 with the new curve. For those years, the savings have been calculated to between 2.5 - 3 GWh annually. This corresponds to 0.4 % of the annual production.

6.1.3.1 LAVA-kalkyl

The LAVA-kalkyl is used frequently by the DH industry. The purpose of the tool is to make a rough estimation to determine the cost savings that can be made in a district heating system by temperature level changes, partly through a reduced return temperature and by a change in the supply temperature.

The Lava Kalkyl uses both historical data from production as well as actual components from the grid e.g. pumps, boilers etc. The model has also been supplemented with functions for calculating the change in environmental data at the changed system temperatures and also changes due to reduced power output.

The supply temperature can be said to consist of two parts. Firstly, the design supply line temperature at the DUT (= Dimensioning outdoor temperature) and also the lowest supply temperature at partial load. The latter is usually called base temperature ($T_{fram,Bas}$). The final temperature level in the district heating network is the result of these three temperatures ($T_{return}$, $T_{fram,DUT}$ and $T_{fram,Bas}$).

The resulting return temperature $T_{return}$ is itself a function of a number of parameters such as supply temperature, flow, cooling of the district heating (FC), circular paths of distribution-network, and network losses.

When supply and return temperature are changed, the district heating system can be affected in the following ways:

- An increase in $T_{supply}$ or reduction of $T_{return}$ allows a higher maximum power output of the existing distribution system, that is, increased delivery capacity.
- It is possible that the amount of waste heat that can be recovered from the industry can be increased when $T_{return}$ can be reduced.
- An increase of $T_{supply}$ and/or a reduction of $T_{return}$ reduce the total flow in the distribution system.
- The flow reduction results in reduction in energy costs for pumps.
- Lowering $T_{return}$ and/or $T_{supply}$ reduces heat loss from the distribution pipes.

6.1.4 Test conclusions

To change the supply temperature curve is a very simple way of reducing fuel in the production due to less needed energy and gives direct impact on production costs and less environmental footprint. Divided for different fuels in this calculation the savings are given in Table 6.1.

<table>
<thead>
<tr>
<th>Production unit</th>
<th>Fuel</th>
<th>MWh less production</th>
</tr>
</thead>
<tbody>
<tr>
<td>LUKAB</td>
<td>Surplus gas from steel plant</td>
<td>479</td>
</tr>
<tr>
<td>HVC 1</td>
<td>Electricity</td>
<td>121</td>
</tr>
<tr>
<td>HVC 2</td>
<td>Oil</td>
<td>124</td>
</tr>
<tr>
<td>HVC 4</td>
<td>Wood powder</td>
<td>68</td>
</tr>
</tbody>
</table>
In Figure 6.3, below the result sheet from the LAVA-kalkyl can be seen. During the period from December to March the saving in money amounts to around 376106 Swedish crowns. These savings are calculated by thermodynamically correlating with the heat losses. Depending on different days the savings may vary depending on the outside temperature and the fuel costs. For the calculations, the following assumption are used:

- fixed cost for oil, gas and wood pellets
- electricity price was retrieved from the Nordpool spot market, which is available at the following website: http://www.nordpoolspot.com/Market-data1/#/nordic/table

Furthermore, depending on the temperature the need for increased pumping was considered (resulting in higher electricity consumption for pumping).

![New supply temp December 2015- March 2016](image)

**Figure 6.3: Calculated reduction of heat losses in Lava and the economical profit from the lowered production from the different production units.**

Moreover, it is of interest to understand the potential if all of Europe’s district heating grids would lower the heating losses in the grid by 0.4% of the yearly production because of lowered supply temperature. The saving has been applied for the different fuels. In Figure 6.4, the heat sources for district heating from EU27 countries is summarized and has been used for calculations (DHC+ Technology platform, 2012).
Using the numbers in Figure 6.4 together with the total energy from district heating, the total calculated energy from the different fuels is summarized in Table 6.2 below. Shown in the same table is also the average district heating grid in Europe based on numbers from Heat road map Europe, (Schlinnertz, 2012).

Table 6.2: Fuel for district heating for EU27 countries and definition of the average DH-network in Europe

<table>
<thead>
<tr>
<th>Energy in EU27</th>
<th>Total production [GWh]</th>
<th>Total production [TWh]</th>
<th>Average DH-network [GWh]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fossil fuels, direct use</td>
<td>152689</td>
<td>152,7</td>
<td>28,3</td>
</tr>
<tr>
<td>Renewables (geothermal, biomass and waste) direct use</td>
<td>46981</td>
<td>47,0</td>
<td>8,7</td>
</tr>
<tr>
<td>Recycled heat, renewable CHP (waste and biomass)</td>
<td>90047</td>
<td>90,0</td>
<td>16,7</td>
</tr>
<tr>
<td>Recycled heat, fossil, CHP and industries</td>
<td>540283</td>
<td>540,3</td>
<td>100,1</td>
</tr>
<tr>
<td>Total production</td>
<td>830000</td>
<td>830,0</td>
<td>153,7</td>
</tr>
</tbody>
</table>

Table 6.3: Saving of the different fuels as result of the lowered heat losses in the network.

<table>
<thead>
<tr>
<th>Reduced fuel due to lowered supply temperature (0,4%)</th>
<th>Reduction/fuel [GWh]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fossil fuels, direct use</td>
<td>611</td>
</tr>
<tr>
<td>Renewables (geothermal, biomass and waste) direct use</td>
<td>188</td>
</tr>
<tr>
<td>Recycled heat, renewable CHP (waste and biomass)</td>
<td>360</td>
</tr>
<tr>
<td>Recycled heat, fossil, CHP and industries</td>
<td>2161</td>
</tr>
<tr>
<td>Total production</td>
<td>3320</td>
</tr>
</tbody>
</table>

The reduction of energy for district heating is more than 3.3 TWh/year only by reducing the supply temperature and lowering the heat losses. Since the reduction is as greatest when it is cold weather there is also the usage of fossil fuels. Especially the direct use of fossil fuels is of great interest to reduce in the work of reducing the fossil footprint for the European countries. Recalculating the total fuel that can be saved it
represents the amount of energy for 6 sites in the size of Luleå, only by reducing the heat losses in the grid by reducing the supply temperature.

6.1.5 Simulation tests & results

The analytical assessment of a new temperature curve usually provides a good understanding of the expected average savings that can be achieved using modified temperature curve. Nevertheless, this approach lacks an understanding of the operational conditions that will be the consequence of a modified curve, namely instantaneous pressures, flows and temperatures that are occurring throughout the network over time. Such dynamic phenomena together with the operational characteristics of actuators like pumps, auxiliary units and valves can be studied with the help of OPTi-Sim.

OPTi-Sim thereby enables the study of operational aspects of a changed control scheme, like the modified temperature curve. It is not uncommon that pumps will saturate when certain the supply temperature curve is change too much or that auxiliary units fire using unfavourable fuels from both economic and environmental perspective.

![Simulation result for modified temperature curve. Power with desired power in red (upper left), outdoor temperature evolution (upper right), pump speed (lower left), supply temperature with desired in red (lower right).](image)

In Figure 6.5, oscillations can be observed in the beginning which are the result of the transient behaviour when OPTi-Sim starts from a deviating operating condition. This transient behaviour is normal for the simulation and should be disregarded, as OPTi-Sim needs to align its internal states with the real-life system. After that the power and temperature curve are tracked well and that the power is increasing while the outdoor temperature drops. It is important to note that the pumps are not saturating during the tested scenario, which means that the current control scheme should operate well during similar real-life conditions.

6.2 Test Case: LTC02 Optimizing Valves

6.2.1 Background and test description

Historically over-dimensioned control valves create problems with the production mainly in the presence of disturbances. Large valves open completely and consume large flows which decrease the differential
pressure further out in the grid and in turn causing problems. By introducing physical limitations that are
limiting the maximum flow, the effect of disturbances is limited in magnitude and if the controller is designed
to manage these actuator limitations properly and no wind-up of integrators occur, peaks due to
disturbances are reduced.
Another problem is the controller tuning for substations where there is a lack of automatic tools to generate
appropriate parameters for PID controllers. With respect to the prior limitation of the actuators, the
controller tuning, and anti-windup design need to be appropriately adapted.
The tests will then be performed in two ways:
• Change of control valves in several buildings
• Controller tuning using the automated tuning tool
The test evaluation need to consider different examples for disturbances that act on substations.

6.2.2 Performed test
Initial tests were done in 2015 where eleven oversized control valves were changed, see Table 6.4. A close
collaboration with the Municipality of Luleå enabled the exchange of valves in their substations and those
buildings were measured before and after the change and an analysis has been made. Further replacements
have been performed during 2016 and the beginning of 2017.

<table>
<thead>
<tr>
<th>Year of replacement</th>
<th>Old KVS values</th>
<th>New KVS values</th>
</tr>
</thead>
<tbody>
<tr>
<td>2015</td>
<td>339</td>
<td>77</td>
</tr>
<tr>
<td>2016</td>
<td>291</td>
<td>143</td>
</tr>
<tr>
<td>2017</td>
<td>151</td>
<td>66</td>
</tr>
</tbody>
</table>

| Sum                 | 781            | 286            |

In Table 6.4, the change in the valve size is shown. In average the valve size is reduce to 23% of the original
size and in one case down to 10% of the original size, for 2015. In Figure 6.6, an example for the change in
valve size is shown, where the valve size is reduced down to 16%.

Moreover, in WP5 an auto tuning tool for the PID controllers in a building substation was derived. Initial test
with the auto tuning tool at Luleå Energy’s building were performed during autumn of 2016. The focus was
the hot tap water, with the aim to optimize the control effect such that oscillations of the actuator are
avoided while being fast enough to quickly reduce temperature fluctuations. Step response experiments was performed on the hot tap water temperature in a closed loop setting to learn the dynamic behaviour of the system as a whole and especially the actuators. Based on the experiment a dynamic model was learned and new parameters for the controller were derived in an automatic fashion. In Figure 6.6, the step response experiment is depicted together with the simulated model output during the experiment. The model is tracking the transients well, while disturbances are not tracked. The model does not receive any disturbance inputs during simulation, which explains the absence of any reaction in the model output.

![Figure 6.7: Step response experiments and dynamic model performance.](image)

The auto tuning tool derived a model for the substation, which is given as a transfer function as follows:

\[
G(s) = \frac{0.01 (s - 0.00004)}{(s + 0.05530)(s + 0.00018)}
\]

Based on the estimated model a PI controller can be tuned. In an initial test an aggressive controller is tuned, which was focussed on reduced settling time. In a second test the controller was tuned to achieve a 2% settling time of 100 seconds. For the design the internal model control principle was used. The controller parameters in the substation are then updated accordingly and tested.

### 6.2.3 Test evaluation

The initial test with changed control valves measurements were made before and after the change but unfortunately the data was not sufficiently fine grained to draw any conclusions. Therefore, additional equipment will be used to measure finer grained during future tests.

The first test using the auto tuning tool provided new controller parameters, which were used unchanged in the control system of the substation. For this first test, a rather aggressive strategy was chosen to determine the new controller parameters. As a result, the control action became too aggressive and it was concluded the auto tuning tool need to consider the aggressiveness in the tuning approach. The picture shows how the temperature has oscillations and that indicates that tuning isn’t working properly. In Figure 6.7, the set point and temperature measurement are depicted. The controller parameters were updated shortly before $2.6 \times 10^4$ seconds. Thereafter a large load disturbance was initiated which the controller need to counteract. The controller is largely overreacting and creating oscillations of the closed loop system.
In the second test the controller tuning was less aggressive and compared quantitatively with the current tuning. The results were already reported in Chapter 4 of D5.4 and will only be shortly summarized here. The tuned controller achieved a standard deviation of 0.34°C which is approximately 25% of the original controller tuning. Further, the control action was in average 50% less with the new controller tuning. It has to be noted that the disturbance scenarios are never the same in real life testing, which means that the improvement in control performance might be less in different disturbance scenarios.

Figure 6.9: Experimentation with the updated controller tuning. (a) hot tap water temperature: measured (red), set point (blue). (b) opening of the control valve.

6.2.4 Test conclusion

The conclusion from the valve change tests is that no direct savings from an energy perspective can be seen in normal operating conditions, when there is no saturation of the valves. Even though the valves were
reduced by more than 63%, no complaints on lack of hot tap water have been received during the life-cycle of the project.

Moreover, it has been shown that the substation tuning tool can be used for the tuning of the substation controllers in an easy way and it provides a tuning which improves the control performance while not overly actuating on the valves. The tuning tool is essential when valves are changed, as the controller parameters need to be updated in order to be compatible with the new valve sizes. When such a valve exchange occurs, it is expected that the controller becomes slow and will actuate too little with unchanged controller parameters.

6.2.5 Simulation tests & results

The demand models in OPTi-Sim are currently not detailed enough to simulate the effect the valve changes on the operation of the DH system. To be able to simulate this phenomenon, more detailed consumer models with a direct representation of the individual substation valves is needed.

Instead the simulation tests were focusing on understanding the effect of the valve change on the operation of a substation and in what way the operation of the DH system is affected. For this end the substation model for the DHW of the Luleå Energi AB main building at Energigränden is used. The model has been derived by the substation tuning tool and an appropriate tuning of the PI controllers is derived.

The closed loop system can then be tested and compared for unconstraint operation and constraint operation, where the size reduction is implemented as an actuator saturation. The PI controller is also implemented using an anti-windup scheme, which means that the effect of actuator saturation is managed appropriately. Obviously, when no saturation is occurring the performance of the two loop is the same and so it the energy usage, but what happens in the saturation case and what is triggering the saturation.
In Figure 6.10, a comparative plot is shown for the substation that is operated with reduced valve size and with large valve size. For the simulation study a load disturbance was simulated, which resulted in a drop in the DHW water temperature. In both the limited and unlimited case, the controller tries to counteract the load disturbance. Naturally, in both cases occur deviations on the temperature, which are attenuated by the closed loop system. There, the deviations are larger for the reduced valve size, as the valve ends up in saturation. Nevertheless, in the simulated case, the deviations are not problematic for the reduced valve size. Further, the valve opening for the smaller valve is also limited, in this case to 20% of the large valve. As a result, the flow on the primary side is limited and less heat is extracted from the DH system.

The reduced valve size has similarities to a peak load limitation and thereby limits the maximum possible heat extracted from the DH system during load disturbances. The amount of savings by this approach is largely depending on the disturbance scenario, and difficult to measure. It requires a high resolution in time to capture the phenomena, and resolutions of 15 minutes and one hour are not sufficient.

The largest benefit of the reduced valve size lies in the reduced short-term extraction of heat from the network, and the reduced short-term flow peaks. Such peaks propagate into the network and will render pressure and flow oscillations, which in turn affect equipment life-time in a negative way.

6.3  **TEST CASE: LTC03 PEAK LOAD REDUCTION**

6.3.1  **Background and test description**

In the work of making the grid more smart and efficient one of the main focus in OPTi is to use buildings as accumulators of energy in the grid. This would enable several positive effects for the production units and the environment.

- Less start-ups of auxiliary boilers
- Lower production costs
- Lower environmental footprint
- Stronger bound between customer and DHC company

Several tests have been performed in order to get more knowledge about how buildings react when energy is borrowed from them during periods of time when there is a shortage of energy in the grid.

6.3.2  **Performed test**

There have been done several different tests to reduce the peak loads in the buildings and learn how they react. An initial contact was made with the largest housing company in Luleå (Lulebo AB) to have a strong and knowledgeable companion.
Some of the tests are presented below:

- Test made with scheduled lowering of supply temperature on heating at Luleå Energy
- Test made with scheduled lowering of supply temperature on heating at Smultronstigen
- Test made by cutting off all energy input to Luleå Energy’s building
- Test made by cutting off all energy input to Smultronstigen’s buildings
- Initial test made to accumulate heat in building at Luleå energy building

6.3.3 Test evaluation

The tests have been evaluated from data collected before and after the tests. Evaluation was done by applying equation (1) in the definition of peak load reduction.
6.3.4 Test conclusion

The initial test when the supply temperature in the building was lowered we managed to reduce the total energy during peak hours by 10-15% without having any impact on the indoor climate at all.

Since one of the most important things for LEN is to manage a reduction of peaks as much and as long as possible, without having negative impact on the residents living in the apartments. This means we needed to push the limits of how long it is possible to reduce the power output, see Figure 6.17 and Figure 6.18. After six hours without heat the average indoor climate at Smultronstigen the temperature had dropped about 0,4 degrees and then the test was aborted. The outdoor temperature was -5° when the test started and +5° when it ended. This test showed a potential of a 65% reduction in supplied energy at this outdoor temperature. The rest is the tap water consumption and cannot be cut off without causing immediate discomfort. This building is of older building standard and has no complicated ventilation system. This makes

![Figure 6.13: Pattern in energy use during test.](image-url)
this building type very suitable for peak load reduction both from controlling perspective and comfort for residents.

![Indoor temperature Smultronstigen (average)](image)

**Figure 6.14:** Average indoor temperature with all heat cut off for six hours between 06-12.

![Power output during peak load reduction test with all heat cut off for six hours 06-12.](image)

**Figure 6.15:** Power output during peak load reduction test with all heat cut off for six hours 06-12.

The same test was made at Luleå Energy’s office building however there some problems occurred with the air temperature from the ventilation. This test had to be aborted after two and a half hour when the temperature went under what is comfortable for the people working there. However, the initial peak reduction was almost 90%. The larger number here ought to be due to less tap water consumption during the morning in an office building compared to a residential building.

This building has a more complicated ventilations system with heating in the ventilation. This type of building is also suitable for peak load reduction, but the ventilation must be controlled in a more advanced way to limit that it cools the building.
6.3.5 Analytical approach to peak load reduction

During 2017 a master thesis was conducted at Luleå Energy. One of the areas to observe in the project was to calculate the economic savings by performing peak load reduction in the district heating network in Luleå. The way of work has been to analyse production data and applying the assumptions below when finding potential scenarios where peak load could have been used.

Assumptions for calculation:

- The largest buildings from the biggest consumers in the grid were picked for the calculations, assuming they would be part of the system for peak load reduction.
- These buildings represent more than 30% of the dimensioned power in the grid. Here the assumption has been that it is possible to lower the power from these buildings by 33% at any outdoor temperature. During pilot tests performed in OPTi, shown in chapter 6, it has been clear that this is possible to achieve.
- Assumed production demands that allow peak load reduction:
  - According to above stated demands, a lowering of mostly 10% (33% of 30%) of the total power can achieved.
    \[
    \frac{\sum \text{Peak production}}{\sum \text{Total production}} = X_{\text{peak load}}
    \]
    \[
    X_{\text{peak load}} \leq \frac{\sum \text{Peak production}}{\sum \text{Total production}} \leq 0,1
    \]
  - The same conditions occur when the temperature is colder, and the production is higher. The difference then is that for example that some of the auxiliary boilers then are part of the base production and that other fuel is used at peak times.
  - The peak load reduction cannot be performed during more than 5 hours.
  - The time after the peak load, time that is used to load back the lack of energy to the building (reloading), should be at least doubled the time that the peak load has been in progress. Meaning it must be room to fill the lack of energy by a cheaper fuel during this time.
  - From a production perspective the fuel used for “reloading” (buildings) should be cheaper than the fuel that would have been used during peak load reduction.

Figure 6.16: Power output during peak load reduction test with heat cut off for two and a half hours.
The production should overall be at stable conditions, meaning that no production disturbances should be occurring at the time for the peak load reduction.

6.3.5.1 Example of a peak load scenario

At a temperature of \(-10\)°C during a Monday in Mars the total production varies according to the figure below during the day. There are two well defined peaks in production, one in the morning and one in the afternoon, see Figure 6.17. The maximum power that would be needed from an auxiliary boiler during is around 10 MW, which correspond to approx. 5% of the total production, well below the 10% that is assumed to be able to move.

To perform a peak load reduction during an event like this is both from an economic and environmental perspective very good. The time after and before the peaks is also longer than the “peak time” and well below the maximum of base production. This means that it should be possible to “load back” the lack of energy during a peak load reduction with a cheaper fuel.

When applying peak load reduction in the case below it would be possible to reduce 100% of the peak production with the assumptions made.

