HEATSTORE

Deliverable D3.6

Incorporation of a new generation smart energy management algorithm (HeatMatcher) in CHESS

Prepared by: Ewoud Werkman (ed), TNO
Martijn Clarijs, TNO
Ryvo Octaviano, TNO

Checked by: Koen Allaerts, VITO
Martijn Clarijs, TNO

Approved by: Holger Cremer, HEATSTORE coordinator

Please cite this report as: Werkman,E & Clarijs,M & Octaviano, R., 2019: Incorporation of a new generation smart energy management algorithm (HeatMatcher) in CHESS, GEOTHERMICA – ERA NET Cofund Geothermal. 23 pp.

This report represents HEATSTORE project deliverable number D3.6

HEATSTORE (170153-4401) is one of nine projects under the GEOTHERMICA – ERA NET Cofund aimed at accelerating the uptake of geothermal energy by 1) advancing and integrating different types of underground thermal energy storage (UTES) in the energy system, 2) providing a means to maximise geothermal heat production and optimise the business case of geothermal heat production doublets, 3) addressing technical, economic, environmental, regulatory and policy aspects that are necessary to support efficient and cost-effective deployment of UTES technologies in Europe.

This project has been subsidized through the ERANET cofund GEOTHERMICA (Project n. 731117), from the European Commission, RVO (the Netherlands), DETEC (Switzerland), FZJ-PtJ (Germany), ADEME (France), EUDP (Denmark), Rannis (Iceland), VEA (Belgium), FRCT (Portugal), and MINECO (Spain).

About HEATSTORE

High Temperature Underground Thermal Energy Storage

The heating and cooling sector is vitally important for the transition to a low-carbon and sustainable energy system. Heating and cooling is responsible for half of all consumed final energy in Europe. The vast majority – 85% - of the demand is fulfilled by fossil fuels, most notably natural gas. Low carbon heat sources (e.g. geothermal, biomass, solar and waste-heat) need to be deployed and heat storage plays a pivotal role in this development. Storage provides the flexibility to manage the variations in supply and demand of heat at different scales, but especially the seasonal dips and peaks in heat demand. Underground Thermal Energy Storage (UTES) technologies need to be further developed and need to become an integral component in the future energy system infrastructure to meet variations in both the availability and demand of energy.

The main objectives of the HEATSTORE project are to lower the cost, reduce risks, improve the performance of high temperature (~25°C to ~90°C) underground thermal energy storage (HT-UTES) technologies and to optimize heat network demand side management (DSM). This is primarily achieved by 6 new demonstration pilots and 8 case studies of existing systems with distinct configurations of heat sources, heat storage and heat utilization. This will advance the commercial viability of HT-UTES technologies and, through an optimized balance between supply, transport, storage and demand, enable that geothermal energy production can reach its maximum deployment potential in the European energy transition.

Furthermore, HEATSTORE also learns from existing UTES facilities and geothermal pilot sites from which the design, operating and monitoring information will be made available to the project by consortium partners.

HEATSTORE is one of nine projects under the GEOTHERMICA – ERA NET Cofund and has the objective of accelerating the uptake of geothermal energy by 1) advancing and integrating different types of underground thermal energy storage (UTES) in the energy system, 2) providing a means to maximize geothermal heat production and optimize the business case of geothermal heat production doublets, 3) addressing technical, economic, environmental, regulatory and policy aspects that are necessary to support efficient and cost-effective deployment of UTES technologies in Europe. The three-year project will stimulate a fast-track market uptake in Europe, promoting development from demonstration phase to commercial deployment within 2 to 5 years, and provide an outlook for utilization potential towards 2030 and 2050.

The 23 contributing partners from 9 countries in HEATSTORE have complementary expertise and roles. The consortium is composed of a mix of scientific research institutes and private companies. The industrial participation is considered a very strong and relevant advantage which is instrumental for success. The combination of leading European research institutes together with small, medium and large industrial enterprises, will ensure that the tested technologies can be brought to market and valorised by the relevant stakeholders.

Document Change Record

This section shows the historical versions, with a short description of the updates.

Version	Short description of change
2019.11.15	First version
2019.12.4	Review VITO & TNO
2019.12.11	Integrate comments. Final version

Table of Content

1 Introduction

Heat networks play an important role in the acceleration towards a sustainable heat supply for the build environment and industry. While the end user demands an affordable and reliable heat supply, the supplier requires a technically and economically feasible system. For the past years several technologies have been introduced that make integration of previously unfeasible sustainable sources, such as data centre heat and aqua thermal energy, in heat networks possible. Furthermore, thermal storage systems allow heat systems to be more flexible and robust, for example by using seasonal storage and peak shaving.

1.1 Challenges in future heat networks

From an economic perspective these trends reduce the cost of a sustainable heat system, with a lesser dependency on fossil fuels. Unfortunately, technically these heat systems become more complex. For example, a flexible gas-fired boiler is easier to operate than a geothermal source, as ramp-up and -down times are significantly different. Adding multiple sources to the same heat system requires coordination over these sources, e.g. when to dispatch a source based on its marginal costs.

To address these technical challenges, simulation of such heat systems gives insight in these constraints and their effect on the business case. These insights help decision makers to choose the most cost-effective heat system solution. But the output of the simulation is as good as its controller. When e.g. sources are inefficiently dispatched, the complete system will never yield its energy efficiency and cost numbers calculated for its design. Therefore, simulations not only give insight in cost information such as CAPEX and OPEX, but also in the effectiveness of its controller.

1.2 Integration of smart control and simulation

This deliverable describes the integration effort of a smart controller (HeatMatcher) with a dynamic heat network simulator (CHESS) in the context of a use case with seasonal storage:

- Adaptations of the HeatMatcher smart controller to heat networks.
  This effort is described in Chapter 3.
- Integration of a subsurface model of an ATES into the heat network simulator CHESS.
  Since subsurface model calculations are time consuming, integrating an ATES in a heat network simulator requires a simplification of the subsurface model to be useful in dynamic simulations. This work is described in Chapter 4.
- Integration of the HeatMatcher smart controller with the CHESS simulator.
  Both HeatMatcher and CHESS are different software products and a bridge is required to connect these two together. This effort is described in Chapter 4.

Chapter 6 will describe some future work and summarize the findings.

2 Dynamic simulations and smart control

A dynamic (time-dependent) simulation exists of roughly two components:

- The simulation of the heat system itself, such as the sources and demands and their effect on the flows, temperatures and pressures in the pipes of the heat system
- The control of the heat system, such as the dispatch of sources and actuation of pumps and valves.

2.1 Dynamic simulations with CHESS

The goal of CHESS (Controlled Hybrid Energy Systems Simulator) is to allow the user to design energy systems, by connecting components in *any* way he or she sees fit, using a drag&drop interface. Control algorithms can be easily selected to operate the various components, providing a range of conventional and modern (smart) controllers. Scenarios are conveniently created by defining external conditions like weather and commodity prices. With the system created and the boundary conditions set, a dynamic simulation of the system can be started, calculating all energy flows, temperatures, fuel consumptions, losses, efficiencies and – if defined – KPI's at a component or system level, throughout time. The system in operation is visualized in animation, leading to insight into the dynamics at hand. Operationally relevant parameters can be logged over the simulated time period. This way, various system designs can be quickly and objectively compared. CHESS combines the following solvers to enable full system simulation:

- a hydraulic solver
- a thermal solver
- simulation of device dynamics

2.2 Smart control

HeatMatcher is an innovative controller for heat networks [1, 2]. The initial focus of the HeatMatcher controller was controlling heat networks in buildings and apartment complexes. Several field trials have shown that in heat systems that are equipped with gas boilers, heat pumps and thermal storage tanks HeatMatcher outperforms standard rule-based control systems by 20%, i.e. it is better in dispatching sustainable sources and smarter in utilizing the thermal storage systems in those buildings. This results in 20% reduction in gas consumption and 12% reduction in energy costs [3].

