Local heating concepts for upgrading district heating networks, a real world case study

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Abstract:

During the last decade, CHP-based centralized production has been the dominant concept within the district heating (DH) systems. However, new Danish energy policies such as reducing the electricity heating tax challenges this concept. The new regulations have encouraged DH companies to exploit heat production by heat pumps and electric boilers in distribution network level to meet the increased demand in newly developed areas which require substantial investments in transmission line for new pipes and other infrastructures. This paper compares these two approaches in details within the framework of a real world case study. In addition, the effect of incorporating storage tanks in both approaches is investigated. For this purpose, an hourly-based database of expected heat demand and marginal heat production costs for the case study region within a sample year is collected. In addition, Capital and Operational costs including tax and tariff rates as well as technical constraints are taken into account. Then, using mixed integer linear programming, different production scenarios are compared. The results reveal that incorporating storage tanks reduces total costs substantially in both approaches. In addition, it is observed that exploiting production and storage capabilities in distribution network level is more attractive than merely upgrading the current DH transmission line and its associated heat exchanger.

Keywords:

District heating systems, Design optimization, Energy policy, Heat storage, Local production.

1. Introduction

District heating (DH) networks play an essential role in providing hot water as well as space heating in many regions throughout the word, especially in Scandinavian countries like Denmark [1]. District heating is in its nature centralized and consist of several hierarchical chains including production, transmission, distribution and consumption. Each layer involves its infrastructures such as pipes, pumps and heat exchangers. During the last decade, the CHP-based centralized production has been the dominant concept within the district heating systems [2]. Therefore, the focus of researchers has been on optimizing the production and consumption chains [3-7]. Also, there have been two conventional approaches to supply the increased demand in new developed areas. The first one is centralized approach which includes the upgrading of transmission line and its associated heat exchanger. The latter is localized production by using individual suppling units such as residential heat pumps, electric boilers and storage tanks for each building in consumption side.

The cost of centralized heat production is usually stated as marginal heat production price, i.e. the cost of producing one additional unit of heat in the heat transmission grid. The most expensive operation asset dictates this price. For instance, during peak hours in winter it could be oil-boilers which are the most expensive units in grid. Hence, if heat demand is decreased by one MWh, the marginal price is saved. Marginal heat production price is usually less than localized production costs because it exploits already-existing production assets. In localized production, each asset has its own variable and fixed production costs. Variable production costs depend on the delivered heat and are calculated on hourly basis while fixed production costs depend only on the maximum capacity of the asset and are calculated on a yearly basis.

Although localized heat production seems less efficient than a centralized strategy, it could reduce network-upgrading and distribution costs significantly. Indeed, the cost of meeting extra demands is composed of two major components: the extra production costs plus network-upgrading and distribution costs. While the first term has been widely investigated in the literature [9-12], there are few papers concerning the second term [2].

Meanwhile, incorporating heat storage tanks in central approach permits to store heat when marginal heat production price is low and use it later. Likewise, considering the deregulation and restructuring of the energy market, storage capability can be exploited to reduce local production costs by producing heat in low price hours (e.g. during night) and then use it when the electricity price is high [13]. Then, not only the DH network would benefit from lower production costs, but also the electricity network would take advantage of its balancing.

However, new Danish energy policies challenge these concepts and pave the way for an intermediate solution. New Danish energy policy will eliminate production commitments in the form of combined heat and power (CHP) plant requirements and the fuel commitment to natural gas for small district heating areas. It also eliminates the base subsidy for electricity produced by CHP plants. On the other hand, it reduces the electricity heating tax from 40 €/MWh to 20 €/MWh to incent people as well as DH companies to choose green solutions such as heat pumps [8]. The modifications have encouraged DH companies to exploit heat production by heat pumps and electric boilers in distribution network level to supply the increased demand in new developed areas which requires substantial investments in transmission line for new pipes and other infrastructures. It is completely different from localized production by using individual suppling assets for each building in consumption side. In addition, it is different from island district heating systems. Fig.1 illustrates the concept.

