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Linking Retail Electricity Pricing and the Decarbonisation of the Energy Sector: a Microeconomic Approach

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Linking retail electricity pricing and the decarbonisation of the energy sector: a microeconomic approach

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Abstract

In this paper we address the problem of policy coordination in the electricity sector when the supply side is subject to a carbon constraint. We specifically evaluate the link between retail electricity pricing and GHG emissions reduction. Moreover, we incorporate in the analysis both the variability of electricity demand and the uncertainty of clean energy supply. By developing an analytical framework grounded in the standard microeconomic theory, we model peak pricing, block pricing and real time pricing from the perspective of a representative consumer. We then estimate the impact of each pricing scheme on the social welfare function, with a specific focus on the external cost function where GHG emissions are explicitly accounted for. We find that the impact of peak and block pricing on the carbon emissions form the electricity sector is strongly influenced by the relative emissions intensity of baseload and peak generation. In contrast, the role of real time pricing as an environmental policy tool depends on the possibility for retail customers to discriminate their consumption over the quality and price of the electricity demanded.

1 Introduction

With the 2030 Climate and Energy Framework, European states have committed to design their national energy policy for climate change mitigation according to three key targets to be achieved by year 2030: 40% cuts in GHG emissions relative to 1990's level, 27% share of renewable energy, 27% improvements in energy efficiency. The fulfilment of these targets should also satisfy the objectives of security of supply and affordability of energy for all customers. Providing appropriate coordination between demand and supply side policy instruments becomes then of great relevance: failing to do so may result in the pursuit of competing objectives across energy markets, with the risk of offsetting the effectiveness of policies thereafter (Del Río 2014).

As a result of the energy and climate policy framework, electricity markets across Europe

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are subject to a carbon constraint and are increasingly reliant on intermittent and variable renewable energy sources, notably in the form of wind and solar energy. However, the integration of clean generating technologies in the existing system imposes new challenges, calling for a deep restructuring of the electricity markets to guarantee adequacy and security of supply (Winkler et al. 2016).

In this context, retail electricity pricing can actively contribute to the energy transition by changing consumers' behaviour. Specifically, different retail pricing designs can impact GHG emissions by leveraging the price elasticity of demand, consequently leading to load changes in either its size or distribution. With increasing shares of renewable energy, an efficient electricity pricing mechanism should mitigate the impact of a fluctuating demand, but also reflect the time variability and diversity of the quality of electricity supply (Bistline 2017). The availability of renewable electricity varies over time, it is differentiated by location and is characterised by intermittency. Moreover, renewable sources are used in a fuel mix also consisting of dispatchable, fossil fuel-based energy sources. The electricity produced with the current mix of technologies is therefore characterised by a variable marginal economic value (Hirth, Ueckerdt, and Edenhofer 2016).

Before such a complex supply side, retail pricing can accelerate GHG emissions by improving the flexibility of electricity markets, whereby flexibility refers to the capability of the different elements of the electricity sector to timely respond to the availability of clean energy sources (Huber, Dimkova, and Hamacher 2014). Thus, the necessity for flexibility implies inciting the responsiveness of different end-user groups to align the demand for electricity, especially during peak times, to the availability of renewable electricity, given the intermittency of clean energy sources such as wind (Moura and Almeida 2010). As flat rate retail tariffs fail to reflect the efficiency gains of demand management, dynamic pricing designs represent an effective mechanism to provide consumers with a more efficient price signal (O'Connell et al. 2014).

Another way for retail electricity pricing to achieve sustainability is to induce energy efficiency, that is the adoption of technologies to reduce the energy intensity of consumption, and energy conservation, defined instead as overall demand reduction (Harris et al. 2008). In absence of a cost reflective electricity tariff, customers cannot discriminate their consumption as a function of the environmental quality of the commodity purchased. There is therefore a sub optimal level of feedback information that can be addressed by retail pricing policies to achieve energy efficiency and energy conservation (Fischer 2008). Similarly, behavioural, and informational externalities such as the lack of knowledge on the availability of energy efficient technologies and the individual learning costs further justify the adoption of tariffs that are more informative for consumers (Jaffe and Stavins 1994).

Although it is outside the scope of this paper, retail electricity markets also play a crucial role in the diffusion and integration of distributed clean generation technologies, which is part of the strategy to lower the carbon emissions intensity of electricity markets. While distributed renewable energy source can both produce zero emissions electrical power and displace investment in fossil fuel generation, the existing pricing inefficiencies and demand side market failures currently prevent the electricity sector to fully benefit from the diffusion of small generation technologies (Duke, Williams, and Payne 2005).

Producing electrical power from renewable energy sources substantially redefines the economic value of electricity, having direct policy implications for retail markets and pricing design. The substitution of conventional generation technologies with intermittent clean energy sources adds further dimensions of irregularity that need to be considered when setting the price of electricity. Hence, the design of retail pricing mechanisms to regulate consumption, and indirectly production of electricity can importantly be evaluated as an environmental policy for the energy sector.

With the aim of clarifying the alternative ways for retail markets to enhance GHG emissions reduction, we focus on the role of retail electricity pricing as the main price signal faced by consumers. By developing a theoretical framework, we study the implications of three types of retail electricity pricing for the reduction of GHG emissions, when the fuel mix is composed by dispatchable technologies with different carbon intensities and intermittent renewable energy source. Thus, in Section 2 we discuss the economic literature addressing retail electricity pricing as a policy tool for the management of the demand side of the electricity sector, while in Section 3 we present the baseline version of our microeconomic framework, both with and without renewable energy sources in the fuel mix. In Section 4 we enlarge the scope of our model to test the welfare and environmental impact of the main designs of retail electricity tariff and we conclude in Section 5.

2 Literature review

In the context of climate change mitigation, it has been shown across the economic literature that a Pigouvian tax on carbon emissions characterises the firs best solution of the environmental externality of pollution (Cropper et al. 1992). However, despite the efficiency of this option, the optimal definition of the policy framework to curb GHG emissions is complicated by different factors. First, since the scope of climate policy covers different domains of the economic activity, carbon prices necessarily interact with other policy instruments and these interactions impact the effectiveness of carbon pricing as a first best instrument. Moreover, there are multiple market failures in the environmental domain which justify the implementation of a set policies, as opposed to a single instrument, to accelerate GHG emissions reduction across sectors and to improve the cost effectiveness of tackling climate change (Duval 2008). This is especially relevant for the energy sector as it is prone to multiple externalities. Second best policies may therefore prove to be less costly solutions for society and may improve the efficiency of the process of decarbonisation (Kalkuhl, Edenhofer, and Lessmann 2013).

For different instruments to be used as complementary both the direct and indirect interplay of policies should be considered. In the electricity sector, carbon prices interact with price-based demand side policies: while carbon markets are a direct measure to tackle GHG emissions, they can be made more effective by coordinating them with pricing policies to regulate electricity consumption (S. Sorrell 2003).

For this reason, there has been increasing interest in using pricing policies to align the patterns of consumption to the specific needs of a low carbon energy system within the electricity sector. Across Europe, though, the opportunity of using retail pricing for demand side management to accelerate the energy transition has been restrained by a yet incomplete process of liberalisation of electricity markets. While markets may drive the retail tariff choice towards cost reflective prices, most governments have kept price regulation for utilities in place, thus hindering the possibility to expose consumers to variable and more efficient pricing (Glachant and Ruester 2014).

Since the process of neither liberalisation nor decarbonisation have been completed yet, more research can improve the understanding of how retail pricing policies can contribute to the reduction of pollution from the electricity sector while preserving consumers welfare and ensuring adequate revenues for producers and retailers. In this light, the focus of this paper is on consumers prices as drivers of GHG emissions savings when the supply side of the power sector is subject to a carbon constraint.

2.1 Do consumers respond to retail electricity pricing?

Although with different objectives, the adoption of variable retail pricing instruments is motivated by the assumption that rational consumers choose their electricity consumption to minimise costs, hence non invariant retail pricing can induce behavioural changes by increasing the price elasticity of electricity demand. Indeed, it has been noted that consumers may have sub optimising-behaviours, therefore they may not be responsive to highly elaborate pricing policies (Ito 2014). Hence, the typically low values of the price elasticity of demand can limit GHG emissions savings within the electricity sector (Azevedo, Morgan, and Lave 2011).

There is nonetheless a substantial body of empirical research estimating the impact of different forms of retail electricity pricing in the context of the energy transition. Particularly, these studies often suggest that enabling consumers to timely adapt their electricity demand to price changes can enhance the effectiveness of dynamic retail pricing in reducing or shifting the load, therefore improving the efficiency and welfare impacts of electricity consumption.

It has been shown in the literature that technologies such as smart meters can improve the salience of dynamic pricing thus achieving demand response (Gilbert and Graff Zivin 2014). By making information accessible to electricity consumers, the adoption of these devices can scale the benefits of changes in the demand profiles, as in the case of peak reduction. Faruqui and Sergici 2010 report the structure and findings of 15 cases of application of a dynamic retail tariff in the residential sector. As opposed to the typical low values of price elasticity of demand under a flat rate, it is shown here that dynamic pricing elicits price responsiveness of electricity consumption.The authors find that on average time of use (ToU) pricing reduced peak consumption by 3-6 %, while critical peak pricing (CPP) by 13-20 %. Notably, coupling CPP with enabling technologies or feedback information yields an average peak demand reduction between 27-44%. Moreover, Jessoe and Rapson 2012 estimate that households only facing a time varying price decrease consumption by 2-6% on average, while consumers also receiving real time information with a home display reduce their consumption up to 14%. Similarly, Gans, Alberini, and Longo 2013 find that dynamic pricing and real time consumption information can decrease electricity demand by 11-17%

and Carroll, Lyons, and Denny 2014 show that total demand is reduced by 1.8%, with an average peak reduction by 7.8%.

When electricity demand is relatively price elastic, retail tariffs may reduce emissions by easing the penetration of renewable energy sources, decreasing overall demand, and enforcing indirect load control. Variable pricing instruments are typically linked to the highest probability of reducing GHG emissions. As opposed to flat rates, variable tariffs also send a price signal that is closer to the marginal cost of electricity, thus improving the efficiency of the market.

2.2 The environmental impact of variable electricity pricing

Among the variable pricing mechanisms, time-based tariffs can be a tool to deliver environmental benefits while reducing generation costs and market power (S. Borenstein 2013). Moreover, dynamic tariffs incentive changes in demand and encourage the substitution of fossil fuel with increasing shares of renewable energy sources. Absent viable large scale electricity storage solutions, variable tariffs can also be a cost effective demand side management tool to reduce the consumption of fossil fuel and increase the market value of renewable energy sources (Finn et al. 2011).

Cappers et al. 2012 show that among all the time-based retail rates, real time pricing (RTP), if combined with enabling and remote control technologies, is the most effective type of tariff to accommodate renewable energies. Variable and dynamic electricity tariffs can also be considered as elements of the smart grid infrastructure. As such, it is argued in Darby, Strömbäck, and Wilks 2013 that different pricing instruments can induce substantial GHG emissions savings by activating demand response. The largest opportunity for this lies in the residential sector, because of a more accommodating regulatory environment. When modelling GHG emissions reduction from all the smart grid components, the authors estimate that dynamic pricing can contribute to a decrease by 27% in emissions per year up to 2020. Depending on the composition of the fuel mix, tariffs varying over time may incentive electricity customers to align consumption to the temporal variability of the GHG emissions of electricity production. In this case, the changes in demand induced by a time based price signal reduce GHG emissions (Finenko and Cheah 2016).

As a high resolution time based rate, real time pricing represents an opportunity to improve the efficiency of electricity markets by enabling demand response. In contrast to other retail electricity tariffs, RTP sends a price signal that is directly linked to the wholesale market and consumers receive highly granular information. However, the effectiveness of RTP and other time-based tariffs as an instrument to foster GHG emissions savings is still unclear across the existing studies.

Stoll, Brandt, and Nordström 2014 crucially explain that this uncertainty depends on the misalignment between CO_2 intensity of supply and demand response. By comparing three types of price signal,they find that in Great Britain 10% emissions savings are achieved by time of use tariff, 12% with real time pricing and 14% with an emissions-based price signal. In Ontario, time of use yields $4\% CO_2$ emissions reduction, real time pricing and the carbon-based signal 30%. Although the emissions savings vary across all countries, a clear trade-off emerges for Sweden between the economic efficiency of real time pricing and the resulting impact on GHG emissions, which increases by 36%. This is mainly due to the mix of power generation technologies and its correlation with the variability of demand.

