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Carbon pricing and the affordability of residential heating: A theoretical model with endogenous technology choice

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Abstract

This paper analyses the impact of carbon pricing on residential heating affordability using a theoretical household model with endogenous choice of a renewable heating technology. We compare two compensation policies: a renewable heating subsidy and a lump-sum transfer. The subsidy is the most effective policy to reduce the household's burden if the renewable heating technology is the optimal choice with carbon pricing alone. Otherwise, the relative effectiveness of the compensation policies depends on whether they shift the household's choice towards renewable heating. Overall, our study emphasizes the need of considering technological adjustment when analyzing how carbon pricing affects heating affordability.

JEL Codes: D63, H23, Q58
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1 Introduction

1.1 Background, research questions, and key findings

Carbon pricing is considered an efficient instrument for reducing CO_2 emissions, increasingly utilized to decarbonize the residential building sector. For instance, Germany introduced a carbon price on heating fuels in 2021 and an emissions trading system for heating fuels will be introduced in the European Union from 2027. Achieving decarbonization through carbon pricing as a key policy will significantly increase the price of heating fuels for private households (Abrell et al., 2024). Thereby, carbon pricing also incentivizes the use of renewable heating technologies and upgrading the energy performance of buildings, and inherently imposes additional financial burdens on private households. This has sparked discussions about the affordability impact of carbon pricing, particularly since heating is regarded as an essential energy service.[1] Affordability can be understood as the ability of a household to meet its basic needs for heating services without compromising on the consumption of other basic goods (Gawel & Bretschneider, 2010; Pye et al., 2015). Hence, understanding the affordability implications of carbon pricing in the residential sector is of great importance. This also holds in light of public opposition to carbon pricing and the recent energy crises (Guan et al., 2023; Sommer et al., 2023). Similarly, there is an ongoing debate and research regarding the affordability of other related basic goods, such as housing and water (Gawel & Bretschneider, 2014; Martins et al., 2023; Pierce et al., 2021; Yui Leung & Ping Tsang, 2023). In this context, our paper seeks to analyze how carbon pricing impacts the affordability of residential heating if a household may respond by both reducing consumption and choosing a renewable heating technology. We also ask how compensation policies, such as a renewable heating subsidy and a lump-sum transfer, impact the affordability outcome in this context and which policy is most effective in reducing the household's heating-related expenditure burden.

We employ the conventional affordability ratio (CAR) as a measure of affordability, which relates the heating-related expenditure of a household to its income. We develop a microeconomic model for the consumption of a heating service and other goods and the heating technology choice of the household. We derive conditions for the household's ability and willingness to choose a renewable heating technology amidst carbon pricing, embedding these results into the CAR. On the one hand, this reflects that a household can avoid the carbon price by choosing a renewable technology. On the other hand, we consider the associated higher capital expenditure compared to a fossil heating technology as a burden. In addition, we also analyze impacts of carbon pricing on household utility. This enables us to control for conceptual weaknesses of the CAR and allows for a more comprehensive understanding of how carbon pricing affects a household beyond an expenditure-based metric.

We show that the burden imposed by carbon pricing as well as the effects of two

[1] For example, in Germany heating is explicitly included as part of the individual tax-free minimum subsistence level (Bundesministerium der Finanzen, 2022).

compensation policies (renewable heating subsidy and lump-sum transfer) depend on whether the household is able and willing to choose a renewable heating technology. First, our results show that carbon pricing increases the burden as measured by the CAR if the household is able and willing to choose a renewable heating technology in response. This increase is driven by the higher capital expenditure associated with the renewable heating technology. However, by choosing a renewable heating technology, the household is better off in terms of utility compared to choosing a fossil technology with carbon pricing. Moreover, the household can consume more of the heating service in this case. This suggests that choosing a renewable heating technology may help to moderate possible affordability impairments caused by carbon pricing. Subsidizing the renewable technology is the most effective policy to reduce the household's burden in this case. However, in terms of utility the subsidy is as effective as the lump-sum transfer. Second, carbon pricing does not increase the CAR if the household is not able or able but not willing to choose the renewable heating technology either due to income constraints or insufficient incentive effects of the carbon price. In this case, the fixed burden arises from the isoelastic energy demand function in our model which is therefore likely to be overly optimistic with respect to the reduction in consumption. It is ambiguous which of the two compensation policies is most effective in reducing the burden and enhancing the household's utility. This depends in particular on the impact of the policies on the household's heating technology choice. Overall, our analysis highlights that considering the choice of a renewable heating technology in response to carbon pricing is central to a comprehensive understanding of the affordability impacts of carbon pricing and choosing the most effective compensation policy.

1.2 Related literature and contribution

Our paper contributes to several strands of literature. First, the affordability of basic goods such as energy services, water or housing is analyzed in various theoretically based studies (Gawel & Bretschneider, 2014; Hancock, 1993; Hulchanski, 1995; Kessides et al., 2009; Lerman & Reeder, 1987; Leung & Tang, 2023). Second, another strand of literature examines the affordability of energy services like heating under the heading of fuel poverty, energy affordability, or energy poverty.[2] These predominantly empirical studies quantify the extent of affordability problems and identify socio-economic factors at household level as well as infrastructural conditions that contribute to affordability problems (Antunes et al., 2023; Chaton & Gouraud, 2020; Heindl & Schüßler, 2015, 2019; Pereira & Marques, 2023; Spandagos et al., 2023). However, neither of the two strands of literature investigates how price increases induced by public policies like environmental taxes af-

[2]The terms fuel poverty and energy poverty are often used interchangeably, but have fundamental differences in terms of the definition of the problem, approaches to measurement and the economic and climatic context. Fuel poverty mainly refers to problems of affordability of space heating in the Global North, while energy poverty primarily addresses the lack of access to modern energy services in the Global South (Li et al., 2014). Some studies also differentiate between the affordability of access and the affordability of consumption (Estache et al., 2002). The focus of our study concerns the latter.

fect affordability. Third, a more closely related strand of literature analyses the impact of carbon pricing, energy taxes or levies on the cost burden for energy services for private households. Two perspectives on the cost burden can be distinguished here. Distributional analyses compare the distribution of the cost burden across different societal groups, often linked to the question of the extent to which normatively undesirable distributional effects can be alleviated by revenue recycling schemes (Douenne, 2020; Hänsel et al., 2022; Kaestner et al., 2023; Klenert & Mattauch, 2016; Nikodinoska & Schröder, 2016; Rose et al., 2012; Weitzel et al., 2023). However, these studies do not investigate the affordability impacts of carbon pricing. Affordability analyses are indifferent towards the distribution of cost and compare a household's burden to a normatively set threshold, indicating an affordability problem if exceeded. Studies find that carbon pricing decreases the affordability of energy services like residential heating and thus more households are affected by affordability problems (Berry, 2019; Bourgeois et al., 2021; Flues & Van Dender, 2017; Priesmann et al., 2022; Tovar Reaños, 2021; Vandyck et al., 2023). While most studies consider adjustments in consumption, the possibility of technological adaptation remains largely unconsidered. An exception is the work by Kaestner et al. (2023) who consider the adoption of low-carbon technologies and find that this mitigates the regressive effects of carbon pricing in the long term, suggesting that affordability of energy services improves as well. However, the study abstracts from economic constraints on households' technology choice. Another exception is the work of Bourgeois et al. (2021) who allow for endogenous investments into energy efficiency upgrades and find that carbon pricing still increases the overall number of households experiencing affordability problems via higher energy expenditure. However, the investment decision does not include any binding economic constraints. Tighter credit constraints faced by low-income households are only implicitly reflected through a discount rate that decreases with income. Moreover, the capital expenditure on energy efficiency improvements is not included in the burden on households and therefore not as a potential contributor to affordability issues. Hänsel et al. (2022) follow a similar approach like ours by allowing for endogenous investments into energy efficiency enhancing capital but their analysis focusses on distributional effects of carbon pricing. Finally, in addition to energy efficiency improvements, the use of low-carbon technologies is a key means to decarbonize residential heating, which suggests that an important factor is not considered (Rosenow & Hamels, 2023). Thus, our study's primary contributions are i) endogenizing the choice of heating technology under economic constraints for the affordability analysis of carbon pricing and ii) including the capital expenditure associated with a heating technology in the household burden. The consideration of these aspects has two implications. First, it allows for the fact that the affordability impacts may differ depending on how a household responds to carbon pricing in terms of heating technology choice. Second, by including the capital expenditure for a heating technology, we consider another factor that affects heating-related expenditure and therefore affordability.

