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Load Matching in Highly Energy Performing Buildings

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Abstract

The European Union, as well as in the public and private building sector, have goals, requirements and definitions that encourage energy efficiency improvement to enable reduced import of energy to the building as well as greenhouse gas (GHG) emissions. One of these definitions is nearly zero energy buildings (nZEB). Most of the nZEB definitions are based on annual values for delivered and exported energy. In order to reach nZEB in a robust and resource effective way, the energy grids may be used for both delivery and export. However, the reduction of primary energy (PE) demand and climate impact is not automatically achieved just by using the grid. The load matching between the building's energy demand, the renewable energy production and the exported renewable energy is depending on when in time this occurs. An environmental assessment method for buildings' energy use has been developed, taking into account the time resolution of energy use, import and export. For exchange of heating between the building and the district heating (DH) grid each DH system is analysed individually. A marginal mix of fuels influenced by a change in heat demand is calculated and resulting environmental impacts analysed. The assessment of electricity exchange between the building and the grid is done by a marginal approach identifying the technologies in the North European electricity system affected by a change in electricity use. By using the method as a sensitivity and risk analysis in the planning phase of new buildings, the stakeholders can avoid unpredicted consequences.

Keywords – energy solutions, buildings, consequense analysis, environmental assessment, method

1. Introduction

The requirements on energy performance of buildings are increasing through, for example, sharper building regulating codes in combination with Green Building demands [1], [2]. Office building developers strive for creating functional office space and indoor climate for their tenants, and for low running and maintenance costs for their clients the landlords. But at the same time building developers have a responsibility to create and choose solutions that are sustainable in the long run. The amount of purchased energy per square meters in office buildings has thus decreased during the last 15 years.

The next step is to investigate solutions using not only energy efficient building parts but also add the energy supply preferably from renewable energy sources (RES). Decreasing prices for solar photovoltaics (PVs) and governmental support have increased investments in small-scale RES in Sweden. Many small-scale energy solutions (ES) produce electricity and/or heat only at specific weather conditions, not necessarily matching the buildings' electricity and/or heat demand. The implications for the energy system have so far almost exclusively been analysed based on total annual values.

But which solutions and combinations of onsite and offsite RES are both more energy efficient in an annual energy balance and have lower environmental impact? To quantify the consequences of choosing different RES combinations and infrastructures, and even different ES, there is a need for a transparent, research- and fact-based method [3]. This paper presents a new method for quantifying the environmental consequences of different ES in buildings. The method takes into account time aspects, load matching and grid interaction and may be used for planning new buildings' ES with optimal environmental performance of the energy balance.

2. The Method in General Terms

Our method shows the effects of different ES compared to a reference building without such solutions and provides a basis for planning of building ES. ES can in this context be both solutions for energy efficiency improvement and RES. The starting point has been to analyse the consequences of a change in net energy demand in the building. In life cycle assessment (LCA) terminology, this is often referred to as consequential LCA [4]. So the method is only applied to climate impact and not on the full range of environmental impacts.

The method addresses both the long-term development of the energy system and the short-term time resolution, which refers to variations over shorter time periods in a year, i.e. over seasons, months and days. Time resolution is necessary to take into account for ES that are, for example, whether dependent. The time resolution necessary for reliable environmental assessment of building ES will vary depending on e.g. energy carrier (heat or electricity), type of DH grid and from present time to the future.

A procedure in eight steps has been developed to calculate, analyse and compare the environmental impact of various ES (Fig. 1). The first four steps relates to the building's ES and balance. Step 1 includes definition of the reference building against which various ES will be compared. It can be either an existing building or a fictive building design. The ES to be studied are then identified. Step 2 deals with the time-resolved energy balance of the building which is preferably calculated by an energy simulation program. The energy balance includes use, import and export of various energy carriers (electricity, heating cooling). The building's effect signature per energy carrier is then, in Step 3, calculated by correlating the building's hourly net energy use to the outdoor temperature. The effect signature is then used to calculate the building's energy signature, i.e. the energy use per degree (Step 4).

