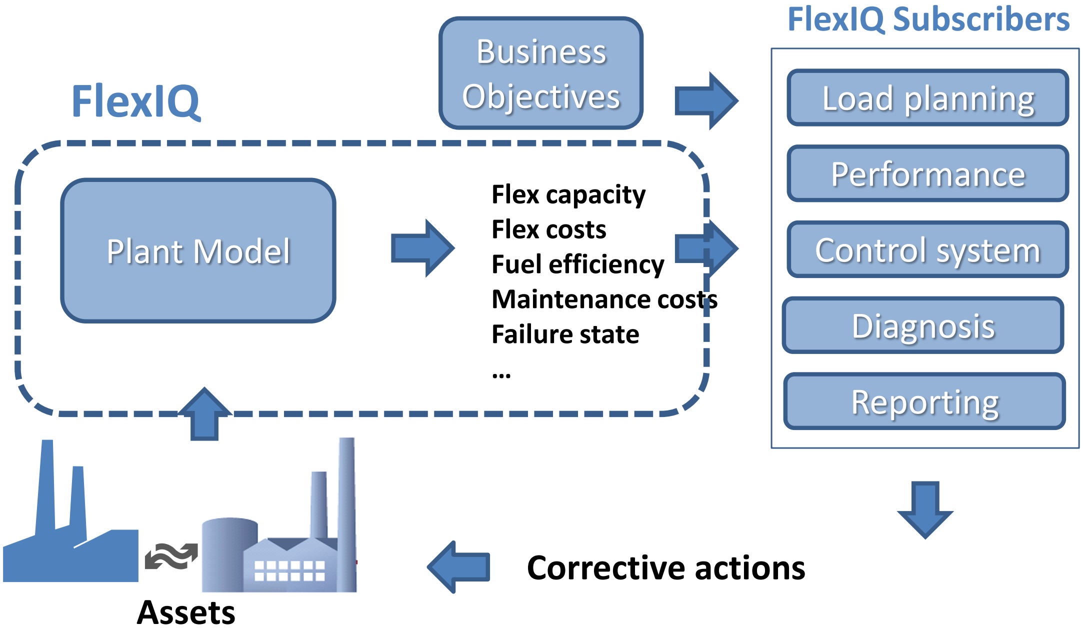
Green Flex

Mobilization of operational flexibility in green energy production



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1 Project details

Project title	Green Flex – Mobilization of operational flexibility in green energy production
Project identification (program abbrev. and file)	64013-0133 Green Flex
Name of the programme which has funded the project	EUDP (Smart Grid and Systems)
Project managing company/institution (name and address)	Added Values, Lysholt Allé 10, 7100 Vejle
Project partners	Sønderborg Fjernvarme, Aalborg Universitet, EMD International
CVR (central business register)	35 04 56 27
Date for submission	2013

2 Short description of project objectives and results

The objective in project Green Flex is to develop and demonstrate a software tool named FlexIQ that can support economic optimal planning and control of integrated green energy plants in mobilizing flexibility for power and heat markets. The project has developed, implemented and demonstrated the first version of FlexIQ which includes on-line interfacing to process measurement, steady-state models of boilers, model calculation algorithms and a business layer for calculation of performance indicators. These functionalities have been implemented in the developed tool architecture. The scalability of the tool has been proven, and on-site demonstration of performance monitoring in Sønderborg has indicated potential values in daily operation. R&D results on dynamic modelling and performance optimization of absorption heat pumps have been published.

3 Executive summary

Increasing capacity within wind and photovoltaic power production leads to increasing market needs for power balancing. Denmark has been a frontrunner in solving the balancing challenges, including increasing operational flexibility of conventional CHP units, large central units as well as smaller decentralized CHP units. Until now efforts have been focused on retrofitting the production units and on increasing the awareness of market interfacing using planning tools in daily operation. Still there is a large non-utilized potential for improving operational flexibility of energy production units, and especially in smaller units which typically encompass high process complexity and the challenge involves numerous performance measures in daily operation.

High complexity is typical of modern CHP companies, and the complexity will increase further in years to come. Plant operators and managers are learning that utilization of complex plants in the markets is very difficult to handle in daily operation and that supporting tools are needed. Key business questions seen from the asset owner’s point of view are:

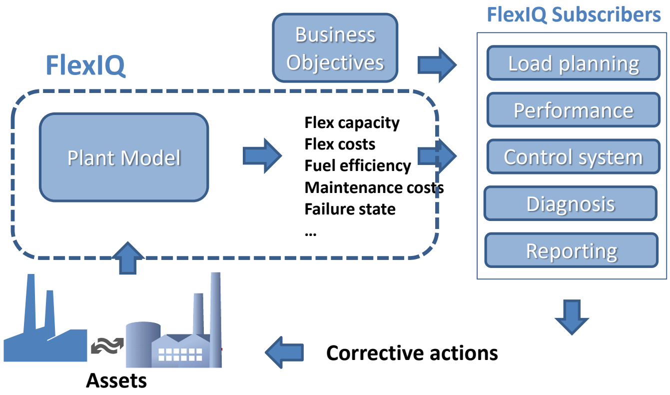
- How much flexibility can we offer to the market, e.g. regulation power and intra-day?
- What is the span of possibilities if we take the flexibility of the district heat supply into account?
- How and why does it change the fuel costs of the subsystems?
- How does it change the environmental impact?
- How does it affect maintenance costs in terms of wear and service life consumption?
- Which failure conditions or performance reductions should be taken into account?

The objective in project Green Flex is to develop and demonstrate a software tool named FlexIQ that can support economic optimal planning and control of integrated green energy plants in mobilizing flexibility for power and heat markets. The tool will close the gap between the market needs and the potential responsiveness of existing energy plants.

The tool will embrace a high degree of technology variability and deliver forecasts on key measures to users/subscribers:

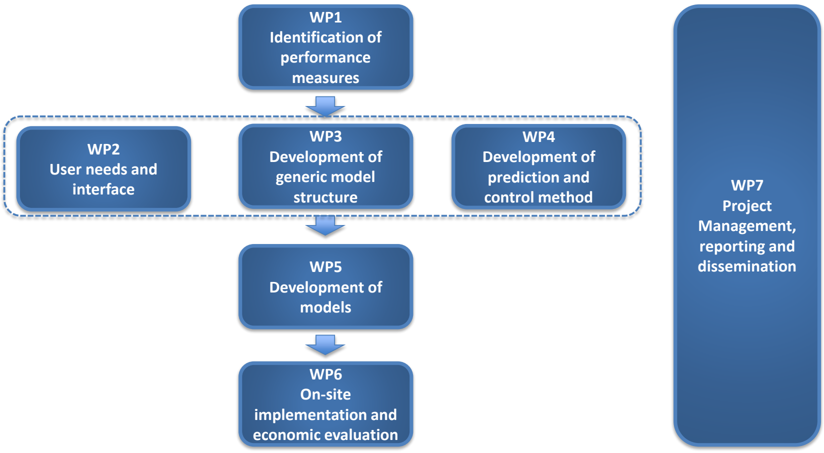
- Plant operators will have to monitor efficient, safe and reliable operation
- Load scheduling either done manually or supported by a software tool
- Control system to optimize set-points for sub-plants and sub-systems
- Planning and reporting staff, etc.

FlexIQ will be based on physical models of the thermal processes involved combined with cost models related to fuel efficiency, maintenance and environmental impact. The project will focus on developing a pilot version of such a tool and demonstrate the value on a real plant at Sønderborg FJV. The scientific challenges will primarily be development of process models and economic models. Research will be needed on methods for translating models into quality predictions of business performance measures covering the full envelope of operation.



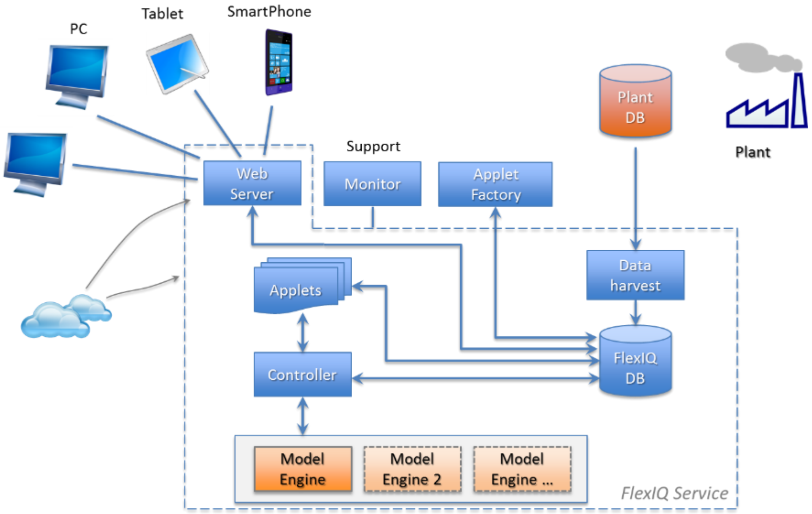
R&D, implementation and demonstration have been driven by two pilot cases which have been defined from specific challenges in Sønderborg:

- Steady-state modelling and performance monitoring of the waste-to-energy boiler
- Dynamic modelling and performance optimization of the absorption heat pumps



The project execution has been organised in 7 work packages and 8 milestones which was split in to 4 technical milestones and 4 commercial milestones.

The 7 work packages and mutual interfaces are shown in the figure. Added Values has been in charge of the project management and responsible of most of the work packages, except WP2 lead by EMD and WP4 lead by AAU. Sønderborg Fjernvarme has provided the pilot cases and has been supporting on practical issues. The project implementation has in broad terms been followed as described in the EUDP application except for a few minor changes.



The FlexIQ infrastructure and workflow for a single customer is shown in the figure below. The core FlexIQ Service shown within the dashed envelope runs unsupervised in the cloud. Measurement data are continuously harvested from the plant SCADA-database through a secure connection across the internet and stored on a database within the FlexIQ data center. The heart of FlexIQ is the Controller running on a separate server. The controller computes the plant state e.g. every minute. At first, the measurement data are retrieved from the database and conditioned to proper quality and missing data are interpolated to a certain extent from previous points in time. Once data are available, a job is composed and submitted to the Engine. A model engine runs in its own process and may even run on a different server. The Engine executes the plant model and returns the result to the Controller. The result is stored and if the computation succeeded, the applets are invoked to compute the subscribed results which also are stored on the database.

FlexIQ at its present state by the end of the project and future developments of the tool will have several value propositions to the end users, and these have been demonstrated by examples throughout the project:

- **Minimized operational costs**. On-line information on efficiencies and calculation of performance consequences of production scenarios will ensure that operators and control system can interact with the physical process manually or automatically. The Sønderborg on-site application has demonstrated this type of value creation, and the Verdo case as a full commercial application has confirmed the benefits. Expected yearly fuel savings in general are 0,5 % of fuel costs or in case of Waste-to-Energy a 0,5% surplus of earnings on power markets.

- **Optimized market bids**. Physical plant models will give more accurate information on how much flexibility a plant can offer to the market – depending on the planned load schedule on other markets and depending on the operational state of the plant. The project has demonstrated these issues through two cases. Optimized operation of the absorption heat pump ensuring maximized COP was demonstrated on the Sønderborg plant, even though it was not deployed as an on-line application. Improved information on market flexibility for improved load scheduling has also been simulated for selected plants, showing significant potential.
- **Reduced maintenance costs**. FlexIQ will provide the operators with indicators of upcoming failure modes and of slowly varying degradation hence makes it possible for the operators to intervene in due time – e.g. to increase service life or prevent forced outages. This was demonstrated through the on-line applications through on-line calculation of superheater fouling in Sønderborg waste-to-energy boiler. In general, expected yearly savings are 1% of maintenance costs.

The overall project results can be summarized as:

- A FlexIQ architecture supporting scalability in terms of scope and fidelity. The architecture has been tested off-line and demonstrated through on-line applications in Sønderborg and in Verdo (commercial application).
- Steady state modelling method based on physical component models combined with optimized parameter tuning based on measurement data.
- Dynamic modelling method which can be used for high fidelity modelling of complex systems. The method has been tested by simulations of a complex absorber heat pump system in Sønderborg. A number of papers has been published on this.
- A convergence method for benchmarking different performance measures using steady-state models combined with on-line measurements and business logics. This has also been demonstrated on-line in Sønderborg and commercially in Verdo.
- An optimization method based on Genetic Algorithms and utilizing high-fidelity models. This has been tested through simulations. A number of papers has been published on this.
- A concept for a business layer including a controller structure for execution models, controlling data flows and executing business logic. This has been demonstrated in Sønderborg and commercially in Verdo.
- A subscriber application on performance monitoring has been demonstrated in limited version on a waste-to-energy boiler in Sønderborg and commercially based in full version on Verdo plants.
- A subscriber application on diagnostics has been demonstrated in limited version in the two plants. This part was partly developed in a sister project funded by Markedsmodningsfonden.
- A subscriber on load planning has been simulated and visualized through utilizing EMD load planning software, showing potential large value creation.

4 Project objectives

4.1 Background

Increasing capacity within wind and photovoltaic power production leads to increasing market needs for power balancing. Denmark has been a frontrunner in solving the balancing challenges, including increasing operational flexibility of conventional CHP units, large central units as well as smaller decentralized CHP units. Until now efforts have been focused on retrofitting the production units and on increasing the awareness of market interfacing using planning tools in daily operation. Still there is a large non-utilized potential for improving operational flexibility of energy production units, and especially in smaller units which typically encompass high process complexity and the challenge involves numerous performance measures in daily operation.

High complexity is typical of modern CHP companies, and the complexity will increase further in years to come. Plant operators and managers are learning that utilization of complex plants in the markets is very difficult to handle in daily operation and that supporting tools are needed.

An example could be a CHP system like the Sønderborg Fjernvarme comprising a Waste–to-Energy boiler, a gas turbine, an exhaust boiler with steam turbine, a geothermal plant, a wood-chip fired boiler, an absorption heat pump, a solar heat plant including a photovoltaic plant and a district heat storage tank. Altogether, this site should maximize its market opportunities while delivering green power and flexibility to the power market without compromising the security of supply to the district heat costumers. During this market optimization, the internal costs should be visible to and controllable by decision makers. Key business questions seen from the asset owner’s point of view are:

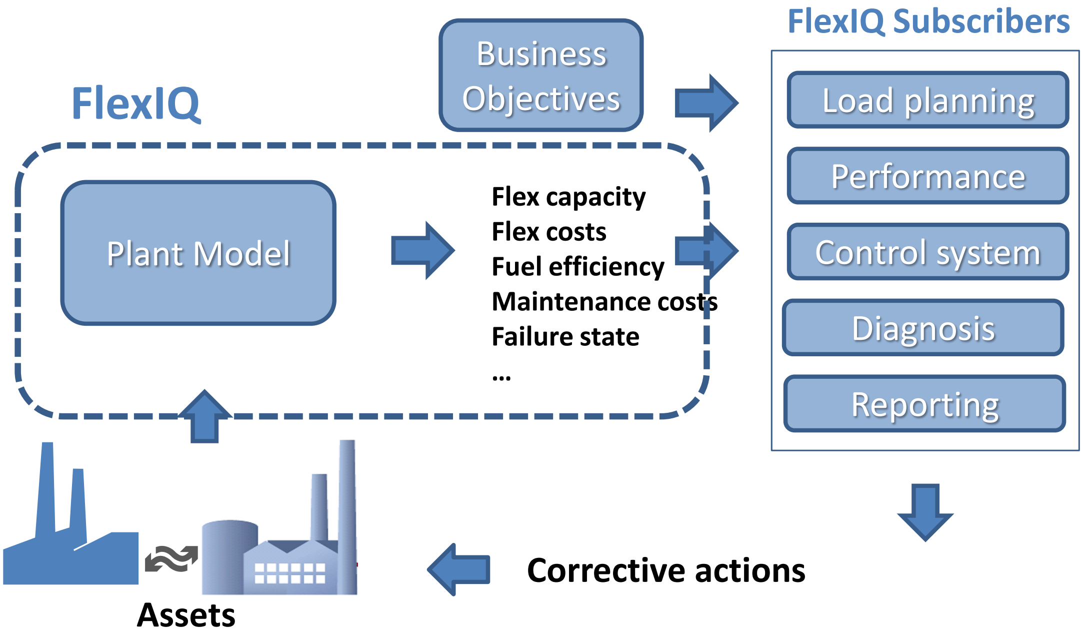
- How much flexibility can we offer to the market, e.g. regulation power and intra-day?
- What is the span of possibilities if we take the flexibility of the district heat supply into account?
- How and why does it change the fuel costs of the subsystems?
- How does it change the environmental impact?
- How does it affect maintenance costs in terms of wear and service life consumption?
- Which failure conditions or performance reductions should be taken into account?

The state-of-art of tools for combined optimization of market opportunities and of operational costs can be summarized as:

- Tools for hourly load planning based on market predictions and simple fixed cost structures of CHP units are available in the market – EnergyPro from EMD is one example. These tools are applied on a number of plants and primarily on units with low process complexity.
- Tools for advanced control of processes are available in the market – e.g. as built-in functionalities in the control systems. However, the applications are limited to simple feed-forward and feedback control based on local process measurements. Incorporation of business performance measures directly in the control structures has not been implemented because plant-wide model tools are not available.
- Tools for combined estimation/prediction of market opportunities and cost consequences are not available in the market. The available tools cover a very limited part of the span of complexity – e.g. performance monitoring systems for identification of reduced fuel efficiency. And they are not integrated across the plant components for fast and high quality overview.

4.2 Objectives

Altogether, there is a need for tools providing combined opportunity and cost information into the decision making of daily operation. This need will grow with future increase of both market needs and complexity of production plants. Project Green Flex will develop and demonstrate a prediction tool, FlexIQ, to close this gap – as illustrated in the figure below.



The core is a model-based prediction tool, FlexIQ, which will embrace a high degree of technological variability and deliver forecasts on key measures to users/subscribers:

- Plant operators will have to monitor efficient, safe and reliable operation
- Load scheduling either done manually or supported by a software tool
- Control system to optimize set-points for sub-plants and sub-systems
- Planning and reporting staff, etc.

The end product will in addition to FlexIQ include interfacing and adaption of subscriber functionality.

The subscribers will be able to make requests for new forecasts/predictions during daily operational decision making. Requests for predictions on distinct time horizons will be a key feature, as different markets are optimized on different time horizons – e.g. district heating on a 24h and weekly scale, and power on minute scale (ancillary services), an hourly scale (intra-day) and a 24h scale (day-ahead). The optimization will span the chosen markets thus yielding a unified decision base.

FlexIQ will be based on physical models of the thermal processes involved combined with cost models related to fuel efficiency, maintenance and environmental impact. The project will focus on developing a pilot version of such a tool and demonstrate the value on a real plant at Sønderborg FJV. The scientific challenges will primarily be development of process models and economic models. Research will be needed on methods for translating models into quality predictions of business performance measures covering the full envelope of operation. Besides the competencies that each partner brings along, the project will include relevant previous work supported by Danish programs – e.g. the ForskEl project "Aktivering af 200 MW affaldskraftvarme opreguleringseffekt" reported in 2011.