1.3 Outline

The remainder of the paper is structured as follows. Section 2 introduces the theoretical framework and derives conditions for the optimal heating technology choice under carbon pricing. Section 3 applies this framework to analyze the affordability impacts of carbon pricing with and without a renewable heating subsidy and a lump-sum transfer as compensation policies. Section 4 discusses our results with regard to the previous findings from the literature and several limitations of our theoretical framework. Section 5 concludes.

2 Theoretical framework

2.1 Conventional affordabiltiy ratio

There is a variety of indicators in the literature for measuring the monetary burden related to the consumption of basic utilities such as heating, each of which is characterized by its own conceptual strengths and weaknesses (Castaño-Rosa et al., 2019; Charlier & Legendre, 2021; Gawel et al., 2017; Heindl & Schüßler, 2015). A common affordability measure is the conventional affordability ratio (CAR) (Gawel & Bretschneider, 2014; Hulchanski, 1995). It sets the expenditure for an energy service in relation to the household income. We deliberately choose the CAR due its frequent use both in the scientific and public debate for a wide range of utilities (Bourgeois et al., 2021; Glied, 2009; Malpezzi, 2023; Martins et al., 2023). We apply this measure to the case of residential heating and define it as

$$r = \frac{(p_e + \tau\gamma)e + K}{B}. \tag{1}$$

We consider the heating expenditure consisting of two components. First, the energy expenditure which is the product of energy consumption e and the energy price p_e and a carbon price τ. The carbon intensity γ denotes the CO_2-intensity of the energy carrier. Second, capital expenditure K on the employed heating technology, which occur independently from energy consumption. The consideration of this expenditure novel, as it is usually not part of the CAR or other indicators. The inclusion is crucial to understand the affordability impacts of the endogenous technology choice. Think of K for instance as the costs for purchasing and installing a heating technology. This could be the total cost or, for example, a monthly loan payback in case of a homeowner or a rent premium that is passed on to a tenant by the landlord. Total heating-related expenditures are divided by income B to obtain the burden of the household. An affordability problem occurs if this burden exceeds some normatively defined threshold. There exist several approaches on how to define such a threshold. For instance, the ten-percent rule indicates an affordability problem if the share of expenditure on an adequate quantity of heating or energy services exceeds ten percent of the household's income (Boardman, 1991). However, any threshold requires multiple normative definitions (Gawel & Bretschneider, 2014; Gawel et al., 2017). We refrain from such definitions and the use of a threshold as our primary research interest is whether and how carbon pricing increases the burden on a household. An increase in the burden does not have to be problematic per se, but can be an indication that affordability is impaired. To this end we set up a microeconomic model to derive the optimal heating-related expenditure of a household which we shall embed into (1). However, the CAR exhibits weaknesses in terms of adequately measuring affordability issues which have been amply demonstrated in the literature (Gawel & Bretschneider, 2014). First, preference-related high consumption of heating services, for example, can lead to a high measured burden that is not based on an affordability problem (so-called "overconsumption" or false-positive indication). Second, the consumption of heating services may already have been severely restricted due to a low income, so that the CAR does not show a high burden even though there is an affordability problem (so-called "underconsumption" or false-negative indication). To address these issues, we complement the analysis by considering the impacts of carbon pricing on household utility.

2.2 Household model

In a given period, a household with income B consumes two goods: a heating service s, e.g. the average room temperature in degree Celsius, and a composite good x with the price $p_x = 1$. To consume s the household purchases energy e at price p_e and transforms it into s with $e = s$. We assume a Cobb-Douglas utility function which reads

$$U = U(s, x) = s^{\alpha} x^{1-\alpha} \tag{2}$$

with $0 < \alpha < 1$. We deliberately omit the usual subsistence quantities to maintain tractability when determining the household's optimal heating technology choice. We will discuss the implications of this assumption later. The household needs to choose a heating technology $j \in \{F, R\}$. F represents a fossil fuel-based technology (e.g., a gas boiler) and R a renewable technology (e.g., a heat pump operated with electricity generated from renewable energy sources). The technologies exhibit two attributes. First, the carbon intensity γ_j which indicates the CO_2-emissions associated with transforming one unit of e into one unit of s. We assume $\gamma_F > \gamma_R = 0$. Second, capital expenditure K_j with $K_R > K_F$. Assuming $B > K_F$ ensures that the household is at least able to use technology F. The resulting emissions $\gamma_j e$ are subject to the carbon price τ, which is borne by the household.[3] Note that we do not consider any non-pecuniary individual benefits of emissions reduction (e.g., avoided climate damages or air pollution) in order to keep the

[3] We abstract from any other publicly set price components such as energy, fuel or electricity taxes. That is the difference in the price of consuming one more unit of heating services with the two technologies is solely determined by the carbon intensity.

analysis as simple as possible. The budget constraint of the household reads

$$B = (p_e + \tau\gamma_j)e + x + K_j. \tag{3}$$

Inspired by Levinson (2019), our model represents the consumption and technology choice as a static decision problem, so we abstract from intertemporal considerations. To solve the household's decision problem analytically, think of it as a two-stage optimization problem (Deaton & Muellbauer, 1980; Harker Steele & Bergstrom, 2022). In the first stage, the household chooses the heating technology at cost K_j. In the second stage, it chooses the consumption quantities of s and x. Assuming perfect information across the two stages we derive the household's optimal choices with backwards induction. Maximizing utility (2) subject to the budget constraint (3) yields the following first-order conditions:

$$\frac{x}{e} = \frac{1-\alpha}{\alpha}(p_e + \tau\gamma_j) \tag{4}$$

$$B = (p_e + \tau\gamma_j)e + x + K_j \tag{5}$$

and optimal quantities:

$$e^* = \alpha\frac{B - K_j}{p_e + \tau\gamma_j} \tag{6}$$

$$x^* = (1-\alpha)(B - K_j). \tag{7}$$

The optimal choice of technology is not obvious and the demand functions illustrate the trade-off the household faces. With $j = F$ it has more income at its disposal to consume heating services and other goods but will face a higher consumer price for heating services due to the carbon price. With $j = R$ it can reduce the consumer price for heating services by eliminating the carbon price at the cost of paying a higher up-front cost for the heating technology and having less income at its disposal for the consumption of heating services and other goods. The optimal technology choice is determined by comparing the indirect utility for each of the two technologies (Deaton & Muellbauer, 1980; Thompson, 2002). The household chooses the technology for which it can obtain the maximum indirect utility from consuming s and x:

$$\max\left\{\underbrace{\left(\alpha\frac{B-K_F}{p_e+\tau\gamma_F}\right)^{\alpha}((1-\alpha)(B-K_F))^{1-\alpha}}_{\text{utility with } j=F \text{ (\textit{fossil fuel heating})}}, \underbrace{\left(\alpha\frac{B-K_R}{p_e}\right)^{\alpha}((1-\alpha)(B-K_R))^{1-\alpha}}_{\text{utility with } j=R \text{ (\textit{renewable heating})}}\right\}.$$

To determine the conditions under which a household chooses the renewable technology, we apply the following inequality:

$$\left(\alpha\frac{B-K_F}{p_e+\tau\gamma_F}\right)^{\alpha}((1-\alpha)(B-K_F))^{1-\alpha} < \left(\alpha\frac{B-K_R}{p_e}\right)^{\alpha}((1-\alpha)(B-K_R))^{1-\alpha}. \tag{8}$$

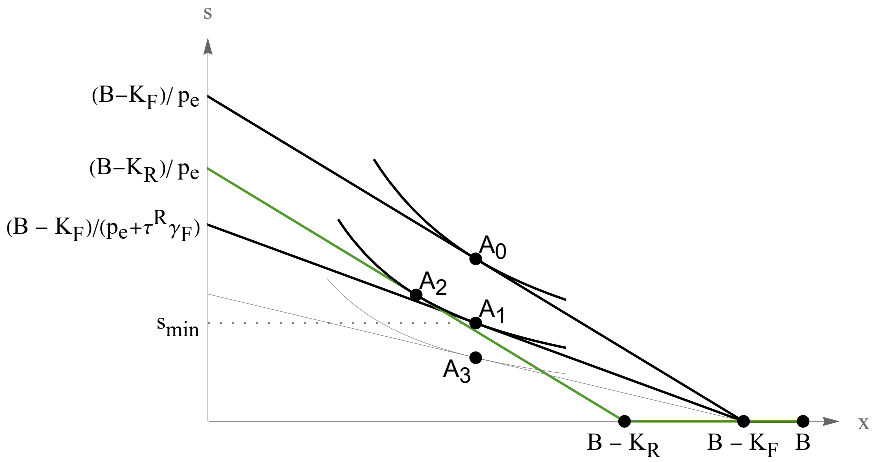

Figure 1: Comparative static analysis of the impact of carbon pricing on optimal consumption and technology choice if the household is able to choose the renewable heating technology $(B > K_R)$.

