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Rethinking European energy taxation to incentivise consumer demand response participation

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A B S T R A C T

The European Union considers demand response to be an integral part of its future energy vision, in particular as a supporting mechanism for renewable resource integration. To achieve high demand response participation, the European Union recognises the need for adequate financial incentives for all consumers, especially for residential and service sector consumers. However, the European Energy Tax Directive, which regulates energy taxation in the European Union, is currently not in alignment with this vision, as it does not provide any financial incentives for demand response participation. This paper explores the potential of energy taxes to provide such incentives. First, through an analysis of the current energy taxation and demand response literature. Second, by quantifying the difference in financial incentives between two tax designs (*per-unit* and *ad valorem* taxes) in a simulation case study of consumers heat pumps in the Netherlands. Results show that financial incentives are 3.5 times higher for the *ad valorem* tax than for the *per-unit* tax. The paper concludes with recommendations for policy makers for the design of energy taxes that provide residential and service sector consumers with adequate financial incentives for demand response participation.

1. Introduction

There is a growing understanding among researchers, policy makers and stakeholders that demand response is pivotal for the reliability, security and efficiency of the power system as it transitions to intermittent renewable resources (Cappers et al., 2012; Bergaentzlé et al., 2014; Smart Energy Demand Coalition, 2015; Bertoldi et al., 2016; Hu et al., 2018). Within the European Union (EU), the importance of demand response for the power system is set out in various Directives, including the Third Energy Package (European Parliament and the Council of the European Union, 2009), and the Directive on energy efficiency (European Parliament and the Council of the European Union, 2012). These Directives detail the role of demand response as an instrument to achieve climate and energy goals. Specifically, demand response is considered to provide a cost effective means of balancing high shares of intermittent renewable resources, thus supporting their integration in the power system (Bertoldi et al., 2016).

Demand response is defined as the "changes in electricity use by consumers from their normal consumption patterns in response to price signals, or to incentive payments" (Albadi and El-Saadany, 2008; Aghaei and Alizadeh, 2013). Thus, providing consumers with financial incentives is considered by many to be key to achieve a so-called "demand follows supply" power system paradigm (Albadi and El-Saadany, 2008; Aghaei and Alizadeh, 2013; Ashouri et al., 2016). This is a power system where demand is, to some degree, flexible and can use variable renewable generation when it is available. The European Parliament and the Council of the European Union (2017) recognise that currently residential and service sector consumers do not receive price signals that incentivise demand flexibility. The Proposal for a new Directive on the Internal Electricity Market focuses on real-time retail prices as a means to convey these price signals (European Parliament and the Council of the European Union, 2017). The efficacy and benefits of such real-time price signals on consumer participation is shown by Faruqui and Palmer (2011). The present paper argues that in addition to these real-time retail prices, the European energy tax legislation needs to be rethought to provide consumers financial incentives for demand response participation, thus paving the way for higher renewable resource utilisation.

In the European Union, energy taxes constitute a considerable part of the final consumer electricity bill. The European average is 26%, the range spanning from 4.8% in Malta, to 68% in Denmark (EurElectric, 2012; Eurostat, 2018). The framework for European energy taxes is set out by Directive 2003/96/EC on Energy Taxation (European Parliament and the Council of the European Union, 2003). This Directive is solely geared towards incentivising energy efficiency and energy conservation. It does not give any financial incentives for shifting demand in

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time, and thus providing demand flexibility. In its current form, it is thus inconsistent with the European energy vision, that requires both energy efficiency and demand flexibility.

European Member States can set their own energy taxes within the boundaries determined by the Energy Taxation Directive. In almost all European countries, electricity consumption is taxed with a so-called "*per-unit* tax", *i.e.* a fixed amount of tax per kWh consumed electricity (EurElectric, 2012; Eurostat, 2018) (*e.g.*, 0.12 € per kWh in the Netherlands (Statistics Netherlands, 2018)). Spain is a noteworthy exception with a tax rate which is an "*ad valorem* tax", *i.e.* a percentage (5.1113%) of the generation price paid by the consumer instead of a fixed amount of tax per kWh (Jefatura del Estado, 1992). A side-effect of implementation of energy taxes as *per-unit* taxes is the lack of financial incentives for demand flexibility.

This paper argues that if the European Union implements real-time retail prices to encourage demand response, the clarity of the price signals for end-consumers will be dampened by the *per-unit* energy tax, as currently used in the vast majority of European Member States. The dampening effect is larger if the share of energy taxes in the final electricity bill is higher, as a smaller portion of the bill is affected by the generation price fluctuations. On the contrary, if an *ad valorem* energy tax is implemented, real-time price fluctuations affect both the generation cost and the tax portions of the electricity bill, providing a stronger financial incentive for demand flexibility.

Thus far, relatively little attention has been paid to the effect of consumer energy taxes on demand response incentives. The issue is briefly mentioned by a few authors (O'Connell et al., 2014; Eid et al., 2016a), who merely note that with the existing consumer electricity bill structure, energy taxes negatively affect price clarity. The lack of attention for the issue can be explained by focus limitations of different fields addressing energy taxes and demand response. This paper (1) provides a review of the literature of energy taxes and demand response across different research fields (Section 2), and (2) shows in a simulation case study how taxes impact consumers' financial incentives for demand response participation (Sections 3, 4 and 5). The case study compares financial incentives of *per-unit* and *ad valorem* taxes for demand response with heat pumps in the Netherlands. The results of the case study show that an *ad valorem* tax provides a much stronger financial incentive for demand response participation as compared to a *per-unit* tax. The paper calls for an open discussion on the role of energy taxes with respect to financial incentives for consumer demand flexibility.

2. Literature review

Both energy taxation and demand response currently receive increased interest among researchers, policy makers and stakeholders as a result of societal and political concerns regarding climate change. A considerable and growing body of literature is available on both topics. Literature on energy taxes primarily addresses how they can be used to internalise the negative environmental costs of energy use. Literature on demand response analyses the extent of the technical potential of demand response in future power systems and how consumers can be incentivised to offer demand flexibility. The following paragraphs provide a review of the (disconnected) research fields of energy taxes and demand response.

2.1. Energy taxes

Energy taxes, environmental taxes and carbon taxes are often named in one breath, or even as synonyms (Organisation for Economic Co-Operation and Development, 1997; Parry et al., 2012). They all serve the purpose of internalising negative external environmental costs, but have different scopes and bases. The OECD defines an *environmental tax* as "a tax whose tax base is a physical unit (or a proxy of it) that has a proven specific negative impact on the environment" (Organisation for Economic Co-Operation and Development, 2018). It distinguished four types of environmental taxes: energy taxes, transport taxes, pollution taxes and resource taxes (Organisation for Economic Co-Operation and Development, 2018). Energy taxes are taxes which are levied based on energy use (*e.g.*, fuel or electricity), while carbon taxes (a type of pollution taxes) are expressed per unit emitted CO_2 (Fisher et al., 1995). This paper focuses on energy taxes for electricity use.

Energy taxes are an example of excise taxes, they discourage the consumption of electricity based on the negative environmental impacts which arise from power generation from fossil fuels (Cnossen, 2011; Parry et al., 2012; Organisation for Economic Co-operation and Development, 2018). Excise taxation is indeed the guiding principle behind the existing EU Energy Taxation Directive, which stipulates that EU Member States are required to levy a minimum energy tax for electricity consumption (0.5 €/MWh for businesses and 1 €/MWh for non-business users) (European Parliament and the Council of the European Union, 2003).

Current literature on energy taxes specifically, and environmental taxes in general, addresses the question *how to set such tax rates correctly*, *i.e.* what should be taxed and by how much (Parry et al., 2012; Organisation for Economic Co-operation and Development, 2018). The choice of tax base and level are classically addressed by Pigouvian Theory (Pigou, 1920), that states that energy taxes, being a type of excise taxes, should equal the marginal cost of the damages they cause. The taxes should be levied directly on the source of emission (Pigou, 1920). The OECD adheres the Pigouvian Theory (Organisation for Economic Co-operation and Development, 2018).

