Available online at www.sciencedirect.com

ScienceDirect

Energy Procedia 158 (2019) 6419–6424

Energy Procedia

www.elsevier.com/locate/procedia

10th International Conference on Applied Energy (ICAE2018), 22-25 August 2018, Hong Kong, China

Waste-heat integration in smart thermal networks - A dynamic thermoeconomic approach

Stefano Coss[a,b]*, Vittorio Verda[b], Olivier Le Corre[a]

[a] *IMT Atlantique, 4 Rue Alfred Kastler, Nantes 44000, France*
[b] *Politecnico di Torino, Corso Duca degli Abruzzi 24, Torino 10129, Italy*

Abstract

The transformation of large district heating networks (DHN) towards smart thermal networks is one way of contributing to a decarbonized integrated energy system. DHN might operate as a backbone receiving a variety of different energy vectors. As a smart thermal network, a DHN is therefore able to solve both spatial- and temporal mismatch of energy demand-supply, while its operation is mostly governed by fluctuating or batch-like supply of thermal exergy. Thermoeconomics is used to provide information upon third-party excess, exergetic destruction and the feasibility of waste-heat integration but currently mainly focuses on system evaluation. In this work, thermoeconomics is used to extend the information on operational level, focusing on the dynamic behavior of exergy flows in systems with various producers and consumers. The aim is to evaluate the individual contributions of *energy service* by the substations (the consumers on component level) to the thermoeconomic cost generation in the system. This is done through applying the principles of exergy costing to network nodes of a graph-based network model. Furthermore, product and fuel flows, which are intrinsic part of the theory of exergy cost, are defined on control volume level and on component level. A matrix formulation of the approach is developed which can be directly applied to graph-based models using the incidence matrix for topology representation. The thermoeconomic model is applied to a case study of a real existing DHN in current operation. The effect of waste-heat integration of a typical batch-like waste heat profile at 80 °C shows that the exergetic costs are dependent on the position of the network and can be quantified in economic terms, which provides important information for decentralized integration, third-party access and dynamic pricing.

Keywords: district heat network, smart thermal network, exergy, thermoeconomics, graph-based network models

* Corresponding author. Tel.: +33769408036
E-mail address: stefano.coss@imt-atlantique.fr

1876-6102
10.1016/j.egypro.2019.01.187

1. Introduction

Energy systems thinking is the approach of linking the different components of today's fragmented energy production- and consumption systems in order to profit from the individual strengths and benefits of technologies while reducing their weaknesses [1]. The enabling technology for the heating sector in that context is what is called *4^{th}- generation district heating networks* [2]. The main strategy of 4^{th} -gen DHN is a decrease of the network's operating temperature which, is stated, to enable a wider adoption of waste-heat utilization, solar thermal integration and a higher efficiency of heat pumping technology.

Much effort is taken to utilize waste-heat from industrial plants (IPs). Regional studies, as one for Denmark, show that excess heat from IPs is widely available on different temperature levels [3] and could be of possible use to provide low-temperature heat to DHN consumers. For the utilization in smart thermal networks, the usefulness of waste-heat according to its exergy content is proposed by [4]. Authors argue that the true feasibility of waste-heat integration into DHNs depends on the demand of exergy at a given moment and not necessarily on the network temperature. Considering a DHN system showing a volatile consumption pattern, low-exergy waste heat might be clearly useful in cases where temperature (and therefore thermal exergy) demand is low.

Thermoeconomics is a method for accounting of exergy destruction in thermal processes. It can therefore be applied to evaluate the usefulness of waste-heat integration from an exergetic point of view. In [5], authors highlight the usefulness of applying exergy analysis and thermoeconomic costing to estimate unit costs of energy services in a DHN. This leads to a better understanding on the economic implications of lower network temperatures. Cost accounting based on exergy is particularly useful to evaluate the primary energy savings associated with retrofitting options applied to buildings connected with district heating [6] or to compare the production costs of different producers depending on their position and the quality of their heat produced [7].

In this work, waste-heat integration is studied from a perspective of smart thermal networks, operating as thermal markets with decentralized integration. This demands for special attention to the position and the exergetic content of the waste-heat plant to be integrated. For that, a dynamic thermoeconomic model is developed which uses a thermo-hydraulic model, previously deployed by [8]. The latter estimates temperature and pressure distribution during DHN operation. This model is validated through several case studies addressing key issues such as peak-shaving of thermal demand [9].