The last four steps relate to the environmental assessment of the energy exchange between the building and the energy grids. The method can be used to analyse many different resource and environmental aspects. In this paper, we have chosen to exemplify by climate impact measured by emissions of carbon dioxide equivalents (CO_{2e}). Steps 5-7 involve environmental assessment of energy exchange with the electricity, DH and/or district cooling grids (see section below). In the final and last Step 8 the results of different ES are compared to each other to allow choosing the best solutions from an environmental point of view.

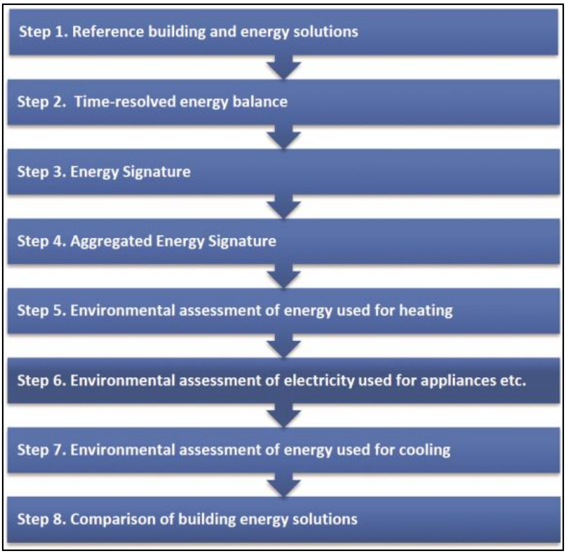

Fig 1. Eight-step procedure for environmental assessment of building ES.

3. Environmental Assessment of District Heating

DH systems are local in nature, and therefore a general methodology has been developed that may be used to analyse site-specific impacts of different heating demand, export and import for different ES. An individual DH system could have a rather complex mix of different plants in operation at different time steps and at different outdoor temperatures. A method for identifying the DH production technologies, and subsequent environmental impact, affected by a change in heating demand has been developed. The production and DH plant data necessary for making the calculations of consequences of a change in DH demand is preferably gathered from the DH company.

The method for identifying the consequences of various ES on DH demand, import and export is based on outdoor temperature data to produce a so-called marginal mix for each temperature interval. The marginal mix is produced by arranging the DH plants according to a specific operating order for each hour to cover the heat demand in the system. The order of operating the plants is defined by the variable cost, which is influenced by various parameters, such as electricity and fuel prices. Fig. 2 shows a simulated annual DH production for a large Swedish DH grid.

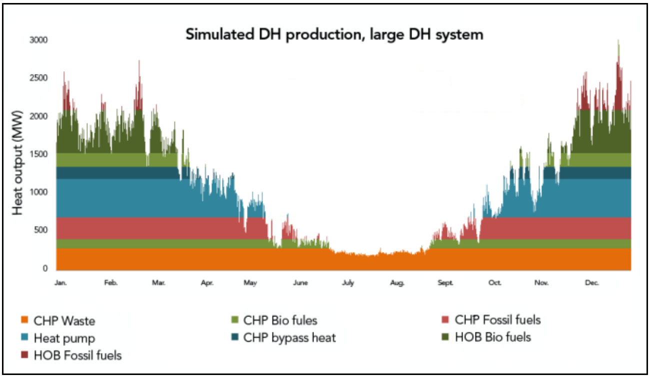

Fig. 2. Simulated annual DH production for a large Swedish DH system (example)

The production mix is then sorted after the outdoor temperature. The result is a marginal mix consisting of the fuels at each temperature which are most likely to be used for DH production during hours of that specific temperature. The method is based on temperature instead of time because the DH production is more dependent on temperature than the time of day. Different DH production plants may be affected at different occasions with the same temperature and thus the marginal production of DH being is mix of technologies. In addition, there can be a delay between a change in temperature and the change in DH production, because of the inertia in the heating system due to e.g. heat storage in DH pipelines, buildings thermal inertia and accumulator tanks. The marginal mix gives a probability distribution of the likelihood that DH is produced from a specific production technology at a given temperature. One example of a temperature dependent marginal mix for a large Swedish DH system is shown in Fig. 3.

