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A multi-criteria analysis of climate, health and acidification impacts due to greenhouse gases and air pollution—The case of household-level heating technologies

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HIGHLIGHTS

- We analyse the substitution of residential oil heating with biomass-based appliances.
- Emission measurements and estimates of climate, health and acidification impacts.
- Comparison of appliances' social costs and marginal costs to meeting policy objectives.
- Potential misalignment with social and policy costs from climate and air pollutant policies.
- Current policies might steer toward socially sub-optimal technology choices.

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ABSTRACT

This paper considers the climate, health and acidification impacts associated with household-level heating technologies; the policy-based incentives that current emission limits might create for switching between these technologies; and the societal costs that would arise from the externalities associated with the emissions. The data and selection of appliances are applicable to Finland, but the approach can be used to analyse also other countries with similar environmental policies. The results indicate that none of the assessed technologies outperforms the others in every impact category, and that trade-offs need to be made between the impacts. Two perspectives are used to compare these trade-offs. From a policy point of view, a switch from light oil to any of the studied biomass-based appliances would help to achieve national emission limits for CO_2 and SO_2. However, such a switch could potentially increase the externality costs to the society due to increased population exposure to primary $PM_{2.5}$. Based on this, the results suggest that the present emission reduction policies create incentives that can possibly direct decisions toward sub-optimal technology choices.

1. Introduction

The European Union (EU) has set a policy to limit its greenhouse gas (GHG) emissions by 20% from the 1990 levels by the year 2020. The policy defines specific limits for emissions covered by the Emission Trading System (ETS) – consisting mainly of power sector and industrial emissions – and member state's national limits for emissions excluded from the ETS. Each member state has an economic incentive to meet its national emission limit cost-efficiently. Toward this aim, a phase-out of residential oil heating has been identified as a particularly cost-efficient measure in Finland (Hast et al., 2012). This emission category produced 5% of the national non-ETS sectors' GHG emissions in 2010, and therefore provides a large reduction potential when compared to the required reduction of 13% from 2010 levels.

Currently available technologies that can replace oil heating include electric heating appliances (radiators, air source and geothermal heat pumps), district heating and biomass-based appliances (fireplaces, stoves, central-heating boilers). Each of these will contribute to the attainment of the national emission

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limits because emissions from electricity and district heat generation fall primarily inside the ETS, and biomass is accounted with zero GHG emissions due to the assumed carbon neutrality.

However, replacing oil heating can have important environmental effects other than those accounted for in the national GHG limit. Substitution with appliances based on electricity or district heating would increase emissions in the ETS sector, as their marginal production is most often from power plants belonging to the ETS and using fossil fuels – particularly when heating demand is the highest. The environmental impacts of biomass-based heating depend on the technology used, and can differ from oil heating with regard to, e.g. climate change impact, acidification, and particulate matter ($PM_{2.5}$) exposure of surrounding population. As the technologies have differing compositions of GHG and air pollutant emissions, substitution with biomass-based heating may increase the emissions of some species and decrease the emissions of others. Therefore the substitution can affect the various externalities that energy use inflicts on the environment and population, and also either aid or hinder in achieving the multiple emission limits of the revised Gothenburg protocol and National Emission Ceiling (NEC) directive, which control NO_x, SO_2 and $PM_{2.5}$ emissions.

The problem setting at hand therefore considers how alternative heating technologies compare to each other by their climatic, air pollution and health impacts due to their different emission characteristics; whether technology substitution could reduce these externalities and aid in meeting the emission targets for GHG's and air pollutants; and whether current policies steer toward a lower overall level of these externalities. If oil heating can be substituted with a technology that has lower air pollutant emissions, and therefore also environmental and health impacts, the non-ETS emission targets would induce co-benefits. Otherwise the substitution would involve trade-offs between climatic, health and other environmental impacts.

Past research have suggested that climate and air pollutant policies can generally have synergies or co-benefits between them (Bollen et al., 2010; McCollum et al., 2013). More detailed analyses have, however, shown that this is not necessarily always the case. Åström et al. (2013) analyzed multiple low-CO_2 emission scenarios for Nordic countries and concluded that air pollution co-benefits did accrue only in some scenarios. Leinert et al. (2013) estimated that vehicle taxation based on CO_2 emissions would increase NO_x emissions in Ireland, creating a trade-off between the climate and air pollution impacts.