![Production during a Monday in Mars at -10°C](image)

**Figure 6.17: Production in the Luleå network during a Monday at -10 oC in Mars. The curve is based on the production black box model**

6.3.5.2 Result of the analytical approach

If peak load reduction would have been used during 2016 according to the stated demands the following result would have been achieved:

- **Fuel that can be shifted to cheaper fuel**
  - Wood pellet 1684 MWh
  - Oil 520 MWh
  - Electricity 360 MWh

- **Economic savings generated form shifting of fuel:**
  - 700 000 - 800 000 SEK/year

6.3.6 Simulation tests & results

In peak load reduction, the use of heat by a consumer is reduced by enforcing a reduced consumption of heat at a single point. When performing a peak load reduction in a complete network, the question is how this affects operation of the DH network. Moreover, the systematic reduction of heat consumption at multiple users does not only enable a reduction of the peak, but also enables the use of more environmentally friendly fuels during peak times.
The simulation test will therefore make use of the OPTi-Forecaster, presented in chapter 12, to determine the simulation scenario. The scenario is comprised of a normal operational scenario based on historic data, where the consumer side is adapted by reducing the in-door temperature and making use of the passive storage of heat in the building mass. With respect to this there are different control strategies that can be put into effect:

- Imposing a predefined heat loss in the buildings by reducing the set-point temperature during the peak load reduction events
- Imposing predefined heat loss in the buildings by reducing the set-point temperature during the peak load reduction events, which will be complemented by pre-heating or post re-heating of the buildings in relation to the event.

In the simulated case, the first strategy was imposed on the buildings.

![Graph showing outdoor temperature and consumer power consumption](image)

*Figure 6.18: Peak load reduction scenario for a 25-hour period with a dip in outdoor temperature, consumer side.*
In Figure 6.18 and Figure 6.19, the outdoor temperature is dipping rendering a peak in the consumption. When the peak was identified by the OPTi-Forecaster, the reduction in in-door temperature can be imposed, which results in a different generation scenario. The new scenario can then be simulated, and the operational characteristics can be analyzed. Thereby, it is possible to understand how the peak load reduction scenario will affect the operation of the DH system.

The Peak load reduction shows a reduction in the generated thermal energy. In average, the MWH for the simulated test case causes an average reduction of 5.15 MW for the period between hour 5 and hour 20. This yields in total a reduction of 77.25 MWH.

In addition, the peak load reduction can help in preventing auxiliary boilers to fire. In general, the energy consumed by turning on and off an auxiliary boiler is not calculated and it is a non-revenue energy. An additional advantage of avoiding firing an extra boiler is that life cycle of the equipment will be extended. This will improve the efficiency of the equipment’s and ensure a better operation over the long run.

6.4 TEST CASE LTC04: PEAK LOAD REDUCTION VIA ADR AND CONSUMER INCENTIVIZATION

6.4.1 Background and test description

In order to improve the efficiency of the district heating network, OPTi employs ADR programs to reduce the peak load consumption at specific peak times (forecasted via the baselines). These programs coupled with appropriate incentives (rewards) and different targeting approaches with the associated policies aim to increase consumer’s willingness to actively participate in ADR. The evaluation of these ADR programs and their associated incentive - based targeting schemes requires the involvement of real users and, in particular, at apartment level, for which consumption measurements should be available. It also requires monetary incentives to be provided to them. However, due to the limitations in the residential trial sites in terms of the availability of apartment level consumption data and most importantly the non-possible interaction with users (feedback provided at the time of the ADR event/test) via the virtual knob this test case will be performed and evaluated only in a simulated environment.
The overall objective of this use case is to enable the provider to reduce the demand of energy during the peak hours up to an upper threshold $Q^S$ by offering the minimum total incentives to the consumers as a reimbursement for the inconvenience caused by any alternations in their consumption pattern. In order to be closer to the real environment setting, we utilise data available from the OPTi trials. In particular, we exploit the measurements available from the OPTi trial sites and perform an initial analysis of the available data. For our experiments, we focus on the residential environments. In particular, we consider two different buildings/locations, namely Kompanivägen 29-31 and Smultronstigen 16, with 104 and 126 apartments respectively, although the listed data correspond to fewer apartments that the originally chosen ones. More information regarding the selected buildings and apartments can be found in deliverable D6.1. Our aim is to apply different targeting approaches and the associated policies, as they are described in D3.2, in order to identify the optimal approach that will enable the reduction in peak demand with the least total incentives. For that purpose, measurements corresponding to the whole building and each apartment should be available. However, due to lack of consumption measurements per apartment (only measurements of inside temperature are available), we use the following heuristic to estimate the consumption values per apartment in each building.

We assume a set of buildings $B$ consisting of a set of apartments $N_j$. For each apartment $i \in N_j, \forall j \in B$, the average consumption $C_{i,j}^{avg}$ is estimated as the percentage of contribution of the inside temperature of the apartment $T_{i,j}^{in}$ to the inside temperature of the building $T_j^{in}$.

$$C_{i,j}^{avg} = T_{i,j}^{in} \times \frac{C_{j}^{avg}}{T_j^{in}}$$  \hspace{1cm} (2)

where

$$C_{j}^{avg} = \frac{\sum C_j}{N}$$  \hspace{1cm} (3)

In this way, we obtain average consumption values for each apartment in each of the selected buildings. Moreover, as demographic data for each building and apartment is available, the modelling of the buildings and apartments can be performed based on the CNHA methodology presented in deliverable D3.2, according to which the apartments differ in terms of physical characteristics, i.e. insulation, thermal characteristics, and consumption patterns, as they are defined by the baseline methodology. Buildings and apartments are assumed to have already signed contracts, according to which, when targeted for DR, they give up control of specific appliances - in our case this refers to space heating only. Our basic timeframe in which DR is applied is a single day divided into timeslots (say 1 hour or 4 timeslots of 6-hour duration), indexed as $t \in T := \{1, 2, \ldots, T\}$. This day corresponds to a known context. Furthermore, we consider the case where the energy provider has full information with regards to the building models; more specifically, each building manager declares truthfully to the provider the comfort model of the building that the manager is responsible for, which in turn is formed by aggregating the comfort models of the apartments within the building.

Whenever it is predicted that the total demand will exceed the energy provider’s supply threshold, the provider activates the ADR programs and resorts to targeting a subset of the consumers by employing one of the following approaches:

- **Targeting Per Building and Apartment (TPBA):** first the algorithm selects among the set of available buildings and then for each targeted building, the algorithm

  - Imposes the same reduction in consumption to the included apartments of the selected building without employing any additional sorting criterion or optimization procedure. Although, in essence, the problem can be solved hierarchically, in our setting we assume that the energy provider and the building manager are cooperative, therefore the provider solves
the overall problem at the top level and conveys the detailed solution per building to each building manager; we refer to this approach as Targeting Per Building (TPB) in order to distinguish it from the following:

- Imposes a different reduction in consumption to the included apartments of the selected building and afterwards selects among the set of available apartments; henceforth, we refer to only this approach as TPBA

- Targeting per Apartment (TPA): each apartment is considered as a single user and the algorithm selects directly among the set of available apartments

In both cases, the sorting criterion remains the same; however, the estimation method depends on whether the targeting is performed at the level of a building (TPBA) or of a single apartment (TPA). In the case of TPBA, a second level of optimization and targeting within each building may also take place.

### 6.4.2 Performed simulation test

As we mentioned earlier, for our tests, we use real consumption data from 2 buildings with several apartments in Lulea. The data consists of sensor readings at a granularity of one hour. We assume that appliance level measurements for only one appliance are available, i.e. space heating, due to the restrictions imposed by environment in Lulea. The readings in both cases presented below are extracted for a given context, that is weekday 23 January 2017, and for each day and consumer, the recorded data is used to obtain consumption in Watt-hour for each time slot with a duration of 6 hours during the day. So, we obtain the optimal consumption of each building. Employing the heuristic defined by Eq. (2) and (3), we estimate the optimal (in average) consumption of each apartment in each building.

The main objective of the energy provider is to narrow the total demand by a value $\Delta Q$ that amounts to 10% of the unconstrained total optimal consumption, by employing Policy 1: Constraining the reduction in consumption that is described in deliverable D3.1, as it is easier to be implemented than Policy 2: Constraining the reduction in utility. Following (9) in Section 4.3.4 of deliverable D3.1, the value of the maximum percentage reduction to be imposed to each user ($\eta_{max}$) must be greater or equal to 10%. To be more consistent to the conditions of the real environment in Lulea, we consider $\eta_{max} = 11\%$, i.e. that consumers are not imposed large reductions in their consumption, hence the contracts offered are more attractive and consumers are more likely to participate.

As we have already described, the overall objective of this use case is to reduce the total demand during the peak hours up to an upper threshold by employing that targeting approach which ensures the minimum total incentives offered. Since the demand reduction is implemented by means of ADR, which in essence guarantees that the desired reduction in supply is achieved, our aim is to evaluate the results regarding the incentives offered, the social welfare achieved and the set of selected consumers. Note that when applying TPBA, we distinguish two approaches of implementing it:

a) We first impose a percentage reduction $\eta_{max}$ in the building as a whole, the algorithm selects among the available buildings and then we apply the same percentage reduction $\eta_{max}$ in the apartments of each building without applying any further sorting or targeting procedure. As already mentioned, we refer to this approach as Targeting Per Building (TPB) in order to distinguish it from the following.

b) We impose the same percentage reduction $\eta_{max}$ in the apartments of a building and in the building as a whole. The difference with TPB lies in the fact that in this case the algorithm selects to target for
ADR among the set of available apartments within a targeted building; henceforth, we refer to only this approach as TPBA

### 6.4.3 Simulation test evaluation

Table 6.5 depicts the results of the different targeting approaches based on the performed simulations. Both the social welfare achieved after DR, i.e. the total social welfare of all buildings in the system \( \hat{SW} \) and the social welfare of each building \( \hat{SW}_{B_j} \), as well as the total amount of incentives \( I \) to be offered are expressed in SEK. For more information with regards to the cost function of the provider please refer to D3.1.

<table>
<thead>
<tr>
<th>( \eta_{max_q} ) per user</th>
<th>Targeting Set</th>
<th>( I ) (SEK)</th>
<th>( \hat{SW} ) (SEK)</th>
<th>( \hat{SW}_{B_j} ) (SEK)</th>
</tr>
</thead>
<tbody>
<tr>
<td>TPB 11%</td>
<td>B2</td>
<td>1042,7</td>
<td>4835,4</td>
<td>3578,1</td>
</tr>
<tr>
<td></td>
<td>B1</td>
<td></td>
<td></td>
<td>1257,3</td>
</tr>
<tr>
<td>TPBA 11%</td>
<td>B1 (all apartments)</td>
<td>280,73</td>
<td>5581,8</td>
<td>1516,3</td>
</tr>
<tr>
<td></td>
<td>B2 (72 apartments)</td>
<td></td>
<td></td>
<td>4065,5</td>
</tr>
<tr>
<td>TPA 11%</td>
<td>47 apartments (19 from B1 and 28 from B2)</td>
<td>806,23</td>
<td>6035,0</td>
<td>-</td>
</tr>
</tbody>
</table>

*Table 6.5: Results of targeting approaches*

According to the results, TPBA and its variation TPB select the same set of buildings to target for ADR. Although TPB constitutes a simple, quick and viable way to implement ADR, it also implies that all apartments inside a selected building are mandated to reduce their consumption in this straightforward manner (with no extra optimization being performed). This means that the final total incentives derived are higher compared to TPBA, as even the most expensive and less flexible apartments are forced on reductions.

On other hand, by offering an extra flexibility of choosing a specific subset of apartments in each targeted building to participate in ADR based on the sorting algorithm of NBIADR methodology, TPBA guarantees higher social welfare after ADR, for both the society and each participating building, with lower total incentives than TPB. Finally, for the more demanding approach of targeting directly specific apartments, rather than buildings, the results indicate that TPA leads to higher social welfare and lower total incentives needed to be offered than TPB and TPBA.

### 6.4.4 Simulation conclusions

Our theoretical work and the results of our experiments indicate interesting insights on the designing of incentive-based ADR contracts in an effective way. In general, the combination of ADR with the application of the different targeting approaches and the associated polices yields in better results compared to programs without any selection options, since different users may be targeted in each event thus limiting the fatigue and “exhaustion” stemming from the constant participation as well as avoiding “draining” the same users and users that do not exhibit great flexibility in alternations of their consumption. However, the energy provider should decide on the optimal combination of the targeting approach and the associated policies by taking into account the trade-offs between the total incentives to be offered and the social welfare achieved, as well as the associated implementation overhead.

Focusing on the different targeting approaches and the associated policies, the outcomes reveal that applying TPBA (Targeting per Building and per Apartment) is a more effective targeting approach, as it can be implemented both as a single process by the energy provider – whenever the information is available- or
hierarchically in two stages, whereby the energy provider applies the targeting process for buildings and then the building manager (if existent) is in turn responsible for the targeting process of apartments; thus leading to better results in comparison with the other approaches. To this extent, the building manager can establish a notion of fairness in respect to the allocation of reductions and can contend more effectively with the complaints that may be issued by the modifications in the consumption schedules within a selected apartment.

6.5 **Test case LTC05: Energy reduction**

The test case LTC05, does not have a real-life testing component and is completely conducted in simulation only. All simulations are conducted in OPTi-Sim using real-life historic data that define the simulation scenario. It need to be kept in mind that OPTi-Sim is currently able to run at 3-4 times real-time, which means that the simulation for a complete day takes between 6 to 8 hours.

6.5.1 Background and test description

For the energy reduction case it is assumed that the losses in the system can be addressed through and optimized use of the network, which means that passive thermal storage in the network together with lowered supply temperature can be used to save energy while maintaining desired comfort levels at the consumer side.

![Figure 6.20: Schematic setup of the DH system with the indicated supply temperature curve.](image)

6.5.2 Performed test

A control scheme that allows pre-heating and pre-cooling needs to make use of forecasts for weather, consumer demand. The OPTi-Forecaster that is presented in Chapter 12, is used as the basis to predict the weather conditions and the heat demands. Clearly, there is an uncertainty in the prediction which increases with the prediction horizon, at the same time the size of the DH system set the requirement for the needed prediction horizon. The OPTi-Forecaster predicts the instantaneous energy consumed in the network for a given time and outdoor temperature (Static model for consumption). Using the calculated average network losses, the possible production that will meet this demand under steady state operation (Static model for generation) is predicted. A lowered supply temperature curve is defined as a base temperature curve that can operate the system under steady state operation, which will then be automatically adjusted based on the stored energy in the water volume and circulation in the network. The targeted average reduction in the supply temperature is 2°C, while fulfilling heat demands using a prediction horizon of 6 hours.
The test will be conducted on an 8-day time frame where the outdoor temperature is fluctuation between 0°C and -28°C. The historic data for production and consumption will be used as a baseline to compare the new temperature curve concept with the currently used one. OPTi-Sim is used for the simulation.

6.5.3 Test evaluation

The simulation is done two times, first with the currently used temperature curve and thereafter with the proposed temperature curve. In Figure 6.21, the supply temperature for the 8-day scenario is plotted. There it can be seen, that the proposed temperature curve (red) is usually raising the supply temperature earlier than the current one and reducing it earlier. Further, the proposed temperature curve is acting faster on changes in demand and weather conditions.

![Figure 6.21: Comparative plot for the currently used supply temperature and the proposed temperature curve for the 8-day scenario.](image)

The supply temperature during the scenario is in average 1.25°C lower than the temperature using the current supply temperature curve, while covering the heat demand. In Figure 6.22, the total power at the generation side is given. Besides resulting in a swifter behaviour, the proposed temperature curve results often in reduced peak level for the production. The total power for the scenario is in average reduced by 1.5MW.

For comparison, the measured total power is plotted. It must be noted that the consumer models in OPTi-Sim are coarse, which means that the heat demand is usually a worst-case scenario where many consumers have the same heat demand at the same time. As a result, the total power is less at peak time and more at non-peak times, which can be observed by the behaviour of the yellow curve in Figure 6.22.

Although not shown in a graphic, the operation of the DH system during the scenario does not lead to saturation phenomena in the pumping, which is one of the prerequisites for a successful temperature curve concept.
6.5.4 Test conclusion
The test shows that a new predictive approach to control the load in the network with the aid of the supply temperature curve improves the peak behavior and reduces the totally used energy. Further, the losses in the network are reduced since the supply temperature is reduced.

The average energy reduction during the simulation scenario is 300MWh and extrapolating for the annual heat production the saving amount to approximately 13GWh, corresponding to 1.6-2.0% reduction.

It can also be concluded that the simulation test proves that the OPTi approach where OPTi-Sim can be used to validate new control approaches is functioning correctly.

6.6 TEST CASE LTC06: IMPROVED EFFICIENCY
The test case LTC06, does not have a real-life testing component and is completely conducted in simulation only. All simulations are conducted in OPTi-Sim using real-life historic data that define the simulation scenario. The test case is also used to showcase the tools that are developed for improved efficiency.

6.6.1 Background and test description
The efficiency of the DH system does not only depend on its operation in terms of set points for low level control, but also a properly design low level control layer which is the foundation for the supervisory control layer and the optimization of operation layer. Interactions in large scale systems usually render oscillations which very often originate in the regulatory layer of the system and then propagate to the high layers. These oscillations are hard to deal with on the higher layers of the hierarchy and usually remain present. Those oscillations rarely affect the overall energy usage in a system since the energy usage in average is the same as having no oscillations.

Nevertheless, these oscillations render inefficiencies in the transmission of energy and cause strain on the components in the DH system. Such strain leads to early degradation and even may result in leakages in the network. It is therefore important to manage such inefficiencies by proper selection of the control configuration and proper design of the controllers.

The test will apply the result from WP5 on the DH system in a simulated test, where the current control configuration is assessed, and alternative control approaches are proposed and then tested in some relevant operational scenario.

Figure 6.22: Power consumption for the simulated case using the current temperature curve and the proposed temperature. For comparison the historically measured power is plotted.
6.6.2 Control configuration selection for the DH system

Control configuration selection is a model-based technique which determines an appropriate structure for a control system. In WP5, several tools are newly developed or further developed such that an workflow for the control configuration selection in DHC systems could be established. The workflow for the control configuration is as follows:

1. Approximate a linear model from OPTi-Sim for an operational scenario
2. Pre-process the model
3. Perform an automated control configuration selection
4. Confirm the control configuration selection using ProMoVis

The individual steps are now shortly discussed including their results.

6.6.2.1 Approximation of a linear model

OPTi-Sim make use of FMUs that are operated jointly to simulate a complete DHC system. Modern tools for FMUs do not only operate the FMUs but can also approximate a linear time invariant model during simulation. These linear models are based on the calculation of the Jacobian of the complete system at the current point of operation. This provides a convenient approach to determine a model which can be used for control configuration selection but also for the design of controllers.

This model can then be represented in the standard state space or transfer function description for a linear time-invariant model

\[
\begin{align*}
\dot{x} &= Ax + Bu \\
y &= Cx + Du
\end{align*}
\]

where the matrices \(A, B, C,\) and \(D\) are matrices of appropriate size, depending on the size of the vector \(x, u,\) and \(y.\)

In the case of the approximated model for the Luleå DH system, \(u\) contains 51 signals which are either actuators or exogenous signals like for example consumer demands, \(y\) contains 64 signals which are either measurements or signals that are judged of importance for the simulation studies, while not being measurable in the current implementation of the DH system. The state vector \(x\) is mainly composed of physical variables which are usually not measurable, here there are initially 3263 states.

From a control perspective it must be understood that the simulation model and the control model do not have the same purpose and as such have properties that need to be compatible. Moreover, a model with a dimension of 3263 states is usually not numerically useful for controller design and controller implementation, as a controller would have essentially a similar complexity.

For this reason, the approximated model need to be processed to be useful for the control configuration selection and control design.

