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Residential biomass burning is estimated to cause 29,000 premature deaths in Europe and North America annually. A number of studies show that existing regulations, primarily affecting *new* stoves, in the European Union and North America are effective in reducing emissions. However, it is not clear from these studies if there is a net welfare gain from regulation, nor how regulations should be designed in order to maximise the net welfare gain. We use an integrated assessment model to compare the net welfare gains of different schemes for regulating *existing* wood-burning stoves in Denmark. Most schemes we asses generate a net welfare gain, but a geographically differentiated tax on stove use generates the largest net gain. The results for Denmark suggest that there could be substantial welfare gains from imposing geographically differentiated regulation of *existing* residential wood-burning stoves in parts of North America and the EU.

Keywords: wood-burning stoves; particle emission; cost-benefit; regulation; integrated assessment

1. Introduction

Air pollution causes health problems and loss of life years due to premature death. Calculations of the health costs associated with air pollution for the European Union suggest that these costs are 3%–7% of GDP (European Commission 2013; WHO and OECD 2015). Particle emissions from residential biomass burning are an important part of the problem, resulting in an estimated 29,000 premature deaths in Europe and North America annually (Chafe *et al*. 2015). Because climate policies in many countries call for increased reliance on renewable energy sources, the role of biomass heating may increase in the future (Rajagopal and Zilberman 2008; Mitchell *et al*. 2017).

A substantial literature investigates wood burning stove technologies, emissions and the importance of user behaviour (e.g. Borrego *et al*. 2010; Gram-Hanssen 2010; Cerutti *et al*. 2015; Wöhler *et al*. 2017; Carvalho *et al*. 2018). Emission regulations in place today include eco-design standards and labels for wood-burning stoves in the European Union and technical emission limits for *new* installations in the United States of America, Canada and a number of European countries (Chafe *et al*. 2015). While a number of studies have demonstrated that such measures can be effective in

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reducing emissions and health costs (e.g. Levander and Bodin 2014; Yap and Garcia 2015; Giannadakil, Lelieveld, and Pozzer 2016) it is not clear from these studies if there is a net welfare gain to society from regulation, In addition, it is not clear how regulations should be designed in order to maximise the net welfare gain.

The purpose of our study is to investigate the potential net welfare gain of different types of regulation of *existing* wood-burning stoves. Thus we investigate the welfare gains from substantially more intrusive regulations than those typically used in Europe and North America today, which only apply to new installations. There is substantial geographical variation in the health costs inflicted by emissions (Brandt *et al*. 2001) and so there may also be welfare gains from designing regulation, which takes this variation into account. Therefore, we also analyze the geographical variation in the benefits and costs of regulation.

We do this using an integrated modelling framework for Denmark consisting of a health impact assessment model and an economic model simulating the reactions of owners of wood-burning stoves to regulation. The integrated modelling framework is used to calculate the costs and benefits of regulating air pollution from wood-burning stoves through either a ban on the most polluting stoves (corresponding to imposing technical emissions limits such as those typically used in North America and parts of Europe on all existing installations) or a tax on stove use, which is geographically differentiated according to the emission category of the stove and the geographically distributed external health costs of these emissions.

The core of the integrated modelling framework is the health impact assessment model system, EVA (Brandt *et al*. 2013a, 2013b). The EVA model system is based on the impact pathway methodology and includes the whole chain from emissions, atmospheric chemistry-transport models, human exposure, health impacts and economic valuation of the health impacts. The atmospheric chemistry transport model system consists of a coupling of a regional scale model covering the Northern Hemisphere and a high resolution ($1\,\text{km} \times 1\,\text{km}$) local scale model covering Denmark, where the contribution of emissions from wood-burning stoves to health impacts can be calculated. EVA is used to calculate the health benefits of imposing regulations that reduce emissions in different parts of Denmark. This type of integrated assessment model has been widely used to investigate the effects of various types of air pollution across the world (see e.g. UNEP WMO 2011; Brandt *et al*. 2012)

To calculate the impact of regulation it is important to take into account how users of wood-burning stoves react to the regulation. For example, if the emission limit is tightened, the user of an old polluting stove may choose to stop using a wood-burning stove in the future and instead rely on other types of energy for space heating (e.g. electricity). However, the user could also choose to buy a new less polluting stove. New stoves are generally more energy effective and therefore cheaper to operate than old stoves, which is likely to influence the future use of the new stove. We specify an economic model of stove use and replacement, which allows us to simulate user reactions to regulation in different areas of Denmark. The economic model also allows us to back out the utility costs for stove users implied by the reactions. The economic model also takes into account the differences in administrative costs of the applied regulatory schemes. This makes it possible to evaluate the net welfare gains to society of different regulatory schemes.

We find that both types of regulation of wood-burning stoves yield large net welfare gains. The highest gain is achieved by the differentiated tax on stove use, but a ban on all stoves with emission levels higher than eco-labeled stoves (Nordic Swan eco-label emission standard) also yields a substantial gain. Most of these gains derive from the regulation of stoves used in densely populated areas, where the related external health costs are the highest.

To our knowledge, this study is the first to integrate the modelling of emissions, atmospheric transport and chemical transformation, and the valuation of external health costs at a very high spatial resolution with an economic model simulating the behaviour of users of wood-burning stoves caused by the regulation. This integration makes it possible for us to simulate the effects of different regulation on the health costs caused by stove users and to estimate the welfare costs inflicted on stove users by these regulations. This ensures that the evaluation of both costs and benefits of a given regulation are conducted in an internally consistent way. Being the first integrated assessment of alternative regulatory design in this area, we believe our study makes a methodological contribution. We also hope that our results will be of interest to policy makers in Europe and North America who face regulation problems similar to the Danish regulation problem we study.

