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A framework for local and regional energy system integration between industry and municipalities—Case study UPM-Kymmene Kaukas

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Abstract

The integration of different energy systems, e.g., industrial and municipal, is potentially important for the efficient utilization of energy. It is important that the tools for analysing this type of integration can handle the energy systems on different levels, e.g., regional, site, plant and process levels. In this work, a framework for investigating the cost-efficient integration of large-scale energy systems is presented and tested at the *UPM-Kymmene Kaukas* pulp and paper plant and in the municipality of *Lappeenranta*, Finland. In addition to the different levels, the framework also aims to take into account several sub-problems, e.g., fuel logistic, optimal heat exchanger network and overall efficiency versus flexibility. The case in question shows that the presented framework can be used as a systematic tool for analysing the potential of integrating large energy systems and that it is able to handle both the synthesis of flexible heat exchanger networks and analyse the cost-efficiency of changes to the existing systems.

Keywords: Regional energy system; Integration; Optimisation

1. Introduction

In this work, a new framework for improving an energy system by investigating energy integration between municipalities and the industry is presented and applied to the *UPM-Kymmene Kaukas* pulp and paper plant and the municipality of *Lappeenranta*, Finland. The framework consists of several different methodologies that focus on different levels of the energy system. The emphasis of the energy integration is on fuel and heat transfer between the municipalities and the industry. The purpose of this work is to show how the framework can be used to design an improved regional energy system where the locally available fuel, costs of changes to the industrial processes at the Kaukas plant and the heat demand in the city's district heating network are

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Nomenclature

A	heat exchanger surface area (m^2)
a	coefficient
b	coefficient
C	annual costs (€/a)
c_p	specific heat capacity (kJ/kg K)
h	enthalpy (kJ/kg), hours
I	annual income (€/a)
M	Coefficient for the big-M formulation
m	mass flow (kg/s)
n	period
P	price (€/MWh)
Q	heat flow (MW)
r	interest rate
s^+	slack variable
T	temperature (K, °C)
U	overall heat exchanger coefficient (W/m^2K)
W	work (MW)
y	binary variable
θ	temperature difference (K, °C)

Abbreviations

F-HEN	flexible-heat exchanger network
HEN	heat exchanger network
HHV	higher heating value
LMTD	logarithmic temperature difference
LP	linear programming
M	prefix, mega (10^6)
MINLP	mixed integer nonlinear programming
MILP	mixed integer linear programming
NLP	nonlinear programming

taken into account. The focus of this work is the investigation of possible modifications to the industrial processes and the transfer of heat to the district heating network.

The task of improving an energy system can be seen as a synthesis of flowsheet schemes. There are different approaches to achieving this synthesis. One possibility is to focus on thermodynamics: Nishio et al. [1], for instance, developed a thermodynamic approach to steam-power system design. This approach uses heuristic rules and is limited to steam cycles. Chou and Shih [2] proposed a similar procedure, and developed a systematic procedure for the design and synthesis of plant utility systems. Perhaps the most-used thermodynamic methodology for analysing thermal energy systems is *pinch-technology* (discovered independently by Hohmann [3] and Linnhoff [4]). With respect to the process industry, there are two factors that traditional pinch-technology do not address. The processes often consist of sub-processes, and there are several reasons, e.g., controllability, why these sub-processes should not be grouped together as one large process. A common problem with the thermodynamic approach is the lack of handling trade-offs. Even if several adaptations to the thermodynamic methods have been made to address this problem in special cases, the general problem still remains. In an attempt to overcome this, *mathematical programming* has been applied. In their two articles, Biegler and Grossmann [5,6] give a good overview of mathematical programming and its application to process design and process system engineering. By using mathematical programming, it is easier to find cost-optimal solutions for simple problems, which include both changes to the process parameters and process structure, as well as logical statements. The mathematical programming formulations of process synthesis problems are often nonlinear and contain binary or integer variables (mixed integer nonlinear programming (MINLP) problems). MINLP problems can be solved to a global optimum with algorithms that exist today. However, for complex problems, these algorithms soon become prohibitively inefficient, which means that, for sufficiently large and complex systems, the mathematical programming solvers are unable to solve the problems. An approach to avoiding these problems is to reduce the problem size. In their work, Manninen and Zhu [7] tried to reduce the MINLP problem size by using thermodynamic analysis. The problem was reduced by imposing tighter bounds on the variables, as well as reducing the size of the superstructure. Similar ideas were presented by Hostrup et al. [8], where the focus was on the synthesis of flowsheets for chemical processes. One of the methodologies in the framework presented in this work, REGOPT by Tveit [9,10], reduces the mathematical problem by using a combination of simulation and experimental design. The methodology is suitable for the synthesis of large-scale and complex problems with few degrees of freedom.

Heat exchanger network (HEN) synthesis is a complex and important part of flowsheet synthesis of energy systems. Methods for HEN synthesis have been developed by, for example, Cerda et al. [11], Papoulias and Grossmann [12] and Yee and Grossmann [13]. These authors aim to design a HEN that yields a reasonable trade-off between capital and operating cost through sequential or simultaneous approaches. Furman and Sahinidis [14] have contributed a thorough review of HEN synthesis and reported that over 400 papers have been published on the subject over the last 40 years. When the environment introduces significant changes in the operating conditions, a synthesised HEN must also be thermodynamically feasible for different operating modes, i.e., it must be flexible. Many authors have discussed this subject: the most important of these discussions can be found in Marselle et al. [15], Swaney and Grossmann [16], Kotjabasakis and Linnhoff [17], Floudas and Grossmann [18], Swaney and Grossmann [16], Papalexandri and Pistikopoulus [19,20] and Tantimuratha et al. [21]. One of the most recently published works is by Konukman et al. [22]; this introduces simultaneous flexibility targeting and the synthesis of the minimum utility heat exchanger networks. In the framework presented in this work, the F-HEN methodology devised by Aaltola [23,24] is used for the HEN synthesis. In this methodology, the simplified superstructure presentation proposed by Yee et al. [25] is applied to generating flexible HENs over a specified range of variations in the flow rates and temperatures of the streams, so that the total annual costs resulting from utility charges, exchanger areas and selection of matches are minimised.