Air pollutant emissions and population exposure caused by residential wood combustion in Finland have been studied by Karvosenoja et al. (2011), who emphasized the large difference in emission-population exposure ratios between urban and rural areas. A later study (Karvosenoja et al., 2012) compared the health costs due to PM and the cost of CO_2 between pellet and light oil heating scenarios in Finland. Their conclusion was that in urban areas the health costs outweigh the benefits from CO_2 reductions, but in rural areas the CO_2 reduction benefit might be slightly higher.

This paper extends the scope of these earlier studies by evaluating the potential trade-offs between health, climate and acidification impacts due to the emissions of eight agents – $PM_{2.5}$, CO_2, CH_4, CO, NO_2, SO_2, black carbon (BC) and organic carbon (OC) – from a number of current and future household-level heating technologies that might substitute oil heating. The specific aims are to investigate whether the assessed technologies could reduce the health, climate and acidification impacts when compared to oil heating; and whether such technology switching could seem attractive from a policy or social-cost perspective.

A multi-criteria assessment is first used to quantify the possible trade-offs between the assessed impact categories. In order to estimate the desirability of these trade-offs, two approaches are used to value the impacts on a commensurate scale. First, the emissions of CO_2, NO_x, SO_2 and primary $PM_{2.5}$ are valued toward the marginal cost of meeting national GHG and air pollutant emission limits. Then, approximate estimates on some of the social costs – the climatic and health externalities of emissions – from each technology are presented. It is nevertheless worth to note that the selected coverage of social costs is not complete, and other important externalities relating to bioenergy and heating oil production – such as habitat protection or biodiversity – are not covered in our analysis.

After a sensitivity analysis on the main factors behind these valuations, the paper discusses a possible misalignment between marginal policy and social costs. An optimal policy would be such that equalizes the marginal costs and the marginal benefit from avoiding an externality. In an ideal setting, each emission limit is set in the way that the marginal cost of meeting a policy objective – in this case an emission limit – would equal the marginal externality cost to the society from the emission, and that this marginal policy cost would be passed on to the decision makers who choose between different technologies. The social cost associated with every technological option at hand would thus be included in the considerations of an individual decision maker, in addition to the technical costs, and a socially optimal technology choice should result. If, however, the emission limit is set incorrectly – so that the marginal policy cost does not equal the social costs – the incentives created by the emission limit can steer the decision maker toward a societally sub-optimal technology.

The paper is structured as follows. Section 2 presents the methodology behind the impact estimates; namely descriptions of the emission measurements for the assessed heating appliances, method for calculating the population exposure to PM, metrics used in estimating climate and acidification impacts, and the parameters for policy and social cost estimates. A multi-criteria assessment of the impacts is presented in the beginning of Section 3. This is followed by a valuation of the emissions against marginal policy costs and social costs, and a sensitivity analysis for the cost estimates and emission factors. Section 4 concludes and discusses the main insights from the results.

2. Methods

Emission data for household-level heating technologies were based on emission measurements conducted for six appliance categories: light fuel oil boilers; conventional, current and future batch-wise combustion; pellet or wood chip stoves; and gasification technology with pellets or wood chips. The emissions of multiple pollutants were expressed as mass emitted per GJ of fuel used. The measurement data was combined with $PM_{2.5}$ dispersion modeling as well as climate, acidification and health impact metrics per GJ of fuel used. The health impact is based on the population weighted exposure to primary $PM_{2.5}$ due to heating energy use that is distributed according to current spatial distribution of oil boilers. The measurements contain multiple emission types that cause climate and acidification impacts, and the overall impact will be described as CO_2 and SO_2 equivalent emissions, respectively. Further sections will describe the development of the emission data, the impact metrics and the multi-criteria approach in more detail.

This paper focuses on household-level, off-grid appliances, and excludes electric or district heating due to three reasons. First, the applicable emission factors for marginal electricity and heat production depend on intricate interactions in the whole energy system (Soimakallio et al., 2011), complicating the comparison of impacts between technologies. Second, the geographic availability