6.6.2.2 Pre-processing and selection of input/outputs of interest

When a model is approximated form a large scale dynamic model, numerical issues may render a linear time invariant model which contains:

- Close pole-zero cancellations
- Unstable modes

While close pole-zero cancellations can be dealt relatively easy, unmotivated unstable modes are more difficult to deal with. Moreover, the initial model is not given in a numerically robust realization. The pre-processing is therefore initiated by the following steps:

1. Removal of close pole-zero cancellation by deriving a minimal realization
2. Transforming the resulting model into a balanced realization for numerical robustness

The result these two steps yields a model with the same input \(u\) and \(y,\) but the state vector was reduced to a size of 1166 from 3263. The model also contained unstable modes which were located very close to the
origin, rendering a time behaviour of close to weeks. Such modes may occur due to trend behaviours in the original model and are not necessarily unstable. From a first principle perspective, it is also unreasonable to assume that the DH system would exhibit unstable behaviour. The next steps are therefore:

3. Separation of stable and unstable system as \( G(s) = G_S(s) + G_{US}(s) \)
4. Truncation of the unstable dynamics
5. Truncation of dynamics with time constants larger than 24 hours.

The resulting reduced model then has an order of 1058 which is stable and has reasonable dynamic behaviour as also experienced by engineers. Still, the model has a very high order. The high order is motivated if all states contribute equally much to the input-output behaviour of the system, otherwise a model order reduction can be imposed. The model order reduction can be conducted using an analysis of the Hankel singular values, which are ranked such that the all the singular values which contribute with an overall ratio of 99% are present in the reduced order model. This can be in the following two steps:

6. Hankel singular value analysis and state ranking for 99% contribution
7. Truncation of the dynamics to represent 99% of the input-output behaviour

The resulting model now has an order to 24, which is very low compared to the initial 3263. In a final step the inputs and output which are of interest for control will be selection and the partial model is extracted from the reduced model.

The above steps 1-7 are all automated and performed by a pre-processing tool.

6.6.2.3 Automated control configuration selection

In OPTi, several methods have been developed that enable the automated selection of control configurations. These methods are combined into a tool that runs several optimization schemes to determine the most feasible control configuration and determines stability and integrity properties of the proposed configuration.

The automated control configuration provides the following output:

<table>
<thead>
<tr>
<th>STARTING OUTPUT SELECTION</th>
</tr>
</thead>
<tbody>
<tr>
<td>The IONSRGA is used for output selection, which means that the input must be a matrix with more rows than columns. Same output set is returned.</td>
</tr>
<tr>
<td>Starting output selection using gramians NSRGA and gramians give the same output selection</td>
</tr>
<tr>
<td>STARTING IO PAIRING</td>
</tr>
<tr>
<td>IO pairing using the RIA has been found</td>
</tr>
<tr>
<td>The pairing given by the static RIA is valid for all the frequency domain</td>
</tr>
<tr>
<td>There are 1 pairings which satisfy the advanced integrity/stabilizability test</td>
</tr>
<tr>
<td>The pairing which was calculated for the RIA satisfies the advanced integrity/stabilizability test</td>
</tr>
<tr>
<td>The static RIA gives the same pairing than the one considering the RIA of all the Partial Relative Gains</td>
</tr>
<tr>
<td>STARTING SPARSE CONTROL CONFIGURATION SELECTION</td>
</tr>
<tr>
<td>No sparse configuration has been found, perhaps because of bad scaling or bad selection of threshold delta2 in function GramCCSelection</td>
</tr>
<tr>
<td>Sparse configurations have been found starting with a decentralized controller and increasing the complexity using gramian-based IMs</td>
</tr>
<tr>
<td>All the considered gramian-based IMs give the same solution when starting from a decentralized controller: PM, HIIA and PEIA</td>
</tr>
<tr>
<td>ANALYSIS IS CONCLUDED</td>
</tr>
</tbody>
</table>

The tool also provides a suggestion for a sparse control configuration which is displayed in Table 6.6. There a decentralized control configuration should be used, where the pairs of controlled variables and manipulated variables is indicated by “1”. There is also a strong indication that the currently used decentralized control scheme is the only strategy which provides integrity and stability, meaning there is no other feasible decentralized control strategy. There can though be multivariable control strategies which provide the
desired properties, but those are more complex to design and implemented, it would mean that an 8x7 controller of at least order 31 would need to be designed and implemented. Such a centralized control scheme could not be distributed in the network and would need to operate over vulnerable communication links.

The only extra interconnection that should be used is the connection between the KVV pump speeds and the supply temperature from the KVV plant. This would mean that a multivariable controller should be used for the controlled variables \{'C_629145_dp','KVV_Temp_595'\} and the manipulated variables \{'KVV_speed_r','KVV_speed_s','KVV_power'\}. It is also worth noting that the implementation of such a multivariable controller can be done in the control system at the CHP plant which is reasonable. Nevertheless, the complexity of the resulting controller will be high.

### Table 6.6: Result of the automated control configuration selection

<table>
<thead>
<tr>
<th>Manipulated variables (Inputs)</th>
<th>KW_speed_r</th>
<th>KW_speed_s</th>
<th>HVC1-speed_r</th>
<th>HVC1-speed_s</th>
<th>TSP1-speed_r</th>
<th>TSP1-speed_s</th>
<th>TSP2-speed_s</th>
<th>KVV_power</th>
</tr>
</thead>
<tbody>
<tr>
<td>C_629145_dp</td>
<td>1</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>C_607428_dp</td>
<td>0</td>
<td>1</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>C_648830_dp</td>
<td>0</td>
<td>0</td>
<td>1</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>C_620804_dp</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>1</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>C_613475_dp</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>1</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>C_611219_dp</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>1</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>C_627925_dp</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>1</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>KVV_Temp_595</td>
<td>1</td>
<td>1</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>1</td>
</tr>
</tbody>
</table>

### 6.6.2.4 Confirmation of the control configuration with ProMoVis

ProMoVis has been further developed in WP5 where an import and update feature was developed and it was adapted to DHC. The model which was generated from OPTi-Sim and preprocessed can be directly imported in ProMoVis and graphically represented with its interconnections, as depicted in Figure 6.23. After the model import, the DH system can be directly analyzed using the analysis features that are available in ProMoVis.

Since there is an overlap between the method that are used in the automated selection and the user driven one in the GUI of ProMoVis, the same conclusions can be drawn. In Figure 6.24, an example for the analysis of the DH system using the functional transfer energy method. The method quantifies the significance of interconnections based on the ratio of signal energy that is transmitted over the different interconnections in a system. Naturally, the indications of the method depend on the model quality and need to be judged in relation to that quality.

There is can be seen that the extra interconnection from the KVV pumps to the temperature is confirmed. Moreover, there are additional interconnections which imply a higher amount of interactions relating to TSP1 pump speeds and the two differential pressure measurements \{'C_613475_dp','C_611219_dp'\}. From this analysis it can be concluded that a decentralized controller is feasible, but that there should be a multivariable controller in place to control the supply temperature and flow from KVV jointly.
Figure 6.23: ProMoVis model view of the Luleå DH system. Measurement variables or controlled variables (green nodes), manipulated variables (red nodes), model interconnections (red arrows).

Figure 6.24: ProMoVis analysis view for the Functional Energy Transfer analysis. Measurement variables or controlled variables (green nodes), manipulated variables (red nodes), interconnection significance indicated by the width or the arrows (magenta).
6.6.3 Predictive control approach using adaptive MPC

Following the results of the control configuration selection, the expected correlation between the supply water temperature and pump speed was emphasized. The classic control strategy of controlling the pump speed to regulate the differential pressure at a point in the network and controlling the thermal power to regulate the supply water temperature will cause an oscillation in the network. This oscillation might be happened at high rates or slow rates that cannot be seen in historical data due to low sampling rate as shown in Figure 6.25. The oscillation can be happened when the pressure drops at the controlled point, then the pump will start to increase the flow which leads to reduce the supply water temperature suddenly. To increase the supply water temperature, the plant will increase the thermal energy injected to the network that will make the consumer reduce the valves opening that will lead to increase the pressure. Accordingly, the pumps will reduce the flow that will lead to increase the supply water temperature. Then, the thermal energy injected to the net should be reduce and that will cause the consumer to open their valves and so on.

![Pressure vs Time](image)

![Supply Water Temperature vs Time](image)

**Figure 6.25: Oscillations in the network due to the interactions between control loops and aliasing effects**

To overcome this problem, a multi input multi output (MIMO) controller should be considered. The Model predictive control is considered as a good approach that can overcome this problem. The only drawback of the MPC is the dependence on the linearized model of the plant. In the DHC network case, the model is highly nonlinear, and the linearized model will depend on the operational point. Also, the linearized extracted model will be of a very high order. Thus, the model should be reduced to ensure an efficient operation of the MPC. Due to the nonlinearity and the model reduction, the using of a classic MPC will not provide an effective control results. The Adaptive MPC is based on the idea that the model that is used by the MPC is not constant, but it is varying with time and a system identification block will be used to identify the model and feed it to the controller. Figure 6.26 shows the principle structure of the adaptive MPC controller and Figure 6.27 shows the complete building blocks and how the adaptive MPC relates to the plant.
6.6.4 Test evaluation

The simulations show satisfactory results of controlling both the differential pressure and the supply water temperature. Figure 6.28 shows the simulation results with a period of saturation. It can be noticed that the supply temperature set point started to rise which cause the KVV power to saturate and accordingly the thermal energy in the network also decreased. The differential pressure in the network will drop due to the fact the water temperature is low and the consumers will start to pen their valves to draw more heat. After a while, an auxiliary boiler what fired on. The MPC controller could immediately regulate the signals without any oscillations. The Oscillation that is shown in the figure in the first hours is happened due to the mismatch between the network model and the MPC model because the MPC was initialized with a linearized model of the plant at an operational point differing from the starting point. Also, the system identification could recover the model, which was then fed to the MPC.

Energy savings cannot be expected from the control scheme despite minor savings which occur after a quick recovery of the controller after saturation, which is usually not as efficient in decentralized PI-based controllers. Thus, not quantifiable improvement in energy savings based on improved control on the regulatory control layer. It should be kept in mind that better control will enable more efficient supply
temperature optimization on the higher level, but it would require an implementation of the adaptive MPC at the CHP plant.

Figure 6.28: Simulation results showing the response of the system with a period of saturation.

6.6.5 Test conclusion

The simulation test case has proven that the tool chain developed in WP5 is functioning correctly in a real-life scenario can be used in an efficient way to improve the control of DH systems. The tool chain is independent of the current pilot and can be generally applied in DHC system.

Further, it can be concluded that the improved control scheme has

- Good tracking and disturbance rejection properties
- No observable oscillations due to interactions
- Swift recovery from saturation
- No quantifiable energy savings

The reduction of the oscillations will render less strain on the network and the components and should therefore improve the operational life expectancy of the components. In order to quantify these effect a real-life implementation of the control scheme would be needed and a long term study with the updated controller would need to be implemented.
7 MALLORCA TESTS & RESULTS

The Mallorca trial is situated in the Hospital Son Llatzer, in Mallorca (Spain), a Hospital with a total floor area of 90,000 m² and hosts 500 beds. For the building HVAC consist in a power plant generating cold water and hot water to be supplied to the different Air Handling Units (AHU or UTA), adapting the co-generation power plant production and the Hospital demand is one of the issues of this project. In the deliverable 6.1, more details about the trial can be found.

7.1 BACKGROUND AND DESCRIPTION:

DH networks normally cover most of the demand from a power plant designed with high efficient technology, co-generation engine for example, above this demand, auxiliary sources are needed to produce the energy demanded, which are less effective technology, specifically, temporary high increases of the demand implying high resource consumption and emissions, these events are called “peak loads”.

In Son Llatzer, peak loads are those in which the thermal demand (cold or heat water) is not covered by the co-generation engine and the absorption chiller (high efficient technology) and then electric chillers or gas boilers have to be activated (auxiliary sources). The co-generation plant generates electricity with a gas engine and uses the exhaust combustion gas to produce cold water through an absorption chiller and/or hot water through a heat exchanger. When the cold water demand exceeds the production of the co-generation plant, the electrical chillers are turned on, with the consequent high electricity consumption. On the other side, when the hot water demand exceeds the production of the co-generation heat exchanger, those demand is covered by gas boilers.

On days with very extreme temperatures (hot days in summer and cold days in winter) the electric chillers or the gas boilers are turned on practically the whole day, so Demand Response will not be very effective, but there are other situations when the demand for cold or heat water is not covered by the co-generation plant only for a few hours a day (peak loads) and Demand Response can be profitable. It is in these last cases where it will be interesting to study the behaviour of demand and try to modify it.

Following the premises indicated above, 3 peak load situations have been defined in which it is interesting to modify the demand to avoid a peak of demand that forces to activate auxiliary equipment of cold and heat:

- Cold water demand higher than co-generation plant absorption unit production, and low demand of hot water. That situation occurs typically in Summer, between 11 AM-5 PM.
- Hot water demand higher than co-generation plant heat exchanger production, with low demand of cold water. That situation occurs typically in the morning of winter days, at the beginning of the consultation hours, when there is a high hot water demand for heating and a residual cold water demand for certain areas of the hospital.
- Combination of cold and hot water demand exceeds the production of thermal energy available by the co-generation plant. It occurs on the morning hours of spring and autumn days.
Based in these three situations, it is defined the different typical days that may occur:

<table>
<thead>
<tr>
<th>SUMMER SOFT DAY PEAK</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Description</strong></td>
</tr>
<tr>
<td><strong>Objective</strong></td>
</tr>
<tr>
<td><strong>Solutions from</strong></td>
</tr>
<tr>
<td><strong>energy</strong></td>
</tr>
<tr>
<td><strong>production side</strong></td>
</tr>
<tr>
<td><strong>Solutions from</strong></td>
</tr>
<tr>
<td><strong>demand side</strong></td>
</tr>
</tbody>
</table>

In the following graph, it is shown the cold water production in a typical summer day described above, with the absorption chiller cold water production and auxiliary cold water production (electrical chiller). It can be observed how shifting some demand before 12h can decrease the auxiliary production, using the inertia of the building.

*Figure 7.1: ‘Summer soft day’ cold water demand example (10/9/2015). All values are expressed as the % of co-generation absorption unit production at maximum load (100%). If cold water demand>100, electrical chillers (AUX) are necessary.*
**WINTER MORNING PEAK**

<table>
<thead>
<tr>
<th>Description</th>
<th>During most of the winter, CHP machine is enough to fulfil the hot water demand by itself. However, certain peak loads in the morning due to the switch ON of the heating system at several areas of the building (8 AM, office entry time) overloads CHP hot water production.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Objective</td>
<td>Identify the peak of hot water demand and shift some demand by changing the HVAC setpoint on certain areas of the hospital for a specific time.</td>
</tr>
<tr>
<td>Solutions from production side</td>
<td>Anticipate the start-up of the CHP to increase the energetic efficiency, reducing the gas boilers activity. Identify the peak loads to increase CHP load.</td>
</tr>
<tr>
<td>Solutions from demand side</td>
<td>1. Pre-heating some hospital areas that are scheduled to switch ON at 8 AM (office entry time), to reduce the initial morning peak load.</td>
</tr>
</tbody>
</table>

In the following figure, hot water demand in a winter day is shown. During the evening hours, due to the low price of electricity, the CHP is OFF and all the demand is covered by gas boilers. At 8 AM (typical entry time in a labour day) the demand increases and the co-generation machine is switched ON.

![Figure 7.2: Winter demand example (21/1/2015). All values are expressed as the % of co-generation heat transfer unit production at maximum load (100%). If hot water demand is greater than CHP production, gas boilers are switched ON.](image-url)
<table>
<thead>
<tr>
<th>SPRING &amp; AUTUMN PEAK</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Description</strong></td>
</tr>
<tr>
<td><strong>Objective</strong></td>
</tr>
<tr>
<td><strong>Solutions from production side</strong></td>
</tr>
<tr>
<td><strong>Solutions from demand side</strong></td>
</tr>
</tbody>
</table>

In the following figure, the hot water demand peak at 8 AM (office entry time) cannot be covered by the co-generation plant because there is also a significant demand of cold water, and the absorption chiller is more efficient than the heat exchanging in that machine in hot water. So, to cover all hot water demand, it is necessary to switch ON the gas boilers for some hours.
Figure 7.3: Spring & Autumn demand example (20/4/2015) for hot water (above) and cold water (below). All values are expressed as the % of co-generation production at maximum load (100%).

7.2 Trial plans and schedules

7.2.1 Trial plan schedule

In the deliverable 6.1 and 6.2, the different Test Cases planned were described, However, due to the project necessities a new Test Case was defined in Opti. Therefore, the Test Cases defined are the following:

- **MTC01 Overall Peak Load Reduction**: the tests will aim to reduce the energy demand of the whole hospital during peak hours. The energy demand for heating or/and cooling will be reduced during certain periods of time during a day (peak demand periods) or shifting the demand from peak hours to off-peak hours.

- **MTC02 Hospital Room Peak Load Reduction**: In this case the peak load will be reduced by the reduction of consumption in the wards. It would, therefore, involve reducing the energy demand from heating or cooling of the patient’s room consumption during certain periods of time during the day (peak demand periods) or shifting the demand from peak hours to off-peak hours.

- **MTC03 Mallorca Plant Simulator**: In this test case a simulator tool for demand prediction based on external temperature and set-point temperature will be developed. The aim of that tool is to predict the effectiveness of set-point modifications.

In the project, the trial tasks are divided in three phases:

- **Trial preparation** where all equipment needed is set up (from month 6 to 16 (June 2016))
- **Trials related with MTC01** (from month 17 to 26). First tests will evaluate DR events to prevent ‘summer soft day peak’, based on precooling of certain hospital areas. Last tests will evaluate DR events focused on Winter morning peak.
- **Trials related with MTC02** (from month 27 to month 37). In this case the tests will be focused on two AHUs which include all sensors necessary to monitor water energy consumption and air delivered energy. Initial test will focus on cold water energy balance and final tests (december’17-February’18) will focus on hot water energy balance.
- **There were no trials related to MTC03** since it is a simulated test case. All simulations were run by the end of the project tests (from month 31 to 37).
7.2.2 Performed Test

Several tests have been performed at Mallorca plant. At table 7.2 is presented a short description of those tests.