When analysing the integration of large systems, for instance, the integration of an industrial site and a large district heating network, there are several different levels. The analysis can be carried out at a regional, site, plant and process level. There are also several sub-problems, e.g., fuel logistic, optimal HEN and overall efficiency versus flexibility that must be taken into account. To be able to handle the different levels and sub-problems encountered when trying to investigate the possibilities of cost-efficient integration between industrial and regional energy systems, a framework of algorithms and methodologies was developed. The framework is presented in Section 2, while the application of the framework is presented in Section 7.

2. Methodology framework

The framework is comprised of four different methodologies that focus on different levels and details of the energy systems. The methodologies are FUELOPT, COMBSITE, REGOPT and F-HEN.

The ways in which the different methodologies interact are case-dependent. The interactions between the methodologies for this case are shown in Fig. 1.

The purpose of the FUELOPT methodology is to discover the availability and price of by-product fuels from the forest industry and forest residue fuels from regeneration cuttings. In addition to raw materials, the forest industry can supply wood fuel to the pulp and paper plant. By optimising the use of wood fuel in the region, transportation distances and costs can be decreased. Thus, the domestic renewable wood fuel can be a competitive option to replace the fossil fuel in industry and communities.

The objective of the methodology COMBSITE, which is presented in the work by Laukkanen [26], is to analyse and structurally optimise the energy system of an industrial plant, so that the energy consumption of

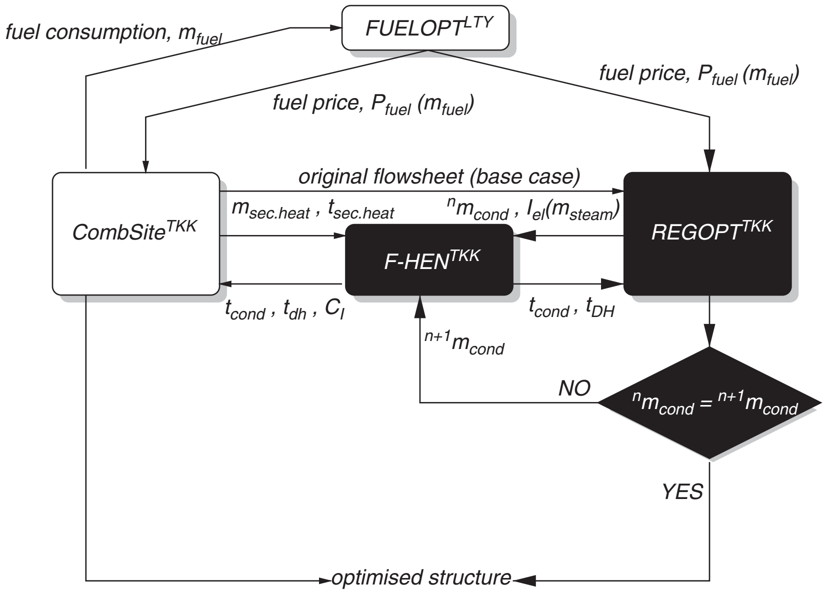

Fig. 1. Methodology framework; P_{fuel} is the price of fuel, m_{fuel} is the fuel consumption, m_{cond} is the mass flow of steam to the condensing turbine, I_{el} is the income from sold electricity, t_{cond}, t_{dh} and $t_{sec.heat}$ are target temperatures and C_I is the annual investment costs of the heat exchanger network.

the production processes is minimised only if it is justified economically. In COMBSITE, heat exchange between the production processes is allowed, but this is secondary to heat exchange inside a production process and is allowed only if it is beneficial to the energy consumption of the whole system and acceptable to the continuous and reliable operation of the process.

The REGOPT methodology presented by Tveit [10] tries to find a cost-optimal flowsheet of complex energy systems by combining simulation, experimental design and mathematical programming. The F-HEN methodology is used to generate flexible HENs over a specified range of variations in the flow rates and temperatures of the streams. A more detailed explanation of how the methodology handles variations in the stream data can be found in the work by Aaltola [23,24].

In this work, the main purpose is to present how the REGOPT and F-HEN methodologies can be used to analyse the possibilities of integrating the energy system at Kaukas with the district heating network of Lappeenrannan Energia. An important task is to show how sensitive the structural changes are to variations in the electricity and natural gas prices. The two methodologies, REGOPT and F-HEN, are described in more detail in Sections 5 and 6.

All the optimisation models were solved using GAMS from *GAMS Development Corporation* [27]. The solver for the FUELOPT LP-models was CPLEX. The solver for the MINLP models was DICOPT for both the F-HEN and REGOPT models. For the F-HEN models CONOPT and CPLEX were used as, respectively, the nonlinear programming (NLP) and mixed integer linear programming (MILP) solver, while for REGOPT, MINOS5 was used as the NLP solver, and IBM optimization solutions and library (OSL) as the MILP solver. More information about the solvers can be found in the solver manual from GAMS Development Corporation [28].

In the following two sections, Sections 3 and 4, respectively, the city of Lappeenranta and the UPM-Kymmene Kaukas pulp and paper plant are described.