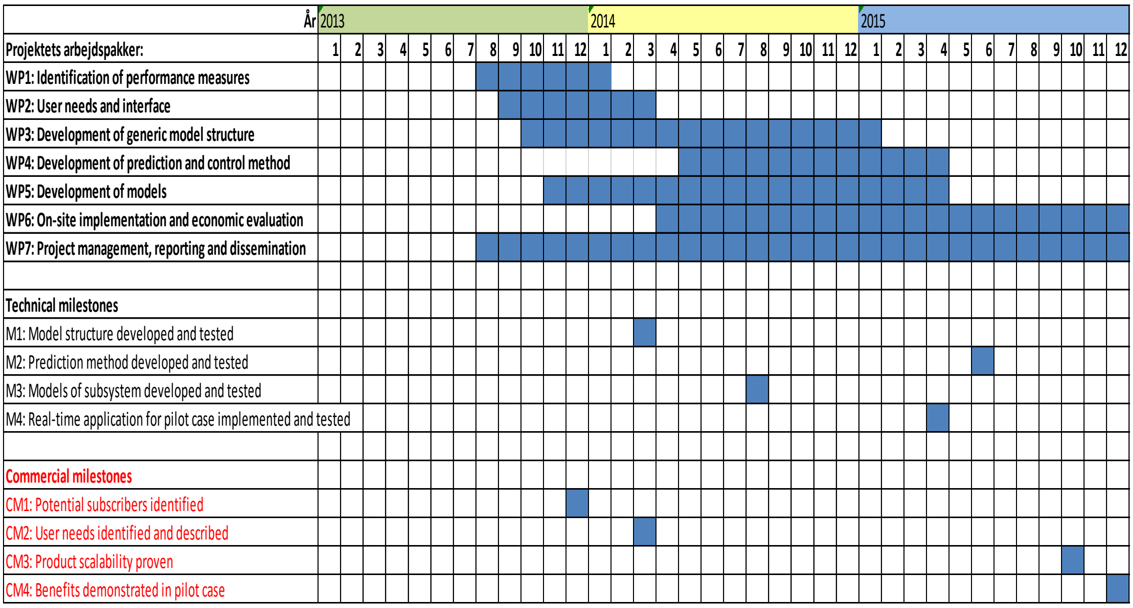
By the end of the project, a subsystem of the total model-based concept will be demonstrated on-site. The scalability of the concept will be proved by simulations. Before market introduction, further maturing regarding on-line robustness, further development of other plant-specific process models and user guidelines will be undertaken.

The objective in project Green Flex is to develop and demonstrate a software tool named FlexIQ that can support economic optimal planning and control of integrated green energy plants in mobilizing flexibility for power and heat markets. The tool will close the gap between the market needs and the potential responsiveness of existing energy plants.

4.3 Project implementation and evaluation

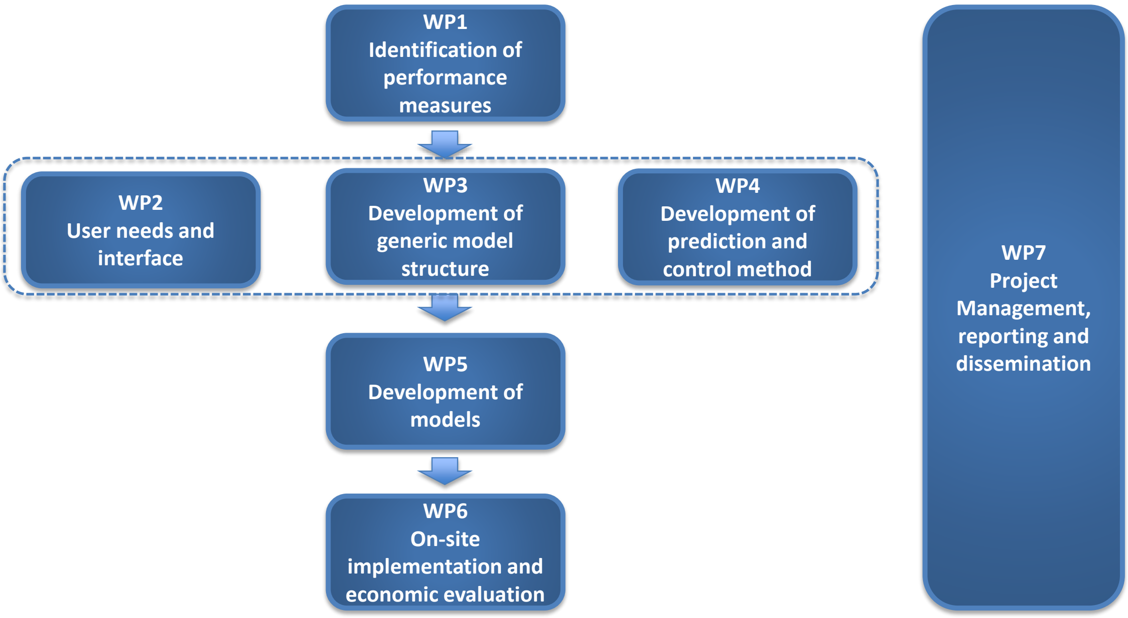
The project execution has been organised in 7 work packages and 8 milestones which was split in to 4 technical milestones and 4 commercial milestones as shown in the Gantt diagram.

Milestones are described in details in the EUDP application.



År	2013												2014												2015											
Projektets arbejdspakker:	1	2	3	4	5	6	7	8	9	10	11	12	1	2	3	4	5	6	7	8	9	10	11	12	1	2	3	4	5	6	7	8	9	10	11	12
WP1: Identification of performance measures								■	■	■	■	■	■																							
WP2: User needs and interface									■	■	■	■	■	■	■																					
WP3: Development of generic model structure										■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■											
WP4: Development of prediction and control method																	■	■	■	■	■	■	■	■	■	■	■	■								
WP5: Development of models											■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■								
WP6: On-site implementation and economic evaluation																■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■
WP7: Project management, reporting and dissemination								■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■
Technical milestones																																				
M1: Model structure developed and tested															■																					
M2: Prediction method developed and tested																														■						
M3: Models of subsystem developed and tested																				■																
M4: Real-time application for pilot case implemented and tested																												■								
Commercial milestones																																				
CM1: Potential subscribers identified												■																								
CM2: User needs identified and described															■																					
CM3: Product scalability proven																																		■		
CM4: Benefits demonstrated in pilot case																																				■

The 7 work packages and mutual interfaces are shown in the figure below. Added Values has been in charge of the project management and responsible of most of the work packages, except WP2 lead by EMD and WP4 lead by AAU. The project implementation has in broad terms been followed as described in the EUDP application except for a few minor changes.



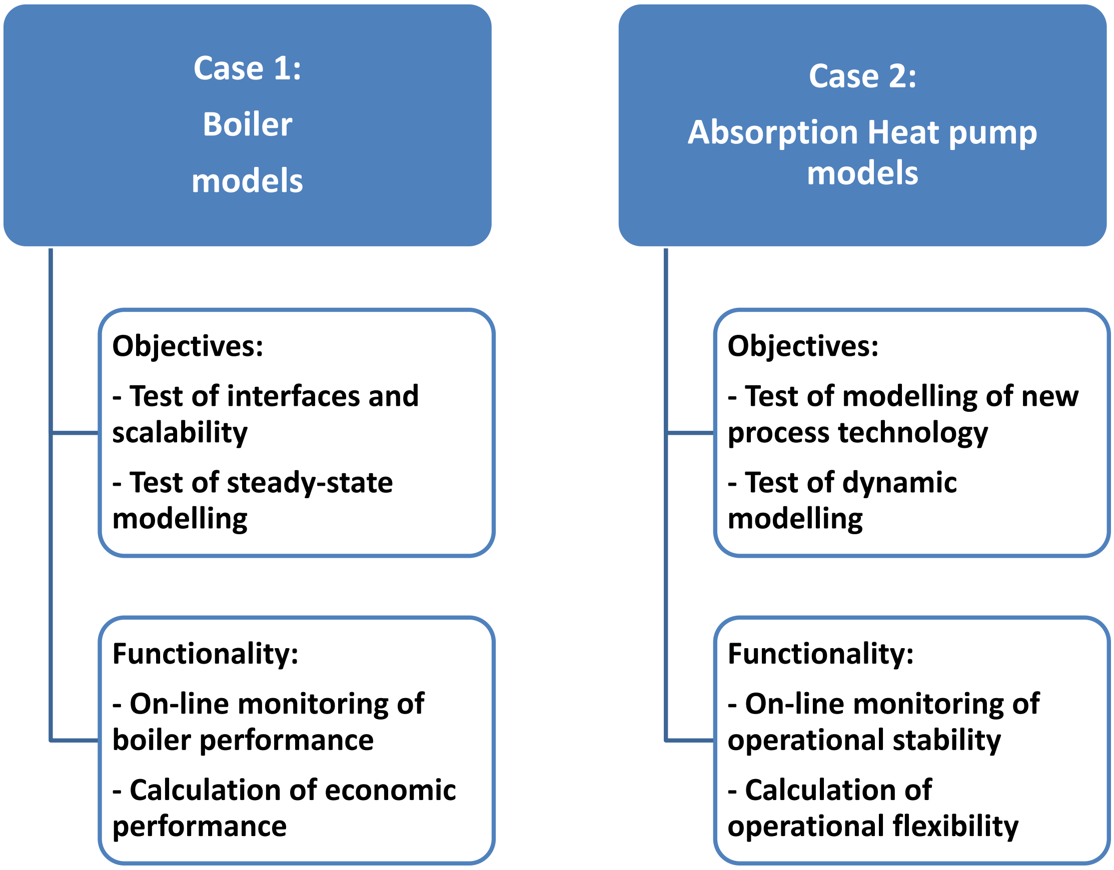
In general, evaluation of the project execution can be resumed as follows:

- The overall time schedule has been extended by ½ year due to commercial load on key resources.
- All milestones have been met.
- Project meetings have been held by the principle of need, including meetings in the total project group and bilateral meetings.
- Practical focus has been maintained in close cooperation with Sønderborg Fjernvarme and driven by the early identification of two pilot cases.
- Practical on-line testing has been achieved, although even more testing would have been preferable (Rem.: This is pursued after project termination).
- A Bachelor Engineer project and a Master Engineer project has been integrated in the project.
- Dissemination activities:
  - Papers and conference presentations
  - Presentation at costumers and branch fora (not EUDP financed)
  - Reporting to EUDP

5 Project results and dissemination of results

5.1 Introduction to project cases

In order to support the project objectives and milestones two pilot cases have been defined: modelling of a boiler and an absorption heat pump as shown below.



Both pilot cases are real cases from Sønderborg Fjernvarme and in addition to the specific objectives shown in the figure, they both serve general objectives on applicability and demonstration.

The two cases will be used as examples and demonstrations through the description of project results in the following sections.

5.2 Tool architecture

The entire tool, FlexIQ, is divided into several components {data sources, plant models, IT-infrastructure} and the issue of fidelity applies to each one and their assembly.

5.2.1 Fidelity

Fidelity of the results of a stationary model depends on sufficient

- Existence and quality of plant component data
- Existence and quality of measurements
- Completeness of plant couplings, i.e. all possible primary energy and mass flows throughout the plant
- Completeness of plant events, e.g. start, stop and cleaning
- Compensation of dynamic contents of measurements

The requirements posed by modelling of performance go beyond those of normal operation for which the plant was designed, i.e. primarily ensuring stable and safe operation.

The quality assurance of model and measurement data shall prevent a model computation based on false premises disguised as an apparently valid one.

All of these extended requirements pose challenges and are mitigated as follows.

Existence of component data and measurement points:

The development of a plant model and the required measurement and component data is performed iteratively: An initial model is proposed and the necessary component data and measurement points are identified. Some component data may be missing or too inaccurate as they are irrelevant to normal operation or not disclosed by the component supplier. Likewise, some measurement points may not be installed or are not easily to connect to the SCADA-system or do exhibit poor quality. This may necessitate development of sub-models using other measurement points to achieve an indirect assessment of the missing data. This compensation process is iterative and explorative in nature as it implies a trade-off between cost of instrumentation and cost of modelling.

Quality of measurement data

Quality of measurement data is crucial to the fidelity of model results. As the model design is iterated, the quality assessment must consider a wide selection of measurement tags and it should preferable take place during the initial phase of model development to prevent model rework.

Quality is assessed on historical data representing active states of all tags considering:

1. Availability: A required measurement tag may have missing values at single points of time or for longer periods. FlexIQ compensates for up to 2 consecutive missing values by interpolation, otherwise the computation is skipped.
2. Timeliness: The model requires a set of measurement values representing the same point in time. If the timestamp of a value does not identify said point in time, a method for assigning it to the correct point in time must be devised. FlexIQ compensates a timestamp deviation of 1 sample interval.
3. Synchronicity: Some measurements may be displaced in time from others e.g. moisture content of wood chips is measured far from the furnace thus implying a time delay that varies with load. When moisture contents vary significantly, a sub-model to compensate for the time lag is necessary.
4. Stationarity: The plant model assumes a near-stationary operation i.e. slow changes of measured data. This will never be the case during load shift or redirection of energy flows e.g. during change of electricity production at hour shifts. FlexIQ employs detection algorithms to assess whether a plant is instationary and in case skips the computation.
5. Averaging: If the plant is stationary, the measurement values must be averaged over a defined time interval to eliminate high order noise. Averaging is a normal procedure on most SCADA-systems but must be verified when setting up the retrieval process.
6. Offset and gain errors: These instrument errors are by nature hard to detect unless during calibration. In some cases, they may surface if a model component ends up in a physically invalid state e.g. if heat injection results in a lower output temperature. In such cases, FlexIQ employs a proactive approach and checks for such states before commencing the model computation.
7. Outliers: A measurement value may be out-of-bounds, which is easily detectable and in addition, a value at a boundary may indicate truncation by the SCADA-system. In both cases,

the model computation is abandoned. Also, a value may be an outlier in a statistical sense such that it over a period exhibits significant deviations from the population. Subtler, a tag combined with another tag may as a pair deviate from the population. As statistical outlier detection is a compute-intensive process, FlexIQ takes a reactive approach such that a failed model computation is diagnosed by inspecting measurement time series for anomalies.

Completeness of plant couplings

Combined Heat Power plants are built to order so no two plants are identical, that is we have a lack of standards. This necessitates a manual mapping of component characteristics and plant flow couplings through interviews and inspection of diagrams. The error-prone nature of this method is mitigated by frequent dialogue with and confirmations of the model state by the plant staff. In that context, it is important to display the model state close to the familiar views used by the SCADA-system, e.g. by using diagrams of mass flows and components and preferably using actual measurement values. It is our experience that the operational staff as a whole know their plant intimately and are easily triggered by deviations from daily patterns of measurements values.

Completeness of plant events

The plant or sub-plants thereof may be inactive for some period of time due to scheduled or unplanned shutdown or as a consequence of the state of other sub-plants. In some cases, these events are not registered by the SCADA-system hence must be assessed indirectly.

1. Plant activity: FlexIQ employs particular algorithms for assessing active operation of each sub-plant. Furnace activity is most imminently detected by oxygen contents of the flue gas and/or selected temperatures downstream the incineration point.
2. Cleaning operations: Furnace heat surfaces are exposed to slagging (deposits) over time due to the ash contents of the solid fuel (waste, biomass). Various cleaning methods like soot blowing with steam or hot water, or detonation of carefully placed explosives remove the slagging sufficiently. Soot blowing injects a substantial amount of moisture into the flue gas thus affecting pressure drops along the furnace path and the heat uptake by the heat surfaces. Soot blowing may be performed manually without registration of the event and with variation of the cleaning programme. FlexIQ employs direct indicator measurements where possible and otherwise indirect algorithms specific for the plant.
3. Turbine bypass: Bypass serves to increase the district heating (DH) output by redirecting the steam from the turbine to DH heat exchangers. Bypass is mostly applied when electricity prices are low or during very high DH-demand and may happen several times a day. As bypass is a novel mode of operation, some plants perform bypass manually with no registering by the SCADA system. FlexIQ applies plant specific algorithms to detect bypass.
4. Plant revision: During revision, components are maintained or even replaced. This alters e.g. their heat transfer characteristics hence necessitating a model recalibration. FlexIQ support staff must rely on notifications from the plant staff to handle this situation.
5. Change of plant: During daily operation the staff may have to mitigate an outage by recoupling energy flows. Often, these events are not registered hence the model computation may be severely disturbed. The lack of registration may result in a tedious fault-tracing as this kind of error cause is one of many possible.
6. Documentation of plant: Often the component suppliers are very secretive about the inner specification of e.g. a turbine. This leaves fewer options to calibrate detailed models hence increasing the error envelope. The missing documentation is compensated by subjective knowledge by the staff although it may be difficult to verify.

5.2.2 Scalability

Scalability of FlexIQ has several dimensions summarized as:

1. Scalability of the model: complexity, compute time
2. Scalability of the IT infrastructure: customers, users, data storage, compute capacity

Ad 1: Scalability of the plant model:

- A typical plant model comprises of the order of 1000 non-linear equations to be computed every minute. As a point of reference, a plant model subdivided into 4 sub-plants computes within 10±5 seconds[1] depending on the actual plant state. This time comprises the entire loop from one point of time to the next. Thus scaling is not seen as a challenge with regard to computing power.
- The periodical regular computation of the plant model every minute or two has a predictable maximum draw on computer resources. As the model is controlled by a number of parameters like fuel calorific value, a change of parameters by default only affects future computations. If a re-computation of the past is desired, the computational load increases significantly as no real-time delay needs to be respected and as the subscriber expects a fast if not instant re-computation.

Ad 2: Scalability of the IT infrastructure

The statements below are based on the cloud-based deployment of FlexIQ. This choice offers several advantages over on-site deployment: Scalable resources within a few minutes, no investments or fixed costs, and built-in and extendable data protection to name the most important.

