Human health-related externalities in energy system modelling the case of the Danish heat and power sector

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**Abstract**

This paper discusses methodology of energy system modelling when reduction of local externalities, such as damage to the human health from energy production-related air pollution, is in focus. Ideally, the local energy externalities should be analysed by adopting the impact pathway approach of ExternE study, and following the pollutants from their release to the personal uptake and resulting health effects. This would require inclusion of air pollution modelling and monetary valuation of the impacts into an energy system optimisation process. However, this approach involves a complex study and generalisations are needed.

The way local externalities are included in the existing energy system models is identified and discussed in the paper. Only a few studies include localisation aspects when internalising local externalities in an energy system optimisation. The performed analysis of the Danish heat and power sector verifies that it is cheaper for the society to include externalities in the planning of an energy system than to pay for the resulting damages later. Total health costs decrease by around 18% and total system costs decrease by nearly 4% when health externalities are included in the optimisation. Furthermore, including localisation aspects can reduce health costs of the heat and power sector in Denmark by additional 7%.

**1. Introduction**

Conventional energy production causes air pollution and subsequent negative environmental impacts. Results from several investigations have shown that exposure to increased concentrations of air pollution, due to the release of local air pollutants such as SO₂, PM₂·₅, and NOₓ, causes health effects – mortality and morbidity. Health impacts are the most important damage category of air pollution in Europe today and account for around 90% of the estimated local impacts [1].

A number of measures can contribute to the reduction of air pollution from the energy sector, including shift to cleaner fuels or renewable and pollution free resources, increased fuel efficiency of energy plants, installation of abatement technologies, end-use energy efficiency measures and other. Several studies [2–6] have shown that it is more cost effective for the society to consider environmental impacts when planning energy systems than to pay for the resulting damage later. Hence energy planning tools – energy system optimisation models that are capable of efficiently including these externalities are needed.

There exist a number of modelling tools for assessing damage from air pollution and for planning of future energy systems. Atmospheric air pollution and health impact assessment models represent the relation between air pollutant release and resulting environmental and health damage with a great detail. Whereas energy system modelling [2,3,5–10] focuses mainly on the technological and economic characteristics of the system, and monetary values of human health damage due to local air pollution are often included in an aggregated and simplified manner. This article argues that in order to efficiently incorporate local air pollution related externalities it is important to consider the factors that define relations between energy production and resulting health damage. The focus here is on spatial variation of the local externalities due to a combination of meteorological conditions (wind direction) and population distribution throughout a country or a region. The goal and contribution of this study is to reduce the gap between atmospheric pollution and energy system models by including these aspects of local health externalities into an energy system optimisation model of the Danish heat and power sector. Actual local external costs as opposed to average should be included in the operation costs of energy plants in order to increase efficiency of efforts to reduce negative impacts of heat and power production.

The article is organised as follows:

- The purpose of Section 2 is to gather the information and give a theoretical background for the relations between energy production, emissions, resulting air pollution concentrations and subsequent human health damage.
A number of studies have been performed using the existing energy optimisation models and including local externalities. These studies are reviewed and the recent methodology of internalising local externalities is discussed in Section 3.

The Danish energy sector is one of the major contributors to the emissions of the classical local air pollutants (SO2, NOx and PM2.5) causing health damages. In Section 4 the energy system optimisation model Balmoral has been altered and used to perform the study of internalisation of local health externalities into planning of the Danish energy system. The results of including local externalities and the effects of taking the location of energy plants into account are analysed and discussed here.

Finally in the Section 5 conclusions are drawn on the basis of the achieved results and in the light of the literature review.

2. Health-related externalities and air pollution from energy system

This section gives a theoretical background for the relations between energy production and air pollution related human health externalities. Human health effects of air pollution are the results of a chain of events that starts with the release of pollutants, and through atmospheric transport, dispersion and (chemical) transformation, causes changes in ambient concentration of pollutants, and leads to population exposure, personal intake, consequent dose and the resulting health effects (Fig. 1).