HeatMatcher is an agent-based controller. This means that each heat producing component (sources) and consuming component (demands) is represented by an agent in the controller. This agent is responsible for the control of the component and exchanges information with the controller to optimize its dispatch. HeatMatcher's control algorithm is market-based. A market is a virtual trading place where energy is exchanged. The agents act on this market and express their demand and/or supply in terms of a bid. This bid defines information at which price a certain energy volume is consumed or produced. When all bids are received, HeatMatcher calculates for each market the optimal dispatch such that consumption and production are equal. The agents are subsequently required to implement this dispatch.

Since HeatMatcher is aimed for use in buildings, several aspects were not taken into account in the algorithm which are, however, relevant for heat networks. These aspects are:

1. Distances between sources and demands are significantly larger. This means that the time between dispatch and consumption, delays and thermal inertia become relevant when flexible temperature regimes are used.
2. Thermal losses in pipes cannot be neglected and should be taken into account.
3. Capacity constraints of the pipes

This means that sources nearby should take preference over sources further away when their marginal costs are equal. The topology of the network is the originator of these aspects, i.e. when the topology changes these aspects also change. Therefore, the HeatMatcher algorithm should take the topology of the network into account when optimizing the dispatch in heat networks.

2.3 Use case

The ATES being built by ECW in the Netherlands is used as use case to develop and test the integration with HeatMatcher and CHESS. The production for that network currently exists of a 43 MW (3 doublets) geothermal well, and two additional biomass plants of 18MW each are under construction. Additionally, the ATES is in development. The network is feeding multiple greenhouses.

The future network is depicted below:

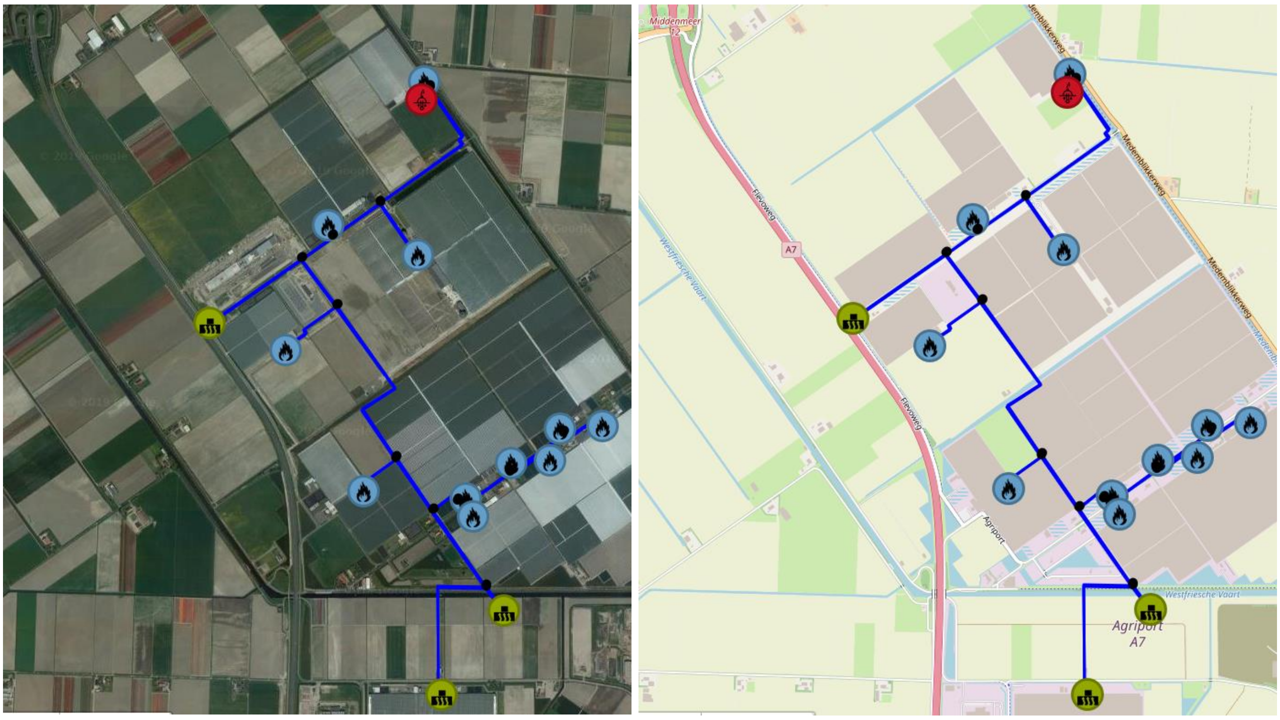

Figure 1: The ECW heat network on satellite image (left) and topographic image (right), including future developments. Red icon is storage (ATES), green icons are production (Geothermal well on the bottom, others are the planned Biomass installations) and blue is demand (greenhouses, currently modelled as 11 distinct demands).

Each greenhouse's heat supply is composed of the heat supplied by the above network and local installed heat supply. This local supply is generated by CHPs and local storage tanks. As a CHP can generate heat, power and CO2, the actual demand from the network depends on the requirements of the crop (e.g. is lighting necessary, or more CO2 required).
In terms of merit order, geothermal is dispatched first, then the biomass plants and then additional CHPs at the discretion of the greenhouses.

3 HeatMatcher control for Heat Networks

3.1 Locational Marginal Pricing

In order to support controlling heat networks by HeatMatcher, the algorithm needs to be adapted to support the characteristics of those networks. The HeatMatcher algorithm is based on a principle called Locational Marginal Pricing (LMP) but was only in part implemented for controlling heat systems in buildings. Topology information, such as length of pipes, was not necessary when operating a heat network in buildings and was left out. This is different for heat networks.

LMP is widely used to perform congestion management in the interaction between *electricity* wholesale markets and *electrical* transmission networks [4]. Locational marginal pricing reflects the value of the energy at the specific location and time it is delivered:

- When the lowest-priced electricity can reach all locations, prices are the same across the entire grid.
- When there is congestion (heavy use of the transmission system) the lowest-priced energy cannot flow freely to some locations. In that case, more expensive electricity is ordered to meet that demand. As a result, the locational marginal prices are higher in those locations. [5]

As location information is relevant in full LMP, HeatMatcher needs to be extended with topology information, such that it can take e.g. pipe length in to account. When pipe lengths are available, bids can be updated to reflect the location information of a supplier or consumer. This information can also be used to calculate network losses and transportation costs. This will improve the accuracy of the algorithm.
Delays are also relevant, but will be addressed in a later study.

The adaptations required for HeatMatcher are geared towards fully implementing LMP for *heat* networks.

3.1.1 Bids

As said, in HeatMatcher agents exchange bids. A typical bid is depicted in Figure 2.

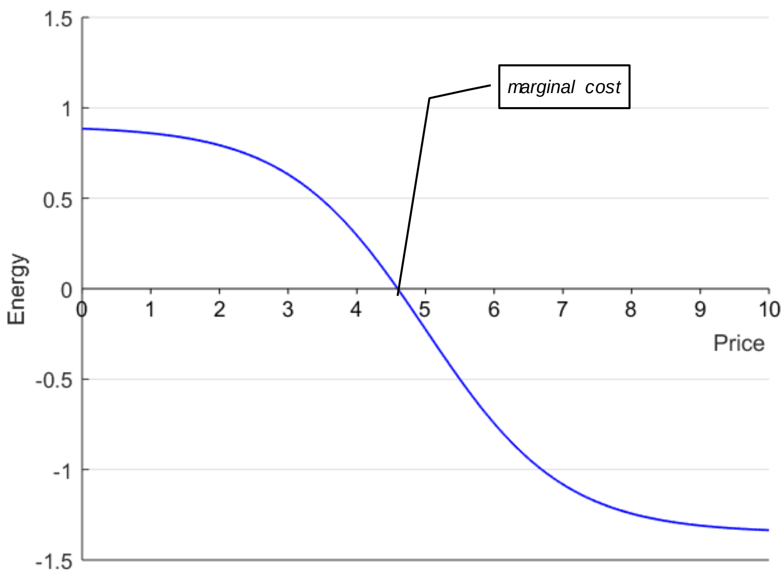

Figure 2: A bid from an agent in which it defines its willingness to consume or produce. The marginal cost defines the price at which it is profitable to produce or consume.