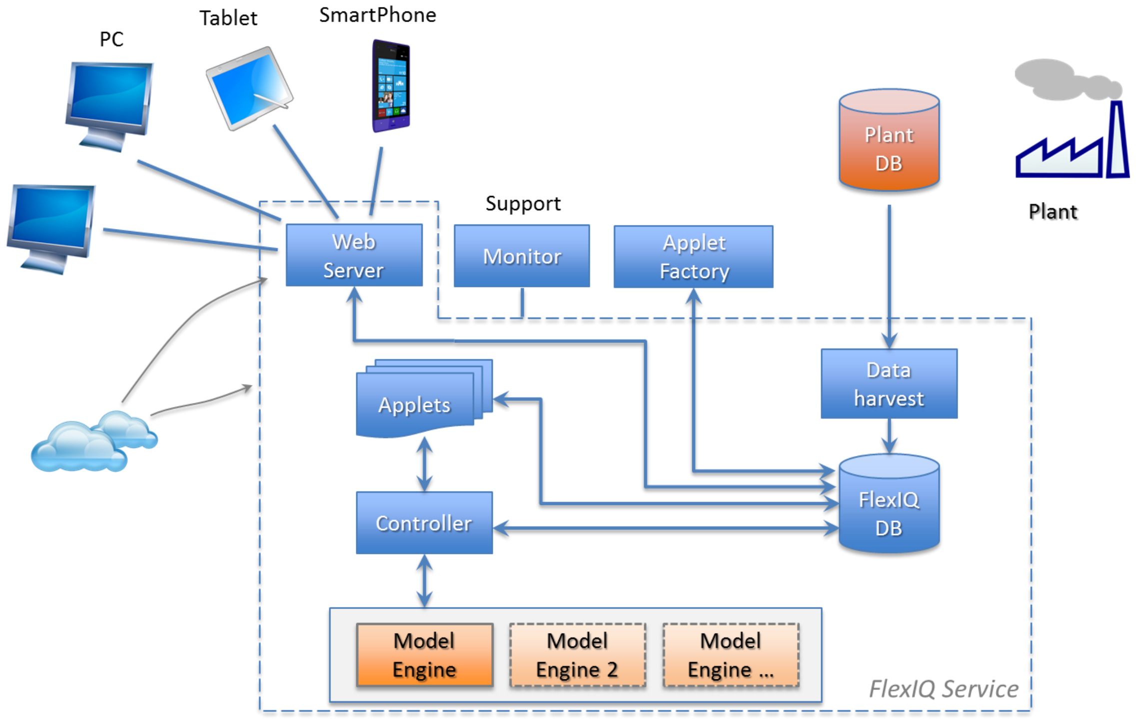


Fig. 1: Conceptual sketch of FlexIQ IT infrastructure. The dashed envelope depicts the cloud-based unsupervised service and the modularity of its components.

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[1] Measured on a 2-core 4 GB AMD Opteron server

The FlexIQ infrastructure and workflow for a single customer is shown in Fig. 1. The core FlexIQ Service shown within the dashed envelope runs unsupervised in the cloud. Measurement data are continuously harvested from the plant SCADA-database through a secure connection across the internet and stored on a database within the FlexIQ data center. The heart of FlexIQ is the Controller running on a separate server. The controller computes the plant state e.g. every minute.

At first, the measurement data are retrieved from the database and conditioned to proper quality and missing data are interpolated to a certain extent from previous points in time. Once data are available, a job is composed and submitted to the Engine. A model engine runs in its own process and may even run on a different server. The Engine executes the plant model and returns the result to the Controller. The result is stored and if the computation succeeded, the applets are invoked to compute the subscribed results which also are stored on the database.

Applets are developed and tested outside the Service box before being deployed. Once the structure of an applet is deployed, applet instances may be modified, added and removed without disturbing the Service. Currently, only one applet, performance monitoring, is implemented.

Alongside this process runs one or more web servers receiving and executing user requests. When a user issues a request, the web server searches the database for available data and if found, executes the request and presents the result to the user. A range of specialized tools enables the support staff to access the FlexIQ Service for maintenance and diagnosis.

In this way, the computation process executes asynchronously to the subscriber activity and the database serves as a hub of this decoupling. The FlexIQ Service is placed at a Cloud provider.

Scalability is designed into the infrastructure by encapsulation of processes into components that may be scaled independently.

Separation of model and subscriber computations from user requests services offers these advantages:

- The capacity of the computation and user service processes may be scaled independently.
- Alternative access methods other than a web browser may be applied.

Choice of web browsers as the primary user access point offers these advantages:

- No on-site deployment, only central deployment and maintenance.
- Web pages adapt automatically to the physical format of the browser device, that is one single deployment for smartphone, tablet or pc.
- User authentication available out-of-the box and adaptable to customer needs.

Division of labor between service components offers:

- A common infrastructure across customers easing development, maintenance and deployment.
- Customer specific parts are separated from generic parts, e.g. plant models and applets are separated from the computational setup and database structure.
- Applets are developed and maintained independently.

Disadvantages of the tool architecture:

- Larger initial development costs due to separation of parts and prediction of needs.

- For the same cost of development, web pages offer less interactivity.

The infrastructure is designed to be generic across customers and the customer specific parts, in particular plant models, are described entirely by data in a common structure. This allows for a highly predictable deployment and maintenance of new customer solutions once the data and models have been settled.

The infrastructure is partitioned such that each customer resides on a separate database. In principle, the number of available databases is unlimited. The FlexIQ-controller and model engines run in separate processes on a server, and an entry-level server may host one or more customers. Again, the number of available servers is principally unlimited. The user’s access through a web portal also allows for scaling, as the capacity and number of web servers are as scalable as the other components. A single web server may serve users of more customers as authentication only permits access to a specific customer setup.

The database is designed to match the demands in terms of granularity and coincidence.

Although the infrastructure components are individually scalable, the tool offers features that differ by frequency of use and computational load. This makes it difficult to estimate the computational capacity with respect to expected response time.

5.2.3 Challenges on subscriber needs

- FlexIQ is a new product category hence the customers may have an above-normal risk perception with respect to the value of the tool, what workflow to apply, etc.

- Subscribers are prone to transfer their user experience expectations from the SCADA-system onto this tool, in particular regarding response time and interactivity. This may cause some initial disappointments depending on the implementation.

- Data ownership and security: Plant data are retrieved from the SCADA-system and stored in a separate database in order to offload the SCADA-system. The separate database may be external to the plant and located in any data center. This raises issues of data security during transfer and when stored. The customer also has to maintain ownership to the stored measurement data and computed model data. These issues are solved by mature technologies and off-the-shelf legal agreements.

5.3 Steady state modelling

5.3.1 Challenges to consider

The most notable difference between static and dynamic models of a system is that dynamic models represents state variations in time whereas static models are at equilibrium in a steady state / quasi steady state. In many practical situations, it is appropriate to use a static model to evaluate a specific process, rather than a dynamic model. In a static model one can easily rearrange the unknown variable and thus use the online measurement data to determine e.g. a performance factor of a heat exchanger in a model. Hence a static model can easily obtain information on a given state in a process, based on available measurement data.

There are a variety of challenging conditions that must be met in order to perform an online quasi-static simulation of a power plant. The starting point for the calculation is a valid design-model, which are calibrated against measurement data at steady state conditions. While running online, the measurement data should be time-synchronous and available as often as we want a simulation. Selected measurement data are used as boundary conditions for the mathematical model, which ideally should be able to handle all relevant operating situations of the plant. There are special requirements for the numerical model. It must be quick to find a solution to the current operating situation, which can vary from low load to overload. The numerical model must accommodate a high degree of accuracy to reflect the physical processes that occurs in the plant.

5.3.2 Plant description and challenges

The Sønderborg plant shown in Fig. 2 has a waste-fired furnace / boiler line designed for the combustion of waste at a rate of 8 tons / hour. The steam from the furnace is utilized in the steam turbine generator for electricity production. The thermal input is 23.3 MW and the corresponding thermal power is 20 MW and electric power is 4.5 MW. Parallel to the waste line is installed a gas turbine generator, with a subsequent exhaust boiler, which produces steam to the above steam turbine. The thermal input is 110 MW and the corresponding heat power production is 42 MW and the electric power is 52 MW. Flue gas cleaning system is the wet type, which "washes" the flue gas of acidic components and heavy metals as well as SO2 and Dioxin. This wash water is treated in the plant's own wastewater treatment plant.

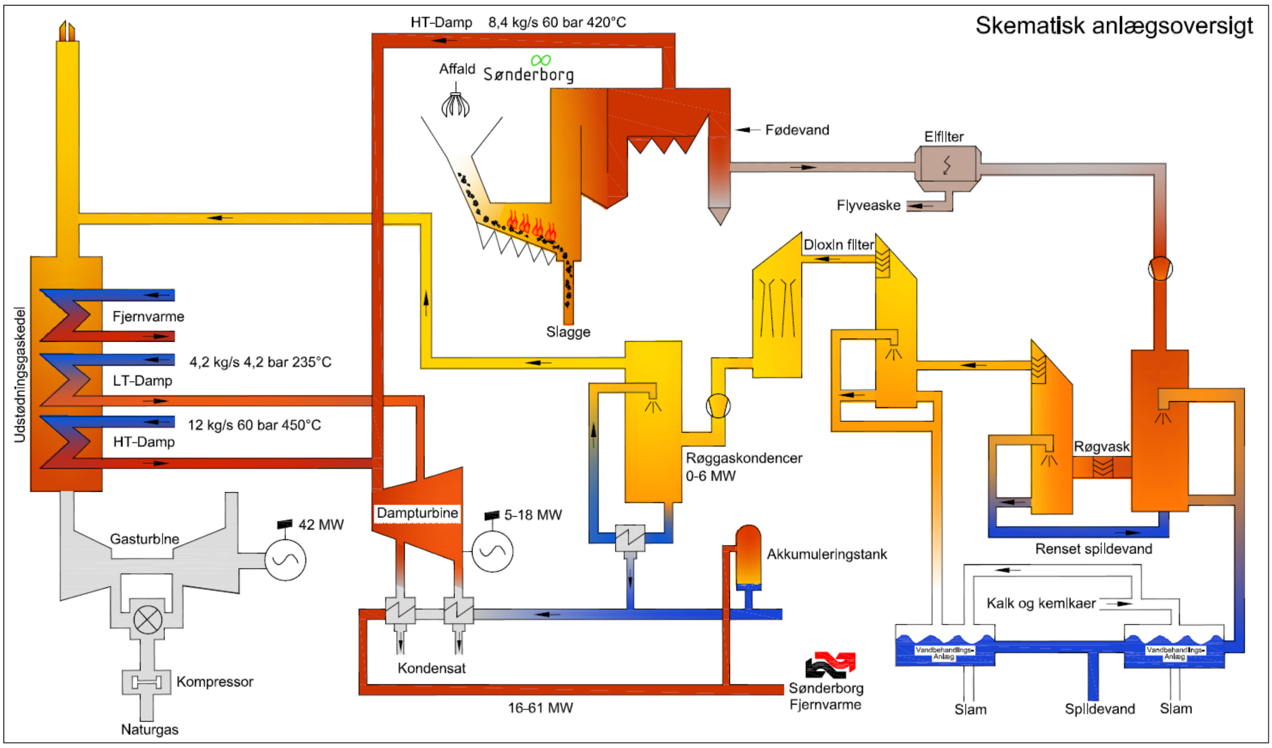


Fig. 2: Process view of plant at Sønderborg Fjernvarme

The plant consists of the following main components:

<u>Waste-fired furnace / boiler</u>

The plant has a waste-fired furnace / boiler line designed for incineration of 8 tons / hour of waste. The waste is dried, gasified and incinerated on a grate that mechanically is transporting the waste slowly through the oven. Combustion heat converts the water in the boiler tube to 420 °C hot steam with a pressure of 60 bar. The steam is utilized in a back-pressure turbine and a district heat exchanger.

<u>Gas turbine with generator</u>

The gas turbine drives, via a reduction gear, a generator that produces electricity for the power grid. The exhaust gas from the turbine is at a temperature of about 470 °C. The exhaust gas is fed to an exhaust boiler.

Exhaust boiler

The exhaust boiler produces steam at 60 bar - 440 ° and 4.5 bar - 220 ° C and district heat. There are chosen steam production at two pressure steps to maximize the power output from the steam turbine.

Flue gas cleaning

The process water to waste gas cleaning is treated wastewater from the municipal treatment plant. After the flue gas cleaning process, the water is treated in the plant's own water treatment plant, so that it adheres to the same emission requirements as municipal wastewater.

5.3.3 The modelling system

Numerical modelling of the boiler at Sønderborg Fjernvarme (SKVV) is performed by AVpower. AVpower is a simulation programme developed by Added Values P/S for calculation of turbine and water/steam circuits in general. AVpower is the result of more than 3 years of continuous development and is tuned through the experience gained from energy projects worldwide. The system is a static calculation programme, which with a comprehensive component library and advanced water/steam and gas library, can be used for design and consequence calculation of power station units. AVpower equips engineers to carry out accurate pressure, temperature and flow analysis from a position of knowledge, and rapidly achieve an optimized design. This cuts production costs and improves product quality. The system is run on a Windows platform and comprises a pre-processor, which can run in a design and in an off-design mode so that based on a design calculation, consequence calculations can quickly be established in the form of off-design calculation. AVpower includes an equation solver, which numerically is very robust. AVpower solves (minimizes a functional) a constrained non-linear equation system by establishing a Jacobiant matrix which is solved iteratively by means of a modified Newton Rapson algorithm. The solution vector is accepted during an iteration process when the Euclidean norm is less than a user specified accuracy, which is the convergence criterion. The solution vector is supervised by a control routine, which ensures that the solution will always be within a predefined definition interval.

Moreover, AVpower includes a comprehensive component library of turbines, generators, boilers, condensers, pre-heaters, pipes, valves and controllers which are all implemented in the AVpower code. In general, the involved components are very detailed and fulfil the above descriptions of the SKVV plant. A comprehensive water/steam (IAPWS 97) and gas library is connected covering the pressure and temperature range from 0 to 1000 [◦C] and 0 to 800 [bar].

5.3.4 Description of principles

The background for static modeling and associated performance analysis of a power plant, is a successful model calibration. This is done by creating a "design" model, which corresponds to a model calibration, based on validated measurement data and related information about plants couplings and other instrumentations. The analysis is based on time series of data at high load, so that all thermo-hydraulic phenomena can be modeled at different load conditions. In a design situation we select data material, that represents a clean boiler, i.e. immediately after a purification process or major repair. Hence the design model is used to determine the size of the devices in the plant, i.e. the length of a superheater tube.

The numerical model can be used in an "off-design" state, where all device constants are locked (designed). The exercise is now to change the main boundary conditions in the model to match the actual load conditions. The boundary conditions can be feed water flow or steam exhaust temperature. In this way, we can calculate all the thermo-hydraulic state properties, which connects the individual devices in the model.

There are different variants of the off-design calculations. The first calculation, which we perform in the online environment, is a "must-value" calculation, where the model addresses an operating state, which is similar to the calibrated condition, meaning a clean and perfect operating boiler. Thus we get an optimal reference state, that can be compared against the current operation state.

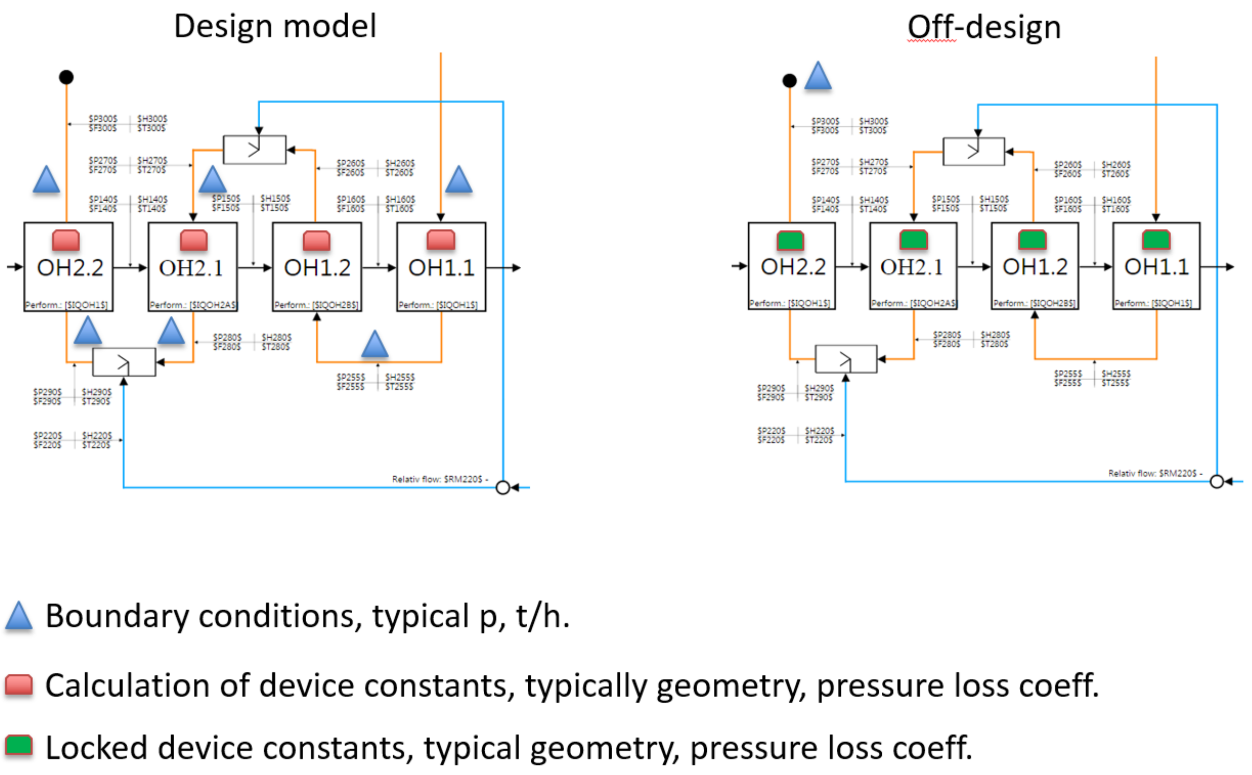


Fig. 3 The principle of design and off-design simulation of a plant model.

With the so-called "must-value" reference simulation, we can quantify several not directly measurable quantities, such as the calorific value of the waste, amount of fuel and its moisture contents, pressure, temperature and flow throughout the process circuit.

The second calculation step in the online simulation, is called "is-value" which reflect the current operating situation. By involving more measuring data in the off-design calculation, we can estimate a performance factor for a specific device in the plant. This performance factor is expressing a load independent performance indicator for a specific plant device. The principle of design and off-design simulation is illustrated in Fig. 3. It may be a heat exchanger, which does not provide sufficiently high steam temperature, as a result of fouling or a fouled heating surface, which generates a larger pressure loss. Below are given examples of performance evaluation of heating surfaces:

- Evaporator / Condenser
- Superheater
- ECO, Preheater
- LUFO/GAFO

5.3.5 Plant modelling

In this project we have developed two mathematical models, an exhaust boiler and a waste boiler model. Because of the very few hours of operation, the exhaust boiler is not established as an online tool, while the waste boiler is running online permanently, with a calculation frequency of one minute. In Fig. 5 is illustrated a design model of the exhaust boiler that includes a simple model of a gas turbine, which generates combustion gases with a given stoichiometric composition, pressure, flow and temperature. The flue gas is passed through the HP-OH, which is a high-pressure super heater. The flue gas is then passed through a high-pressure evaporator, which is connected to a high-pressure drum. Next, the HP ECO 2 is to preheat the feed water to the high-pressure drum. The low pressure super heater occurs immediately before the low pressure evaporator, which is connected to a low pressure drum. The flue gas passes two parallel economizers (HP-ECO and LP ECO) and beyond in a district heating exchanger.