While agreeing that RTP may increase system emissions, Madaeni et al. 2013 estimate that coordinating RTP and wind output improves the cost effectiveness of fuel switching. Although the type of fuel used for baseload and peak generation limits the emissions benefit of wind energy, this is offset when wind energy is coupled with RTP, yielding higher emissions savings per unit of marginal dispatch cost: 13% CO_2 emissions reduction and up to 12% SO_2 and NO_x emissions savings. Kopsakangas-Savolainen et al. 2017 suggest that the extent of GHG emissions savings that can be induced by RTP is correlated to the hourly distribution of electricity consumption. Thus, the authors find that up to 6% emissions savings can be achieved over a year by changing the hourly distribution of consumption, while load shifting to a lower emissions hour results in 3% GHG reduction over a week. S. P. Holland and Mansur 2006 estimate that because of the different emissions rates of the fossil fuels used for power generation, RTP decreases hourly CO_2 by 0.16% but increases the emissions of SO_2 and NO_x by 0.75% and 0.26 % respectively.

In line with this literature, Bergaentzlé, Clastres, and Khalfallah 2014 argue that the effectiveness of dynamic retail pricing, both as individual instruments and as a combination of tariff designs, varies across countries and is dependent on the composition of the fuel mix and the possibility for interconnection. Moreover, Kök, Shang, and Yucel 2016 show that the type of renewable resource available to produce electricity impacts the effect of different tariffs designs on GHG emissions. The authors illustrate how a flat rate yields higher emissions savings, as it fosters higher investment in renewable energy than peak pricing. This holds if the output of the renewable resource is greater during peak rather than off -peak periods. If the opposite applies, then peak pricing results in higher investment in clean generation technologies. Similarly, Ata, Duran, and Islegen 2016 argue that the composition of the fuel mix determines the GHG emissions impact of dynamic pricing. It is suggested here that the difference in the emissions intensity of baseload and peak generation drives the variability of results across electricity markets.

It emerges from the literature that there is scope for retail electricity tariffs to be a tool for the environmental policy mix in the electricity sector. Particularly, most of the existing studies suggest that time varying pricing can deliver GHG emissions reduction while improving the efficiency of retail markets. However, this may not hold true and there may be a trade-off between the complementary interaction of a tariff with climate policy objectives and the economic efficiency aspects of retail markets. Different factors need therefore to be accounted for to evaluate pricing policies as an effective demand side management instrument to accelerate CO_2 emissions reduction.

As suggested by the literature, key drivers of the uncertainty of the GHG emissions impact of retail rates in electricity markets are the correlation between the carbon intensity of electricity supply and the variability of demand, the fuel mix composition and the distribution of variable renewable energy sources, as well as their pattern relative to demand profiles. To clarify these points, we develop an analytic framework to study the conditions for retail pricing policies to be complementary to climate policy in the energy sector.To do so, in the following section we first review the main retail electricity pricing designs and then we propose a model to examine their impact on GHG emissions and their interaction with different fuel mixes.

3 Microeconomic framework

3.1 Types of retail electricity tariff

The types of pricing mechanisms that have been used across different retail electricity markets are flat rates, block pricing, peak pricing and, more recently, real time pricing. Flat rates have been extensively implemented in the past and are defined as a time invariant tariff that is charged to consumers at the end of every billing period, with a typical monthly or bi-monthly frequency. As outlined by Severin Borenstein and S. Holland 2005, static types of tariffs prevent the retail electricity market from being efficient, mainly because the price is not aligned with the marginal cost of electricity production. Moreover, the slow adjustment of the level of prices and the sporadic nature of the price information impede consumers to adopt price elastic behaviour according to the market based signal received, see for example (Cosmo and O'Hora 2017).

Another peculiar feature of electricity markets is the variability of demand, fluctuating both within day and over seasons (Muratori, Schuelke-Leech, and Rizzoni 2014). This results in the misallocation of resources, which defines the capacity problem (Steiner 1957) . Since the earliest literature on retail electricity pricing design, as of (Houthakker 1951) among the others, peak pricing has been studied as a tool to reflect the relative scarcity of supply during peak demand (Boiteux 1960). Peak pricing usually takes the form of a daily time of use tariff, or of a peak price premium during critical events (critical peak pricing). In both instances, consumers are likely respond to the time varying signal by shifting a part of load from peak to off-peak or by shedding the load, reducing their overall demand (Torriti 2012). Block pricing has instead been implemented to induce energy conservation behaviour. This motivation stems from a broader environmental policy framework (Harris et al. 2008), as well as from the technical needs of utilities and network companies to guarantee security of supply. A block type of tariff can be designed with increasing or decreasing block rates (Severin Borenstein 2016). The retailer divides the customers consumption in tiers and, with increasing block rates, the first units of electricity have the lowest marginal retail price, while the price increases as consumption falls into higher tiers. Conversely, with decreasing block rates the customer faces the highest marginal price for the first block of consumption while the price decreases when moving to the following tiers.

With the increasing possibility for large scale application of automated control and information technologies, real time pricing has also been tested in many different jurisdictions. Real time pricing is a pricing mechanism where the retail price is linked to the wholesale prices and it has a high, usually hourly granularity.In this way, consumers are charged with a time varying tariff changing according to how the marginal cost of electricity production varies,which is becoming more relevant because of the increasing power generation from low marginal cost and intermittent clean energy sources with priority of dispatch. While it aims at improving the efficiency of retail markets and reducing market power, it may also deliver environmental benefits by easing the integration of renewable energy sources (S. P. Holland, Mansur, et al. 2008).

3.2 Baseline model

We provide here a formal illustration of the impact on GHG emissions of changes in electricity consumption, driven by different types of retail pricing. Our model builds on the analytic framework developed by Chan, Gillingham, and Eth 2015 where the authors define a utility maximisation problem to examine the welfare impact of the microeconomic rebound effect in the energy sector. To do so, their model links the consumer's demand for energy services to the related fuel consumption.

We adopt a similar analytic strategy, as it allows the demand for energy services to be associated to its generating source. However, as opposed to the reference framework where the broader energy sector is accounted for, we focus on the electricity sector and we link the demand for energy services to its energy carrier electricity. This restriction allows us to investigate more closely the impact on GHG emissions of price responses of consumer's electricity demand. In this sense, the scope of this research diverges from the reference one as the purpose of our analysis is to provide a theoretical framework to assess the environmental impact of retail pricing as a demand side management instrument. Before modelling the welfare impact of different pricing instruments, we review the features of the microeconomic structure that are relevant for our analysis.

We begin by acknowledging that consumers, as noted by Steve Sorrell and Dimitropoulos 2008, do not demand electricity, but the energy services, or useful work, that they can obtain from electrical power. We denote by s_m the vector of energy services demanded by a representative consumer, which maximises her utility over an aggregate numeraire good x and energy services s_m. Thus, within a given consumption bundle, good x aggregates all those good that do not directly imply electricity consumption. The consumption of energy services requires the provision of q_{mn} units of electricity, where the subscript m refers to the associated energy service while n relates to the energy source that is used to generate electrical power. For example, an energy service s can be running a washing machine, which typically requires about 1 kWh of electricity. This, in turn, is provided by a power generating technology employing an energy source such as coal or natural gas. The technology used to generate electricity is denoted by n.

The direct link between energy services and the production of electrical power implies that the maximisation problem of the utility derived from energy services is constrained by the associated electricity consumption. Being our focus on the electricity sector, we can further specify the features of the demand for energy services to account for its time variability.

We focus here on a specific case, where the representative agent consumes only two finite sets of energy services denoted by the vectors s_i and s_j, $i = 1, ..., y$ and $j = 1, ..., z$. Having a typical residential load profile in mind, we can think of s_i and s_j as corresponding to base and peak demand, respectively.

In this context, let s_i be the vector of energy services that are consumed during baseload electricity demand and s_j the set of energy services used during peak demand. To better account for the difference between baseload and peak demand, we impose that the demand for energy services is satisfied by producing electricity from two technologies using two different energy sources, hence $n = 1, 2$. Each energy source can satisfy one set of demand for energy services, and each set of energy services can be produced by only one energy source. Specifically, it is assumed that s_i is satisfied by a baseload plant producing q_{i1} units of electricity, while s_j requires a peak plant to be activated to generation q_{j2} units of electricity. The following assumption can therefore be defined for our model:

Assumption 1

There are two finite sets of energy services s_i and s_j which identify baseload and peak energy services respectively. The demand for energy services requires the production of electricity. We represent by q_{in} the amount of baseload electricity corresponding to the demand for s_i energy services, while q_{jn} is the peak electricity demand associated to s_j.Assuming that there is a one to one correspondence between energy services and fuels, q_{mn} units of electricity can be produced by a power plant using one fuel $n = 1, 2$, where $m = i, j$. The baseload demand for energy services s_i is satisfied by q_{in} units of electricity, generated by the fossil fuel 1. Therefore $s_i = q_{i1}$. Similarly, q_{j2} is produced by a peak thermal plant using fossil fuel 2 to produce s_j energy services. Hence $s_j = q_{j2}$.

A representative consumer maximises her utility over the vectors of direct baseload and peak energy services s_i and s_j and a composite numeraire good x. To write the budget constraint, we denote disposable income by w . We normalise the price of x to 1, and we define p as a flat rate tariff charged to the consumer for electricity consumption, $p_i = p_j = p$.

$$\begin{aligned} \max_{x,s_i,s_j} \; & U\big(x, s_i, s_j\big) \\ & \text{subject to} \\ & s_i = q_{i1} \\ & s_j = q_{j2} \\ & w = x + p(q_{i1} + q_{j2}) \end{aligned} \tag{1}$$

As described in problem (1), consumer's utility is defined over the numeraire good x and the energy services s_i and s_j, which are relative to base and peak electricity demand respectively.The maximisation program is subject to three constraints. The first and second conditions are imposed to associate the consumption of energy service s_i and s_j to the demand for q_{i1} and q_{j2} units of electricity.The third condition represents instead a standard budget constraint, where the price paid for energy services is a flat rate electricity tariff. Following a standard procedure, the solution of the consumer's utility maximisation problem yields the following first order conditions:

1. $u_{mg}(s_i) = \lambda_i$
2. $u_{mg}(s_j) = \lambda_j$

3. $s_i = q_{i1}$
4. $s_j = q_{j2}$
5. $\bar{w} = p(q_{i1} + q_{j2})$

Where $\bar{w}$ is the available income net of the expenditure for the numeraire good x and u_{mg} is the marginal utility of either baseload (1.) or peak (2.) energy services. Moreover, $\bar{w} = w - x$ and λ_1, λ_2 are the shadow value of energy services s_i and s_j, respectively . Using conditions (3.) and (4.) and substituting for the budget constraint we derive the demand for energy services s_i^* and s_j^*, which read as:

$$s_i^* = \frac{\bar{w}}{p} - q_{j2} \tag{2}$$

$$s_j^* = \frac{\bar{w}}{p} - q_{i1} \tag{3}$$

3.2.1 Social welfare

We now turn to the definition of the impact of changes in electricity demand on GHG emissions when there is an exogenous change in electricity prices. To do so, we define a social welfare function which accounts for the external costs (EC) arising from electricity production and consumption.

Following the reference framework, we assume linear separability of the utility function in the numeraire x, so that $U(x, s_i, s_j) = x + u(s_i, s_j)$. Moreover, it is assumed that $u(s_i, s_j) = u(s_i) + u(s_j)$. When representing external costs, it is also assumed that these costs are linearly separable across a population of k identical consumers.

The social welfare function SW is therefore defined as:

$$SW = x + u(s_i, s_j) - EC \tag{4}$$

By the EC function we study the externalities arising from electricity consumption. It is commonly recognised that the consumption of energy services s_m^* may have a range of associated externalities.To keep our focus on the environmental aspects of electricity consumption, only the external costs in terms of GHG emissions resulting from electricity demand q_{ij} are considered here.

We define μ_n as the GHG emissions factor measured in terms of CO_2 that is associated to each fuel n= 1,2. Another way of examining μ_n would be as an average carbon emissions rate across all the baseload or peak fuels used, when a group of technologies rather than a single one satisfies flat and peak demand.In our example, μ_1 represents the emissions rate of the fuel used for the generation of q_{i1}, while μ_2 is the rate at which the fuel used to produce q_{j2} emits greenhouse gases.

The external costs are defined by the following EC function:

$$EC = k(\mu_1 q_{i1} + \mu_2 q_{j2}) \tag{5}$$

Being interested in the impact of alternative retail pricing designs, we study the outcome of an exogenous change in retail electricity price on welfare. In general, it can be seen that an increase in price from p to $p + \Delta p$ implies a changes in welfare defined by:

$$\int_{p}^{p+\Delta p} \frac{\partial SW}{\partial p} dp \tag{6}$$

Where the integrand can be found as:

$$\frac{\partial SW}{\partial p} = \frac{\partial SW}{\partial x}\frac{\partial x^*}{\partial p} + \frac{\partial SW}{\partial s_i}\frac{\partial s_i^*}{\partial p} + \frac{\partial SW}{\partial s_j}\frac{\partial s_j^*}{\partial p} + \frac{\partial SW}{\partial EC}\frac{\partial EC}{\partial p} \tag{7}$$

We evaluate each term from the solution of the utility maximisation problem 1-5 and the demand functions 1.1 and 1.2 to obtain the change in social welfare as a consequence of an increase in the flat rate electricity tariff.

$$\frac{\partial SW}{\partial p} = -(q_{i1} + q_{j2}) + \frac{\bar{w}}{p^2}\left[k(\mu_1 + \mu_2) - (u_{mg}s_i^* + u_{mg}s_j^*)\right] \tag{8}$$

The main findings are straightforward. Provided that price is charged to consumers in the form of a flat rate, an increase in retail electricity price decreases the consumption possibilities for consumers. Hence, it reduces social welfare proportionally to the budget constraint and the marginal utility of peak and off-peak energy services. However, as an increase in the flat rate price reduces demand for energy services, therefore electricity demand, it also improves welfare by saving GHG emissions.

