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ORIGINAL ARTICLE

Minimum energy performance standards for the 1.5 °C target: an effective complement to carbon pricing

Jonas Sonnenschein · Robert Van Buskirk · Jessika Luth Richter · Carl Dalhammar

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Abstract Radical energy efficiency improvements are needed to keep global warming within 1.5 °C until the end of the century. Minimum energy performance standards (MEPS) are a widely applied policy instrument to improve the energy efficiency of appliances and reduce CO_2 emissions, but they are criticized as redundant if an overarching carbon pricing scheme is in place. In order to better understand how MEPS could play a more effective role in reaching the 1.5 °C target, life cycle costs (LCC) for four home appliances were modelled considering a cost for emitting CO_2. First, a significant social cost of carbon was introduced in a LCC optimisation model and it was found that a modest tightening of MEPS is sufficient to account for the climate externality. Second, more stringent MEPS were modelled and it was found that the switching prices needed to incentivize a shift up one or two efficiency classes were far higher than current carbon prices. These results have several implications for climate policy towards the 1.5 °C target. MEPS can easily internalize the climate externality and have the advantage over carbon pricing that policy makers can be certain that consumers actually move to more efficient appliances. While stringent MEPS do not appear to be economically efficient on the short-run, they are likely cost-effective in long-run 1.5 °C-consistent scenarios.

Keywords MEPS · Carbon pricing · Social cost of carbon · Life cycle costs · Appliances · 1.5 °C target

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J. Sonnenschein (✉) · J. L. Richter · C. Dalhammar
IIIEE, Lund University, PO Box 196, 22100 Lund, Sweden
e-mail: jonas.sonnenschein@iiiee.lu.se

R. Van Buskirk
Enervee, 2100 Abbot Kinney Blvd, Venice, CA 90291, USA

Introduction

Energy efficiency improvements are crucial for limiting global warming to 1.5 °C by 2100, which is the aspirational target of the Paris Agreement (United Nations, 2015). A review of 1.5 °C-consistent scenarios found that 'returning warming to below 1.5°C by 2100 becomes infeasible if final energy demand is not kept to very low levels' (Rogelj et al., 2015a, p. 526). Despite economic and population growth, global final energy consumption has to be roughly kept at the current level of about 8 Gtoe/year to maintain chances to stabilize global warming at 1.5 °C by the end of the century (Akimoto et al. 2017). In contrast, scenarios with significantly increasing energy demand are not compatible with reaching the 1.5 °C target (Rogelj et al., 2015b). Moreover, high-energy demand scenarios are associated with high total mitigation costs (Bertram et al., 2015a; Rogelj et al., 2016).

A large and rapidly growing area of energy consumption is home appliances (Cabeza et al. 2014). Market forecasts indicate annual growth rates of the market for home appliances of 6% until 2022 (Oristep Consulting, 2017) and growth in the sales of white good units from

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640 million in 2016 to 850 million in 2021 (Kithany et al., 2017). If materialized, such growth is not compatible with 1.5 °C-consistent scenarios unless significant improvements in energy efficiency are realized. Current appliances vary largely with respect to their energy efficiency, with the best available technology (BAT) often being 30–50% more efficient than what regulatory standards require (Lucon et al., 2014). By cutting off the worst performing appliances and targeting BATs, there is potential to reduce global annual CO_2 emissions by 13% in 2030 (Letschert et al., 2013, p. 80), thereby making a significant contribution to achieving the 1.5 °C target.

Minimum energy performance standards (MEPS) are a central policy instrument to promote energy efficiency in home appliances by banning the worst-performing appliances from the market, thereby forcing manufacturers into innovation and consumers into the adoption of more energy-efficient technology (Sachs, 2012; Siderius, 2014). For the EU, MEPS set under the overarching Ecodesign Directive are estimated to deliver 991 TWh of energy savings in the residential sector alone by 2020 (VHK 2016). In 2010, the products covered by the Directive were responsible for 1955 Mt CO_2e of GHG emissions, 41% of the total EU-28 emissions (VHK 2016). In 2030, the emission reduction for the average product is estimated to be 30% vs. business as usual, implying a reduction of approximately 11% of the EU total GHG emissions (VHK 2016). This abatement potential is remarkable when considering that MEPS are not primarily climate policy instruments. While the EU's standard setting process includes life cycle analysis (LCA), and thus considers climate aspects, the analytical determination of MEPS is generally made by determining which efficiency requirement leads to an overall minimum life cycle cost (LCC) for end users (EU 2009, Article 15). LCC includes purchase price and running costs, but climate externalities are generally not included.[1]

In order to account for the role that MEPS could play in reaching the 1.5 °C target, one approach is to consider these climate externalities—the so-called social cost of carbon (SCC)—in LCC modelling of home appliances. Similarly, the shadow price of carbon associated with 1.5 °C-consistent climate mitigation scenarios could also be considered in LCC modelling. From a methodological perspective, the integration of shadow prices in LCC modelling is equivalent to the integration of SCC. In this study, mainly the term SCC is used, but differences to shadow carbon prices are noted whenever relevant. Accordingly, the first objective of this study was to show how SCC can be integrated into LCC modelling of home appliances and to present the potential implications for setting MEPS. For this purpose, the LCC optima with and without SCC were identified for four different home appliances (refrigerators, dishwashers, tumble dryers and televisions) across different energy efficiency classes.

The role of MEPS in the climate policy mix is controversial. Despite the existing track-record of MEPS around the world (Molenbroek et al. 2015), putting a price on carbon through taxes and emission trading schemes (ETS) has been argued as the first-choice policy to deliver cost-effective abatement and innovation incentives by internalising climate externalities (Aldy and Stavins 2012; Goulder and Parry 2008). The overlap of MEPS and emissions trading schemes has been argued to be economically inefficient, as emissions are not abated where the market finds it cheapest but where mandated by policy makers (Böhringer et al. 2016). That said, there is evidence suggesting that efficient home appliances are among the cheapest abatement options (Hood 2013; Wada et al. 2012), but this abatement potential has been underutilized so far, indicating market failures and behavioural anomalies (Gerarden et al. 2017; Gillingham and Palmer 2014). MEPS, in turn, have been argued to address several of these failures (Houde and Spurlock 2016; Schleich et al. 2016), which may even increase the overall economic efficiency of emissions abatement by ensuring that the low-cost abatement potential in this area is utilized (Hood 2013).