The existing Pigouvian excise taxes approach for energy taxation implicitly assumes that the use of electricity is equally damaging for the environment regardless of the timing of electricity consumption. This is true for electricity generated from fossil fuels. The picture is more complex for power systems with a high share of renewable resources. Energy conservation, incentivised by excise taxes, is expected to remain an important part in such high-renewables power systems (Jacobson and Delucchi, 2011; European Parliament and the Council of the European Union, 2012). Although renewable resources such as solar and wind energy are abundant, materials and area to capture and transform them to electricity are limited (Delucchi and Jacobson, 2011; Jacobson and Delucchi, 2011). Thus, energy conservation is expected to remain important in power systems with high shares of renewable generation. However, the degree of energy conservation necessary varies on very short time scales in such power systems. Since renewable resources such as wind and solar are intermittent, the *timing* of energy use, and thus demand flexibility, becomes key (Lund et al., 2015). Electricity demand at times of high solar or wind generation leads to direct consumption of renewably generated electricity, and thus low environmental impact. Demand at times of low solar or wind requires storage or long-distance transportation of renewably generated electricity, or generation from non-renewable resources, and has thus a higher environmental impact (Delucchi and Jacobson, 2011; Jacobson and Delucchi, 2011; Edenhofer et al., 2012). To the best of our knowledge, taxes which are explicitly time-dependent currently do not exist.

The question thus arises what the role of energy taxes will be as power systems transition to increasing shares of renewable generation. The following two arguments can be used in favour of diminishing or abolishing energy taxes for electricity generated from renewable resources. First, since energy taxes are excise taxes, they are designed to internalise negative environmental costs associated with electricity generation. As these costs are considerably lower in case of renewables than in case of fossil fuels, consumption of electricity generated from renewables can be partially or fully exempt from energy taxes. This provision already exists in the Energy Taxation Directive (European Parliament and the Council of the European Union, 2003). Second, the European Union seeks to move to real-time retail pricing (European

Parliament and the Council of the European Union, 2017). Such pricing schemes are considered to be optimal as they have the theoretical potential to perfectly convey the real cost of electricity to consumers. Taxation of such optimal pricing schemes is therefore said to induce economic inefficiencies (Borenstein and Holland, 2003). Thus, the low environmental impact of renewables and the optimality of real-time retail pricing can be used as arguments to discontinue energy taxation in power systems with high shares of renewables.

However, in practice it is unlikely that governments would (soon) entirely forego current income from energy taxes. In 2016, the European Member States collected 275 billion euro from energy taxes (Eurostat, 2018). These energy taxes are typically not earmarked for specific use, and thus seen as a part of governmental income (Vollebergh, 2012). Recent literature addresses the role environmental taxes can play for general government spending purposes such as deficit reduction and infrastructure financing (Rausch and Reilly, 2015; Yuan et al., 2017). Moreover, a number of authors argue that high environmental taxes and low labour taxes can be used to transition to a “green” or “circular” economy, with low resource utilisation and high employment rates (De Mooij et al., 2012; Vollebergh, 2012; Groothuis, 2014). Thus, assuming continued existence of energy taxes in power systems with high shares of renewables, their impact on financial incentives for demand response requires further study. Providing such financial incentives for demand response through taxes can result in either a decrease in governmental energy tax income, or increased taxation of consumers not participating in demand response, depending on the energy tax design. This paper further errs on the conservative side and assumes a budgetary *status quo*. It shows that existing *per-unit* energy tax can be substituted by *ad valorem* energy tax without income loss for the government, while providing incentives for demand response participation. The ultimate choice to increase or decrease the total energy tax income is part of political processes that are out of scope of this paper.

2.2. Demand response

Demand response is widely considered an important part of high-renewables power systems as a supporting mechanism for the integration and utilisation of renewable energy (Cappers et al., 2012; Bergaentzlé et al., 2014; Smart Energy Demand Coalition, 2015; Bertoldi et al., 2016; Hu et al., 2018). The existing body of literature addresses demand response from different angles. This review is limited to literature which deals with financial incentives for demand response participation by residential and service sector consumers in retail markets, and participation barriers for these consumers. These topics provide the closest links with energy taxation literature, although the fields thus far remain disconnected.

The existing literature of financial incentives for demand response usually pertains only to the energy generation component of the consumers' electricity bill because this is currently the only component subject to market competition[1] (Albadi and El-Saadany, 2008; Bommel, 2016). Two types of incentives or so-called “remuneration programmes” are typically distinguished (Albadi and El-Saadany, 2008; Vardakas et al., 2015; Lamprinos et al., 2016): *price-based* (or *indirect load control*) programmes, and *incentive-based* (or *direct load control*) programmes. *Price-based programmes* provide dynamic tariffs to customers. Price-based programmes include Real Time Pricing (RTP), Time of Use (TOU), Critical Peak Pricing (CPP), and Extreme Day Pricing (EDP) programmes. *Incentive-based programmes* provide consumers with a remuneration fee for their participation in demand response. Such programmes are primarily geared towards large, industrial consumers. Detailed reviews of remuneration programmes can be found in Albadi and El-Saadany (2008), Vardakas et al. (2015), and Lamprinos et al. (2016).

Most of the literature concerned with different price-based programmes or “pricing schemes” either analyses the benefits and challenges of roll-out of large-scale demand response programmes in the power system (Albadi and El-Saadany, 2008; Torriti, 2012; Aghaei and Alizadeh, 2013; Gyamfi et al., 2013; O'Connell et al., 2014), or describes the results of specific pilot projects (*e.g.*, D'hulst et al. (2015), Bradley et al. (2016) for residential consumers and Jang et al. (2016) for service sector consumers). Literature on the roll-out of large-scale demand response programmes includes studies which address consumer price elasticities, *i.e.* the changes in electricity use due to changes in electricity prices (Gyamfi et al., 2013; Torriti, 2012). To the best of our knowledge, none of the existing studies explicitly discusses the fact that *per-unit* taxes superimposed on a dynamic electricity price negatively affect the clarity of price signals, and thus consumer response.

The European Commission recognises that “the potential for optimal demand response remains untapped” and acknowledges that the current regulatory framework “does not provide the consumers with signals and value for participation in the market” (European Commission, 2015). Academic literature seeks to give insights in barriers for consumer demand response participation. Bergaentzlé et al. (2014) show that the existence of fixed, regulated prices, that prevent new market parties from providing consumers with real price signals, are a barrier to demand response success. This issue is addressed by the European Proposal for a new Directive on the internal electricity market which offers consumers the choice for real-time retail prices, aiming to provide price signals incentivising demand flexibility (European Parliament and the Council of the European Union, 2017). Several authors identify additional barriers for demand response which arise from various issues related to smart meters. Bergaentzlé et al. (2014) consider the lagging roll-out of smart meters as a main obstacle to large-scale demand response. Lamprinos et al. (2016) argue that norms and regulations governing smart meters and smart devices are inadequate both to protect the privacy of consumers and to incentivise market parties to invest in these devices. Vallés et al. (2016) similarly identify the ambiguity in roles and responsibilities of smart meter and data management as a main barrier. Some of these authors further name broader demand response recognition and regulatory issues. Lamprinos et al. (2016) show that incumbent parties, such as transmission system operators (TSOs), do not always recognise demand response as a systems resource, limiting its uptake possibilities. Vallés et al. (2016) underscore the regulatory uncertainties on the remuneration of distribution system operators (DSOs), the feasibility of cost-reflective network tariffs, and the lack of regulation of suppliers and aggregators in their role as demand response providers.

Energy taxes are not identified as a barrier in these analyses. Only a few authors, O'Connell et al. (2014) and Eid et al. (2016a), briefly mention the obscuring effects of the existing tax tariffs on the final price signal clarity for the end-consumers, and thus on the financial incentives for demand response participation. However, the authors do not provide any further analysis on the interaction between demand response and energy taxes.

2.3. Synthesis: knowledge gap

Neither the existing academic literature on energy taxation and demand response, nor European regulations and proposals provide insights on the impact of energy taxes on financial incentives for end-consumers' demand response participation. Energy taxation literature focuses on setting energy taxes correctly, implicitly assuming time-independence of environmental impacts of energy consumption. Demand

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[1] Currently interest is also increasing for dynamic tariffs for regulated network charges. Analyses and position points from different parties can be found in European Distribution System Operators (2015), Picciariello et al. (2015), Bommel (2016), EurElectric (2016). Network charges are left out of scope in this paper.

response literature is limited to the generation component of the consumers' electricity bill, as this is the only component subject to market competition. Existing studies do not address how market signals sent through dynamic pricing are affected by *per-unit* energy taxes used in the vast majority of European Member States.

Reconsideration of energy taxation can provide an important opportunity for policy makers to financially stimulate demand response. A future energy tax design can be consistent with both energy efficiency targets, and renewable resource integration targets, *i.e.* demand flexibility. This paper highlights the potential of energy taxation to achieve both goals and thus align energy taxation regulations with the European climate and energy strategy.