This inequality holds and the household chooses the renewable technology if the following conditions are met.

- *Ability condition*: The household's income exceeds the capital expenditure for the renewable heating technology:

$$B > K_R. \tag{9}$$

- *Willingness condition*: The carbon price is sufficiently high to render the renewable heating technology the optimal choice:

$$\tau > \tau^R. \tag{10}$$

The willingness condition is obtained by rearranging (8) for τ. The carbon price threshold reads

$$\tau^R = \frac{p_e}{\gamma_F}\left(\left(\frac{B-K_F}{B-K_R}\right)^{\frac{1}{\alpha}} - 1\right). \tag{11}$$

Hence, the optimal technology choice is given by

$$j^* = \begin{cases} F & \text{if } B > K_R \wedge \tau \leq \tau^R \vee B \leq K_R, \\ R & \text{if } B > K_R \wedge \tau \geq \tau^R \end{cases}. \tag{12}$$

If neither (9) nor (10) is met, the household's optimal technology choice is the fossil-fuel technology (F). Note that (11) is only defined for $B > K_R$ such that it only applies if the ability condition holds for the household. Further note that $\frac{\partial \tau^R}{\partial B} < 0$ which means that the carbon price threshold declines with income. The higher the income, the lower ceteris paribus the carbon price necessary to render the renewable heating technology the optimal choice.

A comparative static analysis allows for a closer examination of the adjustment reactions to the carbon price. Suppose the ability condition holds ($B > K_R$). When a carbon price is introduced the household simply reduces consumption of heating services if the carbon price not greater than τ^R. This is illustrated in Figure 1, where the optimal consumption bundle changes from point A_0 to point A_1. At point A_1 the carbon price equals τ^R such that the household is indifferent between the two technologies. If $\tau = \tau^R$ the household consumes the quantity

$$s_{min} = \alpha \frac{B - K_F}{p_e + \tau^R \gamma_F} = \frac{\alpha}{p_e} \frac{(B - K_R)^{\frac{1}{\alpha}}}{(B - K_F)^{\frac{1-\alpha}{\alpha}}} \tag{13}$$

which represents the minimum amount of heating services the household is willing to consume (e.g., a minimum room temperature). Note that $\frac{\partial s_{min}}{\partial B} > 0$ holds which shows that s_{min} increases with income and thus ceteris paribus a lower income means that the household is willing to curb consumption of heating services to a lower level than with a higher income.[4] Assuming the carbon price exceeds τ^R and the technology choice $j = F$ remains unchanged, the household would have to reduce the consumption of heating services below s_{min}, i.e. consume the bundle A_3. However, a utility maximizing household chooses to adopt the renewable heating technology, thus reducing consumption of other goods and increasing consumption of heating services (bundle A_2). As a result of the carbon price being eliminated, the relative marginal prices of the two goods change. The first-order condition in (4) indicates that the household now consumes relatively more heating services. The relative increase in consumption of heating services between bundle A_1 and A_2 is driven not only by reduced consumption of other goods (due to the higher capital expenditure K_R) but also by increased consumption of heating services (due to the lower per unit price of heating services). This is straightforward because a utility-maximizing household would not be willing to reduce the consumption of other goods without increasing the consumption of heating services.[5] If the ability condition does not hold ($B \leq K_R$) the household can and will only adjust by reducing consumption of heating services and there is no minimum quantity of heating services.

3 Affordability analysis

In this section, we turn to answering our research questions. First, we embed the renewable technology choice conditions (ability and willingness) into the CAR to investigate

[4] $\frac{\partial s_{min}}{\partial B} = \frac{(B-K_F)-(1-\alpha)(B-K_R)}{(B-K_R)\left(\frac{B-K_F}{B-K_R}\right)^{\frac{1}{\alpha}} p_e} > 0$ holds since $(B - K_R) \quad \frac{B-K_F}{B-K_R}\Big) p_e > 0$ and $(B - K_F) - (1 - \alpha)(B - K_R) > 0$.

[5] The consumed quantity of heating services is strictly greater with the renewable heating technology if $\tau > \tau^R$. The inequality $\alpha \frac{(B-K_R)}{p_e} > \alpha \frac{B-K_F}{p_e+\tau^R\gamma_F}$ reduces to $K_R > K_F$ which is true by assumption. Note that without a carbon price, the household would strictly consume more heating services because it would always choose the fossil technology and thus would have more income available compared to the renewable technology.

the affordability effects of the carbon price under endogenous technology choice. We then analyze the impact of the introduction of compensation policies on affordability, also considering that compensation policies may change the household's technology choice. We complement the analysis of the CAR by considering the corresponding impacts on household utility.

3.1 Carbon pricing only

We first embed the derived conditions for the optimal technology choice and corresponding consumption of energy and associated capital expenditure in the CAR. Substituting the optimal energy consumption (6) and capital expenditure K_j for each technology j into the CAR (1) yields:

$$r = \begin{cases} r_F = \alpha + \frac{(1-\alpha)K_F}{B} & \text{if } B > K_R \wedge \tau < \tau^R \vee B \leq K_R, \\ r_R = \alpha + \frac{(1-\alpha)K_R}{B} & \text{if } B > K_R \wedge \tau > \tau^R \end{cases} . \quad (14)$$

If the household is not able to choose the renewable heating technology ($B \leq K_R$) it faces the burden r_F which does not change with the carbon price (see the orange line in Figure 2. This is because the household allocates a fixed share α of its income (net of K_F) to the procurement of energy to consume heating services. This means as the carbon price internalizes external costs and increases the consumer price of energy, the household will reduce consumption of heating services proportionally. If the household is able but not willing to choose the renewable heating technology ($B > K_R \wedge \tau < \tau^R$) it also faces the burden r_F which is however lower in this case due to the higher income (see the blue line in Figure 2). The burden increases if the carbon price is sufficiently high ($\tau > \tau^R$) such that the household is willing to choose the renewable heating technology ($j^* = R$). The total of the increase is described by $r_R - r_F = \frac{(1-\alpha)(K_R - K_F))}{B}$ and can be decomposed into two effects. First, the expenditure share on heating services decreases by $\frac{\alpha(K_R - K_F)}{B}$ as the income available for consumption is reduced. Second, the expenditure share on capital expenditure increases by $\frac{K_R - K_F}{B}$. The latter effect outweighs the former. Carbon pricing thus increases the household's burden through the choice of the renewable technology. Note that $\frac{\partial(r_R - r_F)}{\partial B} < 0$ and $\frac{\partial(r_R - r_F)}{\partial(K_R - K_F)} > 0$, i.e. a higher income ceteris paribus reduces the increase in the burden, while a larger difference between capital expenditures amplifies it.

We complement this perspective by considering the impacts of carbon pricing on household utility. Overall, carbon pricing results in a loss of utility regardless of the household's ability and willingness to choose the renewable heating technology (see Figure 3). However, given the ability condition holds ($B > K_R$), the household can potentially limit the utility loss (see the blue line in Figure 3). That is, if $\tau > \tau^R$, the household makes itself better off by choosing the renewable technology compared the choice of the fossil fuel technology (see the part of the blue line right of τ^R). This corresponds to the increase in the burden from r_F to r_R. If on the other hand, the ability condition does not apply

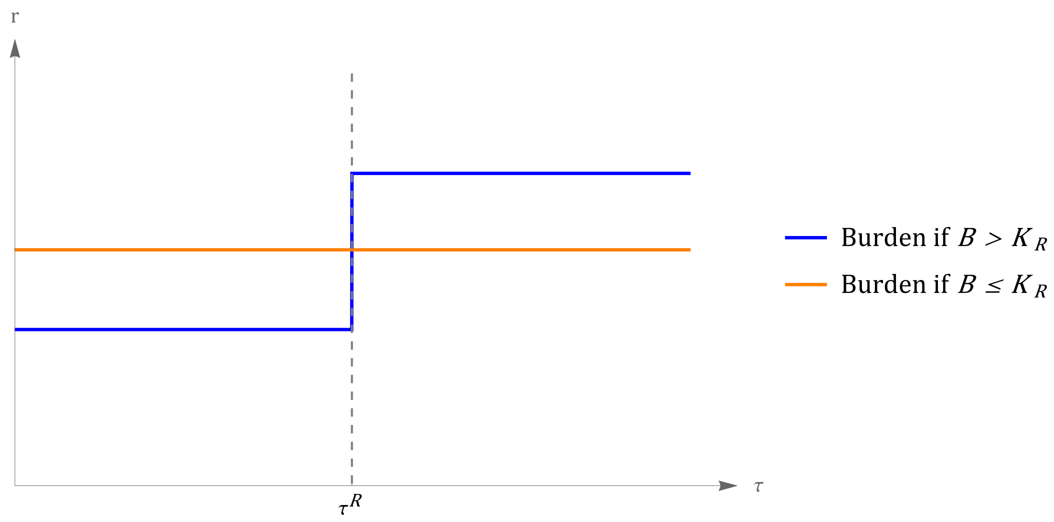

Figure 2: Heating-related expenditure burden on the household, differentiated by whether the ability condition for choosing the renewable heating technology is met $(B > K_R)$ or not $(B \leq K_R)$.