The cost-effectiveness of policies targeted at home appliances can be assessed by looking at their marginal abatement costs in comparison to other low-carbon energy technologies. In the context of technology pathways for ambitious climate change mitigation, such as the 1.5 °C target, specific 'switching prices' have been calculated, i.e. the carbon prices required to incentivize a shift towards low-carbon energy supply technologies, such as renewable energy or carbon capture and storage technology (IEA 2016a; Stiglitz et al. 2017). While on the demand side there seems to be general evidence for low abatement costs of energy efficiency technology, in the case of home appliances, evidence for *specific* switching prices is lacking. Thus, the second objective of this study

[1] Indirectly, climate aspects might be partly considered via existing carbon pricing instruments.

was to investigate the switching prices that correspond in their incentive effect to stringent MEPS. For this purpose, carbon prices were estimated that would be needed to make the LCC of less efficient, but cheaper, appliances on the market at least as high as the LCC of more efficient and more expensive appliances. This would then be the minimum requirement for consumers who fully consider LCC in their purchase decision to switch to a higher efficiency class.

The empirical case that was used to address the two research objectives was the UK market for home appliances in 2016. While the analysis was focused on the UK, the sensitivity of results was tested with respect to key factors that may differ in other countries, including the CO_2 emissions factor of the electricity mix and the electricity price, making the results applicable in different contexts. The results of this empirical study have implications for designing ambitious MEPS as part of a deep decarbonisation policy mix consistent with 1.5 °C warming by 2100.

The article is structured as follows. First, previous research on SCC is introduced and the method that was used to model the LCC of appliances is described. Second, quantitative results of LCC modelling with and without SCC are presented. Special attention is given to the robustness of these results regarding changes in key assumptions. Third, the methodological novelty and limitations are discussed. Finally, implications for 1.5 °C-consistent energy efficiency policy are highlighted.

Research design and methods[2]

Estimations of the social cost of carbon and shadow carbon prices in 1.5 °C scenarios

In theory, an efficient carbon price takes into consideration estimates of damages from climate change in the form of an SCC and marginal emission abatement costs (MAC). As long as the MAC does not exceed the SCC, further abatement efforts should be undertaken, as they are beneficial from a societal perspective (Aldy and Stavins 2012). However, estimating the costs and benefits of climate change mitigation involves many uncertainties and assumptions (Arent et al. 2014; Nordhaus 2007; Schelling 1992; Stern 2007). With respect to electric home appliances, carbon prices increase LCC by pricing the carbon content of fuels used in generating the electricity that is used by the appliances. In turn, the SCC reflects the social costs of CO_2 emissions associated with the use of electric appliances.

Estimates for the SCC vary from one digit values (in USD) per ton CO_2 (Tol 2005) to several hundred (Moore and Diaz 2015) and even over a thousand (Ackerman and Stanton 2012). The central US Government SCC estimate is 43 USD/tCO_2 in 2020, assuming a social discount rate of 3% (Revesz et al. 2014). Prior to 2009, the UK Government used an SCC estimate of USD 83, based on the Stern Report (Stern 2007). At the top of the spectrum, Sweden bases several of its policies on a SCC estimate of more than USD 130 (Trafikverket 2016). While much research needs to be done on the SCC (Burke et al. 2016), a range up to 150 USD/tCO_2 covers most of the current estimates.

Recent energy-economy modelling suggests, on the other hand, that the global shadow price for carbon in 2030 centres around 100 USD/tCO_2e in scenarios consistent with the 2 °C target (Clarke et al. 2014; Guivarch and Rogelj 2017) and 200–300 USD/tCO_2e in 1.5 °C scenarios (Rogelj et al., 2015a). While SCC reflects costs associated with climate change, these shadow prices indicate mitigation costs. It is important to note that shadow prices can represent various actual policy instruments, including carbon taxes and ETS, but among others also technological regulations, mandates or subsidies, which are all associated with different implicit carbon prices (Guivarch and Rogelj, 2017).

UK appliance market data

The appliance data that were used in LCC modelling (incl. appliance price, electricity use, product features, efficiency rating) stem from online marketplaces for energy-efficient appliances[3] and reflect the market offering in the UK in 2016. Table 1 provides an overview of this data, comparing it with actual sales data for products in the respective categories in the EU. Note that the sales breakdown for the UK may well be different than for the EU and that sales might have shifted between 2013 and 2016.

[2] A spreadsheet with data and analysis is available in the supplementary material of the online version of this article.

[3] Enervee market, https://enervee.com/ and http://www.johnlewis.com/ in the UK.

Table 1 Description of the dataset by appliance type and efficiency class, including sales shares in EU for latest available years

Appliance (current MEPS)	*n* =		A+++	A++	A+	A	B	C
Refrigerators (A+)	978	Number of models	37 (4%)	317 (32%)	624 (64%)	0 (0%)		
		% sales in EU 2015	5%	25%	68%	2%		
Dishwashers (A+)[a]	358	Number of models	54 (15%)	89 (25%)	184 (51%)	31 (9%)		
		% sales in EU 2013	3%	23%	35%	38%		
Tumble dryers (B)[b]	148	Number of models	4 (3%)	49 (33%)	13 (9%)	0 (0%)	63 (43%)	19 (13%)
		% sales in EU 2015	4%	28%	14%	1%	33%	19%
Televisions (D)[c]	189	Number of models	0 (0%)	2 (1%)	79 (42%)	89 (47%)	19 (13%)	0 (0%)
		% sales in EU 2013	0%	1%	23%	45%	13%	3%

[a] In Fig. 2 we graph only models with 12 place settings as 82% of models sold in the EU in 2009 were 12 place settings (European Commission 2010). The category with a capacity of 12 place settings includes 57 models in the Enervee dataset

[b] Class C includes slim models. In Fig. 2 we graph only models with 8kg capacity (the median size) with 60 models in that category

[c] 16% of sales were of unknown energy class

Source: Michel et al. (2013, 2016); VHK et al. (2014)

Adjusting product prices and energy efficiency to product characteristics

Before starting the actual LCC modelling, the market data regarding appliance price and annual unit energy consumption (UEC) had to be prepared for analysis in order to separate the effect of efficiency from the effects appliance size and other product features have on price and UEC. For that purpose, a regression analysis was performed independently for price and UEC (Van Buskirk et al., 2014—supplement). Fixing product attributes to their average market value and then evaluating the regression function results for both price and UEC as a function of efficiency level provides the price vs. UEC relationship, factoring out the influence of changes in attributes between efficiency levels. The key assumption of the method is that the function that describes price and UEC as a function of attributes and efficiency level can be determined using regression analysis from market data.