### Table 7.2: Plant tests at Mallorca Site during Opti project

<table>
<thead>
<tr>
<th>Test Case</th>
<th>Test Number</th>
<th>AHU affected</th>
<th>Increase (+) / Decrease (-) of set point</th>
<th>Time schedule</th>
<th>Initial date</th>
<th>Final Date</th>
<th>Successfull</th>
</tr>
</thead>
<tbody>
<tr>
<td>MTC01</td>
<td>1</td>
<td>36,53, 58A, 79</td>
<td>+2</td>
<td>Pre 1h</td>
<td>17/3/2016</td>
<td>17/3/2016</td>
<td>No</td>
</tr>
<tr>
<td>MTC01</td>
<td>2</td>
<td>54</td>
<td>+2</td>
<td>12:00-12:30</td>
<td>02/05/2016</td>
<td>03/05/2016</td>
<td>Yes</td>
</tr>
<tr>
<td>MTC01</td>
<td>3</td>
<td>50</td>
<td>+2</td>
<td>12:00-12:30</td>
<td>04/05/2016</td>
<td>05/05/2016</td>
<td>Yes</td>
</tr>
<tr>
<td>MTC01</td>
<td>4</td>
<td>42</td>
<td>+2</td>
<td>12:00-12:30</td>
<td>06/05/2016</td>
<td>09/05/2016</td>
<td>Yes</td>
</tr>
<tr>
<td>MTC01</td>
<td>5</td>
<td>45</td>
<td>+2</td>
<td>12:00-12:30</td>
<td>10/05/2016</td>
<td>11/05/2016</td>
<td>Yes</td>
</tr>
<tr>
<td>MTC01</td>
<td>6</td>
<td>47</td>
<td>+2</td>
<td>12:00-12:30</td>
<td>12/05/2016</td>
<td>13/05/2016</td>
<td>Yes</td>
</tr>
<tr>
<td>MTC01</td>
<td>7</td>
<td>39</td>
<td>+2</td>
<td>12:00-12:30</td>
<td>16/05/2016</td>
<td>17/05/2016</td>
<td>Yes</td>
</tr>
<tr>
<td>MTC01</td>
<td>8</td>
<td>39</td>
<td>+2</td>
<td>12:00-13:00</td>
<td>01/06/2016</td>
<td>03/06/2016</td>
<td>Yes</td>
</tr>
<tr>
<td>MTC01</td>
<td>9</td>
<td>47</td>
<td>+2</td>
<td>12:00-13:00</td>
<td>07/06/2016</td>
<td>09/06/2016</td>
<td>No</td>
</tr>
<tr>
<td>MTC01</td>
<td>10</td>
<td>47</td>
<td>-2</td>
<td>12:00-13:00</td>
<td>13/06/2016</td>
<td>15/06/2016</td>
<td>Yes</td>
</tr>
<tr>
<td>MTC01</td>
<td>11</td>
<td>39, 42, 45, 47, 50, 54</td>
<td>-2</td>
<td>12:00-13:00</td>
<td>21/06/2016</td>
<td>23/06/2016</td>
<td>Yes</td>
</tr>
<tr>
<td>MTC01</td>
<td>12</td>
<td>*green AHU</td>
<td>Pre 2h</td>
<td>28/06/2016</td>
<td>01/07/2016</td>
<td>Yes</td>
<td></td>
</tr>
<tr>
<td>MTC01</td>
<td>13</td>
<td>*green AHU</td>
<td>Pre 4h</td>
<td>04/07/2016</td>
<td>08/07/2016</td>
<td>No</td>
<td></td>
</tr>
<tr>
<td>MTC01</td>
<td>14</td>
<td>*green AHU</td>
<td>Pre 6h</td>
<td>19/07/2016</td>
<td>22/07/2016</td>
<td>No</td>
<td></td>
</tr>
<tr>
<td>MTC01</td>
<td>15</td>
<td>*green AHU</td>
<td>Pre 4h</td>
<td>01/08/2016</td>
<td>04/08/2016</td>
<td>Yes</td>
<td></td>
</tr>
<tr>
<td>MTC01</td>
<td>16</td>
<td>*green AHU</td>
<td>Pre 6h</td>
<td>08/08/2016</td>
<td>10/08/2016</td>
<td>No</td>
<td></td>
</tr>
<tr>
<td>MTC01</td>
<td>17</td>
<td>*A1 green AHU</td>
<td>Pre 2h</td>
<td>17/01/2017</td>
<td>03/02/2017</td>
<td>Yes</td>
<td></td>
</tr>
<tr>
<td>MTC01</td>
<td>18</td>
<td>*A2 green AHU</td>
<td>+2</td>
<td>18:00-20:00</td>
<td>06/03/2017</td>
<td>08/03/2017</td>
<td>Yes</td>
</tr>
<tr>
<td>MTC01</td>
<td>19</td>
<td>*A2 green AHU</td>
<td>+2</td>
<td>18:00-20:00</td>
<td>13/03/2017</td>
<td>17/03/2017</td>
<td>No</td>
</tr>
<tr>
<td>MTC02</td>
<td>20</td>
<td>65</td>
<td>+1</td>
<td>20:00-22:00</td>
<td>3/7/17</td>
<td>4/7/17</td>
<td>Yes</td>
</tr>
<tr>
<td>MTC02</td>
<td>21</td>
<td>66</td>
<td>+1</td>
<td>20:00-22:00</td>
<td>6/7/17</td>
<td>7/7/17</td>
<td>No</td>
</tr>
<tr>
<td>MTC02</td>
<td>22</td>
<td>65</td>
<td>-2</td>
<td>5:00-7:00</td>
<td>10/7/17</td>
<td>11/7/17</td>
<td>Yes</td>
</tr>
<tr>
<td>MTC02</td>
<td>23</td>
<td>66</td>
<td>-2</td>
<td>5:00-7:00</td>
<td>12/7/17</td>
<td>13/7/17</td>
<td>Yes</td>
</tr>
<tr>
<td>MTC02</td>
<td>24</td>
<td>65, 66</td>
<td>+2</td>
<td>22:00-7:00</td>
<td>30/11/17</td>
<td>1/12/17</td>
<td>Yes</td>
</tr>
<tr>
<td>MTC02</td>
<td>25</td>
<td>65</td>
<td>-2</td>
<td>12:00-14:00</td>
<td>9/1/18</td>
<td>10/1/18</td>
<td>Yes</td>
</tr>
</tbody>
</table>
*A1 green AHU: AHUs supplied by ‘A’ heat exchanger: 89, 51, 59, 60, 61, 62, 29, 56A, 55, 56, 58, 57A
*A2 green AHU: AHUs supplied by ‘A’ heat exchanger: 75, 55A, 94, 81, 86, 90, 92, 85A, 59, 60, 61, 62
(during the trial preparation it was defined different colours of the AHU depending of the user sensitivity of the AHU’s area. For example, green for corridors, yellow for waiting rooms and red for ICU red.)

The aims of those tests are the following:

<table>
<thead>
<tr>
<th>Table 7.3: Mallorca test cases objective</th>
</tr>
</thead>
<tbody>
<tr>
<td>Test number</td>
</tr>
<tr>
<td>1-11</td>
</tr>
<tr>
<td>12-16</td>
</tr>
<tr>
<td>17-19</td>
</tr>
<tr>
<td>20-25</td>
</tr>
</tbody>
</table>

7.3 TEST CASE MTC01: OVERALL PEAK LOAD REDUCTION

7.3.1 Background and description

The aim of MTC01 test cases is to define global strategies that leads to a reduction of peak loads for the whole year. Peak loads have been detected for hot and cold water thermal demand and test cases has been defined for reducing those peak loads in the following way:

- Summer test cases. Focused on the reduction of cold water demand peak loads, mainly defined as set point temperature modification during night hours to test a precooling scenario.
- Winter test cases. Focused on the reduction of hot water demand peak loads, mainly defined as set point temperature modification in night hours to test a preheating scenario.

7.3.2 Test evaluation in Summer test cases; Precooling

In summer test cases, it is evaluated the reduction of cold water thermal demand during peak load. Those situations typically occur in summer, but also in early autumn or spring, when some days the temperatures achieve more than 28°C.

Test cases 12 to 16 are evaluated in this chapter. Those Test cases consist on a precooling scenario of 2, 4 and 6 hours. Due to the features of the Hospital, most of the AHUs has an operating period that lasts from 8h to 20h. This causes a peak load for cold water demand at 8 AM. Shifting part of the demand to early hours is a way to avoid this peak load.

Another aspect to consider is the rebounce of the demand increase before 8AM as a demand decrease in later hours, to have a negative or non-positive energy balance of the whole DR event.
At Figure 7.4 the real cold-water demand and the forecasted values for those demand in DR event and non-DR event situations are observed. As can be observed in the figure, the correlation between forecasted and real values are better during night time than between 12-20h. Considering that the precooling DR-event is executed during this time slot, their effects can be observed in the figure, in this case as a demand increase at 6-7 AM. What is not observed in the figure is the demand rebounce after the DR-event.

Before analysing the results for all test cases and comparing them with the forecasted demand, we should consider the behaviour of the forecast tool in those cases. The forecast tool, developed after these test cases (summer 2016), uses 15-days historic demands and weather forecast to determine, 48h in advance, cold and hot water demand. So, DR event executed in the previous 15 days will affect the forecasted demand.

Considering those aspects for demand prediction, the following tables for test case 12 and 14 are calculated. As the prediction tool uses the last 15 days demands for predicting the new demands, data from the test cases 13, 15 and 16 is not been considered in the study.

**Table 7.4: Cold water demand shift (Forecast – Real) Results for test case 12**

<table>
<thead>
<tr>
<th></th>
<th>Non-DR event</th>
<th>DR-event</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 AM – 4 AM</td>
<td>-107±264</td>
<td>16±116</td>
</tr>
<tr>
<td>6 AM – 8 AM</td>
<td>-214±367</td>
<td>64±198</td>
</tr>
<tr>
<td>9 AM- 12 AM</td>
<td>-125±504</td>
<td>74±205</td>
</tr>
</tbody>
</table>

**Table 7.5: Cold water demand shift (Forecast – Real) Results for test case 14**

<table>
<thead>
<tr>
<th></th>
<th>Non-DR event</th>
<th>DR-event</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 AM – 3 AM</td>
<td>-180±357</td>
<td>14±257</td>
</tr>
<tr>
<td>5 AM – 8 AM</td>
<td>-308±320</td>
<td>37±322</td>
</tr>
<tr>
<td>9 AM- 12 AM</td>
<td>-299±408</td>
<td>290±411</td>
</tr>
</tbody>
</table>

For each day a forecasted cold water demand is available, based on weather forecast data and also on previous days demands. Real demands are different than forecasted values, sometimes higher and sometimes lower. If the cold water demand is forced to be increased for certain hours due to a DR event, that behaviour should be observed if the difference between the forecasted and the real value is analysed.

As it is observed in Table 7.4 and Table 7.5, the results have a bigger standard deviation than mean results, which means that no conclusions can be taken from those results. Considering the overall cold water demand and using several days, it is produced a high deviance in the results.
7.3.3 Test evaluation in Winter test cases; Preheating

The aim of ‘winter test cases’ is to evaluate the reduction of hot water thermal demand during peak load. Test cases 17 to 19 are evaluated in this chapter.

The objective of those test cases is to analyse the benefits of pre-heating the office hospital areas. Those areas HVAC system is switched ON at 7-8 AM and OFF at 15-17h. The AHU start related to those areas sometimes causes a significant peak load, consequently switching ON auxiliary sources, increasing the energy cost.

Two different test branches were carried out in Winter test cases. The first one, it was evaluated the DR event benefits obtained comparing the forecasted value results against the real demand. In this case there is a high dependence against the good behaviour of the forecast tool. As it is shown in test cases 12-16 that kind of study produces high deviance in the results, therefore it is difficult to extract conclusions.

The second way to evaluate the results is comparing the DR results in twin AHUs, where the setpoint of the first one is modified, and the other AHUs maintains the original set point. Son Llatzer Hospital plant has two main heat exchangers that supplies thermal energy to the Hospital’s AHUs, labelled as ‘A’ AHUs and ‘B’ AHUs, depending on which heat exchanger provides them.

7.3.3.1 Pre-heating tests

In the following test cases, it is modified the set point of the ‘A’ AHUs to pre-heat certain parts of the building. At Figure 7.5, a comparison between the hot water demand of AHUs ‘A’ and ‘B’ is shown in two different days, left one (04-01-2016) corresponds a non-DR event situation and right one (24-01-2016) corresponds to a “DR event” situation. As it can be observed in the day 24-01-2016 plot, when a DR event is applied there is an increase on the demand of the ‘A’ AHUs compared to the ‘B’ AHUs at 6-7 AM in front of the results observed in 04-01-2016 plot, where that difference between ‘A’ and ‘B’ AHUs is not observed.

The plots shown at Figure 7.5 are obtained for two days with similar demands at both ‘A’ and ‘B’ AHUs. However, hot water demand has a behaviour difficult to predict. First, hot water thermal demand behaviour depends on external temperature over other parameters, as close as the external temperature approaches to set point temperature, the demand is reduced, obviously. But this lineal dependency does not exist when external temperatures are lower than 10 degrees, since the AHUs are at maximum load and the hot water thermal demand is fixed to a maximum. That behaviour can be observed at Figure 7.6.
At Figure 7.7 the ratio between ‘A’ AHUs demand and ‘B’ AHUs demand is shown. Four labour days in January with similar weather conditions are selected, two in DR event conditions (January 24<sup>th</sup> and 27<sup>th</sup>) and two in normal conditions (January 17<sup>th</sup> and 20<sup>th</sup>).

As it is shown in the precious figure, there is a big difference in the relations between these two heat interchangers for those days. In one hand, both days the ratio increases (due to the ‘A’ AHUs demand increase) when the set point is modified (preheating) in the DR event days (inside the purple circle), as this ratio shows a smooth behaviour in the ‘non-DR’ situations. On the other hand, the ratio is reduced when the ‘B’ AHUs are started in the normal situation, 2 hours after the ‘A’ AHUs in the DR days (inside the blue circle). For the ‘non-DR’ situation, the ratio shows also a smooth behaviour.

That result can be considered as a ‘qualitative’ behaviour that follows this hypothesis, but it cannot be analysed numerically to obtain the amount of thermal demand moved in a DR event due to the higher deviance in the demand values.
7.4 TEST CASE MTC02: HOSPITAL ROOM PEAK LOAD REDUCTION

This use case directly affects the room patients, people sensitive to temperature changes. Therefore, tests will take place affecting as less as possible their comfort.

7.4.1 Background and description

The aim of those test cases is to analyse the behaviour of single AHUs in front of set point modifications that increase or decrease temperature less than 3 degrees. One AHU affects several rooms, as well as the corridors and common areas. A set point modification of AHU will modify all the rooms affected by that AHU.

Room temperature can also be changed by modifying manually the user comfort display, which modifies the set point of the room’s inductor, supplied by the common AHU. As it is not possible to collect the data of the room display during the DR event and in normal operation, it is discarded test cases based on that display’s modification.

7.4.2 Test evaluation in Summer cases

Test cases 21-24 were programmed in summer’17, after installing temperature sensors for all parameters at AHUs 65 and 66. Those AHUs are one of the biggest that can be used to perform DR events. Sensors installed were:

- Air temperature sensors (external input air, output air and return air)
- Cold water sensors (input and output) for main AHU
- Cold water sensors (input and output) for AHUs inductors
- Hot water sensors (input and output) for main AHU
- Hot water sensors (input and output) for AHUs inductors

**DR event description**

In those test cases the setpoint temperature of AHU65 (UTA65) is increased one degree 2 hours earlier (20:00) than entering to night mode (with a big setpoint change), at 22:00 for both AHUs, 65 and 66.

**Energy supplied to air**

As can be observed in Figure 7.8, air outlet temperature of the AHU adapts to the new setpoint, but this has a limited effect on the room temperature, which is measured in the return of the AHU, and which has a value of about 25°C (8°C higher than the set point). AHUs outlet temperature easily reaches new setpoint in the case of the DR event an also in the 4°C sudden setpoint modification of 22:00 (entering to night mode), but that change doesn’t modify room temperature and, therefore, user comfort feeling in the same way.

It can be concluded that user comfort feeling remains almost at the same level when 1 degree set point modification is applied.
Energy delivered by cold water

The change of setpoint produces a reduction in the cold-water flow of the AHU (the valve is closed slightly), as can be observed at Figure 7.9 (up), where the opening percentage of the valve is shown (0%-close, 100%-open). However, if it is considered the overall cold-water energy defined as the temperature gradient multiplied by the water flow (obtained as the maximum flow multiplied by the valve opening percentage, Figure 7.9 low), the effects of the DR event cannot be observed clearly.

For the 4°C modification of the setpoint at 22:00 the shift on cold water energy is observed, but after a 30 minutes stabilization, the behaviour of AHU 65 and 66 (UTA 65 and UTA66) is very different. AHU65 recovers the same cold water energy demand, as the AHU66 cold water demand is reduced.
7.4.3 Test evaluation in Winter cases

Test cases 24 & 25 are performed to precisely define the amount of energy increased or decreased at a single AHU during a DR event. Those DR events modifies the set point of a AHU for two hours. The data analysed includes all the parameters of the modified AHU and of a non-modified AHU with similar performance. Analysed parameters include:

- Air temperature sensors (external input air, output air and return air)
- Cold water sensors (input and output) for main AHU
- Cold water sensors (input and output) for AHUs inductors
- Hot water sensors (input and output) for main AHU
- Hot water sensors (input and output) for AHUs inductors

Analysis of air impulsion temperature

In Figure 7.10 it can observed that the air impulsion temperature of both AHUs. The graph is divided into several zones for study.

- Zone A: This zone is not affected by the DR event. AHU air output temperature reaches setpoint temperature all the time.
- Zone B: This zone is affected by the DR event. As in zone A case, AHU air output temperature reaches setpoint temperature.
- Other zones: As it can be observed during a large part of the days 8, 9 and 10 of January, the impulse temperature suffers sudden changes that do not follow the impulsion temperature, due to system malfunction. It is not the objective of this study to look for the reasons of these variations, but in any case, these data are not valid for a comparison between the situation of DR event and a situation without DR event.

Analysis of hot water demanded energy
The upper figure of Figure 7.11 shows the hot water temperature gradient (input water temperature minus output water temperature) of the AHUs related with the DR event (65 and 66). The bottom one shows the hot water circuit valve. The figure is divided in the same areas than previous figure.

- **Zone A:** In this area setpoint temperature of AHU 65 is always a degree higher than setpoint of AHUs 66. Temperature gradient for both AHUs seems to contradict previous assertion, because is always higher for AHU 66, but if we observe the behaviour of the valve, AHU65 valve is more open than AHU66 one, so the quantity of energy may be higher.
- **Zone B:** There are sudden changes in AHU65 temperature gradient and valve due to the DR event.
- **Other Zones:** We can observe that there are many moments in which the valve is fully open, in these situations the AHUs are overloaded and the setpoint temperature cannot be followed.

![Figure 7.11: Hot water thermal demand of single AHUs](image)

**Effects on energy**

The energy consumed by the AHUs is determined from the temperature gradient between hot water flow and return, multiplied by the opening of the hot valve. This energy is transmitted to the air that passes through the AHU with a certain coefficient of efficiency. The energy transmitted to the air can also be calculated as the gradient of air temperature (between incoming and outgoing air) multiplied by the flow, which in this case is constant. However, some corrections should be made, such as that caused by the heat exchanger with the outgoing air, which will reduce the energy consumed.

**Energy comparison between AHU 65 and 66 (UTA65 and UTA66)**

In Figure 7.12 we have the relation between the energies supplied to the air by AHU 65 and 66. Those energies are obtained by multiplying air gradient by AHUs flow. In the figure we can see the comparison when both AHUs follow the same setpoint (non DR event situation) and when the setpoint of AHU65 is modified (DR event situation). As it can be observed, reducing the setpoint 2°C also reduces the energy supplied. For the first DR event day (9/01) there is a 40% reduction in the energy transferred to the air, while in the second DR event day (10/01) the reduction is 34%.
Correlation between energy consumed and supplied

In Figure 7.13 it is shown the relationship between the energy consumed by the water system and that supplied to the air. There is no correlation between them.

There is also no correlation between the water energy (calculated as gradient temperature multiplied by valve opening) of AHU 65 and 66.

So, it is not possible to analytically define a direct relation between water demanded energy and air delivered energy with the data available. As the air energy is clearly related with external temperature and modification of set point, it will be used that value to evaluate analytically the benefits of the DR events on system energy consumption.

7.5 TEST CASE MTC03: MALLORCA PLANT SIMULATOR

Mallorca plant Test cases MTC01 and MTC02 have revealed some information about plant behaviour and which kind of measures can be taken to reduce peak loads and their associated costs.

However, Hospital HVAC thermal demand has revealed unstable forecasting and it is difficult to extract precise and extrapolatable results from the tests performed when the study is focused on water energy
demand of specific days, however, interesting conclusions can be extracted from long term simulations. In this section long term studies will be carried out.

7.5.1 Sampol simulation tool

7.5.1.1 Simulator Background

Test case MTC02

From the test case related with the modification of set-point temperature for one AHU we have obtained several conclusions:

- There is a good correlation between set point temperature and AHU outlet air temperature.
- It is difficult to obtain a correlation between air thermal energy and water thermal energy.
- AHUs maximum capacity is frequently reached in winter and summer, which means that the set point temperature is not reached. That causes a modification of the set point by the users (with room controls) or by the HVAC system manager.

IBM Black Box Model

The demand prediction tool designed by IBM has good results in demand prediction for Mallorca Plant. It was developed using 2015 and 2016 data from Son Llatzer Hospital demand data and also using weather forecast registers of the Spanish weather forecast institution.

It has an error lower than 7% when testing the tool with 2015 and 2016 values (the ones used for training). That error increases when the predicted demand is high and the use of auxiliary sources (as electrical chillers and gas boilers) are required (peak loads). For 2017 data, not used for training, the error ups to 15%, and is also higher for higher real demands.

That tool uses historical demand data (previous 14 days) as well as weather forecast parameters (temperature, humidity, wind speed or sun radiation) for predicting future demand 48h in advance.