$(B \leq K_R)$, the household has no possibility to limit the utility loss. With respect to the impacts of carbon pricing on the affordability of residential heating, we con-clude the following. First, carbon pricing increases the burden if the household is able and willing to choose the renewable heating technology in response. The increase is due to the higher capital expenditure for the renewable heating technology. The choice of the renewable heating technology allows the household to limit the utility loss associated with carbon pricing. Second, carbon pricing does not increase the burden if the household chooses the fossil fuel heating technology. This is the case when the household is able but not willing or not able to choose the renewable heating technology. In the latter case, the household has no possibility to limit the utility loss through the choice of the renewable heating technology.

3.2 Assessment of compensation policies

3.2.1 Impact on the household's optimal technology choice

Now assume that a fixed public budget M is available to reduce the household's burden and improve the affordability of heating services. We consider the use of M for two different policies, a renewable heating subsidy and a lump-sum transfer.[6] Using M as a subsidy reduces the capital expenditure for the renewable heating technology to $K_R - M$. Using M as a lump-sum transfer increases the household's income to $B + M$. We assume that regardless of which of the two policies M represents, its level is constrained to $M < K_R$.

[6]There are other possibilities for compensation policies that we are not considering here. These include, for example, i) a lump-sum or targeted transfer, the amount of which is determined endogenously by the revenue from carbon pricing, ii) a reduction in taxes and levies on low-carbon energy sources or iii) the price subsidization of the amount of energy required to provide a normatively defined basic need of heating services.

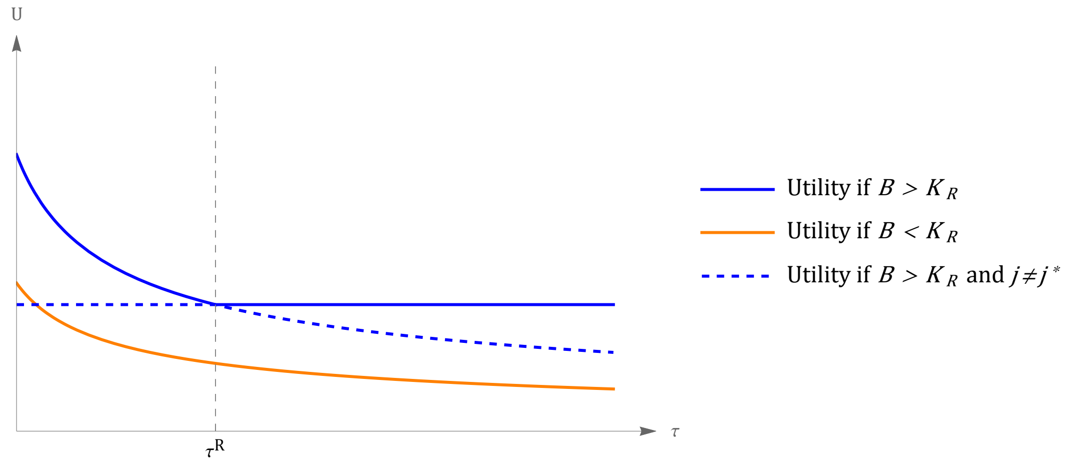

Figure 3: Household utility depending the carbon price. Utility is shown assuming the ability condition for choosing the renewable heating technology is met and the household makes the optimal technology decision ($B > K_R$) or not ($B > K_R$ and $j \neq j^*$) and assuming the ability condition is not met ($B \leq K_R$).

First, we briefly analyze the impacts of the two policies on the household's optimal technology choice (for a more detailed analysis see Appendix A). Subsequently, we analyze the two policies with respect to their impact on the CAR and utility. Using M as a *subsidy* lowers both the ability and willingness condition. The household is able to choose the renewable heating technology if its income is greater than the subsidized capital expenditure. This means that the income level necessary to meet the ability condition is lowered. The ability condition now reads

$$B > K_R - M \tag{15}$$

The willingness condition is lowered since the subsidy ceteris paribus increases the utility level for choosing the renewable technology (corresponding to a parallel shift of the green budget con-straint to the right in Figure 1). Therefore, a lower carbon price is necessary for it to become the optimal choice. The willingness condition is given by:

$$\tau > \tau^R_{sub} \tag{16}$$

with

$$\tau^R_{sub} = \frac{p_e}{\gamma_F}\left(\left(\frac{B - K_F}{B - K_R + M}\right)^{\frac{1}{\alpha}} - 1\right) \tag{17}$$

and $\tau^R_{sub} < \tau^R$.

Using M as a *transfer* lowers the ability condition and the willingness condition too. The ability condition is changed by the increased income to $B + M > K_R$. Hence, the ability condition is the same as in (15). The willingness condition is also lowered, but not as strong as with the subsidy:

$$\tau > \tau^R_{tran} \tag{18}$$

with

$$\tau_{tran}^{R} = \frac{p_e}{\gamma_F}\left(\left(\frac{B-K_F+M}{B-K_R+M}\right)^{\frac{1}{\alpha}} - 1\right) \tag{19}$$

and $\tau^R > \tau_{tran}^R > \tau_{sub}^R$. The heterogenous impact on the willingness condition of the two policies can be explained by their different impact on the utility resulting from the choice of a heating technology. Both policies ceteris paribus increase the utility of choosing the renewable technology by the same extent through relaxing the budget constraint. This renders the renewable technology more attractive compared to a setting without the subsidy or transfer. The transfer also increases utility of choosing the fossil fuel technology. Thus, compared to the subsidy, the relative increase in utility of choosing the renewable technology is mitigated, because the utility of choosing the fossil fuel technology is also increased (see Appendix A for a more detailed analysis).

3.2.2 Compensation effects

We adapt the CAR in (14) for each policy. Using M as a subsidy we get:

$$r^{sub} = \begin{cases} r_F = \alpha + \frac{(1-\alpha)K_F}{B} & \text{if } B > K_R - M \wedge \tau < \tau_{sub}^R \vee B \leq K_R - M, \\ r_R^{sub} = \alpha + \frac{(1-\alpha)(K_R-M)}{B} & \text{if } B > K_R - M \wedge \tau > \tau_{sub}^R \end{cases}. \tag{20}$$

Using M as a lump-sum transfer we get:

$$r^{tran} = \begin{cases} r_F^{tran} = \alpha + \frac{(1-\alpha)K_F}{B} & \text{if } B + M > K_R \wedge \tau < \tau_{tran}^R \vee B + M \leq K_R, \\ r_R^{tran} = \alpha + \frac{(1-\alpha)(K_R)}{B+M} & \text{if } B + M > K_R \wedge \tau > \tau_{tran}^R \end{cases}. \tag{21}$$

The inequalities $r_R > r_R^{tran} > r_R^{sub}$ and $r_F > r_F^{tran}$ apply. For a meaningful analysis of the impact of the two policies on the burden as measured by the CAR, we consider the outcome without any compensation policy as the baseline. This baseline may vary depending on which conditions in (1) are met in the absence of compensation policies, leading to multiple possible outcomes with the introduction of these policies as shown in Figure 4. For example, the impact of a subsidy depends on the household's technology choice in a setting without a subsidy and whether the subsidy changes the choice. This results in ten possible cases per compensation policy which are numbered and labelled with *S* and *T* denoting the subsidy and the transfer, respectively as shown in Table 3 and illustrated in Figure 4. The corresponding impacts on household utility are shown in Table 1.