2.1. Release of the local pollutants

Classical local air pollutants from energy production (mainly using fossil fuels) that impose significant health effects and consequent costs for the society are particles (PM10, PM2.5), nitrogen oxides (NOx) and sulphur dioxide (SO2). The release of these pollutants depends first and foremost on the size and type of energy technology characteristics and operating conditions like load factor. Inadequate combustion conditions, such as too high or too low temperatures, oxygen excess and fuel mixing aspects lead to the formation of intermediate combustion by-products – air pollutants, harmful for the human health and the environment [11]. Release of NOx depends on the conditions of a combustion process. High fuel sulphur content causes increased formation of SO2. Emissions of particles are mainly resulting from the use of solid fuels [12]. The release of particularly SO2 from energy plants in Europe have been successfully reduced by shifting to fuels with lower sulphur content and installing abatement equipment. However, the size of a plant can have influence on the use of abatement technologies, which can rarely pay off for small and individual generation units [13]. Utilisation of plant’s capacity has also influence on the emission rates. For example, experimental tests with a micro gas turbine have shown that emissions of NOx rise considerably when operating at part load [11,14]. For other pollutants, part load emissions increase due to decreased fuel efficiency.

Consequently, the amount of a released pollutant from a plant (EMp) is calculated by multiplying an emission factor – mass of pollutant p emitted per useful energy output e (EFp) or fuel input f (EFp_f) in g/GJ by energy output E or fuel input F in GJ:

\[ EM_p = EF_p^e \cdot E \quad \text{or} \quad EM_p = EF_p^f \cdot F \]  

(1)

The emission factor EFp^e or EFp^f is a function of fuel quality, technology characteristics and operating conditions like load factor.

2.2. Atmospheric processes

On the contrary to emissions of CO2, which stay in the atmosphere long enough to be uniformly dispersed and cause global effects, the resulting pollution concentrations due to emissions of NOx, SO2 and PM2.5 depend on atmospheric transportation, dispersion and chemical transformation of these pollutants. The conditions and the course of these processes depend on the location, height and time of a pollutant release. Emissions at low or ground level from small-scale or micro plants have poor dispersion and dilution possibilities and pollution concentrations close to a source will be higher than those of large plants with higher stacks [13,15]. The atmospheric processes depend on the amount of other substances in the atmosphere, i.e. emissions by other sources, as well as other conditions, such as air temperature and sunlight. The transportation of emitted pollutants depends on the complex meteorological forces – different wind directions in time at different altitudes. Primary particles and SO2 cause effects mainly within 50 × 50 km area, while nitrate and sulphate aerosols, which form secondary particulate matter, tend to travel over longer distances [16,17].

2.3. Location of energy plants

The extent of health damage by the same pollutant at different sites can vary significantly due to spatial variations in population density and consequent exposure. Gulli [13] distinguishes between macro (e.g. north or south Italy) and micro (urban or rural area) localisation. He points to significantly higher external costs from the plants located in the northern Italy, close to densely populated rest of Europe, when compared to southern Italy. In the study by Krewitt et al. [18] differences due to macro location are also reflected in external costs of emissions in western and eastern Germany and EU-15. In Fig. 2 differences in health external costs of three Danish combined heat and power (CHP) plants can be seen.

![Fig. 1. From release of pollutants to health impact. The chain of processes and the affecting factors leading from air pollution release to damage of human health. Based on Hertel et al. [1].](image_url)
Three main factors are important for the health-related externalities from energy production: (1) energy generation mode (technology and fuel); (2) processes in the atmosphere (meteorology and atmospheric chemistry) and (3) population distribution (density and demographics). The first factor is the core of energy models, the second is the subject of atmospheric modelling and the third is dealt with in the quantification of health effects. When planning energy systems it is important to consider the combination of these factors. For instance, ExternE study [19] follows the chain of events (Fig. 1) when estimating local external costs of different energy plants. For optimisation of a whole energy system it would require to include the atmospheric pollution model into an energy optimisation model. This would result in a highly complex structure and a more straightforward solution is sought here. Nine studies [2–10] that include local impacts of NO$_x$, SO$_2$ and PM$_{2.5}$ into the energy system optimisation models have been reviewed (Appendix A).

