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The effect of price regulation on the performances of industrial symbiosis: a case study on district heating

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ABSTRACT

This study of the district heating system of Aalborg (Denmark) analyses how fiscal instruments affect the extent excess heat recovery helps reduce the carbon footprint of heat. It builds on a supply-and-demand framework and characterizes the changes in excess heat supply with consequential life cycle assessment in reference to one gigajoule distributed. The heat supply curve is defined through ten scenarios, which represent incremental shares of excess heat as the constraints of the said legal instruments are lifted. The heat demand curve follows the end-users' response to price changes. The most ambitious scenario doubles the amount of excess heat supplied and reduces the heat carbon footprint by 90% compared to current level, for an end-user price increase of 41%. The price increase results from a higher supply of excess heat at a higher price and an unchanged purchase cost from the coal-fired CHP plant despite a lower supply. This highlights the necessity of a flexible supplier when the share of recovered excess heat is high.

Keywords

District heating;
Heat recovery;
Industrial symbiosis;
Excess heat;
Life cycle assessment;

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1. Introduction

In the 2020 Energy Strategy of the European Commission, the European Union (EU) defined specific climate targets to lower GHG emissions and energy use by 20% and increase alternative energy sources by 20% [1]. A series of more stringent targets are soon to be formulated for 2030 and 2050. A suggested way to reach these targets is to reduce the use of fossil fuels and increase the energy efficiency of specific energy pathways. Industrial symbiosis (IS), a concept defined as the exchange of residual material and energy flows between otherwise unrelated industrial activities within a geographically defined scope [2], is a possible solution for industries and countries to achieve the above-mentioned targets. It is a concept that can potentially improve industrial sustainability and be "*an important strategy for low-carbon development*" [3].

However, the development of IS is not without obstacles, as described by various scholars such as Harris (2007), Lehtoranta et al. (2011) and Desrochers (2001) [4–6]. Both Chertow (2004) and Bojsen & Ulhøi (2000) present obstacles of economic, legislative, organizational or physical nature that often prevent the full deployment of an IS system, if not its emergence at all [2, 7]. For instance, a repressive legal framework can limit incentives for companies to utilize and transform waste materials and excess heat [7]. Also, the development of inter-industrial collaborations on residual materials requires time and resources for the participating parties. It is critical for the development of IS that firms have an economic drive (i.e. lower transaction costs) and political support (i.e. specific goals for lowering emission levels and promoting closed-loop systems) [8]. However, the literature documenting the impacts of such obstacles on the development of IS remains broad and theoretical. To our

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knowledge, there exist no case studies demonstrating the extent to which such obstacles can prevent IS from developing or provide indication on the performance level one could have hoped to see, had they not existed.

The relevance of IS in reducing emissions of greenhouse gases (GHG), notably through the recovery of excess heat for district heating (DH) purposes, has been recognized by governments and scholars alike [9–11]. Heat recovery in the context of DH is understood as the process of retrieving excess heat released by various industrial activities without additional use of energy [10]. The heat is either directly distributed in the DH network for domestic heating purposes or complements the production of a dedicated heat plant. If not recovered, the excess heat usually dissipates into an air or water compartment and is lost.

Furthermore, academic studies point at the importance of conducting system studies exemplifying the benefits of excess heat recovery [9]. Therefore, this study precisely intends to model and describe the influence of legal and economic constraints that prevent the full exploitation of the advantages that IS can deliver in terms of carbon footprint reduction. In this case, IS is based on the context of excess heat delivery in the receiving DH network of the city of Aalborg in Denmark.

This paper is structured as follows. The next sub-section describes the concept of IS. Section two introduces the case study of Aalborg in details. The case is central for this study as it provides a basis for modelling DH supply scenarios with varying shares of excess heat as explained in section 3, namely "Description of the method". Section 4 highlights the most relevant results. Main conclusions are drawn in section 5, followed by a discussion in the last section.

1.1. Industrial symbiosis

Chertow [12] defines the concept of IS as a network of unrelated firms that share diverse resources such as heat, energy, water, waste materials and even information. It results in economic and environmental benefits for the engaged parties as it leads to reduced production and purchase costs while it also decreases the consumption of virgin resources [13]. There exist numerous examples of self-organized IS networks, which, taken to a larger scale, are called *eco-industrial parks*. The cases of Kalundborg (Denmark), Guayama (Puerto Rico), Styria (Austria) or Rotterdam (the Netherlands) are only few of the many successful examples documented in the literature [14]. In Kalundborg only, fifty unique synergies take place between the industries in the area. A third of the synergies are concerned with the exchange of water and heat [14].

2. Case study: Industrial symbiosis and district heating in the city of Aalborg

2.1. Aalborg energy strategy

The city of Aalborg is situated in the Region of Northern Denmark and is part of the Municipality of Aalborg. The municipality has translated the Danish energy ambitions of minimal dependence on non-renewable energy sources into a local strategy for fossil-free heat production. An important message is the emphasis on the need for diversified energy sources which include excess heat from industries, heat pumps, solar and wind power and geothermal energy. One of the short-term goals the strategy contains is the increased use of excess heat in the DH system, delivered at both high and low temperature [15]. There is emphasis on striving for cost-effective technologies for sustainable energy production [16]: cost-effectiveness and price for end-users are important factors at the governance level when considering alternative energy sources.

2.2. Aalborg IS synergies

Not as known as the IS case of Kalundborg, the city of Aalborg has for the past few years multiplied the cases of inter-industrial collaborations among local companies. Figure 1 illustrates the current synergies in Aalborg. The names of the public and private stakeholders remain undisclosed. A fair share of the synergies is related to the local Portland cement producer. The cement producer is strategically located in the industrial area of Aalborg with a direct access to transportation by water and land. The location eases the receiving of waste materials from the coal-fired combined heat and power plant (CHP plant), the harbour and other neighbouring activities. Most of the exchanges documented cover the processing and exchange of alternative fuels and energy flows. The recovery and exchange of excess heat from industries is one of the main "resources" delivered from industries to the local heat distribution company. Some exchanges are constrained in supply by the demand for the primary product they derive from, e.g. the supply of heat from the waste incineration plant is constrained by the supply of municipal solid waste (MSW). It is itself constrained by the level of consumption activity of the local households. In practice, however, the import of MSW from other regions is always possible.

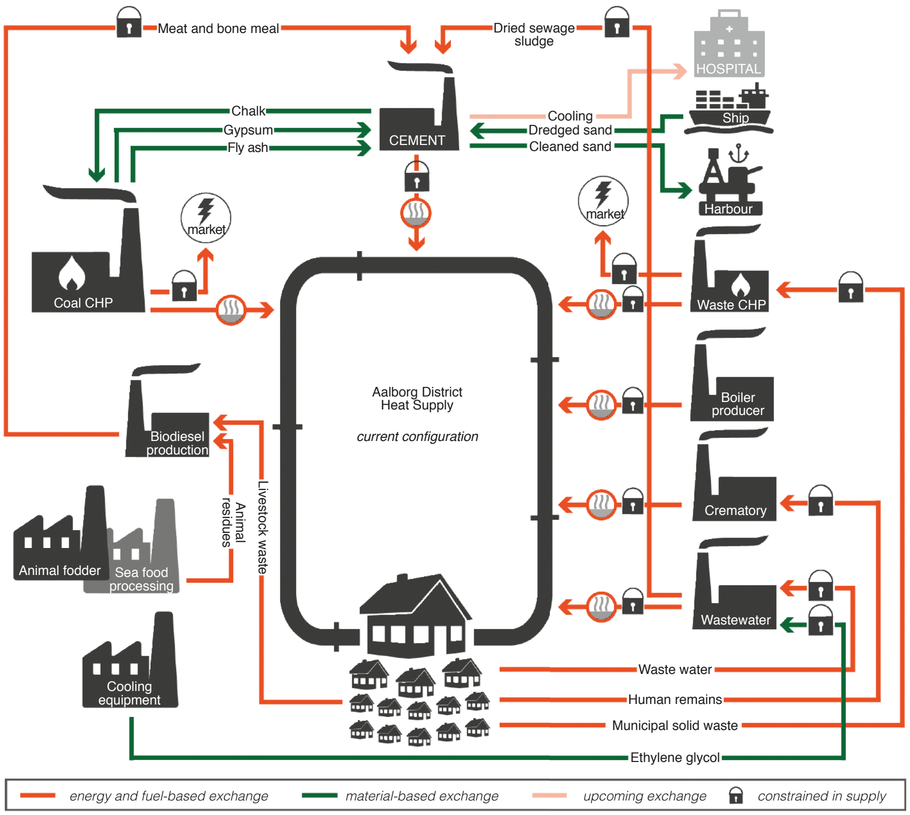


Figure 1: Material and energy flow exchanges in the industrial area of Aalborg

As this paper focuses on DH, the following paragraphs detail IS synergies in the context of DH. Currently, more than 60% of all Danish households, both urban and suburban, are connected to the DH grid [17]. In the urban area of Aalborg, the DH network supplies 80% all of the building stock heated area [18]. As the Figure 2 [19] depicts, the DH grid is sustained by the following suppliers, listed by ascending order of supply priority:

- a waste CHP plant, that co-produces heat and electricity as a result of the thermal treatment of MSW,
- the Portland cement producer, that co-produces heat as a result of white Portland clinker production,
- the municipal crematorium and wastewater treatment plant,
- the coal-fired CHP plant [20], that, when in co-generation mode, co-produces electricity and other co-products along with the supply of heat,
- and several small-scale decentralized natural gas-/biomass-fired heat plants in the outskirt of the city that act as a back-up capacity.

The share of excess heat in the DH grid in 2016 represents almost 40% of the net amount of heat distributed. It is mainly provided by the waste treatment plant and the Portland cement producer. They deliver a steady amount of heat all year through as the latter is aligned on the supply level of the primary activity they derive from, namely waste volume reduction and white Portland clinker. The coal-fired CHP plant is the only unconstrained and dedicated heat supplier that covers for the short-term variations in heat demand throughout the year. Indeed, while the suppliers of excess heat can vary the amount of heat recovered and supplied through investment in heat recovery equipment, they are not flexible regarding the overall amount of heat produced. Hence, the latter is conditioned by the stochiometric requirements of their main activity. In other words, the amount of excess heat produced depends on the demand for cement or the availability of household waste to treat, for the cement producer and the waste CHP plant respectively.

For that reason, excess heat does not bear any environmental burden since a marginal increase in the

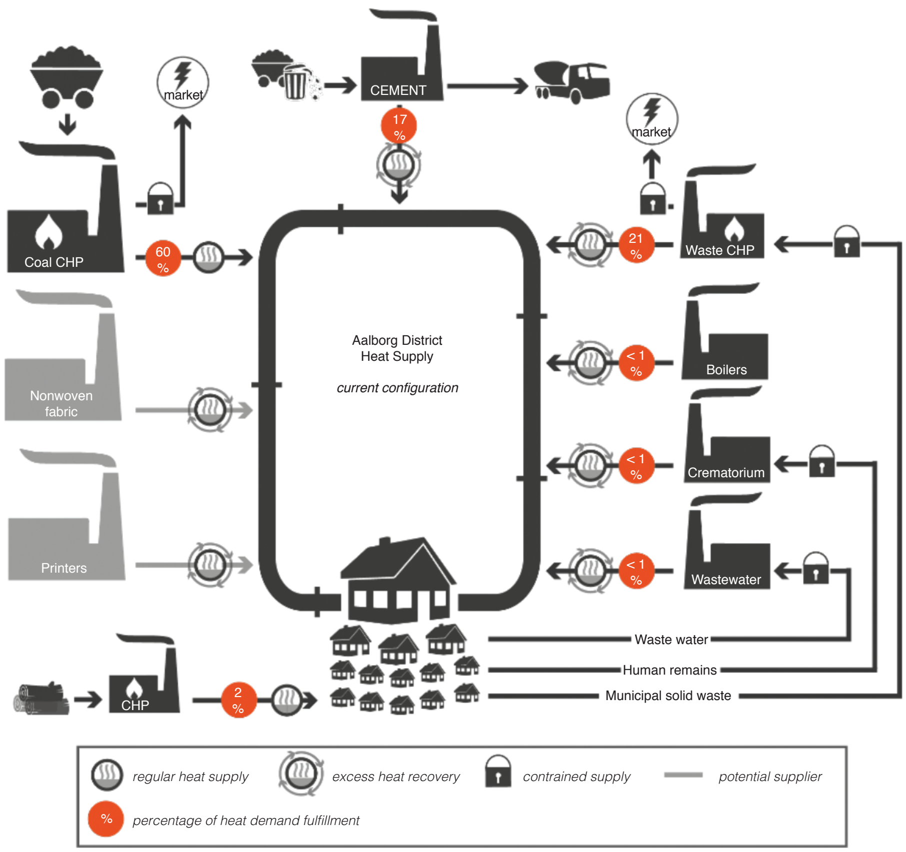


Figure 2: District heat suppliers in Aalborg in 2016. Source: based on [19]

heat supply via investment in additional heat recovery does not lead to any noticeable increase of the plant emissions or activity. Thus, this study considers excess heat carbon neutral [21] at the margin, as the environmental burden is entirely associated to the primary activity the recovered heat derives from.

Unlike recovered excess heat, the production of heat at the coal-fired CHP plant bears all the environmental burden of the plant activity, as the total emissions largely fluctuate according to the demand for heat, not electricity or other co-products when the plant operates in co-generation mode. As such, any additional amount of excess heat in the network displaces demand for heat from the coal-fired CHP plant, which reduces the carbon footprint of a gigajoule (GJ) of heat delivered. It helps the city to achieve its long-term commitment of a *GHG-neutral* DH system by 2050, set by the Danish government [22].

2.3. Aalborg IS constraints

A number of academic studies look into the advantages of excess heat recovery and conclude that there are still unexploited benefits [9, 10, 23]. Unfortunately, many initiatives to engage in IS synergies often find initial investments in infrastructure or transaction costs very high [8]. It is the case notably with large-scale flue gas condensation units needed to enter the market. Additionally, according to our knowledge, there is currently no sufficient documentation on the importance of economic profitability in the context of IS, apart from a Swedish study, where the authors analyse the unexploited potential for excess heat in the context of Sweden [24].

In Denmark, two national fiscal instruments seem to play a role in the decision of investing in excess heat recovery, both stemming from the Heat Supply Act (*Lov om varmeforsyning*, in Danish): a tax on recovered energy (usually passed on to the end-users) as well as a *price ceiling principle (or price cap),* which limits by law the return on investment for heat recovery infrastructures using the so-called substitution principle. This substitution principle sets a price limit for heat that usually corresponds to the lowest purchase price paid to the average conventional heat supplier of the country, namely large-scale coal-fired power plants. The former instrument aims at avoiding the undesirable production of *false* excess heat (where the excess heat is purposely produced with the additional use of fuel), while the latter aims at keeping the end-users heat price as low as possible, with the objective to maximize the social and economic welfare of the end-users. The authors consider the latter instrument may lead to a payback time for investment in *true* excess heat recovery that lays beyond the acceptable time horizon for many private actors in the industrial area of Aalborg.

A paradoxical situation arises where the different stakeholders are caught between the will of the government to maximize the social wellbeing of the DH recipients by offering heat at the lowest possible price and the long-term environmental agenda of the city to gradually decarbonize the DH system. The authors wish to study the effects of the fiscal instruments set in place by the government destined to enforce the former agenda on the ability of the city to pursue their environmental objectives.

In this context, the present study wishes to answer the three following questions:

- What is the effect of the price ceiling principle on the environmental performances of the IS system at delivering low-carbon DH with the current installed capacity?
- To what extent can excess heat recovery help the city fulfil its objective of a GHG-neutral DH system?
- What would be the economic impact on the end-users?

These questions are answered with reference to the distribution of one gigajoule of heat to the end-user at the margin.

3. Description of the method

This study applies both qualitative and quantitative research approaches to provide sufficient data and answer the three questions formulated above. This study relies on a supply-and-demand framework for DH in Aalborg in 2016. It helps to capture the changes in the environmental footprint of the distributed heat as more excess heat is introduced in the network. It follows a seven-step approach.