In the next section, we describe the integrated modelling framework for calculating the net social benefits of the different types of regulation. Section 3 describes the parameterisation of the model and the applied data. The results are presented in Section 4, while different sensitivity analyses are described in Section 5. The conclusion is presented in Section 6.

2. Integrated assessment of net social benefits from regulating wood-burning stoves

Many studies have demonstrated that high concentrations of air pollution, and especially fine particles, cause negative health effects and increase mortality (See, e.g. Anderson (2015), Lelieveld *et al*. (2015), Dominici, Greenstone, and Sunstein (2014) and Pope *et al*. (2002)). Particles from wood-burning stoves are one of the single largest Danish contributors to air pollution in Denmark, estimated to cause almost 400 premature deaths and health costs of over half a billion Euros annually (Brandt *et al*. 2016; Danish Economic Councils 2016).[1] Nevertheless, regulation of these emissions is currently limited.

In theory, a Pigouvian tax corresponding to the external costs of particles could internalise the external costs resulting from wood-burning stoves. However, this would require measuring the actual emissions of particles from each stove, which would be extremely costly. This may be part of the explanation as to why emissions from wood-burning stoves are generally not regulated. Instead, regulators both in the EU and in the USA have implemented and continually tightened emission standards (and labelling) for producers of new wood-burning stoves (Chafe *et al*. 2015). However, the impact of such regulations on emissions is very slow because the typical lifetime of a wood-burning stove is several decades. For example, 37% of all wood-burning stoves in Denmark were installed before 2008 and 17% before 1990 (Evald 2012 and Hansen 2015). To address this problem, authorities in many countries are considering also regulating *existing* stove installations, e.g. Germany has decided to phase out all stoves produced before 2010 over a 10-year period (Bundesgesetzblatt 2010).

However, the cost to stove users of using command-and-control regulation, such as bans, may potentially be very high, which is why more flexible types of regulation may be attractive. A tax on firewood has been considered in Denmark, but such a tax would give an incentive to burn non-wood materials, waste, and home-produced firewood of low quality, which may increase pollution. Instead, installing a temperature metre in the flue of each stove has been suggested (The Ecological Council 2014). This would not measure actual emissions, but would record the number of hours a stove is used, which would make it possible to tax the use of stoves. Such a tax could be differentiated according to local population density and the type of stove, so as to reflect more precisely the actual health costs associated with the use of the particular stove. The meter installation and administrative costs of such a tax are, on the other hand, substantial.

Thus regulators are faced with a dilemma. They must choose between, on the one hand, second-best tax schemes that may generate reasonably efficient incentives, but with extra administrative costs and, on the other hand, different types of bans that may be easy to implement, but may potentially impose substantially higher compliance costs on stove users. This makes empirical evaluation of the costs and benefits of different schemes the only way to ascertain whether regulation is warranted and which scheme maximises net social benefits. We do this using an integrated modelling framework consisting of the EVA health impact assessment model system and an economic model of stove investment and use. In the next subsection, we describe the EVA model system that simulates how emissions within a specific geographical grid cell affect monetarized health costs in all grid cells of the model. In the following two subsections, we describe the economic model that simulates stove users' reactions to regulation within each grid cell of the EVA model.

2.1. Modelling benefits of reduced emissions from wood-burning stoves

The EVA (Economic Valuation of Air pollution; Brandt *et al*. 2013a) model system is based on the impact pathway chain. EVA includes a model of geographical distribution of air pollution emissions (Plejdrup and Gyldenkaerne 2011; Plejdrup, Nielsen, and Brandt 2016), a multiscale integrated model system for atmosphere transport and chemistry and a human exposure and health effect model (Brandt *et al*. 2013a, 2013b; Geels *et al*. 2015).

The atmospheric models that calculate atmospheric transport and chemistry consist of a combination of a regional scale model and a local scale model. The regional scale model is the Danish Eulerian Hemispheric Model (DEHM), which covers the Northern Hemisphere and includes three nested domains over Europe, northern Europe and Denmark, with resolutions from 150×150 km for the domain covering the Northern Hemisphere, 50×50 km for the European domain, 16.7×16.7 km for the domain covering Northern Europe and down to 5.6×5.6 km resolution for the domain covering Denmark (Brandt *et al*. 2012). The local scale model used is the Urban Background Model (UBM), covering Denmark with a resolution of 1×1 km (Brandt *et al*. 2001, 2003). The multiscale integrated model system makes it possible to include the intercontinental and regional transport of air pollution, while maintaining a very high resolution over the area of interest (in this case Denmark). Furthermore, using this approach, geographical distributed changes in human exposure to air pollution resulting from a change in emissions originating from any given area in Europe or Denmark can be calculated. The high resolution model (UBM) is important when calculating the effects of changes in wood-burning stoves, because a large proportion of the effects resulting from this emission source are local.

The EVA model system used to calculate health effects is based on exposure-response functions found in the literature based on epidemiological studies and accepted by the World Health organisation (Brandt *et al*. 2013a). The resulting health effects are then monetarized via unit prizes for each health outcome, e.g. using estimates of the statistical value of lost life years for costs attributed to premature deaths. The EVA system includes 16 different health outcomes and, besides mortality due to short and long term exposure to ozone and atmospheric particles, respectively, the system also includes morbidity, such as cardio-vascular or respiratory hospitalisations, restricted activity days, asthma, bronchitis, lung cancer, etc. (see Brandt *et al*. 2013a for a full list).