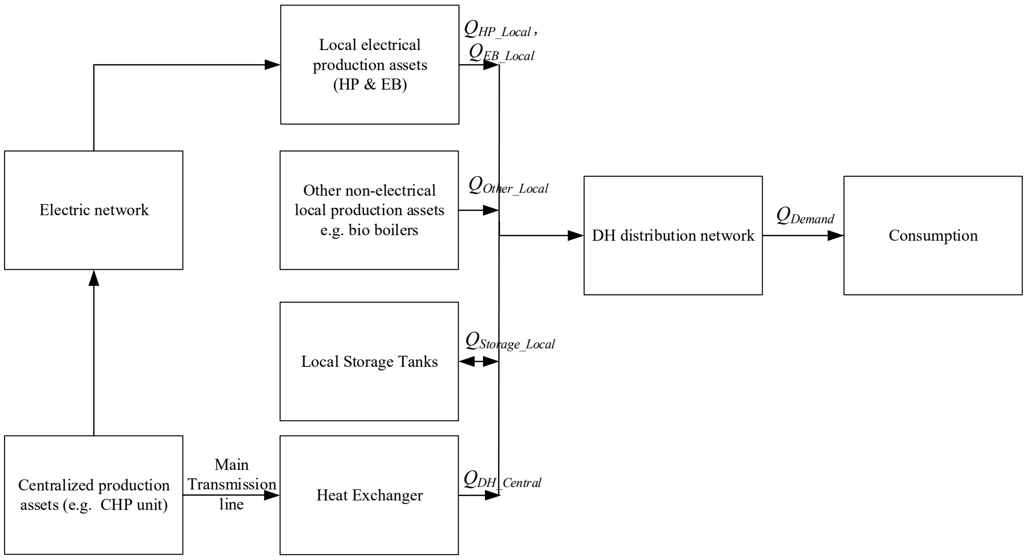

Figure 1. Local production concept investigated in this paper

Considering the new Danish energy policy, it seems that heat production and storage in distribution network level is an interesting alternative to the both conventional approaches to supply extra demand in new developed area. Indeed, it is an intermediate approach which reduces transmission cost in comparison with central approach and proposes more efficient production in comparison with localized approach. Also, the non-monetary benefits of heat production from sustainable energy sources should be taken into account.

This paper investigates the intermediate approach in details and compares it with the centralized approach within a real word case study. In addition, the effect of incorporating storage tanks in both approaches is investigated. For this purpose, a real world case study region is selected and an hourly-based demand profile was developed within a sample year according to the average historical real data from the area. Then, hourly-based marginal heat prices for centralized production were computed according to the day ahead electricity prices of 2014. A same day ahead electricity prices were used to compute the production costs of HP and EB.

Also, the upgrading costs of the current heat exchanger in centralized approach as well as production and storage costs in the both approaches are calculated. Transmission costs, fixed and variable operational costs including tax and tariff rates as well as technical constraints are taken into account.

To incorporate on and off states of the production assets as well as some other technical constraints, it is necessary to introduce binary variables in the optimization problem. Therefore, a mixed integer linear program (MILP) is designed to compare different centralized and local strategies. Many numerically efficient algorithms dealing with MILP have already been developed and implemented in commercial optimization software packages like MATLAB and GAMS.

Four different production scenarios are compared in this research. The first scenario involves upgrading of the current heat exchanger and associated pipelines. It takes advantage of low marginal heat production prices. However, the upgrading and transmission costs are considerable. In the second scenario, the extra demand is supplied by local production assets in distribution network level. In this case, production cost is significantly increased while upgrading and transmission costs are decreased.

In the next step, storage capability is incorporated into the both approaches. The third scenario considers centralized production along with the local storage capability in distribution network level and finally the forth scenario investigates the combination of local production and storage in distribution network level.

The rest of the paper is organized as below. Section 2 introduces the specifications of the case study region. Section 3 is devoted to problem modeling and its associated formula. In this section optimization problem and its respected economical and technical constraints are stablished. Section 4 presents the results and Section 5 is discussion. Finally, Section 6 concludes the paper.

2. Case Study Specifications

The case study is a small suburban area in the south-western part of Aarhus in Denmark. It is about 8 km from the city center. It has largely merged with neighboring area in modern times (Fig. 2). The area is predominantly residential, but also contains a large industrial park.