Step 1. The current DH supply — identification of the current heat supply capacity of the system

Step 2. The current DH demand — collection of data regarding the current demand for heat for the built environment in Aalborg

Step 3. Changes in supply of excess heat — cost and energy modelling of different scenarios with varying shares of excess heat in the system

Step 4. Changes in demand for DH — evaluation of the response of the end-users to varying shares of excess heat (via the price elasticity of demand)

Step 5. Identification of the substitution effect on the marginal heat supplier because of a change in demand

Step 6. Market equilibriums — for each scenario, the market equilibrium is calculated

Step 7. Carbon footprint analysis — the changes in the system because of the incremental supply of excess heat are characterized with the help of consequential Life Cycle Assessment (LCA)

The next sections describe the approaches this study follows to gather the necessary data for each step.

3.1. Step 1. The current DH supply

On the supply side, the current capacity of individual heat producers (the coal-fired CHP plant, the waste treatment plant and the Portland cement producer) are modelled based on technology and cost information provided by the Ministry of Energy, published environmental and financial reports as well as direct communications with company representatives during the spring of 2017. A supplier cut-off criterion of 1% is applied: minor heat suppliers such as the local crematorium, the waste water treatment plant and potential newcomers are excluded as the benefits in terms of results completeness or accuracy would not justify the time spent on modelling them.

The coal-fired CHP plant and the waste treatment plant illustrate a challenging case of cost allocation (between the production costs of heat and electricity). For the coal-fired CHP plant, an additional task was to distinguish the inputs associated to the co-generation mode, as opposed to those associated to the condensation mode, where only electricity is produced. Indeed, the environmental report only gives the aggregated annual use of inputs and outputs. Hence, with a heat-to-power coefficient of 0.78 (given by the ratio between the heat and electricity nominal power output) and an overall reported conversion efficiency of 91% in co-generation mode, it was possibly to obtain the needed inventory. The V and E allocation method suggested by the Ministry of Treasure [25] is used to split the investment and maintenance costs as well as the fuel inputs between the co-products, to estimate unitary heat production costs for heat and electricity, as depicted in Figure 3. The company is free to choose between both V and E allocation methods when reporting fuel use for taxation purpose. Since the share of fuel destined to produce electricity is exempt of taxation, in all logic, the reporting energy company chooses the method that allocates as much resources to electricity production as possible. The same logic is followed in the present model. A 5% profit margin is added on top of the production cost to obtain the per-gigajoule purchase price of heat.

It is important to note that, although it is needed at this stage to perform a cost allocation to determine unitary production costs, the emissions of the plant are entirely associated to the production of heat in the LCA model, as the demand for the latter determines the production of both heat and electricity when in co-generation mode.

3.2. Step 2. The current DH needs

On the demand side, the current need for heating and the overall heat footprint of each square meter of the built environment in Aalborg are calculated based on the method followed by Kragh and Wittchen (2014) [26] and presented in Figure 4. The Danish Ministry of Statistics provides the detailed distribution of the heated area in Aalborg in 2016 per building type, heating technology and building age intervals [27]. Episcope's TABULA model, a European harmonized model for measuring and comparing building thermal efficiency across types and locations, is used to estimate the current energy footprint per heated square meter for the 300 different building typologies in Aalborg [28]. Pre-existing Danish building typologies in Episcope were adapted to the context of Aalborg, under the assumption that the Danish building stock is homogenous enough to do so. Some parameters were adjusted to the context of Aalborg, such as weather-related parameters. Additional building typologies were created on top of those existing in the Episcope database. Presumably, reducing the complexity and variety of heat transfers of the whole building stock in Aalborg down to a few dozens of parameters re-arranged into 300 building typologies is done at the expense of accuracy. This is confirmed when the overall heating demand obtained overestimates the real reported heating demand for 2016 by 10%. Nevertheless, the authors believe it provides a solid base for estimating the price elasticity of demand discussed in the next sections.

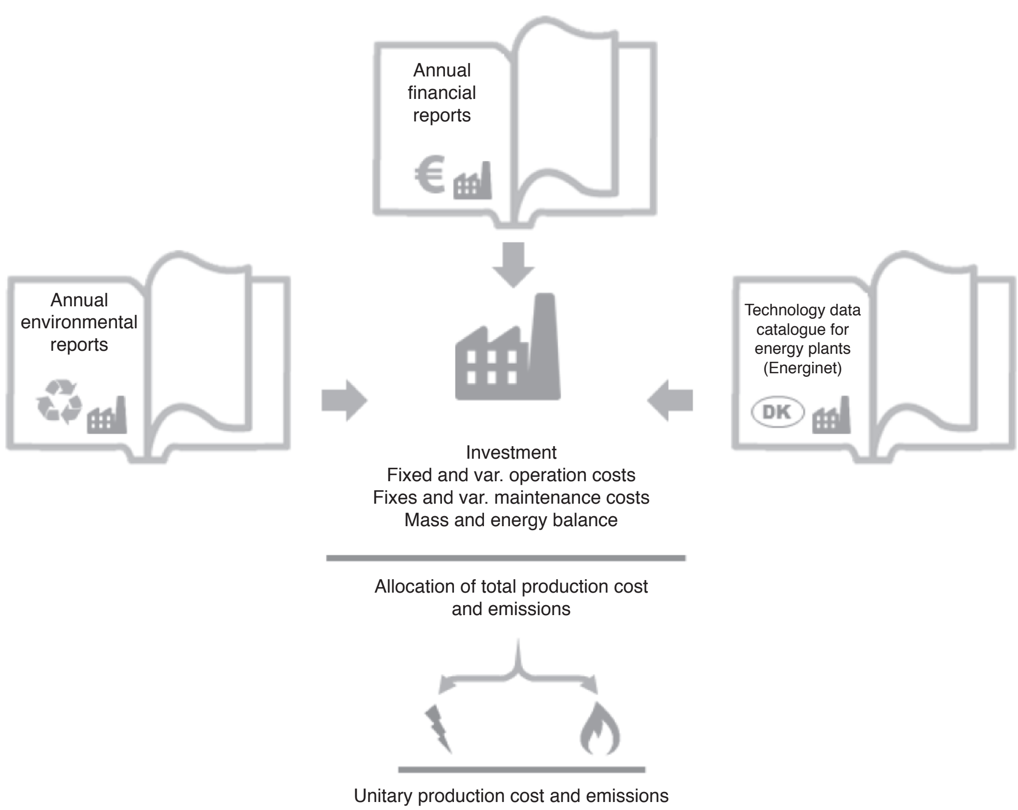


Figure 3: Cross checking of data sources for the approximation of unitary cost and emissions for heat