Renewable heating subsidy The results in Table 3 show that a subsidy strictly reduces the burden if the household's optimal choice is the renewable heating technology without the subsidy (case *S1*). The household is already able and willing to use the renewable technology without a subsidy such that the subsidy simply lowers the burden by reducing the capital expenditure. An ambiguous effect occurs if the subsidy shifts the household's optimal technology choice towards the renewable technology. That is, the household is only able and willing to choose the renewable technology due to the subsidy (case *S2*-*S4* and *S6*-*S8*). Since the difference in the burden on a household for the two technologies depends solely on the level of the respective capital expenditure, the effect of the subsidy depends on the extent to which it compensates for this difference. This means that it depends on the level of the subsidy whether the choice of subsidized renewable heating technology in-creases or decreases the burden on the household. In all the aforementioned cases, the subsidy is also utility enhancing (see Table 1). Finally, there is no effect on the burden if the households' inability or unwillingness to choose the renewable heating technology is not overcome by the subsidy (case *S5*, *S9*, and *S10*). This is straightforward because the household does not benefit from the subsidy. Hence, the utility level of the household is not affected as well.

Lump-sum transfer With regard to the lump-sum transfer the results in Table 3 demonstrate that it strictly reduces the burden if the household's optimal technology choice (be it the fossil fuel or the renewable heating technology) remains unaffected (case *T1*, *T5*, *T9*, and *T10*). Since the choice of technology does not change, and therefore neither do the capital expenditure borne by the household, the increase in income simply reduces the burden on the household. This shows that a transfer in contrast to a subsidy can reduce the burden on a household, even if it is not able or willing to use a renewable technology[7]. An ambiguous compensation effect occurs if the lump-sum transfer shifts the household's optimal technology choice towards the renewable technology (case *T2*-*T4* and *T6*-*T8*). It is therefore not clear whether a transfer that changes the household's decision in favor of renewable technology leads to an increase or a reduction in the burden. Note that here it is not as straightforward as with the subsidy whether the burden increases or decreases. The direction of the effect inter alia depends on the relative level of the capital expenditures and the level of the subsidy. Finally, note that a lump-sum transfer strictly enhances the household's utility level in all cases (see Table 1).

[7]Moreover, the burden (utility) is even lower (higher) than without the carbon price, since in case of the fossil fuel technology it strictly decreases (increases) as the household's income is increased by the lump-sum transfer.

Table 1: Utility impacts of compensation policies.

Compensation policy	**Case**	**Technology choice j^***			**Utility**			
		Without compensation policy	**With compensation policy**	**Change**	**Without compensation policy**		**With compensation policy**	**Change**
Subsidy	S1	R	R	No	$U_{1,R}$	$<$	$U_{1,R}^{sub}$	$\uparrow$
	S2-S4	F	R	Yes	$U_{2-4,F}$	$<$	$U_{2-4,R}^{sub}$	$\uparrow$
	S5	F	F	No	$U_{5,F}$	$=$	$U_{5,F}$	0
	S6-S8	F	R	Yes	$U_{6-8,F}$	$<$	$U_{6-8,R}^{sub}$	$\uparrow$
	S9	F	F	No	$U_{9,F}$	$=$	$U_{9,F}$	0
	S10	F	F	No	$U_{10,F}$	$=$	$U_{10,F}$	0
Transfer	T1	R	R	No	$U_{1,R}$	$<$	$U_{1,R}^{tran}$	$\uparrow$
	T2-T4	F	R	Yes	$U_{2-4,F}$	$<$	$U_{2-4,R}^{tran}$	$\uparrow$
	T5	F	F	No	$U_{5,F}$	$<$	$U_{5,F}^{tran}$	$\uparrow$
	T6-T8	F	R	Yes	$U_{6-8,F}$	$<$	$U_{6-8,R}^{tran}$	$\uparrow$
	T9	F	F	No	$U_{9,F}$	$<$	$U_{9,F}^{tran}$	$\uparrow$
	T10	F	F	No	$U_{10,F}$	$<$	$U_{10,F}^{tran}$	$\uparrow$

Table 2: Impact of compensation policies on the household's burden.

	Case	Ability and willingness with carbon pricing		Technology choice j^*			Further conditions	Burden			
		Without compensation policy	**With compensation policy**	**Without compensation policy**	**With compensation policy**	**Change**		**Without compensation policy**		**With compensation policy**	**Change**
Subsidy	S1	$B > K_R \wedge \tau > \tau^R$		R	R	No		r_R	$>$	r_R^{sub}	↓
	S2	$B > K_R \wedge \tau < \tau^R$	$\tau > \tau_{sub}^R$	F	R	Yes	$K_R - M > K_F$	r_F	$<$	r_R^{sub}	↑
	S3			F	R	Yes	$K_R - M = K_F$	r_F	$=$	r_R^{sub}	0
	S4			F	R	Yes	$K_R - M < K_F$	r_F	$>$	r_R^{sub}	↓
	S5		$\tau < \tau_{sub}^R$	F	F	No		r_F	$=$	r_F	0
	S6	$B \leq K_R$	$B > K_R - M \wedge \tau > \tau_{sub}^R$	F	R	Yes	$K_R - M > K_F$	r_F	$<$	r_R^{sub}	↑
	S7			F	R	Yes	$K_R - M = K_F$	r_F	$=$	r_R^{sub}	0
	S8			F	R	Yes	$K_R - M < K_F$	r_F	$>$	r_R^{sub}	↓
	S9		$B > K_R - M \wedge \tau < \tau_{sub}^R$	F	F	No		r_F	$=$	r_F	0
	S10		$B \leq K_R - M$	F	F	No		r_F	$=$	r_F	0
Transfer	T1	$B > K_R \wedge \tau > \tau^R$		R	R	No		r_R	$>$	r_R^{tran}	↓
	T2	$B > K_R \wedge \tau < \tau^R$	$\tau > \tau_{tran}^R$	F	R	Yes	$K_F \leq a \vee$ $K_F > a \wedge B \leq b \wedge M < c \vee$ $K_F > a \wedge B > b$	r_F	$<$	r_R^{tran}	↑
	T3			F	R	Yes	$a < K_F \wedge B < b \wedge M > c$	r_F	$>$	r_R^{tran}	↓
	T4			F	R	Yes	$K_F > K_R^2/(K_R + M) \wedge$ $B = d$	r_F	$=$	r_R^{tran}	0
	T5		$\tau < \tau_{tran}^R$	F	F	No		r_F	$>$	r_F^{tran}	↓
	T6	$B \leq K_R$	$B > K_R - M \wedge \tau > \tau_{tran}^R$	F	R	Yes	$BK_R/(B + M) > K_F$	r_F	$<$	r_R^{tran}	↑
	T7			F	R	Yes	$BK_R/(B + M) < K_F$	r_F	$>$	r_R^{tran}	↓
	T8			F	R	Yes	$K_R - M < K_F <$ $K_R^2/(K_R + M) \wedge B = d$	r_F	$=$	r_R^{tran}	0
	T9		$B > K_R - M \wedge \tau < \tau_{tran}^R$	F	F	No		r_F	$>$	r_F^{tran}	↓
	T10		$B \leq K_R - M$	F	F	No		r_F	$>$	r_F^{tran}	↓

Note: $a = K_R/2$, $b = K_F K_R/(K_R - K_F)$, $c = B(K_R - K_F)/K_F$, $d = K_F M/(K_R - K_F)$.

Table 3: Comparison of compensation policies with respect to their effectiveness in reducing the household's burden.