All analyses include a rather comprehensive technology and fuel representation. Some studies [2,3,7,8] also include abatement technologies. They demonstrate that air pollution abatement technologies are important for future energy systems when externalities are included in the planning. Kudelko [8] also includes the possibility of installing abatement technologies at the existing plants. In order to find out how competitive different existing/conventional and new technologies are, it is important to include possibility for refurbishment of existing plants.

In contrast to the technology representation, reviewed models use rather aggregated information on local health damage due to air pollution from energy sector. The studies base local externality data on the results from ExternE project [19]. All analyses, except one by Linas et al. [4], include either national or European average externality costs of local air pollutants. By using average external costs the localisation differences with respect to meteorological conditions and varying population density within a country or region is excluded from the evaluation of plants. The operation optimisation of the Spanish electricity system [4] considers location of energy units, however due to the resolution limits of the atmospheric dispersion model, plants are grouped into geographical areas of 100 km grids. This seems to be a reasonable division, since only large plants with presumably high stacks are represented. Optimisation models of the global energy system [2,7] include differentiation of several world regions by fuel sulphur content and by population density. Thus the localisation of energy units is considered to some extent. In the study of possible cooperation benefits of Danish and Swedish district heating (DH) systems [9] differences in externality costs due to different location of the DH plants are not taken into account. Due to prevailing western winds pollution from the Danish plants would be carried over the Øresund and will not have a high effect on human health, while this is not the case for Swedish DH producers, located on the eastern coast of the Kattegat and potentially causing pollution east of Helsingborg.

None of the reviewed studies use different external costs for plants of different size and with different stack height. In a study of the Polish energy system [8], new small heat plants are expected to gain a visible share of the energy production when local externalities are included, due to their lower impact on environment. However such conclusions should be further investigated by comparing differences in externality costs of large and small-scale plants due to different height of emission stacks and localisation with respect to populated areas. The analysis of supplying heat to a region in Sweden [5,6] emission coefficients of local pollutants are included for each type of fuel. The rate of pollutant release is assumed to be the same for district heating plants and for residential heating units. In this case it is neglected that residential heating usually has a higher emission rate and higher population exposure.

As it has been specified earlier, emissions increase when energy plants operate at part load. None of the papers consider this variation. Models for optimisation of future energy investments usually do not include the load factor in the calculations, while this is the task of operation optimisation models.

4. Including local externalities into the Balmorel model of the Danish energy system

The literature study in Section 3 leads to a conclusion that recent energy system studies focus on energy and abatement technologies while only simplified treating external health costs. Most of the studies do not consider different health damage costs at different locations and use a single average externality cost per pollutant, while other studies [4,13,16,18] present the evidence that there are significant differences in human health externality costs.
for such differences. It is clear that the extent of health effects of air pollution from an energy generator depends on population density in an affected area. When a uniform health externality is used for the whole system in an optimisation model, the pollution at different sites is burdened equally. This leads to too high costs for plants affecting unpopulated areas and too low costs for plants affecting densely populated areas.

Human health related external costs taking into account the location of different energy plants have been included into an optimisation model of the Danish heat and power system. The location of energy plants is divided into geographical areas with different health damage cost of the pollutants released from units in a particular area. The model takes into consideration the dominating wind direction and the population distribution in the country. Only health related damages of local air pollution are included in the study.

The study does not include possibility for investing in abatement technologies nor does it treat the differences in the plant size. Both these issues are subjects of future work.

4.1. The model

Balmorel, a linear optimisation model of the Danish power and heat system, has been used for this purpose. The model is originally developed for analysis of heat and power sectors in the Baltic Sea Region [20]. Balmorel minimises operational costs of the heat and power sector by determining optimal operation of the generation units and future investments into energy production plants and supply infrastructure [21]. The model optimises energy production in the existing and new plants annually. This can be seen as a limitation since decision to invest is made only on the basis of the demand and prices in the year of the investment. A year in the model can be further divided into several time periods – weeks and hours. Electricity and heat demand in each time period has to reflect areas with different health externality costs

4.2. Data input and scenarios

Electricity and heat demand is given exogenously in the model and is not a part of the optimisation. The demand is assumed to follow historical trends in Denmark (Table 1) [22]. Three scenarios are calculated:

- No externalities, where only the global CO2 cost of 15 EUR/t is included and no local externalities are taken into account;
- the single average externality cost is included in addition to CO2 cost in the Uniform cost scenario;
- Different area cost scenario includes different local externality costs in areas (see Table 2).