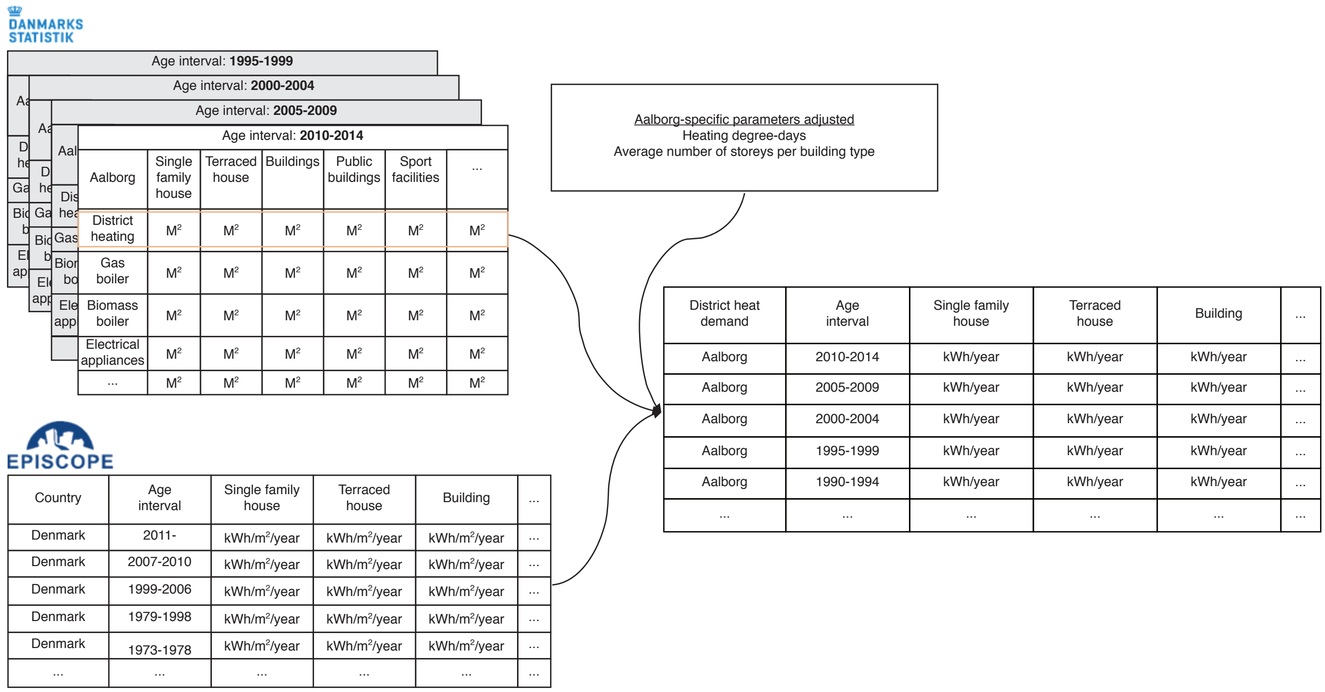


Figure 4: Illustration of the method followed to define the demand for district heat in Aalborg [27, 28]

3.3. Step 3. Changes in supply of excess heat

It is hypothesized in the 'Introduction' section that the current legislative framework hinders the recovery of additional excess heat in the DH system of Aalborg. As confirmed through written and face-to-face communications with the current excess heat suppliers [29–31], there is a current price ceiling on heat recovery which strongly limits the overall profitability of heat recovery operations. Thus, it does not allow a payback time short enough for the present investors.

In this study, such constraint is lifted to deduct its effect. A triangulation method is used to ensure the validity of the data and the conclusions drawn upon it [32]. First, individual semi-structured interviews with existing excess heat suppliers are conducted. They allow to estimate potential supply of additional excess heat. Additional supply capacity from existing suppliers is mainly achieved by means of investment in:

- the extraction of latent heat from the condensation contained in the flue gases,
- the enhanced extraction of latent heat from the flue gases below the dew point with marine scrubbers, further aided by large-scale heat pumps,
- the recovery of radiative heat on rotary kilns.

Second, the financial investments required for retrieving the additional excess heat in question are estimated, completed by the Ministry of Energy's Technology Data for Energy plants documentation [33].

With knowledge on the potential additional heat supply, the associated financial investment and the acceptable investment payback time of the suppliers, an excess heat supply curve in relation to the price level offered to the different suppliers is obtained. The heat supply curve is defined throughout a total of 10 scenarios presented in Table 1. All scenarios supply the demanded amount of heat in 2016 of 6.715 TJ (minus the demand change because of the price elasticity of demand described in the next section), in addition to a 17.5% network loss. They are listed with an incremental share of excess heat, to draw a supply curve for excess heat.

- Scenario 0 corresponds to a supply mix without the presence of excess heat, but only the coal-fired CHP plant;
- Scenario 1 adds the heat supply from the small-scale CHP plants located at the outskirt of the city, i.e. biomass and natural gas heat plants;
- Scenario 2 includes the excess heat delivery from the waste treatment plant;
- Scenario 3 adds excess heat from one of the recovery units located at the cement factory;
- Scenario 4 adds a second heat recovery unit located at the cement factory and represents the

Table 1: Excess heat suppliers mix for each of the 10 scenarios

Supplier	Description	Scen. 0	Scen. 1	Scen. 2	Scen. 3	Scen. 4 (current)	Scen. 5	Scen. 6	Scen. 7	Scen. 8	Scen. 9
Coal-fired CHP plant	• Coal-fired CHP plant • Heat power output of 420 MW at 90°C • LHV of coal: 23 GJ/t • 85% net efficiency rate in co-generation mode in 2016 (91% gross efficiency rate) • 0.78 GJ of electricity co-produced per GJ of heat delivered • Annual operating time: 8760 hours	x	x	x	x	x	x	x	x	x	x
Outskirt CHP plants	Small-scale biomass and natural gas heat plants.		x	x	x	x	x	x	x	x	x
Waste CHP plant	• 94% efficiency (heat and electricity) • LHV of MSW: around 11 GJ/t • Power out of 50 MW at 80°C • 0.3 GJ of electricity per GJ of heat delivered • Annual operating time: 8142 hours			x	x	x	x	x	x	x	x
Cement producer — Recovery unit 1	• Double stage heat exchanger • Power output of 37 MW at 74°C • Power output of 54 MW at 60°C • Annual operating time: 7440 hours				x	x	x	x	x	x	x
Cement producer — Recovery unit 2	• Double stage heat exchanger • Power output of 15 MW at 74°C • Power output of 24 MW at 60°C • Annual operating time: 7440 hours					x	x	x	x	x	x
Cement producer — Recovery unit 3	• Double stage heat exchanger • Power output of 19 MW at 74°C • Power output of 60 MW at 60°C • Annual operating time: 7440 hours • Estimated investment: 8 M€ • Estimated annual maintenance: 0.44 M€						x	x	x	x	x
Waste CHP plant — Extra recovery unit	• Condensing heat recovery unit • power output of 3,4 MW at 80°C • Annual operating time: 8142 hours • Estimated investment: 9.1 M€							x	x	x	x
Cement producer — Recovery unit 4	• Dry flue gas heat recovery unit • Power output of 6 MW at over 100°C • Annual operating time: 7440 hours • Estimated investment: 4.43 M€								x	x	x
Cement producer — Recovery unit 5	• Dry flue gas heat recovery unit • Power output of 15 MW at over 100°C • Annual operating time: 7440 hours • Estimated investment: 9.4 M€									x	x
Heat pump	• Large scale heat pumps • Number of heat pumps required: 38 at 4 MW_{th} • Source temp. in: 60°C, source temp. out: 30°C • Source sink in: 42°C, source sink out: 80°C • Lorentz COP: 12.6 • Annual operating time: 7440 hours • Estimated annual cost: 28 M€										x
Estimated share of excess heat in the DH system (%)		0	0	22	37	43	50	51	57	60	90

current situation in Aalborg (also previously presented in Figure 2);
- Scenario 5 builds on Scenario 4 and adds the heat delivered by a third recovery unit at the cement factory;
- Scenario 6 includes an additional heat recovery from the waste treatment plant;
- Scenario 7 and 8 add radiative heat from the rotary kilns of the cement producer;
- The additional excess heat in Scenario 9 is obtained by the further recovery of latent heat below the dew point of the flue gases of the cement kilns.

Scenario 9 implies that the DH network delivery temperature of 74°C is reduced to 60°C. Recovering heat at a lower temperature allows to extract additional latent energy contained in the moisture of the flue gas. It results in more energy at a lower temperature. The recovered heat is then increased to 80°C with several large-scale $4MW_{th}$ heat pumps and an auxiliary use of electricity, to be usable for residential heating. In earlier scenarios, where the excess heat is delivered at 74°C by the cement factory, the coal-fired CHP plant had the task to add 6°C to the recovered heat to reach an average temperature of 80°C. Recovering the heat at a lower temperature also entails the purchase and installation of water treatment infrastructures to handle and clean the additional condensate water. It also encompasses additional maintenance costs that result from the fouling effect of gypsum-rich condensate water on the heat exchangers.

3.4. Step 4. Changes in demand for DH

This step concerns the modelling of the response of the demand to changes in the end-user DH price. Heating is a necessity good for which the demand is rather inelastic. While an increase in the DH price leads to a decrease in the heat amount demanded, it is necessarily compensated to keep a constant amount of indoor comfort. The possibility for the end-users to switch to alternative means of heating as a response to increments of the DH price is discarded. It is indeed legally and economically difficult to do so once the heated area is connected to the DH grid. A permission to stop using the DH network needs to be asked to the relevant authority. When granted, the annual fixed part of the DH end-user subscription, used to finance the connection to the DH sub-station, still needs to be paid, rendering the switch to other sources of heating uneconomical, albeit not impossible. The study makes instead the simplifying assumption that the reduced demand for DH, because of a price increase, is instead displaced on the thermal renovation of the building envelope.