Figure 2. The Pilot Case

Figure 3. Visualization of new demand areas on satellite photo

Because of new residential and industrial developments, the demand for heat is increasing in this area. Fig. 3 visualizes the new demand areas on a satellite photo. As of today, there is a 26 MW heat exchanger to provide the area with heat from the main pipeline, which is supplied by central CHP unites. The district heating is a conventional one with nominal supply temperature 80$^{\circ C}$ and nominal return temperature 40$^{\circ C}$. It is expected the area will reach a demand peak of 50 MW in near future and the total heat demand within the sample year is approximated to reach about 174000 MWh. To investigate the tradeoff between potential local production assets and existing heat pipe infrastructure, the main heat exchanger with its pipeline is considered as a separate net. In addition, the case study area is virtually divided into two sub-nets. Therefore, there are three different subnets in our model of the case study area, namely:

- subnet 1: Main heat exchanger with its pipeline
- subnet 2: Sub Region 1
- subnet 3: Sub Region 2

Fig. 4 visualizes these three subnets. Fig. 5 shows the heat flow among these subnets. The expected demand peak of subnet 2 and subnet 3 are respectively 30 MW and 20 MW. It is worthy of note that the nature of subnet 1 is completely different from the two others. It will be reflected in the next section when production and investment costs are investigated.

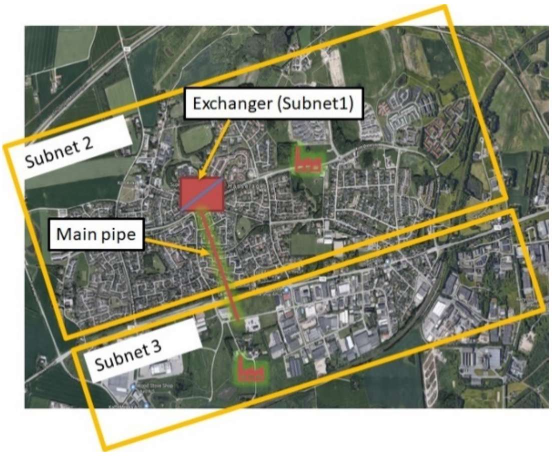

Figure 4. Case study area as three virtual sub-nets

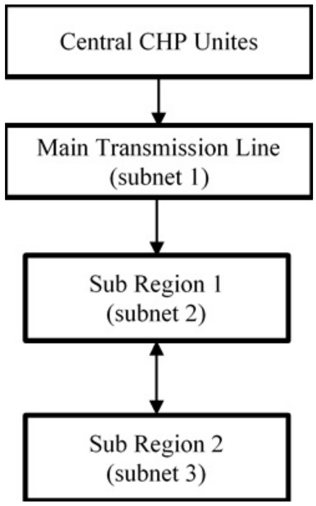

Figure 5. Heat flow among the subnets of case study area

3. Problem modeling

3.1. Objective function

The objective function $(\mathrm{O.F.})$ is defined as below to minimize all different costs within a sample year.

$$\mathrm{O.F.} = \sum_{n=1}^{N}(\mathrm{Production\_costs}_n + \mathrm{Storage\_costs}_n + \mathrm{Investments}_n) + \sum_{\substack{m=1 \\ m \neq n}}^{N}\sum_{n=1}^{N}\mathrm{Transmission\_costs}_{nm} \quad (1)$$

N denotes the total number of subnets. In the following, each term will be explained in details.

3.1.1. Production and storage costs

For n=1 which is corresponding to main pipeline, the production cost is the marginal heat production price by central DH. It is assumed the demand of the case study area is small enough to not influence the marginal heat price.

Other subnets include different local production assets. In this research, two different production assets are examined: heat pumps and electric boilers. The total production cost of each subnet is the sum of its individual assets production costs.

In the following, the variable and fixed production costs of heat pumps and electric boilers are calculated according to definitions in Appendix A (Table A1). Heat source for HP is assumed ambient air.

Variable production costs of HP and EB at k^{th} hour, are calculated as

$$HP_{VP\_Costs}(k) = \frac{Q_{HP}(k)}{COP_{HP}}.(EP_{Price}(k) + EP_{TR} + EP_{TT}) + b_{HPS}(k)HP_{SCost} + Q_{HP}(k).HP_{VMCost} \quad (2)$$

$$EB_{VP\_Costs}(k) = \frac{Q_{EB}(k)}{\eta_{EB}}.(EP_{Price}(k) + EP_{TR} + EP_{TT}) + b_{EBS}(k)EB_{SCost} + Q_{EB}(k).EB_{VMCost} \quad (3)$$

where $b_{HPS}(k)$ and $b_{EBS}(k)$ are binary variables which are "1" only at the start instances.