The remainder of this paper illustrates how financial incentives for demand response participation for small residential and service sector consumers differ between *per-unit* and *ad valorem* taxes. The latter is chosen as an alternative to *per-unit* taxes for two reasons. First, *ad valorem* taxes pass on electricity price signals to end-consumers, thus supporting demand response and integration of renewables, while retaining (part of) the current government revenue from energy taxes. Second, although the Spanish *ad valorem* energy taxation law was signed in 1992, and thus pre-dates the public and political interest in demand response, its implementation shows that this type of energy taxation is compatible even with the current EU regulatory taxation framework. The following case study explores and compares the effects of *per-unit* and *ad valorem* energy taxes on financial incentives for demand response participation.

3. Case study motivation

The case study is motivated by the need for clear financial incentives for demand response programmes. Currently, price signals which can be provided to consumers by commercial parties are dampened by the existing *per-unit* energy taxes. Dampened price signals negatively affect the operation of such commercial parties as consumers receive fewer financial incentives for demand response participation. Thus, the clarity of price signals is relevant for both the consumers and the parties managing the programme. Aggregators are expected to take on the role of new commercial parties enabling and managing demand response in future power systems (Gkatzikis and Koutsopoulos, 2013). This case study simulates a demand response programme managed by an aggregator and shows the impact of *per-unit* and *ad valorem* taxes on the clarity of price signals.

The case study focuses on small and medium-sized residential and service sector consumers. As the penetration of renewables in power systems increases, demand response is expected to play an increasingly important role, requiring demand flexibility from all consumer types. Historically, only large-scale industrial consumers have been targeted for demand response participation because communication with large numbers of small consumers was infeasible (Aghaei and Alizadeh, 2013; Warren, 2014). Recent technological advances in communication and information technologies can facilitate the use of demand response across a broad section of electricity consumers, including residential and service sector consumers. Technological advances thus open the way for so-called “mass market demand response”, which is expected to be required in power systems with high renewables penetration (Cappers et al., 2012). This is the consumer segment addressed in this paper.

Residential and service sector consumers have several flexible and non-flexible appliances. The case study presented in this paper focuses on heat pumps due to (1) their increasing popularity as colder-climate countries move away from fossil-fuelled space heating systems (Darby, 2018), and (2) their large flexibility potential (see further, Section 4). Heat pumps are devices that move heat from a cooler space (*e.g.*, the outdoor) to a warmer space (*e.g.*, the indoor) using electricity in the process. The principle of their operation is similar to that of a refrigerator. A detailed description of heat pump operation can be found in Chua et al. (2010). Individually, consumers' heat pumps (or other appliances) are too small for grid-scale purposes. Therefore, an aggregator or other intermediary party is required to offer their joint demand flexibility in bulk to large incumbent parties (Roos et al., 2014; De Heer and Van der Laan, 2016).

An aggregator, or any other party managing mass market demand response, can provide consumers with financial incentives to offer demand flexibility, such as dynamic tariffs. The case study assumes real-time pricing of electricity, for the following two reasons. Real-time pricing is considered optimal to signal the real cost of electricity (Albadi and El-Saadany, 2008; Vardakas et al., 2015; Lamprinos et al., 2016), and the European Parliament and Council propose to mandate electricity retailers to offer this type of pricing to consumers (European Parliament and the Council of the European Union, 2017).

Today, however, real-time retail pricing is far from being a reality for most residential and service sector consumers (Eid et al., 2016a). Moreover, field experimentation with different energy taxes requires considerable resources. Thus, a simulation approach is best suited to provide insights in the financial incentives given by real-time pricing of electricity generation, with either *per-unit* or *ad valorem* taxes. The following section details the modelling approach and assumptions.

4. Case study methods

This simulation case study quantitatively illustrates how financial incentives for demand response participation for small and medium-sized residential and service sector consumers differ between *per-unit* energy tax and *ad valorem* energy tax. The Netherlands is chosen as the

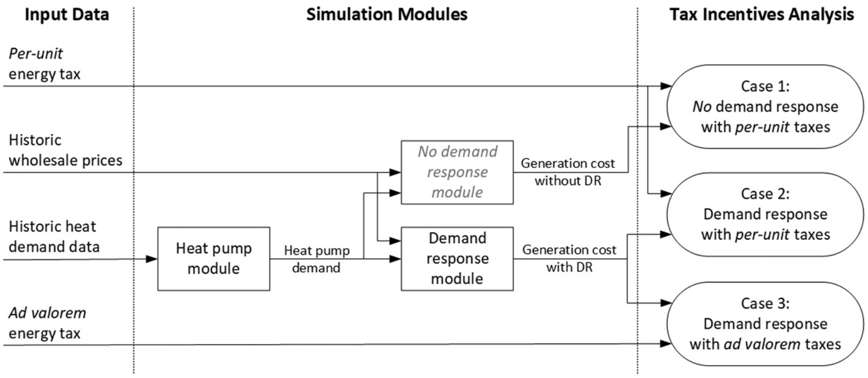

Fig. 1. Flow chart of the case study modelling approach. The case study assumes heat pumps as source of demand flexibility. Heat pump electricity demand is modelled based on historic space heating demand data, represented here by the “Heat pump module” (technical details of this module are provided in the Appendix). The case study compares three cases: (1) no demand response (reference case), (2) demand response with *per-unit* taxes, and (3) demand response with *ad valorem* taxes. For the reference case, heat pump demand profiles are combined with historic wholesale prices, yielding electricity cost without demand response (DR). This conversion step is termed “No demand response module”. The reference case assumes a *per-unit* tax. For the second and the third cases, heat pump demand profiles are modified through demand response, represented here by the “Demand response module” (technical details of this module are also provided in the Appendix). The modified heat pump demand profiles are also combined with wholesale prices, yielding electricity costs with DR. These costs are combined either with existing *per-unit* tax (case 2), or with *ad valorem* tax (case 3). This approach is carried out for three consumer types separately: residential, office, and city centre consumers.

Table 1
Three consumer types considered in this case study: residential, office and city centre. The table summarises the breakdown of the three consumer types in their constituting consumer classes. Percentages shown with each consumer sub-type indicate the share of annual demand this sub-type represents within the given consumer type. These electricity demand shares within each consumer type are representative for the Netherlands (Voulis et al., 2017). For comparison purposes, the three consumer types are scaled to have equal annual heat pump electricity demand of 98 MWh.

Consumer Type	Composition
Residential	100% households
Office	52% large offices, 47% medium offices, 1% small offices
City Centre	2% hotels, 33% restaurants, 14% cafés, 10% shops, 41% supermarkets

geographic region of study. The modelling approach is schematically shown in Fig. 1. Heat pumps for space heating are chosen as the illustrative source of demand flexibility. The model spans one year, from June 1st, 2012 until May 31st, 2013 because detailed historic demand data could be obtained for this period. The model is implemented in Matlab (MATLAB, 2016).

4.1. Consumer types

The case study explicitly considers three different types of small and medium-sized consumers: (1) residential consumers, (2) office consumers, and (3) city centre consumers. These consumer types are considered to be representative for urban areas: respectively residential, business and city centre areas. Table 1 summarises the composition of each consumer type in terms of annual heat pump electricity demand.

The key difference between the three consumer types lies in the *timing* of their demand. Typical heating demand profiles for each of the three consumer types are shown in Fig. 2. The Figure shows that residential heating demand peaks around 10 a.m. and 8 p.m., and is overall relatively high during the day, and relatively low at night (data courtesy of Dutch DSO Alliander). Office and city centre demand peaks around 6 a.m., just before office hours (data based on Deru Deru et al. (2011) and EnergyPlus (2015)). Office consumer demand has a second smaller peak at 8 p.m. City centre consumer demand has a second peak just before midnight. During the course of the day, city centre consumer demand is higher than that of offices. These differences in timing of demand are important for the technical potential to shift demand from more expensive hours to cheaper hours. Fig. 3 illustrates price fluctuations for the same two days as shown in Fig. 2 (data courtesy of Dutch DSO Alliander). A consumer's heat demand profile determines how much demand and at which time can be technically shifted.

4.2. Heat pump demand

The case study focuses on heat pumps as flexible appliances used for demand response. The choice for heat pumps for demand response is motivated by two reasons. First, heat pumps are expected to gain popularity as colder-climate countries move away from fossil-fuelled space heating systems (Darby, 2018). The Dutch government in particular plans to phase out gas consumption by 2050 (Ministry of Economic Affairs, 2016). Second, heat pumps are so-called thermostatically controlled loads (TCLs). TCLs in general are considered particularly suitable for demand response because (1) they can store energy locally in the form of temperature gradients, and (2) their demand can be shifted without major loss of comfort (Rajabi et al., 2017). Heat pumps are thus an upcoming class of large consumer-scale TCLs that have a considerable demand flexibility potential.