Based on this model, a formulation of exergetic costs is proposed to network nodes which allow determining the cost allocation in a dynamic way. The approach is especially suitable for large networks with many producers and consumer connected and is therefore able to model smart thermal networks in a thermoeconomic way. The model is applied to a case study of a real-existing network and the simulation results suggest strong implications of the position and the exergy content of feasible waste-heat integration.

Nomenclature (SI)

A	Incidence Matrix	ψ	Exergy [J]
cv	Control volume	$\dot{\psi}$	Exergy flow [W]
d	Downstream node	ref	Reference
DHN	District heating network	RN	Return network
ext	External	s	Scenario
extIn	External inflows	sub	Substation
extOut	External outflows	SN	Supply network
hp	Heating plant	th	Thermal
IP	Industrial plant	T	Temperature [K]
k	Unit exergy cost [€/J]	u	Upstream node
$\dot{K}$	Exergy cost flow [€/s]	wp	Waste-heat plant
$\dot{m}$	Mass flow rate [kg/s]		
n	Node		

2. Method

2.1. Principles of exergy costing

Exergy costing is one of the foundations of valorizing exergy streams through the assignment of a value, more precisely an economic cost, which represents the cost of deploying a certain exergy flow. This has led to the development of what is called exergy cost [10]. Due to the fact that the amount of exergy degrades through every transformation, the usefulness for utilization declines. This is reflected by the assignment of a cost, which reflects the economic effort necessary to deploy that exergy stream. In exergy costing so called *fuels* and *products* for components participating in the transformation processes are defined. This definition of fuel and product derives from the theory of exergetic costing and is consequently applied to nodes of the graph network.

2.2. Formulation of exergy costs to graph-based network nodes

The architecture of the DHN system in this work focuses to connect producers and consumers through a thermal network. The focus hereby lies on production plants and consumers. The DHN system is composed of the main distribution network (DHN) and the following system components:

- Production plant(s)
- Substation(s)

Even though components like prosumers or storages are not included in this work, the described methodology does not necessarily exclude them. The purpose of the DHN system is to provide an energy service, more precisely a heating service, to external consumers through the utilization of an external energy service from the producers. Based on that, the DHN system is defined in Figure 1.

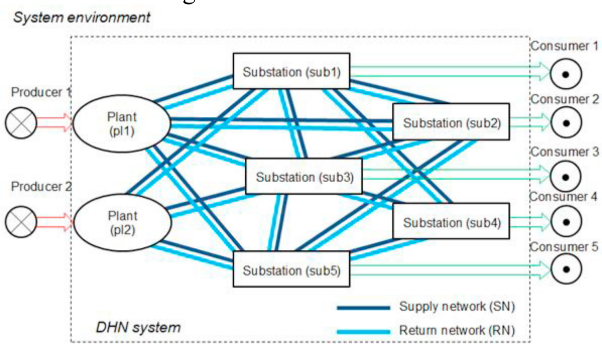

Figure 1: Representation of a DHN system as smart thermal network

The plant component (pl) is a component to integrate generic producers. It receives an energy service in the form of thermal exergy from the producer. The purpose of the plant component is to function as an auxiliary component connected to the DHN. There it extracts energetic flow from the return network (RN) and increases its energetic level according to the request of the supply network (SN). The DHN is the main distribution network without considering subnetworks. DHN is used to abbreviate main distribution network, while SN and RN are used to refer to the supply network and return network, respectively. The substation component (sub) is used to integrate generic consumers into the system. The purpose of the component is to integrate the thermodynamic behavior of the consumer request into the system through the exchange of thermal exergy.

Given the temperature and pressure distribution obtained from applying the model provided by [9], the thermal exergy flows are estimated using an upwind-scheme approach [11]. For more details about control volume definition and boundary conditions as well as to the solving technique refer to [11]. Once the thermal exergy flows are known, the principles of exergy costing are applied to the control volume (cv) of network nodes according to Figure 2.

Unit exergy costs (k_n^{th}) are assigned to node n of the cv as well as to its corresponding up- $\left(k_{u_1}^{th}, k_{u_2}^{th}\right)$ and downstream $\left(k_{d_1}^{th}, k_{d_2}^{th}\right)$ nodes. There is a flow of exergy cost associated with each flow of thermal exergy in the network.