The prevailing wind in Denmark is the west wind. Hence the pollutants are mostly transported to the east. DK_E_Urban area is supposed to include plants, located primarily in the eastern part of the greater Copenhagen area, with Øresund as the neighbour to the east. As a result external costs of pollutants from plants in this area are assumed to be low (even though urban location is

![Fig. 3. The Balmorel model used for inclusion of local externalities.](image-url)
usually associated with high health externality). On the contrary, pollution from energy production in the DK_E_Rural is assumed to have a high health related cost. It is expected that pollution from majority of the plants in this area affects Copenhagen and its densely populated suburbs. The emissions from DK_W_Rural and DK_W_Urban are assumed to be average. The plants located in the western areas cause air pollution in the continental part of Denmark, which is moderately populated. The local external costs per unit of pollutant are documented in Table 2. The average costs account for the health damage, caused by the Danish energy production in Denmark and other affected countries, and are based on [23]. The cost variations between different areas are calculated, based on deviations from average of maximum and minimum local external costs in Spain, derived from the study by Linares et al. [4] (Table 2). The data for spatial variation of health damage costs in Denmark is not yet available. Therefore the differences in local externalities between 100 km² areas in Spain are used in order to construct areas with different costs, based on the Danish average health externality.

Three years are optimised in each scenario in order to account for different investment possibilities: 2005 – where the existing plants are running, 2015 – where some of the plants are phased out, but not all new plants are available yet, and 2030, where almost all existing plants are phased out (see Fig. 4). The assumption is that most of the plants, available in 2005 have around 30 years of lifetime left. Following this assumption only around 11% of initial capacity will still be in operation in 2030, consisting of coal, natural gas and biomass plants. The existing municipal waste capacity is assumed to be kept unchanged.

The only option to reduce air pollution from energy generation is to shift to cleaner production either among the existing plants or by investing in new technologies. Emission rates of the existing plants in the model are based on the Annual Danish Emission Inventory data for energy sector, prepared by the National Energy Research Institute.

The data for new technologies (see Appendix B) is based on the RECABs project [24] and the technology catalogue, prepared by the Danish Energy Authority [25]. New technologies are assumed to have built-in abatement technologies.

The fuel prices are shown in Table 3 and are based on the prognosis of the Danish Energy Agency in 2006.

The price of municipal waste is negative based on the assumption that waste incineration plants receive payment for treatment of waste.

5. Results

Table 4 includes an example of results for year 2015 – emissions of the pollutants and resulting local external cost in different scenarios. Even though the total sum of the emissions is shown, the corresponding total externality cost is a result of different levels of pollution and different local externalities in different areas. Different area health damage costs are used for calculating ex-post local external costs for all scenarios given that actual health damage costs vary from location to location. The total annual local external cost (Etotal) is calculated as a sum of external health costs in each area (E). The latter is obtained by multiplying the amount of pollutant \( p \) (\( p = \text{SO}_2, \text{NO}_x, \text{PM}_{2.5} \)), released from all plants in an area \( a \) (\( E_{a}^{p} \)) with the respective area health damage cost \( (C_{a}^{p}) \):

\[
E_{\text{total}} = \sum_{a} E_{a} = \sum_{p} \sum_{a} E_{a}^{p} \cdot C_{a}^{p}
\]

Furthermore, the reduction in total local externality cost from the scenario without externalities to the scenario with uniform health cost, as well as from Uniform cost to Different area cost scenario is calculated as percentage in Table 4.

It is evident that internalisation of health externalities has an effect on the heat and power production and ex-post total local external cost is reduced by 16–20% when comparing Uniform cost and No externalities scenarios (Fig. 5 to the left). This means that the average health damage cost affects the operation and investment decisions in the model. Furthermore the total external cost due to health damage decreases over time in the scenarios as new, cleaner technologies replace the phased out existing energy plants.