The model is based on measured data (for residential consumers) and realistic simulated data (for service sector consumers). In both cases, historic space heating demand is converted into corresponding heat pump electricity demand for space heating. Technical details of this conversion are described in the Appendix. Heat pumps for all consumer types are modelled in the same manner (Fig. 1). For the purpose of this paper, heat pumps are assumed to be fully available for demand response within technical and consumer-defined comfort limits. Identical limits are assumed across all three consumer types. Moreover, for comparison purposes, the three consumer types are scaled to have an equal annual heat pump electricity demand of 98 MWh (equalling the residential demand, which is based on historic data). Thus, the difference in demand response between the consumer types arises solely from timing differences in their heat demand profiles (Fig. 2).

4.3. Demand response programme

The demand response programme modelled in this case study is run by an aggregator. The aggregator represents consumers of each of the three consumer types separately, offering the heat pump flexibility of the consumers of a single type in bulk to other power market parties. Individual consumers are assumed to have agreements with the aggregator that allow the aggregator to manage their heat pump electricity use on their behalf based on market price signals (consistent with EU Proposal European Parliament and the Council of the European Union, 2017), while respecting the technical limits and consumer-set preferences.

The demand response model seeks to realistically represent the operation of an aggregator. Therefore, the modelled aggregator is assumed to use two commercial software packages, PowerMatcher (Kok, 2013) and Realtime Energy eXchange (R.E.X.) (Energy eXchange Enablers, 2018), to manage heat pump demand. These two software packages in practice enable an aggregator to communicate with the heat pumps (which thus become "smart" devices). This detailed modelling approach is chosen because it can capture the interactions in time-dependent fluctuations in wholesale electricity price, heat demand, and heat pump flexibility (the latter varies with temperature).

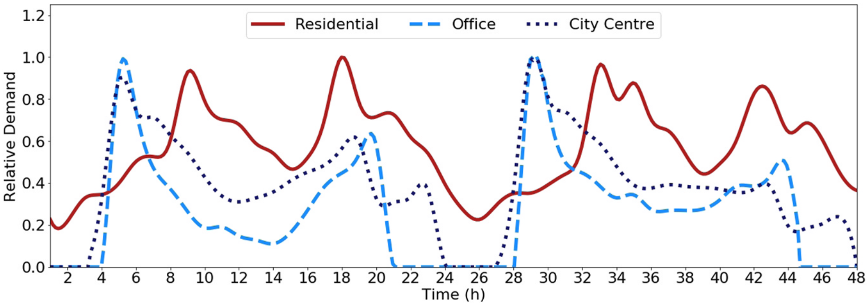

Fig. 2. Heating demand profiles of residential, office, and city centre consumers for two illustrative days (Wednesday January 16th and Thursday January 17th, 2013). The plot shows relative demand, *i.e.* profiles scaled to their respective peaks, for ease of comparison. Residential heating demand data courtesy of Dutch DSO Alliander, office and city centre data based on Deru et al. (2011).

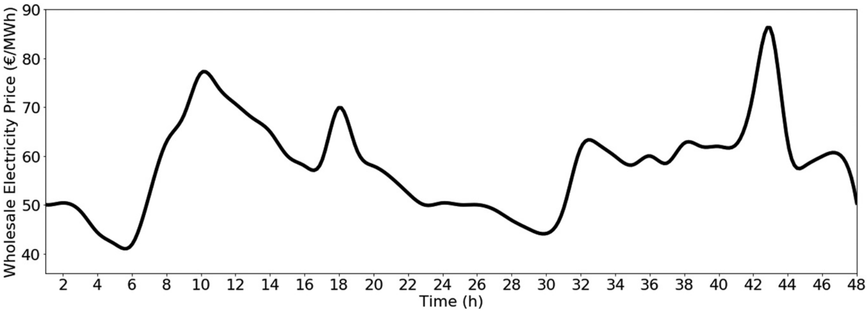

Fig. 3. Historic EPEX wholesale market electricity prices for two illustrative days (January 16th and 17th, 2013). Data courtesy of Dutch DSO Alliander.

The advantage of using detailed demand data (see previous paragraph) and a detailed demand response model is a more realistic representation of the effects of energy taxes on financial incentives for demand response participation.

In the model, the aggregator operates both on the day-ahead and the balancing market. Day-ahead the aggregator receives information about the status of the consumers' heat pumps, and their historic consumption on similar days (that determines the flexibility potential of the heat pumps). After day-ahead market closure, the aggregator receives day-ahead market price information. This price information is passed on to the heat pumps, and used to automatically adjust heat pump demand if necessary (*e.g.,* if the price is high, and technical and user-set preferences allow for a demand shift to a cheaper timeslot). In real-time, if imbalances occur, they are settled on the imbalance market. Thus, consumers are subject to real-time pricing, in line with the EU Proposal for future internal market operation (European Parliament and the Council of the European Union, 2017).

In this case study, historic day-ahead and imbalance market wholesale price data are used to account for fluctuating electricity costs, see Fig. 3. Further technical modelling details of the demand response programme are given in the Appendix. For clarity of subsequent analysis, the aggregator is assumed to have no commercial interests, thus entirely passing on wholesale prices to the consumers, not retaining any financial gains obtained from demand response.

4.4. Electricity bill components

In the Netherlands, the electricity bill of end-consumers, like that of many of their European counterparts, currently consists of the following components (ranges over the period 2012–2017): (1) electricity supply costs ranging between 0.065 and 0.079 €/kWh (Statistics Netherlands, 2018), (2) energy taxes[2] ranging between 0.1063 and 0.1232 €/kW h (Tax and Customs Administration of the Nederlands, 2018), (3) 21% value added tax (VAT) on the sum of electricity generation and energy tax components (Tax and Customs Administration of the Nederlands, 2018), and (4) network charges ranging around 200 € per year for an average household, the exact amount depends on the DSO and the connection type (Statistics Netherlands, 2018). This case study considers only the electricity generation, energy tax and VAT. Fixed costs (network charges) and tax rebates are excluded. Network charges are excluded because they are paid cumulatively for consumer's entire electricity connection, which is used only partially by the modelled heat pumps. A tax rebate is provided to households by the Dutch government, and amounts to 309–319 euro per electricity connection (Tax and Customs Administration of the Nederlands, 2018). This tax rebate is excluded for the following two reasons: (1) it pertains to the entire electricity connection, and (2) a tax rebate does not provide any demand flexibility incentives.

In summary, the total electricity bill considered in this case study consists of three price components: (1) wholesale prices passed on perfectly to the consumers, representing real-time retail prices, (2) energy taxes, and (3) 21% value added tax (VAT) on the sum of electricity generation and energy tax costs. Two energy tax designs are considered. First, *per-unit* energy tax at a rate of 0.1165 €/kWh (average energy tax over the period 2012–2017). Second, an *ad valorem* tax, which is a percentage of the electricity generation costs. Energy taxation is described further in the next paragraph.

4.5. Energy taxation

The case study analyses the effect of taxes on financial incentives to participate in demand response. Two tax designs are compared: *per-unit* energy tax, and *ad valorem* energy tax in the following three demand response cases:

- *Case 1: No demand response*. Consumers do not participate in demand response. They pay real-time electricity prices, plus 0.1165 €/kWh *per-unit* energy tax, plus 21% VAT over generation and tax components.
- *Case 2: Demand response with per-unit tax*. Consumers participate in the demand response programme offered by the aggregator for heat pump space heating. They pay real-time electricity prices, plus 0.1165 €/kWh *per-unit* energy tax, plus 21% VAT over generation and tax components.
- *Case 3: Demand response with ad valorem tax*. Consumers participate in the demand response programme offered by the aggregator for heat pump space heating. They also pay real-time electricity prices, however, in this case they pay an *ad valorem* energy tax, plus 21% VAT over generation and tax components.

This paper proposes to design the *ad valorem* tax in such a way that the government does not forgo any tax revenues if consumers do not participate in demand response. Thus, if consumers do not shift demand, they pay as much tax with the *ad valorem* tax as they would with the *per-unit* tax. This also means that, although *per-unit* tax is modelled in case 1 (no demand response), the same results would be obtained if *ad valorem* tax was assumed for the reference case. The *ad valorem* tax rate $\tilde{\tau}_i$ for each consumer type *i* can be found from the *per-unit* tax rate τ (0.1165 €/kWh) and the customer's average annual electricity cost $C_{e,i}$:

$$\tilde{\tau}_i = \frac{\tau}{C_{e,i}}, \quad \forall\ i \in \{\text{residential},\ \text{office},\ \text{city centre}\} \tag{1}$$

The *ad valorem* tax rates for each of the three consumer types are summarised in Table 2, alongside the average annual electricity costs. The average annual electricity costs differ between consumers because of the differences in demand profiles (see Fig. 2). These differences result in differences in *ad valorem* tax rates. The effects and desirability

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[2] This paper considers the total energy tax, which in the Netherlands is the sum of electricity tax and energy storage tax components. The tax range provided is valid for consumers with an annual consumption of up to 10 MWh. The modelled individual residential and service sector consumers are assumed to fall in this range based on the estimations made in Voulis et al. (2017).