As can be noted from equation (8), consumers subject to a flat rate pricing mechanism do not differentiate between their peak and off peak consumption. Consequently a flat rate price signal fails to elicit the price elasticity of electricity demand and GHG emissions savings are a function of a marginal reduction in overall demand.

3.2.2 Renewable energy

We now enlarge the scope of the analysis to incorporate renewable electricity generation in our microeconomic framework. In the utility maximisation problem (1) we assumed that s_i and s_j can only be obtained by fossil fuel , and that the fuel used for baseload generation differs from the one employed for peak electricity generation. This assumption is relaxed to consider the role of renewable energy sources in the electricity sector.

The adoption of these clean energy technologies has been predominantly driven by the resulting GHG emissions savings, and the possibility of satisfying electricity demand using renewable energy sources is a key feature of current electricity markets. Subject to a carbon constraint, the electricity sector is increasingly reliant on intermittent and variable renewable energy sources to reduce GHG emissions, notably in the form of wind and solar energy. As argued by Ueckerdt et al. 2013, the electricity output of these sources varies over space and time and is driven by weather factors, therefore the availability of renewables is fluctuating in intensity and difficult to predict.Hence, the integration of different generating technologies in the existing system imposes new challenges of adequacy and security of supply (Winkler et al. 2016). Since the variable availability of clean energy sources is likely to affect the GHG emissions impact of retail pricing policies, we represent the main features of renewable sources when allowing the demand for energy services to be satisfied by both fossil fuel and renewable electricity.

To do so, we define $\tilde{q_{mr}}$ as a variable having a random distribution over the bounded interval [0,K], where K denotes the maximum capacity of the renewable energy plant such as a wind or a solar farm. Thus, $\tilde{q_{mr}}$ describes the fluctuating availability of renewable electricity correlated to demand for energy services m, while r refers to the renewable source of energy used to produce electricity.

Renewable energy sources are also variable over time and space, therefore they may serve either baseload or peak demand, or both. Typically, electricity generation requires baseload, intermediate and peak plants. With the current technologies, and specifically because of their highly uncertain availability, wind and solar energy sources are not used for baseload generation. In contrast, this is possible for intermediate and peak plants (see for example Denholm and Hand 2011).

To avoid complexity in our model, we only consider baseload and peak generation, corresponding for simplicity to the allocation of periodic demand. Thus, when considering the possible correlation between zero-emissions electricity and baseload generation, we use the latter term to denote base and intermediate plants. To represent this, we include π_m as a binary variable representing the intermittency of renewable electricity output during period m. Therefore, when $\pi = 1$ then $\pi_m \tilde{q_{mr}}$ describes the pattern of availability of renewable electricity. If $\pi_m = 0$, there is no renewable energy available in m. Our illustration of the uncertainty arising from variable renewable energy sources expands Assumption 1 as outlined below.

Assumption 2

The demand for energy services s_i and s_j is satisfied by the generation of electricity q_{i1} and q_{j2} produced by means of fossil fuel 1 and 2, respectively.Assuming a renewable energy plant of capacity K, s_i can be satisfied by a mix of fossil fuel 1 and renewable energy with probability π_i. Similarly, a mix of fossil fuel 2 and renewable energy can produce the electricity required to meet the peak demand for energy services s_j.The level of availability of renewable electricity is randomly distributed and identified by $\tilde{q_{ir}} if \pi_i = 1, \tilde{q_{jr}}$ if $\pi_j = 1$.

The utility maximisation problem can be changed to include Assumption 2. Specifically, we define a new variable to account for the fact that electricity can be produced by fossil fuel exclusively or by a mix of fossil fuel and renewable energy. We therefore define q_i as the quantity of electricity corresponding to s_i energy services and that is generated by $q_{i1} + \tilde{q_{ir}}$. The same rationale justifies the definition of q_j as $q_{j2} + \tilde{q_{jr}}$. Both the identities of q_i and q_j

are imposed as constraints to the following utility maximisation program:

$$\begin{aligned}
&\operatorname*{Max}_{x,s_i,s_j} U\big(x, s_i, s_j\big) \\
&\qquad \text{subject to} \\
&\qquad s_i = q_i \\
&\qquad s_j = q_j \\
&\qquad w = x + p(q_i + q_j) \\
&\qquad q_i = q_{i1} + \pi_1 \tilde{q_{ir}} \\
&\qquad q_j = q_{j2} + \pi_2 \tilde{q_{jr}}
\end{aligned} \tag{9}$$

By deriving the first order conditions for problem (9) and rearranging, we find that including the level of availability of renewable energy sources in the baseload and peak load fuel mix changes the representation of the demand for energy services s_i^* and s_j^*, thus yielding the following fossil fuel electricity demand functions q_i^* and q_j^*.

$$q_{i1}^* = \frac{\bar{w}}{p} - \pi_1 \tilde{q_{ir}} \tag{10}$$

$$q_{j2}^* = \frac{\bar{w}}{p} - \pi_2 \tilde{q_{jr}} \tag{11}$$

As of equations (10) and (11), the fossil fuel electricity demand in both baseload and peak periods is a negative function of the availability of renewable electricity. The possibility of producing electricity from clean energy sources does indeed impact the definition of the external cost function (5). Particularly, the environmental externalities arising from power generation are reduced by the availability of renewable electricity, which is however fluctuating. The external cost function in (5) is redefined to mirror the variability of zero emissions energy sources to produce electricity.

Thus, the GHG emissions equation in (12) defines the environmental externalities arising from the generation of electrical power as a function of the electricity baseload and peak demand, net of the level of availability of the renewable energy source.

$$EC = \mu_1(q_{i1} - \pi_1 \tilde{q_{ir}}) + \mu_2(q_{j2} - \pi_2 \tilde{q_{j2}}) \tag{12}$$

4 Variable retail pricing instruments

In this chapter we investigate the impact of peak pricing, block pricing and real time pricing on social welfare, paying specific attention to the change in GHG emissions that each of these retail pricing mechanisms implies.

To do so, we modify the original utility maximisation problem and we elaborate on Assumptions 1 and 2 to account for the different settings. We mainly discuss our results in terms of price elasticities of demands based on the assumption that variable retail rates induce different forms of behavioural changes in the demands of the representative consumer.

For each pricing instrument we proceed as follows: we first identify the changes in the utility maximisation problem according to the specific rate, then we derive the related changes in the social welfare function. Specifically, we focus on the external cost function to derive the conditions that need to hold for each variable retail price to result in GHG emissions savings.

By representing the fuel mix both with and without considering clean energy sources, our modelling framework shows how retail pricing can be designed to interact with renewable energy sources to improve the emissions savings that can be achieved within the electricity sector.

4.1 Peak pricing

To derive the corresponding demands for electricity, we relax here the assumption that the tariff charged for baseload and peak electricity is a flat rate that is equal for both demands. To represent a pricing scheme of the peak pricing type we account for a higher price charged for the energy services consumed during peak demand. Denoting by p_1 the price charged for q_{i1} units of electricity and by p_2 the price of q_{j2} we solve the following utility maximisation problem:

$$\begin{aligned} \underset{x,s_i,s_j}{\text{Max}}\ & U\big(x, s_i, s_j\big) \\ & \text{subject to} \\ & s_i = q_{i1} \\ & s_j = q_{j2} \\ & w = x + p_1 q_{i1} + p_2 q_{j2} \end{aligned} \tag{13}$$

Changing the energy services demand functions (1) and (2) accordingly, we derive the electricity demand functions:

$$q_{i1}^{*} = \frac{\bar{w}}{p_1} - \frac{p_2}{p_1} s_j^{*} \tag{14}$$

$$q_{22}^{*} = \frac{\bar{w}}{p_2} - \frac{p_1}{p_2} s_i^{*} \tag{15}$$

Since $p_1 \neq p_2$, we separately evaluate the change in welfare as a result of an increase in peak price p_2. Since the model accounts for variable demand over two periods, we illustrate the change in welfare resulting from a change in the peak price p_2.

$$\int_{p_2}^{p_2+\Delta p} \frac{\partial SW}{\partial p_2} dp_2 \tag{16}$$

$$\frac{\partial SW}{\partial p_2} = \frac{\partial SW}{\partial x}\frac{\partial x^{*}}{\partial p_2} + \frac{\partial SW}{\partial s_i}\frac{\partial s_i^{*}}{\partial p_2} + \frac{\partial SW}{\partial s_j}\frac{\partial s_j^{*}}{\partial p_2} + \frac{\partial SW}{\partial EC}\frac{\partial EC}{\partial p_2} \tag{17}$$

Each term is evaluated as explained below.

The first term $\frac{\partial SW}{\partial x}\frac{\partial x^{*}}{\partial p_1}$ is defined using the budget constraint in the first order conditions

of the utility maximisation problem (13).
We then use the demand functions (14) and (15) to derive $\frac{\partial SW}{\partial s_i}\frac{\partial s_i^*}{\partial p_2}$ and $\frac{\partial SW}{\partial s_j}\frac{\partial s_j^*}{\partial p_2}$.
When elaborating on $\frac{\partial SW}{\partial EC}\frac{\partial EC}{\partial p_2}$ it can be noted that:

$$\frac{\partial EC}{\partial p_2} = \mu_1\frac{\partial q_{i1}^*}{\partial p_2} + \mu_2\frac{\partial q_{j2}^*}{\partial p_2} \tag{18}$$

Let us consider now the own price elasticity of electricity demand ε_{j2} and its cross price elasticity ε_{j1} as defined by:

$$\varepsilon_{j1} = \frac{\partial q_{j2}}{\partial p_1}\frac{p_1}{q_{j2}}$$
$$\varepsilon_{j2} = \frac{\partial q_{j2}}{\partial p_2}\frac{p_2}{q_{j2}}$$

Thus, equation (18) can be written as:

$$\frac{\partial EC}{\partial p_2} = \mu_1\varepsilon_{i2}\frac{q_{i1}}{p_2} + \mu_2\varepsilon_{j2}\frac{q_{j2}}{p_2} \tag{19}$$

Where ε_{i2} is the sensitivity of the baseload electricity demand function to a change in peak price, while ε_{j2} is the own price elasticity of peak electricity demand. The evaluation of the entire term yields:

$$\frac{\partial SW}{\partial EC}\frac{\partial EC}{\partial p_2} = -k(\mu_1\varepsilon_{i2}\frac{q_{i1}}{p_2} + \mu_2\varepsilon_{j2}\frac{q_{j2}}{p_2}) \tag{20}$$

The total change in social welfare for a change in p_2 can be measured as:

$$\frac{\partial SW}{\partial p_2} = -q_{j2} - u_{mg}(s_i)\frac{q_{j2}}{p_1} - u_{mg}(s_j)\frac{\bar{w} - p_1q_{i1}}{(p_2)^2} - k(\mu_1\varepsilon_{i2}\frac{q_{i1}}{p_2} + \mu_2\varepsilon_{j2}\frac{q_{j2}}{p_2}) \tag{21}$$

Absent external costs, an increase in p_2 always decreases social welfare on the margin.
As of expression (21) , welfare is decreased by a reduction in electricity demand. Moreover, an increase in price erodes the utility that consumers obtain from the consumption of energy services s_i and s_j. In contrast, an increase in the retail price of electricity can improve social welfare when considering the external costs function.
Let us consider the price driven change in welfare from the external cost function. As of equation (19), the variation in the external costs $\frac{\partial EC}{\partial p_2}$ needs to be negative to improve social welfare. This is true if the following condition holds:

$$\begin{gathered}\frac{\partial EC}{\partial p_2} < 0 \\ if \mid \frac{\varepsilon_{j2}}{\varepsilon_{i2}} \mid > -\frac{\mu_1 q_{i1}}{\mu_2 q_{j2}}\end{gathered} \tag{22}$$

Thus, the change in the external cost function caused by an increase in peak price decreases the external costs on the margin if the ratio between own price elasticity of peak demand and cross price elasticity of off-peak demand is of opposite sign and greater than the relative CO_2 emissions intensity of baseload and peak generation.
This condition has relevant implications for examining load shifting and load shedding as responses to price changes. Specifically, the own price elasticity of demand measures the rate of change of demand for a unit increase in its price.
As of the electricity demand function (15), the own price elasticity is negative, hence, ε_{j2}

estimates load shedding as a price response. Similarly, the cross price elasticity defines the possibility of substitution between peak and baseload electricity consumption. Moreover, from the electricity demand function (14) ε_{i2} is positive therefore it represents load shifting. Equation (22) therefore implies that there can be a trade off between the type of price responsiveness of demand and its impact on GHG emissions.