For all four appliance types (dishwasher, refrigerator, tumble dryer and television), controlled variables included size (capacity or screen size) and efficiency class. In order to test the robustness of this method, a more comprehensive regression was performed for televisions, an appliance type where difficulties of using LCC approaches have occurred previously due to a lack of clear relation between price and energy efficiency (Siderius, 2013). The additional product features that were controlled for in the case of televisions were NFC (near-field communication), smart television, screen type, screen resolution and number of tuners.

LCC modelling

Once the relationship between price and UEC was established, LCC could be computed. The LCC of an appliance is the sum of its price and the present value of operating costs. In modelling LCC and estimating the LCC optimum for four types of appliances, the approach of LCC optimisation outlined in Van Buskirk et al. (2014) was used.[4] LCC is defined as follows:

$$\mathrm{LCC} = P_A + \mathrm{PWF} \times P_E \times \mathrm{UEC} \tag{1}$$

where P_A is the total average appliance price for one efficiency class, and UEC is the average annual unit energy use in the respective class. P_A and UEC are corrected for product characteristics as described above. P_E is the price of electricity, and PWF is the present worth factor:

$$\mathrm{PWF} = \frac{1-(1+i)^{-L}}{i} \tag{2}$$

where i is the discount rate and L average product lifetime. When including the SCC, the price of

[4] The LCC optimization method is only briefly presented here; for a full explanation, please refer to the "Supporting Information" in Van Buskirk et al., 2014

electricity is increased by the product of the SCC and the emission factor (EF).[5] The revised Eq 1 for LCC including SCC is as follows:

$$LCC_{SCC} = P_A + PWF \times (P_E + EF \times SCC) \times UEC \quad (3)$$

Estimating the LCC optimum with and without SCC

Once the relation between appliance price and UEC has been established, and if there is a clear trend that lower UEC implies higher appliance prices, LCC optima can be computed. As the purchase price of an appliance increases without bound when energy use decreases towards the theoretical minimum, and energy operating costs increase without bound for very low efficiencies, the minimum LCC of an appliance can be usually found somewhere in between the most efficient and the least efficient appliances. Additionally, when appliance prices increase with decreasing UEC, then the LCC vs. UEC relationship is typically as illustrated in Fig. 1 (Van Buskirk et al., 2014). The minimum in the LCC function theoretically determines the optimum value for MEPS.

Focussing on the LCC function near the minimum value, the LCC vs. UEC function can be approximated as a quadratic function[6]:

$$LCC(UEC) = LCC_{min} + C \times (UEC - UEC_{min})^2 \quad (4)$$

where LCC_{min} is the LCC value at the minima, and UEC_{min} is the energy use corresponding to the minimum LCC value, and C is a constant that describes the curvature of the LCC vs. UEC curve near the LCC minimum. When internalising the climate externality with the SCC, the price of electricity increases and the UEC for the minimum LCC shifts to a lower value. Similar to Eq. 4, LCC can now be modelled as a function of SCC and UEC in the following way:

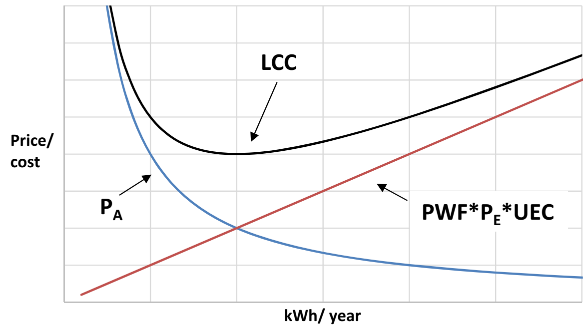

Fig. 1 Schematic illustration of LCC equation and determination of LCC minimum

$$LCC_{SCC}(UEC) = LCC_{min} + C \times (UEC - UEC_{min})^2 + PWF \times EF \times SCC \times UEC \quad (5)$$

The minimum LCC can now be calculated by taking the derivative of the right-hand side of Eq. 5 with respect to UEC, setting it equal to zero and solving for the minimum UEC as a function of SCC and other parameters. This results in the following equation that describes the shift in UEC if SCC is included in LCC optimisation:

$$UEC_{SCC\_min} = UEC_{min} - \frac{PWF \times (EF \times SCC)}{2 \times C} \quad (6)$$

This equation describes that near the old LCC minima, the shift in optimum UEC due to consideration of SCC is proportional to the value of SCC, the EF, and the PWF, and the shift is inversely proportional to the curvature of the LCC vs. UEC curve (i.e. C) near the LCC minimum. Note that this modelling approach can be used when the available data shows an LCC minimum that exists within the range of data used to estimate the model parameters. When data indicates that C is 0 or negative, this modelling approach cannot be used to estimate the shift in optimum UEC indicated by consideration of SCC.

Based on the methodological steps outlined above, empirical data about appliance price, efficiency and UEC were used to statistically estimate the minimum LCC, the value of UEC at the LCC minimum, and the curvature of the LCC vs. UEC function near the LCC

[5] It is assumed that the effect of internalizing the climate externality on appliance prices does not systematically differ between efficiency classes. If, against this assumption, there is a systematic difference, it can be assumed to be small compared to difference in use-phase emissions, because the emissions caused in the production of a home appliance are in most cases small compared to indirect emissions from the use phase. For a thorough discussion of embodied emissions of products under the Ecodesign Directive, see Scott et al., 2017

[6] The quadratic approximation of the LCC near the minimum follows from Taylor's theorem in mathematics since at a minimum, a function has no first derivative. When both the second and third derivatives of the LCC function are non-zero, the quadratic approximation is likely to be valid when $|UEC-UEC_{min}| << |LCC''/LCC'''|$ where LCC″ and LCC‴ are the second and third derivatives of LCC with respect to UEC respectively.

minimum for tumble dryers and dishwashers[7] on the UK market. In this estimation, market data were used to estimate a reference line that provided market average UEC vs. appliance capacity (i.e. the number of place settings for dishwashers, and the kilogrammes of clothes drying capacity for tumble dryers). The LCC was then examined relative to this market average energy use and was fit to a quadratic function of energy use relative to the reference. Finally, Eq. 6 was used to estimate the shift in energy use implied by a MEPS policy that is based on LCC optimisation and considers SCC.