Each bid has specific properties:

- A bid is a “Rational” representation of energy flexibility agnostic of topology
- Production is defined as negative consumption.
- It defines a mathematical function of energy that is monotonically decreasing
- Marginal cost = Price beyond which:
  - Consumption becomes unprofitable and/or
  - Production becomes profitable
- The price is used as a steering signal towards the agent, i.e. based on the price an agent can check its own bid to see what amount of energy it should consume or produce.

The bid in Figure 2 show an agent that can both produce and consume (prosumer), such as a thermal storage. If an agent can only produce, the bid will start at its marginal costs with zero energy and then decrease to its maximum production capacity (as production is negative). This makes the production cost depending on the thermal output of the producer. Consuming agents that require energy whatever the price will produce a flat (horizontal) bid, indicating that there is no flexibility and to make sure they get what they require.

Figure 3 shows an example of an algorithm run. It shows how one producer and two consumers send a bid (in blue) to the root node of the network. At the root node the equilibrium price is calculated and subsequently send back to the two consumers. Based on the bid they supplied, each consumer can find out what the requested energy is they can consume. This also holds for the producer.

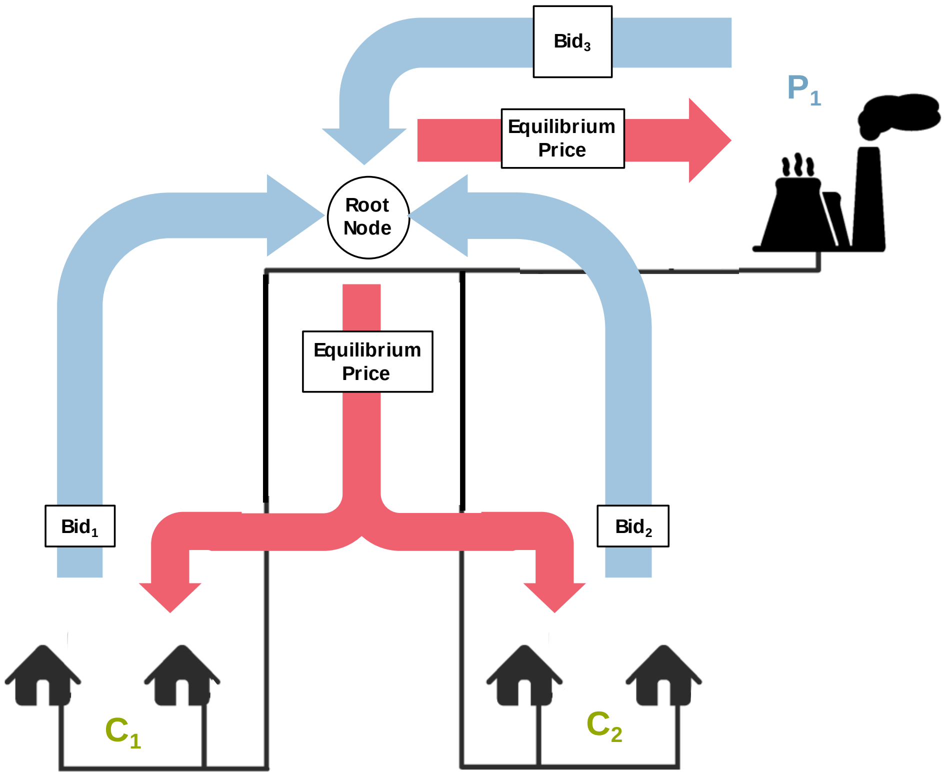

Figure 3: Example of algorithm with one producer and two consumers. First, bids are send to the root node (blue). There, the equilibrium price is calculated and send back to the consumers and producer (red).

The figure shows the current state of the algorithm, i.e. there is only one price (the equilibrium price) and distances between P1 and C1 and P1 and C2 are irrelevant. Furthermore, the line capacities (the black lines) are assumed infinite, something that is not possible in reality.

3.1.2 Line Capacity constraints

When multiple demands share a single transportation pipe in a heat network, the maximum amount both can demand is limited by the capacity of that transportation pipe. This means that bids higher than allowed according to the capacity of the pipe should be capped to the maximum capacity. In other words, bids need to be transformed to a bid that matches the constraints of the network. This procedure is depicted as follows:

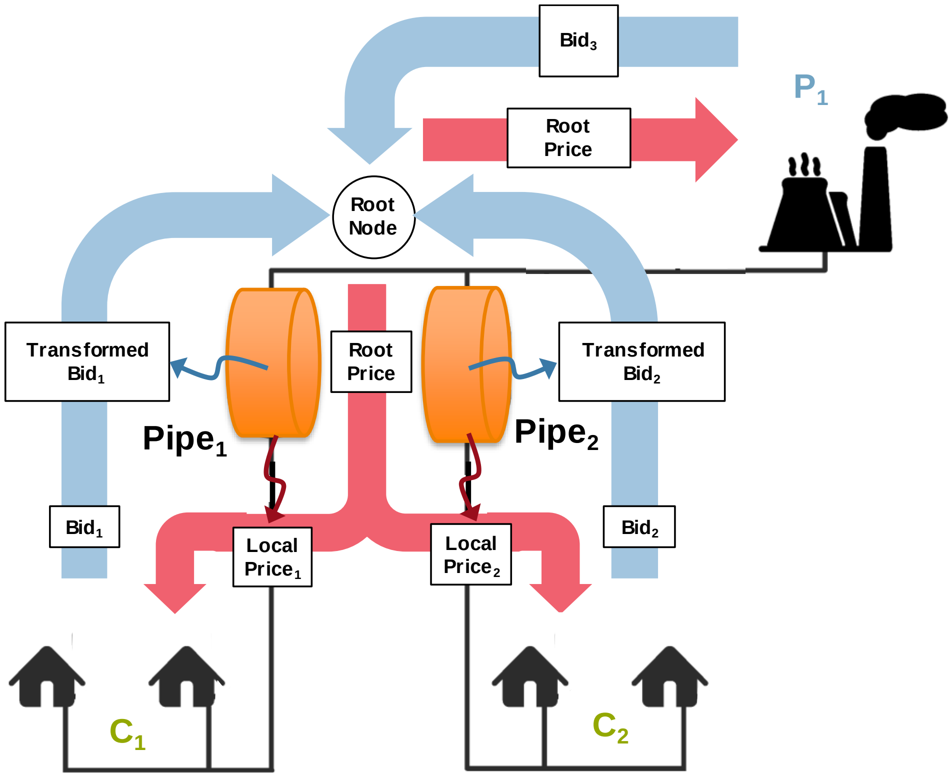

Figure 4: Transforming bids such that they match the network constraints. This renders locational prices in the network.

If for example Bid_2 of C_2 is above the line capacity of $Pipe_2$, the bid will be capped at that maximum line capacity, before it will be sent to the Root Node.
This transformation of bids is based on the recent work done in [6] for electricity networks. The transformation applied is depicted in Figure 5.