We now consider two extreme cases to explain this point. If unit own price elasticity of peak demand $\varepsilon_{j2} = -1$ and no load shifting are assumed, the condition in (22) is fulfilled if $\frac{\mu_1 q_{i1}}{\mu_2 q_{j2}} > 1$. Thus, an increase in p_2 causes a reduction in peak demand of the same amount of the change in price. This reduces the environmental external costs if the carbon intensity of baseload generation is greater than the intensity of the peak plant. In contrast, if only load shifting is assumed, so that $\varepsilon_{i2} = 1$, the corresponding increase in off-peak consumption improves social welfare if the emissions intensity of peak generation is greater than the carbon dioxide emissions factor of baseload generation. We generalise these findings in the following

Highlight 1

Given a periodic demand for energy services defined by two vectors of energy services s_i and s_j, $p_i \neq p_j$, and assuming price elastic electricity demand, an increase in p_j reduces consumers' utility, hence social welfare. However, an increase in p_j reduces the environmental externalities arising from electricity production if one of the following statements holds true.

- $\mid \varepsilon_{j_2} \mid > 0, \mid \varepsilon_{i_2} \mid > 0$ and $\mid \frac{\varepsilon_{j_2}}{\varepsilon_{i_2}} \mid > -\frac{\mu_i}{\mu_j}$
  Given that ε_{j_2} is negative and ε_{cross_i} is positive, the last condition can be stated as: $\frac{\varepsilon_{j_2}}{\varepsilon_{i_2}} > \frac{\mu_i}{\mu_j}$
- $\varepsilon_{j_2} = -1$ and $\mu_i > \mu_j$
- $\varepsilon_{i_2} = 1$ and $\mu_i < \mu_j$

4.1.1 Environmental impact of load shifting

With a dispatchable and fossil fuel based electricity supply it is possible to estimate the GHG impact of price driven changes in consumption such as load shifting and load shedding. Specifically, the impact on the environmental external costs is determined by comparing the relative emissions intensity of baseload and peak load plants with the own and cross price elasticity of electricity demand.When estimating the change in welfare brought about by a change in p_2 from the emissions function, we find :

$$\frac{\partial EC}{\partial p_2} = \mu_1 \frac{\mid \varepsilon_{i_2} \mid}{q_j} + \mu_2 \frac{\mid \varepsilon_{j_2} \mid}{q_i} \tag{23}$$

As explained above, GHG emissions are reduced by an increase in p_2 when $\frac{\partial EC}{\partial p_2} < 0$. Thus, social welfare improves from the external cost function when the following condition holds:

$$\frac{\mu_1 (q_{i1} - \pi_1 \tilde{q_{ir}})}{\mu_2 (q_{j2} - \pi_2 \tilde{q_{jr}})} < \frac{\varepsilon_{j_2}}{\varepsilon_{i_2}} \tag{24}$$

From equation (24) we define how load shifting and load shedding as a price response interact with the level of availability of renewable energy.

In the case of load shifting, $\varepsilon_{i_2} = 1$, yielding:

$$\mu_2 q_{j2} - \mu_1 q_{i1} > \mu_2 \pi_2 \tilde{q_{jr}} - \mu_1 \pi_1 \tilde{q_{ir}} \tag{25}$$

Thus, shifting the electricity demand to baseload demand in direct proportion to the increase in peak price induces GHG emissions savings if the difference in the carbon intensity of fossil fuel production of baseload and peak generation is greater than the difference in the emissions avoided because of renewable electricity.
It is worth noting the following:

a.1 When $\pi_1 = 0$ then $\frac{\partial EC}{\partial p_2} < 0$
if $\mu_2 q_{j2} - \mu_2 \pi_2 \tilde{q_{jr}} > \mu_1 q_{i1}$
which holds when $\mu_2 \pi_2 \tilde{q_{jr}} < \mu_2 q_{j2} - \frac{\mu_1}{\mu_2} q_{i1}$

a.2 When $\pi_2 = 0$ then $\frac{\partial EC}{\partial p_2} < 0$
if $\mu_2 q_{j2} > \mu_1 q_{i1} - \pi_1 \tilde{q_{ir}}$
which holds when $\pi_1 \tilde{q_{ir}} > q_{i1} - \frac{\mu_1}{\mu_2} q_{j2}$

a.3 When $\pi_1 = 0$ and $\pi_2 = 0$
then $\frac{\partial EC}{\partial p_2} < 0$ if $\mu_2 q_{j2} > \mu_1 q_{i1}$

Whether load shifting on the margin from peak to baseload demand decreases the externalities of electricity production depends on the relative carbon intensity of power generation in the two periods.
As of condition a.1, when there is no renewable energy in the baseload fuel mix, if peak electricity consumption is shifted to off- peak demand because of an increase in p_2, GHG emissions are reduced if the net emissions from peak generation are greater than the emissions intensity of baseload production. This means that if $\pi_1 = 0$ and there is a variation in peak price, then load shifting decreases environmental externalities if the pollution that can be avoided by using peak renewable energy is smaller than the difference in GHG emissions from the peak and baseload fossil fuel generation weighted by the relative emissions intensity $\frac{\mu_1}{\mu_2}$. Similarly, we define in a.2 that when $\pi_2 = 0$, marginally shifting the load from peak to off-peak demand improves social welfare from the external cost function if baseload generation is less carbon intensive less peak electricity production.Lastly, condition a.3 mirrors (1.2) in Highlight 1: when there are no renewable sources in both baseload and peak generation, load shifting decreases the external cost function on the margin if the carbon intensity of off-peak generation is lower than peak one.
These results are summarised in Table 1 in the Appendix.

4.1.2 Environmental impact of load shedding

We now consider the case of $\varepsilon_{j_2} = -1$, which identifies the reduction of overall demand, also referred to as load shedding. To do so, we use equation (23) and we find that a change in p_2 implies $\frac{\partial EC}{\partial p_2} < 0$ if :

$$\mu_1 \pi_1 \tilde{q_{ir}} - \mu_2 \pi_2 \tilde{q_{jr}} < \mu_2 q_{j2} - \mu_1 q_{i1} \tag{26}$$

According to equation (26), with a negative unit own price elasticity of peak demand, the positive social welfare impact of a change in p_2 depends on the magnitude of the avoided emissions because of renewable energy and the difference between peak and baseload carbon intensity of fossil fuel production.

Thus $\frac{\partial EC}{\partial p_2} < 0$ if the difference in avoided emissions is smaller than emissions from power generation, so that reducing demand is the optimal way to reduce emissions in this context. We recognise the following conditions for (24) to hold:

b.1 When $\pi_1 = 0$ then $\frac{\partial EC}{\partial p_2} < 0$
if $\pi_2 \tilde{q_{jr}} < q_{j2} - \frac{\mu_1}{\mu_2} q_{i1}$

b.2 When $\pi_2 = 0$ then $\frac{\partial EC}{\partial p_2} < 0$
if $\pi_1 \tilde{q_{ir}} > \frac{\mu_2}{\mu_1} q_{j2} - q_{i1}$

b.3 When $\pi_1 = 0$ and $\pi_2 = 0$ then $\frac{\partial EC}{\partial p_2} < 0$
if $\mu_1 q_{i1} < \mu_2 q_{j2}$

As explained in b.1, when baseload electricity is only generated by fossil fuel, then emissions savings arise if peak renewable energy is less than the difference between the peak fossil fuel generation and off-peak generation, weighted by its carbon intensity relative to peak electricity production.In contrast, when there is not renewable energy for peak generation, load shedding implies GHG emissions reduction if the baseload renewable electricity is greater than peak emissions relative to the off-peak ones, as of b.2.

The specification defined in b.3 states that if only fossil fuel is available for both baseload and peak electricity generation, then load shedding reduces emissions if the emissions intensity of peak generation is higher than the carbon intensity of baseload generation. The requirements for an increase in p_2 to decrease the environmental externality when variable renewable energy sources are part of the fuel mix are summarised in Table 2 in the Appendix.

4.2 Block pricing

We begin the illustration of the impact of a block pricing type of retail pricing on GHG emissions by modifying the utility maximisation problem (13), where peak electricity demand has a higher price than off-peak demand. To account for the fact the electricity consumption is divided into tiers, we now define a third price p_3 that is charged for the consumption of q_{b1} units of electricity. In this case, the energy services s_i served by baseload generation using technology 1 correspond to the demand for $q_{a1} + q_{b1}$ units of electricity , where $a = 1, ...\alpha$ and $b = (\alpha+1), ...y$ and, as of the baseline mode, $s_i = 1, ..., y$. We incorporate these changes in the utility maximisation problem below:

$$
\begin{aligned}
\underset{x,s_i,s_j}{\text{Max}}\; & U\big(x, s_i, s_j\big) \\
& \text{subject to} \\
& s_i = q_{a1} + q_{b1} \\
& s_j = q_{j2} \\
& w = x + p_1 q_{a1} + p_2 q_{j2} + p_3 q_{b1}
\end{aligned}
\tag{27}
$$

By solving the optimisation programme we derive the electricity demand functions for each tier of consumption:

$$q^*_{a1} = \frac{\bar{w} - p_3 s^*_i - p_2 q_{j2}}{(p_1 - p_3)} \tag{28}$$

$$q^*_{b1} = \frac{\bar{w} - p_1 s^*_i - p_2 q_{j2}}{(p_3 - p_1)} \tag{29}$$

$$q^*_{j2} = \frac{\bar{w} - p_1 q_{a1} - p_3 q_{b1}}{p_2} \tag{30}$$

We use these demand functions to evaluate the impact on social welfare of an increase in the price p_3, that is:

$$\int_{p_3}^{p_3+\Delta p} \frac{\partial SW}{\partial p_3} dp_3 \tag{31}$$

As expected, when the environmental externalities are not accounted for, an increase in electricity price p_3 reduces the consumption possibilities, hence decreasing social welfare on the margin.

$$\frac{\partial SW}{\partial p_3} = -q_{b1} - u_{mg}(s_i)\frac{\partial s^*_i}{\partial p_3} - u_{mg}(s_j)\frac{\partial s^*_j}{\partial p_3} \tag{32}$$

The external cost equation is changed to account for the fact that the generation technology 1 satisfies two different electricity demands, q_{a1} and q_{b1}, which are dependent on two different prices, p_1 and p_2.

$$EC = \mu_1(q_{a1} + q_{b1}) + \mu_2 q_{j2} \tag{33}$$

Thus, when evaluating $\frac{\partial SW}{\partial p_3}$ we find that:

$$\frac{\partial EC}{\partial p_3} = \mu_1\Big(\frac{\partial q_{a1}}{\partial p_3} + \frac{\partial q_{b1}}{\partial p_3}\Big) + \mu_2 \frac{\partial q_{j2}}{\partial p_3} = \mu_1(\mid \varepsilon_{a_3} \mid q_{a1} + \mid \varepsilon_{b_3} \mid q_{b1}) + \mu_2 \mid \varepsilon_{j_3} \mid q_{j2} \tag{34}$$

In equation (34)) ε_{a_3} denotes the cross price elasticity of the demand for electricity q_{a1} to an increase in price p_3, ε_{b_3} refers to the own price elasticity of demand q_{b1} and ε_{j_3} defines the cross price elasticity of the demand q_{j2} to a change in price p_3. From the demand functions in (28), (29) and (30) we evaluate the signs of the own and cross price elasticities, and we find that:

$$\varepsilon_{a_3} > 0, \varepsilon_{b_3} < 0, \varepsilon_{j_3} < 0$$

The positive cross price elasticity of demand q_{a1} denotes the possibility to shift the consumption of some of the energy services s_i to the cheaper block of consumption. In contrast, the negative own price elasticity suggest that demand is reduced as a consequence of an increase in p_3. Similarly, the negative cross price elasticity of the demand served by peak generation is reduced by an increase in p_3, which can be interpreted as the conservation effect. While consumers may find convenient to increase the load corresponding to the cheapest tier of consumption, an increase in price p_3 reduces demand for the intermediate price block as well. These findings are summarised in

Highlight 2

When electricity consumption is divided into tiers of consumption, q_{a1}, q_{b1}, q_{j2}*, with a marginal price increasing across blocks, so that* $p(q_{a1}) = p_1, p(q_{j2}) = p_2, p(q_{b1}) = p_3$ *whereby* $p_1 < p_2 < p_3$*, an increase in* p_3*:*