3. City of Lappeenranta

The city of Lappeenranta is situated in the South Karelia region in Eastern Finland. About 90% of the 60,000 inhabitants live in the central urban area and the remaining 10% in the rural parts of the city. Today, about 85% of the inhabitants live in houses heated by district heating. The total district heating consumption

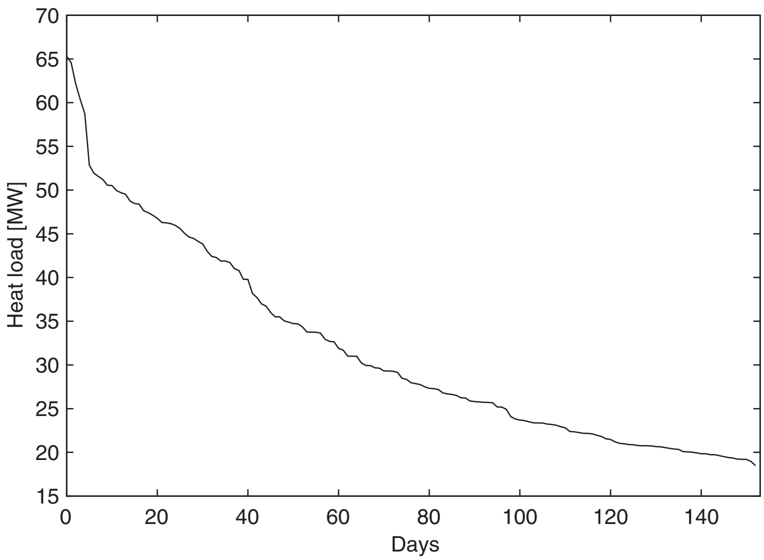

Fig. 2. Duration curve of the district heating consumption for the period under investigation in this work (May to September, 2000).

in 2000 was 546 GW h. The main supplier of district heating is the Mertaniemi combined heat and power plant with a district heating capacity of 150 MW. The plant is in operation for most of the year. However, during the summer the electricity prices are generally low and during this time it might be most economical to shut down the plant. Because of this it would only be possible from an economic perspective to utilise heat from industrial processes in the district heating network during summer. This is why only the summer load of the district heating system is investigated in this work. The period under investigation is from the 1st of May to the 30th of September. The duration curve for a typical summer period is shown in Fig. 2.

4. Kaukas pulp and paper plant

UPM-Kymmene Kaukas lies in Lappeenranta, south-eastern Finland, and consists of a pulp mill, a paper mill, a sawmill, a plywood mill, a chemical factory, a power plant and an effluent treatment plant. In this case study, the focus is on the pulp mill and the power plant, so short process descriptions of these mills are given.

The pulp mill produces 625,000 tons of bleached kraft pulp annually at two separate fibre lines. The first fibre line produces 275,000 t/a short fibre pulp mainly from birch. Sawdust is also cooked in an additional digester. The second fibre line produces 350,000 t/a long fibre pulp mainly from pine.

The main power plant process consists of two bark boilers. Both of these bark boilers have their own steam turbines. At the nominal rate, these steam turbines produce 29.3 and 5.1 MW of alternator power, respectively. The power plant also has a gas turbine and a Kraft recovery boiler which is connected to steam turbines. The power plant provides steam to the production mills at three different pressure levels: 13.5, 11.5 and 4.5 bar.

A new fluidised bed boiler to replace the two bark boilers is being planned. This fluidised bed boiler will burn bark and forest residues. The nominal production rate of this boiler will be 70 kg/s steam at 540 °C and 116 bar and a new steam turbine will be connected to this boiler. The steam turbine will have extraction pressures of 16, 11.5, 4.5 bar, and alternatively 1.2 bar and a condenser pressure of 0.05 bar. The steam consumption of the different production mills will remain unchanged. The gas turbine, odour gas boiler and Kraft recovery boiler together with their turbines will also stay unchanged. The old steam turbines, which are connected to the old bark boilers, will be removed.

The analysis of the possible changes and the cost-optimal integration of Kaukas and Lappeenranta Energia's district heating system was based on information about the current systems and about the planned fluidised bed boiler. The main analysis was made with REGOPT and F-HEN, which are presented in more detail in the next sections.

5. REGOPT

The REGOPT [10] methodology combines *simulation*, *experimental design* and *mathematical programming*. The main idea is to combine the simulation model and experimental design in order to make a regression model of the behaviour of the whole system. The system is analysed for possible improvements, which are included into a superstructure. Mathematical programming is then used to extract the best solution from the superstructure. By using a regression model of the system in a mathematical programming problem, it is possible to model modifications to the process without modelling each unit in the system separately. This makes the mathematical programming problem smaller and makes it possible to model larger systems and systems with more complex dependencies. This is a large advantage in this case, as the detail modelling of the Kaukas plants would be prohibitively complex for the current MINLP algorithms.

6. F-HEN

In F-HEN, the simplified superstructure presentation proposed by Yee et al. [25] is applied to generating flexible heat exchanger networks over a specified range of variations in the flow rates and temperatures of the streams, so that the total annual costs as a result of utility charges, exchanger areas and selection of matches are minimised. The presented optimisation scheme eliminates the modelling of bypasses, so that the nonlinear heat balances, binary variables, temperature variables and flow variables related to each bypass in the superstructure are no longer needed in the model. The elimination of bypass modelling, a stage-wise superstructure presentation and an isothermal mixing assumption make the MINLP model more robust and efficient to solve. Unlike the previous methods the developed method is capable of solving industrial HEN problems simultaneously. This results in a flexible HEN working under different operating conditions without losing stream temperature targets while keeping an economically optimal energy integration. The part of the framework where the network feasibility is tested is developed specifically for the special case of correlated uncertain parameters. In the case in which the HEN is to handle the entire variation of the district heating load, flexibility of the network is paramount, as can be seen from the duration curve in Fig. 2.