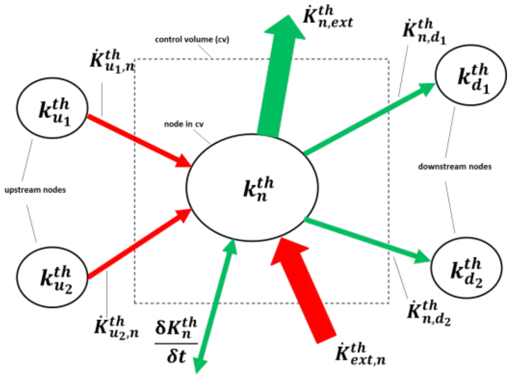

Figure 2: Exergy costing applied to graph-based network nodes

This is e.g. a flow entering from an upstream node u_1 to node n, marked as $\dot{K}^{th}_{u_1,n}$ or a flow from node n to a downstream node d_2, marked as $\dot{K}^{th}_{n,d_2}$, indicating the node pair as a subscript of a given branch. Furthermore, there can be a flow of cost entering $\left(\dot{K}^{th}_{ext,n}\right)$ or exiting $\left(\dot{K}^{th}_{n,ext}\right)$ the control volume from the external surroundings. Those flows are not associated with branches in the graph network but rather represent connections to other system components, like substation- and plant components. Additionally, a transient term $\left(\frac{\delta K^{th}_n}{\delta t}\right)$ must be considered as a product flow. This term represents the dynamic change of costs of thermal exergy in the control volume during heating-up or cooling-down phases.

2.3. Compact matrix formulation for numerical simulation

Given this definition of exergy cost flows, the exergy cost balance for node n can be written as in (1),

$$\sum_i \dot{\psi}^{th}_{u_i,n} \cdot k^{th}_{u_i} + \dot{K}^{th}_{ext,n} - k^{th}_n \left(\sum_j \dot{\psi}^{th}_{n,d_j} + \dot{\psi}^{th}_{n,ext} + \frac{\delta \psi^{th}_n}{\delta t}\right) = 0 \quad (1)$$

while for the total amount of nodes and branches, a matrix formulation can be derived as in (2),

$$\left\{\left[\boldsymbol{A} \times \boldsymbol{I}\dot{\boldsymbol{\psi}}^{th} \times [\boldsymbol{A}^{+}]^{T}\right] + \boldsymbol{I}\left[\dot{\boldsymbol{\psi}}^{th}_{extOut} - \frac{\delta \boldsymbol{\psi}^{th}}{\delta t}\right]\right\} \boldsymbol{k}^{th} = \dot{\boldsymbol{K}}^{th}_{extIn} \quad (2)$$

which uses the incidence matrix of the graph $\boldsymbol{A}(n \times b)$ and $\boldsymbol{A}^{+}$ with $a^{+}_{n,b} = max(a_{n,b}, 0)$ to determine the unit exergy cost $\boldsymbol{k}^{th}$ at every node in the network. The exergy flow vector $\left(\dot{\boldsymbol{\psi}}^{th}\right)$ contains the exergy flows of all branches in the network. The vector of transient flow of exergy $\left(\frac{\delta \boldsymbol{\psi}^{th}}{\delta t}\right)$ contains all transient flows of the network nodes. The vector of external outflows $\left(\dot{\boldsymbol{\psi}}^{th}_{extOut}\right)$ contains all external outflows of the nodes and exit the control volumes at the given specific cost $\left(\boldsymbol{k}^{th}\right)$, while external inflows $\left(\dot{\boldsymbol{K}}^{th}_{extIn}\right)$ enter the control volume from other system components.

In applying (2) numerically for every timestep, the dynamic assignment of unit exergy cost to every node is possible. Furthermore, the principles of exergy costing must be applied to the plant and substation component. Regarding the plants, the exergy cost returning from the RN as well as the thermal exergy from the plant itself are defined as a fuel flow to the plant component while the thermal exergy supplied to the SN is the product flow. The substation is modeled as a counter-current heat exchanger and solved through a NTU solver. The fuel flow is the exergy entering from the SN while the thermal exergy supplied to the consumer, which is the difference in thermal exergy on the secondary side of the HX, and the exergy flow back into the RN are considered product flows. Through this method, a unit cost of thermal exergy supplied to the consumer is assigned and can be used to determine the overall contribution on cost generation in the network.