Cases		Ability and willingness		Further conditions	Change in technology choice		More effective policy
Subsidy	Transfer	Without policy	With policy		Subsidy	Transfer	
S1	T1	$B > K_R \wedge \tau > \tau^R$			No	No	Subsidy
S2-S4	T2-T4	$B > K_R \wedge \tau < \tau^R$	$\tau > \tau^R_{tran} > \tau^R_{sub}$		Yes	Yes	Subsidy
S2-S4	T5		$\tau^R_{tran} > \tau > \tau^R_{sub}$	$K_F + M \leq K_R \vee$ $B < f \wedge K_F + M > K_R \wedge g < K_R$	Yes	No	Transfer
				$B > f \wedge K_F + M > K_R \wedge g < K_R$ $\vee g > K_R$	Yes	No	Subsidy
				$K_F + M > K_R \wedge g < K_R \wedge B = f$	Yes	No	Equal
S5	T5		$\tau < \tau^R_{sub} < \tau^R_{tran}$		No	No	Transfer
S6-S8	T6-T8	$B \leq K_R$	$B > K_R - M \wedge \tau > \tau^R_{tran} > \tau^R_{sub}$		Yes	Yes	Subsidy
S6-S8	T9		$B > K_R - M \wedge \tau^R_{tran} > \tau > \tau^R_{sub}$	$B \leq M \wedge K_R > h \vee$ $B \leq M \wedge K_F < i \wedge K_R \leq h$ $\vee B > M \wedge K_F < i \wedge K_R \leq h$ $\vee B > M \wedge K_R > h$	Yes	No	Transfer
				$K_R < h \wedge K_F > i \wedge B \leq M \vee$ $K_R < h \wedge K_F > i \wedge B > M$	Yes	No	Subsidy
				$K_F + M^2/K_R > K_R \wedge K_R +$ $\sqrt{K_R^2 + 2K_RM - 3M^2} >$ $2K_F + M \wedge B = ((K_R - M)M)(K_F - K_R + M)$	Yes	No	Equal
S9	T9		$B > K_R - M \wedge \tau^R_{tran} > \tau^R_{sub} > \tau$		No	No	Transfer
S10	T10		$B \leq K_R - M$		No	No	Transfer
Note: $f = ((K_R - M)M)/(K_F - K_R + M)$, $g = K_F + M^2/K_R$, $h = (B^2 + BM + M^2)/(B + M)$, $i = ((K_R - M)(B + M))/B$.							

Comparison of the effectiveness of compensation policies We now analyze which of the two instruments achieves a greater compensation effect by comparing the cases outlined above. For a meaningful comparison, it needs to be carefully distinguished whether the two policies are equivalent with respect to their impact on the optimal technology choice j^*. For example, the subsidy could result in $j^* = R$ while a transfer would result in $j^* = F$ (i.e., $\tau_{sub}^R < \tau < \tau_{tran}^R$) which means that we need to compare r_R^{sub} with r_F^{tran}. The results are summarized in Table 3. The relative merits of the two policies in terms of burden reduction depend in particular on i) the optimal technology choice in the absence of any compensation policy, and ii) whether the optimal technology choice is changed by their introduction. We draw the following conclusion with respect to the relative effectiveness of the two compensation policies.

First, the renewable heating subsidy is the most effective compensation policy if the renewable heating technology is the optimal choice with carbon pricing only. This applies if the household is able and willing to choose the renewable technology in absence of any compensation policy (*S1* and *T1*). Thus, for households in no need of any further incentive or support in addition to the carbon price to choose the renewable technology the relief is greater with a subsidy.

Second, the subsidy is also more effective if both instruments alter the household's optimal technology choice toward the renewable technology. This only applies if the lump-sum transfer as well as the subsidy fulfill both conditions for the choice of renewable technology (*S2-S4* and *T2-T4*, *S6-S8* and *T6-T8*). That is, if the household requires further incentive or support beyond the carbon price to choose the renewable technology which can be provided by both instruments, the relief is greater with a subsidy.[8]

Third, while the subsidy is superior in terms of reducing the burden on the household in all of the aforementioned cases, both polices are equivalent in terms of their utility impacts across these cases (see Table 4).

Fourth, the relative effectiveness of compensation policies is ambiguous if only the subsidy alters the household's optimal technology choice towards the renewable heating technology. Hence, the subsidy or the lump-sum transfer might result in a lower burden. This applies if the ability and willingness condition are only fulfilled with the subsidy but not with the lump-sum transfer (*S2-S4* and *T5*, *S6-S8* and *T9*). Which policy is most effective depends on the household's income, the capital expenditures associated with the two heating technologies and the public budget. That is, if the household requires further incentive or support beyond the carbon price to choose the renewable technology which can be provided only by the subsidy, it is not straightforward which policy results in a greater relief. This depends on income, the capital expenditure for the heating technology and the public budget.

Fifth, while the relative effectiveness of the compensation policies in terms of reducing

[8] The different burden indicated by the CAR results from the fact that with the subsidy the capital expenditure K_R in the numerator is reduced by M while with the transfer the income in the denominator is increased by M in equation (20) and (21), respectively.

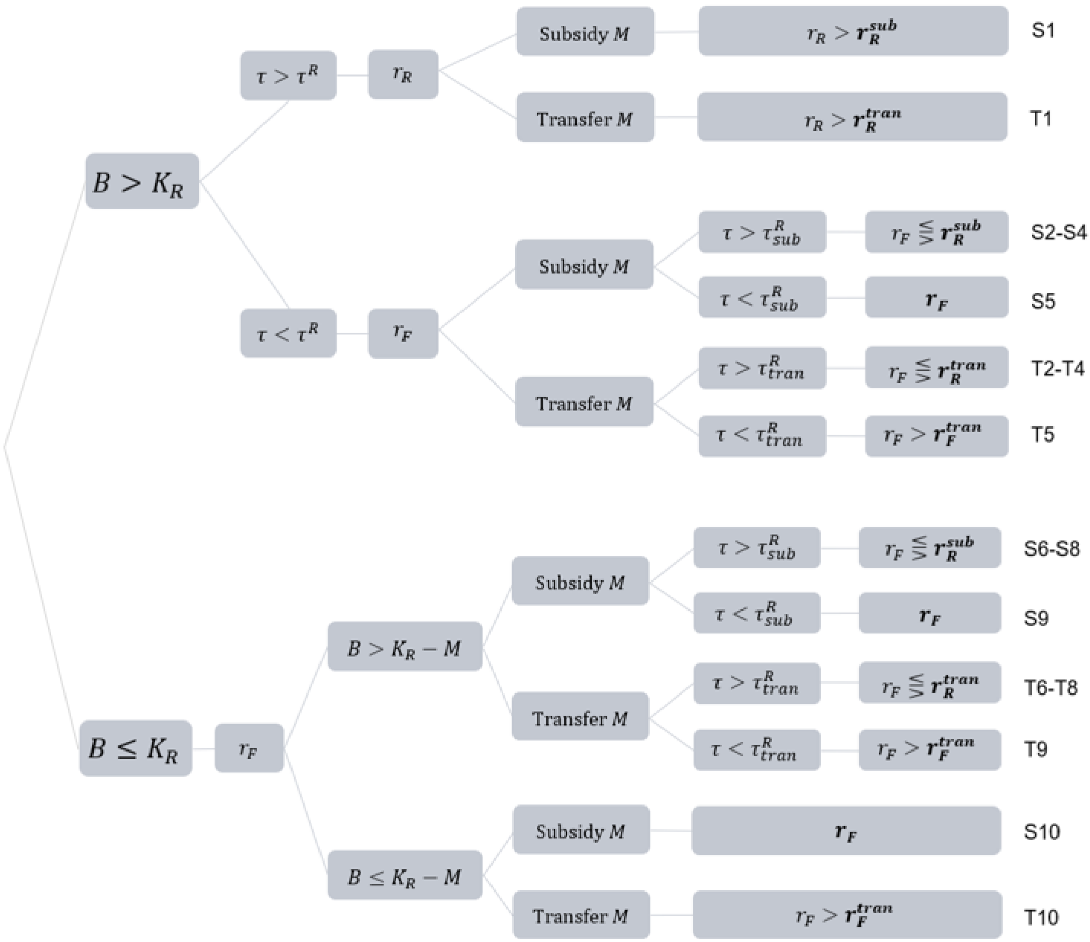

Figure 4: Impact of compensation policies on the household's burden. The burden of the household under the respective compensation policy is printed in bold.

Table 4: Comparison of utility impacts of compensation policies.

Cases		Technology choice j^*					Utility			
Sub-sidy	Trans-fer	Without compen-sation policy	Sub-sidy	Trans-fer	Change		Sub-sidy		Trans-fer	Utility optimal policy
					Sub-sidy	Trans-fer				
S1	T1	R	R	R	No	No	$U^{sub}_{1,R}$	$=$	$U^{tran}_{1,R}$	both
S2-S4	T2-T4	F	R	R	Yes	Yes	$U^{sub}_{2-4,R}$	$=$	$U^{tran}_{2-4,R}$	both
S2-S4	T5	F	R	F	Yes	No	$U^{sub}_{2-4,R}$	$<$	$U^{tran}_{5,F}$	Transfer
S5	T5	F	F	F	No	No	$U_{5,F}$	$<$	$U^{tran}_{5,F}$	Transfer
S6-S8	T6-T8	F	R	R	Yes	Yes	$U^{sub}_{6-8,R}$	$=$	$U^{tran}_{6-8,R}$	both
S6-S8	T9	F	R	F	Yes	No	$U^{sub}_{6-8,R}$	$<$	$U^{tran}_{9,F}$	Transfer
S9	T9	F	F	F	No	No	$U_{9,F}$	$<$	$U^{tran}_{9,F}$	Transfer
S10	T10	F	F	F	No	No	$U_{10,F}$	$<$	$U^{tran}_{10,F}$	Transfer

the burden is ambiguous in the aforementioned cases, the lump-sum transfer is strictly the optimal policy with regard to the household's welfare across these cases (see Table 4). For the cases of *S2-S4* and *T5*, this is illustrated in Figure 5. If cases *S2-S4* overlap with *T5* ($B > K_R \wedge \tau^R_{sub} < \tau < \tau^R_{tran}$), this means that the subsidy induces the choice of the renewable heating technology while the lump-sum transfer leads to the choice of the fossil fuel technology.