In the high resolution modelling at 1×1 km resolution, the emission data, the air pollution modelling and the population density data are applied in the same grid and at the same high resolution. This allows us to calculate the total costs of emissions from wood-burning stoves depending on the location of the wood stoves with respect to population distribution and, thereby, the benefits of imposing regulations that reduce these emissions. In this paper, the calculation of the contribution of wood stoves to health impacts has been divided into six regions of Denmark and has been calculated as a function of different population densities in the four intervals <100, 100–1,500, 1,500–3,000 and $>3{,}000$ people/km^2.

2.2. Modelling private costs and stove users' reactions to regulation

The amount of particles emitted by wood-burning stoves depends on a number of factors, including the type of stove and how much the stove is used, while the geographical location (the grid cell in which the stove is placed) is critical for the health effects these emissions cause. To capture variation in these dimensions, the economic stove investment and use model mirrors the grid specification of the EVA model system. It consists of a number of stove using agents in each geographical grid cell, representing variation in preferences for stove use and the type of installed stove. Each of these agents is a specification of an agent model of a stove owner that can be parameterised for different preferences for stove use, and for different initially installed stove types. In this subsection, we explain the workings of this agent model and how it generates reactions to regulation and compliance costs. In the next subsection, we then explain how the economic stove investment and use model for Denmark is constructed using different specifications of the agent model and how this economic model and the EVA model system interact to generate consistent estimates of costs and benefits of regulation.

The integrated model is used to simulate the net social benefits of a differentiated tax on stove use, a ban on the most polluting (old) stoves and a total ban on the use of stoves. Depending on the type of regulation imposed, owners of wood-burning stoves may stop using the stove, reduce use of the stove or replace the stove with a newer one. For a given type of regulation, user reactions are modelled in two steps. First, we model the stove owner's investment response, then, conditional on this decision, we model the owner's stove use.

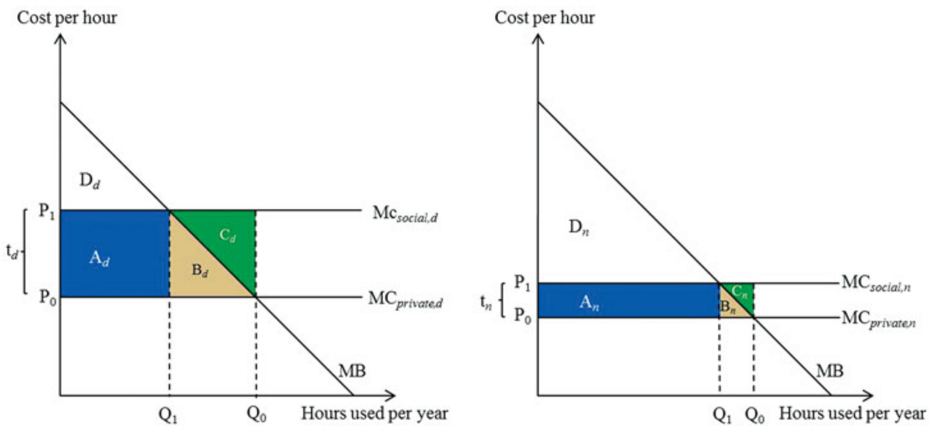

Figure 1. Illustration of the effect of a tax on an old and a new wood-burning stove.

To illustrate the agent model, assume that there are only two types of stoves. A new (n) and an old (d), where the old stove pollutes more than the new. Assuming that a tax on stove use is imposed, the owner has the following investment options:

- Buy new stove now: Replace the old stove with a new one just after implementation of the tax
- Stop using stove now: Stop using the stove (without replacing it with a new one)
- Buy new stove later: Keep the old stove for its remaining lifetime; then replace with a new one
- Stop using stove later: Keep the old stove for its remaining lifetime (without replacing it with a new one)

His investment choice is assumed to be the one that yields him the lowest reduction in his consumer surplus. The change in consumer surplus conditional on keeping the old stove and investing in a new stove respectively is illustrated in Figure 1, where the horizontal axes is the use of the stove (number of hours used) and the vertical axes is the marginal benefit of stove use. Here the marginal benefit curve (denoted MB) indicates benefit derived from the first hour of stove use ($x = 0$) and each additional hours of stove use. The value of the marginal benefit falls towards zero as stove use increases. The stove user will chose the level of stove use where the marginal benefit from an extra hour of stove use just equals the marginal cost of using the stove. P_0 and P_1 are the marginal cost of using the stove before and after the tax is imposed (t_d on the old stove and t_n on the new stove). The stove owner therefore choses stove use levels of Q_0 and Q_1, before and after the tax, respectively. New stoves are generally more effective than old stoves, so the private marginal cost of using a new stove is lower than it is for an old stove ($MC_{private,n} < MC_{private,d}$).

For a user of an old stove, the consumer surplus before the tax is equal to the area $A_d + B_d + D_d$, in Figure 1, because the optimal use level is Q_0 and no taxes are paid. After the tax is imposed, the consumer surplus is reduced to D_d because of tax payment and the reduction in optimal use to Q_1. Let us assume that there is a fixed cost (*f*) associated with the collection of the tax (cost of the metre plus administrative costs) and that the fixed cost is paid by users of stoves. In this case, the consumer surplus

Table 1. Characterisation of the choice of owners of old stoves.

