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Residential heat pumps in the future Danish energy system

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ABSTRACT

Denmark is striving towards 100% renewable energy system in 2050. Residential heat pumps are expected to be a part of that system.

We propose two novel approaches to improve the representation of residential heat pumps: Coefficients of performance (COPs) are modelled as dependent on air and ground temperature while installation of ground-source heat pumps is constrained by available ground area. In this study, TIMES-DK model is utilised to test the effects of improved modelling of residential heat pumps on the Danish energy system until 2050.

The analysis of the Danish energy system was done for politically agreed targets which include: at least 50% of electricity consumption from wind power starting from 2020, fossil fuel free heat and power sector from 2035 and 100% renewable energy system starting from 2050. Residential heat pumps supply around 25% of total residential heating demand after 2035. The improved modelling of residential heat pumps proved to have influence on the results. First, it would be optimal to invest in more ground-source heat pumps, but there is not enough available ground area. Second, the total system costs are higher when COPs are modelled as temperature-dependent compared to fixed COPs over a year.

1. Introduction

The long term goal in the Danish society is to become 100% renewable in all sectors of the energy system from 2050. The intermediate goals include achieving 50% of electricity consumption from wind starting in 2020 and 100% renewable power and heat production from 2035 [1,2]. Achieving such an energy system requires significant efficiency improvements in the chain production-transmission-distribution-end-use of electricity and heat, accompanied by energy conservation measures.

Common understanding of the heat supply configuration in the future Danish energy system includes district heating in areas with high heat density and individual heating technologies in areas with low heat density. In the light of renewable energy targets, district heating will be switching from coal-based CHPs to large heat pumps, waste incinerations and waste heat from production of biofuels. Existing individual heating technologies will be replaced by technologies fuelled by renewable energy, such as residential heat pumps. New buildings will be built according to high standards of energy efficiency while introduction of heat saving measures will decrease heating demands in existing buildings.

Previous studies have shown that residential heat pumps are important elements of the future Danish energy system. Münster et al. [3] have developed three scenarios for the Danish energy system with the intention to analyse the interaction between the electricity market and district heating in the light of heat savings and taxes and support mechanisms. They have found that in all scenarios the individual heat production completely changes from oil and natural gas to residential heat pumps already in 2025. Similar research questions have been analysed in Refs. [4,5]. Their conclusion is that district heating should be gradually expanded around cities and towns while residential heat pumps should supply rural and remote areas in both current and future Danish energy system. According to IDA's Climate Plan 2050 [6,7] district heating production will increase in the future despite significant reduction of heating demands in buildings. District heating will mainly be based on biomass and large scale heat pumps, while two thirds of individual heating will be produced from heat pumps. Analysis of the Danish energy system in 2050 done by Lund et al. [8] showed that heat supply configuration should be composed of district heating and residential heat pumps, while heating demand should be halved compared to today's values. Two main scenarios for the Danish energy system in 2025 are analysed in Ref. [9]. It is concluded that from a socioeconomic point of view, heat pumps

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Nomenclature

R	Set of regions
R	Region
YEARS	Set of years for which there are costs
Y	Year
NPV	Net present value of the total system cost for all regions
ANNCOST(*r*,*y*)	Total annual cost in region *r* and year *y*
$d_{r,y}$	General discount rate
REFYR	Reference year for discounting
$P_h(t)$	Heat power in time t
$P_e(t)$	Electrical power in time t
COP_{av}	Average COP of a residential heat pump
W_h	Maximal annual heating demand which can be covered by a ground-source heat pump
$P_{h,spec}$	Specific extraction power from the ground
A_{av}	Available parcel area
k_{area}	Reduction coefficient of available parcel area for burring of horizontal pipes
T_{flh}	Full load fours of ground-source heat pumps over a year

seem to be cost-effective in buildings not connected to district heating. Mathiesen et al. [10] have analysed how the heating sector can reduce its consumption of biomass. They have shown that district heating systems are important in limiting the dependence on biomass but have also recommended ground-source heat pumps for individual heating systems in areas with low heat density. Torekov et al. [11] have compared the costs of heat supply to residential buildings from private-economic and socio-economic perspective. They have concluded that from the socio-economic perspective air-source heat pumps are the cheapest of the individual heating systems and in the most cases cheaper than the collective heating systems. In a technical analysis of future renewable energy systems of Frederikshavn and Aalborg individual heat pumps and solar collectors were the only heating sources besides district heating [12,13].

