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Heat pumps versus combined heat and power production as CO_2 reduction measures in Finland

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ABSTRACT

Heat pumps have rapidly gained popularity in the Nordic area, as they are marketed to provide considerable monetary savings and CO_2 emission reductions. Heat pumps are installed even in buildings heated by CHP (combined heat and power production). In this paper we calculate CO_2 emission factors of DH (district heating) from CHP and GSHP (ground source heat pumps) in Finland, based on hourly data at present and in various future scenarios. In LCA (life cycle assessment) analyses, usually only annual averages are used. We show that including seasonal variation can result in very different emission factors. Since during warm seasons, electricity production is significantly less carbon-intensive than in cold seasons. We find that the current emission factor of CHP DH consumption change is only 70–100 g/kWh. In the future it is 0…300 g/kWh, depending on the CO_2 intensity of electricity production. The similar GSHP emission factor would develop from the present 200 g/kWh to 50…200 g/kWh. As long as electricity consumption has seasonal variation or coal condensing power is significant in the interconnected network, CHP has lower emissions than GSHP. We recommend using CLCA (consequential LCA) methodology and the inclusion of seasonal variation in heating option comparisons.

1. Introduction

In countries with cold climate, space heating is a major energy consumer and thus a significant source of GHG (greenhouse gas) emissions. CHP (combined heat and power) and GSHP (ground source heat pumps) are seen to be among the best alternatives to reduce GHG emissions of space heating [1]. Concerning Denmark, Lund et al. [2] conclude that the CO_2 emissions of GSHP's and CHP are quite near to each other, CHP being some tens of per cent better in terms of CO_2 emissions.

In CHP production, waste heat from electricity production is utilised for e.g. space heating. In steam turbine process a small part of electricity production is lost in the CHP plant compared to the otherwise similar condensing plant, due to the higher steam extraction temperature from the turbine.

This causes some loss in electricity production. While a normal solid-fuel burning condensing power plant produces about 40 units of electricity when 100 units is used as a fuel, a CHP plant may produce e.g. 30 units of electricity and 60 units of heat. The waste heat can be almost entirely recovered and used for heating use, allowing then a substitution of e.g. oil boilers or electric heating. This is the advantage of CHP in a nutshell.

CHP in space heating is a common solution in e.g. Finland, Denmark, Poland and Russia. In these countries, even over 50% of buildings are heated with CHP connected to the DH (district heating) network, see e.g Ref. [3]. CHP plants produce also a significant amount of electricity. For example in 2010, 23% of the Finnish electricity production was based on CHP linked to DH networks. CHP DH production has steadily increased since its beginning in Finland in the 1960's [4]. Now the growth has stabilised, as most of the economic potential is utilised.

Heat pumps have rapidly gained popularity in the Nordic area, as they are marketed to provide considerable monetary savings and to reduce CO_2 emissions. In Sweden heat pumps have a 32% share of building heating [5]. In Finland their share is only 6%, but currently, the increase in Finland is as quick as it was in Sweden earlier, caused by the rising consumer energy prices [4].

In Finnish LCA (life cycle assessments), the normally used emission factor for electricity is about 200 g/kWh [6,7], which is the production-based annual average in Finland. The average, low factor is based on the fact that in Nordic countries hydropower covers about 30% of electricity production [8]. In addition there are significant amounts of CHP production and nuclear power. However, there is also regulating coal condensing power, which has an emission factor of about 900 g/kWh. The change in electricity consumption impacts most of the time to the amount of coal

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condensing power and thus the emission factor for the change should be in principle that 900 g/kWh.

The challenge is that the impact of the consumption change is not exactly known. In certain situations, especially in times when the demand for electricity is low, the emission factor of the change in use may be also much lower than that of coal condensing power [9]. The emission and cost impact of changes in consumption of electricity or CHP power production (as a consequence of heat use changes) can be addressed in many ways, see e.g Ref. [10]. In every case it is most important to find out what would really happen in the power system in different cases: what kind of alternative production there would be, if CHP power production changes? If a heat pump increases electricity consumption, from what kind of plants would the electricity come from? What kind of power plants or other structures the specified solutions in buildings or in built environment would create or support? This depends on e.g. the diurnal and annual electricity usage profile, which is normally neglected in LCA analyses [11], as higher-resolution data is often not available.

This study utilises hourly electricity price and consumption data from Nordpool, the Nordic power exchange. In addition, we use hourly CHP heat (and thereby also estimated CHP power) production data from Finland. We show that taking into account e.g. the seasonal variation can have very large impacts on the results.