Estimating carbon prices to achieve the same energy efficiency improvements as MEPS

Equation 6 above addresses the question: for a given SCC, what is the corresponding shift in UEC? Alternatively, the reverse question can be asked: for a given shift in UEC, what is the corresponding carbon price (CP) that can make a switch from a lower to a higher efficiency class economically beneficial? To answer that second question, the SCC in Eq. 3 is replaced with CP. Then, Eq. 3 is equalized for pairs of efficiency classes. Solving for CP results in the following:

$$\mathrm{CP} = \frac{\frac{P_{A++}-P_{A+}}{\mathrm{PWF}} + (\mathrm{UEC}_{++}-\mathrm{UEC}_{+}) \times P_E}{(\mathrm{UEC}_{+}-\mathrm{UEC}_{++}) \times \mathrm{EF}} \quad (7)$$

where ++ indicates the more efficient appliance class and + the less efficient appliance class in the pair.

When modelled with market data, solving Eq. 7 resulted in the switching price that is needed in the UK to provide an incentive for economically rational consumers to shift from an average appliance model in one efficiency class to an average model in a higher efficiency class.

Key assumptions and sensitivity analysis

Besides appliance data, further information for key assumptions of the LCC modelling was needed (see Table 2). In order to get the present value of future electricity costs (and savings), a real social discount rate of 3.5% was used, which is the UK Government recommendation for central government policy evaluations (HM Treasury 2013). The *real* discount rate was used because zero inflation of electricity prices was assumed over the lifetime of the analysed appliances. The electricity price of 0.14 GBP/kWh was the average price for a consumer in the first half of 2016.

For the modelling, the average CO_2 emission factor of the UK electricity mix in 2014 of 413 gCO_2/kWh was used, which was likely not only above the average emission factor that can be expected over the lifetime of the appliances but also below the current marginal emission factor of the mix. The average lifetime of the different appliances was taken from literature, which in turn was the basis for calculating the PWF with Eq. 2. The SCC estimate used for this study was 150 USD (120 GBP). A high SCC value was chosen for this study in order to cover the whole range from not internalising the climate externality ('pure' LCC approach) to being confident that it is fully internalized (LCC with SCC of USD 150).

This exploration of a whole range of SCC estimates indicates the sensitivity of results with respect to changes in the assumed SCC. In order to further test the robustness of key results, additional sensitivity analyses were conducted. This included a variation in electricity price, emission factor and PWF by ± 50%. Most current electricity prices in the EU are included in the resulting interval of 0.7 to 0.21 GBP/kWh, and, with few exceptions, the average emission factors of most EU electricity mixes are contained in the interval 207 to 620 gCO_2/kWh (IEA, 2017). For the PWFs of the four appliances, the lower halves of the respective intervals seem to be more relevant, as on appliance markets, consumer discount rates have been found to frequently and significantly exceed market discount rates (Schleich et al., 2016; Wada et al., 2012), reflecting a lower present worth of future energy costs.

Results

Internalising the climate externality in the LCC of home appliances

Figure 2 shows average price and LCC curves for the four analysed appliances and their respective efficiency classes on the UK market in 2016. The general appliance price trend is clear: the lower the annual energy use of an appliance, the higher its price (with the exception of televisions, which will be further discussed below). In

[7] For refrigerators and televisions, the estimated LCC function did not allow for applying the outlined approach because for televisions, the minimum was outside the empirical data range and for refrigerators, the constant *C*, describing the curvature at the LCC minimum, was negative.

Table 2 Key assumptions used in LCC modelling

Description	Value	Source/comment
Discount rate (real)	3.5%	HM Treasury (2013)
Lifetime dishwasher (PWF in brackets)	12.5 years (10)	Boyano Larriba et al. (2017)
Lifetime refrigerator (PWF in brackets)	16 years (12)	VHK and ARMINES (2016)
Lifetime television (PWF in brackets)	7 years (6)	Stobbe (2007)
Lifetime tumble dryer (PWF in brackets)	13 years (10)	Lefèvre (2009)
Electricity price	0.14 GBP/kWh	Department for Business, Energy & Department for Business, Energy, and Industrial Strategy (2016)
Emission factor of the electricity mix	413 gCO_2/kWh	IEA (2016b)
Social cost of carbon	150 USD/tCO_2	High-end assumption based on literature review
Exchange rate USD–GBP	1.25	Approximate market exchange rate in early 2017

contrast, LCC trends vary: the least efficient refrigerators and dishwashers also have the lowest LCC; television models in the least efficient class have the highest LCC; and tumble dryers have the lowest LCC in efficiency class A+ and a higher LCC both for more efficient and less efficient models.

If the SCC is accounted for, the LCC-ranking of efficiency classes is affected only to a small degree.