The total health related externality cost decreases further by 6–8% when actual differences in health effects due to location of the energy plants are taken into account in the model in the scenario Different area cost (Fig. 5 to the right). This leads to a 22–25% reduction in the total externalsystem cost when compared to the scenario with no local externalities. The difference between the two scenarios with included local external costs (Fig. 5 to the right) is highest in 2005 (8%), where the existing capacity with relatively high emissions is still running. High local external costs in the DK_E_Rural in the Different area cost scenario induce larger investments into clean production, namely wind turbines and heat

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**Table 1**

Demand for electricity and district heat.

<table>
<thead>
<tr>
<th>TWh/yr*</th>
<th>2005</th>
<th>2015</th>
<th>2030</th>
</tr>
</thead>
<tbody>
<tr>
<td>District heat demand</td>
<td>27</td>
<td>29</td>
<td>30</td>
</tr>
<tr>
<td>Electricity demand</td>
<td>33</td>
<td>34</td>
<td>41</td>
</tr>
</tbody>
</table>

*Excluding transmission losses.

**Table 2**

External health damage costs of pollutants from different areas, \( C_{a}^{p} \) (EUR/t).

<table>
<thead>
<tr>
<th>Area</th>
<th>SO₂ cost, EUR/t</th>
<th>NOₓ cost EUR/t</th>
<th>PM₂.₅ cost EUR/t</th>
</tr>
</thead>
<tbody>
<tr>
<td>The average cost</td>
<td>9100</td>
<td>5870</td>
<td>10,900</td>
</tr>
<tr>
<td>DK_E_Urban</td>
<td>13,542</td>
<td>10,483</td>
<td>18,533</td>
</tr>
<tr>
<td>DK_W_Urban</td>
<td>5962</td>
<td>2533</td>
<td>7595</td>
</tr>
<tr>
<td>DK_E_Rural</td>
<td>9100</td>
<td>5870</td>
<td>10,900</td>
</tr>
<tr>
<td>DK_W_Rural</td>
<td>9100</td>
<td>5870</td>
<td>10,900</td>
</tr>
</tbody>
</table>

**Table 3**

Fuel prices.

<table>
<thead>
<tr>
<th>EUR/G</th>
<th>Fuel oil</th>
<th>Natural gas</th>
<th>Coal</th>
<th>Wood</th>
<th>Straw</th>
<th>Municipal waste</th>
</tr>
</thead>
<tbody>
<tr>
<td>2005</td>
<td>5.25</td>
<td>4.19</td>
<td>2.07</td>
<td>4.45</td>
<td>2.95</td>
<td>-2.28</td>
</tr>
<tr>
<td>2015</td>
<td>10.50</td>
<td>7.19</td>
<td>2.20</td>
<td>4.59</td>
<td>3.05</td>
<td>-2.28</td>
</tr>
<tr>
<td>2030</td>
<td>13.00</td>
<td>8.50</td>
<td>2.45</td>
<td>4.79</td>
<td>3.18</td>
<td>-2.28</td>
</tr>
</tbody>
</table>
pumps in 2005, than the average external costs, used in Uniform cost scenario. The difference gets smaller in the later years, when some of the existing plants are not in operation anymore and new renewable technologies become more economically viable.

The same trend can be seen when health externality costs of electricity and heat generation in Denmark are expressed in Euro-cent/kWh (Fig. 6). The difference between the scenarios is largest in the early years with existing technologies still operating and is reduced in year 2030 especially in case of heat generation.

Given that in Denmark a significant part of energy is produced in combined heat and power (CHP) plants, air pollution and related external costs have to be allocated between electricity and heat. For extraction CHP plants heat production is assumed to be marginal and the larger part of air pollution is allocated to the production of electricity. For backpressure plants air pollution is allocated according to heat to power ratio. Taking into account these assumptions the results (Fig 6) show that health externality cost of electricity is approximately double as high as health externality of heat in the early years (2005 and 2015) when the existing technologies are still operating. In the year 2030 external costs of power and heat generation are comparable, particularly in Different area cost scenario. This suggests that the potential to reduce air pollution related health externalities of energy is higher in power sector than in heat sector when old technologies are phased out and new technologies are available for energy production.

