Demand during peak hours versus peak-driving demand: Revisiting one size fits all dynamic grid tariffs

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Abstract. Electricity grid tariffs should reflect network costs in order to provide efficient incentives for timing electricity use and investment in new technologies. We compare tariff designs that deal with existing and expected future grid congestion. Although common volumetric tariff designs such as Time-Of-Use are partly cost-reflective, their designs have fundamental drawbacks in terms of the principles of cost allocations and potentially may lead to social disparities.

In a case study of 1.56 million Danish households divided into 90 socio-techno-economic categories, we compare three alternative grid tariffs and investigate their impact on annual electricity bills. This study shows that penalizing consumption above a certain threshold leads to higher costs for owners of electric vehicles regardless of the timing of their consumption. In contrast, penalizing consumption during system peaks mainly affects the electricity bills of heat pump owners. The results of our design simultaneously applying a time-dependent threshold and a system peak tariff show (a) a range of different allocations that distribute the burden of additional grid costs across both technologies and (b) strong positive outcomes, including reduced expenses for lower-income groups and smaller households. Our study offers policymakers a menu that assigns grid costs to demand technologies, thereby giving them valuable input.

Keywords: electricity grid tariffs; household characteristics; network cost distribution; peak; electrification.

1. Introduction

The part of the 2021 European Green Deal aimed at the electrification of heating systems and individual transport poses new challenges for electricity grid infrastructure in Europe [1–3]. With the adoption of heat pumps and electric vehicles, household electricity use is rising significantly, with European governments putting electrification policies in place.

Denmark has renewed its ambitious plans from 2021: the Danish Energy Agency foresees an uptake of 354,000 purely electric vehicles with an approximately yearly electricity demand of 3.6 PJ [4,5]. Similarly, Danish subsidy plans have reduced taxation for heat pumps in order to achieve parity in total installations between gas boilers and heat pumps by 2030 [5,6].

At present, Danish electric grid operators are not yet able to expand or adapt the grid fast enough to keep pace with residential adoption rates for heat pumps and electric vehicles. Grid infrastructure in the form of transformers and distribution lines will likely be congested and require upgrades, leading to increased grid tariffs to recover the additional investments [7]. To limit or defer grid investments, electric grid operators implement grid tariff designs that increase the tariff level during
hours of congestion. Higher grid tariffs during certain hours when the demand is higher nudge residential consumers to shift their consumption to elsewhere in the day, thus limiting potential congestion. In Denmark since 2018, distribution system operators have applied such higher grid tariffs during evening hours in a grid tariff design called Time-of-Use (TOU) [8].

However, TOU tariffs have two drawbacks implicitly built into their design. First, they use a fixed calendar schedule (e.g., from September to April), but only on weekdays between 17:00 and 20:00 [9]. While this simple approach covers most of the residential peak demand according to the load duration curve and is simple for consumers to understand, the schedule is nonetheless not perfectly aligned with the timing of congestion. Second, the future is likely to see competition between users for the available line capacities. While TOU is a cost-reflective and economically fair design, it does not distinguish between consumers’ primary electricity needs (e.g., cooking, lighting and heating [10]) and their secondary ones (e.g., charging an electric vehicle for half a day before driving). The question thus arises of how to design a sound electricity grid that prevents congestion and presents policymakers with options for fairly allocating grid costs across consumer groups and technologies.

To compare grid cost allocations, this study develops and investigates three types of grid tariff we call “Individual Peak Pricing” to limit individual peaks, “Dynamic Critical Peak Pricing” to penalize consumption during hours of congestion, and “Dynamic Critical Individual Peak Pricing” to balance both characteristics by penalizing only high consumption during peak hours. Moreover, to investigate their impact on the cost allocation effects between different consumer groups and technologies, we calculate their impact ex-ante. Our dataset offers unprecedented detail by covering 1.56 million Danish households divided into 90 different socio-techno-economic categories, including dwelling type and area, household income, occupancy, and ownership of an electric vehicle or heat pump.