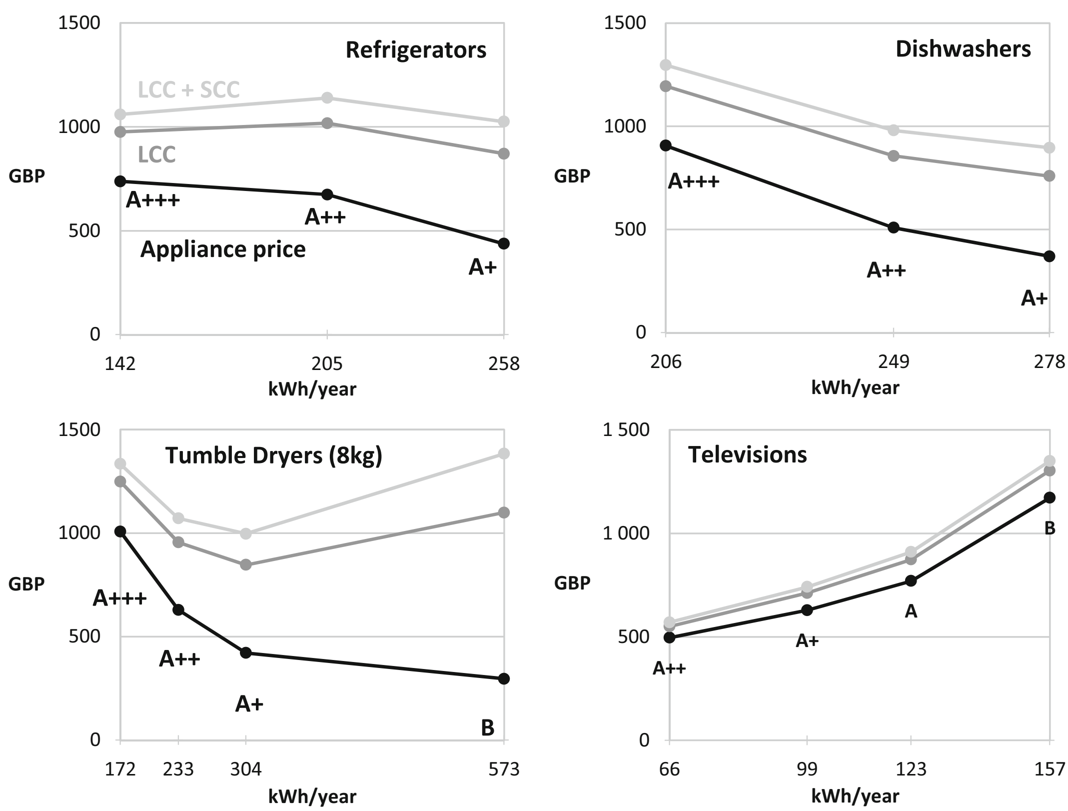

Fig. 2 LCC curves for appliances in the UK, with and without SCC

The main change is that for tumble dryers, the highest LCC moves from the average model in class A+++ to B, which is a strong argument in favour of mandating a standard higher than B. A higher standard may also be justified for refrigerators, for which the LCC difference between efficiency classes becomes very small if SCC is accounted for. Moreover, the individual model with the lowest LCC in each appliance category might well be a more efficient one if SCC is included, which means that the technological potential for cost-effective abatement through MEPS is likely higher than indicated by the aggregated data presented in Fig. 2.

While the inclusion of SCC only somewhat alters the LCC-ranking of appliance classes, it clearly increases the *level* of LCC. The space between the LCC curve and the LCC curve with SCC is where LCC would be located for lower SCC estimates between 0 and 150 USD per ton of CO_2. Furthermore, the area between the curves illustrates where LCC estimates would be located for lower emission factors between 0 and 413 g/kWh (at a constant SCC of 150 USD). Higher emission factors than 413 g/kWh, higher electricity prices than 0.14 GBP/kWh, and a SCC even higher than 150 USD would all result in an upward rotation of the LCC curve, which means a smaller increase of LCC for very efficient appliances and a larger increase for inefficient appliances.

In examining the special case of TVs, the relationship between energy efficiency and product prices appears to be reversed. One explanation for this counter-intuitive finding could be that accounting for screen size was not sufficient to isolate the marginal cost of energy efficiency. If, however, the analytical approach is refined and other product features are accounted for, such as NFC, smart television, screen type, screen resolution and number of tuners, the general trend still holds and price decreases with increasing efficiency.[8] This finding supports a previous study that found the same trend (Siderius, 2013).

Finally, Fig. 2 provides some information about the energy savings (and related mitigation) potential of energy-efficient technologies that are already on the market. A rough indication of this potential can be obtained from comparing average UEC of the median efficiency class (based on the sales data presented in Table 1) to average UEC of the most efficient class. The following differences can be observed: UEC is 45% (116 kWh/year) lower for A+++ refrigerators compared to A+ models, 26% (72 kWh/year) lower for A+++ dishwashers compared to A+ models, 70% (401 kWh/year) lower for A+++ tumble dryers compared to B models and 46% (57 kWh/year) lower for A++ TVs compared to A models. These indicative estimates of energy savings potentials are largely in line with previous research, suggesting that the energy reduction potential of EU product regulation by 2030 is 60% for refrigerators, 33% for dishwashers, 25% for tumble dryers and 64% for televisions (Kemna and Wierda, 2015).

The climate externality's impact on the LCC optimum of home appliances

While Fig. 2 displays the situation for the averages of different energy efficiency classes, a refined estimate of the shift in optimum UEC due to consideration of SCC can be obtained by using Eq. 6. Figure 3 illustrates the estimated LCC curvature close to the LCC minimum for dishwashers and tumble dryers. This quadratic function fit provides an estimate of the LCC minimum and the curvature of the minimum. For dishwashers, the estimated curvature is GBP 0.10 per $(\text{kWh/year})^2$ and for tumble dryers, it is GBP 0.01 per $(\text{kWh/year})^2$.

Using these curvature values, a SCC of 150 USD/ton implies a shift in optimum UEC of 25.4 kWh/year for tumble dryers and 2.5 kWh/year for dishwashers, which in relative terms represents shifts of 7 and 1% respectively. This means that in the context of LCC-optimized MEPS, a relatively small shift in MEPS can already account for the SCC. As can be seen in Eq. 6, this shift is fully proportional to the respective SCC, PWF and emission factor. If, for example, the SCC is doubled, which roughly reflects the shadow carbon prices of 1.5 °C-consistent scenarios in 2030, also the shift in optimum UEC is doubled, in this case to 2% for dishwashers and to 16% for tumble dryers.

The LCC optima that are seen in Fig. 3 were determined by fitting a curve to market data. This approach can be criticized for not capturing all the information there is in the distribution of individual models. There are, for instance, models on the market that have a UEC

[8] The specific average appliance prices and UEC of televisions on the UK market are the following if the more extensive regression model is applied: A++ (GBP 451; 65 kWh/year), A+ (671; 97), A (707; 121) and B (907; 154).

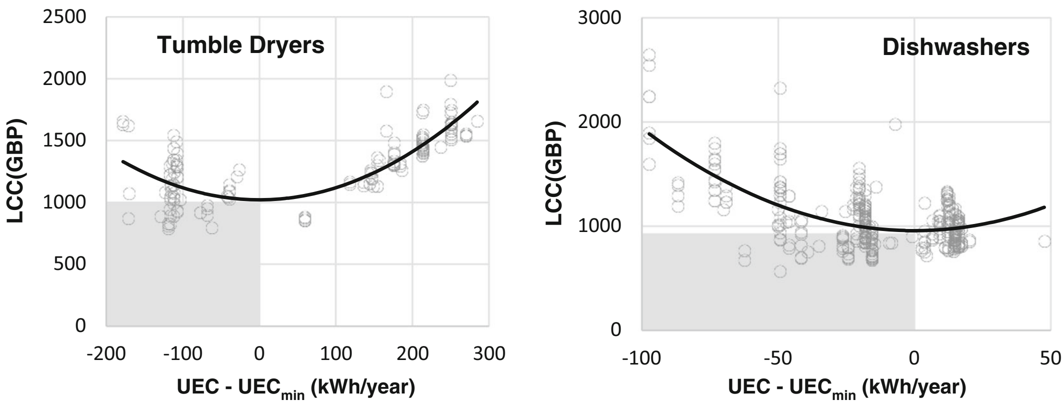

Fig. 3 Curvature of LCC minimum estimated from market data for tumble dryers and dishwashers

below UEC_{min} and LCC below LCC_{min} (see grey boxes in Fig. 3), which implies that the technological potential for cost-effective energy efficiency improvements of home appliances goes even beyond UEC_{min}.