- *elicits a positive cross price elasticity in the cheapest demand function:* $\varepsilon_{a_3} > 0$
- *decreases demand* q_{b1} *proportionally to the increase in the marginal price:* $\varepsilon_{b_3} < 0$
- *induces a conservation effect in the intermediate tier of consumption:* $\varepsilon_{j_3} < 0$

The environmental externalities are reduced as a consequence of an increase in p_3 when $\frac{\partial EC}{\partial p_3} < 0$, which implies:

$$\mu_1 \varepsilon_{a_3} q_{a1} < \mu_1 \varepsilon_{b_3} q_{b1} + \mu_2 \varepsilon_{j_3} q_{j2} \tag{35}$$

Equation (35) holds if one of the following conditions is true:

c.1 $\mid \varepsilon_{a_3} \mid = 0$ and $\mid \varepsilon_{b_3} \mid > 0$ and $\mid \varepsilon_{j_3} \mid = 0$

c.2 $\mid \varepsilon_{a_3} \mid = 0$ and $\mid \varepsilon_{b_3} \mid > 0$ and $\mid \varepsilon_{j_3} \mid > 0$

c.3 $\mid \varepsilon_{a_3} \mid = 0$ and $\mid \varepsilon_{b_3} \mid = 0$ and $\mid \varepsilon_{j_3} \mid > 0$

c.4 $\mid \varepsilon_{a-3} \mid > 0$ and $\mid \varepsilon_{b_3} \mid + \mid \varepsilon_{j_3} \mid > 0, \mid \varepsilon_{b_3} \mid + \mid \varepsilon_{j_3} \mid > \mid \varepsilon_{a_3} \mid$

According to condition (c.1), when only the own price elasticity of demand q_{b1} is greater than zero, an increase in p_3 decreases GHG emissions by reducing electricity consumption. Similarly, when both $\mid \varepsilon_{b_3} \mid > 0$ and $\mid \varepsilon_{j_3} \mid > 0$, an increase in p_3 results in demand reduction in both demands q_{b1} and q_{j2}, thereby reducing the external cost of pollution (c.2). When only the cross price elasticity $\mid \varepsilon_{j_3} \mid > 0$, demand reduction induces GHG emissions savings (c.3), while if $\mid \varepsilon_{a_3} \mid > 0$ there is a reduction in pollution only if the negative price elasticities of demand outpace the increase in consumption in the demand function q_{a1} (c.4).

4.2.1 Environmental impact of demand reduction

We now extend the model of block pricing to incorporate Assumption 2. When renewables are included in the fuel mix, the external cost function (33) becomes:

$$EC = \mu_1(q_{a1} + q_{b1} - \pi_1 \tilde{q_{ir}}) + \mu_2(q_{j2} - \pi_2 \tilde{q_{jr}}) \tag{36}$$

We also recall from equation (34) that an increase in p_3 lowers GHG emissions when $\frac{\partial EC}{\partial p_3} < 0$. As explained above, this holds true if one of the conditions from c.1 to c.4 is satisfied. We can accordingly evaluate the environmental impact of block pricing when considering the variable availability of clean energy sources.

Under condition c.1, an increase in price only elicits the negative own price elasticity of electricity demand q_{b1}. This implies that without renewable energy sources there are positive GHG emissions savings for any positive level of electricity demand reduction, which results in avoided emissions. However, when there are clean energy sources in the fuel mix of electricity generation, there is an overall reduction in pollution only when the GHG emissions avoided by demand reduction are lower than the avoided emissions from clean energy sources, see Table 3 in the Appendix.

Similarly, under condition c.2 there are positive GHG emissions savings when the pollution avoided by demand reduction in both q_{b1} and q_{j2} is lower than the pollution averted by producing from clean energy sources. When only fossil fuel generation is possible, any level of price driven demand reduction will reduce the environmental externality of pollution. These results are summarised in Table 4.

As of Table 5, when only the negative cross price elasticity of demand ε_{j_3} is greater than zero, absent renewables the environmental externalities are reduced by an increase in p_3 at any level of emissions saved via demand reduction. However, when renewable electricity is accounted for, the GHG emissions avoided using clean generation technologies needs to be greater than the pollution saved via demand reduction for the block pricing scheme to reduce externalities.

Lastly, Table 6 summarises the conditions for block pricing to induce GHG emissions savings when all the three elasticities are greater than zero but $\mid \varepsilon_{b_3} \mid + \mid \varepsilon_{j_3} \mid > \mid \varepsilon_{a_3} \mid$. In this case, the environmental externality is reduced as long as the emissions savings from the price elastic behaviour is smaller than the pollution that can be avoided by producing renewable electricity.When the entire demand is satisfied by fossil fuel generation, the condition for GHG emissions abatement is that the demand reduction in q_{b1} and q_{j2}needs to be greater than the increase in demand q_{a1}.

4.3 Real time pricing

Real time pricing is typically set up to signal the variation in the wholesale value of electricity to retail customers. Since with this scheme the price is set equal to the varying marginal cost of power production, real time pricing is considered a tool to improve the efficiency of the market. Moreover, by signalling the variation of the value of electricity, this pricing instrument can encourage consumers to increase the utilisation of renewable energy sources while decreasing the demand for fossil fuel electricity. We focus on the latter aspect to model how real time pricing can interact with renewable energy sources as a demand side management instrument to lower GHG emissions.

We shall note that, absent renewable resources, the representation of real time pricing as a retail price changing with the marginal cost of electricity generation is equivalent to the representation of peak pricing as of the utility maximisation problem (13). Since we assume two different generation technologies 1 and 2 to be used for baseload and peak generation respectively, and provided that these technologies use different fuels having carbon intensity μ_1 and μ_2, $\mu_1 \neq \mu_2$. then the marginal cost of baseload production is different from the cost of peak production, yielding $p_1 \neq p_2$. This can be studied as the peak pricing case.

4.3.1 Environmental impact of standard real time pricing

To illustrate the GHG emissions savings induced by real time pricing when renewable resources are part of the fuel mix, we assume that the total marginal cost of fossil fuel 1 and 2 is the same, whereby the marginal cost of power generation also includes the carbon price. Thus, there is a price p_1 per unit of fossil fuel electricity consumed and a price p_2 per unit of renewable electricity used. As opposed to conventional generation technologies, renewable energy plants such as wind or solar have nearly zero operating costs, and they are not charged a carbon price, therefore $p_1 > p_2$. In this case the utility maximisation problem results changed as follows:

$$\begin{aligned} &\underset{x,s_i,s_j}{\text{Max}}\ U\big(x, s_i, s_j\big) \\ &\qquad \text{subject to} \\ &\qquad s_i = q_{i1} + \pi_1 \tilde{q_{ir}} \\ &\qquad s_j = q_{j2} + \pi_2 \tilde{q_{jr}} \\ &\qquad w = x + p_1(q_{i1} + q_{j2}) + p_2(\pi_1 \tilde{q_{ir}} + \pi_2 \tilde{q_{jr}}) \end{aligned} \tag{37}$$

From the solution of the utility maximisation problem, we derive the demand functions for the fossil fuel based electricity related to either base-load or peak generation as a function of the exogenous availability of renewable electricity.

$$q_{i1}^* = \frac{\bar{w} + p_2(\pi_1 \tilde{q_{ir}} + \pi_2 \tilde{q_{jr}})}{p_1} - (s_j^* - \pi_2 \tilde{q_{jr}}) \tag{38}$$

$$q_{j2}^* = \frac{\bar{w} + p_2(\pi_1 \tilde{q_{ir}} + \pi_2 \tilde{q_{jr}})}{p_1} - (s_i^* - \pi_1 \tilde{q_{ir}}) \tag{39}$$

We use these results to study the social welfare impact of differentiating consumers' price by generation technology. To do so, we consider the change in the social welfare function as driven by an increase in the retail price of fossil fuel electricity, therefore evaluating:

$$\int_{p_1}^{p_1 + \Delta p_1} \frac{\partial SW}{\partial p_1} dp_1 \tag{40}$$

Absent the environmental externalities, the solution for equation (40) is defined by the following terms:

$$\begin{aligned}\frac{\partial SW}{\partial x}\frac{\partial x^*}{\partial p_1} + \frac{\partial SW}{\partial s_i}\frac{\partial s_i^*}{\partial p_1} + \frac{\partial SW}{\partial s_j}\frac{\partial s_j^*}{\partial p_1} = \\ -(q_{i_1} + q_{j_2}) - \big(\frac{(\pi_1 \tilde{q_{i_r}} + \pi_2 \tilde{q_{j_r}})}{p_1^2}\big)(u_{m_g}(s_i) + u_{m_g}(s_j))\end{aligned} \tag{41}$$

When the environmental external costs are not accounted for, an increase in p_1 always decreases welfare because of consumer's budget constraint. However, although the increase in price is faster in reducing social welfare than the improvement driven by renewable energies, these resources have a positive impact on social welfare. Turning to the external cost function EC, this is defined here as the GHG emissions produced to satisfy base and peak demand, net of the availability of clean energy sources:

$$EC = \mu_1(q_{i_1} - \pi_1 \tilde{q_{i_r}}) + \mu_2(q_{j2} - \pi_2 \tilde{q_{j_r}}) \tag{42}$$

Thus, when evaluating the change in the external cost function as a consequence of the increase in price p_1, it can be noted that it is only dependent on the own price elasticities of demand, since the availability of renewable electricity is exogenous. Even if the price signals the possibility to access clean power, consumers cannot control its availability, hence the difference between prices p_1 and p_2 only elicits the demand response of the demand they can decide upon in each period. The change in welfare is therefore defined as follows:

$$\frac{\partial EC}{\partial p_1} = \mu_1(\varepsilon_{p_i}) + \mu_2(\varepsilon_{p_j}) \tag{43}$$

whereby ε_{o_i} is the own price elasticity of electricity demand q_{i_1} and ε_{o_j} is the own price elasticity of demand q_{j_2}. From the demand functions in equations (38) and (39) both have negative values. This implies that any change in the price for fossil fuel electricity p_1 results in demand reduction. Recalling that the environmental external cost of pollution is reduced when $\frac{\partial EC}{\partial p_1} < 0$, we find that an increase in p_1 results in positive GHG emissions savings for any value greater than zero of the price elasticity of demand.

$$\mu_1 \varepsilon_{p_i} q_{i_1} + \mu_2 \varepsilon_{p_j} q_{j_2} > 0 \tag{44}$$

The availability of renewable electricity impacts the GHG emissions reduction that can be attributed to real time pricing only as a driver of the price elasticity of baseload and peak demand. From the demand functions , the two price elasticities take the form:

$$\varepsilon_{p_i} = -\frac{\bar{w} + p_2(\pi_1 \tilde{q_{i_r}} + \pi_2 \tilde{q_{j_r}}}{p_1 q_{i_1}} \tag{45}$$

$$\varepsilon_{p_j} = -\frac{\bar{w} + p_2(\pi_1 \tilde{q_{i_r}} + \pi_2 \tilde{q_{j_r}})}{p_1 q_{j_2}} \tag{46}$$

In both cases, everything else being equal and reminding that $p_1 > p_2$, any additional unit of renewable electricity increases the propensity of consumers to reduce the fossil fuel demand.

In contrast, when both π_1 and π_2 =0, the GHG emissions impact of real time pricing is determined by the extent to which the weight of the increase in p_1 on the budget constraint elicits the negative price elasticity of demand.

This result depends on the fact that although real time pricing signals the different marginal value of electricity over time, consumers do not have enough information to differentiate their consumption accordingly. As a matter of fact , from problem (37) it is not possible to define a demand function for renewable electricity and the lower price p_2 fails to induce a substitution effect within baseload and peak demand in favour of clean energy consumption. As reviewed in Section 1, there are evidences across the literature that the price response of consumers to real time pricing schemes is largely influenced by the possibility for the price signal to be reinforced by feedback information. In this way, real time pricing can help consumers in effectively differentiating their consumption according to the generation technology of electricity.

4.3.2 Environmental impact of real time pricing when coupled with enabling technologies

To explain this point, we rewrite problem (37) assuming that consumers have perfect information. Under the assumption that consumers know that their demand can be differentiated by energy source, we use a different utility function, so that it is defined over x, s_f and s_r. where s_f is the vector of energy services that can be obtained by fossil fuel generation and s_r is the vector of energy services generated by renewable energy sources.

Therefore, $U = U(x, s_f, s_r)$, where $s_f = q_{i_1} + q_{2_j}$, that is the sum of baseload and peak fossil fuel electricity demanded, and $s_r = \pi_1 \tilde{q_i}r + \pi_2 \tilde{q_{j_r}}$, which is the sum of the baseload and peak renewable electricity.