Table 2
Ad valorem tax rates for different consumer types.

	Residential	Office	City Centre
Average annual electricity costs (€/kWh)	0.04711	0.04385	0.04337
Proportional tax rate (percentage of electricity cost)	247%	266%	269%

of such differences are discussed in Section 6.

4.6. Synthesis: tax incentive comparison

The aim of this case study is to illustrate differences in financial incentives that small residential and service sector consumers receive for participation in a demand response programme with different tax designs. Heat pumps for space heating are used as an illustrative example of flexible loads. Total electricity costs, as billed to the consumers, of three cases are compared: no demand response, demand response with *per-unit* tax (current tax design), and demand response with *ad valorem* tax (alternative tax design). Total electricity costs for heat pump operation without demand response are used as a reference for the two cases with demand response. Formally, the metric used to quantify financial incentives (ϕ) is the normalised difference between the electricity costs C_{ref} without demand response (reference), and electricity costs with demand response C_{DR}:

$$\phi = \frac{C_{ref} - C_{DR}}{C_{ref}} \tag{2}$$

The results of the simulation study are presented in the next section.

5. Case study results

This section shows the simulation results of different consumers' financial incentives to participate in a demand response programme. Heat pump electricity demand for space heating is used as an example of flexible load. Electricity costs for heat pump operation are broken down into electricity generation, tax and VAT components and are compared for three cases defined in Section 4.5. Results are shown for three different consumer types: residential, office and city centre consumers. Financial incentives (as defined in Eq. (2)) for demand response participation are expressed in three ways: (1) per unit total demand, (2) per unit shifted demand, and (3) for a representative consumer of each consumer type.

5.1. Financial incentives per unit total demand

Fig. 4 depicts consumers' generation, VAT and tax costs per unit total demand for the three different consumer types (residential, office and city centre, see Table 1), and for three cases: (1) no demand response, (2) demand response with *per-unit* tax, and (3) demand response with *ad valorem* tax. The tables below the cases with demand response show the changes in costs as compared to the case without demand response, *i.e.* the financial incentive as defined in Eq. (2).

No demand response. If consumers do not participate in demand response, the cost of heat pump operation lies around 195 €/MWh. Cost differences between the three consumer types are small (around 2 €/MWh). The cost per MWh is an annual average value as hourly fluctuating wholesale electricity prices are assumed to be passed on to the consumers. This assumption follows the European Parliament and Council Proposal (European Parliament and the Council of the European Union, 2017) that states that every customer will have access to a dynamic price contract that reflects wholesale electricity price fluctuations.

Demand response with *per-unit* tax. If consumers do participate in demand response, they can save between 29% and 38% on their electricity generation costs, depending on the consumer type. These savings come solely from accepting a shift in heat pump demand to hours with cheaper wholesale prices (demand shifting occurs only within technical constraints and consumer-defined preferences). The model assumes that the total heat pump electricity consumption is equal with and without demand response. Further, electricity cost decrease between 29% and 38% represent the total savings. Given the *per-unit* tax design, consumer do not pay less taxes by participating in demand response. As VAT is levied both on generation costs and on taxes, VAT costs decrease only partly (*i.e.*, 8–10%). The total savings also amount to 8–10% (*i.e.*, 15–20 €/MWh). Final electricity costs with demand response with *per-unit* tax are between 174 €/MWh (office consumers) to 179 €/MWh (residential). Differences in costs arise due to differences in demand profiles, and thus differences in the amount of demand which can be shifted to hours with cheaper wholesale prices.

Demand response with *ad valorem* tax. If an *ad valorem* tax design is implemented, consumers can save the same relative amount on their tax, and thus on the VAT component, as on the generation component, *i.e.* between 29% and 38% depending on the consumer type. The total savings in this case are between 56 €/MWh (city centre consumers) and 74 €/MWh (office consumers). The total costs between 120 €/MWh (office consumers) and 137 €/MWh (city centre consumers).

5.2. Financial incentives per unit shifted demand

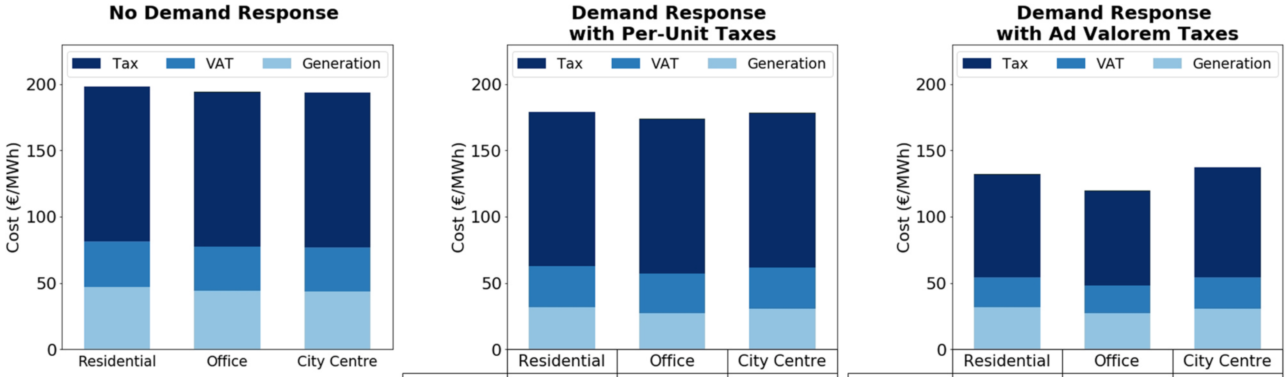
Due to differences in demand profiles, both the amount of annual shifted demand and the financial incentives per unit shifted demand differ considerably between different consumer types. Assuming the same demand response conditions, residential consumers shift 31% of their heat pump demand, offices 20% and city centre consumers 17%.

Table 3 shows cost savings per unit shifted demand. Although office consumers shift less demand than residential consumers, per unit shifted demand they obtain the highest savings (86 € per MWh shifted demand). Residential consumers obtain the least savings (50 € per MWh shifted demand). For *demand response with per-unit tax* , generation savings do not yield any tax savings, and thus only partial VAT savings. Office consumers save 104 € per MWh shifted demand, city centre consumers 90 € per MWh shifted demand, and residential consumers 61 € per MWh shifted demand. For *demand response with ad valorem tax* , generation savings lead to proportional savings on the tax and VAT components. Office consumers save 379 € per MWh shifted demand, city centre consumers 330 € per MWh shifted demand, and residential consumers 211 € per MWh shifted demand.

5.3. Financial incentives per consumer

Table 4 illustrates financial incentives of demand response participation for representative individual consumers. An average single household, an average Dutch office (with an area of 7649 m^2) and an average shop (with and area of 284 m^2) are considered representative for respectively residential, office, and city centre consumer types. Annual heat pump electricity demand for the household is calculated to be 1.6 MWh, for the office building 18.3 MWh, and for the shop 6.6 MWh.

In case of *no demand response*, the household pays 309 € per year for heat pump electricity costs, the office building 3554 € per year, and the shop 1268 € per year. The breakdown of the costs across the generation, VAT and tax components is shown in Table 4. For *demand response with per-unit tax* , the total costs decrease to respectively 280 € per year for the household, 3182 € per year for the office building, and 1167 € per year for the shop. This is a decrease of 8–10%, as also shown in Fig. 4. For *demand response with ad valorem tax*, total costs decrease to



Demand Response with Per-Unit Taxes

	Residential	Office	City Centre
Tax	-0%	-0%	-0%
VAT	-10%	-10%	-8%
Generation	-33%	-38%	-29%
Total	-10%	-10%	-8%

Demand Response with Ad Valorem Taxes

	Residential	Office	City Centre
Tax	-33%	-38%	-29%
VAT	-33%	-38%	-29%
Generation	-33%	-38%	-29%
Total	-33%	-38%	-29%

Fig. 4. Overview of consumer generation, VAT and tax costs per unit demand for three cases (no demand response, demand response with *per-unit* tax and demand response with *ad valorem* tax), and for three consumer types (residential, office and city centre). The tables below the cases with demand response show the changes in costs as compared to the reference case without demand response.

respectively 207 € per year for the household, 2195 € per year for the office building, and 898 € per year for the shop. This is a decrease of 29–38% (equal to the relative savings shown in Fig. 4).