Sixth, a lump-sum transfer is the most effective compensation policy if both policies do not change the ability or willingness to choose the renewable heating technology. This is the case when both of the renewable technology choice conditions are not met with any of the compensation policies (*S5* and *T5*, *S9* and *T9*, *S10* and *T10*). That is, if the household requires further incentive or support in addition to the carbon price to choose the renewable technology which cannot be provided by both policies, the relief is greater with a transfer. Finally, the superiority of the lump-sum transfer in the aforementioned cases also applies to the utility level of the household (see Table 4). This is illustrated in Figure 5 for the cases *S5* and *T5*, i.e. for $B > K_R$ with $\tau < \tau^R_{sub}$.

4 Discussion

4.1 Relation to previous literature

Overall, our analysis shows that the impact of carbon pricing on the affordability of heating depends on the household's optimal technology choice. The burden on the household increases with the carbon price-induced choice of a renewable technology due to the associated higher capital expenditure. However, despite the increase in the burden, the household is better off in terms of utility compared to the choice of the fossil technology and can thus limit the pecuniary utility losses associated with carbon pricing. Our analyses show that different burden situations arise and thus heterogeneous affordability outcomes can be expected for a given set of policies depending on the ability and will-

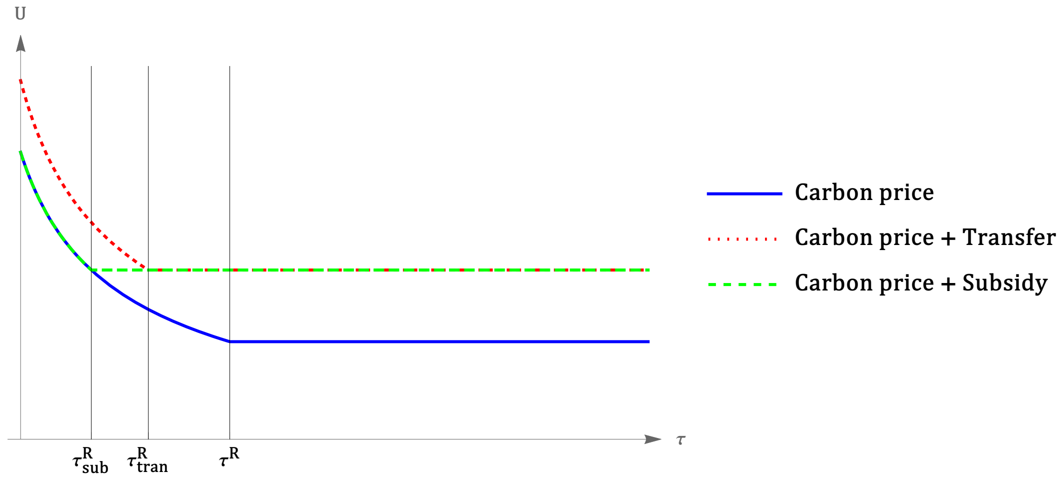

Figure 5: Utility depending on the carbon price without and with compensation policies for $B > K_R$.

ingness of the household to choose a renewable heating technology. Moreover, we define the burden differently by including the capital expenditure on a heating technology. In contrast to the existing literature, we examine the impact on the affordability of an individual household and therefore cannot make any statements on aggregate effects of carbon pricing and compensation policies.

Kaestner et al. (2023) find that the adoption of low-carbon technologies mitigates the regressive incidence of carbon pricing in the long term with assumption of unlimited availability of capital for households. On the one hand, this seems to be consistent with our finding that the choice of a renewable heating technology limits the utility loss due to carbon pricing. On the other hand, we include the capital expenditure for the renewable technology in the burden and show that this increases the burden. Moreover, capital expenditure can represent a barrier in the form of non-ability or non-willingness to choose renewable technology. Bourgeois et al. (2021) allow for the partial avoidance of carbon pricing cost by retrofitting and find that carbon pricing still increases affordability problems in the aggregate via higher energy expenditure. In comparison, our model includes a different means of adjusting to carbon pricing by choosing a renewable heating technology. Our results highlight capital expenditure on a renewable heating technology as another factor in increasing the burden.

With respect to compensation via a lump-sum transfer preexisting studies which do not consider adjustment in technologies find that this reduces the burden on energy services (Berry, 2019; Tovar Reaños, 2021; Vandyck et al., 2023). This is consistent with our results as in cases where the heating technology choice is not changed by the transfer the burden strictly decreases. With regard to the effects of compensation policies when they induce a change in choice of heating technology, it is difficult to relate these to the existing literature. This is because there are no comparable analyses that endogenize the heating technology choice and consider the associated capital expenditure as a burden.

4.2 Limitations

Our analysis exhibits several limitations worth a closer consideration. The first aspect concerns the Cobb-Douglas utility function in our household model which results in a fixed energy expenditure share. Consequently, the burden only changes, given the household's ability to adopt the renewable heating technology, if the carbon price exceeds a certain threshold, i.e., the willingness condition is met. This means that if the household is either not able or able but not willing to choose the renewable technology no change in its burden is observed. In the analysis of the impacts of environmental taxation on the consumption of basic necessities such as energy services, it is typically assumed that the household is restricted to consume an exogenously defined subsistence quantity (Ballard et al., 2005; Geary, 1950; R. Stone, 1954). This means that the household first covers its subsistence needs for heating services before the remaining income is spent according to preferences and relative prices. This results in an inelastic demand function and an expenditure function which is increasing with the price. We expect that including a subsistence quantity for heating services in our model to have several implications. First, the CAR would increase with any marginal increase of the carbon price and not solely with the adoption of the renewable heating technology, i.e. once a certain threshold is surpassed. Second, the ability and willingness condition would become more restrictive. For the ability condition, the income available to cover the capital expenditure for the renewable technology would be lower. Furthermore, the ability condition would become dependent on the carbon price in addition to the capital expenditure for the renewable heating technology. With respect to the willingness condition, we similarly expect that a higher carbon price would be necessary to incentivize the choice of renewable technology. In summary, our model is likely to be overly optimistic with respect to i) the household's reduction in consumption of heating services and ii) its ability and willingness to choose the renewable heating technology. We partially address the concern of subsistence quantities due to the inclusion of endogenous technology choice. As shown above this gives rise to a minimum quantity of heating services s_{min} consumed by the household and therefore puts a lower bound to the consumption of heating services if the household is able to choose the renewable heating technology.[9]

Further limitations concern the assumptions of a homogeneous energy price p_e and efficiencies across the two heating technologies. Empirically, prices for fossil and renewable energy carriers (e.g., electricity generated from renewable energy sources) differ. In many European countries, for example, the price of electricity is higher than the price of gas (Rosenow et al., 2023). However, the technical efficiency of heat pumps, for example, is significantly higher, meaning that despite the higher price of electricity, the price per unit of heating services is lower than for fossil fuel technologies (Öko-Institut & Fraunhofer ISE, 2022). The significance of the technical efficiency for the per unit price of en-

[9] In addition, our attempts to include subsistence quantities showed that this severely limits the tractability of the model. In particular, the optimal technology decision cannot be derived analytically without additional strong assumptions regarding preferences, that is assuming $\alpha = \frac{1}{2}$.

ergy services has been demonstrated theoretically e.g. by Levinson (2019). However, our model still allows for one of the key trade-offs of the technology decision problem of the household. That is, it has to consider higher capital expenditure and a lower per unit price with the renewable heating technology against lower capital expenditure and higher per unit price with the fossil fuel technology. We therefore argue that these assumptions do not significantly limit the explanatory power of our model.