Choice	Condition
Differentiated tax:	
Buy new stove now	$D_n - f - I_n > D_d - f$ and $D_n - f - I_n > 0$
Stop using stove now	$0 > D_n - f - I_n$ and $0 > D_d - f$
Buy new stove later[a]	$D_d - f > D_n - f - I_n > 0$
Stop using stove later[a]	$D_d - f > 0 > D_n - f - I_n$
Ban on old stoves:	
Buy new stove now	$D_n + A_n + B_n > I_n$
Stop using stove now	$D_n + A_n + B_n < I_n$

Note: [a]Here it is assumed that the user continues to use the old stove for its remaining lifespan and then either buys a new stove or stops using his wood-burning stove.

after tax is $D_d - f$. As noted above, the user may also consider buying a new stove instead of keeping the old one, but there is an investment cost (I_n). If the user chooses to buy a new stove, his consumer surplus (after investment and fixed administrative costs) is $D_n - f - I_n$. So the user will buy a new stove if $D_n - f - I_n$ is positive and $D_n - f - I_n > D_d - f$. Conditional on the investment decision, optimal use is, as already noted, reduced to Q_1 because the tax has increased marginal private use costs. Conditions for other choices by the owner of old stoves subject to a differentiated tax are indicated in the top half of Table 1. If the regulator bans old stoves instead of imposing a user tax, the stove owner can either buy a new stove or stop using a stove altogether. However, since stove use is not subject to tax, it is optimal for the owner to set this at Q_0 (rather than Q_1) if he invests in a new stove. The resulting conditions which the investment choice options leave open to him under a ban are shown in the lower half of Table 1.[2]

2.3. Costs and benefits of regulation

The social welfare effect of regulation depends on the choice made by the owners of stoves. Let us again consider a situation with the use tax where the user has an old stove. If the user of the stove decides to keep his old stove, he will reduce his use from Q_0 to Q_1 due to the tax t_d (see left side of Figure 1). For a stove user placed in a specific grid cell, the EVA model then estimates the health benefits (the reduction in health costs) that result from the reduction in emissions that this amount of use reduction for this particular stove type value causes. Assuming the tax rate is set equal to the marginal health costs of stove use (corresponding to the standard Pigouvian recommendation), the welfare gain from reduced air pollution is equal to $B_d + C_d$. The reduction in consumer surplus due to the tax is $A_d + B_d + f$, but A_d is the tax revenue, which should not be considered a loss from the point of view of society. When the tax revenue is ignored, the social net benefit is $C_d - f$.

It can be argued that the tax revenue collected through an externality correcting tax provides an additional benefit because it makes it possible to reduce other distortionary taxes (the so-called weak double dividend). The value to society of non-distortionary tax revenue is equal to the marginal costs of public funds (m). If this double dividend is included, the social net benefit becomes $C_d - f + m \cdot A_d$.[3]

Table 2. Social net benefit conditional on the choice of the owners of old stoves.

Choice	Social net benefit[a]
Differentiated tax:	
Buy new stove now	$C_d - D_d + D_n - I_n - f + m \cdot A_n$
Stop using stove now	$C_d - D_d$
Buy new stove later	$C_d - f + m \cdot A_d$
Stop using stove later	$C_d - f + m \cdot A_d$
Ban on old stove:	
Buy new stove now	$C_d - D_d + D_n - C_n - I_n$
Stop using stove now	$C_d - D_d$
Ban on all stoves:	
Stop using stove now	$C_d - D_d$

Note: [a]Note that the social net benefit should be interpreted as short run effects. For example, in the situation with the differentiated use tax, the owner of an old stove may choose to keep the old stove for its remaining life span and after that either buy a new stove ('buy new stove later') or stop using wood-burning stoves altogether ('stop using stove later'). The two situations obviously have different implications for welfare in the long-run.

If the owner of the old stove chooses to stop using his old stove (without replacing it with a new one), he experiences a loss in consumer surplus equal to $A_d + B_d + D_d$, but there is also a greater gain due to lower air pollution equal to $A_d + B_d + C_d$. The net benefit is, therefore, equal to $C_d - D_d$. The social net benefit in the situation where the owner decides to replace the old stove with a new one is calculated in the same way, except that the cost of the new stove (I_n) has to be deducted.

The social net benefits from a differentiated tax and a ban on old stoves conditional on the choice of the stove owner are summarised in Table 2. In the table, we have also included the social net benefit of a ban on all stoves. Here, the only option left to the owner is to stop use altogether.

We used Figure 1 to illustrate the choice and derived welfare effects of regulation for a given initial use level of an old stove (Q_0). However, there are substantial differences in preference for stove use across households, which are captured in our model by shifting the demand curve (MB curve) in Figure 1, which results in a corresponding shift in initial stove use Q_0. Clearly both D_d and D_n are affected and, potentially, so are the investment and use reactions of the stove owners and the social net benefit of the regulation (see Tables 1 and 2). For example, stove owners are more likely to stop using a stove after a tax has been introduced when their initial use of the stove is low (and therefore D_d and D_n are small). There are also important differences in the type of old stove that owners have. Very old stoves have higher marginal costs of use, which are captured in our agent model by shifting the cost curve up. These stoves also have higher emissions per hour of use, which would imply higher taxes under tax regulation. With these simple parameterizations of the agent model, we are able to capture the key dimensions of variation between stove users.