In the case several DH networks are interconnected, for example in regional networks, these should be considered as a common system where a change in DH demand in one area of the region may very well cause consequences in a DH plant elsewhere in the region.

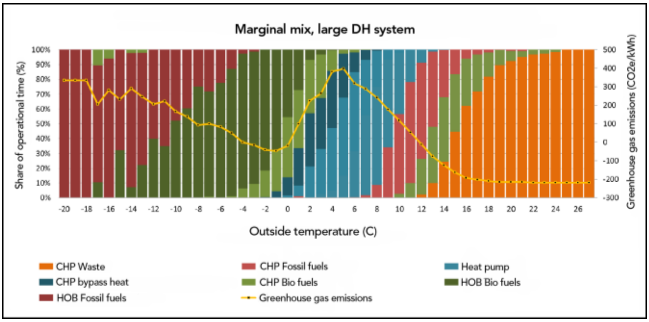

Fig. 3. Example of calculated marginal mix of one large Swedish DH system (the same as in Fig. 2) at different outdoor temperatures. The arising GHG emissions at different temperatures are shown by the dotted line.

4. Environmental Assessment of Electricity

The electricity system is larger geographically compared to DH systems. A change in Sweden may very well lead to consequences outside Sweden. Our method considers a North European perspective to cover the effects of a change in electricity demand in Sweden. A building ES can affect the building's electricity balance, including import and export of electricity from the grid. This can affect the short-term marginal electricity (STME), i.e. the power production with the highest variable cost and/or the long-term marginal electricity (LTME), i.e. the production capacity of a technology where decisions to invest or shut down power plants are on the table. To simplify communication, the STME is sometimes called operating marginal electricity. The LTME is sometimes (and somewhat too narrowly) called build marginal electricity.

We have identified the present STME and use three different electricity scenarios to handle the great uncertainty related to the future LTME. Within the next 0-10 years, the marginal electricity for Sweden is likely to be STME only, because of the current overcapacity in the electricity production [5]. This STME is assumed to be electricity from fossil fuels (mainly coal and to some extent natural gas) abroad, e.g. in Denmark and Germany at all times during the year and day and in all three scenarios. This fossil fuel based electricity production has high variable cost and is thus the production that comes in last in the electricity mix. The extensive Nordic hydropower is not marginal electricity (other than in very rare occasions), but is regulating the changes in electricity demand over both days as seasons. The hydropower meets rapid changes in demand and can also be saved from base-load to top-load occasions, i.e. both from day to night and from summer to winter. The regulating capacity of the hydropower makes the STME rather constant in the short term.

The three different scenarios for the future electricity system are a *reference scenario*, a *high fossil scenario*, and a *high renewable scenario*. Building ES that show low climate impact in all scenarios can be assumed to have low climate risk. Likewise, solutions that provide high impact in many scenarios are assumed to be associated with a high climate risk.

The *reference scenario* is based on the reference scenario of the Swedish Energy Agency [6], estimating a short-term increase in annual nuclear electricity production through already planned investments. From 2020 there is a reduction in nuclear power production when the oldest reactors are shut down. New RES electricity is also built in this scenario. Due to overcapacity in the reference scenario, a change in electricity demand even after the STME (2015-2025) only affects the operation of existing power plants and not the building of new power plants. The affected STME is different dependent on whether the change occurs on base-load, middle-load or top-load time.

Renewable power production is expanded also in the *high fossil scenario*. However, we assume that there is a concurrent electrification of the transport sector giving rise to a faster increase in electricity consumption compared to the reference scenario. It thus becomes profitable to build additional production facilities in various locations in northern Europe. A change in the electricity consumption will in the short term mainly affect the use of existing facilities (i.e. the STME). Subsequently the production capacity of new power plants is adapted to the new demand for electricity. This means that effects of a changed electricity demand will be visible on the LTME, which in this scenario is assumed to be coal-fired and natural gas-fired power or CHP plants.