Sourcing from a database that contains updated prices on thermal renovation projects in Denmark (Molio pris database) [34], a solver is used to find the optimal combination of renovation works for each building typology in Aalborg in order to comply with the current regulation for renovated buildings (BR2015) [35] at a minimal cost.

The need for additional insulation is calculated with reference to an indoor comfort temperature of 20°C, as indicated in the BR2015 regulation, with a 5-year average annual heating degree-days for the region of Aalborg. A series of constraints have been added to the solver. For example, buildings before 1930 cannot undergo façade walls renovation (for aesthetic preservation reasons), while only buildings built between 1900 and 1950 can undergo wall cavities filling with glass-blown granulates (buildings built after 1950 are assumed to be already insulated that way). Additionally, the economic cost of wall insulation from the inside includes the lost liveable indoor area multiplied by the current average square meter cost in Aalborg.

Estimating the cost of thermal renovation for each building type allows to define the DH price level at which the building owner would rather invest in the insulation of the building envelope rather than accept the change in DH price (price elasticity of demand). The heavy assumption made here is that building owners follow a strictly economic rationale, which might not always be true in practice. The decision of investment happens when the return on investment over the lifetime of the renovation project (that is the ratio between the avoided heating cost over the project lifetime and the total cost of insulation) reaches a ratio of 1.33. While the ratio of 1.33 may seem arbitrary, it is the one considered by the BR2015 guidelines [35]. Such exercise allows to approximate a demand curve for DH in relation to its price, presented later in Section 4.1 'The DH demand curve'.

3.5. Step 5. Substitution effects and price elasticity of demand

As the scenarios introduce an increasing share of excess heat in the DH grid, the price and quantities purchased from each supplier by the utility company to satisfy the demand change too. Additionally, as the share of excess heat supply increases, the share of heat supplied by the dedicated coal-fired CHP plant reduces to keep a constant supply output on the market. Doing so increases the unitary heat price from that coal-fired CHP plant as fixed capital and investment costs allocated to the production of heat still run despite a lower production level. The relation between the amount of heat demanded from the coal-fired CHP plant and the purchase price level is depicted in Figure 5.

In parallel, a reduced heat delivery from the coal-fired CHP plant also leads to a reduced co-delivery of electricity (as the coefficient of co-production of the coal-fired CHP plant between both outputs in co-generation mode is assumed constant). The missing delivery of electricity will be compensated by an equivalent production of electricity from a mix of marginal electricity-supplying technologies in Denmark, coming mostly from biomass and wind power [36].

It is assumed that the energy distribution company runs at marginal costs — which is confirmed by the two latest financial reports of the Aalborg utility company [37, 38]. This means that any increase in heat purchase costs translates in an increase in price on the side of the end-users. Considering the price elasticity of demand, an increase in price for the end-users translates in an overall reduced demand for heat. Such reduction is obtained from the demand curve calculated in Step 4. The model reduces the required heat supply by an equivalent amount from the marginally least-preferred heat supplier in the mix of suppliers, namely the coal-fired CHP plant. This returns a *mid- to long-term* market equilibrium

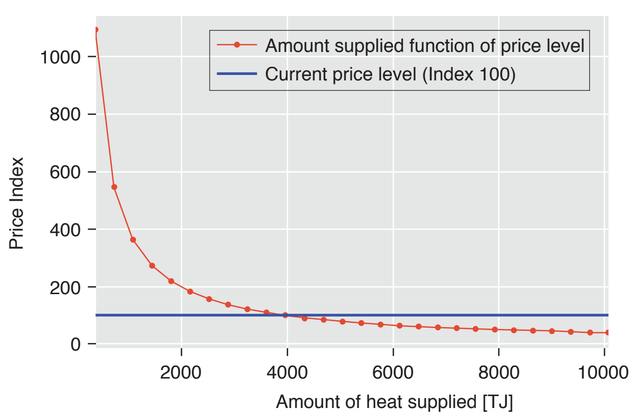


Figure 5: Relation between the amount of heat purchased from the coal-fired CHP plant and the purchase price level

(Step 6, discussed in Section 3.5) for which the carbon footprint of a distributed gigajoule of heat can be calculated (Step 7, discussed in Section 3.6).

At the same time, as the demand reacts (decreases) and the supply from the coal-fired CHP plant reduces, the model considers the amount of transportation activity, the production of insulation materials and all other requirements necessary to support the renovation works needed to preserve the initial indoor comfort temperature of 20°C on the share of the building stock that reacts to the DH price change. Common thermal transmittance values are used for mineral wool and a local production is assumed for most materials (mineral wool, concrete, bricks, gypsum boards, windows, doors, ventilation systems, etc.) as well as an average transportation distance of 150 km from their production facility to the renovation site.

3.6. Step 6. Market equilibriums

Knowing the calculated supply and demand preferences at any given price level allows to calculate the market equilibrium for each scenario. As the share of excess heat increases through the scenarios, it returns a new end-user price level. The latter induces a decrease in demand for DH and an increase in demand for thermal insulation. This affects in turn the supply of DH and its price level. This is the mid-term equilibrium at which a new DH quantity is supplied for a corresponding end-user price level.

3.7. Step 7. Carbon footprint analysis

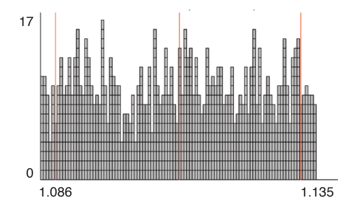
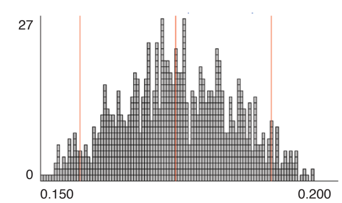
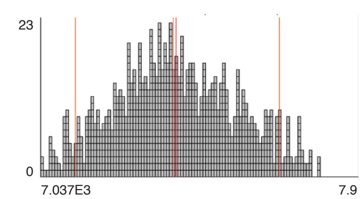
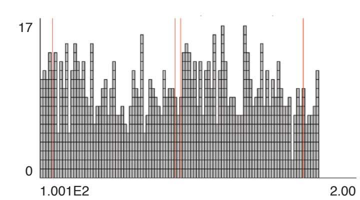
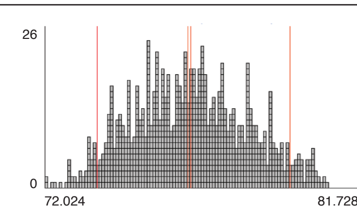
'Carbon footprint', as defined by Wiedmann and Minx (2008) is the amount of GHG emitted through the life cycle of a product or service, supplied by an organization or by a process [39]. To consider the consequences of increasing the supply of excess heat on the carbon footprint of the heat produced, a consequential LCA is conducted and thus provides a comparison of the environmental impacts of each scenario [40]. The results from the LCA can give a good starting point for developing a discussion on the potential solutions for Aalborg in delivering GHG-neutral DH to its end-users with the current available resources.

When the market equilibriums for the different scenarios are defined, the LCA model calculates the carbon footprint of one GJ of heat distributed to the end-user at the margin as an increased share of excess heat is introduced in the system. The material and energy requirements to deliver one GJ of heat in each scenario are modelled in OpenLCA, the LCA tool used in this study. Background processes — e.g. transport activities, production of insulation material, supply of electricity — are modelled using the consequential life cycle inventory database ecoinvent version 3.3.

The presence of large uncertainties in the underlying economic model of each supplier calls for the use of uncertainty-handling techniques, such as the Monte Carlo analysis. To do so, uncertain parameter inputs were identified, in accordance with the communications with the excess heat suppliers. An uncertainty distribution profile was associated to several of these parameters. Table 2 lists some of the uncertain parameters at the excess heat recovery level.

The Monte Carlo algorithm iterates 1,000 times through each scenario. For each iteration, a random variable is picked within the uncertainty distribution of each model input for which uncertainty was defined. The algorithm then builds a technology matrix which is passed to the LCA solver class of OpenLCA. The solver multiplies the inverse of the technology matrix by an environmental matrix and a demand vector to return the total material and energy inventory of each scenario.