Another limitation concerns the CAR as a measure of affordability due to the conceptual shortcomings discussed in Section 2.1. Against this background, affordability research has developed alternative indicators that address these weaknesses. These include, for example, the potential affordability ratio (Lerman & Reeder, 1987), the residual income approach (Dolbeare, 1966; M. E. Stone, 2006) and the low-income high-cost indicator (Hills, 2012). We therefore acknowledge that considering alternative affordability indicators could enrich the analysis and yield different results. However, we address the shortcomings of the CAR by considering corresponding impacts on household utility.

Another set of limitations concerns behavioral and intertemporal aspects. Since our model is static, jointly analyzing a consumption and investment decision, we abstract from the discounting of cost and benefits that may arise in periods succeeding the technology choice. Furthermore, we thereby disregard myopic behavior implicitly assuming perfect foresight of the household with regard to e.g. the trajectory of future carbon price levels (e.g., in case of an emissions trading system). For example, imperfect foresight of future carbon price levels could lead to a sub-optimal technology choice in our model. Moreover, concerning compensation policies, the impact of the lump-sum transfer and the subsidy on the budget constraint with the renewable heating technology is equivalent in our model, but could be perceived differently by a household in a dynamic setting. In practice, subsidies are commonly granted as a (large) one-time payment in the period of technology choice, whereas a transfer is payed over a longer period of time. Discounting of future lump-sum transfer payments means that their present value is lower than that of a subsidy of the same amount paid up-front. Furthermore, a lack of trust in policy makers to maintain the implementation of a lump-sum transfer over a longer period of time could have similar effects. We expect the consideration of these aspects to widen the gap in the incentive effects of the two instruments and therefore also to have an impact on the optimal choice of technology and the burden on the household.

5 Conclusion

Carbon pricing is an efficient instrument to reduce emissions and is gaining increasing significance in the climate policy mix in many jurisdictions with rising price levels. In addition to the desired incentive and transformation effects, the associated higher prices for heating fuels entail the risk that the affordability of basic needs such as heating services is impaired. This also ac-counts for the capital expenditure associated with the adoption of renewable heating technologies. We study the impacts of carbon pricing on the affordability of residential heating using a microeconomic household model. The key contribution of this paper consists of endogenizing the choice between two heating technologies in our model. To measure the affordability of heating services we employ the CAR which relates the heating-related expenditure to the household's income. We complement this analysis by also considering the impacts on household utility to account for conceptual weaknesses of the CAR.

Overall, our results suggest that the impact of carbon pricing on the affordability of residential heating hinges on the households' ability and willingness to choose a renewable heating technology in response. This means that the adjustment possibilities available to the household are relevant with respect to the affordability impact of carbon pricing. Carbon pricing increases the household's burden for heating services if the household is able and willing to choose a renewable heating technology. The increase is due to the higher capital expenditure for the renewable technology. However, the autonomous choice of the renewable heating technology enables the household to limit the reduction in consumption of heating services and the associated utility losses. In contrast, carbon pricing does not increase the burden if the household is not able or able but not willing to choose the renewable technology. This is due to the isoelastic demand for heating services in our model such that household reduces the consumption of heating services in proportion to a price increase. Given that the household is not able to choose the renewable technology due to low income, it does not have the possibility to choose a renewable technology and thus potentially limit the pecuniary utility losses due to carbon pricing. Moreover, given these results, we argue that it is crucial to include the household's technological adjustment possibilities into the affordability analysis of carbon pricing.

We also analyze the use of a lump-sum transfer and a renewable heating subsidy as two possible means to compensate the household and improve the affordability of heating services. Our findings suggest that there is no clearly preferable instrument with respect to the effectiveness in reducing the burden on the household and potentially improving the affordability of heating services. What is particularly important for the relative effectiveness of the compensation policies is the optimal technology choice of the household with carbon pricing only, and whether the introduction of the subsidy or lump-sum transfer changes the optimal technology choice in favor of renewable technology. We find that a subsidy is more effective than a lump-sum transfer in reducing the household's burden if i) it is able and willing to choose the renewable technology without either of the compensation policies and ii) if both policies change the optimal choice of the household towards the renewable technology. In terms of utility, both policies are equivalently effective in these cases. If only the subsidy leads to the choice of renewable technology, it is unclear which of the two policies achieves the stronger relief effect while the lump-sum trans-fer is superior in terms of utility. If both the lump-sum transfer and the subsidy do not lead to the choice of renewable technology in addition to the carbon price, only the lump-sum transfer has a relief effect and increases utility.

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A Compensation policies

Renewable heating subsidy Using M as a subsidy on K_R changes the budget constraint of the household in case of choosing the renewable technology to

$$B = p_e e + x + K_R - M. \tag{22}$$

This results in the demand functions for e and x of

$$e^*_{sub} = \alpha \frac{B - K_R + M}{p_e} \tag{23}$$

and

$$x^*_{sub} = (1-\alpha)(B - K_R + M), \tag{24}$$

respectively. Solving the inequality

$$\left(\alpha \frac{B - K_F}{p_e + \tau\gamma_F}\right)^{\alpha} ((1-\alpha)(B - K_F))^{1-\alpha} < \left(\alpha \frac{B - K_R + M}{p_e}\right)^{\alpha} ((1-\alpha)(B - K_R + M))^{1-\alpha} \tag{25}$$

for τ yields

$$\tau^R_{sub} = \frac{p_e}{\gamma_F}\left(\left(\frac{B - K_F}{B - K_R + M}\right)^{1-\alpha} - 1\right). \tag{26}$$

Compared to a setting without a subsidy, consumption of e and x in case of $j = R$ changes in terms of

$$e^*_{sub} - e^* = \alpha \frac{B - K_R + M}{p_e} - \alpha \frac{B - K_R}{p_e} = \alpha \frac{M}{p_e} \tag{27}$$

and

$$x^*_{sub} - x^* = (1-\alpha)(B - K_R + M) - (1-\alpha)(B - K_R) = (1-\alpha)M, \tag{28}$$

respectively. The consumption quantities and thus the utility level in case of $j = F$ remain unchanged with a renewable heating subsidy.

Lump-sum transfer Using M as a lump-sum transfer changes the budget constraint of the household to (22) for $j = R$ and

$$B + M = (p_e + \tau\gamma_F)e + x + K_R \tag{29}$$

for $j = F$, respectively. This results in the demand functions for e and x of $e^*_{tran} = e^*_{sub}$ and $x^*_{tran} = x^*_{sub}$, for $j = R$, as well as

$$e^*_{tran} = \alpha\frac{B - K_F + M}{p_e + \tau\gamma_F} \tag{30}$$

and

$$x^*_{tran} = (1 - \alpha)(B - K_F + M) \tag{31}$$

for $j = F$. Solving the inequality

$$\begin{aligned} &\left(\alpha\frac{B - K_F + M}{p_e + \tau\gamma_F}\right)^{\alpha}((1 - \alpha)(B - K_F + M))^{1-\alpha} \\ < \quad &\left(\alpha\frac{B - K_R + M}{p_e}\right)^{\alpha}((1 - \alpha)(B - K_R + M))^{1-\alpha} \end{aligned} \tag{32}$$

for τ yields

$$\tau^R_{tran} = \frac{p_e}{\gamma_F}\left(\left(\frac{B - K_F + M}{B - K_R + M}\right)^{\frac{1}{\alpha}} - 1\right). \tag{33}$$

Without further assumptions $\tau^R_{tran} > \tau^R_{sub}$ holds. Compared to a setting without a lump-sum transfer, consumption of e and x changes in terms of

$$e^*_{tran} - e^* = \alpha\frac{B - K_R + M}{p_e} - \alpha\frac{B - K_R}{p_e} = \alpha\frac{M}{p_e} \tag{34}$$

and

$$x^*_{tran} - x^* = (1 - \alpha)(B - K_R + M) - (1 - \alpha)(B - K_R) = (1 - \alpha)M \tag{35}$$

in case of $j = R$ and

$$e^*_{tran} - e^* = \alpha\frac{B - K_F + M}{p_e + \tau\gamma_F} - \alpha\frac{B - K_F}{p_e + \tau\gamma_F} = \alpha\frac{M}{p_e + \tau\gamma_F} \tag{36}$$

as well as

$$x^*_{tran} - x^* = (1 - \alpha)(B - K_F + M) - (1 - \alpha)(B - K_F) = (1 - \alpha)M \tag{37}$$

for $j = F$. Further note that for the renewable technology the real situation of the household is identical with both compensation policies. It holds that $e^*_{tran} = e^*_{sub}$ and $x^*_{tran} = x^*_{sub}$ if $j = R$ as the household faces the same budget constraint and relative prices and hence the same utility level.