The waste boiler is illustrated in Fig. 6 and Fig. 7 in design- and off-design mode, respectively. The model includes two combustion modules, of which gas combustion at this time is not in action. The waste incineration process studied in this project is based on statistical data of waste, where a stoichiometric model is structured so that the flue gas composition can be calculated as function of the calorific value of the waste, excess air and moisture content. In Fig. 4 is shown a plot of the stoichiometric fragments of the waste, as a function of the dry calorific value.

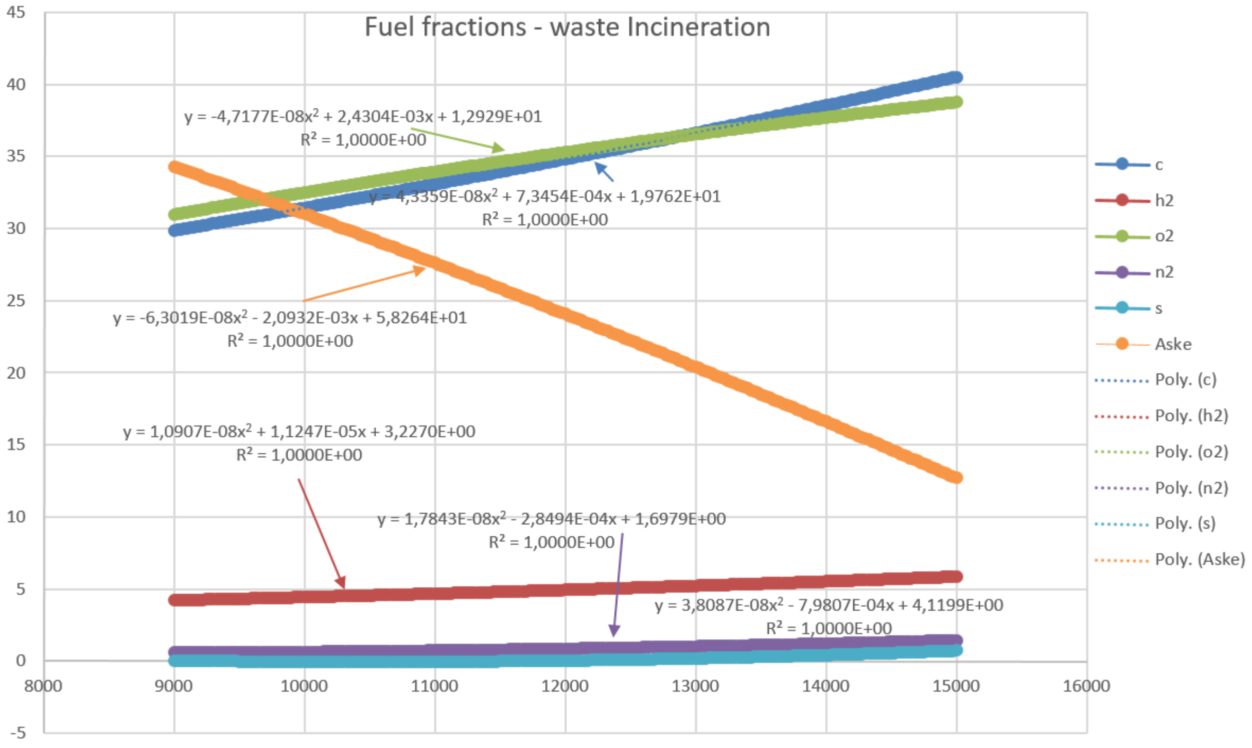


Fig. 4 Stoichiometric fragments of waste, as a function of dry calorific value.

The calculated flue gas from both combustion devices is passed to a mixer device, from which the gas is led through a vaporizer device, that delivers power absorbed in the associated drum, then passes the flue gas through a SNCR injection station, which mixes water with the flue gas. Hereafter, the flue gas passes through four superheaters and two economizers, after which it passes through an electrical filter and a scrubber station, which also feeds moisture into the flue gas and hereby reduces the outlet flue gas temperature. The air intake is preheated in part through a steam-driven air-preheater (LUFO). To control the steam super heater temperature, the model is equipped with two water injection stations. Moreover, the model is provided with two fresh air fans and a flue gas recycle fan. In the off-design scenario, we calculate five performance factors:

Thermal performance factor of OH2.2

Thermal performance factor of OH2.1

Thermal performance factor of OH1.1

Pressure loss of ECO 1 + 2

Electrical efficiency

Heating efficiency

Total efficiency

The performance factors are available for the end users/subscribers as an instant value or as time series.

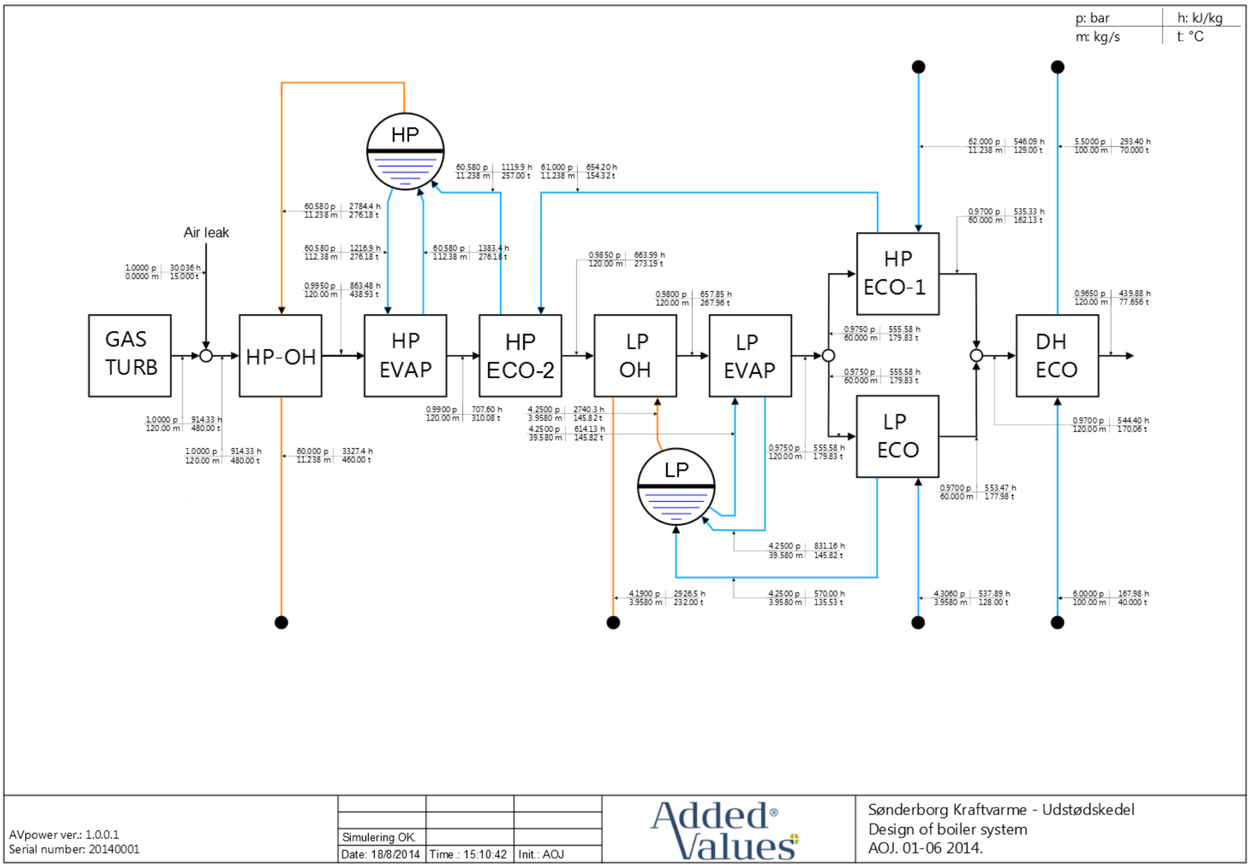


Fig. 5 Design model of SKVV - Exhaust boiler.

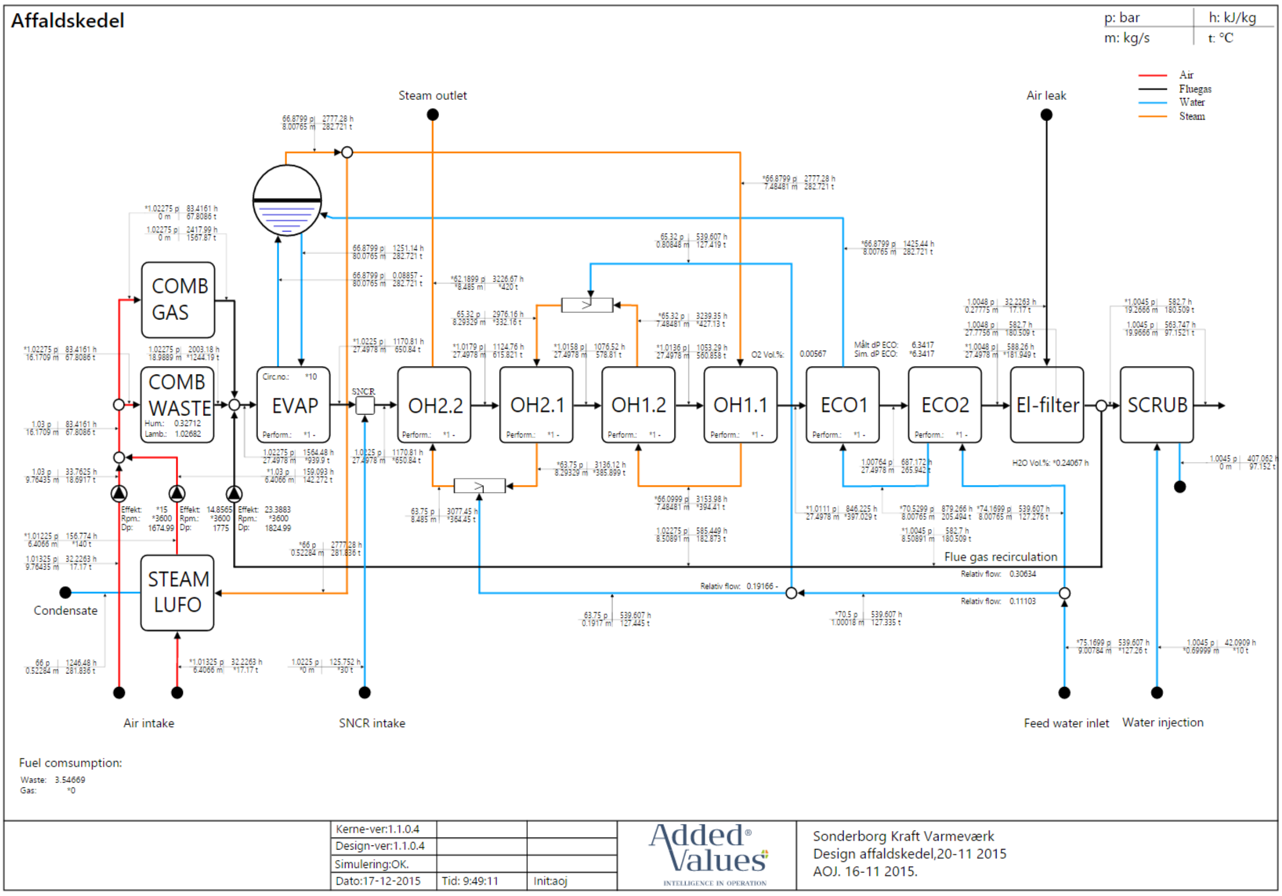


Fig. 6 Design model of SKVV - waste boiler

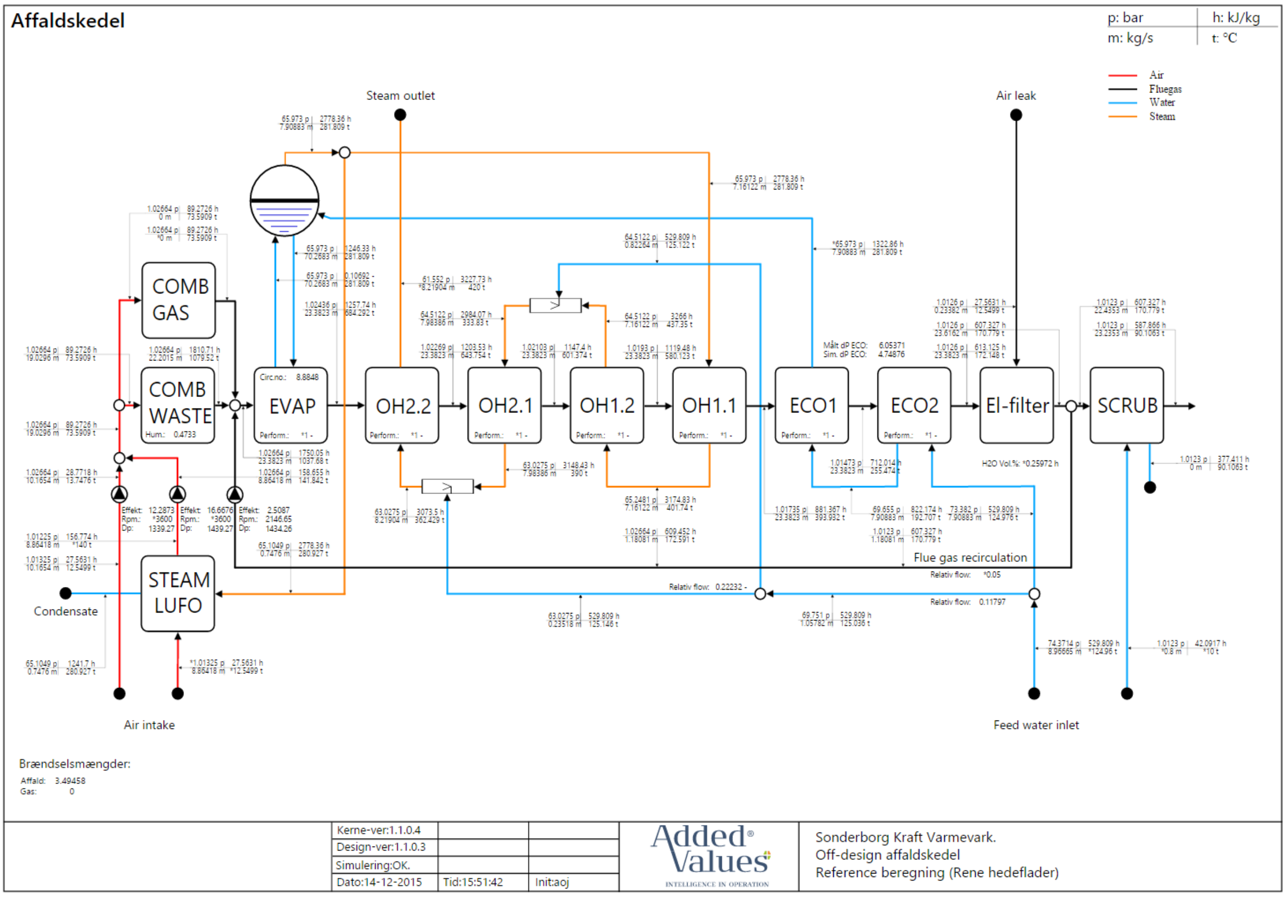


Fig. 7 Off-design model of SKVV - waste boiler.

5.4 Dynamic modelling

FlexIQ should be able to provide simulation results from two different types of plant models: *static* and *dynamic*. This section describes a dynamic model of an absorption cycle heat pump (ACHP) process owned and operated by Sønderborg Fjernvarme (SFJV). It was selected for a number of reasons:

- None of the project participants had any prior knowledge of ACHP processes so the modelling and simulation of one such would make a substantial contribution to the academic level of the overall project.
- An ACHP has a significant but qualitatively unknown dynamic behavior that should be exploited by the FlexIQ subscriber.

5.4.1 Challenges to consider

Dynamic modelling and simulation implies a number of new challenges to be considered. First, since the model should eventually be part of an online simulation framework *real-time requirements* are important. A FlexIQ subscriber should be able to get results from the dynamic simulation model fast enough to allow for real-time corrective actions back to the process. So if the input sample time is, say, 1 minute, the computational time for the simulation must be well below that number.

Flexibility is a second, important issue: The simulation framework in FlexIQ should be able to handle plant models of different complexity, developed in different modelling environments and with a minimum reconfiguration effort. For example, a large nonlinear system model could be developed in Modelica, a simple linear grey-box model for control-purposes could be developed in Matlab, and a high-order FEM model of life consumption of a specific component could be developed in Ansys.

Robustness towards bad or missing input data from the actual plant is a third, important challenge to consider.

5.4.2 Plant description and challenges

Central Vestermark/Central Spang is a complex district heating plant as shown in Fig. 8. It consists of:

- four absorption cycle heat pumps (ACHP), powered by
- two wood chip boilers (WCB),
- a geothermal well,
- two flue gas scrubber/condensers,
- pumps, pipes, valves, and
- control systems.

Information about geometry and internal control principles of the ACHP’s has been very sparse, so a number of assumptions and functional analyses have been made during the project in order to quantify some of these unknown factors.

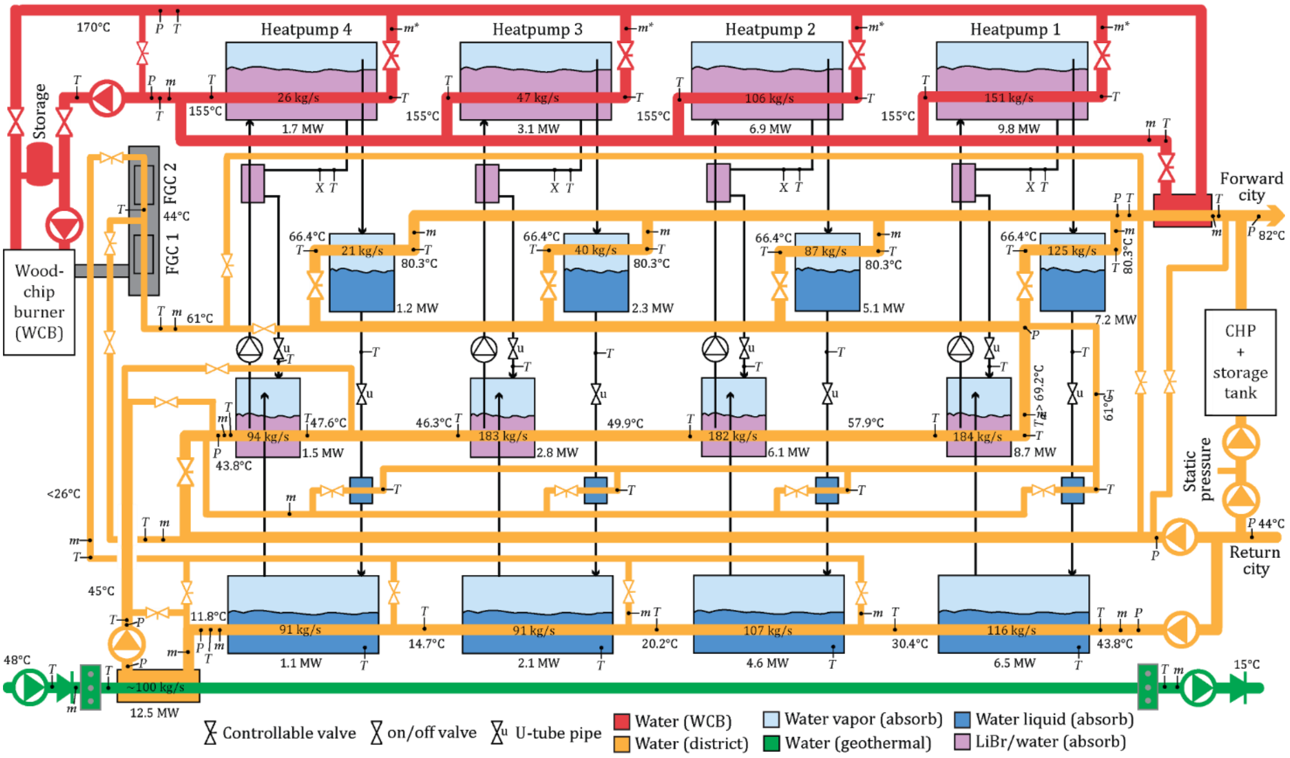


Fig. 8 Overview drawing of Central Vestermark/Central Spang consisting of four heat pumps, a geothermal well, wood-chip burners, and flue gas condensers (FGC1-2). Nominal heat flow rates, mass flows, and temperatures are also shown.