To account both for the periodic demand and for the differentiation between energy services served by fossil fuel and clean energy source, two further constraints need to be imposed. We denote by q_{i_n} the total amount of baseload electricity demanded and by q_{j_n} the overall quantity of peak electricity demanded: q_{i_n} is defined by the the baseload electricity obtained by fossil fuel and renewable energy $q_{i_1} + \pi_1 \tilde{q_{i_r}}$, while q_{j_n} is the total amount of fossil and clean electricity consumed $q_{j_2} + \pi_2 \tilde{q_{j_r}}$. The real time pricing method is represented in the budget constraint, where a price p_1 is charged for fossil fuel electricity and a lower price p_2 applied to zero emissions electricity. A representative consumer maximises her utility by solving the following problem:

$$
\begin{aligned}
\underset{x,s_f,s_r}{\text{Max}}\; & U\big(x, s_f, s_r\big) \\
& \text{subject to} \\
& s_f = q_{i_1} + q_{j_2} \\
& s_r = \pi_1 \tilde{q_{ir}} + \pi_2 \tilde{q_{jr}} \\
& q_{i_n} = q_{i_1} + \pi_1 \tilde{q_{i_r}} \\
& q_{j_n} = q_{j_2} + \pi_2 \tilde{q_{j_r}} \\
& w = x + p_1(q_{i1} + q_{j2}) + p_2(\pi_1 \tilde{q_{ir}} + \pi_2 \tilde{q_{jr}})
\end{aligned}
\tag{47}
$$

From the solution of problem (47) we derive the demand functions for the fossil fuel electricity corresponding to baseload (48) and peak (49) generation respectively:

$$q^*_{i_1} = \frac{\bar{w} - p1(q_{j_2}\pi_2\tilde{q_{j_r}}}{p_1} + \frac{p_2}{p_1}(\pi_1\tilde{q_{ir}} + \pi_2\tilde{q_{jr}}) \tag{48}$$

$$q^*_{j_2} = \frac{\bar{w} - p2(q_{i_1}\pi_1\tilde{q_{i_r}}}{p_1} + \frac{p_2}{p_1}(\pi_1\tilde{q_{ir}} + \pi_2\tilde{q_{jr}}) \tag{49}$$

When evaluating the change in social welfare because of an increase in p_1 we find the solution to the integral

$$\int_{p_1}^{p_1\Delta p} \frac{\partial SW}{\partial p_1} dp_1 \tag{50}$$

as:

$$\frac{\partial SW}{\partial p_1} = \frac{\partial SW}{\partial x}\frac{\partial x^*}{\partial p_1} + \frac{\partial SW}{\partial s_f}\frac{\partial s^*_f}{\partial p_1} + \frac{\partial SW}{\partial s_r}\frac{\partial s^*_r}{\partial p_1} + \frac{\partial SW}{\partial EC}\frac{\partial EC}{\partial p_1} \tag{51}$$

whereby, absent externalities, the change in welfare is given by:

$$\frac{\partial SW}{\partial p_1} = -(q_{i_1} + q_{j_2}) - u_{m_g}(s_f)\frac{\bar{w} + p_2(\pi_1\tilde{q_{i_r}} + \pi_2\tilde{q_{j_r}})}{p_1^2} - u_{m_g}(s_r)\frac{q_{i_1} + q_{j_2}}{p_2} \tag{52}$$

The social welfare impact of real time pricing when consumers can differentiate between fossil fuel and renewable energy services is overall negative as a result of an increase in the price of the electricity produced by polluting sources. However, this effect is mitigated by the possibility to substitute the consumption of fossil fuel with clean energy at a lower price p_2. If both $\pi_1 = 1$ and $\pi_2 = 1$, then any increase in the amount of renewable electricity produced partially offsets the welfare reduction caused by an increase in p_1. When accounting for the external cost of pollution associated to conventional electricity consumption, and using the demand functions, the element $\frac{\partial EC}{\partial p_1}$ is evaluated as follows:

$$\frac{\partial EC}{\partial p_1} = \mu_1(\frac{\partial q^*_{i_n}}{\partial p_1}) + \mu_2(\frac{\partial q^*_{j_n}}{\partial p_1}) = \mu_1 \mid \varepsilon_{1_{p_1}} \mid \frac{q_{i_n}}{p_1} + \mu_2 \mid \varepsilon_{2_{p_2}} \mid \frac{q_{j_n}}{p_1} \tag{53}$$

whereby the own price elasticity of the baseload and peak fossil fuel electricity demands $\varepsilon_{1_{p_1}}$ and $\varepsilon_{2_{p_2}}$ relative to a change in p_1 are defined by:

$$\varepsilon_{1_{p_1}} = -\frac{\bar{w}}{p_1 q_{i_1}} - \frac{p_2}{p_1 q_{i_1}}(\pi_1\tilde{q_{i_r}} + \pi_2\tilde{q_{jr}}) \tag{54}$$

$$\varepsilon_{2_{p_1}} = -\frac{\bar{w}}{p_1 q_{j_2}} - \frac{p_2}{p_1 q_{j_2}}(\pi_1\tilde{q_{i_r}} + \pi_2\tilde{q_{jr}}) \tag{55}$$

Using the definitions in (54) and (55) we find that the own price elasticity of demand has a negative sign, implying that an increase in p_1 always lowers the quantity of fossil fuel electricity consumed. Moreover, the elasticity is defined by two components.

The first one $\frac{\bar{w}}{p_1 q_{i_1}}$ for $\varepsilon_{1_{p_1}}$ and $\frac{\bar{w}}{p_1 q_{j_2}}$ for $\varepsilon_{2_{p_1}}$, is determined by the budget constraint as an increase in p_1 reduces the possibilities of consumption for the representative agent. The second component reads as $\frac{p_2}{p_1 q_{j_2}}(\pi_1\tilde{q_{i_r}} + \pi_2\tilde{q_{jr}})$ for the own price elasticity of both demands, which denotes the possibility for consumers to substitute fossil fuel electricity by increasing the demand whenever renewable resources are available.

As the main assumption in this setting is that consumers are enabled to differentiate their electricity consumption according to the energy source, there is a shift of the quantity demanded towards the cheaper product, which is the electrical power produced by renewable energy sources.

Since $\frac{\partial SW}{\partial EC} = -k$, GHG emissions are reduced when $\frac{\partial EC}{\partial p_1} < 0$, that is when $\mu_1 \mid {\varepsilon_1}_{p_1} \mid \frac{q_{i_n}}{p_1} + \mu_2 \mid {\varepsilon_2}_{p_2} \mid \frac{q_{jn}}{p_1} < 0$, where both the own price elasticities have negative signs hence $\frac{\partial EC}{\partial p_1} < 0$ for any value greater than zero of the price elasticities of baseload and peak demand, yielding:

$$\frac{\partial EC}{\partial p_1} < 0 \text{ when } \frac{\bar{w}}{p_1} > -\frac{p_2}{p_1}(\pi_1 \tilde{q_{i_r}} + \pi_2 \tilde{q_{jr}}) \tag{56}$$

Absent clean energy sources, any increase in p_1 reduces electricity demand, hence reducing GHG emissions. In contrast, when there is a positive renewable electricity supply, the income effect of fossil fuel demand reduction reduces the environmental cost of electricity consumption as long as the cost of consuming fossil fuel electricity exceeds the relative price of renewable electricity.

The main findings of our model of marginal cost pricing are summarised below:

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When modelling real time pricing as the retail pricing mechanism for electricity customers, it is worth noting the following three key findings:

- *Absent renewable energy sources and accounting for the fact that fossil fuel electricity is produced by baseload and peak technologies having carbon intensity μ_1 and μ_2 respectively, the utility maximisation problem when consumers are subject to a retail pricing setting the price equal to the marginal cost of production can be solved as the case of peak pricing.*
- *If consumers are maximising their utility over baseload and peak demand for energy services, an increase in the price of fossil fuel electricity reduces electricity demand. However, real time pricing in this case fails to induce consumers to consume more renewable electricity when this is available. Although the price varies with the marginal cost of production of electrical power, consumers take the availability of clean energy as exogenous and, while they can adjust their consumption as a result of an increase in the price of fossil fuel electricity, this doesn't change their consumption of renewable electricity*
- *Consumers may be enabled to differentiate their electricity demand by energy source, thus fully adjusting their consumption to the availability of cheaper clean electrical power. This case is represented by assuming that the utility function is defined over fossil fuel and renewable energy services, as opposed to baseload and peak energy services. Thus, when there is an increase in p_1 GHG emissions are reduced by both fossil fuel demand reduction because of the impact on the budget constraint and by the opportunity cost of increasing the consumption of renewable electricity while decreasing fossil fuel demand.*

4.4 Results

When modelling a peak pricing type of tariff, the demands for baseload and peak energy services over which the utility is defined imply two different demands for electricity. These depend on two different prices p_1 and p_2, respectively, being the peak price p_2 higher than p_1. It is shown in our model that this results in a loss of welfare compared to a flat rate price, proportionally to the weight of the increase in the unit price of electricity on the budget constraint of consumers. The impact of peak pricing on the external cost function is determined instead by the own price elasticity of peak demand and the cross price elasticity of baseload demand, whereby the negative own price elasticity can be defined as load shedding while the positive cross price elasticity estimates the possibility of load shifting. Hence, absent renewable energy sources, peak pricing implies GHG emissions reduction according to the relative carbon intensity of baseload and peak generation.

Specifically, we find that peak pricing lowers the environmental externalities of electricity production when the ratio between the propensity to curb peak demand and the propensity to shift some peak consumption towards baseload demand is greater than the carbon intensity of baseload generation relative to the one of peak production. Similarly, when accounting for intermittent clean energy sources in the fuel mix, peak load shifting and peak load shedding result in GHG emissions reduction as long as the emissions saved by eliciting the price response of electricity demands are greater than the pollution that can be avoided thanks to the availability of clean energy sources.

Block pricing is considered here in the form of three inclining block rates. Thus, the model encompasses three electricity demands priced at an increasing marginal value. Moreover, we examine the case of the cheapest and the most expensive tiers of consumption being satisfied by baseload generation while the intermediate demand coincides with peak generation. It can be noted that when the intermediate block is satisfied by baseload generation and the most expensive one by peak production, the change in welfare can be studied as a form of peak pricing. In our model, instead, we study the impact of a block pricing mechanism on social welfare, focusing on the external cost function, by evaluating the implications of an increase in the price charged at the third block of electricity consumption.

We find that this elicits the own price elasticity of the third demand, with a negative sign: an increase in p_3 induces demand reduction. Moreover, an increase in p_3 activates the cross price elasticity of the cheapest demand, with a positive sign, and the cross price elasticity of the intermediate demand, having negative sign instead. The positive cross price elasticity of the first demand characterises the opportunity for retail customers to shift some units of the most expensive demand to the least expensive block of consumption. In contrast, an increase in p_3 stimulates a negative cross price elasticity of the intermediate demand, indirectly inducing a further conservation effect.

To understand the GHG emissions impact of block pricing then, we examine all the possible combinations of values of the three elasticities. We find that, when the fuel mix is entirely composed by fossil fuel, there are positive GHG emissions savings for any negative price elasticity that is greater than the magnitude of the positive cross price elasticity of the cheapest demand. When renewable resources are accounted for, the environmental externalities are reduced by block pricing when the pollution avoided by means of clean generation technologies is greater than the GHG emissions curbed because of behavioural changes, that is the net impact of the three responsiveness of electricity demands to an increase in the highest price p_3.

The impact on GHG emissions of both peak and block retail pricing schemes is determined by how the cross and own price elasticity of demand interact with the relative carbon intensity of baseload and peak generation and the allocation of the available clean energy sources. This holds as well when real time pricing is considered in the context of a conventional fuel mix, since in this case the model can be solved as a peak pricing utility maximisation problem.

In contrast, setting retail prices equal the variable marginal cost of electricity production implies that the GHG emissions impact is only dependent on the own price elasticity of fossil fuel demand. There are therefore lower environmental externalities associated to electricity consumption as real time pricing incentives a reduction in baseload and peak fossil fuel electricity demand as a price response.

Although consumers receive a dynamic price which indirectly signals the availability of renewable energy sources, they are not enabled to modify their demand accordingly. Hence, consumers only respond to the economic signal, simply reducing their demand proportionally to the increase in the price of fossil fuel electricity. We show instead that this is not the case when consumers are endowed with enabling and information devices, such as smart meters, which implies that consumers can differentiate their electricity consumption over quality and prices. We show that when consumers can do so, they are enabled to fully respond to the price signal according to the availability of renewable electricity.

This implies that real time pricing results in GHG emissions reduction because of consumers response to the economic signal, that is fossil fuel demand reduction, as well as an environmental signal, leading to a substitution of fossil fuel consumption with an increase in the demand for clean electricity.

5 Conclusions

In this paper, we investigate the link between retail electricity pricing and GHG emissions savings by developing an analytic framework. In the context of climate change mitigation, we study how retail electricity pricing can be coordinated with the primary goal of GHG emissions reduction when both the variability of demand and supply are accounted for.