7. Applying the REGOPT and F-HEN framework to the case

The first stage of the analysis is to decide which new modification should be investigated. The possibilities are connected to the new fluidised bed boiler and the new steam turbine that is connected to the new boiler. The analysis of the modifications was carried out together with representatives from the Kaukas plants and the energy company in Lappeenranta. The suggested additions and modifications are:

(1) District heating is produced using 4.5 bar steam.
(2) District heating is produced using 1.2 bar steam.
  (a) Assume the addition of a condensing turbine.
  (b) Preheat of the condense is possible.
  (c) Preheat of the district heating is possible.

In Fig. 3, the superstructure for the modified process is shown. Note that the figure does not include the superstructure for the HEN, only the streams. The next step is to develop a simulation model of the energy system that is used by REGOPT. After the simulation model is ready, the development of the mathematical programming model can begin. During the development it will be clear what kind of regression models is needed. When the regression models are integrated, the final mathematical programming model is ready and can be solved. Based on the results from the mathematical programming, F-HEN generates the suggested flexible HENs. The values for the preheating is fed back to REGOPT, and if the optimal flow of condense

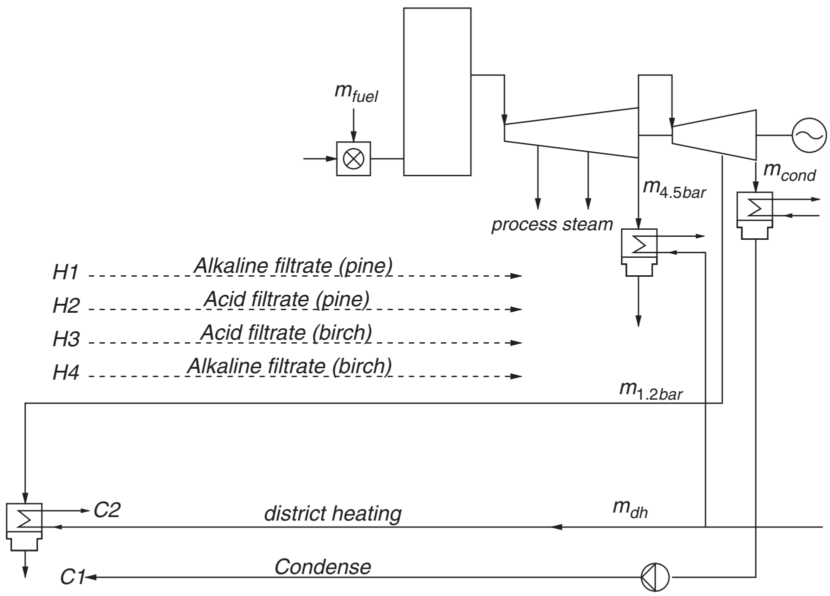

Fig. 3. Superstructure of the modified process; for clarity the superstructure for the heat exchanger is not included, only the hot and cold streams labelled H1–H4 and C1–C2, respectively. The stream data can be found in Table 1.

found in the new run is equal to the previous one, the analysis terminates. Otherwise, the value of the mass flow found by REGOPT is fed back into F-HEN and a new iteration loop is started.

The results of the analysis made by FUELOPT show that the price of fuel is approximately 6.65 €/MW h. The price increases linearly from 6.65 to 6.87 €/MW h when the fuel consumption is between 1000 and 1300 GWh/a. The base case for the study is provided by COMBSITE, and, on the basis of this, the simulation model to be used for the regression modelling is developed.

7.1. Simulation model

The simulation model used by REGOPT is made in *Prosim* from Endat Oy. Prosim is a software package for steady state simulation of power plant processes. See, for instance, the article by Giglmayr et al. [29] for more details. Prosim contains ready-made modules for the most typical power plant units. The separate modules are connected with streams to make a model of the process. In Fig. 4, the flowsheet of the simulation model is presented. The two cold streams that are used by F-HEN, namely the condense from the condensing turbine and the district heating are included in the simulation model. The hot streams from the pulp process are not included in the simulation model, but are extracted from a simulation model of the pulp process.

7.2. Mathematical programming model

The objective of the analysis is to choose the modifications to the system that maximise the profit of the modifications.

The income from the modifications to the system consists of the additional income from the generated electricity and from the heating of district heating water. The annual costs of the modifications to the system are the additional costs of fuel and the investment costs of the new units. The new units are the condensing turbine and three heat exchangers. The annual costs of the turbine are calculated as a function of the power of the turbines. The turbine power can be related to the steam mass flow through the turbine, so it is possible to relate the costs of the turbine to the mass flow of steam. The heat exchanger costs are comprised by a fixed cost and a cost depending on the size of the heat exchanger, in this case, the heat exchanger surface area. These factors, together with the physical models and constraints, yield the mathematical programming model. The