When simulating, we only take the direct effects from changes in stove use into account. Therefore, we assume that these regulations do not have any indirect effects on health benefits. Such effects could, for example, result if regulations that reduce the use of wood-burning stoves also induce greater use of other types of heating which are associated with unregulated external health costs. While regulation of wood burning stoves will probably result in increased use of other types of heating, all the likely substitutes are tightly regulated in Denmark. Although we cannot be certain that these are actually regulated at the optimal level so that there are no remaining indirect external effects, it seems likely that any remaining indirect external effects are small. It is, however, important to stress that if our evaluation framework were to be applied in another setting, where important substitute heating sources are not regulated at close to the optimal level, it would be important to take indirect external effects through substitution into account. We also assume that there is no second-hand market for wood-burning stoves when simulating.[4] While this is a reasonable approximation in the Danish context, it may not be the case in other settings.

3. Model solution, parameterisation and data

In principal, our framework includes agent models that represent stove users covering the relevant span of preference variation and types of old stoves for each grid cell in the EVA system. To facilitate model solution and simulation, all grid cells have been grouped into 24 grid cell types, each of which is represented by one set of agent models. Table 3 summarises the levels/categories of the three dimensions over which our agent models vary.

The EVA model system was run for the year 2013 based on meteorological data and emission data for the same year. Geographically distributed population data were entered for the year 2008 and scaled with the total population between the years 2008 and 2013 to represent the year 2013. The value of life years lost (1.3 million DKK) is derived from a value of statistical life at 31 million DKK, which is the mean of three

Table 3. Number of levels of external cost, use of stoves and emission categories of the stoves.

External health cost	Health cost in Denmark of emission of particles in 24 different emission areas. The 24 areas are defined using combinations of the 6 different regions in Denmark and population density in each region (0–100, 100–1,500, 1,500–3,000 and more than 3,000 inhabitants per km^2).
Use of stoves	First a distinction is made between type of user according to location of dwelling and dwelling type: • Urban user • Rural user • Holiday cottage (also in rural areas) For each type of user/dwelling, we then distinguish between 10 different levels of use. Altogether, this yields 30 different use levels.
Emission categories of wood-burning stoves	We have data (Evald 2012 and Hansen 2015) to distinguish between the number and geographical distribution of 5 categories of wood-burning stove (emission levels described in Table 4) • Before 1990 • 1990–2008 • 2008–2015 (not eco-labeled) • Eco-labeled[a] emission standard 2008–2015 • Eco-labeled[a] emission standard revised 2015[b]

Notes: [a]The Nordic Swan ecolabel used in Scandinavia; [b]According to the Danish Association of Biomass stoves Industry (DAPO), almost all wood-burning stoves sold from 2015 have emission levels within the levels necessary to obtain the Nordic eco-label. Therefore, there is no category for non-ecolabeled stoves from 2015.

Table 4. Emissions for different categories of wood-burning stoves (g $PM_{2.5}$ per GJ).

Stove year/type	g $PM_{2.5}$ per GJ
Before 1990	930
1990–2008	740
2008–2015 (not eco-labeled)	514
Eco-labeled standard 2008–2015	206
Eco-labeled standard revised 2015	155

Source: Nielsen *et al*. (2015) and supplement information from the Danish Centre for Environment and Energy (DCE).

Table 5. Overview of central data and parameters in baseline calculations.

Data/parameter	Size	Remarks and Source
Marginal private cost	EUR 0.45–0.53 per hour	Cost of firewood per hour depending on the energy efficiency of each emission category of stove.
Distribution of annual use of wood-burning stoves before regulation (Q_0)	0–3,277 hours per year	Two national surveys of the use of wood-burning stoves in 2011 and 2013 were pooled (Evald 2012 and Hansen 2015). The use of stoves was divided into three dwelling locations/types: Urban areas, rural areas and holiday cottages. From the distribution of use for each of these categories, the average number of hours of use for each decile was calculated (yielding 30 use levels altogether).
Number and distribution of wood-burning stoves	750,000 stoves in Denmark	The aggregate number of stoves and its distribution according to the five emission categories of stoves, dwelling location (urban, rural and holiday cottages) and the 24 different geographical emission areas (see Table 3). Based on the same data sources and assumptions which are applied in the annual emission inventories to UNECE (Nielsen *et al*. 2015).
Demand curve assumed linear with slope:	–0.0007	Same slope assumed for all 30 different initial use levels (see Table 3). The slope parameter corresponds to an average own price elasticity of –0.9 which is found for fire wood in a Norwegian study (Halvorsen, Larsen, and Nesbakken 2010).
Annual cost of temperature metre (*f*)	EUR 67 per year	Rough estimate of the annualized production costs of a metre and the annual administrative cost associated with collecting the tax (DKK 500 equal to EU 67). Estimate based on information from producers of measurement equipment and cost estimate of administration of electricity metre readings.
Annual cost of new stove (I_n)	EUR 86 per year	Based on a cost of €1,300 for a new stove, which is assumed to last 25 years (discount factor of 4%).
Marginal cost of public funds (*m*)	0.20	Recommended value for use in social cost-benefit analysis from the Danish Ministry of Finance.

Note: In general, it is assumed that the size of wood-burning stoves corresponds to a capacity of 5 kW.

Danish studies (Kidholm 1995; Gyrd-Hansen, Kjaer, and Nielsen 2016; Traaholt, Kjeldsen, and Navrud 2016).[5]

Emissions from 'standard' use of new stoves are considerably lower than for old stoves. For example, emissions from an old stove produced before 1990 are six times higher than emissions from a new eco-labelled stove (See Table 4).[6] We use these values as the best available estimate of mean emissions from use of this type of stove in our simulations.

Other core parameters, data and assumptions underlying the simulation model are summarised in Table 5. A number of these have a rather weak empirical foundation, so we present extensive sensitivity analyses after the results section.