In the *high renewable scenario*, new RES electricity is built on a large scale for political reasons, leading to a surplus in production capacity and low electricity prices. A considerable political pressure on decommissioning of nuclear power plants together with low market electricity prices make nuclear power non-profitable and lead to a close down of the oldest and least efficient power plants [7]. This scenario thus includes a decrease in nuclear power production already after a few years. The short-term effect is the closure of old nuclear plants. After a few more years, this scenario assumes new plants are being built at the margin, mainly advanced CHP plants using biogas or synthetic natural gas produced from renewable raw materials.

In all scenarios the current marginal electricity is not time resolved, whereas the future marginal electricity is assumed to be dependent on time. This time resolution is managed by sorting the hours of the year into base load, middle load and top load time. Fig. 4 illustrates the results of climate impact in the three scenarios at base, middle and top load time.

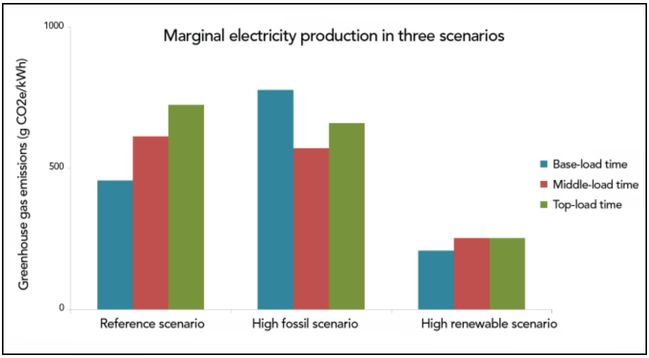

Fig. 4. Average GHG emissions from marginal electricity production over the period 2015-2040, divided into base-load, middle-load and top-load time.

5. Results – case studies

The resulting consequences on energy balance and environmental performance for different ES compared to the reference are achieved by combining the difference in energy need for the building with the difference in DH and electricity production in three scenarios. Since the method identifies the specific production technologies affected by a change in energy demand, the results cannot be compared to result of a total environmental performance of the reference building. To test and demonstrate the method, we calculated results for three ES:

- Solar heating with export to the DH grid
- Solar heating with seasonal heating storage not using the grid
- Solar PV with export to the power grid

Fig. 5 illustrates the difference in energy performance (energy balance) between the three cases and the reference building. The energy balance of each case is calculated by summing the building's annual import and export of electricity and heat to/from the grids (electricity and heat), which is then compared to the energy balance of the reference building.

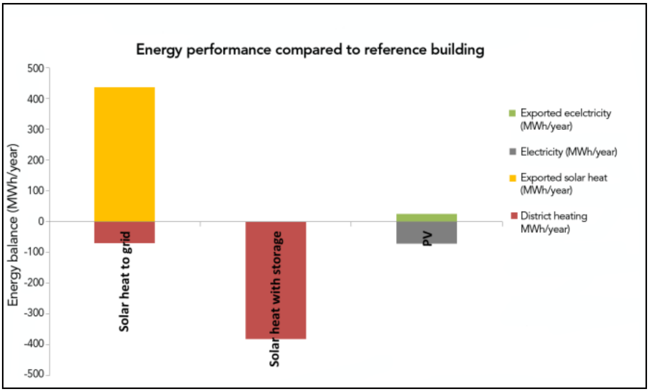

Fig. 5. Energy performance for the different renewable ES compared to a reference building.

In the first case with solar heating panels on the roof the main part of the produced solar heat is exported to the DH grid. In the second case the solar heat is stored and used to replace DH all over the year. In the third case the solar heating panels are replaced by solar PVs. The solar heating cases are based on the same solar collector area. They are not comparable to the solar PV case since they are based on different assumptions regarding the annual energy (heat and electricity respectively) generation.

The resulting energy balance has been applied to the results of the DH marginal mix and the three electricity scenarios to give the resulting difference in GHG emissions compared to the reference. Fig. 6 and Fig. 7 show the results for two examples of DH systems (one large and one small).