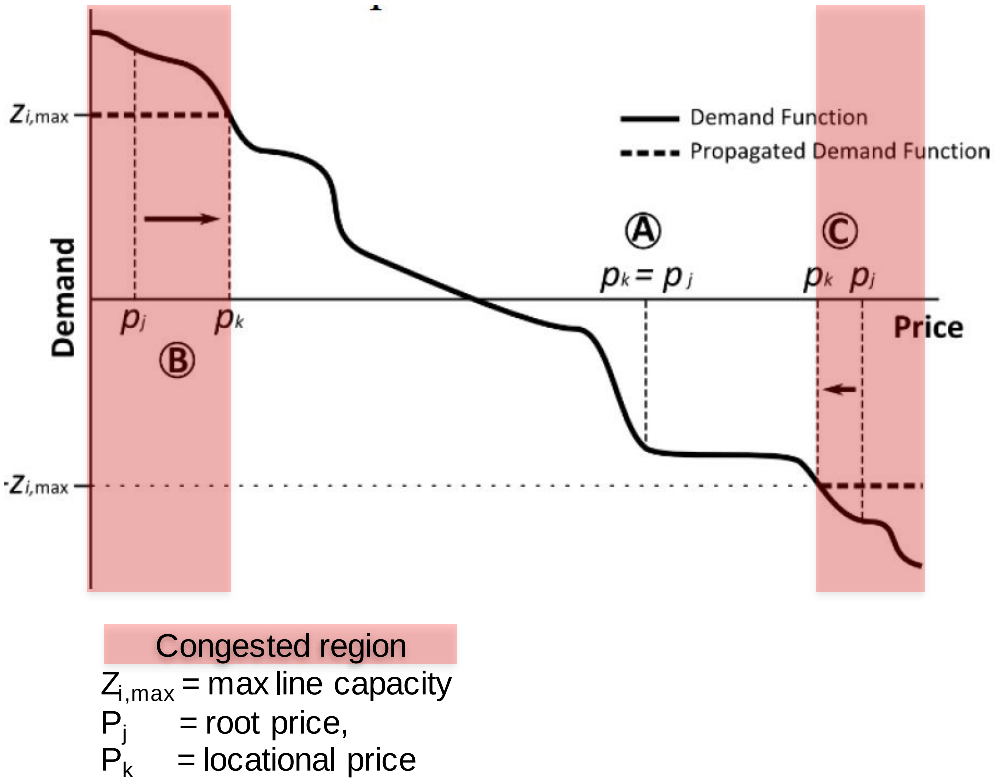

Figure 5: Bid transformation for applying capacity constraints, adapted from [6]. In situation A, there is no issue regarding congestion, as the price is not in the congested area. In Situation B and C, the root price (P_j) is in the congested area and therefore the root price is transformed to a locational price (P_k) such that it matches the maximum line capacity ($Z_{i,max}$), but not more.

The principle of bid transformation in Figure 4 is generic and can be applied for losses and transportation costs, too, only the transformation is different.

3.1.3 Losses

When energy is transported through a pipe, energy is lost by dissipating to the environment of the pipe (e.g. the ground). Longer pipes result in more losses and are therefore relevant when controlling a heat network. If a demand can be supplied by two producers where one producer is close to that demand, while the other is several kilometres away, it is preferable to dispatch the closest producer to reduce the losses in the system. Additionally, the producer should compensate for the losses by producing a bit more, such that the amount of heat demanded is met.

To compensate for losses in a pipe from a consumer perspective, the bid should be transformed such that the amount of losses in the pipes from the consumer to the root node are added to the demand of the consumer itself. From a producer perspective the bid should be transformed such that the amount of losses in the pipes from the producer to the root node are subtracted from the amount that the producer can produce. This is depicted in Figure 6.

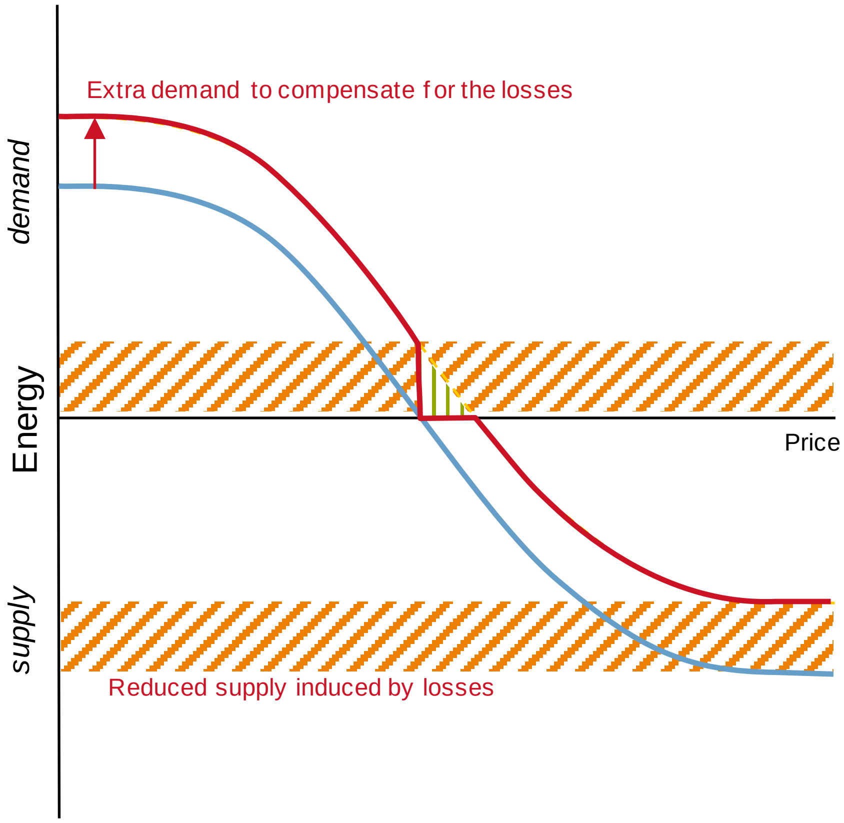

Figure 6: Bid transformation for coping with losses. The initial bid is coloured blue, while the transformed bid is depicted in red. The orange shaded area depicts the losses for the demand and supply. The green shaded area shows an unfeasible region where the losses are more than the demand.

The figure shows how the original bid is transformed into a bid that if feasible when losses are at play. The bid shifts up by the amount of losses in the pipe to compensate for the losses, while still getting the requested demand. Two shaded areas are identified that show infeasible solutions. The top one shows an infeasible area where demand is lower than the losses. Therefore, the bid is adapted such that the bid turns to zero in that area. This also means that the marginal cost of the bid is affected, such that e.g. production with higher losses during transport are less preferable than production with lower losses.
The bottom shaded area handles the losses for supply. The amount of supply is reduced by the losses. If e.g. 10MW is supplied and losses are 1 MW, only 9 MW is usable for demands.
At the root node, the transformed bids (with less supply and increased demand to compensate for the losses) are used to calculate the equilibrium price. After calculating the equilibrium at the root node, the root price is send back to the nodes, where the nodes use their *original* bid to determine the allocated dispatch based on the root price.

3.1.4 Transportation costs

Incorporating transportation costs affects the bid by moving it to the right. This is depicted in Figure 7.

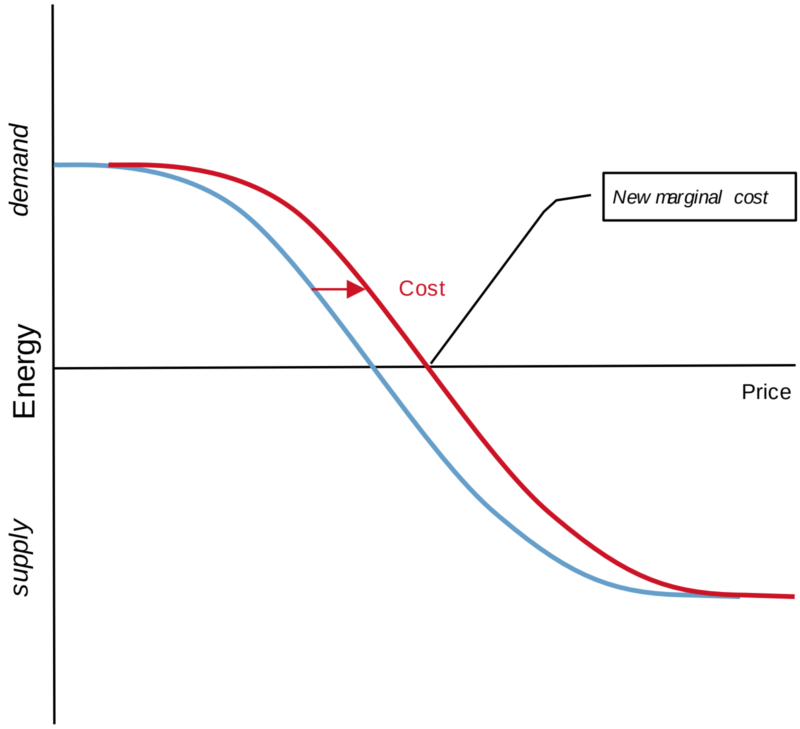

Figure 7: Adding transportation costs is done by shifting the bid to the right by the amount of costs.