The variation in use, type, location and age of wood-burning stoves across Danish households is estimated from two surveys from 2011 and 2013 (Evald 2012 and Hansen 2015). The surveys reveal that stoves located in dwellings in rural areas are used more than stoves in dwellings in urban areas or stoves in holiday cottages. The survey data did not indicate any pronounced correlation between the emission category of stove and use. Therefore, these dimensions are assumed to be independent in our simulation model.

The demand function is assumed to be linear and parameterised to achieve an own price elasticity of -0.9 for the average use level, which is consistent with a recent empirical study from Norway by Halvorsen, Larsen, and Nesbakken (2010). Despite the fact that heating is a necessity good in a cold country like Denmark, a relative high price elasticity is to be expected, because close substitutes (electricity, oil, gas, heat pumps and so forth) are readily available in most dwellings in Denmark. Because the shape and slope of the demand curve is critical for our welfare evaluations, we carry out a number of sensitivity analyses with alternative slopes and functional forms.

4. Results

An important intermediate result from the EVA model system on which the policy evaluations are based is illustrated in Figure 2. This is a map of Denmark where the colour of each grid cell covered by the EVA model indicates the calculated health costs of emitting one kg of particles ($PM_{2.5}$) from that grid cell. Not surprisingly, the health costs of emitting particles are highest in, and close to, Copenhagen and other large cities in Denmark.

Based on these results, the external health costs that result from the use of different categories of stoves for each of the different areas in Figure 2 can be estimated. To illustrate the variation in these costs, Table 6 presents the external health costs resulting from one hour of stove use in the areas with the highest and lowest health costs of emissions, respectively, and for the most and least polluting stove categories. There is clearly substantial variation in external costs. It is worth noting that the external costs are substantial and, in some areas, many times larger than the cost of firewood, which in Denmark is about EUR 0.5 per hour (see Table 5).

Before presenting the aggregated welfare effects of imposing various regulations, we present the simulated responses of a few specific stove owner types and the simulated welfare contributions generated by the different regulations. We consider stove owners in two localities (Copenhagen and Bornholm with the highest and lowest external health costs respectively) with two intensities of use (100 and 1,000 hours per year) and with different stove emission categories. Table 7 presents the simulated contribution to annual social net benefits if the indicated regulation was applied to the stove owner. The simulated behavioural response of the stove owner is indicated in brackets.

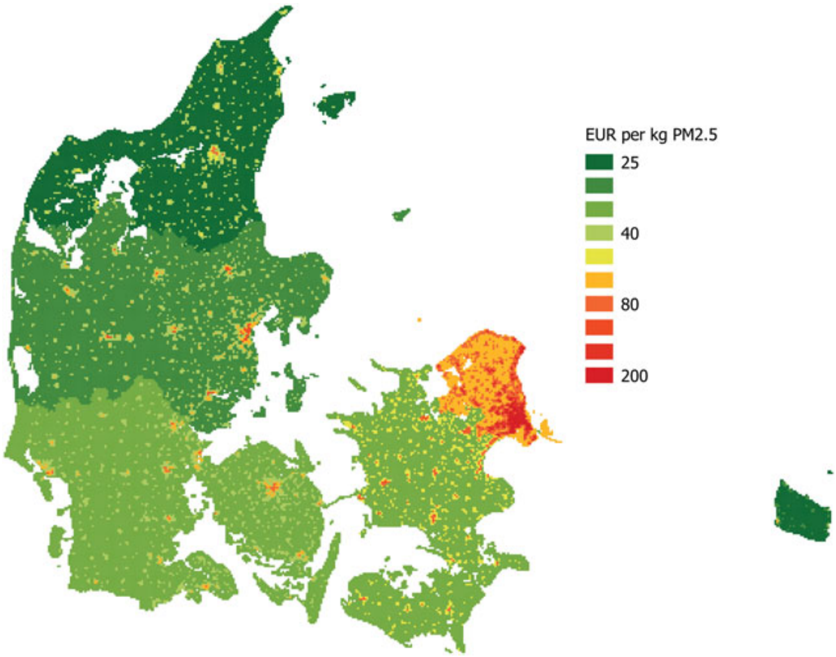

Figure 2. Health cost per kg emitted PM2.5 according to location of emissions in six regions in Denmark. Each region is divided into four different population densities.
Note: Health costs in Denmark for 24 different areas of emissions. The 24 areas were defined using combinations of 6 different regions in Denmark and the population density in each region (0–100, 100–1,500, 1,500–3,000 and more than 3,000 inhabitants per km^2). Note that an area according to this definition may consist of a number of unconnected smaller areas within each region. The calculation of the health costs is based on the EVA model (See Section 2).

The results show a larger net social gain of regulation when the stove is old, when it is used in a densely populated area, such as Copenhagen, and when it is used many hours each year. The behavioural differences between regulation schemes can be seen in Copenhagen. A high-use stove owner in Copenhagen responds to a ban by buying a new stove, but stops using a stove if a tax is imposed. This is because the tax in Copenhagen is so high that it becomes too expensive to invest in a new stove, even though the tax is lower compared to the tax on the old stove.

To simulate the aggregate welfare effects of regulation, calculations of this type are carried out for all 24 regions and for all 30 use levels of wood-burning stoves and then aggregated. Table 8 presents the aggregated annual social net benefits of the

Table 6. External health costs from standard use of wood-burning stove.