6. Discussion

The results of the case study on financial incentives for residential and service sector demand response show that the *ad valorem* energy tax provides considerably stronger financial incentive for demand response participation than the *per-unit* tax. The results of the case study are analysed first, followed by a more general analysis of the *ad valorem* energy tax.

6.1. Case study analysis

The results of the case study are first analysed in terms of comparison of *per-unit* and *ad valorem* energy taxes. Next, differences between the different consumer types are addressed. The analysis ends with a discussion of the case study limitations and possible generalisation of the results.

6.1.1. Per-unit tax versus ad valorem tax

The case study shows that heat pump electricity cost savings are approximately 3.5 times higher with *ad valorem* tax than with *per-unit* tax. For the modelled year, this is, for instance, a difference between savings of 29 € per year and 102 € per year for an average household (Table 4).

Further, case study results show that for demand response with *per-unit* energy tax, the tax becomes a relatively larger portion of the total electricity price (rising from around 60% of the total price to around 66%). This is not the case with demand response with *ad valorem* energy tax, since that tax is defined as a percentage of electricity generation cost, and thus has a constant (approximately 60%) share in the total electricity bill. Thus, the *ad valorem* tax tariff has two main benefits compared to the *per-unit* tax. First, the *ad valorem* tax does not dampen the wholesale price differences. This means that the *ad valorem* tax provides consumers with signals and value for participation in the market, a requirement explicitly named by the European Commission (2015). Second, the *ad valorem* tax maintains the relative tax burden for demand response participants equal to that of non-participants, *i.e.* both consumer groups pay equal amount of tax relative to the electricity generation cost. Demand response is a power system and societal service (Cappers et al., 2012; Bergaentzlé et al., 2014; Smart Energy Demand Coalition, 2015; Bertoldi et al., 2016), and should not be subject to higher relative taxation.

The *ad valorem* energy tax can have additional effects, compared to the *per-unit* tax. First, switching between electricity retailers can become more attractive as electricity generation price differences between retailers are extended to the energy tax portion of the bill, and thus magnified. This effect is a benefit of the *ad valorem* tax in the context of the Third Energy Package (European Parliament and the Council of the European Union, 2009) as it improves competition in the retail market. Second, as the *ad valorem* tax is defined as a percentage of the electricity generation price, electricity retailers have an influence on the governmental revenue from energy taxes, as they can set the retail prices. This effect is similar to the effect of prices of general goods and services on governmental income from VAT, which is also an *ad valorem* tax. This effect can further be addressed as the European Union determines the rules on real-time electricity retail pricing, continuing on the work of the current Proposal (European Parliament and the Council of the European Union, 2017).

6.1.2. Influence of consumer type

The effect of consumer type on the total cost of electricity (including taxes and VAT) and on the savings through demand response depends on the specific demand response case. In the reference case with *no demand response*, the consumer type has little influence on the average unit electricity price which consumers pay (Fig. 4). For the three consumer types analysed, the original average electricity price difference is approximately 2.5%. For *demand response with per-unit tax*, total price differences between consumer types remain small (2.75%), despite the increased differences in electricity price component (14%). For *demand response with ad valorem tax*, differences between consumer types become more explicit in the final price. The differences in the amount different consumer types pay for their generation component (14%) are passed on to the total unit price. The final price difference between different consumer types thus rises to 14%. This price difference is the result of differences in demand shifting potential between the three consumer types, which is in turn due to the differences in heating demand profiles (Fig. 2).

The differences between consumer types are larger when the financial incentives per unit *shifted* demand are analysed (Table 3). All three consumer types shift only a part of their heat pump demand. However, the share shifted varies considerably between consumer types. In this case study, residential consumers shift 31% of their heat pump demand, office consumers 20%, and city centre consumers 17%. This difference arises from the differences in heat demand profiles (see Fig. 2), as all other factors (indoor and outdoor temperatures, technical

Table 3

Comparison of savings per unit shifted demand. Given the same demand response programme, residential consumers shift 31% of their heat pump demand, offices 20% and city centre consumers 17%.

		Residential	Office	City Centre
DR with *per-unit* **tax**	Generation Savings (€/MWh)	50	86	74
	VAT Savings (€/MWh)	11	18	16
	Tax Savings (€/MWh)	0	0	0
	Total Savings (€/MWh)	61	104	90
DR with *ad valorem* **tax**	Generation Savings (€/MWh)	50	86	74
	VAT Savings (€/MWh)	37	66	57
	Tax Savings (€/MWh)	124	223	199
	Total Savings (€/MWh)	211	379	330

heat pump specifications, consumer-defined preferences, *etc.)* are kept equal in the model across consumer types. Differences in heat demand profiles lead both to (1) different amounts of demand shifted, and (2) different financial incentives per unit shifted demand (see Table 3).

6.1.3. Case study generalisation

The case study illustrates the energy tax financial incentives for demand response participation for a single set of assumptions. The numeric results are limited to a single year (June 1st, 2012 until May 31st, 2013), a single country (the Netherlands), a single type of flexible appliance (heat pump), a single retail pricing scheme (real-time pricing), and three consumer types (residential, office and city centre) with a single set of preferences (temperature comfort limits acceptable for 90% of consumers, as shown in Van der Linden et al. (2006)), assuming consumers as price takers. The limitations of this approach and possible generalisations are addressed next.

Single year limitation and generalisation. The main limitation of the single-year dataset, is its inability to capture variations in electricity prices and weather-dependent heat demand between years. Therefore, the absolute values of the costs and savings as reported in the result section are valid only for the modelled year. However, the comparison between *per-unit* and *ad valorem* tax, for instance, the 3.5-fold *difference* in savings, does not depend on the electricity price or the heat demand, because they are expressed as *relative* values. This comparison is the main goal of the case study, and is generalisable.

Single country limitation and generalisation. The main limitation of the assumption of a single country, is the use of the local ratio between electricity generation, energy tax and VAT shares of the final electricity bill. The influence of taxes on the price signal clarity increases as the relative share of energy tax to electricity generation cost increases (as also briefly mentioned in O'Connell et al. (2014), and Eid et al. (2016a). The Netherlands has a relatively high share of consumer energy tax as compared to the electricity generation cost (EurElectric, 2012; Eurostat, 2018) and can therefore serve as a clear example for the difference in financial incentives between *per-unit* and *ad valorem* taxes. The relevance of the results for other countries depends on the local energy tax to electricity generation cost ratio, and is of particular interest for countries with high ratios, such as Germany and Denmark (EurElectric, 2012; Eurostat, 2018).

Single type of flexible appliance limitation and generalisation. The main differences between heat pumps and other flexible loads with respect to their demand response potential, is the timing of their demand, their size, and their flexibility limits. Thermally controlled loads (such as fridges, freezers and heat pumps) and electrical vehicles are generally considered to be the most viable options for residential and service sector consumer demand response (Eid et al., 2016b; Howell et al., 2017; Hsieh and Anderson, 2017). Differences in demand profiles between these appliances are expected to have similar impact as the differences between consumer types as presented in the case study. The absolute values of financial incentives are expected to be (partially) determined by the appliance, however the relative difference between *per-unit* and *ad valorem* tax is expected to differ to a limited extent between appliances.

Single retail pricing scheme limitation and generalisation. The difference in dynamic retail pricing schemes (RTP, TOU, CPP, EDP, see Section 2) lies primarily in the frequency of price changes (Albadi and El-Saadany, 2008; Vardakas et al., 2015; Lamprinos et al., 2016). With RTP these changes occur continuously, with EDP they occur only on some extreme days. The difference in financial incentives between *per-unit* and *ad valorem* energy tax is independent of the frequency of the price signal. It only depends on the amplitude of the price signal, the larger the difference between the cheaper and more expensive prices

Table 4

Comparison of costs per representative consumer type. An average household, office building and shop are used to illustrate costs for respectively residential, office and city centre consumers. Annual heat pump electricity demand of an average Dutch household is calculated to be 1.6 MWh, an average office (7649 m^2 floor space) 18.3 MWh, and an average shop (284 m^2 floor space) 6.6 MWh. The annual costs for each of the customers are shown for three cases: no demand response (DR), DR with *per-unit* tax (current situation), and DR with *ad valorem* tax.