Emissions of different pollutants were compared under different scenarios in the year 2030. Clearly, emissions decrease when health externality cost is included. From Fig. 7 it can be seen that emissions in all areas are lower in the Uniform cost scenario than in the case of No externalities, since the pollution from all the areas is burdened equally. When different area costs are included in the optimisation, more effort is made to reduce emissions in the area,

### Table 4

<table>
<thead>
<tr>
<th>Scenario, 2015</th>
<th>$E_{SO_x}$, t</th>
<th>$E_{NO_x}$, t</th>
<th>$E_{PM_{2.5}}$, t</th>
<th>$E_{SO_x}$, MEUR</th>
<th>$E_{NO_x}$, MEUR</th>
<th>$E_{PM_{2.5}}$, MEUR</th>
<th>Reduction of total external cost, %</th>
</tr>
</thead>
<tbody>
<tr>
<td>No externalities</td>
<td>14,767</td>
<td>29,645</td>
<td>1561</td>
<td>142</td>
<td>172</td>
<td>18</td>
<td>332 (20)</td>
</tr>
<tr>
<td>Uniform cost</td>
<td>11,005</td>
<td>25,523</td>
<td>1394</td>
<td>102</td>
<td>147</td>
<td>16</td>
<td>265 (6)</td>
</tr>
<tr>
<td>Different area cost</td>
<td>11,062</td>
<td>24,941</td>
<td>1283</td>
<td>98</td>
<td>137</td>
<td>14</td>
<td>248 (0)</td>
</tr>
</tbody>
</table>

**Fig. 5.** Total ex-post health external costs – scenario comparison. Figure to the left compares the ex-post total health related external costs of scenarios, when no local externality is included and when the uniform health damage cost is included into optimisation of the Danish energy system; and figure to the right compares total health costs of the scenarios with uniform average and different area externality costs.

**Fig. 6.** The average ex-post health externality cost of heat and power production in Denmark.
with high health damage costs and less effort is made, where the external costs are low. As a result the total amount of pollutants almost does not change, comparing with Uniform cost scenario, but are redistributed (see also Table 4). Emissions of NO\textsubscript{x} and SO\textsubscript{2} in the DK_E_Rural area are reduced considerably (by replacing coal generation with wind and heat pump generation), while in the DK_E_Urban area with local external cost lower than average, emissions are higher, when compared to Uniform cost scenario (coal based energy production increases here again). Emissions in DK_E_Urban area increase due to lower cost burden: a more polluting technology is used here; and a part of electricity production is moved from the area with high external cost to the low cost area. In the western Denmark emissions are equal (DK_W_Urban) or marginally higher (DK_W_Rural) in Different area cost scenario, when compared to Uniform cost scenario. When the total system cost (and not different area cost) is minimised, in the optimal situation emissions in some areas can be increased, if it is more beneficial to decrease them in the other areas with the same externality cost. When high pollution costs induce investments into clean technologies in DK_E_Rural area, energy in the DK_W_Rural area can be produced by a more polluting plant, but using cheaper fuel or avoiding additional investments.

The total system cost under different scenarios prove that it is less costly for the society to consider externalities in the energy system planning process than to pay for the resulting damages later. Fig. 8 includes the cumulative energy system costs and cost components of the three analysed years. The top left point shows the total system cost when not internalised health externalities are added to the total cost of the No externalities scenario. It is clear that the total system cost decreases when health externalities are included due to decrease of local external and CO\textsubscript{2} costs, even though the production cost increases.

6. Conclusions

Based on the carried out literature study it can be generalised that local external effects of the pollution from energy production depend on two main groups of aspects. The first group is related to technology (type, fuel, efficiency, capacity utilisation, stack height, size and abatement); and the second is related to location of a plant (with respect to meteorological conditions and population distribution). Technologies are the primary focus of energy models and their characteristics are represented rather detailed, also in the reviewed studies. At the same time the localisation aspects are either not treated or simplified in the models. In order to enable more detailed and representative internalisation of local externalities in energy models, information available from atmospheric air pollution and damage quantification models should be used.