To test the capacity of IBM BB tool to predict changes on set point temperature we have tested the tool for a whole year modifying the temperature value (increasing or decreasing 1 or 2 degrees). That will induce a behaviour of the HVAC system thermal demand similar than modifying the set point of the different AHUs.

A non-coherent performance of the IBM BB tool was observed when applying those changes. We have obtained higher hot water demand when increasing winter temperature, but lower than previously obtained (real values) standard deviation.

Those results lead to the following conclusions:

- IBM BB tool puts more weight on previous demand values than on weather forecast values.
- 1 or 2 degrees modification causes a modification on tool’s forecasted demand that is lower than standard deviation.
- IBM BB tool is not a suitable tool for the purposes of set point modification simulations.

Due to IBM BB tool problems Sampol has developed a Simulation tool suitable for long term simulations and based on external and set point temperature historical measurements.
7.5.1.2 Simulation Description

The aim of the simulation is to predict thermal demand modifications based on set point temperature value changes. Hot and Cold water thermal demand depends on several features, as can be observed in the images contained at Figure 7.14:

- **External Temperature.** This is the most important parameter for thermal demand. As can be observed in figures, cold water demand is mainly increased when temperature increases and hot water demand is mainly decreased when external temperature decreases. However, there is a 'Winter Switch OFF temperature (19 °C)'. When this temperature is achieved in winter time most of the HVAC system is switched OFF.

- **Labour/Non labour day.** Non labour days have less thermal demand due to the fact that most of the offices and their related AHUs are switched off. As can be observed in figure, hot and cold water thermal demand at 2AM or 8 PM for labour/non labour day are similar, but not at 10 AM, when offices have already open and HVAC systems tries to achieve set point temperature.

- **Hour.** The thermal demand depends on the sun radiation, offices opening hours and also on the non controlled air inputs and outputs. During night hours doors and windows are not opening and closing in the same way than during day hours. During night offices are closed.

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**Figure 7.14:**

- **Cold water demand at 2AM in 2015/16**
- **Cold water demand at 10AM in 2015/16**
- **Hot water demand at 2AM in 2015/16**
- **Hot water demand at 10AM in 2015/16**
Figure 7.14: Experimental data (2015 and 2016 values) used for model training

Hospital thermal demand model
The final model has the following features.
- A 4th degree polynomial is used to fit the hot and cold water thermal demand with 2 years (2015 and 2016) real data from Mallorca Plant using temperature as a unique input parameter.
- There is a different polynomial fitting for each hour and also for labour/non labour days.
- Hot water demand model does not use summer base values, as that demand is mostly sanitary water non dependant on temperature.

Some of the model predicted polynomials can be observed at Figure 7.15. In one hand, it can be observed at the left figure, at 4AM the polynomials for labour (hotLAB, coldLAB) are almost the same than the polynomials for non labour days (hotWE, coldWE). On the other hand, at 12 AM the polynomials for labour/non labour day are clearly different. Labour days have higher demands because more offices are open and their AHUs are running.

Figure 7.15: Obtained models for thermal demand based on Hour and Temperature

7.5.2 Simulation Results
A cold water simulation for 3 days can be observed at Fig. 7.16. In that figure the real demand value for those three days is compared with the simulated value for 3 situations:
- Same external temperature as the real situation, obtained from registered weather forecast values.
• One Celsius degree reduction at external temperature. With this situation we want to simulate the effects of increasing one degree the temperature setpoint of the AHUs and, therefore, it is reduced by 1 degree the energy supplied to the air system.

• 2 Degrees reduction at external temperature. Same explanation as 1 Celsius degree reduction. As it can be observed at Figure 7.16 the simulation with the same temperature has higher deviances against the real demand. This result is the same situation that it was observed with IBM forecast tool. However, the overall 3-day simulated demand is closer to the real demand. When 1 degree or 2 degrees reduction of external temperature are applied the demand has a similar behaviour of the “simulated” one but with lower value for the demand. Depending on the hour and the external temperature that demand decrease has different value. An study of the overall reduction on thermal demand due to setpoint temperature modification is showed on KPI 5 chapter.

![Cold Water demand simulation](image-url)

*Figure 7.16: Simulation result for different set-point modification*
8 Discussion

The OPTi project used two different pilot cases which should make use of the approach that was designed in the project. While the ambition was to have a solution, which is sufficiently generic to be used at both pilots, the practical application still required specific adaptations. The different test cases will be short discussed before a detailed assessment of the KPIs and insights and recommendations are provided.

Luleå pilot

LTC01 test case had the focus of lowering the supply temperature by optimizing the controlling of the DHC system and by that reduce the energy losses. The results from LTC01 has shown that optimizing the supply temperature reduce the amount of fuel needed in production units. The potential if optimizing was applied broader in Europe is very large as shown in chapter 6 in the report.

LTC02 test case had the focus of optimization control valves with respect to dimensioning of valves and the controlling performances. The result has shown that the valves in general are over dimensioned and that the size can be reduced very much. By optimization the control parameters of the valves, tests show that it is possible to get a more stable temperature in buildings and less fluctuations on the district heating network.

LTC03 test case had the focus of reducing the peaks in production by applying peak load reduction at consumers. The tests have shown that KPI2 is easily achieved without affecting the indoor climate for residential.

LTC04 test case had the focus of performing peak load reduction by ADR at consumers and the complexity here was very much the needed remote access to consumer sites which was not possible to be established during the project life-cycle.

LTC05 & LTC06 test cases were both conducted using OPTi-Sim. Essentially, new ways to control and optimize the DH system were tested in a sandbox which provides the needed understanding if the developed solutions are feasible and what benefit they would bring. There, a completely new concept to control the DH system in a predictive manner is tested.

Mallorca pilot

Son Llatzer Hospital HVAC system is a complex system with more than 100 AHUs that operates in different ways. Some of them are running continuously, with different set points dependent on the day/night hour. That AHUs are the ones that controls the common areas and the hospitalization areas. Another set of AHUs are switched ON and OFF depending on the opening time of the offices and other non 24-hour opening areas.

Hot water and cold water demands follows a daily pattern, with lower values during night time, due to the set point temperature modification, and with a sudden peak at 7-8 AM, due to the switch ON of the non-24-hour AHUs. However, there are high deviations in the demand between days with similar weather conditions, up to 50%. Those deviations are especially dramatic in the peak load scenarios.

The hot and cold water demand forecast tool developed by IBM has good results, but cannot predict the deviations of the demands between similar days. Therefore, is difficult for the tool to predict peak load situations.

The aim of MTC01 test cases was the reduction of peak loads by applying a precooling or preheating scenario. As is shown in the results, it is difficult to determine if a peak load has been avoided with a preheating or precooling due to the disparity between forecasted demand and real demand.

MTCC02 test cases are focused on modifying single AHUs parameters to evaluate the energy balance in a concrete area. The results indicate that there is a clear relation between the set point temperature of the AHU and the energy consumption.

MTC03 was focused on obtaining a simulation tool that allows the evaluation of temperature set point modifications on the total hot water and cold water thermal demand. With that tool some scenarios that include the modification of the temperature set point in certain hours can be analysed.
8.1 Achievement of OPTi KPIs

Based on the test cases and the results that are aggregated, the achievement of the KPIs as put forward is judged in this section.

8.1.1 KPI1: Reducing energy consumption

KPI1 was split into two tracks, one focusing on the optimization of the DH system for better efficiency which should be reflected in energy savings, and the other focusing on exploiting the comfort zone for reduced energy usage. The two tracks are now assessed separately and then combined.

8.1.1.1 Assessment of Track 1

For track 1, energy savings that relate to increased efficiency of a DHC system with the aid of the OPTi Framework should be identified and quantified. It was anticipated that LTC01, LTC02, LTC05 and LTC06 would contribute to energy savings, where LTC05 has the largest share of contribution.

In both LTC02 and LTC06 it was concluded that the increased efficiency will result in a more efficient transmission of the energy, with reduced short-term fluctuations. These fluctuations contribute to higher losses in an energy system but are very difficult to quantify in terms of energy. In case of LTC02, the impact of the reduced valve size is also in peak load reduction as the effect of short term disturbances is mitigation through a limitation on the demand side. Thus, LTC02 and LTC06 can be disregarded for the KPI-1 assessment.

LTC01 concluded that the reduced supply temperature curve will contribute with a saving of 0.4%, which are mainly attributed to reduced losses in the heat distribution with no adverse effects for the consumers. In LTC05 it was concluded that the predictive concept for the supply temperature curve with the use of pre-heating and pre-cooling enables also a reduced supply temperature and renders a saving between 1.6-2.0% of the annual production, while not effecting the consumers.

Since both LTC01 and LTC05 target the same aspect, the outcome can not be combined and thus at most an energy saving of 2% is achieved.

8.1.1.2 Assessment of Track 2

In track 2, the aim was to reduce the energy usage in building by understanding the comfort zone and subsequently adjusting the indoor temperatures towards the lower end of the comfort zone. By doing that the energy usage of a building is reduced instantaneously without the need for any changes.

Within LTC04, the comfort zone for employees at the Luleå Energi main building was established. Moreover, a grey-box model reflecting the thermal dynamics of the building is available, which means that the relationship between changes in indoor temperature depending on outdoor temperature variations is reflected in the energy usage by the building.

![Figure 8.1: Power consumption of the Luleå Energi main building. Both default set point and changed set point are simulated to have replicable conditions for assessment.](image)

Since weather conditions and the thermal state of the building at the starting point of a test campaign are never the same, it was clear that energy savings could not reliably quantified using experimentation. Instead, a typical historic weather scenario was used, where the grey box model thermal state was fit to the historic data. Then the two cases, default and reduced indoor temperature, were simulated for the weather scenario.
Thereby, the energy usage of the building becomes comparable for the two cases and the energy saving can be quantified. In Figure 8.1, the simulated power consumption for default and changed set point with the measured power for the changed set point are depicted. The simulated and measured power for the changed set point do agree well and that the simulated baseline power for the same conditions is mostly higher.

The resulting saving for the building was calculated to 5% per degree for the testing period, which means a temperature reduction of 2°C yields a reduction of 10% while still being within the admissible range of the comfort zone. While this result is on the level of one building, the saving for a complete network of buildings is difficult to predict. Moreover, to enable these energy savings, the following three steps need to be conducted prior to a quantification:

- Identification of buildings with elevated indoor temperatures in complete or parts of the building
- Assessment of the comfort zone using the virtual knob
- Adaptation of the grey-box model for the building using historic data

Despite the limited testing that could be performed, it is concluded that energy savings of 10% are possible.

8.1.1.3 Joint outcome

The two tracks for KPI1 can be directly combined and therefore enable an energy saving of up to 12% when the OPTi-Framework is used for targeting energy savings, while not compromising on consumer comfort levels. The KPI1 value was changed after reporting period 1 and was altered from 30% down to 10%. Thus, the application of the OPTi-Framework in the context of the test-cases complies with the targeted KPI1 value.

8.1.2 KPI2: Reduced peak loads

To fulfil KPI 2 the following issues must to be addressed:

- Determine when peak loads occur.
- Define how much energy demand can be moved within a DR event.
- Verify DR events have achieved KPI-2 requirements of 40% energy reduction (OPTi goal).

In section 4.2 a definition for the peak loads is given and they are different for the two pilot site, which depends on the characteristics of their operation and how peaks occur. Both pilots will therefore be assessed for their achievement individually. It should also be noted that the two pilots sites have different level of control from the project, which means that the level of detail differs.

8.1.2.1 Mallorca pilot

8.1.2.1.1 Hot Water DR event results

One option to avoid a Peak Load is to reduce the setpoint at 8 AM. That option is not easy to achieve due to the reduction on user comfort. Set point temperature should be reached at 8 AM, as that is the time in which people starts their activity at the hospital.

A second option is to program a 2 hour preheating. That consist on moving part of that demand to the previous hours. However, between 4-6 AM normally the CHP engine is running at 80-85 % of its maximum capacity (due to the low price of the electricity market at that time) and it is possible that this demand increase cannot be covered by the CHP engine and auxiliary boilers will be required to fulfill the demand.

A third option is instead of applying a 2 hour preheating, a long preheating to adapt the hot water demand between 0-7 AM to the production of the CHP engine. The hot water thermal demand will be increased during night hours up to the generated thermal energy to maintain the building temperature higher during the night and to reduce the peak load at 8 AM.

To evaluate DR events proposed on that document, we simulated the thermal energy amount not used between 0-6 AM. Afterwards, we have compared that value with the peak load at 7-8 AM. Taking into account 2016 historical values, the data results are shown at Table 8.1.
### Table 8.1: Hot Water DR events

<table>
<thead>
<tr>
<th>2016 Hot water Peak Loads</th>
<th>44</th>
</tr>
</thead>
<tbody>
<tr>
<td>Peak Load Fully covered by 0-6 AM thermal energy lost</td>
<td>29</td>
</tr>
<tr>
<td>50%-90% of peak load covered</td>
<td>6</td>
</tr>
<tr>
<td>10-40% of peak load covered</td>
<td>3</td>
</tr>
<tr>
<td>Peak Load not covered by thermal energy lost</td>
<td>6</td>
</tr>
</tbody>
</table>

Figure 8.2 represents the days in which a Hot Water Peak Load at 8 AM is produced. As it can be observed, most of the peak load days have a hot water thermal energy loss between 0-6 AM much higher than the thermal energy covered by gas boilers in the peak load hours (7-8 AM) (upside the red line). Using the lost energy to increase the temperature of the closed areas between 0-6 AM will reduce 7-8 AM peak load.

![Graph showing the relationship between thermal energy lost and gas boiler coverage]

**Figure 8.2: Hot Water Demand NOT covered by CHP engine in winter day, Auxiliary fonts used**

That scenario must force a change in the HVAC control system, changing from fixed set points behavior to a ‘Energy available’ system during 0-6 AM.

#### 8.1.2.1.2 Cold Water DR event results

Following cold water peak load definition, 24 situations has been detected during 2016. The situations in which the chiller activation was due to the power OFF of CHP engine for maintenance reasons or economic issues (low electricity prices) has been eliminated from the analysis. On Table 8.2, a resume of the data used is shown.

### Table 8.2: Cold Water DR events in 2016

<table>
<thead>
<tr>
<th>Peak Load duration (hours)</th>
<th>Tests performed</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>3 (26-may, 2-set, 27-set)</td>
</tr>
<tr>
<td>2</td>
<td>11 (31-may, 13-jun, 19-jul, 19-set, 25-set, 28-set, 30-set, 1-oct (2 times), 3-nov, 4-nov)</td>
</tr>
<tr>
<td>3</td>
<td>5 (16-aug, 23-aug, 26-aug, 30-aug, 2-oct)</td>
</tr>
<tr>
<td>4</td>
<td>4 (19-may, 30-may, 25-jul, 9-aug)</td>
</tr>
<tr>
<td>5</td>
<td>2 (3-jun, 17-oct)</td>
</tr>
</tbody>
</table>

For all that situations we have simulate the effect of a thermal demand reduction using experimental results. That thermal demand reduction is based on a modification of the temperature set point during the hours in which the peak load is detected.
For all situations we have obtained that the KPI 2 is accomplished with an increase of 1 or 2 degrees on the temperature set point of non-critical AHUs. That set point modification only lasts for the hours in which the peak load is detected.

### 8.1.2.1.3 KPI 2 simulation and measurement

KPI 2 is defined using the following formula. Project goal is to reduce a 40% the peak load using this metrics. So, the result of this formula when DR events are applied must be lower than 0.6.

\[
\text{Peak Energy Reduction} = \frac{(\text{Mean}_{\text{Peak Period}}(P(t)) - \text{Mean}_{\text{Day}}(P(t)))}{\text{Mean}_{\text{Day}}(P(t))}
\]

Considering all the peak loads defined for that situation, the average value of the Peak Energy Reduction is 0.39, therefore, the KPI2 achieved is of 61%, which is bigger than the defined goal. As it can be observed in figures below, KPI2 accomplishment is more effective in hot water peak loads than in cold water ones. That result is motivated by the different approach to reduce the peak loads in both cases. For hot water peak loads most of the peak loads are completely removed due to the high amount of energy wasted between 0-6 AM that can be reused to increase room temperature in affected areas. For cold water peak loads the solution is to modify set-point temperature and it has less effects on overall auxiliary demand.

![KPI 2 for hot water scenario](image1)

![KPI 2 for cold water scenario](image2)

*Figure 8.3: KPI 2 (peak Energy Reduction) accomplishment for 2016 peak loads*
8.1.2.2 Luleå pilot

The result that has been achieved during pilot tests and simulation tests indicate that KPI2 is very much possible to fulfill if applied in real-life. Since there has been no full-scale tests including all the grid for peak load reduction, the results need to be related to the tests that have been conducted at pilot buildings. Here peak load has been performed and the total supplied energy is reduced by 10-90% depending on how the reduction is controlled, while no impact on indoor climate is imposed.

The theoretical analysis that have been presented in chapter 6 assumed that the energy supplied to a building can be reduced by 33% at any outdoor temperature. The numbers of buildings that have been target for this analysis represent 30% of the total power in the district heating network. This means that around 10% of the total load can be reduced, where 10% load represent a very large portion of the peak production in most real production cases. As shown in the example in chapter 6, up to 100% of the peak production can be reduced if the implementation is done in the scale suggested in this report. By this we state that we fulfill the target of KPI2 by lowering the peak production at peak hours by more than 40%.

8.1.3 KPI3: User thermal comfort flexibility

User thermal comfort flexibility experiment was conducted in LEN office buildings from 9th January 2017 to 21st January 2017 during the LTC03. During the experiment, temperature set-point was varied in the range of 21 and 24 and the feedback from the user were taken about their comfort level. The feedback was taken from an app installed in a device locates at all the three floors in the office of LEN. Further, we also have the data of the energy consumption and hence we can calculate the energy savings from these experiments. For a more detailed description of the test conducted and the results obtained, please refer to D5.3.

In Figure 8.1, we plot the expected power consumption based on the historical data, the actual power consumption, difference in these two, and the set-point temperatures, for the duration of the experiments. As we can observe that, the days where the set-point temperature is lower, we have higher savings. Further, we calculated the energy saving as a function of set-point temperature to calculate the sensitivity in the energy consumption with respect to the set-point temperature as shown in Figure 8.4.

Moreover, we also aggregated the data of the user comfort from the virtual knob devices installed on each floor. We recorded the response from each feedback and performed an analysis. There the comfort indices represent:

<table>
<thead>
<tr>
<th>Comfort index</th>
<th>-2</th>
<th>-1</th>
<th>0</th>
<th>1</th>
<th>2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Explanation</td>
<td>too cold</td>
<td>cold</td>
<td>comfortable</td>
<td>warm</td>
<td>too warm</td>
</tr>
</tbody>
</table>

The average comfort level is plotted against the set-point temperature in Figure 8.4. It can be observed, that the average value of the comfort index steadily increases as the temperature is increases.

![Figure 8.4: Comfort assessment for the experiments at Luleå Energi main building. Feedback count (left), Relation between indoor temperature and comfort (right).](image-url)
Further, for the temperature range from 21.5 to 23.25°C, users seem reasonably comfortable since the average value of the “comfortability index” lies in between -1 and +1. Therefore, we can say that the comfort range has been expanded from a fixed set-point to a range of +/- 1 degree Celsius. It need to be kept in mind that the validity of these results is limited to the used test case and might not be replicable with the same numbers in a different location and different test conditions. Nevertheless, the virtual knob concept can be seen as a tool to assess the comfort zone based on experimentation which is a novelty.

8.1.4 KPI4: Capability of representing real life events

Chapter 5 demonstrated the capability of the OPTi-Sim framework to replicate real-life events with sufficient accuracy. Although we did not reach the intended quality measure as described in KPI-4, the obtained results are nevertheless significant, and the simulation approach provides an important additional tool for the engineers at Lulea Energi.

By and large, the evaluated test cases form three groups. The first group contains events where no auxiliary boiler(s) are needed to provide sufficient power for the network. The second group includes events where auxiliary boilers are required to reach or sustain a certain level of production. The third group represents setups where auxiliary boilers are needed and disturbances in KVV production occur. The individual groups contain a total number of six, seven, and five events, respectively.