		Household	Office (7649 m^2)	Shop (284 m^2)
No DR	Generation (€/year)	74	803	284
	VAT (€/year)	54	617	220
	Tax (€/year)	182	2134	764
	Total (€/year)	309	3554	1268
DR with *per-unit* **tax**	Generation (€/year)	49	496	201
	VAT (€/year)	49	552	203
	Tax (€/year)	182	2134	763
	Total (€/year)	280	3182	1167
DR with *ad valorem* **tax**	Generation (€/year)	49	496	201
	VAT (€/year)	36	381	156
	Tax (€/year)	122	1318	541
	Total (€/year)	207	2195	898

within a pricing scheme, the larger the difference between *per-unit* and *ad valorem* tax financial incentive. The comparison between the two tax designs from this case study is thus equally applicable to other dynamic retail pricing schemes. Moreover, tax incentives can be extended to direct load control programmes (Albadi and El-Saadany, 2008; Vardakas et al., 2015; Lamprinos et al., 2016), although these are less popular for residential and service sector consumers. An *ad valorem* tax proportionally increases financial incentives for demand response participation in direct load control programmes in the same manner as for dynamic retail pricing schemes.

Single set of consumer preferences limitation and generalisation. The chosen consumer-defined preferences of a comfort level acceptable for 90% of the consumers is the most conservative level in the study of Van der Linden et al. (2006). Less conservative preferences lead to marginally larger savings, as shown in Van Etten (2017). The relative effect of *per-unit* and *ad valorem* energy taxes does not depend on the consumer preferences.

Consumers as price takers limitation and generalisation. The case study assumes that consumers are price takers, *i.e.* that demand response does not influence wholesale electricity market prices. If demand response becomes widespread, wholesale prices can become dependent on consumers' demand response participation, resulting in changed price dynamics, such as smaller price differences. This can lead to smaller absolute demand response savings, however, the relative differences between *per-unit* and *ad valorem* taxes remain as long as *any* price differences exist.

In general it can be concluded that the limitations of the case study pertain to the absolute result values. The relative values, *i.e.* the comparison between *per-unit* and *ad valorem* energy tax are generalisable. This comparison is the primary aim of the case study.

6.2. *Ad valorem* energy tax analysis

Within the European Union, an *ad valorem* energy tax currently exists only in Spain. However, the Spanish energy taxation law dates back to 1992, *i.e.* before interest in demand response became wide spread (Jefatura del Estado, 1992). Spanish energy taxation rules can therefore not be simply copied to other countries, as they were not made for demand response *per se*. In fact, demand response in Spain is currently limited to an interruptible load programme for large industrial customers due to other regulatory barriers, such as prohibition of aggregation (Bertoldi et al., 2016). The existence of the Spanish *ad valorem* energy tax primarily shows that alternative energy taxation that provides incentives for both energy efficiency and demand flexibility is possible even within the current EU regulatory framework (European Parliament and the Council of the European Union, 2003). However, a dedicated update of the European Energy Taxation Directive, as a part of the electricity market redesign, is required to remove current inconsistencies with the European energy vision.

6.2.1. *Ad valorem energy tax as part of electricity market redesign*

Recent studies (Picciariello et al., 2015; Rious et al., 2015; Iychettira et al., 2017; Newbery et al., 2017; Obushevs et al., 2017; Ringler et al., 2017; Hu et al., 2018) show that the current European electricity markets are not well equipped to accommodate large amounts of decentralised variable renewable generation, nor flexible demand. These studies reveal the existence of multiple barriers resolving which requires a market overhaul and a design of novel "second generation" high-renewables electricity markets according to many authors (Iychettira et al., 2017; Hu et al., 2018; Newbery et al., 2017; Obushevs et al., 2017; Picciariello et al., 2015; Ringler et al., 2017; Rious et al., 2015).

The market redesign recommendations from recent literature can be broken down in different categories: (1) efficient signals for investment in (renewable) generation (*e.g.*, Lychettira et al., 2017; Obushevs et al., 2017), (2) efficient signals for network investments (*e.g.*, Picciariello et al., 2015), (3) cross-border market variation and congestion management rules (*e.g.*, Newbery et al., 2017; Ringler et al., 2017), (4) market settlement resolution rules (*e.g.*, Hu et al., 2018), and (5) pricing rules for consumers (*e.g.*, Rious et al., 2015). To the best of our knowledge, none of these papers address energy taxation in Europe. Energy taxation as a financial policy instrument used to incentivise demand response can be positioned within the latter category of market design research, *i.e.* electricity pricing policies for end-consumers.

Insights gained from the case study support the use of *ad valorem* energy tax design to provide clear consumer signals for electricity market participation, as required by the European Commission (2015). Further research is necessary to provide more detailed recommendations on the design of energy taxes within a "second generation" high-renewables electricity market with respect to parameters such as tax base, tax level, governmental use of tax revenue, interaction with other taxes and electricity market components.

The results in this paper are limited to the difference in financial incentives between energy taxes for two tax bases, unit electricity demand (*per-unit* tax), and value of electricity (*ad valorem* tax). The choice of tax level is qualitatively addressed in the next section, setting out the need for further quantitative research. Governmental use of tax revenue and the position of energy taxes within a larger "second generation" high-renewables electricity market are topics for future research.

6.3. Setting an *ad valorem* tax level

In the case study, the *ad valorem* tax level is determined as described in Section 4. The aim of the method used, is to ensure that if consumers do not participate in demand response, the government does not forgo any tax income. This assumption errs on the conservative side, retaining the budgetary *status quo*. However, it should be noted that the total governmental income does not influence the relative results. The *relative* effect of *ad valorem* energy tax, as compared to *per-unit* energy tax, as shown in Fig. 4, is independent from the total governmental tax income (as long as both tax designs are compared given the same total tax income).

The method described in Section 4 to determine the *ad valorem* tax level in the presented case study, uses information which is in reality available only ex-post. In reality, the average unit electricity price paid by consumers is not known, and needs to be estimated. Thus, *ad valorem* tax tariff results in extra uncertainty on tax income by governments. The extent of this uncertainty depends on the annual fluctuations in retail prices, and thus (partially) on the future consumer retail price scheme. Policy makers should weigh the disadvantage of increased uncertainty in governmental tax income against the advantages of increased financial incentives for demand response participation for small consumers, which in turn leads to advantages for power system reliability, security, efficiency and sustainability.

The tax level chosen in the case study equals the current tax level if consumers do not participate in demand response. The goal of the *ad valorem* energy tax is to incentivise consumers to do so. If consumers participate in demand response, they save money, both on the electricity generation cost and energy tax with the *ad valorem* tax design. The latter entails that the government tax revenue decreases as more consumers participate in demand response. The decrease in government tax revenue equals the relative average consumer savings multiplied by the share of consumers who participate in demand response.

The question who pays for the decrease in government revenue is both a political and a policy question. A government can consider the decrease in tax revenue as a subsidy for demand flexibility, and carry the difference itself. Alternatively, an estimation can be made of the share of consumers who are expected to participate in demand response programmes, and of their expected savings. A government can then increase the *ad valorem* tax rate, such that it does not forgo any tax income. However, in this case, consumers without demand response capabilities bear a relatively higher electricity cost burden. It is again a policy question whether that is a desirable situation if, for instance, a disproportional share of poorer consumers do not have access to smart appliances and thus to demand response programmes.

This paper sets only the first step towards energy taxation design which takes into account its financial impact on demand response participation. Further research is necessary to support policy makers in choosing the best energy tax design, and determining appropriate tax levels.

7. Conclusion and policy implications

Demand response is widely deemed to be an important enabler for a secure, reliable and efficient power system with a large share of renewables. This paper shows that the EU Energy Taxation Directive and the *per-unit* energy tax widely implemented in the European Member States do not provide consumers with financial incentives for demand response participation. The impact of energy taxes on demand response participation has thus far not been comprehensively addressed in literature. This paper quantifies the financial incentives for demand response participation in a case study on demand response with heat pumps in the Netherlands. Results of the case study show that the financial incentive for demand response participation is 3.5 times higher with an *ad valorem* than with a *per-unit* tax. Based on the results in this paper, the following recommendation for policy makers are given.

First, both European and Member States' policy makers should consider energy taxes as policy instruments to encourage both energy conservation and demand flexibility, *i.e.* demand response participation. In contrast with the European strategy to support demand response, existing European legislation energy taxation (Directive 2003/96/EC European Parliament and the Council of the European Union (2003)) and its implementation by European Member States do not include any incentives for demand response participation. The Directive does, however, not *per se* impede the development of tax tariffs that pass on electricity price signals, as shown by the existence of the Spanish *ad valorem* energy tax. Thus, alternative tax tariffs that financially incentivise demand response participation can be designed within the existing European Energy Tax Framework, and be an important design parameter for its update.

Second, energy tax levels that pass on electricity market signals to consumers should be carefully designed with respect to costs and benefits for all market parties involved (consumers who can and those who cannot participate in demand response programmes, aggregators, retailers, DSOs, TSOs, *etc.)*. This is particularly important to prevent system gaming and abuses, as these risks increase with increasing financial benefits of demand response participation. Furthermore, when deciding upon the level of the taxes, and thus considering government revenue, it is key that policy makers weight this revenue against financial implications for various market parties who can benefit from widespread demand response, and against environmental benefits of renewable integration supported through demand response.