Yearly fixed production costs of HP and EB are assumed to be proportional to their maximum capacity, as follows.

$$HP_{FP\_Costs} = \left(\max_k\left(Q_{HP}(k)\right)\right).HP_{FM\_Coef} \tag{4}$$

$$EB_{FP\_Costs} = \left(\max_k\left(Q_{EB}(k)\right)\right).EB_{FM\_Coef} \tag{5}$$

The total production cost of each asset is calculated by summing all its variable production costs within a year (8760 hours) and then adding its yearly fixed production cost.

For storage costs, it is assumed each MWh_Qinput or output energy costs 0.53 €.

Remark about COP of heat pump.

COP is yearly weighted-average for a standard consumption profile. The technology data catalogue states that an ambient air heat pump has an annual average COP of 3.6 with 0.09 MW_{El}/MW_Q for ancillary processes.

In our calculations, we used a heat-pump COP of 3.6 MW_Q/MW_{El} = 0.278 MW_{El}/MW_Q and auxiliary systems consumption of 0.09 MW_{El}/MW_Q, resulting in a heat-pump system COP of 0.368 $MW_{El}/MW_Q = 2.72\ MW_Q/MW_{El}$.

The exact way the tax is calculated is 20 €/MW_{El} going into the heat pump compressor and only 0.53 €/MW_{El} going to auxiliary systems (pumps, and heat exchanger fans mainly).

3.1.2. Investments

Investment in subnet 1 includes the cost of upgrading the current heat exchanger. Table B1 (Appendix B) shows the cost of a new heat exchanger. Here, we assume that the slope can be used also for upgrading the exchanger.

Investments in other subnets depend on the maximum capacity of their production assets and storage tanks as listed in Table B2.

After calculating the investment on each asset, it is distributed among its total life period according to the annuity formula:

$$\text{Yearly Investment} = \frac{r(\text{Total Investment})}{1-(1+r)^{-\text{life}Period}} \tag{6}$$

where r is interest rate. Please note when r approaches "0", the annuity formula is simplified to

$$\text{Yearly Investment} = \frac{\text{Total Investment}}{\text{life}Period} \tag{7}$$

3.1.3. Transmission costs

Transmission costs involves the cost of new pipes between the subnets. Since the length of pipeline is fixed, the maximum transmission capacity dictates the total transmission costs. Table C1 and Table C2 (Appendix C) show fixed and variable transmission costs.

3.2. Technical constraints

A few technical and economic constraints should be taken into account for a reliable design. The first is balancing among production, demand and storage in subnets, e.g.

$$Q_{t_{12}}(k) + Q_{p_{n2}}(k) = Q_{d_{n2}}(k) + Q_{s_{n2}}(k) + Q_{t_{23}}(k) \tag{8}$$

$$Q_{t_{23}}(k) + Q_{p_{n3}}(k) = Q_{d_{n3}}(k) + Q_{s_{n3}}(k) \tag{9}$$

Note that $Q_{t_{32}}(k) = -Q_{t_{23}}(k)$.

Also, the tank dynamics is given by

$$E_{s_{n2}}(k) = (1-\gamma_s)E_{s_{n2}}(k-1) + Q_{s_{n2}}(k) \tag{10}$$

$$E_{s_{n3}}(k) = (1-\gamma_s)E_{s_{n3}}(k-1) + Q_{s_{n3}}(k) \tag{11}$$

In addition, there are some technical minimum production or transfer limits as

$$Q_{t_{12}}(k) \geq \alpha_{t_{12}}.\max_k Q_{t_{12}}(k) \quad OR \quad Q_{t_{12}}(k) = 0 \tag{12}$$

$$Q_{t_{23}}(k) \geq \alpha_{t_{23}}.\max_k Q_{t_{23}}(k) \quad OR \quad Q_{t_{23}}(k) = 0 \tag{13}$$

$$Q_{HP_2}(k) \geq \alpha_{HP_2}.\max_k Q_{HP_2}(k) \quad OR \quad Q_{HP_2}(k) = 0 \tag{14}$$

$$Q_{HP_3}(k) \geq \alpha_{HP_3}.\max_k Q_{HP_3}(k) \quad OR \quad Q_{HP_3}(k) = 0 \tag{15}$$

In this research, factors $\alpha_{t_{12}}$, $\alpha_{t_{23}}$, α_{HP_2} and α_{HP_3} were set to 0.1.

Also, the transfer direction between subnet 2 and subnet 3 should not change frequently to avoid cold plug problems. For this purpose, it is assumed that the signs of $Q_{t_{23}}(t)$ and $Q_{t_{32}}(t)$ are fixed for at least one week at a time. This constraint can be converted to a set of linear constraints by using the technique used in [14].