Key findings of our study include:

1. **Individual Peak Pricing** primarily penalizes higher consumption that is correlated with larger households, but in particular with ownership of electric vehicles and heat pumps. At the same time, this type of tariff also penalizes consumption during uncongested hours and therefore does not offer users cost-reflective incentives at all times.

2. **Dynamic Critical Peak Pricing** increases the household’s grid cost for heat pump usage due to its correlation with system peaks. In contrast, a household with an electric vehicle can reduce its grid costs. However, while this type of tariff gives consumers cost-reflective signals, it puts the cost burden on primary consumption (needs) while reducing the cost for electric vehicles.

3. **Dynamic Critical Individual Peak Pricing** raises grid costs during hours of congestion while penalizing high consumption, thereby offering a mix of the advantages of the previous two types. Moreover, this type of tariff targets consumer behavior rather than the connection of new technologies that would come with a higher technologically specific subscription or with capacity chargers.

This paper is organized as follows. Section 2 provides a thorough literature review of existing studies of grid tariff design. Section 3 introduces the Danish case study and the dataset, including consumer groups and categories, and describes a methodology for all three grid tariff designs, including the mathematical approach. Section 4 presents the case-study results, while Section 5 discusses those results. Section 6 concludes and offers policy recommendations.

2. Literature review

In this paper, we review three overarching types of literature that are relevant to this study. At first, congestion management studies are of interest because they provide the technical reasoning for energy or volumetric grid charges solving bottlenecks and preventing network breakdowns. Second, surveys and framework studies are reviewed, revealing consumer choices on grid management, as
well as priorities and preferences regarding energy usage and grid tariff designs. Lastly, we present studies modeling grid tariff designs and their impact on consumer groups.

[11] reviews existing congestion management methods in distribution systems, including market-based approaches and control-based schemes. The authors conclude that market-based approaches are likely to be the most efficient organizational schemes, since they take into account the maximization of private welfare and lead to optimal outcomes. While [11] focuses on the technical feasibility of congestion management methods, socio-economic considerations are not part of the study. Also, [12] acknowledges the market-based approach for congestion management to be the most feasible, including a dynamic grid tariff design that lets the local network status shine through the price. Moreover, the authors also mention the competition effects between the different actors, which are resolved through willingness-to-pay mechanisms. At the same time, the competition between different technologies and consumer needs such as heating versus vehicle charging is not touched upon. [13] investigated consumer’s preferences to have Distribution System Operators (DSOs) directly controlling their electric vehicle charging and heat pump usage in Switzerland. While the study focuses more on the acceptance of direct control by the DSO on their private equipment, the outcomes still give indications of the prioritization between the services of the two technologies. However, the investigation leaves out other consumption needs that are considered more fundamental to consumers and therefore does not address the challenge of prioritizing different types of demand. A survey performed in [14] investigates consumer preferences and their definition of fair dynamic grid tariffs to some degree. The study reveals that fairness is perceived differently across consumers. [14] summarizes their survey by stating, first, that peak price design should be simple enough for the consumer. Second, peak pricing should not threaten basic energy needs. Third, peak pricing should not be used as a tool for the redistribution of grid costs at the expense of poor households. Fourth, peak pricing should be somewhat predictable for the consumer. [14] emphasizes that a mixture of acceptability and fairness should be harnessed when designing grid tariffs. [15] designed network tariffs for Austrian households divided between energy, peak and fixed charges. The survey includes socio-economic data but also details on technical equipment. Coincidental peak charges were found to be the highest influence factor due to the random and short-term overlapping usage of several appliances. The timing of the peak is independent of network congestion, and high levels of dependence on demand charges can lead to redistributions of -50% to +500% of the annual cost to households. However, the dataset is relatively small, containing 765 households probably with survey biases, thus limiting the results to households with specific characteristics. Like [15], the authors of [16] investigate grid tariff designs for the whole of the city of Chicago. Their economically efficient grid tariff model yielded the most significant redistribution of annual bills between low- and high-income households at the expense of the poor. A simple adoption of the design using a strong existing correlation between coincidental peaks and income in the US can turn the redistribution around at the expense of wealthy households. The issue of grid capacity competition effects is not addressed by [16], and thus, the authors conclude that volumetric charges are less efficient than time-invariant charges. [17] further points out that flat volumetric tariffs also increase the distributional inequity between different income groups because wealthy households invest their way out by adopting distributed energy resources and avoiding energy charges. The authors conclude that present-day tariffs should lean toward more allocative designs. At the same time, energy charges are not considered a solution, and moreover, energy savings and competition effects for existing networks are not part of the study.