5.4.3 Description of principles

The main plant subsystem considered for dynamic modeling is a single-effect absorption cycle heat pump. Hence in the project, a model of it was developed for the specific purposes of investigating control design issues and plant optimization. In our model, the main heat transfer takes place in a chemical absorption/desorption cycle involving a solution of water and Lithium-bromide (LiBr) and we considered both mass and energy storage. Component models of the absorber, generator, condenser and evaporator were formulated based on various modelling papers found in the literature. Further, heat exchangers and flow models were modeled using a staggered grid discretization scheme and LiBr properties were implemented in a separate library with focus on fast simulation. Model parameters were then fitted using actual plant data.

Since the plant is a strongly coupled thermo-hydraulic process a component-oriented approach was taken. In that way, rigorous testing of all sub-components could be carried out before aggregating them to a hierarchical system model.

Because component-oriented physical modelling inevitably leads to (large) systems of nonlinear differential algebraic equations (DAE) the freely available modelling language Modelica was chosen along with following reasons:

- It is component- and object-oriented which has the advantage of extensive code re-use.
- Components, models, examples, documentation etc. can be organized in *packages* (libraries) and re-used or shared with other Modelica users. Likewise, third-party libraries can be used in the project.
- Its syntax is based on mathematical descriptions of a component's *behaviour* (declarative language) rather than an algorithmic listing of computational operations. This makes it suitable for physical modelling and simulation.
- It strongly encourages *acausal modelling*. This implies that the decision of boundary values upstream/downstream to the information path is done just before the simulation. This is

opposed to causal modelling (e.g. Simulink) where the signal path is an essential part of the model design.

To translate and simulate the Modelica models the commercial integrated development environment (IDE) Dymola was used.

Fig. 9 shows the component hierarchy that constitutes the aggregated system model of Central Vestermark. The figure should be read as follows: *Central Vestermark Consists of controllers, pumps, valves, heat exchangers and heat pumps. The heat exchangers consist of pipe walls and flow models which, in turn, are made from flow and volume elements.* And so on. The figure also shows that some of the low-level components are repeated in several aggregated models which emphasizes the advantage of a component-oriented approach.

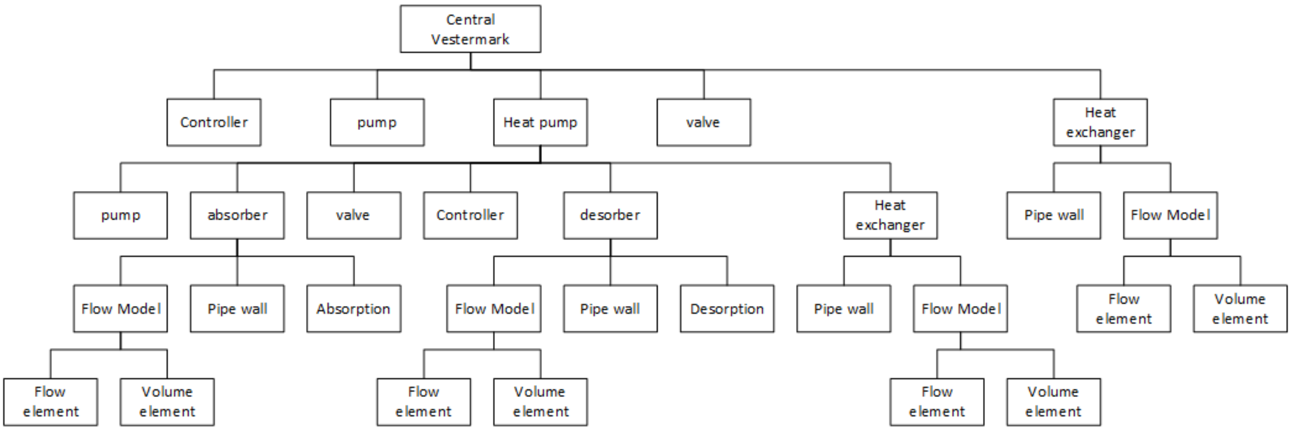


Fig. 9 Hierarchy of components in the Central Vestermark model.

The robustness of each sub-model and aggregated model has been validated with respect to

- varying mass/heat flow rates (positive, negative and zero),
- initialization capabilities (fixed/free initial values and steady-state initialization),
- number of control volumes (spatial discretization),
- coupling with adjacent components (considering the overall discretization scheme).

This has reduced the risk of errors in the larger models.

The ACHPs are equipped with control that ensures stable operation for varying operating conditions. These existing control loops in the plant has also been implemented in the simulation environment to mimic the behavior of the real system. However, the exact control implementation was unknown. A systematic control structure analysis, using relative gain arrays and scaled condition numbers, was therefore performed, to identify suitable pairings of inputs and outputs for decentralized control.

The final stage of model derivation is to identify model parameters that match the particular plant in question. The main parameters in the ACHP model are masses, volumes, and heat transfer coefficients. Fitting these parameters by hand is a time consuming and challenging task due the strong cross-coupling of the system. However, masses and volumes can be determined using datasheet information, and an automated procedure can be used for the remaining heat transfer coefficients. For the automated parameter identification procedure it is proposed to use a genetic search algorithm, which is reliable for global constrained optimization and can be implemented using freely available Python libraries.

5.4.4 Results from modelling and analysis

In this section we will show some of the results from the dynamic modelling and analysis of the actual process.

Dynamic Absorption Cycle Heat Pump Model

Three Modelica packages were developed during the project:

- LiBr_properties: Containing functions for the medium properties (and their partial derivatives) of the LiBr/water solution that is the working fluid of the ACHP in question.

  Implementing the LiBr properties in Modelica rather than calling an external library, *CoolProp*, reduced the computation time of some partial derivatives by a factor 4,000!
- Rankine: A library of common water/steam/flue-gas components used in Rankine Cycles, including evaporator and condenser models of an ACHP. Other water/steam components were available from the Modelica Standard Library.
- GreenFlex: Containing components using LiBr as working fluid (pumps, valves, sensors) and aggregated heat pump models including the full Central Vestermark model.

The figure below shows the icon of a single heat pump stage (left) and its internal composition (right). This is just one example of several components developed in the project.

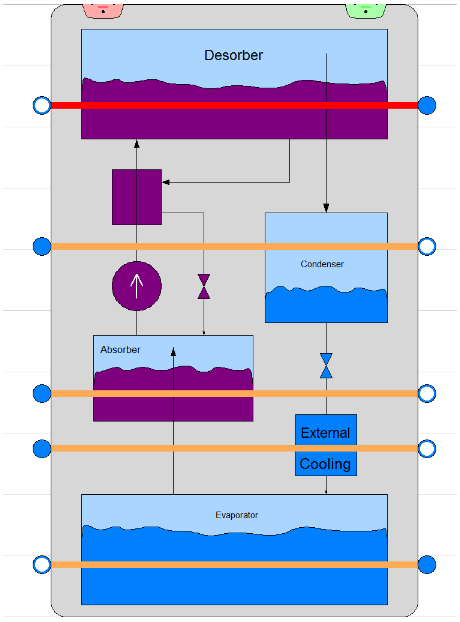


Fig. 10 Heat pump icon.

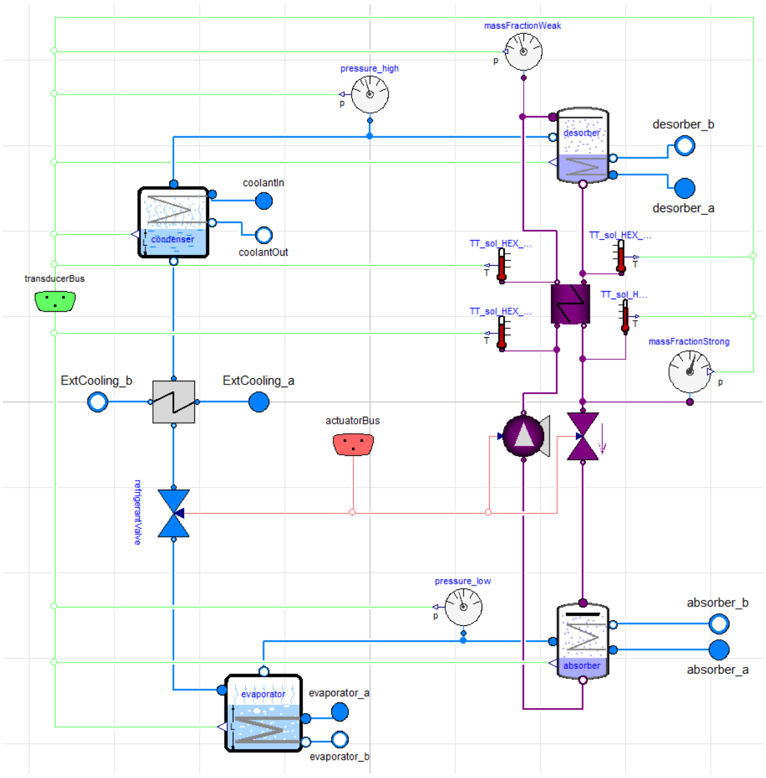


Fig. 11 Diagram for a single heat pump stage.

Control Structure Identification

Numerical analysis of different control structures has resulted in identification of recommended decentralized control loops for stable operation of ACHPs.

First, output selection was performed and feasible sets of four inputs and four outputs were identified (there is a total of four inputs available). Analysis using relative gain array calculation and scaled condition numbers was used to choose the best pairings in these sets and to find a suitable decentralized control structure, which is often favored by industry. Results have shown that in the case with four decentralized controllers at least two and at maximum three of them should control liquid levels in one of the four main ACHP components. Control of LiBr concentration is also important to avoid crystallization and simulation results have shown that selected control structures can give stable operation of the heat pump.

The analysis has in general given valuable insight into the operation of ACHPs and the most promising pairing identified shows good agreement with the behavior of the ACHPs in the plant at SFJV.

Parameter identification

In order to identify the unknown parameters of the model, heat transfer coefficients in particular, two approaches were taken:

1. Manual parameter fit to obtain a "good enough" agreement between simulation results and measurements.
2. Automated/formalized parameter identification using, e.g., a genetic algorithm optimizer (a short description is given in section 5.6) to determine the optimum parameters.

Fig. 12 shows measurements and simulation results for a single heat pump stage using parameters fitted with the two mentioned approaches. A small improvement was achieved with the optimized parameters.

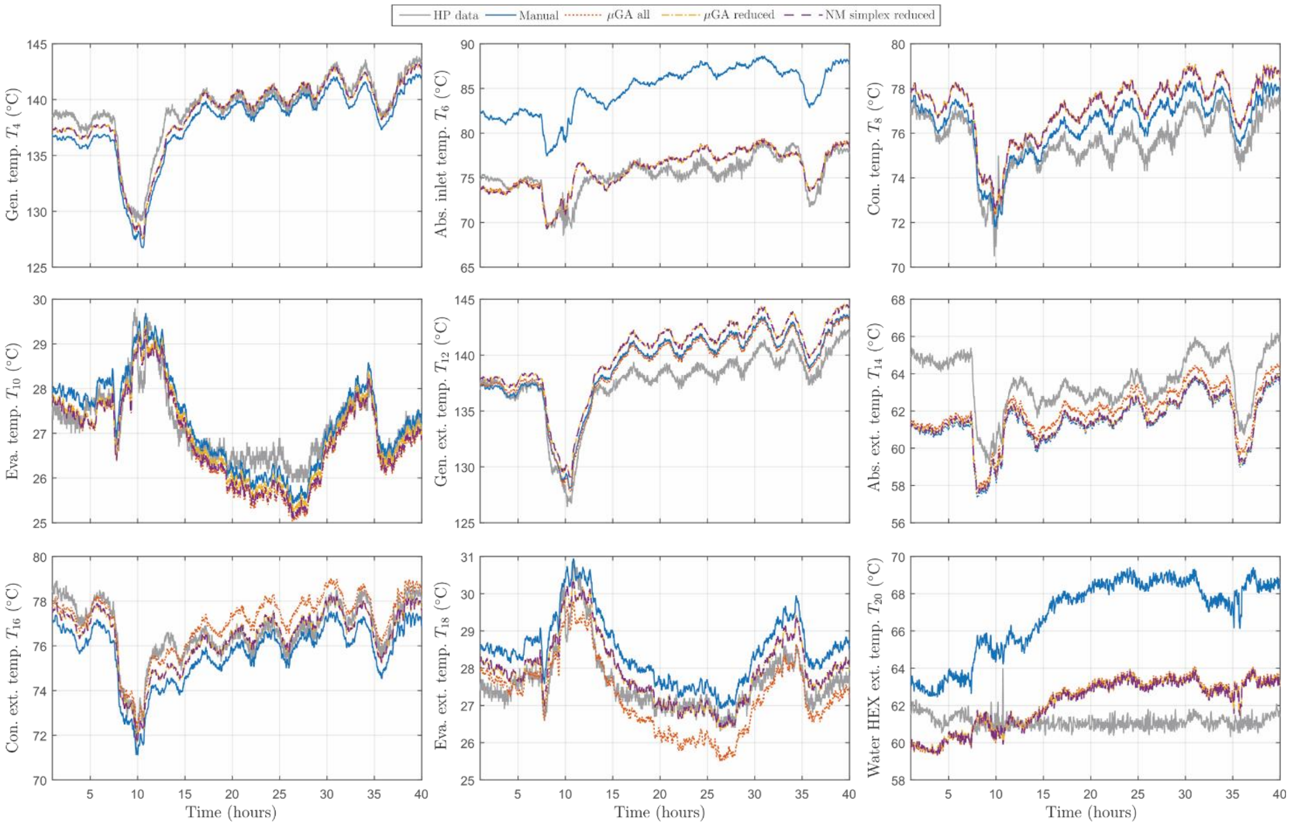


Fig. 12 Key ACHP measurement data along with simulated data using the model and the fitted parameters from manual tuning and different auto-tuned parameters. The first 20 hours was used as training data and the last 20 hours was used for validation.

It was discovered that a few of the parameters were not identifiable with the current set of measurements. For full parameter identification capability, it is recommended to install a sensor to measure the temperature of the solution leaving the absorber and to measure the external mass flow through the generator. However, the model with the identified parameters does show good agreement with measurement data.

5.4.5 *Full plant model*

Fig. 13 shows the complete Modelica model of Central Vestermark/Central Spang.

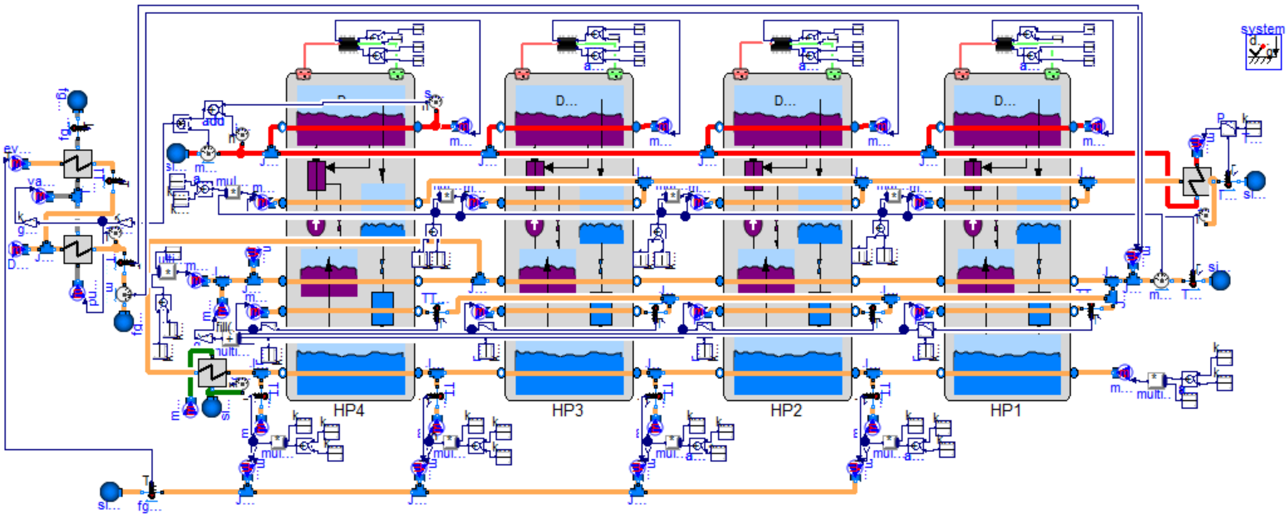


Fig. 13 Top-level Modelica component diagram of the Central Vestermark/Central Spang.

The *translated* model contains 503 dynamic states and 7,722 variables. The time for simulating 20,000 seconds with 2,000 output points is around 1 minute, depending on the initial conditions, input variations and number of discrete events during the simulation. This corresponds to more than 300 times the real-time.

5.4.6 *Description of on-line principles*

During the project a simple mock-up of an online simulator was developed with the purpose of testing various technologies and simulation strategies for an online dynamic simulation in FlexIQ. Since only a limited amount of time was spent on the prototype development an additional effort should be made in order to arrive at a fully functional online dynamic simulator.

The following tools/standards were tested in the mock-up:

- The Functional Mock-up Interface (FMI) standard used to export the nonlinear Modelica model including the numerical equation solver in a Functional Mock-up Unit (FMU).
- Python, a computer language with a large number of freely available packages for database connectivity, mathematics, code parallelization etc. It is supported by a big community and is often used as a capable and free alternative to Matlab.
- PyFMI, a Python package that significantly reduces the coding effort when simulating an FMU.