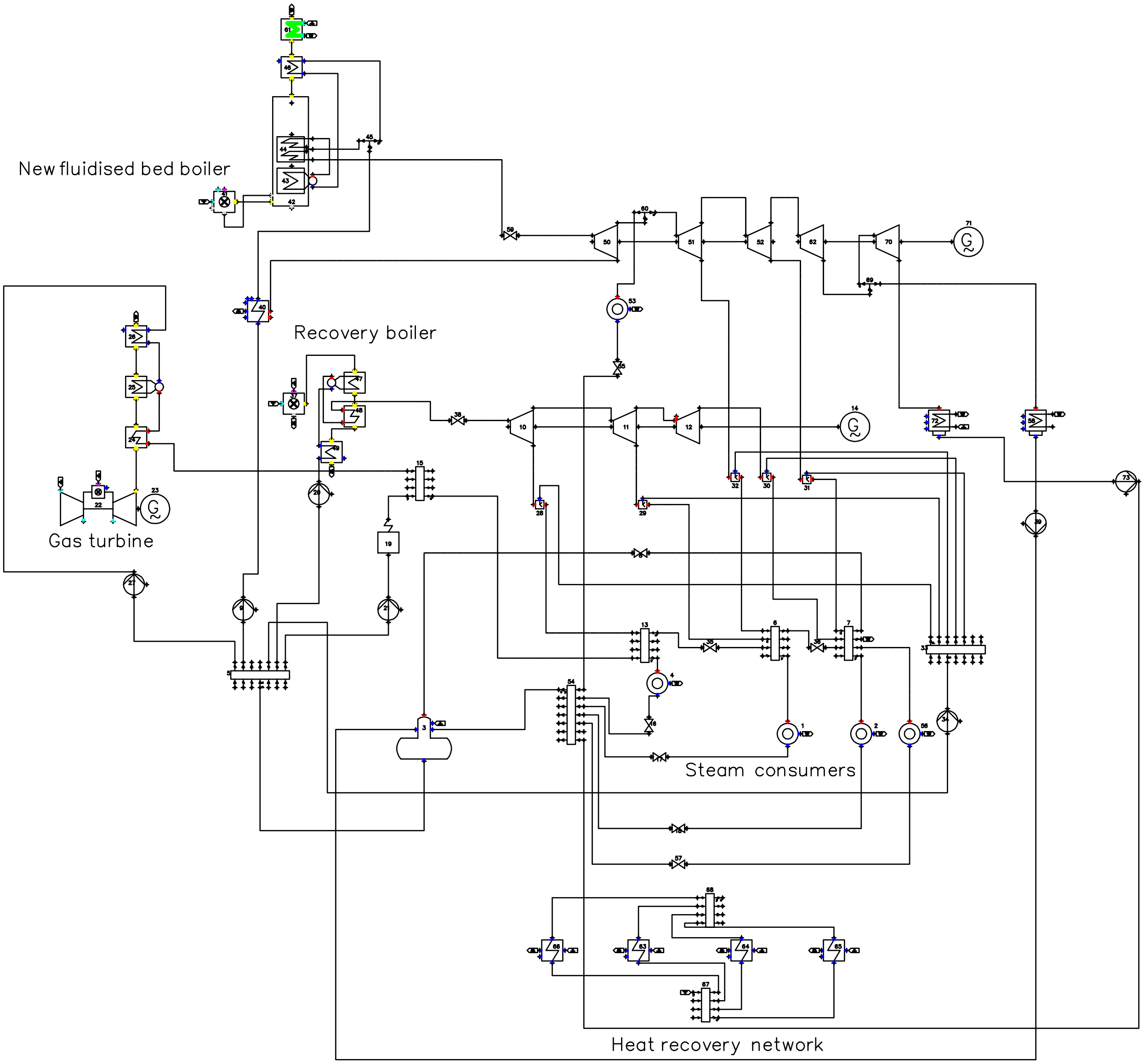

Fig. 4. Simulation model.

full MINLP model can be found in Appendix A. A detailed description of the model and its derivation can be found in the Electronic Annex 1 in the online version of this article.

After solving the mathematical programming model for the fixed fuel and electricity price, F-HEN is used to generate the HEN. The costs related to the HEN used by F-HEN are as follows: The annual costs of steam are 46.4 €/kW and 72.0 €/kW for 1.2 and 4.5 bar steam, respectively. The costs equation for the exchangers is 33,330 €/unit, and, in addition, 666.7 €/m^2 of heat exchanger surface. The payment period is set to 5 years with an interest rate of 10%. The overall heat transfer coefficients for all matches are 4 kW/m^{2}K. The stream data is shown in Table 1.

The optimal flow through the condensing turbine is the same for the new run of the mathematical programming model, so the iteration terminates. When a HEN for the preheating is suggested, the optimisation model from REGOPT is run several times with a varying electricity price. Thus it is possible to see how sensitive the investments are to the difference in the relationship between the price of fuel and electricity.

Table 1
Stream data for the heat exchanger network synthesis (F-HEN); BP = birch pulp, PP = pine pulp. The district heating, Stream C2, varies between the maximum and minimum load

Stream		T_{in}(°C)	T_{out}(°C)	F (kW/K)
Alkaline filtrate PP	H1	88.3	38.0	707.0
Acid filtrate PP	H2	68.4	38.0	238.9
Acid filtrate BP	H3	72.8	38.0	481.1
Alkaline filtrate BP	H4	75.0	38.0	64.4
Condense	C1	29.0	133.0	109.2
District heating (max. dh)	C2	40.0	70.0	2176.8
District heating (min. dh)	C2	40.0	70.0	616.3