From the technical standpoint of congestion management, the literature revealed that most studies see grid tariffs as a solely economic signal. Grid usage is subject to the pure economic power of consumers and their willingness to pay failing to address the importance of social factors and basic energy needs. Conversely, the literature also captures the shortcomings of general economic efficiencies and impacts on different social-economic consumer groups. At the same time, these studies favor grid tariff designs with fixed and coincidence peak charges that present disadvantages to the real-time challenges of congestion management. According to the literature, grid tariffs,
particularly energy charges, are strongly linked to notions of fairness and acceptability. Subsequently, grid tariff design should solve technical challenges, such as preventing congestion, and be economically and allocatively efficient, while at the same time being fair in terms of the redistribution of costs from the rich to the poor.

Our paper aims to capture all those points with innovative volumetric energy charges. In the end, we offer for policymakers a menu of different designs to choose a grid tariff dependent on their perception of fairness and cost allocation principles while always providing price signals accounting for temporally dependent congestion challenges. The study offers deep insight into the impact on households with different socio-economic characteristics such as dwelling type, size, occupancy, and income but also technologies like electric vehicles and heat pumps, which captures the main recommendations made by [15].

3. Methodology

The methodology section is divided into three main subsections. Subsection 3.1 presents the case study of Denmark and describes the network tariffs that were applicable in Denmark as of 2017. Subsection 3.2. presents our approach to designing the three grid tariffs under study. Subsection 3.3. presents the case study, including data, mathematical formulation and scenarios.

3.1. Case study and grid tariff design in Denmark

Denmark is among the leaders in the development of wind and solar energy, which currently covers half of the country’s domestic demand. The low average electricity prices that result from this mix are creating the appropriate economic conditions for the fast uptake of EVs and HPs [5,18,19]. If the current electrification rate in Danish households benefits from existing distribution grid oversizing [20], the continuous growth of EVs and HPs will start to pose increasing problems to grid stability. Consequently, grid congestion arises when households compete on existing grid capacities with different economic power, differing consumption needs and preferences between existential and optional demand. Following allocative cost principles, the question arises which consumers and consumption types should pay more or less in distribution grids that have been sized for specific consumption characteristics but are now facing the introduction of new technologies.

Subsequently, network infrastructure like transformers and lines are likely to be congested, and the total cost will increase to cover the rising expenses for reinforcement that operators recover through grid tariffs. Denmark traditionally divides distribution system grid tariffs for residential users into two parts [21]. The first part is the subscription fee. Customer categories determine the yearly fee level, although most residential customers are in the same category. The second part of distribution system grid tariffs is volumetric tariffs. The volumetric tariff level was flat before 2018, which means that every kWh of electricity consumed is treated equally. After the successful rollout of smart meters in 2017, DSOs started implementing TOU grid tariffs using fixed schedules to delay network investments into the future [8,18]. The step towards TOU had two more shorter-term purposes: At first, an educational effect should accustom households to varying prices with an easily understandable schedule to trigger energy savings or demand response and reduce pressure on the grid [22–24]. TOU consists of two blocks, a base rate and a peak rate. The peak rate applies on a fixed schedule currently extending daily between 5 p.m. and 8 p.m. from October until March [9]. While the schedule is similar across DSOs, the rates vary across all 78 DSOs in Denmark [21,25].

With the EU Commission giving a mandate to DSOs to develop their cost recovery methods and quick adoption of new load intense technologies on the residential side, DSOs now face the challenge of designing further grid tariffs appropriately [26]. Tariff design underpins several principles and guidance leading to overlapping objectives [27]. Among these are cost recovery and reflectivity, non-discrimination, predictability and simplicity. DSOs in Denmark and in Europe continuously develop their tariff designs to prepare their assets for future challenges according to those principles. Rather than a rapid and radical change towards improved designs, updates use incremental steps to take customers along the way [28]. Smaller steps help customers adjust to the new signals and avoid certain groups suddenly being exposed to significant cost increases from one year to another. In this
context, the following subsections introduce the three grid tariff designs being investigated in this study.