2.4. Introduction to the case study

In this case study, the impact of waste-heat integration on the generation of exergetic costs at the substations is studied. For that, a generic waste-heat plant is defined, which is integrated similar to the heating plant according to Figure 3, which shows the geographical topology of the network on the left side, and the mass flow rates obtained through the thermos-hydraulic simulation.

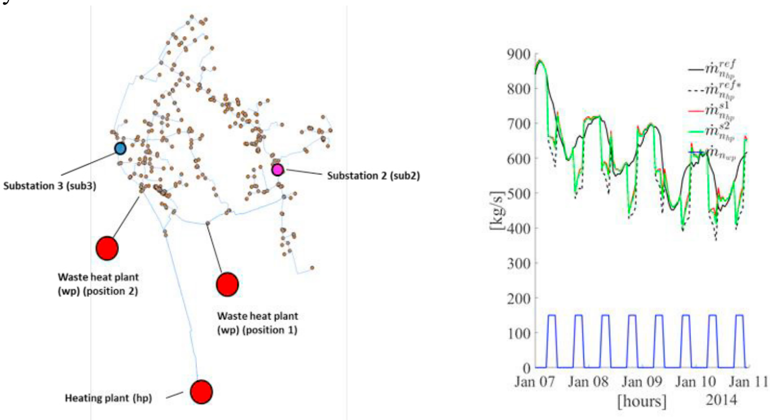

Figure 3: Position of waste-heat plant (left) and mass flow rates in the network (right)

The points in the graph are substations in the network (total 138) and a heating plant is located in the south. Two positions are defined for integration to analyze the effect on two selected substations (sub2 and sub3). Generally, the waste-heat plant is assumed to provide energy in batch-like process. This considers that waste-heat occurs during specific timeframes according to the batch-processes of operation. Furthermore, it offers the possibility to study the dynamic behavior associated with a batch-like integration. The waste-heat plant supplies 150 kg/s in a batch profile at a temperature of constant 80 °C. The following scenarios are studied and compared:

- Scenario Ref: Current operation of the network without waste-heat integration (ref)
- Scenario 1: Integration at position 1 (s1)
- Scenario 2: Integration at position 2 (s2)

The simulation is carried out for a 4-days period given real data on the network conditions and substations demands.

3. Results and Discussion

In order to understand the outcomes of the exergy cost behavior at the selected substations, the network temperatures at the inlets of the substations are provided in Figure 4 on the left side.

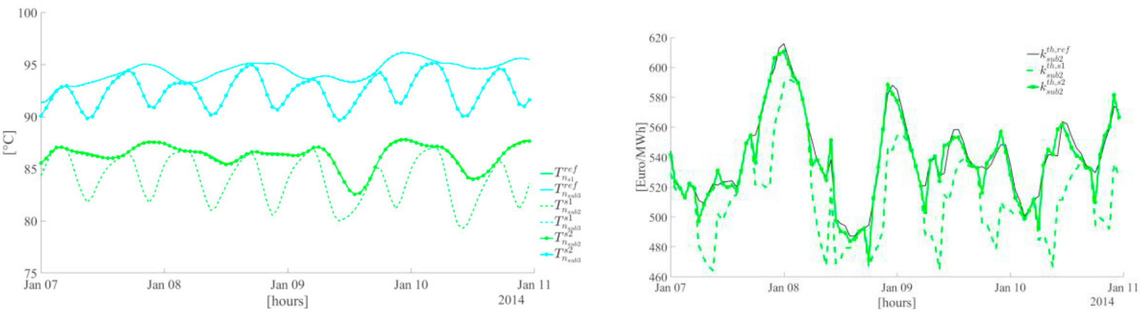

Figure 4: Network temperature at SN node (left) and comparison of unit exergy costs at substation 2 (right)

The two substations and their respective temperatures at the node connected to the SN (T_n) are shown for the reference and the integration scenarios. In scenario 1, the waste heat plant is integrated at position 1. In this case, the temperature at substations 2 increases substantially during the integration phase, while substation 3 is almost not affected. At substation 3 no temperature change can be recorded. Differently to scenario 1, in scenario 2 the opposite behavior can be concluded, where the low-temperature integration has very little impact on substation 2, but on substation 3. Thus the resulting temperature at the substations is far from being equal, but depends substantially on the position of the low-temperature source. This is a very interesting finding and clearly shows the changes in temperature distribution of the network according to a low-temperature integration and its effects on the substations at different locations. Furthermore, that has very important implications on the exegetic behavior at each substation which can be analyzed through the results obtained through the exergetic cost analysis. This is exemplarity shows for substation 2 in Figure 4 on the right side.