The advantage of using the FMI-standard instead of using Dymola's "remote controlling" capabilities (via DDE or OPC) is that the simulation model can be developed with any FMI compatible tool/language (including Modelica, Matlab, Labview and others) and the amount of simulation tool-specific code can be minimized.

The mock-up simulator is capable of:

- Inferring the pairing between a measurement signal and its corresponding model variable. The pairing information is contained in the variable description within the FMU, originating from the Modelica model.

- Retrieving the corresponding measurement points at the current simulation time from the measurement database.
- Validating the measurements against the max/min allowed values of the corresponding model variables. The max/min information is contained in the FMU.
- Performing a dynamic simulation from the current time, 60 seconds onward using the current measured boundary values and the state of the previous simulation as initial conditions.
- Saving the final simulation value of the model variables that have a corresponding measurement in the database

5.5 Performance monitoring of boiler

5.5.1 Customer needs and use cases

The customer rationale of FlexIQ is to acquire information on the plant performance hence its economic viability, an information not provided by the plant SCADA system. The information shall estimate how far the mode of operation is from an optimal mode in terms of monetary losses, degradation of components, and other suitable indicators. Typically, most of these indicators are technical, and not readily convertible to monetary units. Hence the tool must also provide assistance for diagnosing unsatisfactory indicator values.

The indicators shall be continuously calculated and made available for inspection. For each indicator are defined regions of acceptance, i.e. which values represent a normal, warning or critical state. If an indicator enters a non-normal region the assigned staff shall be alerted. These alarms add to the hundreds if not thousands of potential alarms of the SCADA system. The SCADA alarms have priority over the FlexIQ alarms as the former warns of imminent plant failure and safety hazards and the latter monitors slowly evolving degradations of equipment. A decentral CHP may have of the order 30 to 100 indicators.

To prevent information overload, the indicators are presented in two fashions: an overview comprising statistics of the actually most critical indicators, and a detailed view permitting inspection of any indicators as a time series. In a daily setting, only the overview will be presented to the staff.

An administrative user also shall be able to setup the regions of acceptance for each indicator. Any change shall be logged in order to assist a future fault diagnosis.

When an indicator signals a critical situation, the tool shall assist the user in diagnosing the possible causes. FlexIQ calculates hundreds of state values that are or cannot be measured. Two means are provided for inspection of these values:

1. A state diagram comprising major components and their in- and outgoing flows. The diagram is labelled with select state values at a chosen point-of-time.
2. Data extraction of a user-defined subset of measurement and model values as well as indicators over a user-defined period time. Data are downloaded to e.g. an Excel file for further analysis in a common setting.

The further diagnostic process typically is one of trial-and-error due to:

- Performance degradation may be due to a manifold of causes.
- Incidents are infrequent hence statistics are not available.
- Previous incidents may not be documented but in the memory of a few staff.
- Diagnoses based on modelling is a new discipline to be learned by the plant staff.

FlexIQ offers the means to setup a structured fault-finding process where the trivial parts are automated, at least to some extent. Over time, diagnosis of the most frequent incidents of degradation may be formalized and as such reduce the need for human intervention.

The overall purpose of performance monitoring is to increase the economical yield of the plant. This may be accomplished by:

1. Maximize market opportunity which translates into achieving the highest potential for electricity production as the district heating market typically is fixed on the short term.
2. Identify and prevent an outage due to a fast developing degradation.
3. Scheduling maintenance of components to minimize planned plant shutdowns.

Another purpose of performance monitoring is to identify significant degradation phenomena and assist the diagnosis of the root causes. Root causes may be categorized as:

1. Natural degradation e.g. slagging and fouling of heat transfer surfaces
2. Faulty instrumentation e.g. calibration errors
3. Non-optimal mode of operation.

5.5.2 Challenges on subscriber needs

- FlexIQ is a new product category hence the customers may have an above-normal risk perception with respect to the value of the tool, what workflow to apply, etc.
- Subscribers are prone to transfer their user experience expectations from the SCADA-system onto this tool, in particular regarding response time and interactivity. This may cause some initial disappointments depending on the implementation.
- Data ownership and security: Plant data are retrieved from the SCADA-system and stored in a separate database in order to offload the SCADA-system. The separate database may be external to the plant and located in any data centre. This raises issues of data security during transfer and when stored. The customer also has to maintain ownership to the stored measurement data and computed model data.

5.6 Performance optimization of heat pump

5.6.1 Subscriber/user situation and needs

One of the district heating plants at Sønderborg Fjernvarme (SFJV) A.m.b.a. is called "Central Vestermark". It consists of four interconnected absorption cycle heat pumps (ACHPs) primarily driven by geothermal heat and a wood-chip burner (see Fig. 14). Day-to-day production of district heating water in this plant needs to be adjusted to match the availability and prices of energy sources and the expected district heating demand. Once the desired production is determined, the next challenge is to choose set-points in the plant for optimized operation. The primary set-points are the mass flows through the individual heat pumps. However, setting these is not trivial, as they must be within the constraints of the individual units and because of the complex combination of parallel and series interconnection of ACHP components.

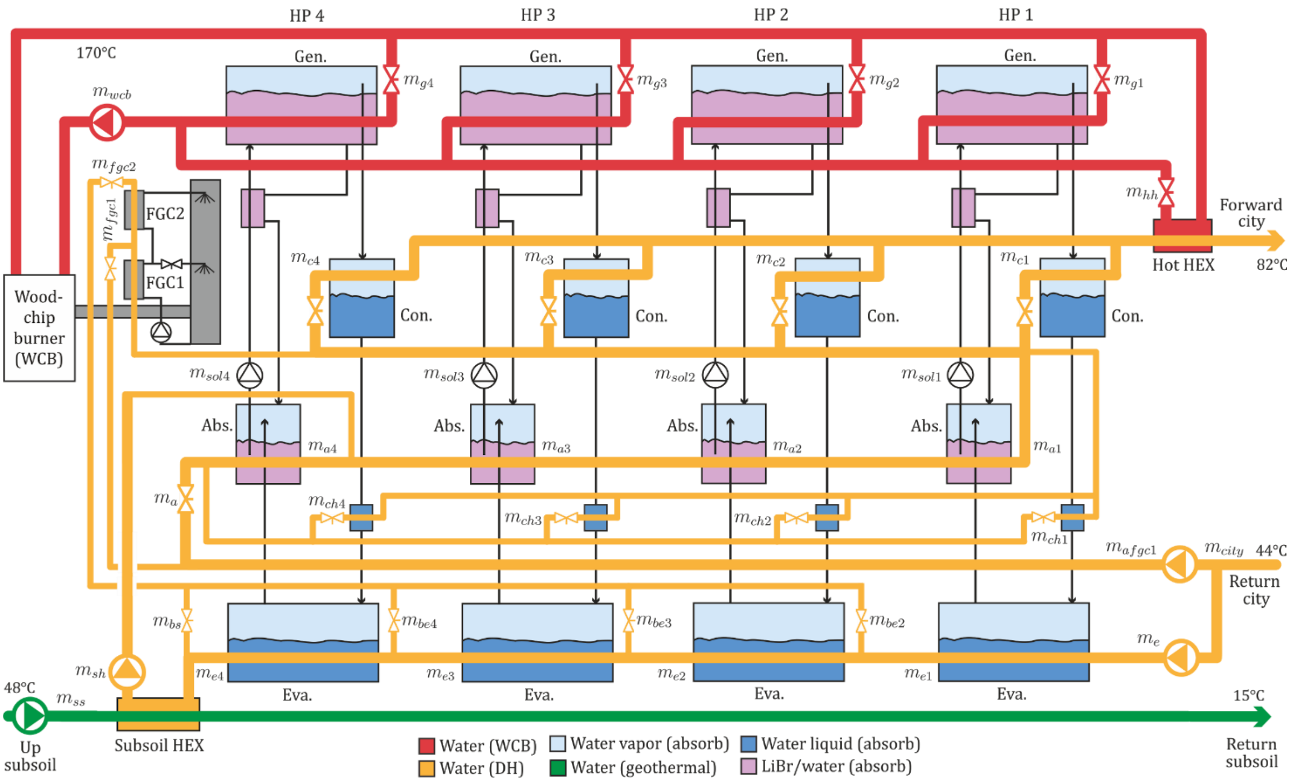


Fig. 14: Overview drawing of Central Vestermark configured to run in geothermal mode. Mass flows are indicated with m.

The ACHP manufacturer has specified a set of flow scalings together with acceptable deviations for each of the heat pumps. The flow scalings specify what the absorber and condenser flow should be relative to the flow in the evaporator. These scalings are designed for nominal operation with inlet temperatures equal to those shown in Fig. 14. However, the plant often operates at lower capacity, which gives different inlet temperatures. This gives operational problems such as dilution safety shutdowns to prevent crystallization of LiBr, which halts operation for ½-1 hour.

Measurement data from an example of a dilution safety shutdown on HP4 is shown in Fig. 15. All heat pumps operate until HP4 shuts down, which is indicated by the generator valve opening degree (OD). The solution temperature at this point is on the safety boundary, which is 5 K above crystallization, even though the absorber and condenser mass flows are well within their max/min bounds.

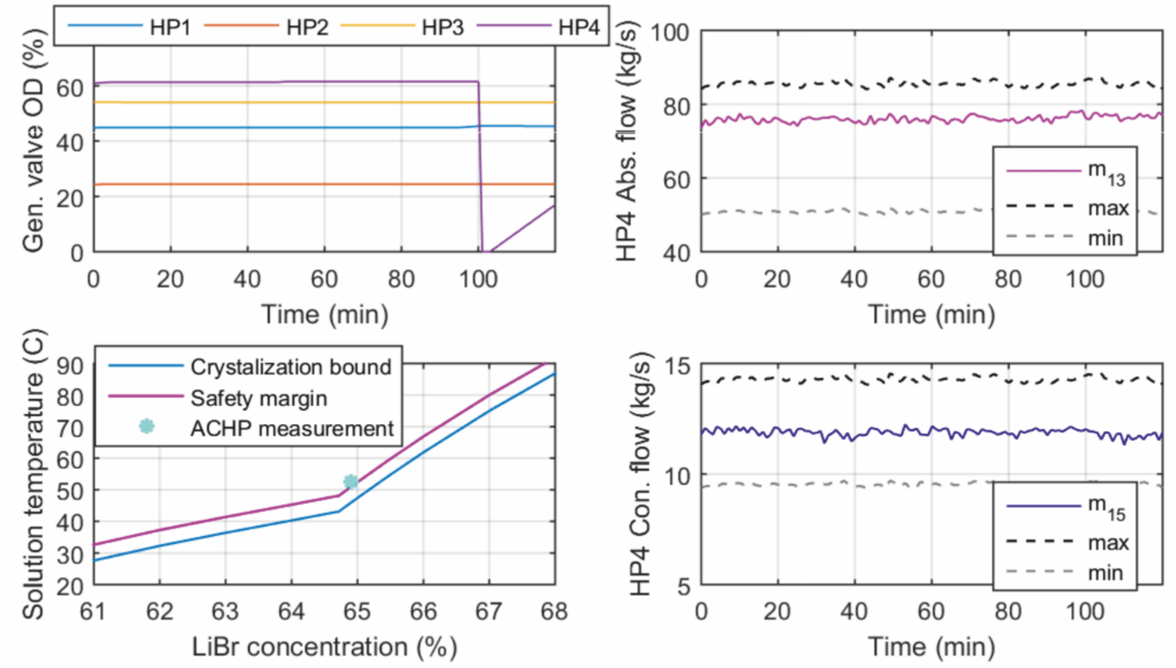


Fig. 15 Operational data during a dilution safety shutdown event on HP4 (happened 17/12-2013, 02:00-04:00).

One purpose of the project has therefore been to provide a tool for the plant operator that can automatically find optimized operational set-points for "Central Vestermark" within the real physical constraints of the plant, rather than using fixed flow scalings. Further, this will also showcase the potential use of the developed dynamic model in the FlexIQ platform.

5.6.2 Concept description, examples

The energy delivered by the wood-chip burner can be considered as an expense in the district heating plant whereas the subsoil water can be seen as a free source of energy (limited by amount of water that can be pumped up). The optimization task is therefore to use the least amount of wood-chip energy given a certain district heating demand. Further, constraints will be present such as target temperature of the water going to the city, temperature boundaries due to the risk of LiBr crystallization and water freezing, and liquid level boundaries in the vessels for adequate heat transfer.

An initial investigation on a single ACHP, illustrated in Fig. 16 (HP1 in Fig. 14), has shown how each inlet mass flow, each inlet temperature, and each set-point for internal controllers affects the overall heat pump performance. The results show that the best set-point for each individual input is located at an extreme value of the investigated ranges.

An example of a performance map for different values of condenser mass flow and generator LiBr concentration reference is shown in Fig. 17. The nominal point is given by measurement data from the plant, Opt. 1 is optimal set-points within the mass flow scaling constraints set by the heat pump manufacturer, and Opt. 2 is the optimal set-point using the true constraints of the system.

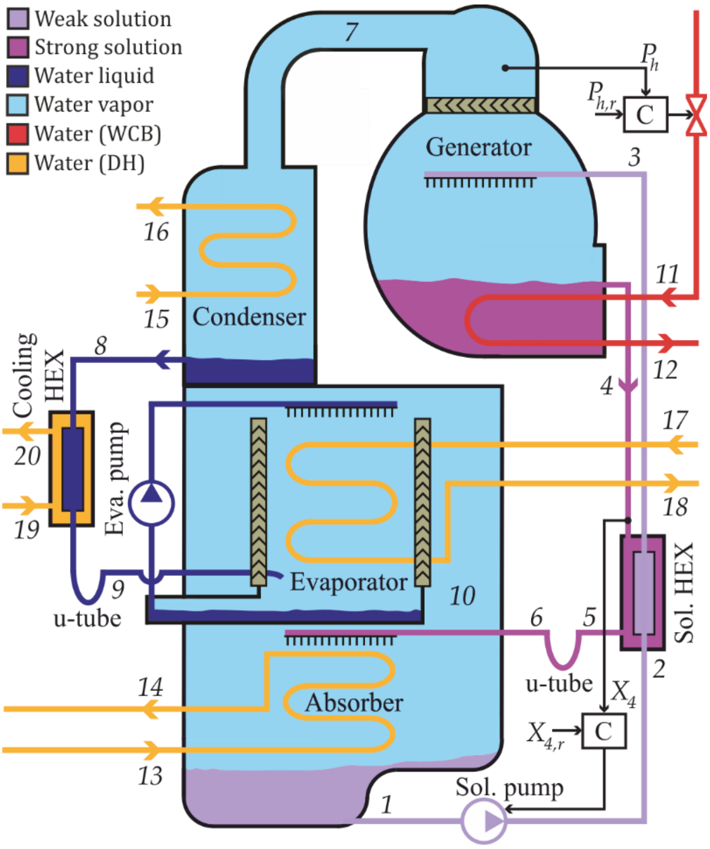


Fig. 16 Illustration of the ACHP under consideration with numbering of thermodynamic state points for reference. Internal controllers are indicated with a C.

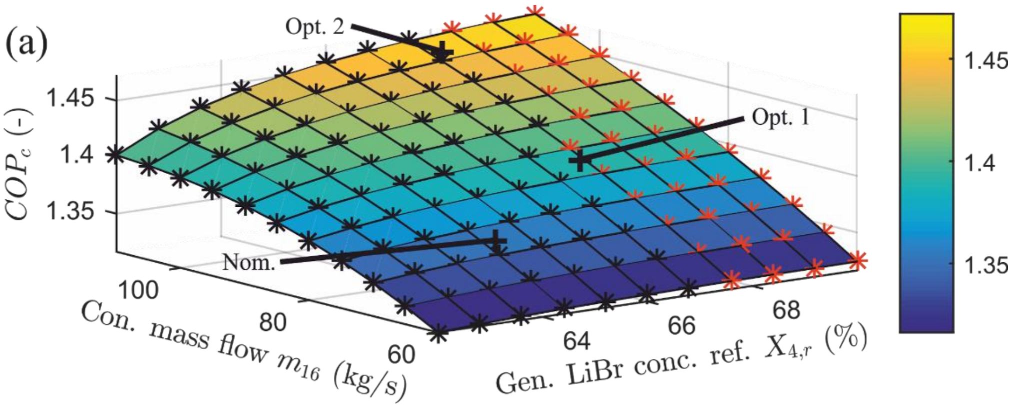


Fig. 17: Performance map for HP1 in terms of the coefficient of performance with indication of nominal and optimized operation. Red data points indication violation of crystallization bounds.

Simultaneous optimization multiple variables is required on the full Central Vestermark plant. Further, optimization of each ACHP individually does not necessarily lead to optimized operation of the whole plant. An example could be that optimization of the first ACHP suggests a high condenser flow, but this means that the condenser flow in the other ACHPs are reduced. The same optimization could also suggest a low evaporator flow, but this could eventually lead to sub-zero water temperatures in the last ACHP, which can destroy the equipment. The set-points will in general interact in highly nonlinear ways, which may lead to many local minima in the objective function. Further, the problem is subject to nonlinear operation dependent constraints to prevent crystallization of LiBr, large maldistribution of liquids in ACHP components, and freezing of water.

A heuristic stochastic approach for solving the optimization has been pursued based on research within genetic algorithms (GAs). GAs are gradient free methods, which are deemed more flexible and efficient than deterministic approaches for complex global optimization problems. The basics of GAs is imitation of biological/Darwinian evolution, i.e., survival of the fittest individuals (e.g., sets of set-points) in a population as it evolves over many generations. They rely on clever manipulation of random number generation to find a solution to a problem.

The type of GA employed in this project is called "micro-GA." It typically uses a small population of only five individuals as opposed to larger populations used in other types of GAs, which can be beneficial if the fitness evaluation of each individual is time consuming, as is the case here. Further, micro-GA is easier to implement than standard large-population GA, as it does not require tuning of parameters like mutation rate or population size. Additionally, the convergence speed is important because each evaluation of a potential set of set-points on the complex dynamic simulation model is time consuming and micro-GA is often quicker than large-population approaches.

Four different optimization case studies on the full Central Vestermark model, with micro-GA as solver, has been investigated with an increasing number of independent optimization variables.

Case 1: $m_{c2}, m_{c3}, m_{c4}, m_{be2}, m_{be3}, m_{be4}, m_e$.

Case 2: $X_{4,r,1}, X_{4,r,2}, X_{4,r,3}, X_{4,r,4}, P_{h,r,1}, P_{h,r,2}, P_{h,r,3}, P_{h,r,4}$.

Case 3: $m_{c2}, m_{c3}, m_{c4}, m_{be2}, m_{be3}, m_{be4}, m_e, X_{4,r}, P_{h,r}$.