	Copenhagen[a]	Bornholm[a]
	EUR per hour use	
Stove from before 1990	5.5	0.7
New eco-labeled stove (revised 2015-standard)	0.9	0.1

Note: Calculated for a stove size corresponding to 5 kW (a typical stove size in Denmark).
[a]The parts of Copenhagen with a population density above 3,000 inhabitants per km^2 and the parts of Bornholm with a population density below 100 inhabitants per km^2. Bornholm is the island on the far right of the map in Figure 2.

Table 7. Examples of annual social net benefits per stove.

Area and stove emission category	Initial consumption	Social net benefit (choice of stove owner) Tax	Ban on old stoves
Copenhagen[a]	Hours per year	EUR 1,000 per year	
Before 1990	1,000	5.2 (Stop using)	4.5 (Buy new)
1990–2008	1,000	3.6 (Stop using)	3.0 (Buy new)
2008–2015	1,000	2.2 (Stop using)	1.6 (Buy new)
Nordic eco-label 2008–2015	1,000	0.7 (Stop using)	0.0 (Buy new)
Before 1990	100	0.5 (Stop using)	0.5 (Stop using)
1990–2008	100	0.4 (Stop using)	0.4 (Stop using)
2008–2015	100	0.3 (Stop using)	0.3 (Stop using)
Nordic eco-label 2008–2015	100	0.1 (Stop using)	0.1 (Stop using)
Bornholm[b]			
Before 1990	1,000	0.5 (Buy new)	0.6 (Buy new)
1990–2008	1,000	0.3 (Buy new)	0.4 (Buy new)
2008–2015	1,000	0.1 (Buy new)	0.1 (Buy new)
Nordic eco-label 2008–2015	1,000	−0.0 (Keep stove)	−0.1 (Buy new)
Before 1990	100	0.1 (Stop using)	0.1 (Stop using)
1990–2008	100	0.0 (Stop using)	0.0 (Stop using)
2008–2015	100	0.0 (Stop using)	0.0 (Stop using)
Nordic eco-label 2008–2015	100	0.0 (Stop using)	0.0 (Stop using)

Note: The table shows examples of the stove owners' choice (in brackets) and the annual social net benefits per regulated stove depending on the type of regulation, stove emission category, geographical location of stove and level of stove use.
[a]All parts of Greater Copenhagen, where the population density is above 3.000 per km^2 (highest health cost per emitted kg of $PM_{2.5}$ in Denmark).
[b]All parts of the island of Bornholm, where the population density is below 100 per km^2 (lowest health costs per emitted kg of $PM_{2.5}$ in Denmark).

different types of regulations for Denmark. We find a positive social net benefit with all examined types of regulation. The social net benefit is highest with the tax scheme, but a ban on all stoves that do not comply with emission standards for eco-labelled stoves from 2008–2015 is a close runner up. The net gain of both these schemes is approximately EUR 0.4 billion per year. In comparison, the external health costs without regulation are EUR 0.54 billion per year. Only banning the oldest emission category of stoves (from before 1990) yields a substantially smaller social net benefit of about EUR 0.14 billion per year.

Table 8. Aggregated annual net social benefit of different types of regulation.

	Regulated type of stoves	Aggregated annual net social benefit Denmark	Only urban areas
		EUR bn per year	
Tax	All	0.41	0.32
Banning	Before 1990	0.14	0.11
Banning	Before 2008	0.33	0.25
Banning	All without nordic eco-label	0.38	0.28
Total ban	All	0.25	0.24

Note: In 2013 prices. Urban areas defined as where population density exceeds 100 per km^2.

Table 9. Predicted change in number of premature deaths, total health costs and number of wood-burning stoves.

	Stove category regulated	Total health costs	Premature deaths	No. of stoves
		DKK bill per year	Per year	1,000
No regulation		0.54	391	750
Tax	All	0.07	54	268
Ban of stoves:	Before 1990	0.40	277	688
Ban of stoves:	Before 2008	0.20	114	574
Ban of stoves:	Without eco-label	0.15	70	527
Total ban	All	0	0	0

Note: In 2013 prices. Lost life years are on average 86% of the total health costs. Each premature death due to air pollution corresponds to around 10 lost life years; see Watkiss, Pye, and Holland (2005) and Brandt et al. (2013a).

If the regulation is only implemented in urban areas where the external costs are generally the highest, the annual net social gain with the tax is EUR 0.32 billion. This illustrates that most of the benefits derive from emission reductions in urban areas.

The impacts of the different regulation schemes on predicted external health costs, premature deaths and the number of wood-burning stoves remaining in service are summarised in Table 9. We find that the number of wood-burning stoves after regulation is lowest when the external costs are internalised with a use tax.

5. Sensitivity analyses and discussion

In Table 10, we present the results of a few key sensitivity variations to indicate the robustness of our welfare ranking of alternative regulatory schemes.

Sensitivity to the assumed slope and shape of the demand curves is illuminated in the first three columns after the baseline results: column 2) the slope is reduced by 50%, column 3) the slope doubled and column 4) a constant own price elasticity functional form is used (at an elasticity equal to –0.9). All have modest impact on the overall welfare effect, except in the situation where there is a total ban on the use of all types of wood-burning stoves. The ranking of the other regulation schemes and the overall finding of a substantial welfare gain from regulation is unaffected.

Table 10. Sensitivity analyses for aggregated annual net social benefit.