In our microeconomic model the variability of demand is accounted for by assuming that the consumer's utility function is maximised over a numeraire good, representing all consumption goods other than electricity, and two energy services standing for baseload and peak demand respectively. Moreover, the uncertainty of supply enters the model by introducing the possibility for the fossil fuel mix to be partly substituted by renewable energy sources which have a random distribution and uncertain availability. Our strategy involves the modelling of retail electricity pricing and the analysis of the implications of different pricing mechanisms on a social welfare function. In it, the environmental externality of the pollution produced to satisfy demand for energy services is explicitly considered.

Three types of retail pricing are studied here to unveil the changes in consumption that each of the instruments elicits. We evaluate the associated change in welfare and we focus on their impact on GHG emissions. To so we adopt the perspective of a representative consumer. The model is defined as a separate utility maximisation problem for the case of peak, block, and real time pricing. For each pricing policy the solution of the utility optimisation programme is used to estimate the change in social welfare brought about by a change in the retail pricing mechanism. Results are compared against the baseline model of a flat rate tariff.

We find that an increase in price always decreases consumers' welfare proportionally to their available budget constraint, as a higher unit price for electricity restricts the consumption possibilities for retail customers. Results vary instead across retail pricing designs when considering the external cost function which represents the GHG emissions function from electricity consumption.

While the baseline model assumes a price that is the same for every unit of electricity demanded, for peak pricing we study the effects of a change in the price of peak demand. When modelling block pricing, we evaluate how welfare changes as a consequence of an increase in the price of one tier of consumption. Real time pricing is instead represented as a mechanism imposing a marginal price higher for fossil fuel than renewable electricity.

Being the retail price a flat rate tariff, we show that consumers are not induced to change their patter of consumption. In contrast we find that peak pricing elicits demand response in the form of peak load shifting or shedding, according to the value of the own and cross price elasticity of peak and baseload demand respectively.

A block type of tariff activates both the own price elasticity of demand and the cross-price elasticities of the other two demands. Thus, an increase in the price of the most expensive tier of consumption reduces the related demand. Moreover, it induces a conservation effect in the intermediate demand while it may increase demand where the price is the cheapest.

We find that a tariff of the peak and block type can achieve GHG emissions reduction by inducing changes in the electricity consumption pattern. However, the impact on carbon emissions is determined by how the new consumption behaviour interacts with the relative carbon intensity of baseload and peak generation, whereby the carbon intensity accounts for both the emissions rate of fossil fuel production and the availability of of clean energy sources.

While peak pricing proves to be effective in reducing the inefficiency of variable demand, it only enhances GHG emissions savings when peak demand reduction implies lowering the usage of the most emitting power plant. Block pricing instead induces energy conservation, saving carbon emissions thereafter as long as demand is reduced when the pollution intensity of electricity generation is the highest. However, the predictability of the impact of retail pricing on GHG emissions is complicated by the variable availability of renewable resources. Depending on the overall mix of energy sources satisfying baseload and peak demand, the conservation and income effect of block pricing do not necessarily imply GHG emissions savings.

In both cases, the price signal received by consumers changes electricity demand but may fail to harmonise price-based demand side management with the decarbonisation of the electricity sector of the retail tariff is not coordinated with the emissions content of the existing fleet of generation technologies.

When estimating the change in consumption associated with real time pricing, it emerges that this is determined by the propensity of consumers to curb their demand for the most expensive electricity. In the model of real time pricing, this is the one produced by means of fossil fuel-based technologies. However, only when consumers are enabled to vary their consumption according to the quality of electricity, real time pricing achieves active demand response. In this case then, consumers can fully adapt their demand to the real time price signal reducing the consumption of fossil fuel electricity and partially substituting it with clean electrical power.

Our findings suggest that retail pricing policies can corroborate the policy framework for climate change mitigation in the electricity sector. Particularly we show that real time pricing on the demand side can complement carbon pricing on the supply side in achieving GHG emissions reduction. When consumers are fully informed about the nexus between the price and the quality of the electricity they consume, real time pricing enables retail customers to discriminate over quality, hence it incentives the consumption of renewable electricity over the one produced by means of fossil fuel technologies. For real time pricing to be effective in fostering the energy transtition, consumers should therefore be endowed with enabling technologies of the type of smart meters.

Our findings suggest then that real time pricing can be a direct instrument for environmental policy, as long as there are available renewable resources. If this is not the case, the choice of a retail pricing instrument able to accelerate the abatement of carbon emissions is restricted to peak or block pricing. As explained above, though, the impact of these retail pricing policies on GHG emissions depends upon the carbon intensity of the baseload and peak fuel mix.

References

[ADI16] Baris Ata, Asligul Duran, and Ozge Islegen. “An Analysis of Time-Based Pricing in Electricity Supply Chains”. In: (2016), pp. 1–46. URL: `http://papers.ssrn.com/sol3/papers.cfm?abstract%7B%5C_%7Did=2826055`.

[AML11] Inês M Lima Azevedo, M. Granger Morgan, and Lester Lave. “Residential and Regional Electricity Consumption in the U.S. and EU: How Much Will Higher Prices Reduce CO2 Emissions?” In: *Electricity Journal* 24.1 (2011), pp. 21–29. ISSN: 10406190. DOI: `10.1016/j.tej.2010.12.004`.

[BCK14] Claire Bergaentzlé, Cédric Clastres, and Haikel Khalfallah. “Demand-side management and European environmental and energy goals: An optimal complementary approach”. In: *Energy Policy* 67 (2014), pp. 858–869. ISSN: 03014215. DOI: `10.1016/j.enpol.2013.12.008`. URL: `http://dx.doi.org/10.1016/j.enpol.2013.12.008`.

[BH05] Severin Borenstein and Stephen Holland. "On the Efficiency of Competitive Electricity Markets with Time-Invariant Retail Prices". In: *The RAND Journal of Economics* 36.3 (2005), pp. 469–493. ISSN: 07416261. DOI: `Article`. URL: `http://www.jstor.org/stable/4135226`.

[Bis17] John E. Bistline. "Economic and technical challenges of flexible operations under large-scale variable renewable deployment". In: *Energy Economics* 64 (2017), pp. 363–372. ISSN: 01409883. DOI: `10.1016/j.eneco.2017.04.012`. URL: `http://dx.doi.org/10.1016/j.eneco.2017.04.012`.

[Boi60] M. Boiteux. "Peak-Load Pricing". In: *The Journal of Business* 33.2 (1960), pp. 157–179.

[Bor13] S. Borenstein. *Effective and Equitable Adoption of Opt-In Residential Dynamic Electricity Pricing.* Vol. 42. 2. 2013, pp. 127–160. ISBN: 1115101293. DOI: `10.1007/s11151-012-9367-3`.

[Bor16] Severin Borenstein. "The economics of fixed cost recovery by utilities". In: *Electricity Journal* 29.7 (2016), pp. 5–12. ISSN: 10406190. DOI: `10.1016/j.tej.2016.07.013`.

[Cap+12] Peter Cappers et al. "An assessment of the role mass market demand response could play in contributing to the management of variable generation integration issues". In: *Energy Policy* 48 (2012), pp. 420–429. ISSN: 03014215. DOI: `10.1016/j.enpol.2012.05.040`. URL: `http://dx.doi.org/10.1016/j.enpol.2012.05.040`.

[CGE15] Nathan W Chan, Kenn Gillingham, and Eth. "The Microeconomic Theory of the Rebound Effect and Its Welfare Implications". In: *Journal of the Association of Environmental and Resource Economists* 2.1 (2015), pp. 133–159. ISSN: 2333-5955. DOI: `10.1086/680256`. URL: `http://dx.doi.org/10.1086/680256`.

[CLD14] James Carroll, Seán Lyons, and Eleanor Denny. "Reducing household electricity demand through smart metering: The role of improved information about energy saving". In: *Energy Economics* 45 (2014), pp. 234–243. ISSN: 01409883. DOI: `10.1016/j.eneco.2014.07.007`. URL: `http://dx.doi.org/10.1016/j.eneco.2014.07.007`.

[CO17] Valeria Di Cosmo and Denis O'Hora. "Nudging electricity consumption using TOU pricing and feedback: evidence from Irish households". In: *Journal of Economic Psychology* 61 (2017), pp. 1–14. ISSN: 01674870. DOI: `10.1016/j.joep.2017.03.005`. URL: `http://dx.doi.org/10.1016/j.joep.2017.03.005`.

[Cro+92] Maureen L Cropper et al. “Environmental Economics : A Survey”. In: *Journal of Economic Literature* 30.2 (1992), pp. 675–740.

[Del14] Pablo Del Río. “On evaluating success in complex policy mixes: The case of renewable energy support schemes”. In: *Policy Sciences* 47.3 (2014), pp. 267–287. ISSN: 00322687. DOI: `10.1007/s11077-013-9189-7`.

[DH11] Paul Denholm and Maureen Hand. “Grid flexibility and storage required to achieve very high penetration of variable renewable electricity”. In: *Energy Policy* 39.3 (2011), pp. 1817–1830. ISSN: 03014215. DOI: `10.1016/j.enpol.2011.01.019`. URL: `http://dx.doi.org/10.1016/j.enpol.2011.01.019`.

[DSW13] Sarah Darby, Jessica Strömbäck, and Mike Wilks. “Potential carbon impacts of smart grid development in six European countries”. In: *Energy Efficiency* 6.4 (2013), pp. 725–739. ISSN: 1570646X. DOI: `10.1007/s12053-013-9208-8`.

[Duv08] Romain Duval. “A taxonomy of instruments to reduce greenhouse gas emissions and their interactions”. In: *OECD Economics Department Working Papers* -.636 (2008), pp. ——-. ISSN: 1815-1973. DOI: `10.1787/236846121450`.

[DWP05] Richard Duke, Robert Williams, and Adam Payne. “Accelerating residential PV expansion: Demand analysis for competitive electricity markets”. In: *Energy Policy* 33.15 (2005), pp. 1912–1929. ISSN: 03014215. DOI: `10.1016/j.enpol.2004.03.005`.

[FC16] Anton Finenko and Lynette Cheah. “Temporal CO2 emissions associated with electricity generation: Case study of Singapore”. In: *Energy Policy* 93 (2016), pp. 70–79. ISSN: 03014215. DOI: `10.1016/j.enpol.2016.02.039`. URL: `http://dx.doi.org/10.1016/j.enpol.2016.02.039`.

[Fin+11] P. Finn et al. “Facilitation of renewable electricity using price based appliance control in Ireland’s electricity market”. In: *Energy* 36.5 (2011), pp. 2952–2960. ISSN: 03605442. DOI: `10.1016/j.energy.2011.02.038`. URL: `http://dx.doi.org/10.1016/j.energy.2011.02.038`.

[Fis08] Corinna Fischer. “Feedback on household electricity consumption: A tool for saving energy?” In: *Energy Efficiency* 1.1 (2008), pp. 79–104. ISSN: 1570646X. DOI: `10.1007/s12053-008-9009-7`.

[FS10] Ahmad Faruqui and Sanem Sergici. “Household response to dynamic pricing of electricity: A survey of 15 experiments”. In: *Journal of Regulatory Economics* 38.2 (2010), pp. 193–225. ISSN: 0922680X. DOI: `10.1007/s11149-010-9127-y`.

[GAL13] Will Gans, Anna Alberini, and Alberto Longo. "Smart meter devices and the effect of feedback on residential electricity consumption: Evidence from a natural experiment in Northern Ireland". In: *Energy Economics* 36 (2013), pp. 729–743. ISSN: 01409883. DOI: `10.1016/j.eneco.2012.11.022`. URL: `http://dx.doi.org/10.1016/j.eneco.2012.11.022`.

[GG14] Ben Gilbert and Joshua Graff Zivin. "Dynamic salience with intermittent billing: Evidence from smart electricity meters". In: *Journal of Economic Behavior and Organization* 107.PA (2014), pp. 176–190. ISSN: 01672681. DOI: `10.1016/j.jebo.2014.03.011`. URL: `http://dx.doi.org/10.1016/j.jebo.2014.03.011`.

[GR14] Jean Michel Glachant and Sophia Ruester. "The EU internal electricity market: Done forever?" In: *Utilities Policy* 31 (2014), pp. 221–228. ISSN: 09571787. DOI: `10.1016/j.jup.2014.03.006`. URL: `http://dx.doi.org/10.1016/j.jup.2014.03.006`.

[Har+08] Jeffrey Harris et al. "Towards a sustainable energy balance: Progressive efficiency and the return of energy conservation". In: *Energy Efficiency* 1.3 (2008), pp. 175–188. ISSN: 1570646X. DOI: `10.1007/s12053-008-9011-0`.

[HDH14] Matthias Huber, Desislava Dimkova, and Thomas Hamacher. "Integration of wind and solar power in Europe: Assessment of flexibility requirements". In: *Energy* 69 (2014), pp. 236–246. ISSN: 03605442. DOI: `10.1016/j.energy.2014.02.109`. URL: `http://dx.doi.org/10.1016/j.energy.2014.02.109`.