4. Results

In this section, the optimization results for four different centralized and local production scenarios are presented. Table 1 summarizes the concepts behind different scenarios.

Table 1. Summary of Different Scenarios:

Scenario	**Extra Production**	**Storage tanks in distribution network level**
1	Centralized (upgrading the current heat exchanger and associated pipelines)	No
2	Distribution network level (keeping current heat exchanger)	No
3	Centralized (upgrading the current heat exchanger and associated pipelines)	Yes
4	Distribution network level (keeping current heat exchanger)	Yes

In the first scenario, the current heat exchanger and associated pipelines are upgraded from 26 MW to 50 MW in order to meet extra demand. In the second scenario, the extra demand is met by production in distribution network level. In the next step, the effect of exploiting storage tanks in distribution network level is investigated. The third scenario augments centralized production with the storage capability while the forth scenario investigates the effect of augmenting production in distribution network level with storage capability. Table 2 shows the summary of optimization results for the four scenarios.

Table 2. Summary of optimization results:

	Plant and pipe/exchanger capacities in each net								The extra cost to supply new demand (€/MWh)
	Tank net2 MWh-Q	Tank net3 MWh-Q	HP. net2 MW-Q	HP net3 MW-Q	EB. net2 MW-Q	EB. net3 MW-Q	Transfer net1 → net2 MW-Q	Transfer net2 → net3 MW-Q	
Scenario 1	0.00	0.00	0.00	0.00	0.00	0.00	50.00	20.00	29.8
Scenario 2	0.00	0.00	17.29	0.00	0.00	8.65	26.00	17.30	31.2
Scenario 3	600.00	198.86	0.00	0.00	0.00	0.00	49.52	16.31	28
Scenario 4	254.55	108.61	7.36	4.89	0.00	0.85	26.00	10.34	29.7

5. Discussion

Analyzing the results of Table 2 reveals some exciting points. First, incorporating local storage tanks in distribution network level reduces total costs substantially in the both approaches. It is worthy of note that, the storage capability can be implemented not only by physical storage tanks in distribution network level, but also by other means such as the buildings thermal mass in consumption side [15].

Although merely production in distribution network level is not so interesting, it is observed that its combination with storage capability is as attractive as merely upgrading the current DH transmission line and its associated heat exchanger. Considering the non-monetary benefits of heat production from sustainable energy sources, it would be even more appealing. Moreover, it would be much valuable if the upgrading of current heat exchanger sites were impractical because of technical issues.

Finally, it should be noted that in this study Elspot (day-ahead) price of electricity was considered for calculation. In the second and forth scenarios, the heat company could potentially participate in the regulating power market and make more profit. Investigating this point is beyond the scope of this paper.

6. Conclusion

Reducing the electricity heating tax and other new Danish energy policies have encouraged district heating companies to exploit heat pumps and electric boilers in distribution network level to supply the increased heat demand in new developed areas that requires substantial investments in transmission line for new pipes and other infrastructures. This paper investigates the new approach and compares it with conventional centralized approach in details within the framework of a real world case study. In addition, it studies the effect of incorporating storage capabilities in the both approaches. To this end, an hourly-based database of expected heat demand and marginal heat production costs for the case study region within a sample year is collected. In addition, Capital and Operational costs including tax and tariff rates as well as technical constraints are taken into account. Then using a mixed integer linear programing, different production scenarios are compared. The results reveal that incorporating storage tanks in distribution network level reduces substantially the total costs in the both approaches. In addition, it is observed that augmenting the production in distribution network level with storage capabilities is as attractive as merely upgrading the current DH transmission line and its associated heat exchanger. Considering the non-monetary benefits of heat production from sustainable energy sources, it would be more appealing. Moreover, it would came in handy if the upgrading of current heat exchanger sites were impractical because of technical issues.