In the first group, five out of six simulated events passed the acceptance criteria. One simulation did not reproduce the expected magnitude of the flow and power in the network. Moreover, simulated and observed peaks did not coincide. The reason here is most likely due to shortcomings in the black box models.

In the second group, basically all simulated events passed the acceptance tests. Here, we observed several abnormalities whose cause we were not able to pin down. However, each of these uncommon incidents had only minor significance altogether.

In the third group, four out of five events passed the acceptance criteria. The only failure concerned the reproduction of the temporal variation of the supply temperature and not reaching its set point.

In total, we thus successfully reproduced sixteen out of eighteen events, resulting in an overall positive rate of roughly 90 per cent. This value is close to our intended 95 per cent target value from KPI-4. The small difference is remarkable given the different levels of detail in our modeling approach. The black box models followed a data-driven approach where no physical relation between input, output, and the inner workings of the model entity is assumed. Modeling of the DHC network involved intricate physics and engineering principles, much more detailed than a black box model. Finally, the controller models also included fine-tuned and approximate constructs to regulate the entire DHC network, its pumps, supply station and much more.

In conclusion, the OPTi-Sim framework provides a beneficial tool to simulate the behavior of DHC networks under different operating conditions. The evaluation of numerous real-life events of the Lulea DHC network illustrated its capabilities, but also revealed its shortcomings. Even if we fell short of the intended KPI-4 target value of 95 per cent, the obtained reproducibility rate of almost 90 percent is a remarkable result. Further refinement in modelling the involved processes, parts, and structures are likely to push this significant number even closer to the KPI-4 target value.

8.1.5 KPI5: Economic benefit

8.1.5.1 Introduction

To evaluate KPI-5, OPTi defined a list of finer-grain KPIs addressing several economic aspects of the DHC environment aiming to demonstrate that the project’s developed methodologies produce comparatively improved results (economic benefits in our context), compared to current practices.

In our specific context and taking into account the specificities and limitations of our trials we evaluated the following key economic benefits from adopting OPTi assets:
1. The economic benefit for the utility company (Lulea Energy) after applying a new decreased supply temperature in the DH network
2. The economic benefit for the utility company (Lulea Energy) after peak load reduction over different periods of the year
3. The economic benefit for the consumers (Lulea Energy customers) and social welfare calculation after demand modification through ADR
4. Economic benefit for the customer (Hospital de Son Llatzer) and the company (Sampol) after demand modification through DR

Please note the following:

- The above cases account for most of our test cases (LTCs and MTCs) that OPTi Assets were used. Nevertheless, due to the different contexts of the test cases (e.g. environment performed, tools used, pilots vs. simulations, consumers availability, industrial and non-industrial buildings, public buildings with strict regulations like the Son Llatzer hospital, etc.) different methodologies were utilised to estimate the resulting economic benefits.
- Achieving a 15% economic benefit for the involved value chain participants was only achievable under specific environments and assumptions (also do not forget that the OPTi project contains small scale pilots). However, we clearly demonstrate that our methodologies and tools once deployed and replicated on a larger scale could provide significant advantages on both a technical and economic scale.
- OPTi-Sim, our core asset, was used in most cases to both design/plan the modifications needed to the DH networks but also to evaluate the technical side-effects to the network that sometimes cannot be easily quantified in economic terms.
- WP3 that ended earlier in the project and WP5 had already provided us with insights and results on the economic benefits achieved in some cases, such as in using ADR. Please refer to deliverables D3.2, D3.4 and D5.3 for more information including the theoretical background and the algorithms used.
- In addition to the aforementioned, WP3 developed a CBA tool that can be used as a template to evaluate the economic benefits of introducing OPTi Assets to the network. The CBA is demonstrated as a template in D3.2 and as an example used in the case of evaluating the benefits of ADR in Section 8.1.5.3. We evaluate the real case that LEN implements for its network an ADR solution using two of projects Assets: the Virtual Knob and the ADR tool (and purchasing external tools for implementing the control part).
- In our holistic view of creating business impact the economic benefits should be seen as part of the proposed business models that can be used to exploit the OPTi assets i.e. justifying our business cases and the value proposition of our offerings. In WP7 we have dealt with the business part of this analysis (such as proposing a set of business modelling canvas’).

The following sections elaborate more on the aforementioned presenting a summary of our results. For more information the reader is advised to go through the respective OPTI documents (references are given in the text) and other sections of this report (Test Cases results).

8.1.5.2 Economic benefit for Lulea Energy after a new decreased supply temperature

Changing the supply temperature curve is a very simple way of reducing fuel in the production due to less needed energy and gives direct impact on production costs and less environmental footprint. When this is changed, the district heating system can be affected in the following ways:

- An increase in $T_{\text{supply}}$ or reduction of $T_{\text{return}}$ allows a higher maximum power output of the existing distribution system, that is, increased delivery capacity.
It is possible that the amount of waste heat that can be recovered from the industry can be increased when \( T_{\text{return}} \) can be reduced.

An increase of \( T_{\text{supply}} \) and/or a reduction of \( T_{\text{return}} \) reduce the total flow in the distribution system.

The flow reduction results in reduction in energy costs for pumps.

Lowering \( T_{\text{return}} \) and/or \( T_{\text{supply}} \) reduces heat loss from the distribution pipes.

As described in Section 6.1, the following new supply curve has been applied in LEN’s DH network:

![Supply curve after changes](image)

**Figure 8.5: New and old supply curve.**

During the winter period December 2015 until March 2016 the calculated energy saving is almost 800 MWh (see Table 8.3Table 8.3: Impact on the different fuels needed due to the new supply temperature curve.**Table 8.4**), which corresponds to 0.1% of the annual production.

**Table 8.3: Impact on the different fuels needed due to the new supply temperature curve.**

<table>
<thead>
<tr>
<th>Production unit</th>
<th>Fuel</th>
<th>MWh less production</th>
</tr>
</thead>
<tbody>
<tr>
<td>LUKAB</td>
<td>Surplus gas from steel plant</td>
<td>479</td>
</tr>
<tr>
<td>HVC 1</td>
<td>Electricity</td>
<td>121</td>
</tr>
<tr>
<td>HVC 2</td>
<td>Oil</td>
<td>124</td>
</tr>
<tr>
<td>HVC 4</td>
<td>Wood powder</td>
<td>68</td>
</tr>
</tbody>
</table>

During the period from December to March the saving in money based on the fuel prices at that period amounts to **376106 SEK**, but a comparative figure in relation to the annual cost cannot be given due to confidentiality reasons. These savings are calculated by thermodynamically correlating with the heat losses. Depending on different days the savings may vary depending on the outside temperature and the fuel costs (market data was retrieved from the Nordpool spot market\(^1\)). Furthermore, depending on the temperature the need for increased pumping was considered (resulting in higher electricity consumption for pumping).

Calculated savings varies for different years depending on the outdoor temperature. For example, for a whole year such as 2013 and 2014 (where full historical datasets where available) the savings with the new curve have been calculated to between **2.5 - 3 GWh annually. This corresponds to 0.4% of the annual production.**

In addition to the above calculations and in order to calculate possible side-effects from the new supply curve, our project asset OPTi-Sim enabled us to study of operational aspects of a changed control scheme, like the modified temperature curve such as the saturation of the pumps when the supply temperature curve is changed too much or that auxiliary units fire using unfavourable fuels from both economic and environmental perspective. These are presented in Section 6.1.5.

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\(^1\) [http://www.nordpoolspot.com/Market-data1/#/nordic/table](http://www.nordpoolspot.com/Market-data1/#/nordic/table)
Furthermore, and in addition to the above in the context of LTC05 a new predictive approach to control the load in the network with the aid of the new supply temperature curve was proven to improve the peak behaviour and reduce the totally used energy. Further, the losses in the network are reduced since the supply temperature is reduced. The average energy reduction during the simulation scenario was 300MWh and extrapolating for the annual heat production the saving amount to approximately 13GWh, corresponding to 1.6-2.0% reduction.

8.1.5.3 Economic benefit for the utility company (Luleå Energ) after peak load reduction

8.1.5.3.1 Estimating the benefits

As part of LTC03 (see Section 6.3.5) we used different approaches to estimate what would be the savings for Lulea energy from reducing its production peaks (irrespective of the application of a specific hardware solution). For example, at a temperature of -10°C during a Monday in March there are two well defined peaks in LEN’s production (Figure 8.6). The maximum power that would be needed from an auxiliary boiler during that period is around 10 MW, which correspond to approx. 5% of the total production, well below the 10% that is assumed to be able to move, see Section 6.3.5.1. When applying peak load reduction in the case below it would be possible to reduce 100% of the peak production with the assumptions made as this is further discussed in Section 6.3.6.

Figure 8.6: Production in the Luleå network during a Monday at -10°C in March. The curve is based on the production black box model

As shown in this report, the peak reduction that we can achieved varies depending on the production case. However, we have showed in OPTi-Sim that it is possible to cut of up to 100% of the shorter peaks and use a cheaper fuel when loading back thus reducing costs and the environmental footprint. We assume we lower the total power in the network by 10%, this is usually a large part of the peak, but varies in % of the peak.

Some of the assumptions made were:

- The largest buildings from the biggest consumers in the grid were picked for the calculations, assuming they would be part of the system for peak load reduction.

- These buildings represent more than 30% of the dimensioned power in the grid. Here the assumption has been that it is possible to lower the power from these buildings by 33% at any outdoor temperature. During pilot tests performed in OPTi, shown in chapter 6, it has been clear that this is possible to achieve.

- To achieve the 33% reduction, we need to lower the set point temperature so that this is fulfilled. For example, at 0 degrees outside you would have to change the setpoint from 20 degrees indoor to around 14. 14 is not a temperature that would actually be the reached indoor temperature, it is only
to trick the heating system to deliver less heat than needed and use the inertia of the building to avoid the peak in production.

- To replicate the above for the whole network, all consumers need to be integrated in the system, around 400 buildings in total. The cost is very hard to estimate, it so much depends on what technology is installed at all costumers, and what technology should be used. In the next sub-section we provide a sample cost-benefit analysis from using the OPTi virtual knob.

Based on the analytical calculations of LTC03 if peak load reduction would have been achieved during 2016 according to the stated demands the following result would have been achieved:

- **Fuel that can be shifted to cheaper fuel**
  - Wood pellet 1684 MWh
  - Oil 520 MWh
  - Electricity 360 MWh

- **Economic savings generated form shifting of fuel:**
  - 700 000 - 800 000 SEK/year

To analyse how the peak load reduction in a complete network will affect its operation the question we used the OPTi-sim and OPTi-Forecaster as described in Chapter 12.

### 8.1.5.3.2 Implementing a complete ADR solution using OPTi assets (Virtual Knob and ADR tool) – A Cost-benefit Analysis

As discussed in Section 4 of Deliverable D5.3, implementing an ADR solution entails the used of specific hardware installed at customer premises, for example in order to alter the internal temperature and also receive consumer’s feedback. We have given in the past two commercially available examples for dealing with the control aspects of a system, the NODA solution and the NGenic both with certain requirements and limitations. The NODA\(^2\) is the closest to our view of how such a system could be implemented (a NODA version has been internally tested in LEN premises as well).

In addition to the control part, as part of our proposed solution in the context of OPTi, the ‘Virtual Knob’ (VK) tool was developed to serve as a means of obtaining live feedback from users on the indoor temperature variation. This is also necessary for the optimisation of our ADR algorithms. An android app was developed along with the back-end storage system. The figure below shows the complete Virtual Knob system envisaged by OPTi. Furthermore, the ADR tool, an OPTi asset, can be used for planning the ADR events (targeting users and offering incentives) based on users’ contracts and company’s objectives.

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\(^2\) [https://noda.se](https://noda.se)
Figure 8.7 The Virtual Knob System (from D4.4)

We assume that our VK tool could be part of a system where instead of controlling individual thermostats, there is the option to remotely control the supply temperature for the heating. This introduces a bias on the measured outdoor temperature and thereby creates a command input to the control loop for the supply temperature. Consequently, the overall apartment temperature can be affected remotely.

We assume based on our market research key costs of such an ADR system to be deployed for 400 buildings to be:

- 30000 SEK per installation (i.e. per building) for the control system (sample NODA cost) that includes hardware and installation. Also, a yearly cost of 10000 SEK for the subscription and software license.
- 1500 SEK for the Virtual Knob hardware and installation such as the one used for OPTi trials (e.g. for a low-cost tablet).
- The two project Assets used (the Virtual Knob and the ADR tool) are already developed in the context of the project and provided for free to LEN. i.e. there is no cost for the a) VK UI implementation and b) the ADR algorithms design and planning tool like the ADR tool developed by OPTi as well as for the maintenance of the databases (VK storage) inside the LEN premises. However, we account for a cost for further developing and testing/validation of the OPTi prototypes before the final product release, all incurred by the energy company.
- A certain amount of monetary incentives to be given to the consumers (e.g. yearly or % reduction in their bill) for participating in the ADR programs, always with little inconvenience cost (comfort loss). As we discussed in WP3 new contracts need to be made but this is out of the scope of the current analysis.

All the above (including a lot more fine-grain financial metrics) are configurable CAPEX/OPEX factors in our OPTi CBA tool (a programmable spreadsheet) that can be altered by the user (LEN in this case). So, for example the company can evaluate beforehand and choose wisely how many incentives it can provide in order not to diminish its economic benefits and how many buildings to use for integrating the solution. Our aim is to provide a template and a decision support tool for evaluating different economic scenarios for this particular test case and OPTi Assets. In any case, the final decision of such an investment would be made by the company’s management taking into account other factors and criteria as well. Also, someone needs...
to bear in mind that certain (and accurate) economic figures of an energy company are confidential and not available to us, therefore (realistic) assumptions had to be made for the purposes of this research project.

Moreover, it should be highlighted that similar (based on the same financial engineering methodologies) CBA tools have been developed by AUEB, OPTi’s economic experts, in the context of other Energy projects. Also, AUEB is a key member of the Business modelling working group of the H2020 BRIDGE\(^3\) initiative where these tools are presented and discussed with experts. BRIDGE is a European Commission initiative which unites Horizon 2020 Smart Grid and Energy Storage Projects to create a structured view of cross-cutting issues which are encountered in the demonstration projects and may constitute an obstacle to innovation. However, this is the first time a CBA tool was developed and tailored for DHC in particular. AUEB has already started to disseminate this using the BRIDGE channels with very positive feedback.

For our results for the particular scenario investigated, the following cost-benefit metrics were calculated:

- a cumulative –over time- comparison (called “SUM”), in terms of absolute benefits when OPTi technologies are adopted,
- a cost-benefit ratio (referred to as “SUM%”), in terms of benefits in State B (ADR implemented) relative to the benefits in State A (business as usual scenario),
- a cumulative –over time- comparison (called “PV”) that is the sum of all the discounted future benefits in the defined timeframe (not absolute values). Computing the present value of the respective cash flows stream is widely accepted as a better measure of profitability, calculated starting from the baseline year and by applying a discount rate in the projected benefits that our assets are expected to generate, when a cash flow today is more valuable than an identical cash flow in the future.

Based on various economic metrics calculated we can estimate that such an investment can potentially result in positive figures of approximately 10 million SEK in a period of 20 years (with revenues gradually increasing after the first few years of the investment). A summary of the figures is presented in the next table.

<table>
<thead>
<tr>
<th>Benefit Category</th>
<th>SUM</th>
<th>PV (Present Value)</th>
<th>SUM (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Deferred Generation Capacity Investments</td>
<td>0</td>
<td>0</td>
<td>N/A</td>
</tr>
<tr>
<td>Deferred Distribution Capacity Investments</td>
<td>-484,425,000</td>
<td>-435,491,499</td>
<td>-2.8%</td>
</tr>
<tr>
<td>Reduced Ancillary Service Cost</td>
<td>0</td>
<td>0</td>
<td>N/A</td>
</tr>
<tr>
<td>Reduced Equipment Failures</td>
<td>69,300,000</td>
<td>63,276,147</td>
<td>72%</td>
</tr>
<tr>
<td>Optimised Generator Operation</td>
<td>454,553,793</td>
<td>409,378,452</td>
<td>0%</td>
</tr>
<tr>
<td>Reduced Distribution Operation Cost</td>
<td>-84,800,000</td>
<td>-76,513,145</td>
<td>-58%</td>
</tr>
<tr>
<td>Reduced Distribution Equipment Maintenance Cost</td>
<td>-5,400,000</td>
<td>-4,872,299</td>
<td>-38%</td>
</tr>
<tr>
<td>Reduced Meter Reading Cost</td>
<td>6,000,000</td>
<td>5,413,666</td>
<td>75%</td>
</tr>
<tr>
<td>Reduced Electricity Losses</td>
<td>0</td>
<td>0</td>
<td>N/A</td>
</tr>
<tr>
<td>Reduced Momentary Outages</td>
<td>24,068,997</td>
<td>21,655,927</td>
<td>113%</td>
</tr>
<tr>
<td>Detection of anomalies relating to Contracted Power</td>
<td>30,008,607</td>
<td>28,102,812</td>
<td>7.1%</td>
</tr>
<tr>
<td>Result</td>
<td>9,306,397</td>
<td>10,950,062</td>
<td></td>
</tr>
</tbody>
</table>

**Figure 8.8 Example economic (CBA) results for ADR implementation over a 20-year period**

The analytic economic values and formulas of the CBA are of sensitive/confidential nature (containing LEN’s financial data) and therefore are not presented here. Nevertheless, the CBA methodology has been presented in previous OPTi deliverables (D3.2).

\(^3\)https://www.h2020-bridge.eu/
8.1.5.4 The economic benefit for the consumers (Lulea Energy customers) and social welfare calculation after demand modification through ADR

As presented in earlier (period 1) WP3 work, OPTi designed and validated a set of methodologies for designing novel ADR contracts. These:

- Offer to the user **monetary incentives** to reduce her consumption at peak load times while at the same time maintaining an acceptable (for her) level of comfort. The defined policies aim at maximising the **net benefit** of the consumer, i.e. the **difference of profits before and after the implementation of the ADR program and hence the reduction to her consumption**. In addition to that, the consumer is also benefited indirectly as she is expected to attain **savings in her bill due to reducing her total energy consumption**.

- Result in significant savings for the energy provider through **reducing the operation of costly and environmentally inefficient peak load plants**.

- **Allow for shaping the demand by alleviating the peak loads** and distributing the energy demand more evenly throughout the day.

- **Maximise the social welfare of the society** i.e. **the difference of the sum of user utilities minus the total cost of energy production**. This objective is central in the OPTi ADR approach, achieved by: a) imposing a maximum reduction in consumers’ utility, b) employing different targeting approaches and reduction policies to achieve the aforementioned reduction and c) exploiting the altruistic nature of certain consumers and assessing their impact on the overall utility of the community, thus facilitating the usage of non-monetary incentives too, due to behavioural motivations.

OPTi, due to the non-availability of users in the Lulea pilot trials has evaluated in a simulation environment (however with real OPTi consumption data) these methodologies and the results appear to be promising. For example, certain simulation results (included in D3.1 and D3.2) suggest that under specific settings and assumptions a provider can achieve a reduction in total peak demand by approximately **20%** by limiting the comfort of consumers by only **10%** while compensating them with a relatively low total amount of incentives. Moreover, in the cases where altruistic users are also considered, a very small percentage reduction in user’s comfort (5%) can lead to even lower reduction in the total comfort. Hence, it is beneficial for the provider to identify the set of altruists and their levels of altruism, to exploit the outcomes of the demand reduction strategies and targeting policies effectively to meet its goals, ensuring at the same time the system welfare.

In addition, choosing a subset of users to participate in ADR, by employing different targeting approaches, can offer greater flexibility to the provider and lead to even better results in terms of the social welfare achieved. Indicatively and as described in D5.3, the more granular based approach of Targeting per Building and per Apartment (TPBA) reveals to be a more effective targeting approach, as it can be implemented both as a single process by the energy provider – whenever the information is available- or hierarchically in two stages, whereby the energy provider applies the targeting process for buildings and then the building manager is in turn responsible for the targeting process of apartments; thus leading to better results in comparison with the other approaches, e.g. circa 73% lower total incentives, 15% higher social welfare achieved after the ADR and smaller subset of users to be targeted (not all users are targeted) than according to the Targeting per Building (TPB) approach. This implies that the volume, type and granularity of available information, e.g. energy consumption, demographic characteristics etc., are of significant role for the selection of the optimal ADR program (including the targeting approaches and the associated policies).