The performed inclusion of local health external costs into the energy system optimisation model Balmorel have shown that local external costs of heat and power production in Denmark decrease by around 18% in total for all 3 years analysed, when local health externalities are included in the model. Furthermore, the system costs show that it is around 4–6% cheaper for the society to internalise these externalities than to bear the monetary value of the resulting human health damage. Already when only few areas with different local external costs are distinguished in the energy system and included in the optimisation model, the total health related external cost of the system is reduced by additional 7%. Thus the total result is reduction of total local external costs of the Danish heat and power system of around 25%. Investment and operation decisions, when different area health externalities are added to the model, favour modern pollution free wind and heat pump production in high health impact areas and conventional coal-based generation in the low impact areas. While when the uniform average external cost is applied to the whole system
these modern technologies are more evenly distributed geographically regardless of the location-dependent health benefits. The different health costs are applied to the existing areas in the model. After combining the knowledge of the atmospheric processes, the dominating weather patterns and population distribution, it should be possible to identify characteristic areas, with specific population exposure and consequent health damage costs of different pollutants. Based on the findings of the air pollution and health cost study of the three Danish cogeneration plants a larger deviation from the average local external cost, or at least the higher health cost in some areas can be expected, than the one, used in the calculations. The division of the system into more areas would also lead to larger cost differences between the areas and could induce more significant changes in energy production.

It should be noted that the effect of internalising local externalities can be larger if a possibility of refurbishing the existing plants by installing abatement technologies is included as an option for reducing air pollution from energy production in the early years. This has not been possible in the presented model runs. Shifting to cleaner fuels or emission free technologies can also bring other benefits, such as reduction of CO₂ emissions, increased use of renewable energy resources and decreased dependency on fossil fuels. End of pipe emission abatement technologies used for conventional energy plants solve on the other hand only local and regional air pollution problems. Another important option that can effectively reduce emissions of local pollutants is investments in energy savings. Option to invest into energy savings is not implemented in the present model; it is the subject of the future work.

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Appendix A

Overview of energy system optimisation studies that internalise local externalities.

<table>
<thead>
<tr>
<th>Study</th>
<th>External costs</th>
<th>Defining factors</th>
<th>Localisation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Global electricity generation MESSAGE-MACRO 1990–2050 [7]</td>
<td>Exogenously estimated SO₂ and NOₓ costs for each technology in each region in €/kWh of output electricity. Source: ExternE</td>
<td>Externalities included for each technology in 11 world regions by: fuel type and sulphur content; abatement technology; plant efficiency; population density</td>
<td>Worlds 11 regions</td>
</tr>
<tr>
<td>Global electricity generation Global MARKAL 2000–2050 [2]</td>
<td>Exogenously estimated SO₂, NOₓ and CO₂ costs for each technology in each region in €/kWh of output electricity. Source: ExternE</td>
<td>Externalities for each technology in five world regions are adjusted by: fuel type and sulphur content; abatement technology; plant efficiency; population density</td>
<td>Worlds five regions</td>
</tr>
<tr>
<td>Vietnam’s electricity system MARKAL 2005–2025 [3]</td>
<td>In $/t of SO₂, NOₓ, particulates and CO₂ for fossil technologies; and in €/kWh for renewable el. Source: ExternE Germany</td>
<td>External costs from electricity generation in Germany adjusted to Vietnam by GDP and population density</td>
<td>None</td>
</tr>
<tr>
<td>Polish energy sector Partial equilibrium model 2002–2020 [8]</td>
<td>Local SO₂, NOₓ, particulates and CO₂ external costs for EU 15 in €/Mg. Source: ExternE</td>
<td>None</td>
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<tr>
<td>Spanish power system yearly operation optimisation Ecosense and Electricity network model GREEN 1998 [4]</td>
<td>Local external cost of SO₂, NOₓ and total suspended particulate matter in €/ton for different thermal plants in different locations (100 × 100 km). Externalities of nuclear and hydro power in €/kWh. Source: Calculated (Ecocense)</td>
<td>Damages from ten power plants at different locations extrapolated to the nearby (100 radius) plants</td>
<td>100 × 100 km areas</td>
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<tr>
<td>Planning of regional heating system in Sweden MODEST model 10 years period [5]</td>
<td>€ per kWh of energy carrier (e.g. electricity, fuel wood) due to damages of pollution by SO₂, NOₓ, particulates and CO₂, calculated by combining external costs of each pollutant and emission factors of heating plants. Source: ExternE Sweden</td>
<td>Emission factors of plants. External costs from electricity are the damage costs from coal condensing power plants</td>
<td>None</td>
</tr>
<tr>
<td>Planning of regional heating system in Sweden MODEST model 10 year period [6]</td>
<td>€ per kWh of energy carrier (e.g. electricity, fuel wood) due to damages of pollution by SO₂, NOₓ, particulates and CO₂, calculated by combining external costs of each pollutant and emission factors of heating plants. Source: ExternE Sweden</td>
<td>Emission factors of plants. External costs from electricity are the damage costs from coal condensing power plants</td>
<td>None</td>
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<tr>
<td>Cooperation between Swedish and Danish DH systems</td>
<td>SEK per kWh of energy carrier due to damages of pollution by SO₂, NOₓ and</td>
<td>Emission factors of plants.</td>
<td>None</td>
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(continued on next page)
Appendix A (continued)