Table 2: Non-exhaustive list of parameters and associated uncertainty distributions

Parameter name	Description	Distribution parameters	Probability distribution
GJ_in_out_HP	GJ of heat in at 60°C for every GJ of heat out at 80°C delivered by the heat pumps.	Uniform Mean: 1.06 Min: 1.05 Max: 1.08	
Network_loss	Heat loss ratio in the DH network.	Triangular Mode: 0.175 Min: 0.15 Max: 0.2	
Operating_time_ap	Annual number of hours of operation at the cement factory.	Triangular Mode: 7440 Min: 7000 Max: 8000	
Transport_distance	Distance for the delivery of materials necessary to thermal renovation works.	Uniform Mean: 150 Min: 100 Max: 200	
Price_supplier_1	Purchase price of heat from supplier 1.	Triangular Mode: 77 Min: 72 Max: 82	

The inventory is then multiplied by the characterization factors provided by the *IPCC Global Warming 100a* method to obtain a carbon footprint expressed in *kg of* CO_2*-eq per GJ distributed* with a time horizon of 100 years.

4. Results interpretation

This section details the calculated demand (Section 4.1) and supply (Section 4.2) curves as well as the resulting changes in the carbon footprint of one gigajoule of heat (Section 4.3).

4.1. The DH demand curve

Figure 6 illustrates the relation between demanded district heat and the heat price index in Aalborg. The red polynomial regression curve allows to approximate a demand curve for DH in relation to its price. The curve is later used to find market equilibriums for each heat supply mix scenario, presented in the next sub-section.

Two groups of buildings are more prone than others to react to DH price increments:

- Old buildings that would find a significant reduction of their energy footprint through insulation,
- Relatively recent buildings, often public institutions, with a large heated area and a well-insulated envelope that would find interest in upgrading, at limited costs, to a newer ventilation system with heat recovery.

The mild slope of the demand curve indicates a rather inelastic demand to DH price changes. It is because the price elasticity of demand in this study is defined in a context where the change to other means of heating is not permitted and where the building owners act rationally, as explained in the Section 3.4. Thermal renovation projects are expensive and ROI of 1.33 are only reached at high DH price increase. In practice, some building owners would switch to another source of heating, while others would simply not notice price changes. Real and measured data would likely differ with the demand curve illustrated below.

4.2. The new market equilibriums

Figure 7 shows the market equilibriums reached for the 10 scenarios. From left to right, each scenario introduces an increasing amount of excess heat in the supply mix. Scenario 4 represents the current situation in Aalborg. Scenarios 5 to 9 represent market

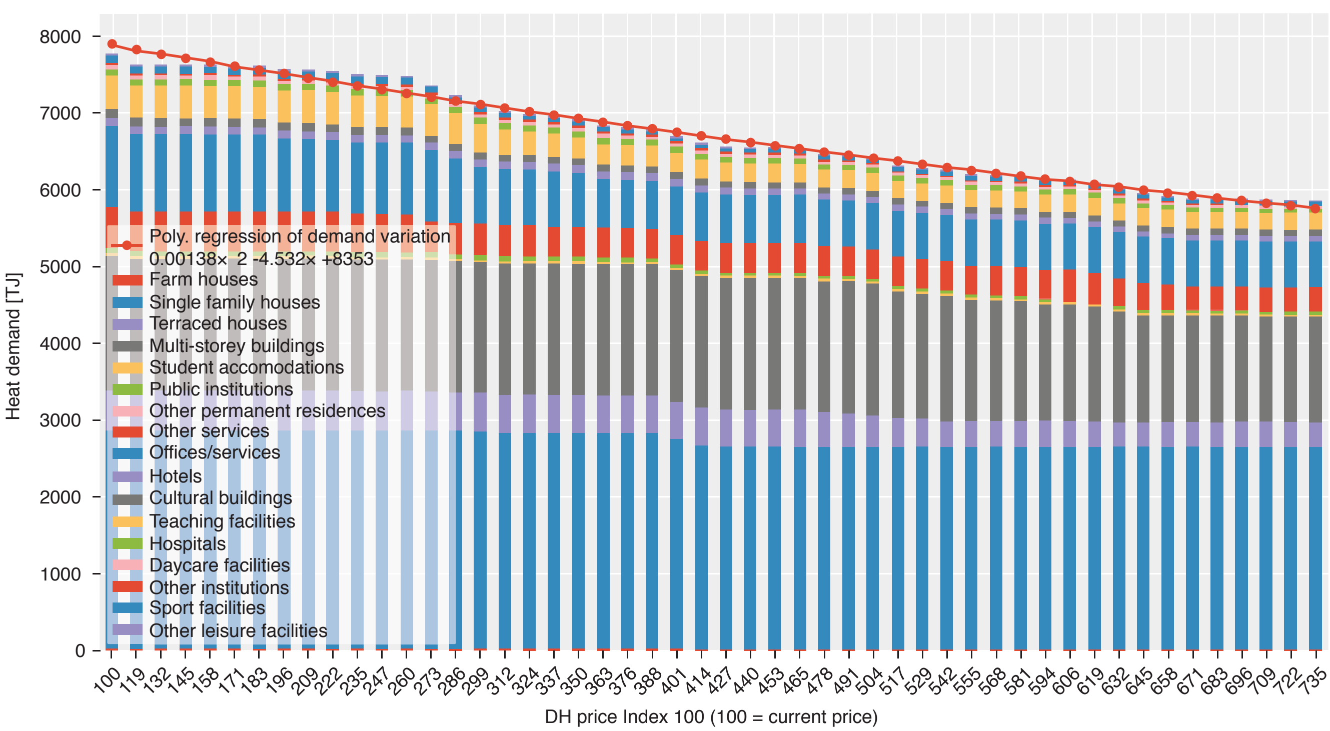


Figure 6: Relation between demanded district heat and the heat price level in Aalborg