The interactions of residential heat pumps with the energy system were analysed in several studies. The Danish energy system with high shares of wind power, CHPs and district heating is analysed in Ref. [14] and it is shown that the installation of heat pumps can contribute to the integration of wind power and provide significant reductions in excess electricity production and fuel consumption. Hedegaard and Münster [15] used the Danish energy system in year 2030 with 50–60% of wind power and 55% of residential buildings heated by district heating as a case study. They have shown that heat pumps significantly contribute to the integration of wind power, reduction of system costs, fuel consumption and CO_2 emissions. Mathiesen et al. [16] have applied Smart Energy Systems approach to design a future Danish energy system based on 100% renewable energy. They have concluded that with more than 20–25% wind power of the electricity demand it is necessary to install large-scale and individual heat pumps in order to effectively integrate fluctuating wind power. In a nearly 100% renewable energy system of Scandinavian countries and Germany in 2060, heat pumps, electrolysis plants and biomass CHPs are providing the needed flexibility caused by variable production from wind power and photovoltaics [17]. Health externalities are added to the optimisation model Balmorel in Ref. [18]. It is shown that investment and operation decisions favour modern pollution-free energy producers such as wind turbines and heat pumps in high health impact areas and traditional coal-based generation in the low impact areas.

No existing studies have been identified in which the operation of residential heat pumps is described by temperature-dependent coefficients of performance (COP). In addition to that, no existing studies dealing with whether there is enough ground area for installation of ground-source heat pumps have been identified. These two issues are therefore the main subjects of this study. We improve the modelling of residential heat pumps by introducing temperature-dependent COPs and use GIS tools to determine the available area for installation of ground-source heat pumps. After that, we use TIMES-DK model of the Danish energy system to test the impact of the improved modelling of residential heat pumps on their investments and operation. TIMES-DK model calculates the cost-optimal solution for the whole energy system until the end of the analysed period and thus show the role of residential heat pumps. Our analysis is done for the existing politically agreed renewable energy targets until 2050. However, we don't focus on the analysis of targets or ways how to fulfil them. The effects of the improved modelling on the heat supply configuration, the total system costs, CO_2 emissions and fuel consumption have also been quantified.

The manuscript is structured as follows. Section 2 briefly describes the operational principles of TIMES models and general features of TIMES-DK. The detailed description of improved modelling of residential heat pumps can be found in Sub-section 2.3. Section 3 lists the analysed scenarios. Section 4 presents the results of energy systems analysis. The sensitivity analysis is presented in Section 5. The results are discussed in Section 6. The conclusion is given in Section 7. Finally, the areas which should be addressed within the future work are presented in Section 8.

2. Methodology

2.1. TIMES model generator

The following description of TIMES models is a combination of authors' insights from working with TIMES and references [19–23]. TIMES (The Integrated MARKAL-EFOM System) was developed and is maintained by the Energy Technology Systems Analysis Programme (ETSAP), an Implementing Agreement of the International Energy Agency (IEA), established in 1976. TIMES is a technology-rich, bottom-up model generator utilised for long-term analysis and planning of regional, national and multi-national energy systems. It is also techno-economic, partial equilibrium model-generator assuming full foresight and perfectly competitive markets. Thus, it covers “4E” aspects of energy systems – energy, economy, environment and engineering.

TIMES models are linear programming problems which consist of the minimization of an objective function defined as a mathematical expression of decision variables, subject to constraints also expressed mathematically. In other words, TIMES models are choosing the investments, operation, primary energy supply and imports/exports over all regions and all time periods in an energy system in such a way that the objective function is minimized. The objective function in TIMES models represent the total system costs discounted to the reference year for discounting and it is expressed with the following equation:

$$NPV = \sum\nolimits_{r=1}^{R} \sum_{y \in YEARS} \left(1 + d_{r,y}\right)^{REFYR-y} \cdot ANNCOST(r,y), \tag{1}$$

where the used symbols have the following meaning:

NPV – Net present value of the total system cost for all regions, i.e. the TIMES objective function.