For more information on this work (that has also been accepted and presented as part of project dissemination in the proceedings of international conferences) please refer to WP3 Deliverables (such D3.2). Furthermore, Section 4 of Deliverable 5.3 presents a discussion on the technical applicability of ADR for DH networks.
8.1.5.5 Economic benefit for the consumer (Hospital de Son Llatzer) and the company (Sampol) after demand modification through DR

To evaluate the economic benefit for the participants (KPI 5) for the Sampol trial, the following must be performed:

- Determine the energy costs of hospital side and co-generation plant side.
- Evaluate which of these costs are fixed or variable.
- Determine how demand modification can affect production costs.

These are presented subsequently.

8.1.5.5.1 Hospital de Son Llatzer economic parameters

The Hospital HVAC system consists AHUs supplying air to the different areas of the building. The HVAC costs mainly depend on the amount of hot water and cold water supplied to the hospital by the co-generation plant.

In the following table there is a description of the different costs applied to the HVAC system from the Hospital side:

<table>
<thead>
<tr>
<th>Costs</th>
<th>Description</th>
<th>Price</th>
<th>Variability</th>
</tr>
</thead>
<tbody>
<tr>
<td>Electricity</td>
<td>Air ventilation costs are fixed, as air renewal is constant due to Hospital regulations.</td>
<td>At the time of the project, the Hospital had electricity fixed price per hour.</td>
<td>fixed cost.</td>
</tr>
<tr>
<td>Hot water thermal energy</td>
<td>Thermal energy measured at the output of heat exchanger of the co-generation plant. Energy consumption is not constant.</td>
<td>The cold/hot water prices are fixed and they are modified every 3-months depending of external conditions (as the gas price). Since the test time scope tests is 24h, it is considered a fixed price.</td>
<td>variable cost.</td>
</tr>
<tr>
<td>Cold water thermal Energy</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

8.1.5.5.2 Co-generation plant economic parameters

Thermal energy is supplied to the Hospital with hot and cold water mainly generated by a CHP engine and an Absorption chiller, a high efficiency technology, however, with limited capacity. If the CHP engine is not running or the thermal demand is higher than the CHP engine and the Absorption chiller’s maximum capacity, the thermal energy is provided by auxiliary sources (Electrical chillers for Cold demand, gas boiler for heat demand).

In the following table there is a description of the different costs applied to the hot/cold water generation system from the co-generation side:

<table>
<thead>
<tr>
<th>Cost</th>
<th>Description</th>
<th>Variability</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gas</td>
<td>Gas consumed by CHP engine for electricity production and gas boilers to supply hot water. Besides the normal gas rate there is a daily maximum amount of gas limit which is contracted with the gas supplier, over this limit the power generator must to pay a fee.</td>
<td>All-day fixed, changes each month. Gas limit overtake fixed by contract.</td>
</tr>
</tbody>
</table>
So, at a certain day load, using more gas for the boilers increases substantially the gas price and depending of the electricity market price might make unprofitable the electricity generation from the CHP.

<table>
<thead>
<tr>
<th>Electricity</th>
<th>Electricity is mainly consumed by refrigeration towers and electrical chillers (small electricity consumption, as pumping inside the power plant, lighting etcetera) will not be considered in this study.</th>
<th>Hourly (depending of the electricity market)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Water</td>
<td>Water consumed by refrigeration towers.</td>
<td>Fixed cost</td>
</tr>
</tbody>
</table>

8.1.5.5.3 Hospital de Son Llatzer KPI5 calculation

Hospital de Son Llatzer HVAC system has some fixed costs and variable costs. The fixed costs are considered as Baseline costs such as the electrical cost of maintaining air renovation and the thermal energy cost of maintaining a fixed setpoint temperature for certain areas of the hospital (such as the Intensive Care Unit, Neonatal department, laboratories, etc).

Other HVAC variable costs are related with the comfort conditions of the areas that do not have strict temperature restrictions (for example common areas and waiting rooms).

**Cost reduction (KPI 5) for the Hospital is defined as the HVAC costs variations due to DR events.**

**Basic Hospital costs**

\[
Hospital \ Cost \ = \ HW \ price \cdot HW \ demand[kWht] + CW \ price \cdot CW \ demand[kWht]
\]

Where CW=Cold Water; HW=Hot Water.

**Baseline cost**

\[
Baseline \ Cost = HW \ price \cdot HW \ baseline \ demand + CW \ price \cdot CW \ baseline \ demand
\]

**Variable cost**

\[
Variable \ Cost = Hospital \ Cost - Baseline \ Cost
\]

**KPI 5**

\[
KPI5 = \frac{Yearly \ variable \ cost_{demand \ modification}}{Yearly \ variable \ cost_{normal \ operation}} < 0.85
\]

8.1.5.5.4 Co-generation Plant KPI5 calculation

The HVAC over costs regarding the co-generation plant are related to demands that overflow the maximum capacity of CHP plant. In case of high cold water demand, electrical chillers are activated and in the case of high hot water demand, gas boilers.

If some amount of gas is used by gas boilers, the plant will produce less electricity therefore less income from selling electricity (due to the daily gas limitation). The gas cost is combined with a reduction of plant income due the fact of the maximum gas available per day. That parameter, obtained from the combination of electricity income and gas cost, is called ‘Plant electrical margin’.

An additional cost for HVAC system is the cost associated with the refrigeration towers. This cost includes the electricity cost and the water consumption cost. As the water cost is much lower than the electricity cost, we will consider only the electricity cost in KPI 5 calculation.

In the following equation is for calculating Co-generation plant costs regarding the HVAC demand.

**Co-generation plant HVAC costs**
Plant HVAC Costs

\[
\text{Plant HVAC Costs} = \text{Electric price} \left( \frac{\text{€}}{\text{kWh}} \right) \cdot (\text{Refrigeration Tower Consumption}[\text{kWh}] + \text{Electrical Chiller consumption}[\text{kWh}]) + \text{Gas boilers consumption}[m^3] \cdot (\text{Gas cost} \left( \frac{\text{€}}{m^3} \right) + \text{Plant Electrical Margin} \left( \frac{\text{€}}{m^3} \right))
\]

KPI 5

\[
KPI5 = \frac{\text{Plant HVAC Cost}_{\text{demand modification}}}{\text{Plant HVAC cost}_{\text{normal operation}}} < 0.85
\]

8.1.5.5.5 Baseline

As it is explained the section 8.1.5.5.3, as hospital baseline demand, we define the minimum thermal demand required by the hospital HVAC system. This baseline demand is related with critical areas as operating rooms or laboratories, the set point temperature of those spaces cannot be modified during DR events. The baseline demand represents approximately a 50% of the total HVAC consumption.

Two baseline demands have been defined per each thermal demand, hot water and cold water. The first one is a fixed value for all year and the second one depends on calendar, having different values depending the season of the year.

The fixed baseline is defined as the minimum amount of energy delivered to the HVAC system during the whole year. Regarding calendar baseline, due to local weather conditions, heating system is switched OFF from June to September. Cooling system does not operate for the most areas of the hospital during winter, but it has not a fixed date to be switched OFF, so cold water demand has not an abrupt change in a concrete date.

From hospital measurements it was obtained the Cold water demand ‘fixed’ baseline. Cold water demand ‘calendar’ baseline is 500 kWh in winter, and 1300 kWh in summer, with a soft gradient between those values, as it is shown in Figure 8.9.

On the other hand, hot water demand ‘calendar’ baseline is 100 kWh during the summer period and 1000kWh during the winter season, as it is shown in Figure 8.10. Fixed one has a constant value of 100 kWh.

![Figure 8.9: Cold water demand and its baseline during 2016](image-url)
8.1.5.5.6 Plant Electrical Margin

In winter peak load situations, from the hot water thermal energy generation side, gas boilers are needed. These peak loads reduce the amount of gas available for the CHP plant to produce electricity, therefore, the income of the plant is reduced due to electricity selling. When a DR event avoids starting the gas boilers, the plant profits will include the gas cost reduction (from the gas boilers) and, therefore, an income increase due to the use of this gas for electricity production. However, this income increase will depend on the electricity selling price and the engine availability.

As it can be observed in Figure 8.11, electricity price varies during the day. Power plant production is normally increased when electricity price and profit are at their maximum value.
Figure 8.11: Daily variation of electricity price and related costs

The graph above shows how the electricity price has a strong influence in the power plant profits. As this parameter is not fixed, KPI5 estimation must be calculated for each hour.

8.1.5.5.7 KPI 5 simulation for Hospital side

Hospital Demand (Hot Water and Cold Water) variations has been simulated using the tool developed in MTC03, applying different DR events based on set point modification during certain hours.

In the following table the results for KPI5, from Hospital side, are shown for different metrics and different set-point modification scenarios. Three different KPI5 calculations have been defined, the first one without defining a baseline, the second one using a fixed baseline calculated from the measurements and the third one with a baseline depending on the season.

<table>
<thead>
<tr>
<th>Scenario</th>
<th>KPI 5 results [%] (goal &gt; 15%)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Without Baseline</td>
</tr>
<tr>
<td>1°C Set-point modification All day-All year (+1 set point in summer, -1 set point in winter)</td>
<td>5.71</td>
</tr>
<tr>
<td>2°C Set-point modification All day-All year (+2 set point in summer, -2 set point in winter)</td>
<td>11.3</td>
</tr>
<tr>
<td>1°C Set-point modification between 0-6h</td>
<td>4.60</td>
</tr>
<tr>
<td>2°C Set point modification between 18-23h</td>
<td></td>
</tr>
</tbody>
</table>

In the table it can be observed that a setpoint modification of 1°C can achieve a 11.71%. An aggressive reduction of 2°C can achieve a 23%, although it would be possible to apply, however, it would cause a considerable increase on people discomfort. An intermediate setpoint reduction could reduce a 9.37%, with so much discomfort for the users. User comfort can be evaluated following ASHRAE Standard 55-2017 and always within local regulation. An alternative would be to use OPTi’s virtual knob. However, this is not possible to the specific environment (hospital) due to having a lot of public areas and a highly variable number of visitors each day that stay for small periods of time and also the strict regulations.

8.1.5.5.8 KPI 5 simulation for Plant side

As it is explained in Section 8.1.5.5.4, thermal energy costs from the plant side are related with the use of auxiliary sources. In the following Figure 8.12 and Figure 8.13, the 2016 daily costs for hot water and cold water thermal demand are plotted. The first figure includes the electricity cost from the refrigeration towers, and the second one does not include that cost. Refrigeration towers are used to waste heat to the atmosphere produced by several thermal circuits of the CHP plant, not only the one related with the electrical chillers. Therefore, that cost is slightly related with cold water demand reduction.

As it can be observed in both figures the cost related to cold water auxiliary cost is higher than the one related to hot water auxiliary cost. For a whole year, cold water auxiliary cost is 3 times higher than hot water auxiliary cost. This is due to the amount of demand that is not covered by the CHP engine. Cold water demand normally needs auxiliary sources during more hours than hot water demand.
Figure 8.12: Cold Water auxiliary sources cost, including refrigeration tower

Figure 8.13: Cold Water auxiliary sources cost, not including refrigeration tower

Cost reduction due to DR events

Applying precooling or preheating techniques during peak load demand, when auxiliary sources are needed, the demand is shifted to a ‘non peak load’ areas, when the energy production is high efficient.

As it can be observed in next figure, peak load costs are reduced applying DR Events, but only a 1,1% of cost reduction is achieved as it is defined in KPI 5.
Cost reduction using set point modification

In this last section, it was explained how applying DR events to reduce peak loads was efficient reducing production costs, but not to up to 15%. Another way to reduce power plant costs is to reduce the overall thermal demand by modifying the set point of the HVAC system for long time.

In Figure 8.13 and Figure 8.14, a simulation of the yearly cost of auxiliary sources against a set point temperature variation for the whole year is shown. Figure 8.13 is focused on hot water auxiliary costs which mostly happens in winter, so the set point modification is a value decrease. On contrary, in Figure 8.14, since it happens in summer, it is a temperature set point increase.

As it can be observed in the figures below, to fulfil the requirements of KPI 5 (red line), it is needed to reduce at least 0,2°C in hot water and 0,5°C in cold water. Using ASHRAE Standard 55-2017 in comfort these two measures does not affect significantly the user comfort and they does not come into conflict with Hospital HVAC regulation.

![Figure 8.14: Hot water auxiliary sources cost in different scenarios](image)

![Figure 8.15: Cost reduction achieved with set point variation for hot water auxiliary costs](image)
8.2 INSIGHTS AND RECOMMENDATIONS

After completed research and development efforts with subsequent testing and evaluation, it is important to reflect and provide both insights and recommendations on technologies that are put forward by the OPTi Project. These insights are organized in the areas consumer modelling, demand response, virtualization of real-life DH systems and model-based control and optimization.

8.2.1 Consumer modelling

Detailed modelling of consumers’ energy usage enables the development of how the district heating network can be simulated and tested in a virtualized way, which leads to solutions that “work at once” when deployed in the real-life system. There, the usage of the virtual knob during pilot tests has shown to be a valuable tool when making changes to the indoor climate. Quick response from the users is valuable when optimizing the usage of energy with the aim of not affecting the users comfort. But this also comes with a cost, as more detailed metering with improved time granularity is needed and the data need to be securely with data privacy principles in place aggregated.

Currently, the virtual knob device enables the assessment of user comfort and it quantification, but it requires more in-depth studies how the relationship to the perceived comfort actually is. Here, we only used the temperature as a guiding principle, while it is well known that comfort perception is gender dependent and depending on numerous factors like air flows and humidity. Further research in that direction should be conducted. Nevertheless, the virtual knob represents an easy-to-deploy tool which provides consumer insights into the operational decision making both on house and on system level.

8.2.2 Demand response

In this section some recommendations for future DR pilot tests or DR services are described. These recommendations are based on experience and the data analysis based on OPTi, however, they might be applicable for any similar installation running DR.

The most desirable situation to run DR Events is when the HVAC system of the client is automatically modified (automatic DR). However, this situation is very unlikely, the first reason is because HVAC system automation is difficult to program (even when HVAC system has a full control system, make modifications in it implies...
many problems), and the second reason is because there is a responsibility issue (Can the retailer decide the user’s discomfort?). Letting the user decide about the DR increase the uncertainty of the DR Event (is it going to be applied? How much energy?). To solve this problem, there was defined the following indications in Mallorca trial:

- **Define building sections by temperature sensitivity.** Not all the areas in a building have the same sensitivity to temperature changes (for example, in one side corridors have low sensibility, on the other side, Intensive Care areas in a hospital is very sensitive). In the Mallorca trial different sensitivity areas were defined as green areas (corridors, utility room, warehouse...), yellow areas (office, waiting room...) and red areas (wards, Intensive Care Unit...).

- **Estimate the energy consumption of every section.** To design a DR Event, retailers calculate the energy to save during a DR based on the demand forecasting. Estimating the energy consumption of every section, tailored actions can be designed in every DR Event. These actions will consider the sensitivity of the areas, therefore, the Energy Manager will be inclined to apply DR Events more often.

- **Automate DR actions as much as possible.** Energy Manager involvement decreases in time because they are some other duties that distract them. Some automated actions can be carried out by the retailer in the small sensitivity areas (in Mallorca trial, green areas), therefore, some DR Event results are ensured.

Furthermore, DR Event effectivity is very sensible to demand forecast error. When a forecast tool is designed, the global error is a KPI of the tool achievement. Reducing the global demand forecast error, it does not imply to improve the DR performance, since peak loads (when DR Events are applied) are singular events (the global error is mostly related to the tool performance during most of the time, night hours for example, but not during peak loads). Consequently, when the forecast tool is designed, and its specification defined, a low error during peak load period should be focused.

In the same way, demand forecast tool is crucial for designing and analysing DR Event, so when a DR service or DR tests are developed, this tool might be a bottle neck.

Regarding the power generation, pre-heating (winter) and precooling (summer) (modifying 2ºC the set point in certain areas 2 hours earlier) were the most effective way to reduce auxiliary sources production without affecting the user consumption.

Furthermore, when DR Events are designed for cold water, it is very relevant to avoid auxiliary sources to work below 80% of their capacity and for a short period of time (less than two hours), since it can reduce dramatically their efficiency.

The combination of ADR with different targeting approaches and policies (e.g. towards reducing comfort) prevails over the non-selection-based DR programs (where all consumers voluntarily participate) in terms of the active user participation in the programs and the optimal energy reduction allocation. This was evident in all data sets we used. Nevertheless, real-life large-scale pilots are needed to further justify this.

Regarding the application of any DR program, the volume, type and granularity of available information, e.g. energy consumption, demographic characteristics etc, are important for the planning and the selection of the optimal ADR program, including the targeting approaches and the associated policies we deal with in OPTi. In a nutshell, the more information you have (even simple as demographics) the more changes of designing a successful DR program you have.

According to the results of our work, ADR programs can lead to significant benefits concerning the alleviation of the peak demand. However, it is up to the energy provider to decide whether such an investment (in terms of infrastructure to automate the DR programs) can be justified by the savings stemming from the energy reduction. In such a case a cost benefit analysis is essential to identify the potential tradeoffs. See D5.3 Section 4 on a discussion of technical implementations.

In the cases where altruistic users are also considered, a very small percentage reduction in user’s comfort (5%) can lead to even lower reduction in the total comfort. Moreover, appropriate targeting policies and demand reduction strategies that exploit altruism can be beneficial for the users in terms of social welfare.
losses and for the ADR provider in terms of incentive costs. Preselecting altruists improves the social welfare after ADR, but with higher total incentives, as compared to the other policies considered. However, leveraging of altruists should be performed carefully, as their saddling with high energy reductions although yielding in low total incentives, can yet prove inefficient for the social welfare of the system.

Designing real-life pilot experimentations (e.g. in EC research and innovation projects) with users requires a lot of preparation especially with regards to legal and ethical issues: data privacy, modifying existing contracts with the utility company as well as user training, engagement and incentivization.

8.2.3 Virtualization of a real-life DH system

This section summarizes the experiences gained during the evolution of the OPTi-Sim framework, from the very first ideas to the final successful implementation and validation.

The development of the OPTi-Sim framework was a tough challenge. As every larger development process, it started with first concepts and ideas. The OPTi partners already developed these ideas during a workshop held at the project's kick-off meeting in May 2015. During that particular workshop, the project partners also agreed on a modular setup of the OPTi-Sim framework. Finally, the integration approach via the TWT co-simulation framework was also confirmed back then. In summary, the overall strategy how to design the OPTi-Sim framework was already laid down during the beginning of the project.

As a second step, the partners decided how to describe and model the different components involved in the simulation of a DHC system. Here, the need to distribute the modelling tasks into network components, building elements, as well as control and regulation modules was evident. The more difficult issue was how to model the individual components in such a way as to meet three requirements: i) to achieve realistic, physical behaviour of the overall DHC model system; ii) to incorporate control aspects vital to the DHC engineers; and iii) to facilitate integration of all models via the TWT co-simulation framework. The first point is directly related to KPI-4: the OPTi-Sim framework is to be able to reproduce 95% of real-life events. The results of Chapter 5 and their discussion show that this objective is almost achieved. The second point touches on practical aspects for the intended use of OPTi-Sim by DHC engineers and its support of the latter. The third and last requirement meant to make integration as simple as possible.

A crucial point during the implementation phase and later the integration stage was a step-by-step procedure for testing and validating individual model components and their piecewise combination into the system as a whole. Here, the consortium failed to follow an incremental integration approach and rather focused and having all components ready and then integrating them in one single, but tremendous, step. Side effects of this last decision were an overwhelming overhead for the integration process, sometimes incomprehensible behaviour of the simulated system, and a documentation process that was hard to follow. This part of the development process of OPTi-Sim could have been better prepared, with respect to timing, available manpower, and collaboration resp. communication between the integration partners. To schedule and lay down a thorough integration time line has been recognized to be a crucial, if not the most crucial, part of the whole development process.