A carbon price that sets the same incentive as a progressive MEPS

In Fig. 4 below, the perspective taken in Fig. 3 is turned around and a regulated shift one or two efficiency classes up (e.g. from A+ to A++) is compared to the carbon price that would be needed to incentivize the same shift. Note that this approach is not aimed at projecting actual consumer response but at identifying switching prices between average models of different efficiency classes on the UK market for an average consumer who considers full LCC when purchasing appliances. In order to see how assumptions about the electricity grid (emissions factor and electricity price) product lifetimes (as an element of PWF) and consumers' rationality (discount rate as part of the PWF) affect switching prices, Fig. 4 also includes the results of a sensitivity analysis.

The carbon prices displayed in Fig. 4 reveal several clear trends. First, for all appliances except televisions, carbon prices would have to be much higher than they are today, and even higher than the SCC estimate of USD 150 per ton of CO_2, in order to incentivize a switch between efficiency classes. For televisions, on the other hand, no carbon price is needed and lower LCC should already be incentive enough to purchase a model from the most efficient appliance class.

Second, the graphs depicting changes in the emission factor clearly show that the required carbon prices react exponentially. As electricity grids get decarbonized, it gets more and more difficult to incentivize the purchase of more efficient appliances by means of carbon pricing, because the carbon footprint of using an appliance is reduced over its anticipated lifetime. In the extreme case of countries like Norway and Sweden with CO_2 emission factors below 10 g/kWh (IEA, 2017), the required carbon price to incentivize a switch between efficiency classes approaches infinity. This illustrates that carbon pricing may only be a useful instrument to promote the purchase of efficient home appliances in a sufficiently 'dirty' electricity grid. For grids that are largely decarbonized, MEPS can still move appliance markets towards more efficiency, but due to low emission factors, energy savings translate, at best, into marginal CO_2 emissions reductions.

Third, and irrespective of the emission factor, Fig. 4 shows that increasing electricity prices bring the LCC of different efficiency classes closer together so that not such a high carbon price is needed anymore to incentivize a switch to the more efficient model class. But the figure also shows that electricity pricing alone will not be sufficient and significant carbon prices are needed. For the UK data, it is only the shift from A+ refrigerators to A++ refrigerators that could potentially be incentivized by a 50% increase of electricity prices alone.

Finally, and most importantly, Fig. 4 clearly shows that a departure from the unrealistic assumption that consumers fully consider LCC requires exponentially higher carbon prices in order to incentivize a shift to a higher efficiency class. While in welfare policy and SCC estimation it is most suitable to apply a social discount rate (3.5% in this study), implicit discount rates of consumers are typically around 20% or higher (Wada et al., 2012). The high discount rates reflect behavioural

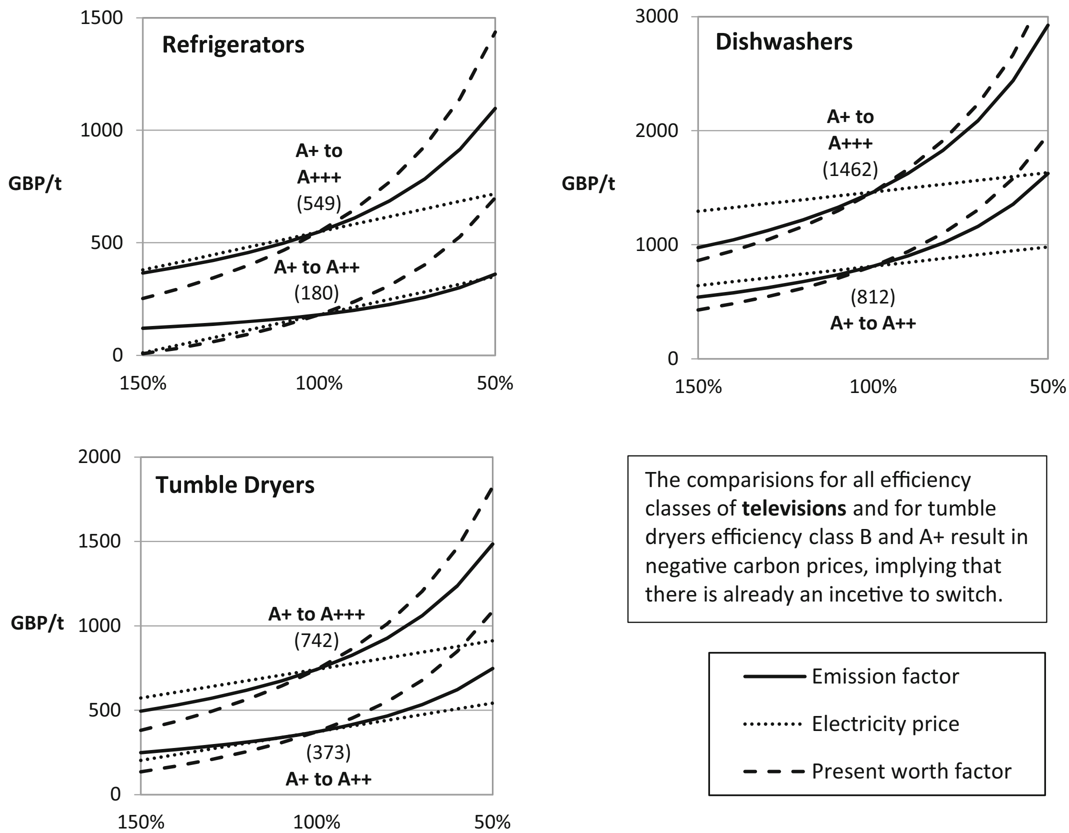

Fig. 4 Sensitivity analysis of switching prices for energy-efficient appliances. Displayed carbon prices represent a shift of MEPS by one or two efficiency classes. Sensitivity of results was tested with respect to changes in emission factor (100% = 413 gCO_2/kWh), electricity price (100% = 0.14 GBP/kWh) and PWF (100% = 10 for dishwashers and tumble dryers and 12 for refrigerators). Note that the analysis does not include the SCC

failures such as inattention, myopia, reference-dependent preferences and bounded rationality (Gerarden et al. 2017; Schleich et al., 2016). At a discount rate of 20% the PWF is roughly cut to half, which—as can be seen in Fig. 4—results in a steep increase of switching prices. If, on the other hand, some consumers expect electricity price increases that go beyond regular inflation, their discount rate might be lower, which results in a higher PWF and lower switching prices. Average consumer discount rates of 20% and more, however, indicate that such consumers are the exception.