The value for the reference scenario $k_{sub2}^{th,ref}$ is highlighted to compare the results of the two scenarios. In scenario 1, position 1 is selected which showed to impact the temperature at substation 2 substantially, see Figure 4 (left). This leads to a deviation in the profile of the unit exergy cost over time for that substation. Detailed analysis shows, that especially during the phases where low-temperature waste is integrated into the network, unit exergy costs decrease while during the non-operating hours of the waste plant, unit exergy costs increase towards the reference value; but never actually exceeds it. The reason for a reduction in thermal unit exergy cost is the lower temperature at the inlet of substation 2 which is sufficient to provide the thermal demand of the consumer. In comparison to that, in scenario 2, the unit exergy costs are very similar to the reference values with slight increases in costs at several points. This is due to the position in the network. Temperature at the inlet is almost not affected by the integration of the waste-heat stream, see Figure 4 (left). Hence, the variation of unit cost is not directly caused by the low-temperature flow of the waste plant but due to the operating conditions of the whole network.

4. Conclusions

This work presents a new formulation of exergy costs to graph-based networks, which can be used to simulate decentralized production and consumptions in DHN with a focus on smart thermal networks. A case-study including a common batch-profile waste-heat flow at common temperature showed that the position of integration has high implications on the individual contributions of cost generation of the substations. This effect is a very complex mechanism which is caused by different influences such as temperature demand of the substation, mass flow rate etc. It allows contributing the cost of *energy service* used by the substations in a rational way and offers the possibility to assess the feasibility of waste-heat integration according to criteria such as position and exergetic content. This may further contribute to new business models through dynamic-pricing or demand side measures to avoid peak demand.

References

[1] Mathiesen B.V., Lund H., Connolly D., Wenzel H., Ostergaard P.A., Moeller B., Niel-sen S., Ridjan I., Karnoe P., Sperling K., Hvelplund F.K. (2015): Smart Energy Sys-tems for coherent 100% renewable energy and transport solutions. Journal of Applied Energy, 145, 139-154

[2] Lund H., Werner S., Wiltshire R., Svendsen S., Thorsen J.E., Hvelplund F., Mathiesen B.V. (2014): 4th Generation District Heating (4GDH). Integrating smart thermal grids into future sustainable energy systems. Journal of Energy, 68, 1-11

[3] Buehler F., Petrovic S., Karlsson K., Elmegaard B. (2017): Industrial excess heat for district heating in Denmark. Journal of Applied Energy, 205, 991-1001

[4] Bendig M., Marechal F., Favrat D. (2013): Defining waste heat for industrial processes. Journal of Applied Thermal Engineering, 61(1), 134-142

[5] Baldvinsson I., Nakata T. (2014): A comparative exergy and exergoeconomic analysis of a residential heat supply system paradigm of Japan and local source based district heating system using SPECO (specific exergy cost) method. Journal of Energy, 74, 537-554

[6] Verda V., Kona A. (2012). Thermoeconomics as a tool for the design and analysis of energy savings initiatives in buildings connected to district heating networks. Journal of Thermodynamics, 15(4), 221-229

[7] Verda V, Caccin M, Kona A (2016): Thermoeconomic cost assessment in future district heating networks. Journal of Energy, 117, 485-491

[8] Guelpa E., Sciacovelli A., Verda V. (2017): Thermo-fluid dynamic model of large district heating networks for the analysis of primary energy savings. Journal of Energy, 1-11

[9] Guelpa E., Barbero G., Sciacovelli A., Verda, V. (2017): Peak-shaving in district heating systems through optimal management of the thermal request of buildings. Journal of Energy, 137, 706-714

[10] Lozano M.A., Valero A. (1993): Theory of exergetic cost. Journal of Energy, 18(9), 939-960

[11] Patankar S.V. (1980): Numerical heat transfer and fluid flow. Series in Computational Methods in Mechanics and Thermal Sciences. ISBN 0-07-048740-5