The after effects of the problems that arose during the integration phase were clearly appreciable during the validation phase. This led to a somewhat reduced portfolio of validation test cases. Despite these obstacles, as described in Chapter 5, the OPTi team finally validated the OPTi-Sim framework, and that with an impressing 90 per cent accuracy.

In summary, the overall modelling and simulation efforts took off rather quickly and efficiently. The process then decelerated and led to moderate delays as of the reasons mentioned above. The most evident roadblock was the incomplete integration strategy. Eventually, the OPTi-Sim development gained momentum again and finished with considerable results and an almost perfect achievement of KPI-4.
8.2.4 Model-based control and optimization

The methodology for the generation of the models based on generating the piping, reduction, and merging of meta connection is highly interesting even for other modelling problems since it does not depend on the underlying models. This will enable the generation of different types of models like, Static (steady state or step wise) or dynamic (slow time scale or fast time scale). In this respect, the results from the automated model generation is generic and will find its application in a variety of areas, as models are a basic requirement for model-based approaches.

The FMU based simulator for OPTi-Sim provides a good approach to share and execute different models and to integrate different sources of models. The only drawback in this issue is the speed of execution. The current modeling includes one very large model that is simulated as a single unit and cannot be executed in parallel. Even using multicore CPUs will not help to speed up the simulation. Only increasing the CPU clock speed will help to speed up the simulation process. For larger networks, it might be important to decompose the system into sections of the network to speed up the simulation process by assigning each FMU to a core. For the size of the Luleå Network, the execution speed for a simulation was essentially around 3-4 times real-time, which means that longer time scenario that expand beyond a week, will require substantial amount of simulation time to draw conclusions. This might prevent the practical application and use. Nevertheless, the model-based design and validation is enabled.

Another issue is the initialization of the simulation with respect to a historic time point and state of the complete DH system. To correctly reflect the system behaviour, the internal states of the simulator need to reflect the internal states of the DH system at the initial time point. This poses several challenges, as there are usually very few measurements available throughout the network that aid in determining the real internal states. Another challenge is the spatial distribution of the environmental conditions and the consumption of heat. Those aspects are in part not possible to measure or determine by other means, which results in deviations between the real DH system behaviour and the simulated one. The approach taken in OPTi was to perform an initial simulation run to an equilibrium state of the DH system, determined by the operating conditions of the initial time point. The actual run is then started from the equilibrium state. While this requires additional start-up time for the simulation, it makes sure that the simulator is in a state which is closely related to the real initial state.

The generated models that are used for simulation are not always feasible for the design of controllers. Although it was anticipated that low complex model could be approximated from the generated models and more specifically from the simulator, this proved to be challenge. The approximated models were not usable directly and required pre-processing steps that needed to be developed. In the end, it could be shown that the pre-processing could be automated in itself and produced well shaped and structured models for control and optimization purposes. An important insight is therefore, that standard approximation methods should not be assumed to provide correct and useful outcomes. Further development of methods that are context and purpose oriented for the approximation and simplification of complex model is certainly needed and would enable tool chains that are not possible yet.

Control and optimization solution which operate on the low level and optimization-based control layer are usually so-called “invisible” technologies, since negative side effects of insufficient control performance are just not there. Nevertheless, any optimization on the higher level and especially the optimization of operation depends on a solid foundation and well-performing underlying system. We have seen that this can usually not be assumed and that variations and limitations are not fundamental in the system, they are imposed by insufficient solutions on the lower level, namely oscillations are important to be addressed. Monitoring of control performance would certainly aid in detecting the limitations and circumventing them at a relatively small cost, compared to costly hardware updates.

Again, this requires a better understanding of the status-quo through improved and more spatially dense sensing. Adding more sensors in the network would also enable optimization of the operation in a better way. This will create a better understanding about the status of the network and avoiding creating dead zones in the grid. Higher sampling rates will enable the detection of some oscillations in the network and will help plant wide disturbance rejection.
8.2.5 Data Management

The tools and algorithms developed in OPTi rely on processing input data to reach the predefined goal. One type of input data is time series data. The different kinds of analyses but also the variety of different platforms for implementation requires a flexible access to input data. The dedicated data management component, which was presented in D4.1 and D4.4, offers such a flexible access. The server part of the data management component makes the set of all stored time series data available by providing a uniform interface for it. The interface is designed in such a way, that enables flexible implementation of small data access clients that can be included in other platforms or environments. A client, implemented for Matlab, provides direct online access to needed input data for algorithms running in Matlab. Other clients are developed to support data access in programs written in Java—Programming language or for data access using normal command-line programs, which eases integration of input data in bigger systems. Another part of the data management component is the collection of time series data. Sensor systems installed at the pilot sites don’t offer a possibility to store measured data directly in an external database by supporting also integration of other vendor’s sensor systems. The data management component implements a distributed system of data collectors. Each can act independently and gather data from one specific system. Gathering of data includes a specific type of connection to the sensor system but also understanding of possibly vendor specific data formats. One type of connection used the file transfer protocol (FTP) while another made use of email (IMAP) communication. After collection of data the content is transferred to a central database using a data format commonly used in OPTi. There, the data is available for all connected clients.
9 CONCLUSION

The OPTi Project designed and planned numerous tests to validate the developed methodologies and tools in a relevant environment, as anticipated for methods and tools reaching the maturity level TRL-5 and in part TRL-7. For this end an ambitious test plan was put into place, which needed to be adapted due to unforeseen circumstances, to match resources and time available. It is the believe of the project team that the adapted test plan which was carried out provides an overall good indication of the performance developed methodologies and tools, and to what degree the core KPIs are achieved.

Some important challenges and hinders that the project team encountered and managed is worth extra mentioning as lessons learnt for the future. For one, building OPTi-Sim as one integrated tool was much more complex than initially anticipated and the delay here led to that most of the simulation test cases being deferred. While this was identified early and closely tracked during the PMT meetings and the consequences mitigated through meticulous re-planning, more focus on this matter early-on in the project could have aided in finishing this truly joint OPTi-Sim development earlier.

Secondly, an integration and validation plan, approved by all partners, is also crucial as it promotes proper planning and execution of tests, and supports documentation of any necessary changes (which almost always occurs). While focusing on development, such plans are not of the highest priority, but the tracking of those helps in foreseeing the consequences of any delays, especially when there are seasonal limitations for the testing.

Thirdly, DR Event or peak load effectivity is very sensible to demand forecast errors. When a forecast tool is designed, the global error is a KPI of the tool achievement. During the project it was realized, that reducing the global demand forecast error, does not imply to improve the DR or peak load reduction performance, since peak loads (when DR Events are applied) are singular or short-term events (the global error is mostly related to the tool performance during most of the time, night hours for example, but not during peak loads). Consequently, an important advice for the design of a forecast tool, is that low errors during peak load period should be aimed for. Note, such tools usually depend on weather forecasts which are uncertain and the accuracy is directly reflected in the performance of any peak load reduction scheme. Again, the availability of seasonal data is very important in this context. The project extension gave us new important data set to train and validate our models.

Despite these adversities, the test plan was executed as presented in the second version of the test report. Moreover, this report documents the work conducted in the context WP6 for the validation tasks. More specifically, all tests conducted in the planned test cases are presented and evaluated, which form the test results. We also described how these test results were used to assess the KPIs of the OPTi project as originally defined in D2.1. Based on the assessment of the test results the achievement of the KPIs was determined and discussed.

The project team concludes that the targeted KPI values are in most of cases achieved or close to be achieved, always under the explicit environment/context of the OPTi pilots (as OPTi is a rather focussed and short research project for replicating results across various and larger environments). Namely, the targeted energy savings and peak load reduction KPIs show clear qualified values. Others are close to the set thresholds, like the economic benefit, OPTi-Sim validation and the widening of the comfort zone. Noteworthy is also that the functionality of OPTi-Framework concept has been validated as an approach of optimising DHC systems, which is an important stepping stone forward for energy efficient DHC systems.
10 REFERENCES


Selinder P, Walletun H (2011) Modell för värdering av ändrade driftförutsättningar i fjärrvärmenät, Svensk Fjärrvärme. Note: The excel based tool is called LAVA kalkyl and was available through Svensk fjärrvärme. Please contact our partner Luleå Energi for further details.
11 APPENDIX A – ARROWHEAD FRAMEWORK FOR THE OPTi APPROACH

As the OPTi project comes to its conclusion, one reflects on its accomplishment and impact. Was it worth it? The answer is: "Yes, absolutely!" if the recipient grasps what has been achieved. OPTi provides the means to optimizing district heating and cooling based on disparate and distributed factors, which include humans, weather, machines and a large network of heat carrier. It allows one to "have his cake and eat it too". We can indoor comfort with a minimum impact on the environment or use of natural resources. OPTi provides a distributed set of tools that model district heating and cooling and thereby predict the impact of any system operation. For example, a cold front is coming Sunday night and Monday morning has its usual heat demand peak; how should the heat production and distribution be planned? how should the consuming building react?

Yes, the OPTi project delivered something valuable. However, to be usable, it must consider some ideas how to implement it in real life. Although the project budget was limited, this has been addressed by leveraging the results of large European Union projects such as the ECSEL Joint Undertaking Project Arrowhead and Productive 4.0. The potential deployment of OPTi relies on ideas from Cyber Physical Systems and Industrie 4.0.

11.1 CYBER PHYSICAL SYSTEMS AND INDUSTRIE 4.0

The third industrial revolution, also known as the digital revolution, is associated with the use of micro-computers and a move toward mechatronics. The fourth revolution emerged when these mechatronic systems could communicate freely over the Internet to become Cyber Physical Systems (CPS). These systems are at times referred to Internet of Things (IoT) devices or, in industrial contexts, as Industrial IoTs. The latter has requirements such as real time behaviour and long lifecycle management.

When this transformation was understood, there was a need to develop a consistent approach to enable those systems to work together and beyond any border (e.g., interoperability and scalability with security). In Germany, the government had a project called Industrie 4.0 that tried to define that. Another such effort has been the Industrial Internet Consortium (IIC). They each proposed reference architectures, RAMI 4.0 (Reference Architecture Model Industrie 4.0) and IIRA (Industrial Internet Reference Architecture). The purpose of these architectures is some consistency between implementations, and there is efforts into merging them.

Figure 11.1 shows a schematic map of how Industrie 4.0 locates itself with respect to the world of cyber physical systems. District Heating and Cooling (DHC), with OPTi, is at the intersection of Industry, Smart Grid and Home Automation. DHC can make use of the technology developed in the industrial context across its
whole concept. In its funding application, the OPTi project proposed to do that using the Arrowhead Framework as implementation of the CPS reference architectures. The idea is to execute the OPTi optimization in real time across the whole district heating and cooling system.

11.2 Using the Arrowhead Framework

A district heating and cooling structure is a very large and complex system. It is really a complex system of systems. It ranges from its management (including operation, simulation, billing, maintenance planning), to heat production, distribution and consumption. To manage complexity, maintain low latency, and increase security, the Arrowhead Framework introduces the idea of local clouds. A local cloud is then a self-sustained system of systems with enough functionality to support Industrial IoT automation tasks for a limited set of CPSs and applications. So, each production site could be a local cloud, the distribution network be a local cloud of its own, each consuming building be a local cloud and OPTi-Sim a cloud. All local clouds can interact with each other by offering or producing services or information to service consumers from other clouds (via the GateKeeper system if authorized by the Authorization system).

Within the OPTi project, we selected to focus on the simplest local cloud to demonstrate how it works. The simplest local cloud is the heating system of a single-family home with its district heating substation and hydronic radiators. The cyber physical systems in the local cloud are the outdoor temperature sensor, radiator feed temperature sensor, the primary circuit control valve. This is extended with a weather station and a set of battery driven thermostatic valves). More concretely, the temperature sensors and valve control are wireless sensor and actuator developed by EISTEC, the weather station is a Davis Vantage Pro, and the thermostatic radiator valves are from Danfoss using Z-Wave technology. They bind together at runtime and each of them provides and consumes services from each other if and only if authorized to do so for security reasons. To connect to the Internet is a gateway, which also connects the different devices and has enough computer power to host the Arrowhead Framework systems (i.e., software modules).

The open source Arrowhead Framework is a Service Oriented Architecture (SOA) based structure that provides a suite of building blocks or core systems for Cyber Physical System and application-specific services to connect correctly and securely at runtime (Kolluru, et. al., 2018). Its central concept is to support most types of devices and systems in interacting with each other, and to enable the exchange of information, regardless of used protocols and semantic solutions. The framework, as per a SOA paradigm, enables loosely coupled services to communicate in a late binding fashion.

The suite of core system is divided in the mandatory core systems and the support systems. The mandatory core systems are the Service Registry, Orchestration, and Authorization systems. The dynamics are quite straightforward at runtime, service providers register their services with the service registry. Service consumers ask the Orchestration system for a specific services. The Orchestration system provides a service address after consulting the Service Registry and Authorization systems to the requesting consumer. In the single-family home use case, the district heating system or application consumes services from the two temperature sensors and that of the valve (to get or set its position). It can obtain information or services from the weather station. To become Arrowhead compliant, a “wrapper” or “shell” was added to the weather station (which is connected via USB to the gateway). The idea of wrapper is described in the RAMI 4.0 documents where the device themselves are called assets.

11.3 Mitigating peak loads

With weather forecast, human behaviour, production plans, OPTi-Sim can estimate a peak load or heat demand. To mitigate this, the house’s district heating local cloud is requested to raise its building by a degree Celsius before the peak and lower its set-point during the peak before returning to its normal set point. The end users should not feel the changes and to prevention of peak load shifting, OPTi-Sim can request different shifts in set points. The concept was demonstrated using the Z-Wave set up with an oversized heater in a small enclosure. Figure 11.2 shows the temperature exponentially raises and lower around the new set points (outdoor temperature in green, indoor temperature setpoint in orange, indoor temperature in black).
11.4 FROM PRODUCTION TO CONSUMPTION

Cyber Physical Systems enable the direct connection from a valve in a consumer building to be connected to a sensor or a software system at the heat plant. For security reasons, a local cloud’s Authorization system would not allow that (unless the security policies required it). What becomes impressive is the fact that the OPTi Project has developed or leveraged technology that enables district heating and cooling to provide comfort to end users while minimizing waste of energy. It is a win-win concept and implementation that makes District Heating 4.0 a reality when one includes different sources of energy that need to be coordinated at runtime.

11.5 MIGRATION AND ADAPTATION

Offering the means to implement the OPTi solution is a nice concept only it comes with a gradual migration to it. If it proposes a “reap and replace” approach, it is useless. It could work to build up of a new district heating and cooling system for a city, and even that might be questionable. The instantaneous cost would be too high and the inertia too difficult. The deployment of the solution must be progressive where the old and new systems co-exists.

The Arrowhead Framework promotes a gradual evolution with its concepts of loosely coupled systems that bind at runtime along with interoperability and scalability. It is built on Internet standards, which are proven scalable. The OPTi Framework, including OPTi-Sim, can run in their own local cloud. When a heat supplier, heat distributor or consumer becomes Arrowhead Framework compliant, it can begin to interact with the systems of local clouds. For example, an older building installation would continue to operate as it currently does, while an upgraded one could respond to peak load reduction requests. One way to encourage consumers to change would be to increase the price of kWh during the peak load period. This would not be unreasonable since the cost of production or distribution might be higher (e.g., backup plants activated or higher pumping effort).

Technology is evolving quite rapidly. Twenty years ago, cyber physical systems did not exist. Tomorrow’s technology is unclear today. The Arrowhead Framework is built on interoperable software modules rather than a monolithic software system. As new solutions become available (e.g., a new communication protocol), the software modules remain interoperable. The proposed solution therefore adapts to future technologies.
11.6  **CONCLUSIONS**

Cyber Physical Systems are key to deployment of large distributed systems in general, and to the results of OPTi. The coordination and operation of these cyber physical systems, which must include security and privacy, can be done at runtime when making use of the open source Arrowhead Framework.

11.7  **REFERENCES**

12 Appendix B – OPTi-Forecaster

Forecasting of production and demand is essential for efficient operation of DHC systems which exhibit transport phenomena with large inertia. To provide consumers with the proper amount of heat or cold in time, it is important to predict production based on forecasted demand, environmental conditions, and operational aspects.

The OPTi-Forecaster is a tool which was developed to enable predictive control and optimization of operation, and is composed of two tools, one for the prediction of production and another for the identification of demand peaks. Those tools have been jointly developed by Luleå Energi AB and LTU and will be shortly described in the next sections.

12.1 Prediction of Production

During the project the tool OPTi-forecaster for the prediction of production was developed in accordance with the workflow as shown in Figure 12.1. Essentially, a so-called static black-box model for production characteristics was developed using machine learning principles.

![Figure 12.1: Development platform of OPTi-forecast.](image)

The developed blackbox models were then moved to Matlab and complemented with forecasting capabilities for weather and fuel prices. For testing purposes, GUIs were added to enable the easy use and testing of the tool. When the tool was sufficiently evaluated it was implemented as a stand-alone application in Visual basic which is no longer depending on Matlab licenses.

Further development is conducted by LTU and Luleå Energi AB to add additional features. The GUI is displayed in Figure 12.2.

It is important to note that the weather data is collected from the 2 weather institutes, namely SMHI and YR. Current daily fuel prices are used and are possible to change for oil, gas and wood powder in the GUI, while the electricity price is updated daily from the market.
12.1.1 Result of forecasted temperature and production

In this section some results from the forecasted temperature and production are shown.

Figure 12.2: Preview of OPTi-forecast.

Figure 12.3: Forecast with accurate temperature prediction.
During testing and evaluation of the result it has been shown that the tool predicts the production very well when the weather forecasts from the services are correct and predict the weather well, see Figure 12.3. While the outcome deviates much when the temperature of the forecast is incorrect which causes problems for production, as can be observed in Figure 12.4.

### 12.1.2 Moving to production environment - LUKAB

LUKAB is a joint venture between SSAB EMEA AB and Luleå Energi AB, and not a partner in the OPTi Project. The testing and development of the OPTi-forecast tool and promising results has raised the interest of LUKAB, who is now performing tests with the OPTi-forecaster to use it in normal operation. Luleå Energi AB provides the tool and support to this third-party company. This is a great step and shows that the projects results are of the kind of quality that industry requires.

### 12.2 Identifying peaks in production

A tool that identifies peaks in the production process has been developed. In the tool there is a possibility to perform a preliminary simulation how peak load reduction at the consumer side would affect the production, which can thereafter be validated in OPTi-Sim.

First, we need to calculate the supposed production (black box) to know the total power needed for the demand forecasted demand. By considering the power limit of base production and limit of every auxiliary boiler we identify if we have a peak load scenario, or not.

The different consumers that are used now are the main consumer types, as follows:

- FV11 manufacturer
- FV 12 single and two familiar houses
- FV13 apartment building
- FV14 ground heat
- FV15 public administration
- FV16 other trade and service

In the next step a tuning of the temperature at the consumer side is performed, which can be the result of the ADR schemes developed in OPTi. Moreover, the signaling and actuation principles described in chapter 11, could be used to interact with the consumer directly. Alternatively, the market products like e.g. the system provided by NODA AB, could also be used. The adjustment of the indoor temperature then leads to a change in demand, and leads to a changed production level.

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**Figure 12.4: Forecast with large deviations on the outcomes.**
Below is an example that shows the identified peak and the treatment of the peak before and after peak load reduction.

![Image of tool for identifying peaks.](image)

**Figure 12.5: Tool for identifying peaks.**

In the tool the outdoor temperature is shown and the peaks that occur in production. By changing the demand at the consumer side, we can see how the production is lowered. In this specific case the production is lowered by 1.3 MW in average during peak load reduction.
13 Appendix C – Snapshots of CBA Tool Used for KPI5

The following snapshots present the results and KPIs of the complex financial calculations that were used for obtaining the final CBA figures presented in Section 8.1.5.3.2. Due to confidentiality reasons these figures are omitted in this version.