By shifting the bid to the right, the marginal cost increases. This means that producers that are further away, have higher marginal costs and are dispatched later than producers closer by. The transformations necessary are similar to dealing with losses.

3.1.5 Delays

Mitigating delays when controlling heat networks will become relevant in the future when temperature regimes become less fixed or consumption becomes more flexible. For the ECW case the temperature regime is 85-35, or 85 °C supply and 35 °C return temperature. As long as the supply temperature stays fixed, and the demand does not change significant every hour, the impact of delays is currently negligible for the HeatMatcher controller. Adding support for delays is nevertheless useful, to improve performance in future flexible demand conditions. Next steps for HeatMatcher is the integration with a Model Predictive Controller (MPC), one that is able to predict the next step and is therefore capable of dealing with delays.

4 ATES simulation in CHESS

Aquifer Thermal Energy Storage (ATES) plays an important role in the integrated heat network by storing the excess heat from geothermal source during low demand season (summer time) and producing the heat during peak load (winter time). The physical model of ATES for ECW case has been developed in the numerical software DoubletCalc3D or Eclipse, however this model is computational expensive and requires several hours to calculate the simulation results which is not really convenient to be used for integrated heat network analysis. Thus, a proxy (fast) model was developed in CHESS and calibrated to the result of numerical model.

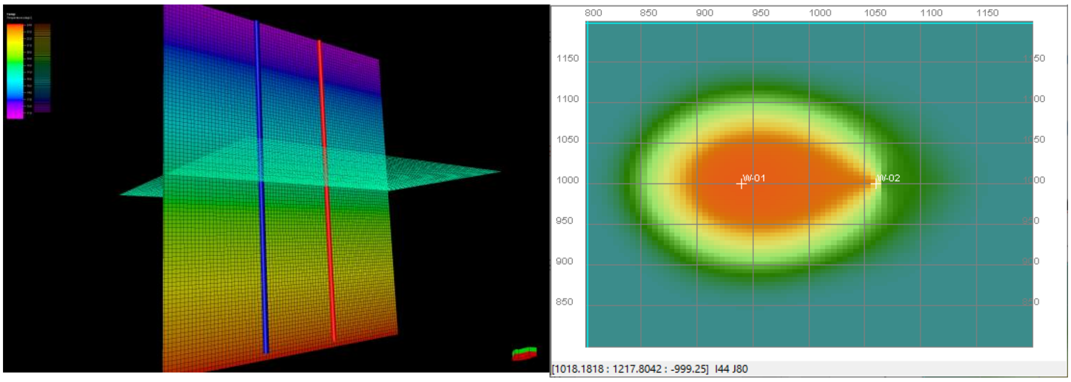

Figure 8: Numerical model of ATES in ECW case.

4.1 Model derivation and implementation in CHESS

Simplified analytical model to predict storage well temperatures are made based on mixing of injected and in situ water and dispersion of heat in subsurface. Two similar models are developed for warm well and cold well.

The model uses F_{mix} from Ward et al. (2009) and F_{temp} to replace the volume left behind in each cycle injection and production.

$$T_{\text{production,warm}} = T_{\text{startcycle,warm}} F_{\text{mix,warm}} + T_{\text{soil}}(1 - F_{\text{mix,warm}})$$
$$T_{\text{production,cold}} = T_{\text{startcycle,cold}} F_{\text{mix,cold}} + T_{\text{injection}}(1 - F_{\text{mix,cold}})$$

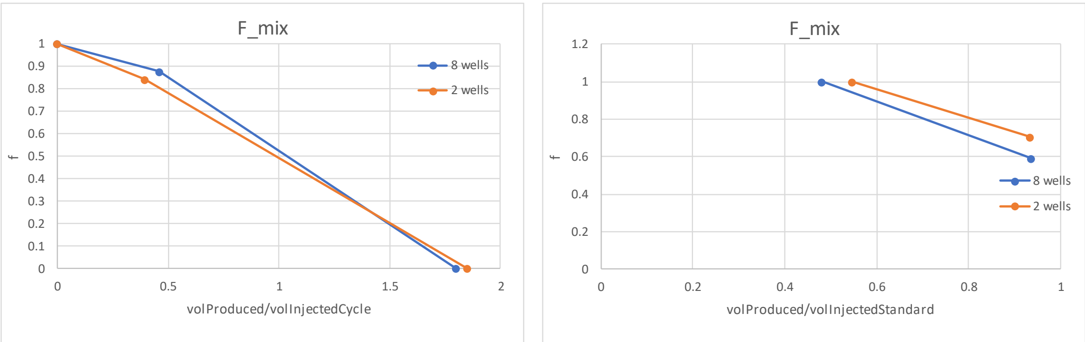

Figure 9: Mixing function of storage volume ratio for warm well and cold well

Where,

$$T_{\text{startcycle,warm}} = T_{\text{soil}} + F_{\text{temp,warm}}(T_{\text{injection,warm}} - T_{\text{soil}})$$
$$T_{\text{startcycle,cold}} = T_{\text{soil}} + F_{\text{temp,cold}}(T_{\text{injection,cold}} - T_{\text{soil}})$$

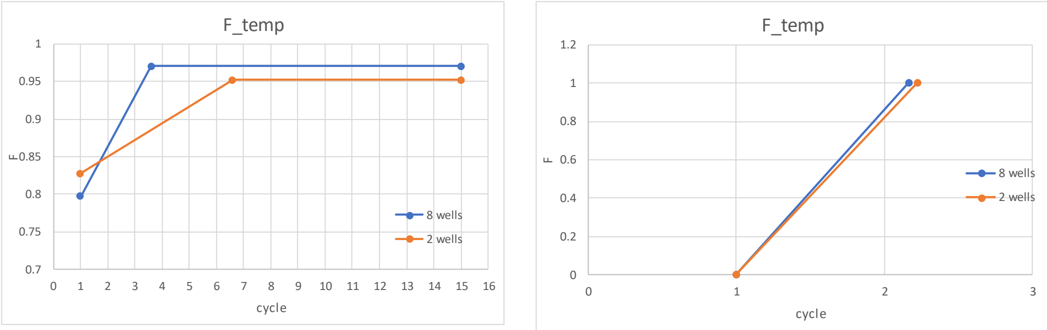

Figure 10: Initial temperature function of each cycle for warm well and cold well.

For each cycle, the ratio of produced volume and injected volume is calculated in order to get the F_{mix} value and the F_{temp} value and based on that calculate the initial temperature of the storage. This model was implemented in CHESS.

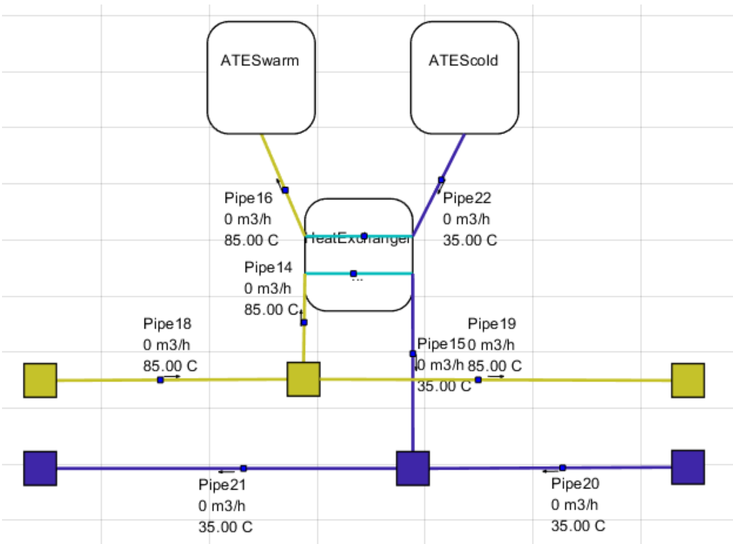

Figure 11: ATES model in CHESS and its connection to the heat network.