Case 4: $m_{c2}, m_{c3}, m_{c4}, m_{be2}, m_{be3}, m_{be4}, m_e, X_{4,r,1}, X_{4,r,2}, X_{4,r,3}, X_{4,r,4}, P_{h,r,1}, P_{h,r,2}, P_{h,r,3}, P_{h,r,4}$.

Each case study is also subject to the following flow constraints:

$$\Delta m_{c1} = 0 - \Delta m_{c2} - \Delta m_{c3} - \Delta m_{c4}$$

$$\Delta m_{bs} = 0 - \Delta m_{be2} - \Delta m_{be3} - \Delta m_{be4}$$

$$\Delta m_{afgc1} = -\Delta m_e$$

Further, a total of nine state constraints are checked in the simulations; the solution temperature in the four ACHPs must be 10 K above crystallization temperature (shutdown happens at 5 K for safety reasons), the absorber level in the four HPs must not deviate more than 30 % from the nominal level (to maintain good heat transfer), and the coldest water in the plant must stay 5 K above freezing temperature (again for safety reasons). More conservative margins can of course be used if safer operation is favored. Note that it is enough to ensure an adequate absorber level, as the levels in the condenser and generator are maintained by overflow mechanisms and the rest of the mass is distributed among the evaporator and absorber.

Table 1 summarizes the result for each of the studied cases. Especially Case 3 seems promising in terms of saving potential (4.6 %) and average convergence time (88 min). However, if time permits, then Case 4 provided the highest saving potential (4.9 %). Note also that the optimization saved a history of the performance of all the set-point combinations that did not violate any constraints. Approximately 14 % difference in performance is observed between the best and worst of these results, which indicate that larger savings could occur if the set-points are poorly chosen.

Parameter	**Nom.**	**Case 1**	**Case 2**	**Case 3**	**Case 4**
Q_{city}(MW)	26.19	26.19	26.19	26.19	26.19
Q_{sh}(MW)	4.688	4.386	5.144	4.774	4.791
Q_{fgc}(MW)	6.346	6.753	6.532	6.964	6.99
Q_{wcb}(MW)	15.16	15.06	14.52	14.46	14.42
Savings vs nom. (%)	0	0.684	4.21	4.616	4.904
Savings vs worst (\%)	0	8.745	5.302	14.17	13.88
Convergence time (min)	0	25.84	131.2	87.66	292.2

Table 1: Summary of optimization results. The heat transfer rates are total city demand Q_city(fixed), subsoil heat exchanger Q_sh, total from the flue gas condensers Q_fgc, and total from the wood-chip burner Q_wcb, respectively. Convergence is the time it takes to reach 90 % of the maximum savings using a standard quad-core CPU laptop.

The presented results involve steady-state operating conditions, which is reasonable since ACHPs are typically not intended for rapid load changes and similar transient behavior. However, as illustrated by the simulation results shown in Fig. 18, the dynamics involved in controlling the ACHP to the optimal operating conditions cannot be ignored entirely. The simulation shows a case where dynamic effects would have caused a dilution safety shutdown when moving from one set-point to another, as well as a choice of control signal which avoids the shutdown.

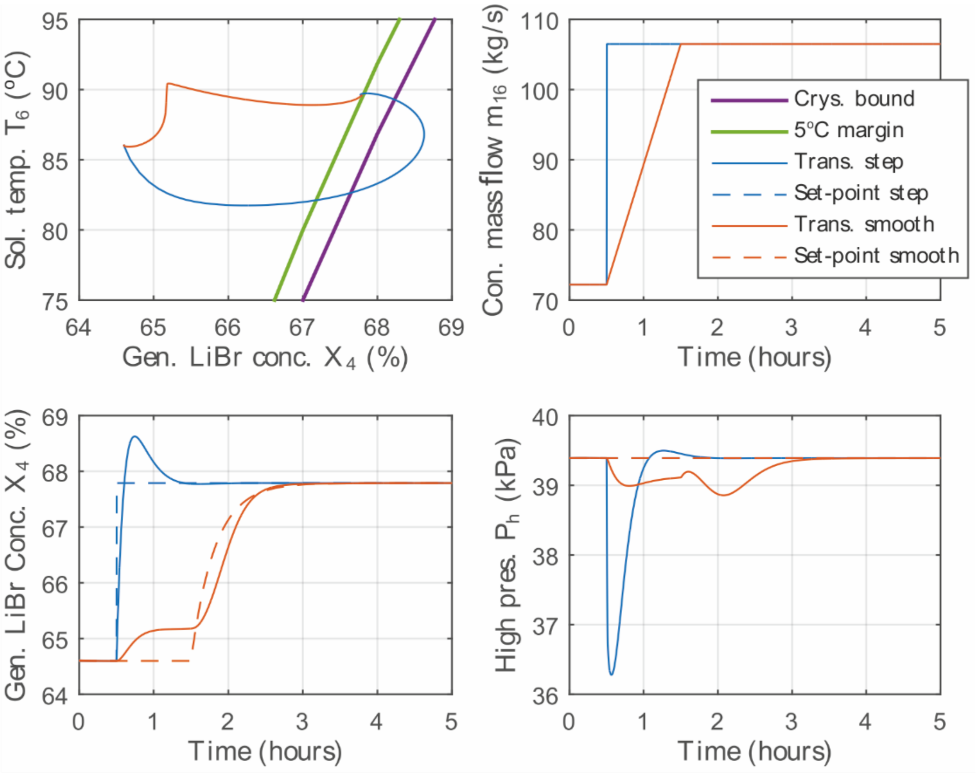


Fig. 18: Simulation results using either a step or a smooth change in set-points, when going from the nominal situation to Opt. 2 in Fig. 17Fig. 5.6.4.

FlexIQ can thus assist an operator not only in finding optimal steady state operating conditions, but also in finding control strategies for realizing these operating conditions without running the risk of safety shutdown.

5.7 Load scheduling optimization

This chapter reviews the work made in WP2 and WP6, concerning use cases and estimated economic gains by using the developed FlexIQ. Finally, the chapter reflect upon the future opportunities for FlexIQ taking into account the development in the electricity markets.

5.7.1 *The use cases and estimated economic gains of FlexIQ*

The selected use cases Sønderborg Fjernvarme, Randers Fjernvarme and Sæby Fjernvarme represents typical plants for using FlexIQ.

Annual heat production in use cases	
Sønderborg Fjernvarme	301,000 MWh/year
Randers Fjernvarme	572,200 MWh/year
Sæby Fjernvarme	77,500 MWh/year

In each case, it is to be expected that by means of the FlexIQ, the performance of some production units can be improved and thereby resulting in a higher operational flexibility and performance of the overall plant. To demonstrate the economic potential of the improved performances of these energy units, an energyPRO model of each system is developed. In the energyPRO models, the improved performances of each unit are in the tables below is as an example assumed to result in a 5% increase in the heat production capacity.

In the Sønderborg case, the effects of improved performances of the wood chip boilers, absorption heat pumps, geothermal well and the waste incinerator are analysed. The below tables shows the specifications of the selected units.

Sønderborg Waste incinerator			
Operation modes	Cogeneration excl. condensing	Cogeneration incl. condensing	Bypass of the steam turbine
Max fuel intake [MW]	23,9	23,9	23,9
Electricity production [MW]	4,0	4,0	0,0
Heat production [MW]	16,3	20,6	25,6
Electricity consumed [MW]	0,0	0,0	1,0

Sønderborg Woodchip fired boiler, absorption heat pumps and geothermal well			
Operation modes	Woodchip boiler	Woodchip boiler and heat pumps	Woodchip boiler, heat pumps and geothermal well
Max fuel intake [MW]	25,3	25,6	25,6
Heat production [MW]	24,0	26,0	29,0

Electricity consumed [kW_{el}/MW_{heat}]	5,73	5,73	9,14

The results of the simulations are shown in the below table. In order to show the sensitivity to low electricity spot prices, the simulation is repeated with 10% reduced prices. In this case, the electricity spot price level has only little effect on the annual savings.

Sønderborg Fjernvarme	**2015 spot prices**		**10% reduced spot prices**	
	Annual result (DKK)	Annual savings (DKK)	Annual result (DKK)	Annual savings (DKK)
Reference	59.124.044	-	58.533.178	-
5% increased heat production from combined plant	60.379.705	1.255.661	59.778.252	1.245.074
5% increased heat production from waste incinerator	59.359.480	235.436	58.751.834	218.656
New bidding strategy: Special regulation*	59.458.024	333.980	58.867.158	333.980

As can be seen in the table, an increased heat production capacity of 5% results in an annual saving of 1.26 M. DKK for the combined plant and 0.24 M for the waste incinerator.

In the Randers case, improved performances of the wood chip fired CHP and the steam-to-hot-water heat exchanger are analysed. The specifications of these units are shown in the below figures.

Randers Woodchip fired CHP		
Operation modes	Summer	Winter
Max fuel intake [MW]	95,9	195,4
Electricity production [MW]	22,0	47,0
Heat production [MW]	70,0	140,0

S Randers team-to-hot-water heat exchanger		
Operation modes	Summer	Winter
Max fuel intake [MW]	95,9	195,4
Heat production [MW]	87,0	176,7

Randers Fjernvarme	**2015 spot prices**		**10% reduced spot prices**	
	Annual result (DKK)	Annual savings (DKK)	Annual result (DKK)	Annual savings (DKK)
Reference	-123.021.773	-	-126.500.160	-
5% increased heat production from woodchip fired CHP	-117.870.749	5.151.024	-121.128.656	5.371.504

The results of the simulations are shown in the below table. An increased heat production of 5% on the woodchip fired CHP results in an annual saving of 5.15 M. DKK. In this case, reduced electricity prices increase the value of the improved performance. This is because the improvement also increases the flexibility of the units because its electricity production is less bound to when heat must be produced.

In the Sæby case, improved performance of the natural gas fired engine and the absorption heat pump is analysed. The specifications of the unit are shown in the figure below.

Sæby Natural gas fired engines incl. absorption heat pump	
Max fuel intake [MW]	28
Electricity production [MW]	12
Heat production [MW]	17

The results of the simulations are shown in the below table. An increased heat production of 5% on absorption heat pump, results in an annual saving of 0.25 MDKK.

Sæby Fjernvarme	2015 spot prices		10% reduced spot prices	
	Annual result (DKK)	Annual savings (DKK)	Annual result (DKK)	Annual savings (DKK)
Reference	-25.327.173	-	-26.416.340	-
5% increased heat production from woodchip fired CHP	-25.072.963	254.210	-26.200.661	215.679

5.7.2 *Electricity market trends*

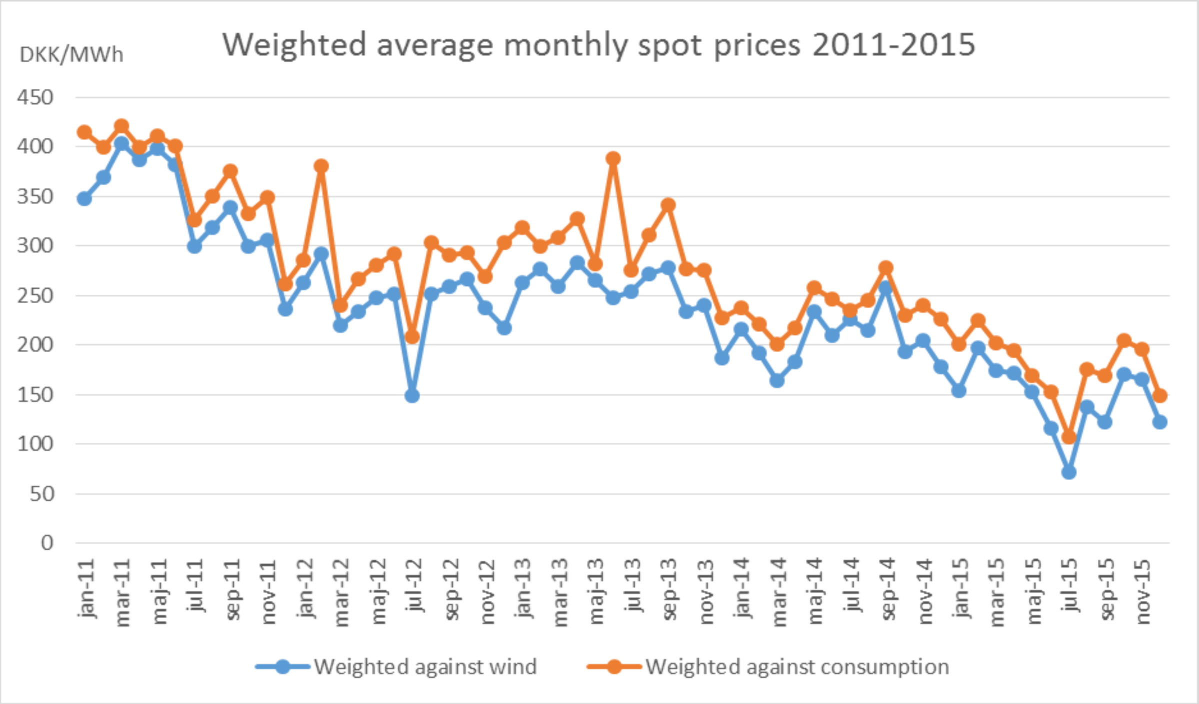
The future opportunities for FlexIQ when taking into account the development in the electricity markets takes it starting point in that the transition to a renewable energy system is characterized by introducing large amounts of fluctuating wind and photo voltaic production. This transition thus requires an overwhelming electrification of society, amongst others of transportation, heating and cooling of individual houses and that district heating and cooling plants (DHCP) which is the focus of FlexIQ primarily will be served by electrical heat pumps and electrical chillers.

Heating and cooling constitutes around half of the EU's final energy consumption and is the largest energy end-use sector, ahead of transport and electricity. Today around 85% of heating and cooling is produced from natural gas, coal, oil products and non-RES electricity. Only 15% is generated from renewable energy.

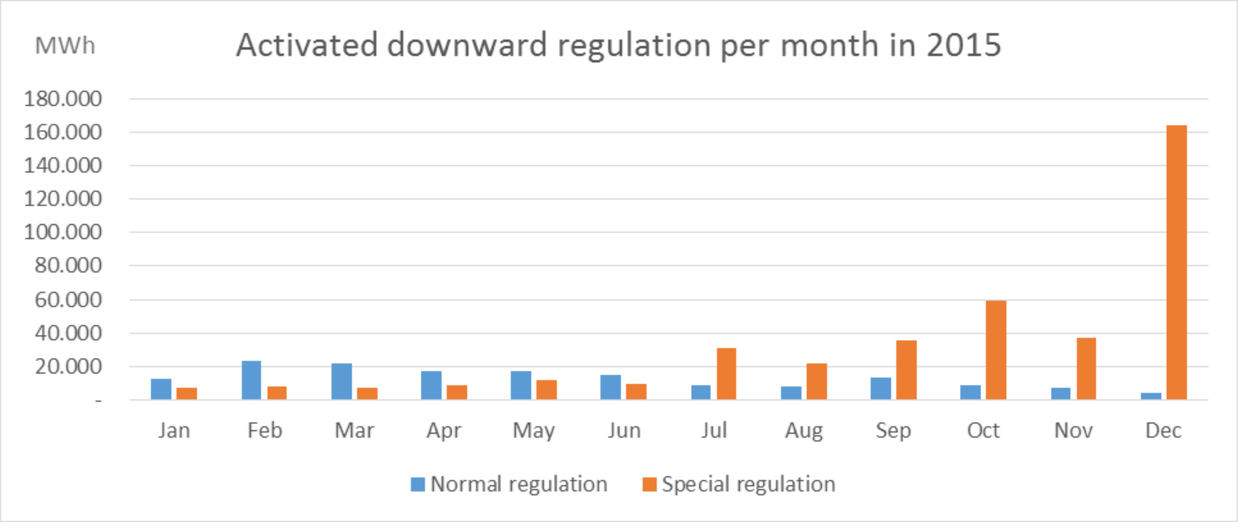
Furthermore, due to urbanization, it is also expected that DHCP have to solve an even larger task in the future.

In existing fossil fuel-based energy systems, DHCP has been characterized by not participating significantly in the integration of the large amounts of fluctuating wind and photo voltaic production. FlexIQ represent a new generation of energy system simulation tools for daily or short term planning of operation of DHCP, also when this operation will be determined from biddings in the electricity markets and affected by availability of fluctuating energy sources and needs for dispatchable productions and demands.

Over the past few years, there has been a decreasing tendency in the electricity prices. Since 2011, the average annual spot price in DK1 has fallen from 357.32 DKK/MWh to only 170.75 DKK/MWh in 2015. The trend is of cause influenced by many different varying factors such as outdoor temperature, precipitation, wind, consumption etc., but as it can be seen in the below figure there is a decreasing tendency even when prices are weighted against monthly wind power production and consumption in West Denmark.



While the spot price has been historically low in 2015, the need for downward regulation in DK1 has been extremely high. Especially the need for special regulation has increased during the last year, which can be seen in the figure below.



This development is due to the fact, that the German TSO to a higher extent than before buys downward regulation in Denmark in order to avoid closure of wind turbines in Northern Germany.

Normal regulation is settled after a marginal pricing system, whereas special regulation is settled as Pay-as-bid. These different pricing systems calls for different bidding strategies, but this is not possible since all bids can be activated as either normal or special regulation. So in order to have the most optimal bidding strategy, it is important to follow the development in this market.

5.8 On-site testing

The performance monitoring has been slight at Sønderborg and extensive at Verdo. The primary use cases of 1) monitoring and 2) diagnosing a fault have been tested.

At Verdo, the tool was tested first by 3 super-users and later introduced to the operational staff through group sessions. A centrally placed computer display was setup to run the tool continuously. Also, the back-office users run it continuously besides other applications.

Scalability: The scalability of the tool was unexpectedly tested when after the initial deployment, the interest and user load was so high that the web and database servers stalled. Once this congestion was discovered, it was remedied in less than 10 minutes by doubling the database capacity and spawning an additional web server.

Relevance: Within the first two weeks after deployment at Verdo, two faults were discovered and diagnosed.

1. Two indicators based on measured and computed pressure drop were unexpectedly critical for a longer period of time. This kind of fault was not reported by the SCADA system and as such raised initial doubt of whether this was a fault of the tool or the plant. A manual inspection of the plant found the cause to be faulty pressure sensors.
2. Another indicator showed poor performance of the heat exchangers of the flue gas absorber-system. This performance degradation could only be computed using a model, as not all measurements were available. The incident elicited a dismantling and cleaning of all four heat exchangers.

Learning: This kind of model-based tools are new to the staff and requires some habituation. The concept of an indicator is well understood, but in case of a critical indicator the next natural step, diagnosis, is fuzzier. The main reason is that the root cause may be one of many and may not be seen before. The tool provides assistance, as time series of model data and indicators may be extracted for further analysis in Excel. Also, the tool's diagram feature enables an overview of states across the plant at specific points-in-time.