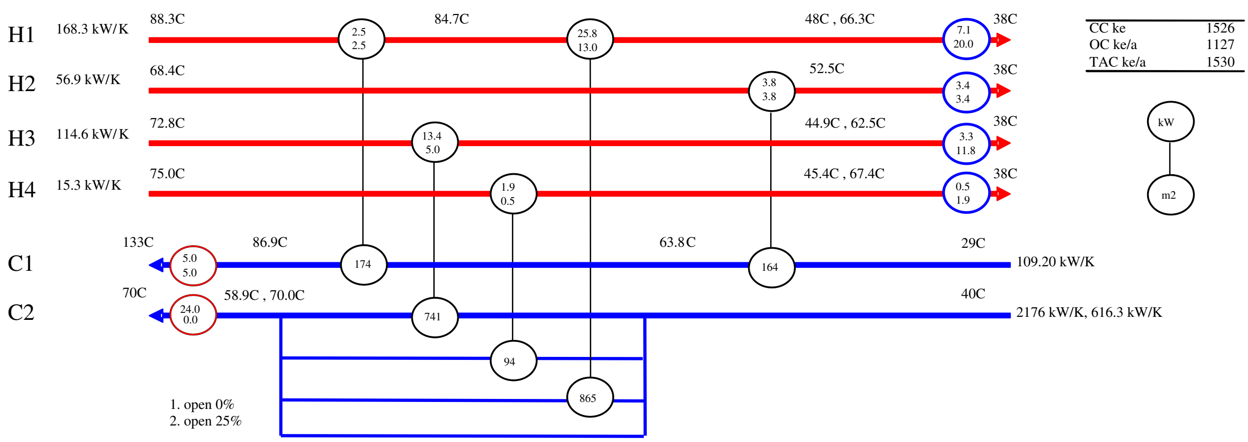

Fig. 5. Heat exchanger network with splits allowed; *cc* = capital costs, *oc* = operating costs and *tac* = total annual costs. The stream data can be found in Table 1.

8. Results and discussion

Two flexible HENs for the preheating of the district heating water are suggested. In the HEN shown in Fig. 5, the splitting of streams is allowed. The annual costs of this network amounts to 1.5 M€. In the second HEN shown in Fig. 6, the splitting of streams is *not* allowed; this results in a more simple, but more expensive, network. The annual costs of the second network are 1.6 M€. The first network has higher investment costs, but the annual costs are lower, due to reduced operation costs. In the upper part of Fig. 7, the optimal annualised investments as a function of the ratio between fuel and electricity prices is shown. The figure shows that the investments are economically feasible when the price of electricity is 3.5 times the price of fuel. The condensing turbine is feasible when the ratio is 4.5. This also means that preheating the district heating water is not considered before the price ratio is greater than 4.5. In the unlikely event that electricity is 8.0 times more expensive than fuel, it is not economically reasonable to generate district heating. The lower part of Fig. 7 shows the annual income from the investments. The break even point is when the fuel and electricity price ratio is 5.0. The breakeven point for the investments including the HEN for preheating is as high as 7.

Based on the above results, it is clear that the costs of all the new investments is economically reasonable only if the electricity price is in the range of 7 to 8 times more expensive than the fuel. For the current electricity prices and the calculated regional fuel prices, this is not the case. Thus, the results of the case-study show that the investments are not economically feasible at the current fuel and electricity prices. The results were made available to UPM-Kymmene and the power company of Lappeenranta: at present, no investments have been made to the energy system at the site.

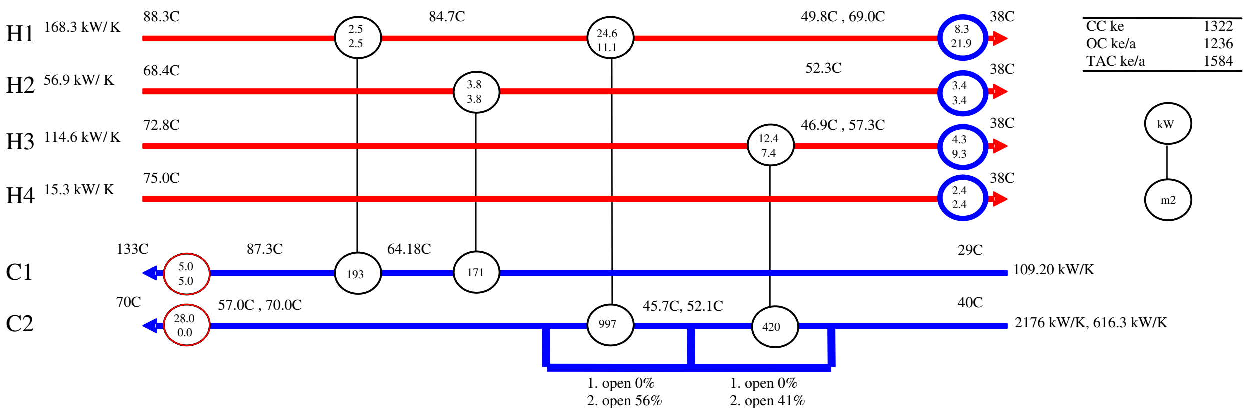

Fig. 6. Heat exchanger network with no splits allowed. The bypass can be avoided if the target temperature is a soft target, and thus is allowed to take values higher than 70 °C. The stream data can be found in Table 1.