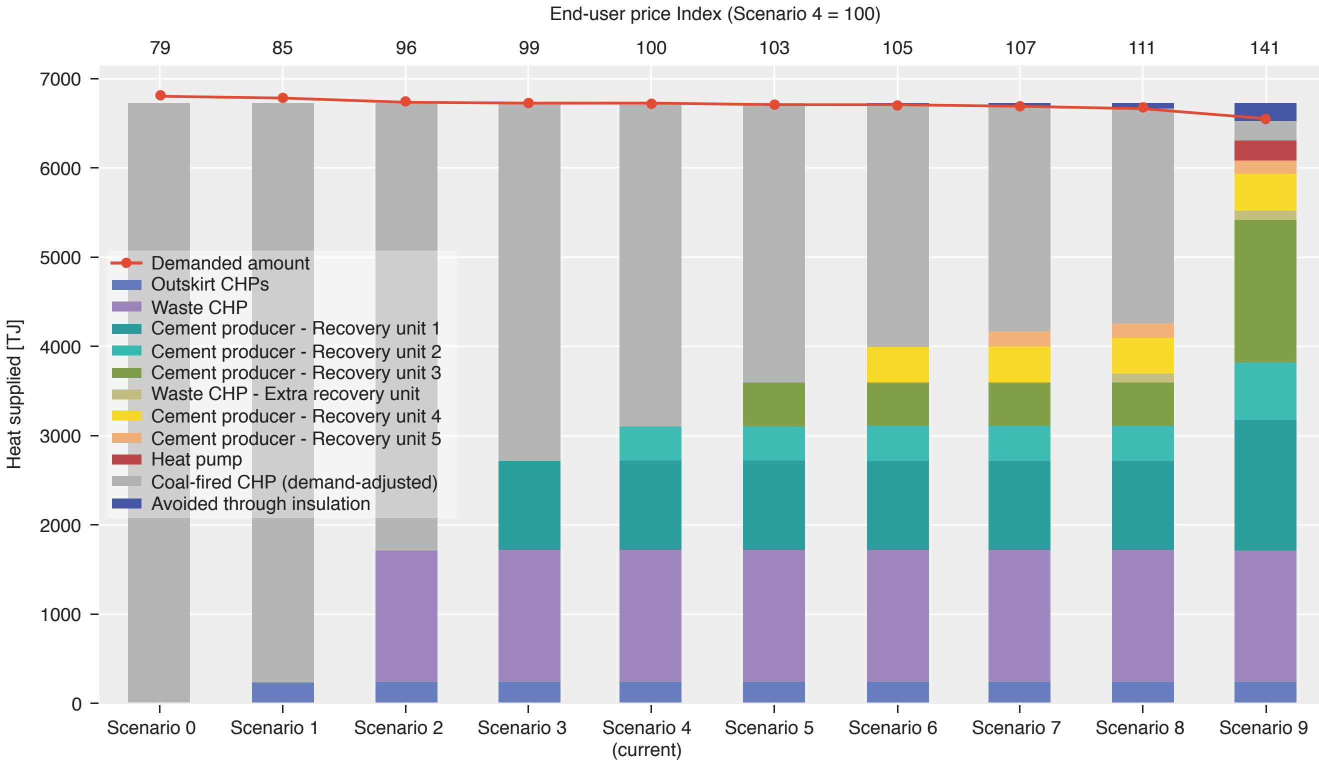


Figure 7: Market equilibriums for each supply mix scenario (red scatter = demand curve for heat). From left to right, increasing shares of excess heat are introduced

equilibriums where the constraint from the price ceiling principle is lifted. Each scenario corresponds to a new price level. As the price level increases, the demand for heat, represented by the red demand curve, decreases. The least-preferred supplier, the coal-fired CHP plant, is affected by the decrease in demand. The missing heat output is compensated by means of heat preservation through insulation of the building stock. Scenario 9 introduces the use of heat pumps to boost the temperature level of the heat recovered at the cement producer recovery units. Hence, the share of the cement producer supply increases. Additionally, the red segment represents the additional supply of heat generated by the auxiliary input of electricity in the heat pumps (calculated as the difference between the amount of heat transferred to the sink and the amount of heat transferred from the source, for the calculated coefficient of operation).

The evolution of the unitary price can be seen in Figure 8. Scenario 9 reaches an excess heat share of 90% for a price increase of 41% compared to Scenario 4. This price increase is the result of the combination of two cost-related aspects. There is an increased cost of purchase of excess heat on one hand and a constant cost of purchase of heat from the coal-fired CHP plant on the other hand. 65% of the purchase cost increase is associated with the investment and maintenance of 38 4MW_{th} heat pumps. They represent an annual cost of 28 M€, of which almost a third (or 20% of the additional purchase cost) is a tax applied on the use of electricity in the context of heat production. The remaining of the purchase cost increase (35%) comes from an increased volume of excess heat purchased from the cement producer and the waste CHP plant at a higher price (that reflects investments in heat recovery equipment and infrastructures to collect and treat condensate water). It is to note that a fourth of these 35% represents the tax on recovered energy discussed in Section 2.3.

Despite its reduced supply throughout the scenarios, the coal-fired CHP plant needs to ensure the role of flexible heat supplier. It can adapt to short-termed seasonal demand fluctuations and complete the supply to meet demand peaks. At the same time, it needs to cover fixed and running expenses despite a lower heat production output level (reference to Figure 5). This creates a lock-in situation where the virtually unchanged

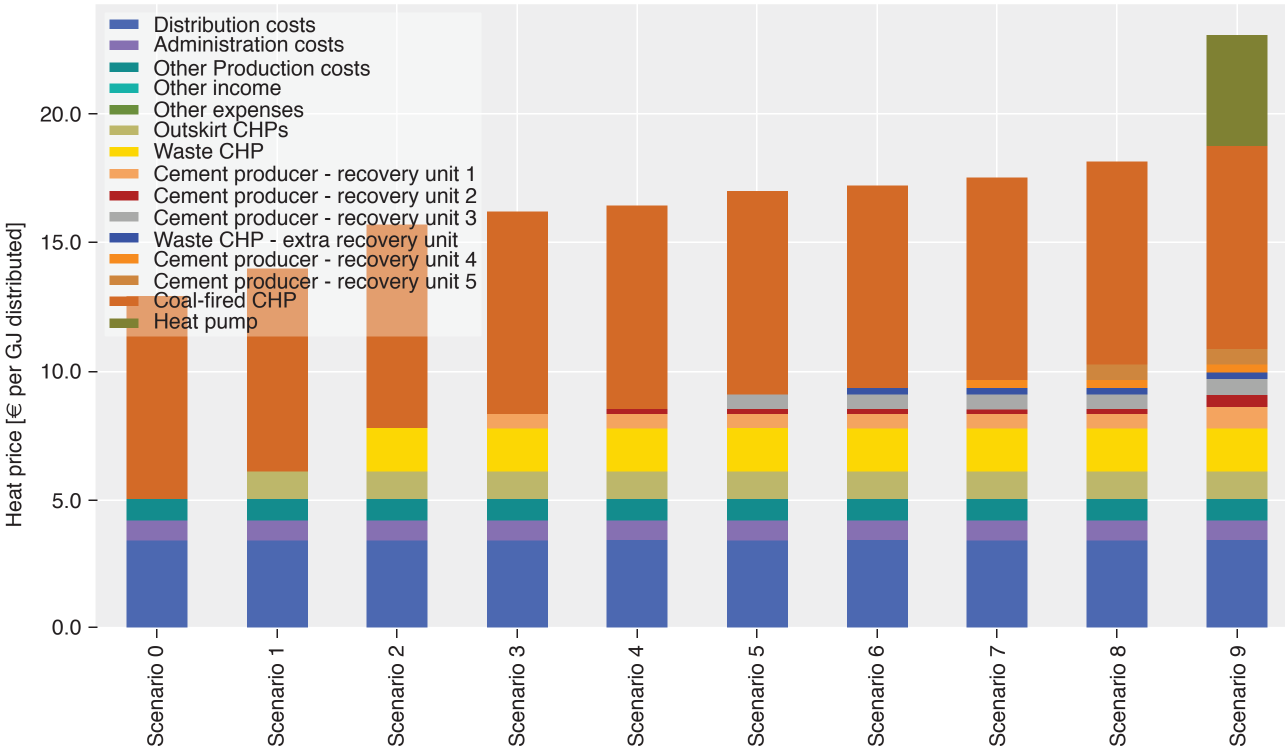


Figure 8: Unitary price structure per GJ distributed

cost of purchase of heat from the coal-fired CHP plant prevents any savings that could be used to finance the above-mentioned investments.

4.3. Carbon footprint results

The results of the Monte Carlo simulation analysis are presented in Figure 9. Uncertainty in the model inputs propagates throughout the outputs. For that reason, it is difficult to conclude on a clear carbon footprint improvement for Scenario 4 over Scenario 3. However, there is a clear statistical improvement trend as the share of excess heat in the DH system increases. For example, compared to the current estimated carbon footprint of about 153 kg of CO2-eq per GJ distributed (Scenario 4), Scenario 9 delivers a GJ of heat at almost a tenth of that value (about 11 kg of CO2-eq per GJ distributed on average). This shows that untapped potential in excess heat recovery can lead to substantially lower carbon footprint levels for the DH system, and bring the city closer to its GHG-neutral heat delivery objective.

5. Conclusions

In the introduction of the paper, three research questions were raised. This section aims to provide answers to each of them, based on the results presented in the preceding section. Furthermore, it elaborates on some weaknesses of the model and what possible drawbacks those can have on the results of the study.