Third, energy tax design incentivising demand response participation should be considered as one of the puzzle pieces in a new approach to market and incentive design for a modern power system. Other barriers preventing demand response participation, and barriers preventing other types of grid modernisation should be taken into account, both in their own right, and with respect to each other.

Further research is necessary to support policy makers in the choice of energy tax design which does provide the necessary financial incentives. Further research should also consider social justice effects, distributive effects, and socio-economic cost-benefits analysis of current and alternative tax designs. The research presented in this paper should be integrated in the efforts to develop novel “second generation” electricity markets which are well equipped to accommodate large amounts of decentralised variable renewable generation and flexible demand, resulting in markets which provide consumers with the right signals for market participation.

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Appendix

This Appendix provides technical details on the modelling of demand response with heat pumps used for space heating. An overview of the simulation approach is shown in Fig. 1 in the main text. The following text describes two modules: “heat pump simulation module” and “demand response module”. The modules are implemented in Matlab (MATLAB, 2016).

1. Heat pump simulation module

In the heat pump simulation module, hourly heat pump electricity demand is calculated based on historic heat demand data. Historic heat demand data describe the hourly demand for electricity for space heating of current heating systems. The case study assumes full electrification of space heating, and the use of heat pumps for this purpose. This assumption necessitates a three-step conversion of historic data: (1) conversion of energy carrier consumption data into thermal heat demand profiles, (2) scaling of the thermal heat demand to account for the decrease in energy consumption due to improved insulation required for switching to heat pumps-based heating systems, and (3) conversion of thermal heat demand profiles into electrical demand profiles of heat pumps.

Conversion of energy carrier consumption data into thermal heat demand profiles. This conversion is somewhat different for residential and service sector consumers due to differences in data availability. For *residential consumers*, available historic data are measured gas demand profiles of 63 Dutch households (data courtesy of Dutch DSO Alliander). These data concern the total gas demand profiles, which includes space heating, hot water and cooking. Space heating gas demand is derived from these total profiles using additional data sources. The study of Menkveld shows that on average space heating represents 73% of the total gas demand in Dutch households (Menkveld, 2009). Thus, residential gas demand profiles are scaled by a factor 0.73. However, this factor varies by the hour of the day. Therefore, daily fluctuations of this average are taken into account based on Friedel et al. (2014). The resulting gas demand profile for space heating is converted into thermal demand profiles assuming the heating value of Dutch Groningen gas ($31.65\ \mathrm{MJ/m^3}$ (GasTerra, 2012)) and conversion efficiency of a high-efficiency boiler (107% (ATHO, 2018)). For *service sector consumers*, modelled historic demand profiles are used due to the lack of measured service sector demand data. These modelled profiles are derived from commercial buildings reference models of the United States Department of Energy (U.S. DOE) (Deru et al., 2011), and scaled to the Dutch context similarly to the approach described in Voulis et al. (2017). The U.S. DOE reference models provide separate space heating demand profiles, which do not need to be scaled further. The models assume both gas and electricity consumption, depending on the building type. Gas demand is converted to thermal heat demand using an efficiency factor of 80% (United States Department of Energy, 2018) and the heating value of Dutch Groningen gas (GasTerra, 2012). Electricity demand is converted to thermal demand using an efficiency factor of 100% (United States Department of Energy, 2018).

Scaling of the heat pump demand to account for increased insulation. Heat pumps operate at a lower temperature than conventional heating systems. Therefore a high degree of insulation is required when switching from conventional to heat pump-based heating systems (Harmsen et al., 2009). The improvements in insulation decrease the total heat demand. In this paper, heat demand for heat pumps is assumed to be 55% of the original heat demand for space heating, based on data from Jeeninga et al. (2001), Harmsen et al. (2009), and Van Melle et al. (2015).

Thermal to electrical heat demand conversion. For both the residential and the service sector consumers, the thermal heat demand profiles are converted into electrical heat demand profiles using the technical heat pump specifications and so-called "COP-values" (Buderus, 2018). COP stands for "coefficient of performance" and equals the ratio between energy supplied to the heated room and electrical energy used. This ratio is temperature dependent. A heat pump supplies the required heat through a cycle of steps. First, heat is extracted from a low temperature source (such as air, water or ground) and transferred to a fluid termed "refrigerant". Second, the refrigerant is compressed (this step requires electrical energy) into a hot, high pressure gas. Third, the heat from the hot, pressurised gas is transferred to the building heating system. Finally, the pressure of the gas is lowered (*e.g.*, through an expansion valve), making the refrigerant ready to resume the cycle. The COP of the heat pump depends on the heat source and on its temperature. In this case study, air is assumed to be the heat source. The outdoor temperature is taken from measured values as reported by the Royal Netherlands Meteorological Institute (2018).

2. Demand response module

The demand response module minimises the operation costs of heat pumps by shifting their demand. Note that in the model, the aggregator simultaneously represents only one of the three consumer types. Thus, the simulation is run three times, once for each consumer type. The demand response module uses Dutch day-ahead EPEX wholesale prices as price signal. The aggregator is assumed to have no commercial interest, and therefore passes on wholesale prices as real-time retail prices. In other words, heat pump electricity demand (as calculated in the heat pump simulation module) is shifted from hours with high wholesale prices to hours with lower wholesale prices. Demand shifting is restricted by both technical constraints and consumer-defined preferences. Technical constraints are based on heat pump specifications in Buderus (2018). Consumer-defined preferences are modelled by assuming thermal comfort limits which are acceptable for 90% of consumers, based on Van der Linden et al. (2006).

Demand response is assumed to be managed by an aggregator. For this purpose, the modelled aggregator uses two commercially available software packages: PowerMatcher and Realtime Energy eXchange (R.E.X.). This approach simulates the operation of a real aggregator. PowerMatcher is a communication platform and protocol for decentralised control of devices (Kok, 2013). It is extended with R.E.X. software developed by Energy eXchange Enablers (a member of the Dutch DSO Alliander) (Energy eXchange Enablers, 2018) which links PowerMatcher to the Dutch EPEX wholesale market. PowerMatcher makes heat pumps "smart devices", the software provides them with a certain degree of local intelligence, and communication possibilities with the aggregator. The joint behaviour of these two software packages as used by the aggregator and the heat pumps, is simulated in the demand response module. The overall logic goes as follows.

The aggregator operates both on the day-ahead and balancing markets. Day-ahead the aggregator needs to determine the amount of electricity to buy for each hour of the next day to satisfy the heat demand of the consumers he represents. The aggregator minimises the consumers' electricity costs if space heating demand is satisfied at a minimum price. Heat pump demand is determined by the heat pump simulation module. The module is used to calculate a minimum and a maximum electricity consumption limits of the consumers for each hour, based on the outdoor temperature and on consumer-defined preferences. The outdoor temperature determines how fast a building cools down. Consumer-defined preferences determine the range of indoor temperature to be maintained. The same preferences are used for all three consumer types, namely indoor temperature settings acceptable for 90% of the people, these settings are described in Van der Linden et al. (2006). Thermal inertia of buildings enables thermal energy storage, which leads to flexibility in the operation of heat pumps. This flexibility is harnessed for demand response. Thus, for each hour of the next day, for each heat pump in the aggregator's portfolio the range of electricity demand is determined. Each heat pump communicates this range in the form of a "bid". A bid is a demand function that represents the electricity demand of a heat pump given a certain electricity price (for instance, "electricity demand of 2 kWh in the next hour at a price below 30 €/MWh and 1 kWh at a price of 30 €/MWh or higher"). To comply with consumer-defined preferences, the minimum electricity demand is satisfied at any electricity price and the maximum electricity demand is satisfied if the electricity price is lower than or equal to zero. The aggregator combines the bids of all heat pumps, and communicates the joint bid for each hour for the following day to the market operator. The market operator clears the day-ahead market, thus returning an equilibrium price for each hour of the next day. This price determines the amount of electricity the aggregator buys for each hour of the following day, and thus the amount of electricity consumed by each heat pump in each hour of the following day. This demand satisfies space heating demand at a minimum day-ahead electricity price. On the day of operation itself, *i.e.* in real-time, if imbalances occur, they are settled by the aggregator on the imbalance market on behalf of the consumers.

The combination of PowerMatcher and R.E.X. provide the software environment to realise the procedure described above. The behaviour of these two software packages is simulated in Matlab (MATLAB, 2016). Further details on the implementation are described in Van Etten (2017). PowerMatcher is described in detail in Kok (2013). Further information about R.E.X. can be found in Energy eXchange Enablers (2018).

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