Value: The point is, that the tool puts the attention of the staff where it is most likely to pay off. This may save some unnecessary effort, repairs and replacements. The diagnosis is hard to standardize as events are rare and may have a manifold of potential causes. But it is also where the staff's experience and knowledge of the plant comes into play. This may provide more staff satisfaction as the path to success becomes shorter and more issues be coped with.

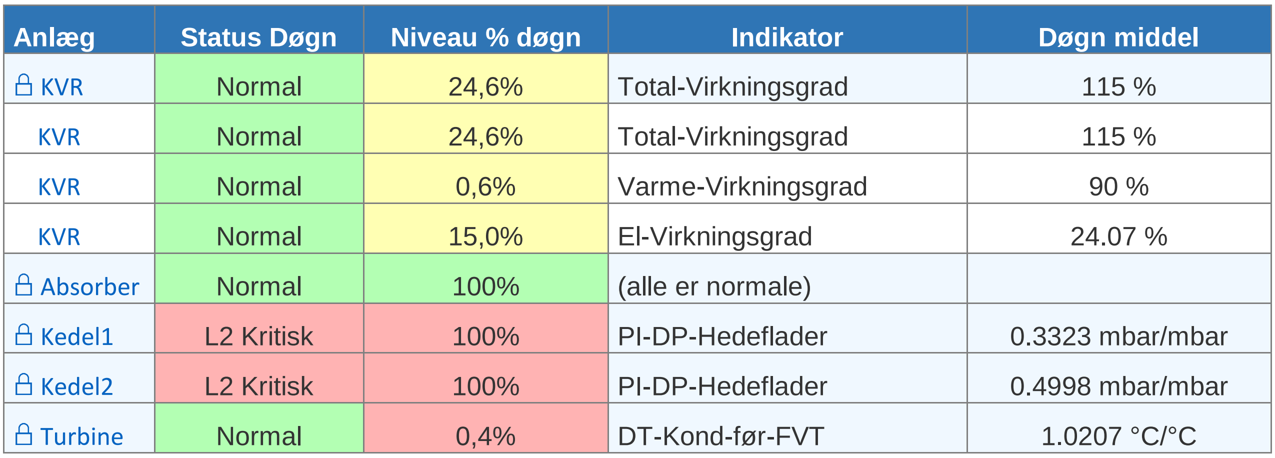
5.8.1 Example of usage of performance indicators

On the Verdo plant are defined 34 indicators across the 4 sub-plants {Kedel1, Kedel2, Turbine, Absorber} and the entire plant {KVR}. An overview provides a rolling statistic over the recent 24 hours and is updated every minute. A snapshot of the overview is shown in Table 2.

Alarm states of indicators are color-coded where {green, yellow, red} indicate {normal, warning, critical} levels. For each plant is computed the most critical indicator, marked with 🔒, and in addition are shown a few customer-selected indicators.

The first thing to trigger attention is the column "Niveau % døgn", which shows the indicator having the most critical state for the largest share of the 24 hours. In the particular case shown in Table 2, the 2nd and 3rd lowermost rows exhibit two indicators both being in the critical state for all 24 hours. Their value should range between 0.0 and 1.0 where 1.0 is the ideal value.

The root cause of the critical level was faulty pressure sensors, faults not signaled by the SCADA system. The Turbine also exhibits a critical indicator but only for 0.4 % (6 minutes) of the 24 hours and the average state was Normal.



Anlæg	Status Døgn	Niveau % døgn	Indikator	Døgn middel
🔒 KVR	Normal	24,6%	Total-Virkningsgrad	115 %
KVR	Normal	24,6%	Total-Virkningsgrad	115 %
KVR	Normal	0,6%	Varme-Virkningsgrad	90 %
KVR	Normal	15,0%	El-Virkningsgrad	24.07 %
🔒 Absorber	Normal	100%	(alle er normale)	
🔒 Kedel1	L2 Kritisk	100%	PI-DP-Hedeflader	0.3323 mbar/mbar
🔒 Kedel2	L2 Kritisk	100%	PI-DP-Hedeflader	0.4998 mbar/mbar
🔒 Turbine	Normal	0,4%	DT-Kond-før-FVT	1.0207 °C/°C

Table 2: Overview of most important indicators of the Verdo plant. The column "Status Døgn" shows rolling average state over the recent 24 hours, the column "Niveau" shows the share of these 24 hours where the indicator was in the most critical state and the column "Døgn middel" shows the average value over these 24 hours.

A detailed view over the most recent 30 days of one of the critical indicators is shown in Fig. 19 Even with a 60 minutes moving average filtering, a significant noise level is observed. This is due to the very dynamic behavior of the flue gas pressure which is measured by a discrete sensor rather than an array of sensors.

The faulty pressure sensors were found by inspection of data-augmented plant diagrams where the calculated values, but not the computed ones, appeared reasonable.

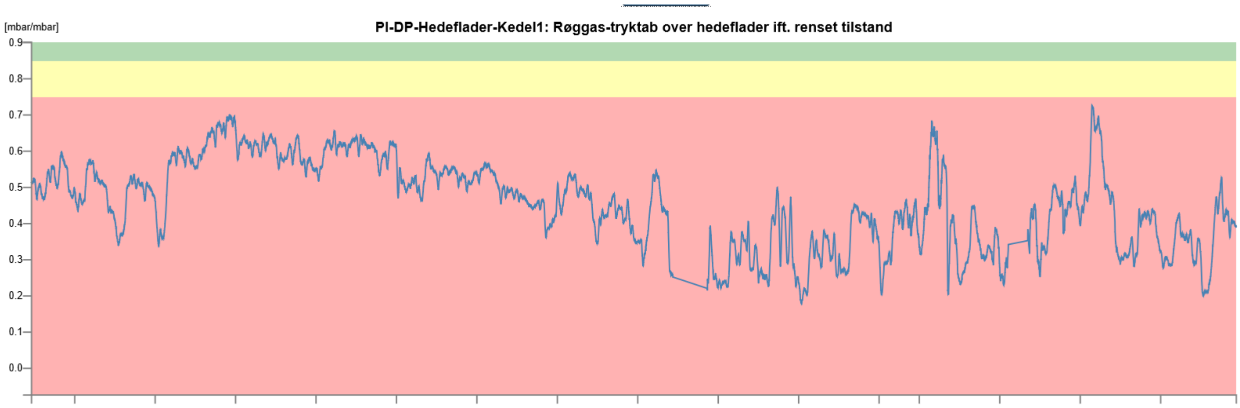


Fig. 19: Indicator "Kedel1.PI-DP-Hedeflader" for the most recent 30 days filtered as 60 minutes moving average.

5.9 Dissemination

5.9.1 List of Publications

K. Vinther, R. J. Nielsen, K. M. Nielsen, P. Andersen, T. S. Pedersen, and J. D. Bendtsen, *Absorption Cycle Heat Pump Model for Control Design*, in: Proc. Eur. Control Conf. (ECC), Linz, Austria, 2015, pp. 2233-2239.

K. Vinther, R. J. Nielsen, K. M. Nielsen, P. Andersen, T. S. Pedersen, and J. D. Bendtsen, *Analysis of Decentralized Control for Absorption Cycle Heat Pumps*, in: Proc. Eur. Control Conf. (ECC), Linz, Austria, 2015, pp. 2240-2246.

K. Vinther, R. J. Nielsen, K. M. Nielsen, P. Andersen, T. S. Pedersen, and J. D. Bendtsen, *Coefficient of Performance Optimization of Single-Effect Lithium-Bromide Absorption Cycle Heat Pumps*, in: Proc. IEEE Conf. Control Appl. (CCA), Sydney, Australia, 2015, pp. 1599-1605.

K. Vinther, T. S. Pedersen, and K. M. Nielsen, *Absorption Heat Pump Parameter Identification using a Micro Genetic Algorithm*, Submitted to Proc. Eur. Control Conf. (ECC), Aalborg, Denmark, 2016.

K. Vinther, R. J. Nielsen, P. Andersen, and J. D. Bendtsen, *Optimization of Interconnected Absorption Cycle Heat Pumps with Micro-Genetic Algorithms*, Submitted to Journal of Process Control, 2016.

T. Moelbak, *Design and Control of Energy Systems in Denmark – Challenges and Opportunities*, Submitted to Journal of Process Control, 2016.

5.9.2 Conference Participation

Conference	**Place**	**Date**	**Attendees**
10th International Modelica Conference	Lund, Sweden	10/3-12/3, 2014	Rene J. Nielsen
14th European Control Conference	Linz, Austria	15/7-17/7, 2015	Kasper Vinther, Jan D. Bendtsen
11th International Modelica Conference	Versailles, France	21/9-23/9, 2015	Rene J. Nielsen, Kasper Vinther
Multi-Conference on Systems and Control	Sydney, Australia	21/9-23/9, 2015	Palle Andersen, Jan D. Bendtsen
15th European Control Conference	Aalborg, Denmark	29/6-1/7, 2016	Awaiting decision
15th European Control Conference	Aalborg, Denmark	29/6-1/7, 2016	Tommy Mølbak

6 Utilization of project results

6.1 Commercial perspectives of tool

Initially, the target group will be power and heat producers in Denmark based on thermal plants, nearly 900 plants. Later on it will be extended to international energy producers whose power markets are expected to develop similarly to the Danish markets. Integrated plants featuring biofuel production are also a future target group.

The target group already experiences an increasing complexity of market demands. CHPs are supposed to deliver not only energy-related products, but also flexibility products – i.e. balancing the power markets. In order to optimize the market offers as well as internal costs there is a need to increase the awareness of the physical capabilities of the plants. FlexIQ will fill this gap.

The end product as it is by the end of the project will have several value propositions for the end users, and these have been demonstrated by some examples through the project:

- **Minimized operational costs**. On-line information on efficiencies and calculation of performance consequences of production scenarios will ensure that operators and control system can interact with the process manually or automatically. The Sønderborg on-site application has demonstrated this type of value creation, and the Verdo case as a full commercial application has confirmed the benefits. Expected yearly fuel savings in general are 0,5 % of fuel costs or in case of Waste-to-Energy a 0,5% surplus of earnings on power markets.
- **Optimized market bids**. Physical plant models will give more accurate information on how much flexibility a plant can offer to the market – depending on the planned load schedule on other markets and depending on the operational state of the plant. The project has demonstrated these issues through two cases. Optimized operation of the absorption heat pump ensuring maximized COP was demonstrated on the Sønderborg plant, even though it was not brought in to and on-line application. Improved information on market flexibility for improved load scheduling has also been simulated for selected plants, showing significant potential.
- **Reduced maintenance costs**. FlexIQ will provide the operators with indicators of upcoming failure modes and of slowly varying degradation hence make it possible for the operators to interfere in due time – e.g. to increase service life or prevent forced outages. This was demonstrated through the on-line applications through on-line calculation of super heater fowling in Sønderborg waste-to-energy boiler. In general, expected yearly savings are 1% of maintenance costs.

Added Values will pursue the market opportunities of the product. The Verdo case briefly described in this report already represents the first full commercial application.

6.2 Value on Danish energy policy

The Danish government has set the long term goal that Danish energy production shall be 100% based on renewables in 2050. The short term goals have also been set, leading to several challenges:

- Through expanded offshore wind production and use of biomass, it is expected that renewables will cover almost 70% of Danish electricity production in 2020, including 50% wind power. This means that fluctuating sources will increase and substitute production from controllable units, leading to a huge balancing challenge. The **need for flexibility and dispatch ability** to compensate the fluctuations of the power system will increase dramatically.

- Combined power and heat production still has high priority to ensure an efficient utilization of resources. This means that secure and efficient supply of district heat is important, leading to increased complexity of daily operation. The **need for performance optimization** of combined heat and power production will increase further, and even further with new products like hydrogen, bio fuels and district cooling.

- Introduction of new technologies to improve utilization of biomass or efficiency of integrated plants are supported (biogas, heat pumps, etc.). Thus productions plants will grow in complexity, leading to challenges in planning and control. The need for **optimizing availability and production planning** of complex plants will increase.

The project has demonstrated that FlexIQ is able to target all of these three challenges by supporting operation and planning on existing plants as well as on new and retrofitted plants. FlexIQ will improve return on investments for the asset owner and ensure adaption to Danish energy policies.

6.3 R&D results

The project has developed the following methodologies in order to address necessary research questions:

- **Prediction of future potential power and heat trajectories**

  In this context, it is important to note that the complexity of the models should be kept as low as possible, so that predictions with many different sets of initial conditions and exogenous inputs can be carried out in a computationally efficient manner, allowing for families of scenarios to be reliably evaluated. A method based on Genetic Algorithms for optimizing dynamic transition of load changes of the heat pump has been developed and demonstrated through simulations.

- **Estimation of "hidden" system states**

  Specific plant structures are likely to require development of new estimation techniques that match the sensor equipment available. An example where the complexity of the model should be investigated would be if the plant operator wants to utilize heat capacity of the water circulated in the tubes of a district heating system. The project has developed a method for balancing and optimizing the district heat production and supply ensuring end user product quality. This was done with a MSc project as center of gravity.

- **Operation of green energy plants under fast gradients**

  In a power market with strongly increased emphasis on flexibility, one competitive edge will be related to the ability to generate steep power gradients. The dynamics of the subsystems constituting the entire plant are important and in some cases it will be imperative to introduce models which allow control with fast transients for which the current control system has not been intended. In this case a high fidelity model of the heat pumps has been used for optimizing the COP without compromising the availability of the plant. Furthermore, a method for bringing this type of model on-line has been developed.

- **Operation of green energy plants away from the usual operational envelope**

  If the full possible envelope of operation is exploited, the system will be operated far away from the set-points for which it was originally designed. This in turn implies that there is a need to develop new modes of operation and new control algorithms such that the system also is operated in the best possible way in these new regions. The combination of high fidelity modelling and GA-based optimization has shown a feasible solution through simulations.

- **Optimizing control of a portfolio of plants with different characteristics**

  The performance specification of the upper level controller will have varying character depending of which services the operator is obliged to deliver. This will include obligations to deliver response times in different timescales, certain quantities of power and certain quantities of energy. To support the operator, it is important to give him access to updated information which can estimate flexibility in terms of possible rate of change, available energy storage capacity and feasible operating range for subsystems and cost in terms of extra fuel consumption, wear etc. The FlexIQ architecture can comply both the steady-state models, the dynamic models, and can execute cross optimized operational measures on the different types of models with diverse fidelity.

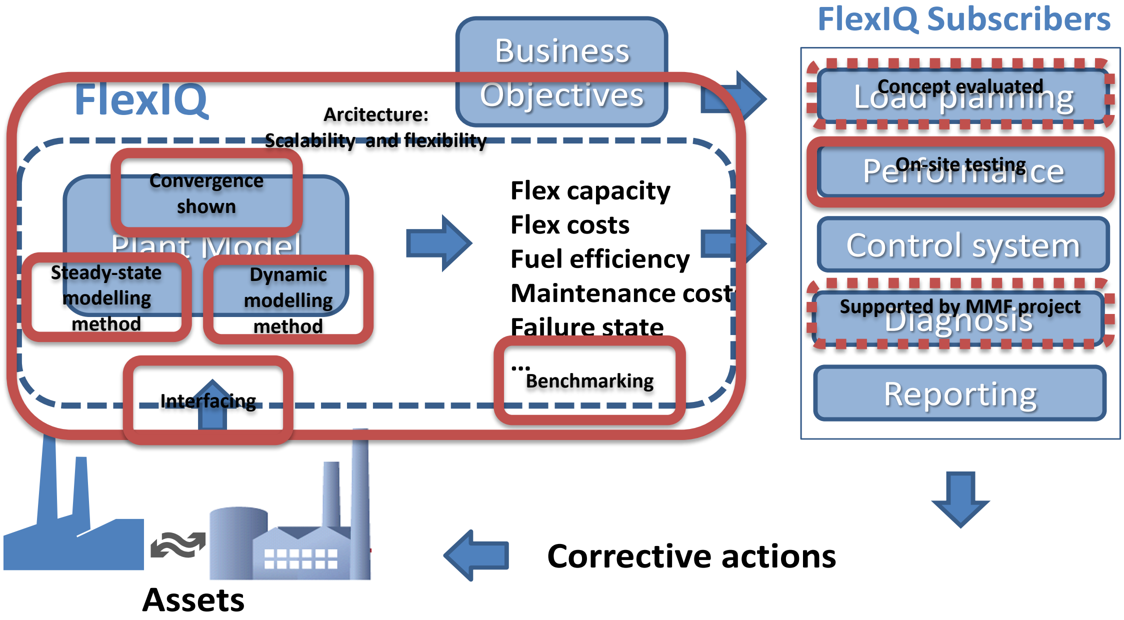
6.4 Perspectives on further development

FlexIQ as a product will through further development be able to go beyond the utilization examples carried out in this project. This will enable even larger value creation and will open up extended market deployment. Examples on future new functional developments are:

- **On-line dynamical models** for improving volatile market services while ensuring high efficiency and availability. RDD on robust application of such methods has been carried out to some extent in this project, but a further maturing is needed.
- **On-line models and concepts on lifetime and maintenance** costs will bring further value in to FlexIQ. This type of modelling has not been covered in the project, and R&D on applied modelling of cross optimization is needed.
- **Inclusion of more subscribers** in order to exploit the FlexIQ models further. Examples are operator what-if analysis, detailed diagnostics of failures, optimization of set-point adjustments and marginal cost calculation. Development of new models and new business layer algorithms are needed.
- **Adaption to small-scale plants** will to target the needs of very small and low-costs production systems. This will require development of an adjusted architecture and models of lower fidelity in order to meet the low-cost demand.

7 Project conclusions

The project has focused on developing a platform for supporting daily operation in volatile markets (power, district heat, fuels, etc.) and this has been accomplished through the indications (red framing) in the figure below.



These overall results can be summarized as:

- A FlexIQ architecture supporting scalability in terms of scope and fidelity. The architecture has been tested off-line and demonstrated through on-line applications in Sønderborg and in Verdo (commercial application).
- Steady state modelling method based on physical component models combined with optimized parameter tuning based on measurement data.
- Dynamic modelling method which can be used for high fidelity modelling of complex systems. The method has been tested by simulations of a complex absorber heat pump system in Sønderborg. A number of papers has been published on this.
- A convergence method for benchmarking different performance measures using steady-state models combined with on-line measurements and business logics. This has also been demonstrated on-line in Sønderborg and commercially in Verdo.
- An optimization method based on Genetic Algorithms and utilizing high fidelity models. This has been tested through simulations. A number of papers has been published on this.
- A concept for a business layer including a controller structure for execution models, controlling data flows and executing business logics. This has been demonstrated in Sønderborg and commercially in Verdo.
- A subscriber application on performance monitoring has been demonstrated in limited version on a waste-to-energy boiler in Sønderborg and commercially based in full version on Verdo plants.
- A subscriber application on diagnostics has been demonstrated in limited version in the two plants. This part was partly developed in a sister project funded by Markedsmodningsfonden.
- A subscriber on load planning has been simulated and visualized through utilizing EMD load planning software, showing potential large value creation.