In Section 2, we present the LCA methodologies used to address these questions and we reflect recent scientific literature addressing similar cases. In Section 3, the Nordic electricity market is shortly described. In Section 4 we present the data used in our calculations and the future scenarios assessed. In Section 5, we present the resulting CO_2 emission factors. In Section 6, we give recommendations for similar LCA studies and discuss the validity of our assumptions. Conclusions are presented in Section 7.

2. Methods

CHP and GSHP are generally seen to be among the best alternatives to reduce the greenhouse gas emissions of space heating. Blum et al. found that GSHPs reduce CO_2 emissions about 45% compared to oil heating [12]. Saner et al. examined also the other environmental impacts of GSHPs and found that the electricity use of the pump is the most important one [13]. Both these studies used European annual average electricity mix, without considering the consequences of the timing of the electricity use. Thorough analysis with proper (e.g. hourly) treatment of the electricity system is rare.

2.1. Attributional and consequential life cycle assessment (ALCA and CLCA) in electricity use

CLCA (consequential life cycle assessment) addresses the impacts of a change in use, “what if …”, contrary to ALCA (attributional life cycle assessment), which gives the average emissions calculated for production or consumption in a stabile state. ALCA is not suitable for determining the short-term impacts of the change in use [14]. Yet, ALCA is very often used for this purpose, as the average data needed for ALCA is often much easier to get than more context- and time-specific data needed for CLCA, which may also include complicated interdependencies. In CLCA, the marginal technology (i.e. technology first affected by the change in use) and the magnitude of this “operating margin” must be specified. This kind of study done in British electricity network with real power plant data is presented by Hawkes [15]. However, the precision of Hawkes’ study is not normally possible as the data of the use of the power plants hour by hour is lacking.

The uncertainties involved in identifying marginal technologies are discussed by e.g. Mathiesen et al. [16]. In addition to specifying the marginal technology now or in history, it is important to estimate what it would be in the future, as investments in energy efficiency or production are generally long-lasting and expensive. Ekvall&Weidema discuss these short-term and long-term impact assessment issues in more detail [17].

When co-producing power and heat in the same process, the alternative production for power must be considered when changing the production of heat. This may vary from hour to hour.

2.2. Earlier ALCA results for this topic

ALCA studies for Finland use about the same official emission factors for CHP DH and electricity in general, about 200 g/kWh [6,7]. This applies to the Finnish fuel distribution, when a benefit sharing method is used, i.e. the fuels used in CHP are distributed to heat and electricity according to the shares of fuel use of imaginary supposed alternative production. For electricity, this is condensing power with the same fuel. For heat, this is a separate heat-only boiler with the same fuel [7]. In Finland, about 80% of CHP DH production is covered with fossil fuels, including peat. If annual average electricity emission factor is used for GSHP heating, the resulting GSHP emission factor is about 70 g/kWh, i.e. one third of that of ALCA-based factor for CHP heating in Finland.

2.3. Earlier CLCA results for this topic

The marginal emission factors in Nordic conditions have been found to be mainly about 600…700 g/kWh in studies by e.g. Holttinen & Tuhkanen [9] and Sköldberg and Unger [18]. The later ones used Markal-Nordic energy system model for years from 2009 to 2037. However, they also found that if the price of CO_2 is high enough (45 €/tonne), the technological optimization gives the emissions of only 160 g/kWh by the 2030’s, as there would be a large amount of coal and oil power with CCS (carbon capture and storage) built in the system. Pehnt et al. found that in the German electricity system, CO_2 emissions are reduced by 600…900 g per each kWh produced by wind energy [19].

Concerning Denmark, Lund et al. [11] have forecasted YAM (yearly average margin) with CLCA approach and suggest that the marginal production would be natural gas or coal condensing power. This means that the impact of the electricity use or production change would be 400…900 g/kWh. Hawkes, in turn, gives a marginal emission factor of 690 g/kWh now and, with power plant modernizations, 510 g/kWh before 2025 for British electricity [15].

The results of different studies are, however, not directly comparable because of the different load profiles used. Also the presupposed role of nuclear and CCS power must be carefully examined before conclusions. E.g. in the German example [19] nuclear power was not an option.

These examples illustrate how contradictory the results obtained with of ALCA (Section 2.2) and CLCA approaches can be in the case of electricity systems.

2.4. CLCA in this study

In this study we have used CLCA. Using CLCA can be justified by the fact that the emission factors are (or should be) used by politicians, organisations and private people to find out the impacts of some change. ALCA is not useful for this purpose.

First we study, what has been the yearly average marginal electricity production method in years 2006–2011, relevant to use in Finland as a part of the Nordic electricity market [20].

Secondly, we try to estimate the possibly different situation in the future electricity system. In the case of seasonally variable space heating energy, this can be done much more exactly than in the case