The results show that solar heating with seasonal thermal storage have better climate performance than both the reference building and the case with solar heating without storage. The reason for this is that the storage enables more effective utilisation of the heat. The results for the large DH system are more diverse than for the small system because of the more complex fuel composition and marginal mix. For example, the small DH system is based on heat boilers without CHP and without electricity boilers. Therefore, the results are not dependent on the electricity scenario. The results for the large DH system vary with electricity scenario since there are both heat pumps and CHP plants in the marginal mix. This is also the reason for the increased climate impact of the solar heating to grid case, where a lot of heat is produced during the summer and thus decreasing the possibility to produce electricity from CHP. The reduced electricity must then be replaced by marginal electricity from the grid.

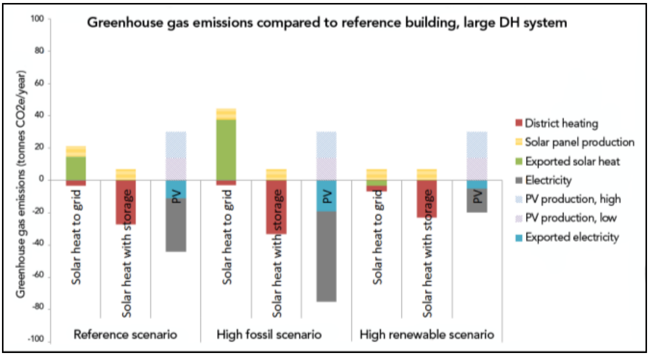

Fig. 6. Reduced or increased GHG emissions in a large DH system for the three building cases in the three different power scenarios.

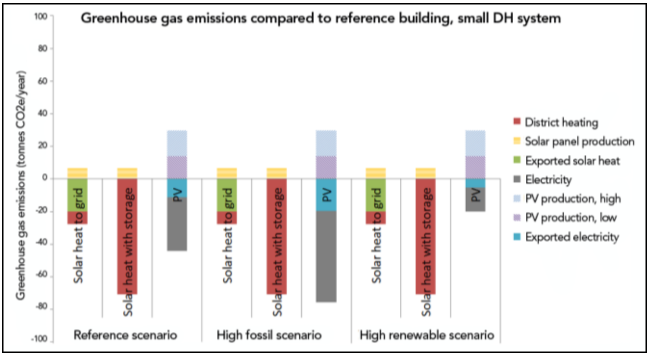

Fig. 7. Reduced or increased GHG emissions in a small DH system for the three building cases in the three different power scenarios.

6. Discussion and conclusions

Development of DH systems depend on e.g. each DH company's existing production facilities, policy instrument, estimates of future demand for heat, investment plans etc. For the electricity system, the long-term development depends on decisions from a variety of electricity market actors, which means that the future electricity system may develop in many different ways. The method handles this uncertainty by various scenarios.

The time resolution refers to variations of seasons, months and days. The conclusion is that the consequences on DH production need to handle time resolution. However, the consequences for the electricity system don't need to take into account the time resolution in the short term, but in the long term. The relevant resolution is also differ between the DH and electricity systems, because DH production depends on the outdoor temperature, while the electricity production depends more on the time of the day.

The results of the method are illustrated by energy balances and GHG emissions from three case studies. However, for robust assessments it is important to take into account other aspects as well, e.g. economic and social aspects, resource efficiency, and other environmental aspects. By using the method as a sensitivity study and risk analysis the stakeholders in a project can avoid unpredicted future consequences.

It is fairly robust to conclude that it is preferable from a climate perspective to take measures to save electricity, regardless of day or year. Similarly ES that generate renewable electricity are likely to be beneficial from a climate point of view.

We also conclude that it is uncertain to predict how ES implemented today will affect future energy systems. Therefore, it should be beneficial to design buildings so that they have the flexibility for the future. Flexibility may relate both to the possibility of using different energy sources but also to equalize / varying power requirements.

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