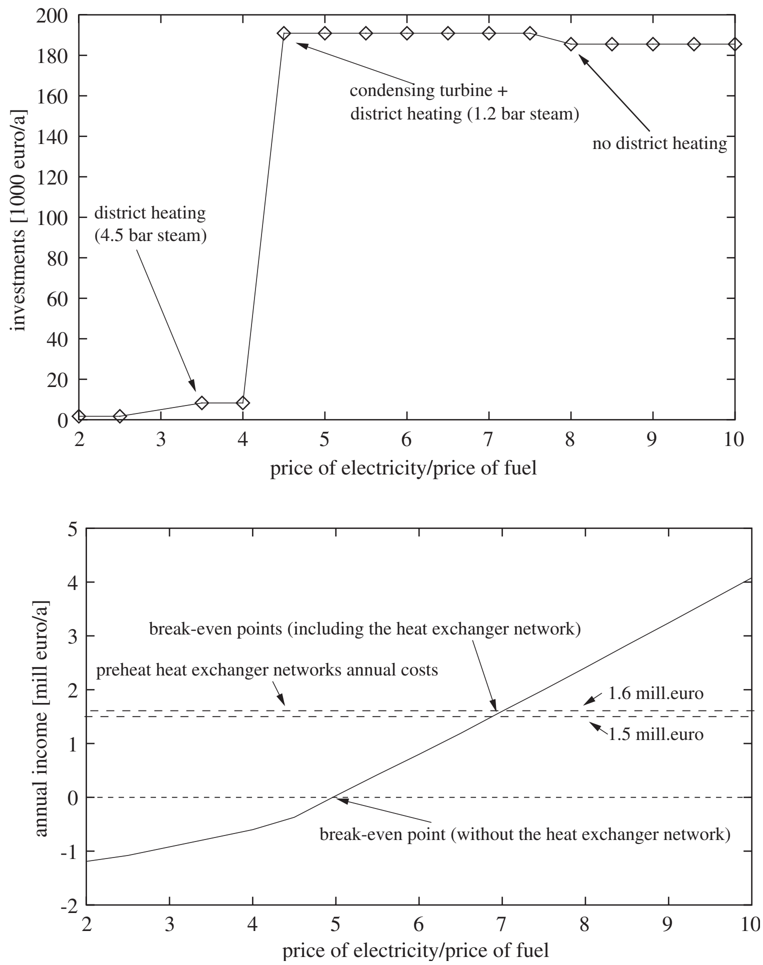

Fig. 7. Annual investments and annual income from the investments as functions of the electricity and fuel price ratio.

The time it took to solve the F-HEN optimisation model was in this case approximately 30 min on a computer with a mobile Intel P III 1 GHz and 1 GB of RAM. The results of the REGOPT model were achieved by solving the model in series and gradually changing the fuel and electricity price ratio. One iteration in the series was solved in approximately 1 s on a SGI Origin 2000 with 560 GB of RAM and 128 MIPS R12000 processors. The performance and limitations of the presented framework are strongly dependent on both the properties of the specific case and on the performance of the methodology comprising the framework. However, the case shows that the framework can be used as a systematic tool for analysing the potential of integration of large energy systems. The case also shows that the interface between the two methodologies, REGOPT and F-HEN, is functioning well, as they are able to handle both the synthesis of flexible HENs and analyse the cost-efficiency of changes to the existing systems. The most time-consuming part of the case study was the data extraction. It is possible to assume that the success of applying the framework to a new case would be dependent on the availability of sufficient and accurate data.

The main limitation for F-HEN is that, due to the complexity of the problem, it is necessary to make compromises between the accuracy and the ability of current algorithms to solve the model. Many properties related to the practical HEN design, such as the thermal-hydraulic properties of the fluids and units, the dynamic behaviour, the discontinuities in cost structure, are strongly simplified or even excluded. In order to solve a large HEN, it will be necessary to reduce the complexity and search space of the problem, introducing tighter bounds at the initialisation level. For smaller problems, the challenge is to make the model more realistic, so that factors such as allowable pressure drop, exchanger type, fouling and controllability can be taken into account. Stream re-piping and exchanger reassignments should also be considered in the retrofit cases.

It has been shown in earlier work by Tveit [9] that MINLP models developed using REGOPT can reduce the size of the optimisation problem considerably. In the earlier work a MINLP model, where all the units were modelled in detail, had about 4.5 times more equations and 8.5 times more variables than a similar MINLP model developed using REGOPT. Thus, the new methodology has better potential than the traditional methods for reducing the optimisation problem and, subsequently, for solving more complex energy system flowsheet synthesis problems. However, as the degrees of freedom of the system increase, the value of the new methodology decreases, since more computational effort is needed to obtain a representative regression model. The optimisation model specifically developed for this case using REGOPT is considerably smaller compared to a model developed in a traditional way, where all the units in Fig. 4 would be modelled in detail.

9. Conclusions

In this work, a framework for investigating the cost-efficient integration of large-scale energy systems was presented. The framework was tested at the *UPM-Kymmene Kaukas* pulp and paper plant and in the municipality of *Lappeenranta*, Finland. The framework is comprised by four different methodologies, namely FUELOPT, COMBSITE, REGOPT and F-HEN. The methodologies focus on different levels and details of the energy systems; an important task of this work was to present how primarily the methodologies REGOPT and F-HEN can be used to analyse the possibilities of integrating the energy system at Kaukas with the district heating network of Lappeenrannan Energia. By integrating two different methodologies, it is possible to create an overview of how different parameters, in this case, the prices of fuel and electricity, affect the cost-optimal investments for the integration of an industrial energy system with a district heating system. According to the case results, the methodologies work well together. The results show that the costs of all the new investments is only economically reasonable if the electricity price is in the range of 7–8 times more expensive than the fuel.

The framework can be further improved by improving the methodologies, to enable them to handle more detailed models of the various parts of the system and to handle more degrees of freedom. However, unlike previous methodologies, it has been shown that the presented framework can handle the integration of energy systems on many different levels. This is an important feature when analysing the cost-efficient energy integration between regional industry and municipalities.

Acknowledgements

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Appendix A. Mathematical programming model (MINLP)

A.1. Objective function

$$
\begin{aligned}
z &= I_{el} + I_{dh} - (C_{fuel} + C_{hex,i}^{annual} + C_{turbine}^{annual}) \\
&= P_{el} \cdot h \cdot (W_{el} - W_{el,bc}) + P_{dh} \cdot h \cdot c_p \cdot \Delta T \cdot m_{dh} \\
&\quad - \left(P_{fuel} \cdot h \cdot (m_{fuel} \cdot HHV) + \sum_{i \in HEX} \left(\frac{r(1+r)^n \cdot (a_i + b_i \cdot A_{hex,i}^B)}{(1+r)^n - 1} \right) \right. \\
&\quad \left. + 2237 \cdot (1000 \cdot W_{st})^{0.41} \right), \qquad \text{(A.1)}
\end{aligned}
$$

where the set $HEX = \{$"1.2", "4.5", preheat$\}$.