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Appendix A [16]

Table A.1. Notations and their Definitions

Notation	Definitions	Unit and Value	Notation	Definitions	Unit and Value
$\boldsymbol{MW_Q}$	Heat Power	MW	$\boldsymbol{HP_{FM\_Coef}}$	HP coefficient for yearly Fixed Maintenance Costs	1987 $€/MW_Q$
$\boldsymbol{MW_{El}}$	Electric Power	MW	$\boldsymbol{EB_{FM\_Coef}}$	EB coefficient for yearly Fixed Maintenance Costs	1100 $€/MW_Q$
$\boldsymbol{O.F.}$	Objective Function	€	$\boldsymbol{Q_{t_{12}}(k)}$	Heat transfer from subnet1 to subnet2 at k^{th} hour	MWh_Q
$\boldsymbol{HP_{VP_{Costs}}(k)}$	Variable Production Cost of HP at k^{th} hour	€	$\boldsymbol{Q_{t_{23}}(k)}$	Heat transfer from subnet2 to subnet3 at k^{th} hour	MWh_Q
$\boldsymbol{EB_{VP_{Costs}}(k)}$	Variable Production Cost of EB at k^{th} hour	€	$\boldsymbol{Q_{t_{32}}(k)}$	Heat transfer from subnet3 to subnet2 at k^{th} hour	MWh_Q
$\boldsymbol{HP_{FP\_Costs}}$	Yearly Fixed Production Cost of HP, see (4)	€	$\boldsymbol{Q_{s_{n2}}(k)}$	Heat transferred to or from tank in subnet2 at k^{th} hour	MWh_Q
$\boldsymbol{EB_{FP\_Costs}}$	Yearly Fixed Production Cost of EB, see (5)	€	$\boldsymbol{Q_{s_{n3}}(k)}$	Heat transferred to or from tank in subnet3 at k^{th} hour	MWh_Q
$\boldsymbol{COP_{HP}}$	The coefficient of performance for the heat pump compressor	3.6 MW_Q/MW_{El}	$\boldsymbol{Q_{d_{n2}}(k)}$	Subnet2 heat demand at k^{th} hour	MWh_Q
$\boldsymbol{\eta_{EB}}$	Electric Boiler Efficiency	0.99 MW_Q/MW_{El}	$\boldsymbol{Q_{d_{n3}}(k)}$	Subnet3 heat demand at k^{th} hour	MWh_Q
$\boldsymbol{EP\_Price(k)}$	Electric Power Market Price at k^{th} hour (2014 prices)	$€/MW_{El}$	$\boldsymbol{Q_{p_{n2}}(k)}$	Local heat production in subnet2 at k^{th} hour	MWh_Q
$\boldsymbol{EP_{TR}}$	Electric Power Tax Rate for producing heat	20 $€/MW_{El}$	$\boldsymbol{Q_{p_{n3}}(k)}$	Local heat production in subnet3 at k^{th} hour	MWh_Q
$\boldsymbol{EP_{TT}}$	Electric Power Transmission Tariff	23.85 $€/MW_{El}$	$\boldsymbol{E_{s_{n2}}(k)}$	Total Heat stored in subnet2 tank at k^{th} hour	MW_Q
$\boldsymbol{HP_{SCost}}$	HP Start Cost	66.6 €/Start	$\boldsymbol{E_{s_{n3}}(k)}$	Total Heat stored in subnet3 tank at k^{th} hour	MW_Q
$\boldsymbol{EB_{SCost}}$	EB Start Cost	66.6 €/Start	$\boldsymbol{Q_{HP_2}(k)}$	HP heat production in subnet 2 at k^{th} hour	MWh_Q
$\boldsymbol{HP_{VMCost}}$	HP Variable Maintenance Costs for each MW_Q	1.8 $€/MW_Q$	$\boldsymbol{Q_{HP_3}(k)}$	HP heat production in subnet 3 at k^{th} hour	MWh_Q
$\boldsymbol{EB_{VMCost}}$	EB Variable Maintenance Costs for each MW_Q	0.8 $€/MW_Q$	$\boldsymbol{\gamma_s}$	Tank Loss Rate	8.0e-05 MW_Q/MWh_Q

Appendix B [16]

Table B1. Heat Exchanger costs

Capacity (MW)	Cost (€)
0.5	132 530
15	1 506 660

Table B2. Investment Data on Production assets and storage tanks

	€/MW(h*)	Life Period (years)
HP	660 000	25
EB	70 000	20
Tank*	3 000	30

Appendix C [16]

Table C1. Variable Transmission costs (€/MW)

		To		
		subnet1	subnet2	subnet3
From	subnet1	-	93 300	-
	subnet2	-	-	53 300
	subnet3	-	53 300	-

Table C2. Fixed Transmission costs (€)

		To		
		subnet1	subnet2	subnet3
From	subnet1	-	85 300	-
	subnet2	-	-	417 300
	subnet3	-	417 300	-

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