Discussion

Methodological contributions and limitations

The analysis of the UK market for four electric home appliances has shown that the SCC (or a shadow carbon price) can easily be included in the modelling of LCC optima. This simple methodological approach has the potential to strengthen the effectiveness of MEPS as climate mitigation policy instruments. However, the approach to include SCC in LCC modelling has the same limitations as the LCC approach itself. It works well if there is a strong association between appliance prices and UEC, i.e. if higher prices imply more efficient products (Siderius, 2013). If this association is weak or even reversed (as could be observed in the case of televisions), LCC optimisation is of little use and other approaches should be used, e.g. a simple rule that a MEPS is set at the bottom end of the best performing quintile on the market, an approach known as 'top-runner' approach (Siderius, 2014).

A challenge of setting MEPS based on LCC optimisation is that this is typically a retrospective approach which has difficulties accounting for experience curve effects (Siderius, 2013). While multiple snapshots over time can be analysed to show trends as part of a real-time LCC methodology, future product improvements are difficult to predict. Also, the approach of looking at whole efficiency classes and fitting data to average trend curves is conservative by nature, because there are always models that outperform the average even in the most efficient class. In this way, technically feasible and cost-effective efficiency improvements are potentially hidden in aggregated data and behind a static retrospective modelling approach.

Another potential limitation of the LCC optimisation method used in this study is that it assumes a quadratic function to identify the LCC minima. There are several other functional forms that could be used to model minima, and an initial analysis showed that including cubic terms in the fitting function changes the SCC-induced shift of UEC at the LCC minimum by about 10%. Further research is needed in order to obtain more robust model specification variability. Still the main conclusion of this research seems to hold independently of the fitting function. If the LCC minimum is well defined, including SCC makes a moderate change in the electricity price, which results in a minor shift of the UEC associated with minimum LCC.

The modelling of switching prices that correspond to stringent MEPS is the second methodological contribution of this paper. In this study, the estimation of switching prices illustrates well the limitations that carbon pricing can have to incentivize investments for energy-efficient technology, particularly if discount rates above the market discount rate are assumed. While currently even the most progressive carbon pricing schemes are unlikely to have a significant steering effect, the overall mitigation effect of carbon pricing interventions also depends on the revenue use, which, in theory, can be fully targeted at climate change mitigation.[9] Revenue use was not considered in this analysis, as in practice, earmarking revenues for climate change mitigation is not yet a priority of existing carbon pricing schemes (Stiglitz et al., 2017). In addition to MEPS and carbon pricing schemes, it should be noted that there are further (combinations of) policy instruments that may address market failures and behavioural anomalies in an effective way but were outside this study's scope (for example product labels, subsidies and rebates).

Finally, the sensitivity analysis illustrates that what is optimal may differ between countries with different electricity prices and emissions factors and even between individual consumers who can discount future operating costs differently and value energy efficiency at different levels. While the analysis considered variation of the average consumer, consumer heterogeneity was not explicitly modelled.[10] Accordingly, stringent MEPS may not be welfare-enhancing for all consumers, and some consumers may be excluded from the market because of higher up-front costs of the most energy-efficient products. In such a case, consumer subsidies, tax breaks or other policies aimed at certain consumer groups may be a useful complement to MEPS. While MEPS appear to have been contentious in only limited cases, for example, the MEPS effectively 'banning' incandescent lightbulbs (see e.g. Frondel and Lohmann, 2011 and Sandahl et al., 2006) and the MEPS for vacuum cleaners in the UK (Barford and Dalhammar, 2015), these highlight the need to also ensure that there are no significant trade-offs with product quality and more stringent MEPS (though other research has found generally that product quality improves—see Brucal and Roberts, 2017).

Implications for 1.5 °C-consistent energy efficiency policy

Energy-economy modelling of climate scenarios has shown that delaying mitigation and increasing energy consumption render the 1.5 °C target unfeasible and the 2 °C target more costly (Clarke et al. 2014; Guivarch and Rogelj, 2017; Rogelj et al., 2015b; Waisman, 2017). Against this background, the policy mix for demand-side technologies needs to be both ambitious and quickly implemented. The results of this research are discussed regarding the potential of MEPS to function as a relevant climate policy towards the 1.5 °C target. In this discussion, special attention is given to the internalisation of SCC, the consistency of MEPS' effectiveness with 1.5 °C pathways, as well as their short- and

[9] It should be acknowledged here that the important issue of revenue use was added to the discussion after an anonymous reviewer highlighted its relevance.

[10] Similarly, standards can be perceived as a costly burden by some manufacturers but not by others. EU appliance manufacturers (BSH et al. 2012) and Swedish industry (Jönbrink and Melin 2008) seem to accept or even be in favour of more stringent product regulation. Such regulation can be a competitive advantage and experienced firms have learned they can comply with it at reasonable costs. However, in countries dominated by low-cost producers, the perceptions may be different and manufacturers may see stringent EU regulations as cost-increasing and as market barriers.

long-term economic efficiency. As MEPS can only be one element of a wider climate policy portfolio, the role of MEPS in the climate policy mix is also discussed.

The results from LCC modelling of four home appliances show that *a significant climate externality can be captured by MEPS* that are not much more stringent than current levels. At minimum, such low-hanging fruits should not be left hanging, even if the additional mitigation resulting from these adjustments cannot be expected to be a sufficient contribution towards reaching the 1.5 °C target. However, while incorporating SCC will internalize an externality, stringent MEPS that go beyond this are needed to drive significant CO_2 reductions from home appliances.