		Aggregated annual net social benefit					
	Stove category regulated	Base	Half slope	Double slope	Constant elasticity	$m = 0$	$f =$ EUR 134
		DKK billions per year					
Tax	All	0.41	0.44	0.39	0.41	0.40	0.39
Ban	Before 1990	0.14	0.15	0.14	0.14	0.14	0.14
Ban	Before 2008	0.33	0.34	0.33	0.32	0.33	0.33
Ban	No eco-label	0.38	0.38	0.37	0.36	0.38	0.38
Ban	All stoves	0.25	0.40	−0.05	0.38	0.25	0.25

The last two columns illustrate the importance of the assumed marginal cost of public funds and the assumed administrative costs of tax collection. Both of these could be critical for our baseline finding that the largest gain from regulation is achieved through a tax scheme. In column 5, we set the double dividend benefit from collecting tax revenue to zero ($m = 0$).[7] In column 6, the fixed cost of collecting the tax on stove use is doubled ($f = 134$). Again the ranking of regulation schemes and the overall finding of a substantial welfare gain from regulation is unaffected.[8] It is, however, notable that the general ban on non-ecolabeled stoves achieves a welfare benefit of over 90% of that achieved by the tax scheme in all alternatives. Even though the different sensitivity analyses suggest that the main conclusions are robust, it should be noted that other factors could result in generally reduced or increased stove ownership and use in the future.

When evaluating the scale of the calculated benefits from regulation, it is important to stress that while we include the external costs of particle emissions in health costs, particles also have negative effects on the environment, which are not included. For example, black carbon components of particles increase global warming. Furthermore, the calculations only included health impacts from emissions of primary particles and the formation of secondary inorganic particles (nitrate, sulphate and ammonium particles) from emissions of the gases nitrogen-oxides (NO_x) and sulfur-dioxide (SO_2). The formation of secondary organic aerosols from emissions of volatile organic compounds was not included, since knowledge is presently lacking on the formation rates of the secondary organic particles.

6. Summary and conclusion

Air pollution has substantial health costs. Residential wood-burning stoves result in emissions which make a surprisingly large contribution to total air pollution-related health costs. In this article, we present the results from an integrated assessment of the net social benefit of different schemes for regulating *existing* wood-burning stoves in Denmark. We find that there are large net welfare gains from most types of regulation of existing instillations, but the largest gains result from imposing a differentiated tax or a general ban on non-ecolabeled stoves. The gains mainly derive from the regulation of wood-burning stoves located in urban areas. Thus supplementing the existing regulation of new installations, with regulation of existing installations would result in a significant welfare improvement in Denmark. We find it likely that this would also be welfare improving in many other parts of Europe and North America where regulations are currently primarily aimed at new installations.

Our results are based on a high resolution air pollution emission inventory and an atmospheric dispersion and exposure model combined with an economic model that takes location, stove type and variation in preferences into account when simulating both stove investment and use behaviour. While baseline uncertainty is substantial, our integrated assessment model allows us to investigate the sensitivity of the welfare ranking of different regulations to key parameter assumptions. Our sensitivity analyses suggest that the welfare ranking is robust. Furthermore, there are environmental and secondary aerosol health benefits from reducing use of wood-burning stoves that are not captured by our model. This suggests that the simulated welfare benefits from introducing the regulation schemes we investigate underestimate rather than overestimate the true benefits.

One area where future research could contribute to better assessments is through studies of stove owner demand response to taxation and other regulatory instruments. While the instrument ranking we find appears to be robust to changes in response estimates, these are critical for the absolute size of net-benefit assessments.

Notes

1. In Europe, emissions of air pollution are typically calculated for 10 different SNAP sectors (Standard Nomenclature for Air Pollution). In Denmark, emissions of primary particles from wood-burning stoves account for 72 percent of all primary particle emissions from SNAP2 (Non-industrial combustion plants, including private wood combustion). The total number of premature deaths in Denmark derived from SNAP2 is 540.
2. Note that with a ban on an old stove instead the user does not have to pay a fixed cost (f) for administering the tax.
3. The marginal cost of public funds is often included in social cost-benefit analyses. However, it has also been argued that the marginal cost of public funds should not be included in such analyses (See, e.g. Kreiner and Verdelin 2012). Therefore, a sensitivity analysis with $m = 0$ is presented in Section 5.
4. In effect, we assume that owners who decide to replace an old stove can only choose a new stove with the lowest emission level (eco-label standard revised in 2015). In Denmark, there is an effectively enforced ban on reinstalling old wood-burning stoves and, therefore, the second-hand market for wood-burning stoves can be disregarded.
5. The value of statistical life in the three studies ranges from 27 to 35 million DKK. The mean value is close to the value found for countries with the same GDP level as in Denmark, in the comprehensive meta-analysis of values of statistical life in OECD (2012). The value of 31 million DKK has recently been adopted as the "official" value of a statistical life recommended by the ministry of finance for use in cost benefit analysis in Denmark.
6. These improvements reflect the fact that new emission regulation standards were adopted in 1990, 2008 and 2015. Note that the quality of wood and the way the stove is used affect emissions. Improper use of the stove may increase emissions substantially above the standard use emission values shown in table 4. However, studies have also shown that there is lower variation in emissions due to incorrect use of a new stove compared to an old stove (Nielsen *et al*. 2010).
7. Some studies have suggested that the marginal cost of public funds should not be included in social cost benefit analysis, see e.g. Kreiner and Verdelin (2012).
8. We have conducted a number of other sensitivity analyses, including variation of the external health cost and the cost of buying a new wood-burning stove (I_n), all of which indicate substantial gains from regulation and that either taxes or, in a few cases, a ban on non-ecolabeled stoves maximizes this benefit.

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No potential conflict of interest was reported by the authors.

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