A.2. Constraints

Electricity production:

$$W_{el} = W_{el,1.2} + W_{el,4.5}, \qquad \text{(A.2)}$$

$$W_{el,1.2} = 16.80 + 1.32 \cdot m_{cond} + 0.83 \cdot m_{1.2bar} - 0.35 \cdot Q_{preheat} - s_{eq.A.3}^{+}, \qquad \text{(A.3)}$$

$$W_{el,4.5} = 16.76 + 1.31 \cdot m_{cond} + 0.69 \cdot m_{4.5bar} - 0.32 \cdot Q_{preheat} - s_{eq.A.4}^{+}, \qquad \text{(A.4)}$$

$$W_{el,1.2} - M \cdot y_{1.2} \leqslant 0, \qquad \text{(A.5)}$$

$$W_{el,4.5} - M \cdot y_{4.5} \leqslant 0, \qquad \text{(A.6)}$$

$$s_{eq.A.3}^{+} - M \cdot y_{4.5} \leqslant 0, \qquad \text{(A.7)}$$

$$s_{eq.A.4}^{+} - M \cdot y_{1.2} \leqslant 0. \qquad \text{(A.8)}$$

Fuel consumption:

$$m_{fuel} = m_{fuel,1.2} + m_{fuel,4.5}, \qquad \text{(A.9)}$$

$$m_{fuel,1.2} = 17.03 + 0.79 \cdot m_{cond} + 0.70 \cdot m_{1.2bar} - 0.29 \cdot Q_{preheat} - s_{eq.A.10}^{+}, \qquad \text{(A.10)}$$

$$m_{fuel,4.5} = 17.13 + 0.78 \cdot m_{cond} + 0.64 \cdot m_{4.5bar} - 0.29 \cdot Q_{preheat} - s_{eq.A.11}^{+}, \qquad \text{(A.11)}$$

$$m_{fuel,1.2} - M \cdot y_{1.2} \leqslant 0, \qquad \text{(A.12)}$$

$$m_{fuel,4.5} - M \cdot y_{4.5} \leqslant 0, \qquad \text{(A.13)}$$

$$s_{eq.A.10}^{+} - M \cdot y_{4.5} \leqslant 0, \qquad \text{(A.14)}$$

$$s_{eq.A.11}^{+} - M \cdot y_{1.2} \leqslant 0. \qquad \text{(A.15)}$$

The upper bound of the mass flow through the condensing turbine:

$$m_{cond} \leqslant 15.95 - 9.25 \cdot \left(\frac{m_{1.2bar} - 18.60}{10.40} \right) + 0.30 \cdot \left(\frac{Q_{preheat} - 0.80}{0.80} \right) + s_{eq.A.16}^{+}, \qquad \text{(A.16)}$$

$$
\begin{aligned}
m_{cond} \leqslant\ & 16.70 - 8.95 \cdot \left(\frac{m_{4.5bar} - 19.40}{10.90} \right) + 0.40 \cdot \left(\frac{Q_{preheat} - 0.90}{0.90} \right) \\
& - 0.05 \cdot \left(\frac{m_{4.5bar} - 19.40}{10.90} \right) \left(\frac{Q_{preheat} - 0.90}{0.90} \right) + s_{eq.A.17}^{+}, \qquad \text{(A.17)}
\end{aligned}
$$

$$s^{+}_{eq.A.17} - M \cdot y_{1.2bar} \leqslant 0, \tag{A.18}$$
$$s^{+}_{eq.A.16} - M \cdot y_{4.5bar} \leqslant 0. \tag{A.19}$$

Electricity produced by the work of the condensing turbine:

$$W_{st} = W_{st,1.2} + W_{st,4.5}, \tag{A.20}$$
$$W_{st,1.2} = 1.32 \cdot m_{cond} + 0.83 \cdot m_{1.2bar} - s^{+}_{eq.A.21}, \tag{A.21}$$
$$W_{st,4.5} = 1.31 \cdot m_{cond} - s^{+}_{eq.A.22}, \tag{A.22}$$

$$W_{st,1.2} - M \cdot y_{1.2} \leqslant 0, \tag{A.23}$$
$$W_{st,4.5} - M \cdot y_{4.5} \leqslant 0, \tag{A.24}$$
$$s^{+}_{eq.A.21} - M \cdot y_{4.5} \leqslant 0, \tag{A.25}$$
$$s^{+}_{eq.A.22} - M \cdot y_{1.2} \leqslant 0. \tag{A.26}$$

District heating production:

$$m_{dh} = \frac{1}{c_p \Delta T_{dh}} \sum_i (m_i \cdot h_i^{fg}) \quad \forall i \in \{\text{“ 1.2” ,“ 4.5” }\}. \tag{A.27}$$

Heat exchanger surface area:

$$A_{hex,i} = \frac{m_i \cdot h_i^{fg}}{U_i \cdot LMTD_i} \quad \forall i \in \{\text{“ 1.2” ,“ 4.5” }\}, \tag{A.28}$$
$$A_{hex,preheat} = \frac{m_{cond} \cdot c_p \cdot (T_{cond,out} - T_{cond,in})}{U_{preheat} \cdot LMTD_{preheat}}, \tag{A.29}$$
$$LMTD_{preheat} = \left(\theta_{1,preheat} \cdot \theta_{2,preheat} \cdot \frac{\theta_{1,preheat} + \theta_{2,preheat}}{2}\right)^{1/3}, \tag{A.30}$$
$$\theta_{1,preheat} = T_{preheat,in} - T_{cond,out}, \tag{A.31}$$
$$\theta_{2,preheat} = T_{preheat,out} - T_{cond,in}, \tag{A.32}$$

$$m_{cond} \cdot c_p \cdot (T_{cond,out} - T_{cond,in}) = m_{preheat} \cdot c_p \cdot (T_{preheat,in} - T_{preheat,out}). \tag{A.33}$$

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