The findings also imply that much more stringent MEPS are, in principle, able to achieve a mitigation effect that is consistent with the 1.5 °C target. For the UK, deep decarbonisation scenarios consistent with the 2 °C target imply reductions of final energy consumption by about 10% in 2030, but to move towards 1.5 °C, further (not quantified) reductions in energy demand are needed (Pye et al. 2015). Our analysis and previous studies (Kemna and Wierda 2015; VHK 2016) have shown that energy savings from home appliances of 25% and more are feasible if the whole market for these appliances in the UK was shifted by stringent MEPS to the average performance of the currently highest efficiency class. If implemented swiftly, the realisation of emissions abatement driven by stringent MEPS still depends on the lifetimes (and associated stock turnovers) of the respective appliances, which in this study range from 7 years (televisions) to 16 years (refrigerators). Moreover, the emission factors of electricity grids determine the specific abatement associated with energy savings. In most countries, including the UK, electricity grids are still 'sufficiently dirty' (IEA 2017), implying a high abatement potential of efficiency improvements in electric appliances (Dietz et al. 2009; Letschert et al. 2013). In summary, the combination of current savings potential, stock turnover duration and emission factor appears to be largely consistent with the UK pathway for reaching the 1.5 °C target.[11]

Moreover, the mitigation effect of national or regional MEPS can be expected to go beyond the boundaries of the regulated markets. US and EU MEPS are effectively adopted by commercial actors in other jurisdictions due to the size of their markets (Bradford 2012) and have been the blueprint for MEPS in other countries (Molenbroek et al. 2015). This is important since it has been shown that climate mitigation efforts of front-running countries and regions (such as the EU) have significant climate benefits, but that they are not sufficient to limit global warming to 1.5 °C (Kriegler et al. 2015), and a wider coverage of comprehensive climate mitigation efforts is needed in the short term.

While stringent MEPS can be highly effective and this effect may spillover to unregulated markets, their short-run economic efficiency appears to be low. This is evidenced from the current switching prices for ambitious energy efficiency improvements found in this study, which range from 180 GBP/t CO_2 (switch from average A+ to A++ refrigerator) to 1460 GBP/t CO_2 (switch from average A+ to A+++ dishwasher). As these switching prices are higher than shadow carbon prices for reaching the 1.5 °C target (of about USD 200–300 per ton), in most cases, stringent MEPS do not appear to be cost-effective on the short run. The exception is stringent MEPS for televisions, which appear to be highly cost-effective already, as LCC of televisions are lowest in the highest efficiency class.

While high switching prices indicate high abatement costs for several appliances, it has been argued that technological roadmaps and policies should not only be based on *current* marginal costs but also on cost dynamics over time (Stiglitz et al. 2017, p. 29), a perspective also referred to as 'dynamic efficiency' (del Río González 2008). From a dynamic perspective, the cost-effectiveness of measures to reach a short-term target then also depends on long-term targets. For a demanding climate objective, such as the 1.5 °C target, the optimal strategy might well be to quickly and simultaneously implement measures with a wide range of marginal abatement costs (Vogt-Schilb and Hallegatte 2014). Moreover, recent evidence suggests that high switching costs for energy efficiency improvements of home appliances disappear (or are even reversed) if a dynamic perspective is taken, as prices for efficient home appliances have declined in relation to performance over time, especially when more stringent standards were enforced (Brucal and Roberts 2017; Van Buskirk et al. 2014). This is in line with previous research showing that the average prices of highly efficient tumble dryers and refrigerators fell with increasing

[11] The energy saving effect of efficiency improvements can be limited by rebound effects, which are estimated to reduce energy savings by 5–15% (Letschert et al. 2013; Sorrell 2007) or enhanced by technological progress, which—to a certain extent—cancel each other out and were not considered in this analysis.

market shares as learning and scale effects factored in (Siderius 2013).

Both their potential for dynamic efficiency and high effectiveness are arguments in favour of using stringent MEPS to complement carbon pricing instruments, but it has been argued that MEPS are not economically efficient, in particular in combination with ETS schemes (Böhringer et al. 2016). However, even from a purely economic perspective, the departure from the first-best policy approach of global comprehensive carbon pricing (Goulder and Parry 2008) does not have to lead to large efficiency losses. For the 2 °C target, energy-economy modelling has shown that a mix of modest carbon pricing with low-carbon energy technology policies can be nearly as efficient as global, comprehensive carbon pricing at a high price level (Bertram et al., 2015b). Considering that likely 2 °C scenarios make nearly comprehensive use of all supply side mitigation measures, and considering further that additional demand side measures are crucial for the 1.5 °C target (Rogelj et al., 2015a), it is likely that energy efficiency technology policy, such as MEPS, compromises the cost-effectiveness of carbon pricing instruments even less in a 1.5 °C context and—as outlined above—may be dynamically efficient. Moreover, if carbon pricing is implemented via emissions trading schemes, such as the EU ETS, emission reductions that are triggered by MEPS can be accounted for by adjusting the emissions cap, so that the carbon price incentive for other sectors is not diluted (Hood, 2013; Richstein et al., 2015; Sonnenschein, 2016). In practice, however, the predictability about impacts of any kind of energy (efficiency) regulation is still limited, so that there is a general need for a flexible adjustment mechanism of the supply with emission allowances (LBST et al. 2013).

Conclusions

Modelling of climate change scenarios has shown that radical energy efficiency improvements have to be realized immediately in order to keep alive any possibility to limit global warming to 1.5 °C until the end of the century. In this context, energy efficiency policy cannot afford to exclusively rely on weak carbon or energy price signals and uncertain market and behavioural response. This study has shown that even the high estimates of carbon prices required to limit global warming to 1.5 °C will not be enough to move markets for several electric home appliances towards BAT. Setting more stringent mandatory standards, on the other hand, can be seen as a way to force markets for home appliances towards more efficiency and realize their emissions abatement potential. In order to make use of the full abatement potential, stringent MEPS have to go beyond the incorporation of SCC in the underlying LCC modelling. If the time perspective is confined to the present, stringent MEPS do not appear to be the most economically efficient abatement option. If, however, technology pathways for reaching the 1.5 °C target are considered, and it is taken into consideration that prices for highly energy-efficient appliances have dropped quickly in the past, stringent MEPS not only are effective but also promise to be a cost-effective abatement policy.

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Compliance with ethical standards

Conflict of interest The authors declare that they have no conflict of interest.

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