<table>
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<th>Study</th>
<th>External costs</th>
<th>Defining factors</th>
<th>Localisation</th>
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<td>MODEST model 10 year period [9]</td>
<td>CO₂, calculated by combining external costs of each pollutant and emission factors of analysed heating plants. Source: ExternE Sweden</td>
<td>Emission factors of plants. External costs from electricity are the damage costs from coal condensing and natural gas power plants.</td>
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<td>Operation of municipal district heating system with waste incineration MODEST model [10]</td>
<td>€ per kWh of fuel due to damages of pollution by SO₂, NOₓ, particulates and CO₂, calculated by combining external costs of each pollutant and emission factors of heating plants. Source: ExternE Sweden</td>
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Appendix B

Technologies available for investment.

<table>
<thead>
<tr>
<th>Technology</th>
<th>From year</th>
<th>Lifetime</th>
<th>Investment MEUR/MW</th>
<th>Variable O&amp;M cost EUR/MWh</th>
<th>Fixed O&amp;M cost kEUR/MW</th>
<th>SO₂ g/GJ</th>
<th>NOₓ g/GJ</th>
<th>PM₁₀ g/GJ</th>
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<tbody>
<tr>
<td>Combined cycle gas turbine</td>
<td>2010</td>
<td>25</td>
<td>0.46</td>
<td>1.70</td>
<td>12.50</td>
<td>0.3</td>
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<td>Heat pump</td>
<td>2000</td>
<td>20</td>
<td>0.30</td>
<td>1.21</td>
<td>2.72</td>
<td>0</td>
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<td>Heat boiler nat. gas</td>
<td>2000</td>
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<td>0.05</td>
<td>0.67</td>
<td>0.54</td>
<td>0.3</td>
<td>17</td>
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<td>Heat boiler straw</td>
<td>2000</td>
<td>30</td>
<td>0.32</td>
<td>4.02</td>
<td>19.28</td>
<td>47</td>
<td>80</td>
<td>17.52</td>
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<tr>
<td>Heat boiler wood waste</td>
<td>2000</td>
<td>30</td>
<td>0.32</td>
<td>4.02</td>
<td>19.28</td>
<td>1.5</td>
<td>80</td>
<td>14.60</td>
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<tr>
<td>Coal CHP with carbon capture</td>
<td>2010</td>
<td>30</td>
<td>1.70</td>
<td>4.80</td>
<td>18.20</td>
<td>30</td>
<td>40</td>
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<tr>
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<td>0.95</td>
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<td>Steam turbine biomass</td>
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<td>3.10</td>
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<td>10.00</td>
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<tr>
<td>Open cycle gas turbine</td>
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<td>15</td>
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<td>32.00</td>
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<td>Offshore wind turbine-2</td>
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<td>20</td>
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<td>20</td>
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<td>Steam turbine coal</td>
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<td>40</td>
<td>3.60</td>
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Source: [24, 25].

References