[HM06] Stephen P Holland and Erin T Mansur. "The Short-Run Effects of Time-Varying Prices in Competitive Electricity Markets The Short-Run Effects of Time-Varying Prices in Competitive Electricity Markets". In: May (2006).

[Hol+08] Stephen P Holland, Erin T Mansur, et al. "IS REAL-TIME PRICING GREEN ? THE ENVIRONMENTAL IMPACTS OF ELECTRICITY DEMAND VARIANCE". In: 90.August (2008), pp. 550–561.

[Hou51] H.S. Houthakker. "Electricity Tariffs in Theory and Practice". In: *The Economic Journal* 61.241 (1951), pp. 1–25. ISSN: 00130133. DOI: `10.2307/2231709`. URL: `http://links.jstor.org/sici?sici=0013-0133(198103)91:361%7B%5C%%7D3C199:RES%7B%5C%%7D3E2.0.CO;2-C%7B%5C&%7Dorigin=crossref`.

[HUE16] Lion Hirth, Falko Ueckerdt, and Ottmar Edenhofer. "Why wind is not coal: On the economics of electricity generation". In: *Energy Journal* 37.3 (2016), pp. 1–27. ISSN: 01956574. DOI: `10.5547/01956574.37.3.lhir`. arXiv: `arXiv:1011.1669v3`.

[Ito14] K Ito. "Do Consumers Respond to Marginal or Average Price ? Evidence from Nonlinear Electricity Pricing". In: *American Economic Association* 104.2 (2014), pp. 537–563.

[JR12] Katrina Jessoe and David Rapson. "Knowledge is (less) power: Experimental evidence from residential energy use". In: *American Economic Review* 104.4 (2012), pp. 1417–1438. ISSN: 0002-8282. DOI: `10.1257/aer.104.4.1417`. URL: `http://pubs.aeaweb.org/doi/abs/10.1257/aer.104.4.1417%7B%5C%%7D5Cnhttp://www.nber.org/papers/w18344`.

[JS94] Adam B. Jaffe and Robert N. Stavins. "The energy-efficiency gap What does it mean?" In: *Energy Policy* 22.10 (1994), pp. 804–810. ISSN: 03014215. DOI: `10.1016/0301-4215(94)90138-4`.

[KEL13] Matthias Kalkuhl, Ottmar Edenhofer, and Kai Lessmann. "Renewable energy subsidies: Second-best policy or fatal aberration for mitigation?" In: *Resource and Energy Economics* 35.3 (2013), pp. 217–234. ISSN: 09287655. DOI: `10.1016/j.reseneeco.2013.01.002`. URL: `http://dx.doi.org/10.1016/j.reseneeco.2013.01.002`.

[Kop+17] Maria Kopsakangas-Savolainen et al. "Hourly-based greenhouse gas emissions of electricity – cases demonstrating possibilities for households and companies to decrease their emissions". In: *Journal of Cleaner Production* 153 (2017), pp. 384–396. ISSN: 09596526. DOI: `10.1016/j.jclepro.2015.11.027`. URL: `http://dx.doi.org/10.1016/j.jclepro.2015.11.027`.

[KSY16] A. G. Kök, K. Shang, and Ş. Yucel. "Impact of electricity pricing policy on renewable energy investments and carbon emissions". In: *Management Science* (2016).

[MA10] Pedro S. Moura and Aníbal T. de Almeida. "The role of demand-side management in the grid integration of wind power". In: *Applied Energy* 87.8 (2010), pp. 2581–2588. ISSN: 03062619. DOI: `10.1016/j.apenergy.2010.03.019`. URL: `http://dx.doi.org/10.1016/j.apenergy.2010.03.019`.

[Mad+13] Seyed Hossein Madaeni et al. "Using Demand Response to Improve the Emission Benefits of Wind". In: *IEEE Transactions on Power Systems* 28.2 (2013), pp. 1385–1394.

[MSR14] Matteo Muratori, Beth Anne Schuelke-Leech, and Giorgio Rizzoni. “Role of residential demand response in modern electricity markets”. In: *Renewable and Sustainable Energy Reviews* 33 (2014), pp. 546–553. ISSN: 13640321. DOI: `10.1016/j.rser.2014.02.027`. URL: `http://dx.doi.org/10.1016/j.rser.2014.02.027`.

[OCo+14] Niamh O’Connell et al. “Benefits and challenges of electrical demand response: A critical review”. In: *Renewable and Sustainable Energy Reviews* 39 (2014), pp. 686–699. ISSN: 13640321. DOI: `10.1016/j.rser.2014.07.098`.

[SBN14] Pia Stoll, Nils Brandt, and Lars Nordström. “Including dynamic CO2 intensity with demand response”. In: *Energy Policy* 65 (2014), pp. 490–500. ISSN: 03014215. DOI: `10.1016/j.enpol.2013.10.044`. URL: `http://dx.doi.org/10.1016/j.enpol.2013.10.044`.

[SD08] Steve Sorrell and John Dimitropoulos. “The rebound effect: Microeconomic definitions, limitations and extensions”. In: *Ecological Economics* 65.3 (2008), pp. 636–649. ISSN: 09218009. DOI: `10.1016/j.ecolecon.2007.08.013`.

[Sor03] S. Sorrell. “Carbon Trading in the Policy Mix”. In: *Oxford Review of Economic Policy* 19.3 (2003), pp. 420–437. ISSN: 1460-2121. DOI: `10.1093/oxrep/19.3.420`. URL: `https://academic.oup.com/oxrep/article-lookup/doi/10.1093/oxrep/19.3.420`.

[Ste57] Peter O. Steiner. “Peak Loads and Efficient Pricing”. In: *The Quarterly Journal of Economics* 71.4 (1957), p. 585. ISSN: 00335533. DOI: `10.2307/1885712`. URL: `https://academic.oup.com/qje/article-lookup/doi/10.2307/1885712`.

[Tor12] Jacopo Torriti. “Price-based demand side management: Assessing the impacts of time-of-use tariffs on residential electricity demand and peak shifting in Northern Italy”. In: *Energy* 44.1 (2012), pp. 576–583. ISSN: 03605442. DOI: `10.1016/j.energy.2012.05.043`. URL: `http://dx.doi.org/10.1016/j.energy.2012.05.043`.

[Uec+13] Falko Ueckerdt et al. “System LCOE: What are the costs of variable renewables?” In: *Energy* 63 (2013), pp. 61–75. ISSN: 03605442. DOI: `10.1016/j.energy.2013.10.072`.

[Win+16] Jenny Winkler et al. “Impact of renewables on electricity markets - Do support schemes matter?” In: *Energy Policy* 93 (2016), pp. 157–167. ISSN: 03014215. DOI: `10.1016/j.enpol.2016.02.049`.

6 Appendix

Renewable energy	**Peak load shifting**
$\pi_1 = 0$ and $\pi_2 = 1$	$\tilde{q_{jr}} < q_{j2} - \frac{\mu_1}{\mu_2} q_{i1}$
$\pi_1 = 1$ and $\pi_2 = 0$	$\tilde{q_{ir}} > q_{i1} - \frac{\mu_1}{\mu_2} q_{j2}$
$\pi_1 = 0$ and $\pi_2 = 0$	$\mu_2 q_{j2} > \mu_1 q_{i1}$
$\pi_1 = 1$ and $\pi_2 = 1$	$\mu_2 q_{j2} - \mu_1 q_{i1} > \mu_2 \tilde{q_{jr}} - \mu_1 \tilde{q_{ir}}$

Table 1: Peak pricing and load shifting: conditions for GHG emissions reduction.

Renewable energy	**Peak load shedding**
$\pi_1 = 0$ and $\pi_2 = 1$	$\tilde{q_{jr}} < q_{j2} - \frac{\mu_1}{\mu_2} q_{i1}$
$\pi_1 = 1$ and $\pi_2 = 0$	$\tilde{q_{ir}} > \frac{\mu_2}{\mu_1} q_{j2} - q_{i1}$
$\pi_1 = 0$ and $\pi_2 = 0$	$\mu_1 q_{i1} < \mu_2 q_{j2}$
$\pi_1 = 1$ and $\pi_2 = 1$	$\mu_1 \tilde{q_{ir}} - \mu_2 \tilde{q_{jr}} < \mu_2 q_{j2} - \mu_1 q_{i1}$

Table 2: Peak pricing and load shedding: conditions for GHG emissions reduction.

Renewable energy	$\frac{\partial EC}{\partial p_3} < 0$
$\pi_1 = 0$ and $\pi_2 = 1$	$-\mu_1 \varepsilon_{b_3} q_{b1} < \mu_2 \tilde{q_{jr}}$
$\pi_1 = 1$ and $\pi_2 = 0$	$-\mu_1 \varepsilon_{b_3} q_{b1} < \mu_1 \tilde{q_{ir}}$
$\pi_1 = 0$ and $\pi_2 = 0$	$\mu_1 \mid \varepsilon_{b_3} \mid q_{b1} > 0$
$\pi_1 = 1$ and $\pi_2 = 1$	$-\mu_1 \varepsilon_{b_3} q_{b1} < \mu_1 \tilde{q_{ir}} + \mu_2 \tilde{q_{jr}}$

Table 3: Block pricing if $\mid \varepsilon_{b_3} \mid$ is greater than zero: conditions for GHG emissions reduction.

Renewable energy	$\frac{\partial EC}{\partial p_3} < 0$
$\pi_1 = 0$ and $\pi_2 = 1$	$-\mu_1 \varepsilon_{b_3} q_{b1} + \mu_2 \varepsilon_{j_3} q_{j2} < \mu_2 \tilde{q_{jr}}$
$\pi_1 = 1$ and $\pi_2 = 0$	$-\mu_1 \varepsilon_{b_3} q_{b1} + \mu_2 \varepsilon_{j_3} q_{j2} < \mu_1 \tilde{q_{ir}}$
$\pi_1 = 0$ and $\pi_2 = 0$	$\mu_1 \mid \varepsilon_{b_3} \mid q_{b1} + \mu_2 \mid \varepsilon_{j_3} \mid q_{j2} > 0$
$\pi_1 = 1$ and $\pi_2 = 1$	$-(\mu_1 \varepsilon_{b_3} q_{b1} + \mu_2 \varepsilon_{j_3} q_{j2}) < \mu_1 \tilde{q_{ir}} + \mu_2 \tilde{q_{jr}}$

Table 4: Block pricing if $\mid \varepsilon_{b_3} \mid$ and $\mid \varepsilon_{j_3} \mid$ are greater than zero: conditions for GHG emissions reduction.

Renewable energy	$\frac{\partial EC}{\partial p_3} < 0$
$\pi_1 = 0$ and $\pi_2 = 1$	$-\mu_2 \varepsilon_{j_3} q_{j2} < \mu_2 \tilde{q_{jr}}$
$\pi_1 = 1$ and $\pi_2 = 0$	$-\mu_2 \varepsilon_{j_3} q_{j2} < \mu_1 \tilde{q_{ir}}$
$\pi_1 = 0$ and $\pi_2 = 0$	$\mu_2 \mid \varepsilon_{j_3} \mid q_{j2} > 0$
$\pi_1 = 1$ and $\pi_2 = 1$	$-\mu_2 (\varepsilon_{j_3} q_{j2} < \mu_2 \tilde{q_{jr}} + \mu_1 \tilde{q_{jr}}$

Table 5: Block pricing if $\mid \varepsilon_{j_3} \mid$ is greater than zero: conditions for GHG emissions reduction.

Renewable energy	$\frac{\partial EC}{\partial p_3} < 0$
$\pi_1 = 0$ and $\pi_2 = 1$	$\mu_1 \varepsilon_{a_3} q_{a_1} - (\mu_1 \varepsilon_{b_3} q_{b_1} + \mu_2 \varepsilon_{j_3} q_{j_2}) < \mu_2 \tilde{q_{j_r}}$
$\pi_1 = 1$ and $\pi_2 = 0$	$\mu_1 (\varepsilon_{a_3} q_{a_1} - (\mu_1 \varepsilon_{b_3} q_{b_1} + \mu_2 \varepsilon_{j_3} q_{j2}) < \mu_1 \tilde{q_{i_r}}$
$\pi_1 = 0$ and $\pi_2 = 0$	$\mu_1 \varepsilon_{a_3} q_{a1} < \mu_1 \varepsilon_{b_3} q_{b1} + \mu_2 \varepsilon_{j_3} q_{j2}$
$\pi_1 = 1$ and $\pi_2 = 1$	$\mu_1 \varepsilon_{a_3} q_{a1} - (\mu_1 \varepsilon_{b_3} q_{b1} + \mu_2 \varepsilon_{j_3} q_{j2}) < \mu_1 \tilde{q_{ir}} + \mu_2 \tilde{q_{jr}}$

Table 6: Block pricing if all the three price elasticities are greater than zero: conditions for GHG emissions reduction.

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