4.2 Comparison result

In order to validate the proxy model in CHESS, we compare the simulation result to the numerical model result. The ECW ATES model dimensions are 400m x 400m x 480m with a spacing of 120m between warm and cold well. The numerical model and CHESS model are simulated for 10 years using assumption constant flow rate[1] of 100 m³/h (during injection and production) and supply temperature 83 ⁰C with the following scenario: 3 months injection, 3 months rest, 3 months production and 3 months rest for each cycle. The production well has a cut-off temperature of 55 ºC. The ATES will stop producing when the cut-off temperature has been reached. It means that the ATES can only deliver shorter than 3 months during the first years.

[1] The maximum flow rate of the real ATES at ECW is not known as the well not in operation yet; current estimates range from 50 to 150 m³/h. For these values a sensitivity analysis was conducted to validate the CHESS model.

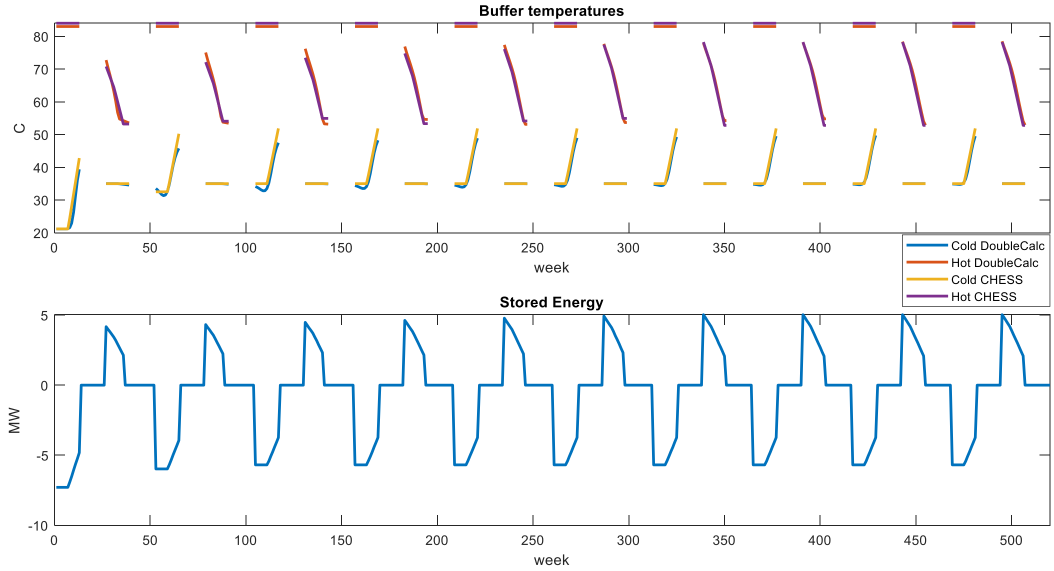

Figure 12: Simulation result comparison between numerical model and CHESS model.

The proxy model has good accuracy with mean mismatch of 0.2°C with standard deviation of 0.9°C for the warm well and a mean mismatch of 0.4 °C with standard deviation of 0.8°C for the cold well. Regarding the cumulative energy produced during winter time for 10 years, the total energy of numerical model is 57.15 GWh and the CHESS model is 57.56 GWh (relative error 0.72%)

5 Integration of controller and simulation

5.1 Controlling real heat systems

One of the design principles of the HeatMatcher software is separation of concerns [7] with regard to control systems. Whether it is a simulation or an actual heat system, the controller should be agnostic of the type of system it is controlling. This approach makes sure that the effort needed to switch from a simulation to a real heat network is small. Furthermore, the hardware of each heat system is different, e.g. different vendors use different communication protocols for their pumps, valves, and other hardware. If the agents would control the hardware directly, each new deployment of HeatMatcher would need adaptation of agents. By separating the agent logic from the hardware and the hardware protocols, only the hardware protocols need to be adapted when using different hardware. In HeatMatcher, the control logic in the agents is separated from the protocols by means of EFI [8].

EFI stands for Energy Flexibility Interface and based on experience from many field trials with HeatMatcher and PowerMatcher. EFI separates control logic (agents) from generic hardware (e.g. a greenhouse) and their protocol (protocol driver). This means that if a piece of hardware is replaced which uses a newer protocol only the protocol driver needs to be rewritten.
EFI is currently being standardized in CEN/CENELEC TC205 workgroup 18, with the goal to make demand-response systems easier deployable throughout Europe.

Figure 13 depict the whole integration architecture and shows that EFI (in blue) is located between the Agents (in white boxes at the top) and Resource Managers (white bottom). The Resource managers connect to the green MATLAB protocol driver, which knows the exact protocol to talk to MATLAB.

5.2 Integration architecture

The architecture is depicted in Figure 13.