Q1: What is the effect of the price ceiling principle on the environmental performance of the IS system at delivering low-carbon DH with the current installed capacity? The below country-average price for the end-users of the DH network in Aalborg is a result of a political decision [41]. Nevertheless, such a price ceiling on the DH suppliers' side may restrict further capital-intensive investments in excess heat recovery. Indeed, this study indicates that the amount of excess heat supplied could be at most multiplied by two, had favourable economic conditions been in place. In other words, the effect of the price ceiling principle on the environmental performance of the DH system is to drastically limit the potential for carbon footprint reduction, aside from keeping the end-users price low. The LCA analysis conducted in this study indicates that increasing the supply of excess heat can substantially reduce the need for coal-based heat, and, altogether with a demand displacement effect, lead to a reduction of the heat carbon footprint by 93% compared to the current situation. As discussed in the Section 2.2, such answer

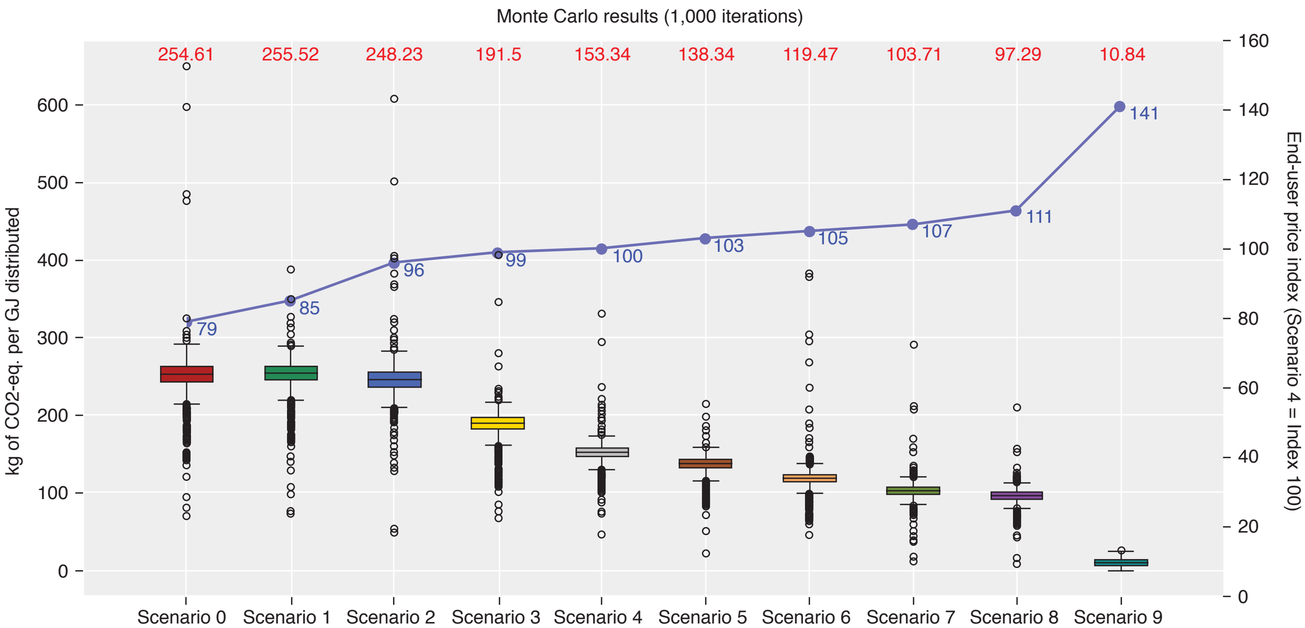


Figure 9: Monte Carlo simulation results for each supply mix scenario (red values = carbon footprint median, blue scatter = end-user price level index). Boxes represent 50% of the distribution while the interval defined within the black horizontal lines represents 90% of the distribution. Cross-shaped points are outliers to the distribution

holds on the assumption that recovered excess heat does not bear any of the environmental burden associated to the industrial process.

Q2: To what extent can excess heat recovery help the city fulfil its objective of a GHG-neutral DH system? The different scenarios built in this study follow the short- and longer-term strategies of Aalborg Municipality of moving away from fossil fuels for heating purposes, e.g. using high-, medium- and low temperature heat from industries. The most ambitious scenario (Scenario 9) results in a tenfold lowering of the carbon footprint of the heat compared to the current scenario (Scenario 4) i.e. from 153 kg of CO_2-eq. per GJ distributed down to about 11 kg of CO_2-eq., provided that the share of excess heat grows from 43% to 90% of the supply mix.

Q3: What would be the economic impact on the end-users? As presented in Section 3.3 'Changes in supply of excess heat', a share of excess heat as high as 90% of the gross supply mix can be achieved through capital-intensive investments in various equipment. It results in an increase of the end-user price of 41% compared to the current price level, *ceteri paribus*. The market equilibrium for each scenario is calculated after consideration of the demand elasticity and displacement of the demand for alternatives, i.e. thermal insulation of the building envelope. The results from section 4.1 'The DH demand curve' show that insulation is a preferred strategy for old buildings, while more recent buildings with large heated area are rather upgraded with a new mechanical ventilation system with indoor heat recovery. But the reader should be aware that the conclusions of this study hold on the assumption that building owners act rationally and that the decision of insulating a house is taken as soon as it is economically viable to do so. This assumption is, without a doubt, weighting heavily on the calculation of the demand elasticity. Some building owners may decide to undergo building renovation well before the project reaches a ROI of 1.33, while others may be unaware of heating price changes. While such uncertainty may have an influence on the end-results, the authors assume the above-described market dynamics and the conclusions drawn from them would remain unchanged.

6. Discussion

A potential drawback about the proposed scenarios in this study is the focus on excess heat as the only viable alternative to coal-based heat. Instead, diversifying the energy sources (e.g. geothermal, wind power-to-heat), an ambition very high on the agenda of Aalborg Municipality [16], could be a plausible alternative. Diversifying the energy mix secures against volatility of prices and supply levels [42].

However, alternative (renewable) energy sources can be costly to implement compared to excess heat recovery. For illustrative purpose, Table 3 shows the average nominal investment per MW of heat for common district heating technologies given by the Danish Ministry of Energy and compares it to the average nominal investment associated to the capacity increment between Scenario 4 (current capacity) and Scenario 9 (most ambitious scenario). Between scenarios 4 and 9, an additional 125 MW of excess heat are installed, for an average nominal investment of 0.2 M€/MW. The low nominal investment figures are explained by the fact that infrastructures already exist and a substantial part of the economic burden is sustained by the activity the heat is a co-product of.

The analysis of the price increase between Scenario 4 and 9 in Section 4.2 shows that the necessity to keep a flexible heat supplier prevents savings that could partly or entirely finance the needed investment in heat recovery equipment, leading to an overall price increase. The supply agreement between the city of Aalborg and the coal-fired CHP plant will last until 2027, after which a national directive phases out heat and electricity production from coal. Hence, should the excess heat recovery be taken to an extent similar to Scenario 9, it would be desirable to opt for a small- to medium-scale renewable-based heat-producing technology that has the ability to adjust to short-term demand variations (e.g. biomass or biogas).

From a time perspective, the excess heat supply is constrained and hardly flexible. There is a risk that the system over-supplies in the summer, when the demand for heat is low, and under-supplies in winter, when the demand for heat is high. To consider the seasonal profile of the demand for heat would require heat storage solutions. This would certainly add an additional economic burden on the end-users.

On a system level, it could also be argued that this study does not fully reflect the positive impacts that IS brings in a global perspective, but only relative to the carbon footprint of the district heat. The case of the DH system of Aalborg was selected due to the ongoing, upcoming and potential IS synergies. The study showcases the benefits that can potentially be drawn from a fully-deployed IS system for both surrounding industries and the society, with an angle on municipal excess heat delivery. Yet, the aim of this study is not to investigate an optimal energy mix for supplying DH to Aalborg, but rather to demonstrate that the city of Aalborg can achieve its ambition of providing a cleaner heat with the available, yet untapped, resources without investing in technologies that require heavy investments and without the use of additional fuel.

The conclusions are relevant for an international audience with an interest in IS, since they provide general insights on how legal and economic instruments can hinder the full development of collaborative industrial projects.

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Table 3: Comparison of nominal investment per MW between common district heating technologies and the additional excess heat supply capacity scenarized in this study

	Nominal Investment (M€/MW-heat)	Source
Solar	2	[34]
Geothermal	2	
Wave Power	7.8	
Electrolysis	1.4 – 6	
Centralized Biogas	3.4 – 5.8	
Cement producer — Recover Unit 1	0.03	Present study
Cement producer — Recover Unit 2	0.04	
Cement producer — Recover Unit 3	0.1	
Cement producer — Recover Unit 4	0.7	
Cement producer — Recover Unit 5	0.6	
Waste CHP plant — Extra recovery unit	0.2	
Heat pumps	0.2	

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