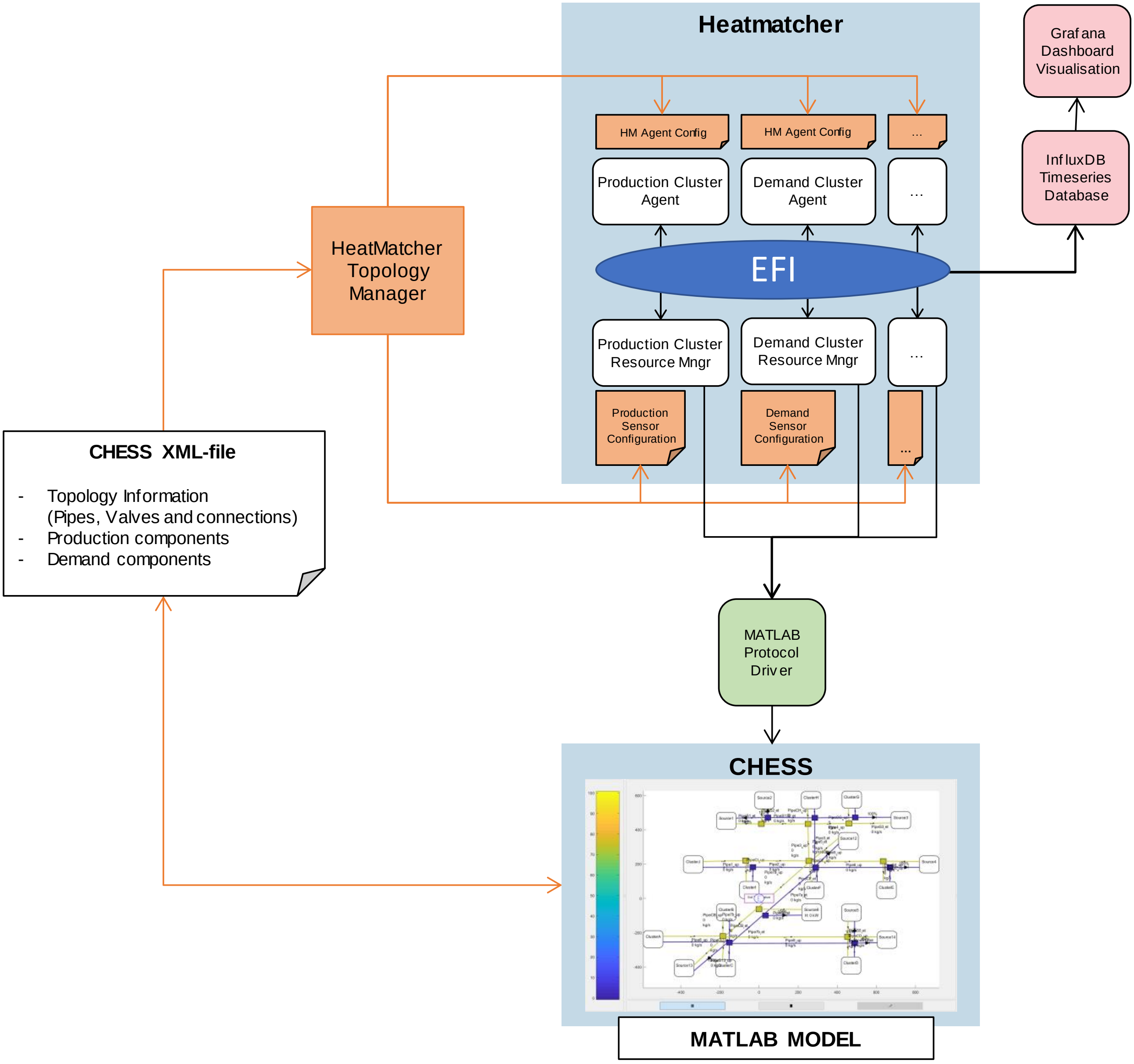

Figure 13: HeatMatcher - CHESS integration architecture. Configuration information / topology information is in orange. The HeatMatcher – CHESS interface is depicted in green. Black lines show the control flow from agents, via EFI to the Resource Managers and finally the MATLAB protocol driver to control the simulation in MATLAB.

5.3 Topology information

HeatMatcher for Buildings, the starting point, did not contain any knowledge about topology information. The first step in the integration of HeatMatcher with the CHESS simulator was to extract topology information from the simulator configuration. Because CHESS stores its topology information and device configuration in an XML-file, this file could be read to gain access to this information.
A new component, the HeatMatcher Topology Manager was introduced to convert the CHESS XML-file to:

- Configure the agents and their place in the topology
- Configure the resource managers

Figure 13 shows all configuration steps in orange. After the HeatMatcher Topology Manager has processed the topology information, it can generate a HeatMatcher controller based on this information. It does that by extracting the configuration information needed to configure the agents (e.g. the Production Cluster Agent in the figure). Example information are the CAPEX and OPEX of a production plant to calculate its marginal costs. Subsequently the Resource Managers are configured for the specific hardware that is used. For example, the names of the sensor values used to read out temperatures from CHESS. When all components are configured, HeatMatcher is ready to control the simulation.

5.4 HeatMatcher – CHESS interface

The CHESS simulator is developed in Matlab, while HeatMatcher is developed with the Java programming language. To bridge these two systems a protocol driver needs to be in place that translates the control commands from HeatMatcher's Resource Managers to actuation settings in CHESS and vice versa sensor readings from CHESS to e.g. temperature settings in HeatMatcher.

The developed protocol driver is based on earlier work together with MatlabControl [9], an open source software library that allows Java programs to access Matlab. The actual interface (the messages exchanged) is based on a Matlab struct in the Matlab workspace that defines for each device which variables are available as sensors and which as actuators. In every simulation step, the actuation values are first read, the simulation is run and afterwards the sensor variables are set based on the values from the simulation. By means of the Matlab Protocol Driver the Resource Managers are able to request and these variables in the Matlab workspace.

5.5 Integration results

This section presents the initial simulation results when using the HeatMatcher controller together with the CHESS simulator. The graphs are taken from the data generated by a running HeatMatcher controller and stored in a timeseries database and subsequently visualized by Grafana, an open source tool to visualize timeseries data. See the integration architecture in Figure 13 for how this is connected.

The scenario that is run is adapted from the scenario described in Figure 1 as the ATES is not included. The ATES model in CHESS took more time than expected and was not yet available for HeatMatcher to take into account for this deliverable.

In the figures below both a DemandCluster (an aggregation of several local greenhouses) and a production plant (Geothermal well, ProductionCluster1) from the ECW use case in the Netherlands are shown for a simulation period of one year. It describes the supply and return temperatures as well as the power provided to the demand or provided by the producer.

Note that in the ECW use case the geothermal well is not the only production facility: each greenhouse has its own CHP to produce heat, electricity and CO_2. This also results in the fact that the demanded power of a greenhouse is higher than the allocated power produced by the production facilities in the heat network.

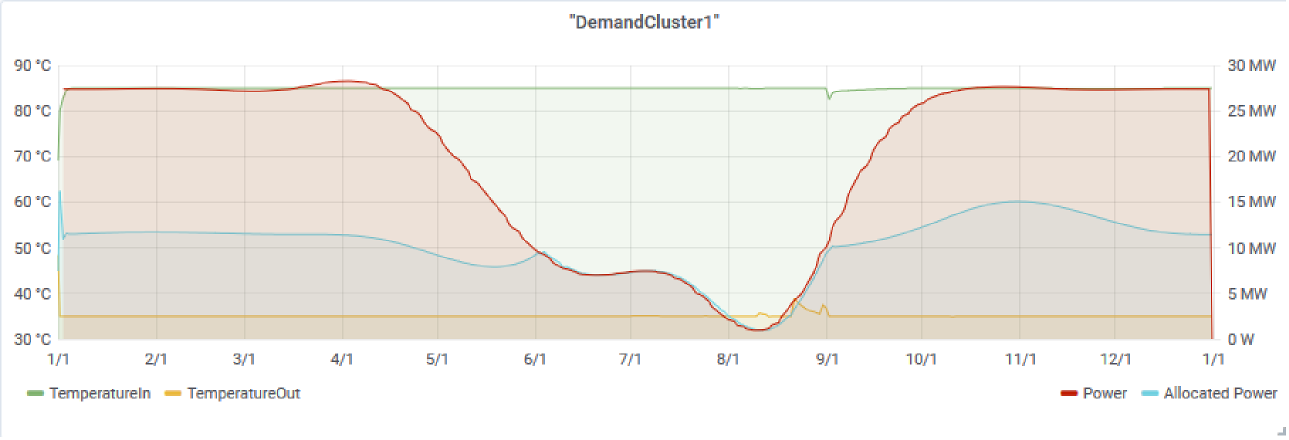

Figure 14: Temperatures (left axis) and power provided to a greenhouse in the ECW use case. The red curve represents the demanded power from the greenhouse, the blue curve the allocated power by the controller for this greenhouse. This means that the difference between red and blue needs to be delivered from the local CHP.

The optimization strategy of the demand agent is to get as much as required from the heat network. What can be seen from the graph is that the fixed temperature regime (83-35) is well matched. When comparing with other greenhouses (11 in this case) each greenhouse gets an equal share of the total production. Furthermore, one can see the seasonal change in demand; in summer the demand almost hits zero MW, while between October and April the demand is at maximum.

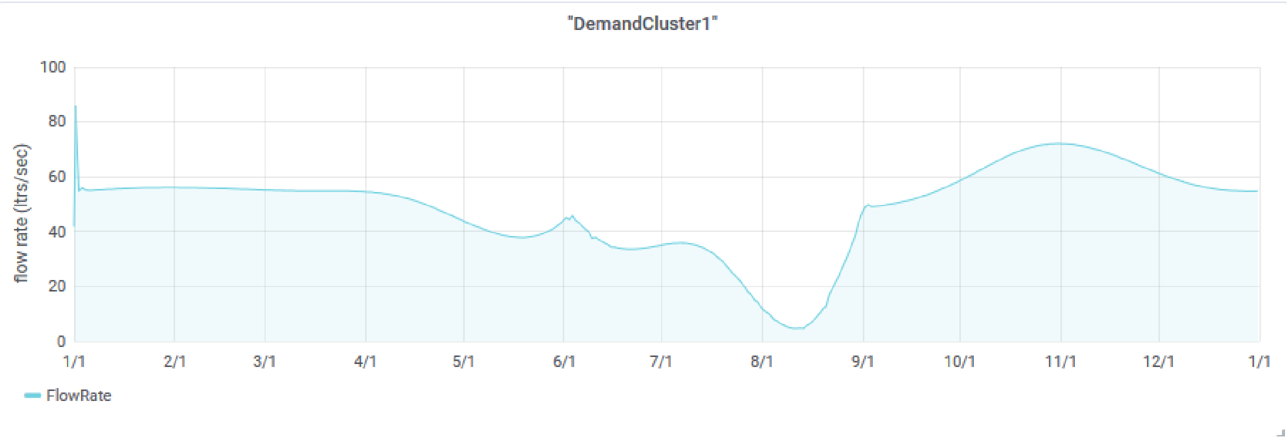

Figure 15: Flow rate for a greenhouse.

The flowrate nicely follows the demand.

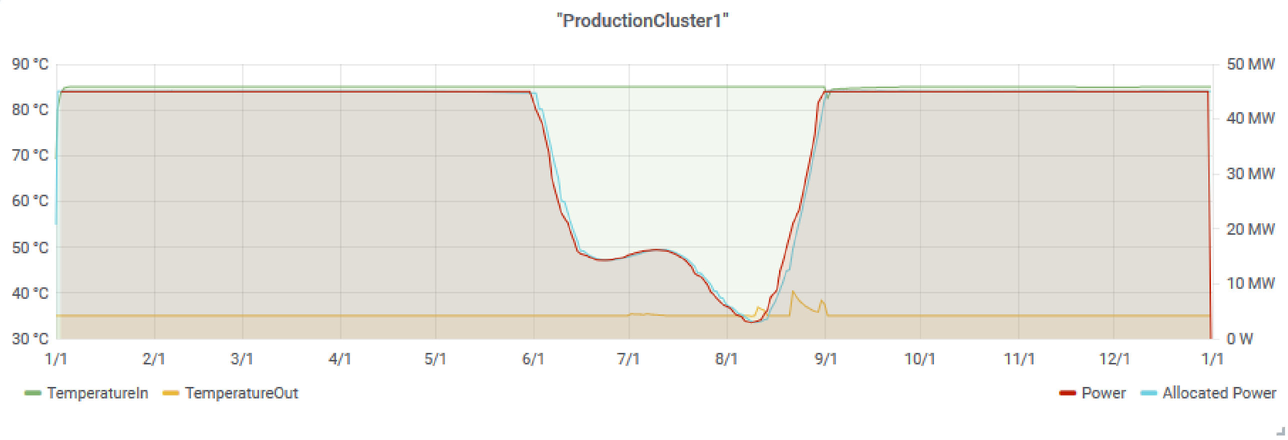

Figure 16: The temperatures and power for the Geothermal well in the ECW use case

The production side of the simulation shows similar results. The optimization strategy here is to produce at full load as long as possible. The temperature regime is matched quite well, with some small disturbances around half of August and beginning of September. This is due to some greenhouses demanding a very small amount of heat while trying to keep to the temperature regime. This affects the return temperature (in yellow) a bit, but not to a problematic value.

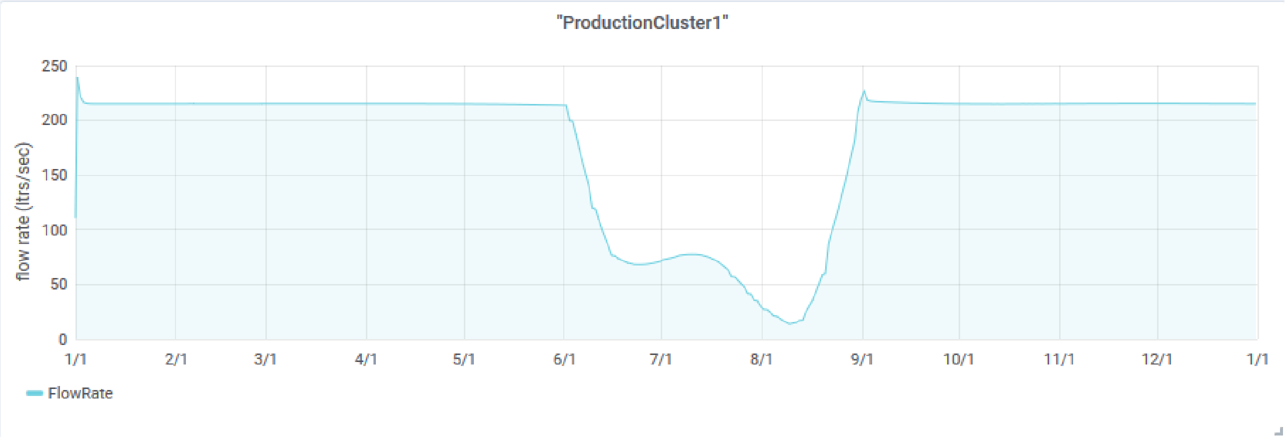

Figure 17: Flowrate of the geothermal well.

The flowrate of the geothermal well shows a stable curve in line with the production power. There are no strange hick-ups identifiable that would point to something problematic.

6 Concluding remarks

The initial results of the integration of HeatMatcher and CHESS are promising as the simulation results show nice graphs in line what would be expected from controlling a heat network such as the ECW use case. The effort to create an ATES model for the CHESS simulator will help in identifying the additional value of seasonal storage and the control strategy to improve the overall energy efficiency of the thermal system.

The next step in this work is including the control of the ATES with HeatMatcher. When that becomes available, several scenarios to optimize the ATES in the network of ECW can be evaluated. By inputting the boundary conditions and constraints of the ATES in the control strategy, its operation would need no intervention when external conditions change as it acts upon the market price.
Furthermore, additional effort is required to test the adapted HeatMatcher algorithm and compare if it generates a more optimized result compared to the results presented in the previous chapter.

7 References

[1] O. Pruissen, V. Kamphuis, A. van der Togt and E. Werkman, “A Thermal grid coordinated by a multi agent energy management system,” in *4th IEEE/PES Innovative Smart Grid Technologies Europe*, 2013.

[2] O. Pruissen, A. van der Togt and E. Werkman, “Energy Efficiency Comparison of a Centralized and a Multi-agent Market Based Heating System in a Field Test,” *Energy Procedia,* vol. 62, 2014.

[3] TNO, “HeatMatcher - Innovation in control for heating and cooling systems and networks,” TNO, [Online]. Available: https://www.tno.nl/en/focus-areas/ecn-part-of-tno/roadmaps/sustainable-energy/smart-energy-system-solutions/heatmatcher-innovation-in-control-for-heating-and-cooling-systems-and-networks/. [Accessed 11 12 2019].

[4] K. Kok, "The PowerMatcher: Smart Coordination for the Smart Electricity Grid," VU Vrije Universiteit, Amsterdam, 2013.

[5] PJM, "Locational Marginal Pricing Fact Sheet," 23 February 2017. [Online]. Available: https://www.pjm.com/~/media/about-pjm/newsroom/fact-sheets/locational-marginal-pricing-fact-sheet.ashx.

[6] K. Kok and A. Subramanian, "Fast Locational Marginal Pricing for Congestion Management in a Distribution Network with Multiple Aggregators," in *CIRED 2019*, Madrid, Spain, 2019.

[7] Wikipedia, “Separation of Concerns,” Wikipedia, [Online]. Available: https://en.wikipedia.org/wiki/Separation_of_concerns. [Accessed 26 11 2019].

[8] FAN, “Energy Flexibility Interface,” Flexible Power Alliance Network, [Online]. Available: https://flexible-energy.eu/efi-energy-flexibility-interface/. [Accessed 26 11 2019].

[9] MatlabControl, “Matlab control - A Java API to interact with MATLAB,” [Online]. Available: https://github.com/diffplug/matconsolectl. [Accessed 26 11 2019].