### 3.2. Investigated grid tariff designs

The first design, Individual Peak Pricing (IPP), penalizes high hourly consumption. In contrast, the second design, Dynamic Critical Peak Pricing (DCPP), penalizes the critical timing of consumption. The third grid tariff design, Dynamic Critical Individual Peak Pricing (DCIPP), is a mixture of both approaches. All three grid tariff designs are subject to sensitivity studies varying the impact on the previously mentioned objectives.

#### 3.2.1. Individual Peak Pricing (IPP): allocative principle in targeting scarcity in capacity and competition effects

Individual Peak Pricing (IPP) charges a higher tariff during the hours of individual peak consumption. Similar tariffs have been tested or applied in various experiments and cases with the main objective of constraining peak effects at the industrial/service level [29–31]. Although the limits of this tariff in reflecting system congestion are recognized [32,33], it nevertheless presents a way to discriminate in pricing households with special characteristics of peak demand, such as households owning an EV or HP. The main challenge is to capture a meaningful threshold of consumption levels that results in certain allocative characteristics. IPP leans on the general Danish income tax design, using two tax brackets dependent on the level of income [34].

The IPP applies every hour of the year. A threshold defines a level that slices individual consumption into two groups. The first group is subject to base tariffs and applies when the total hourly consumption is below the threshold. In contrast, peak tariffs apply when the hourly consumption is higher than the threshold on the entire consumption. Figure 1 visualizes an typical day of a single household consuming electricity below and above a threshold of 1 kW.
Figure 1. Typical IPP grid tariff design applied to an individual household’s consumption pattern.

Figure 2. Typical boxplot of hourly consumption by three different households with and without heat pumps and electric vehicles. The black dotted lines represent different threshold levels.

The peak IPP tariff is represented by the red consumption bars, and the base grid tariff by the green consumption bars. The threshold dividing consumption into peak and base is subject to sensitivity, as its level determines which socio-techno-economic groups are targeted more or less. Figure 2 shows how much household consumption without and with electric vehicles or heat pumps is typically above different thresholds. The lower the threshold, the more essential consumption by the households, such as cooking, could be subject to peak tariffs. This study therefore offers four different levels of thresholds and offers several design options for consideration under several preferences. While the lowest threshold of 1 kWh targets almost all the consumer’s individual peaks, the range between 1 kWh, 1.5 kWh and 2 kWh targets in particular heat pumps and electric vehicles. Advancing towards a 3 kWh threshold excludes most of the traditional consumer groups and heat pump users and defines electric vehicle charging as peak consumption in particular. We aim to observe the allocative effects of different levels by varying the threshold. Network operators can choose thresholds by allocating the available capacity among consumers.

3.2.2. Dynamic Critical Peak Pricing (DCPP): effective temporal congestion management
Dynamic Critical Peak Pricing (DCPP) targets consumption during network-coincidental peak periods. The design is comparable to the current TOU design presented in 3.1. The council of European regulators criticizes the static design of TOU for penalizing all network users equally without acknowledging the correct individual contribution to actual peaks [35]. Thus, DCPP includes a flexible peak block rate triggered by the system operator in periods of congestion instead of applying a fixed block rate regardless of the network status.

The particular aim of the DCPP design is to provide price signals that trigger flexibility at the correct time. The primary objective is to ensure cost reflectiveness on the temporal dimensions. Defining the hours of critical network conditions is done via an approximation. As network conditions with high locational resolutions are unknown, especially at lower voltage levels, the Danish national load curve of 2017 is used as a proxy. Figure A14 in Appendix A.1. visualizes the Danish load duration curve of 2017. A trigger percentage is defined by dividing the peak and base hours. All households pay an increased tariff in hours defined as peak, as shown in Figure 3. For the remaining hours, the base tariff applies (green).

![Figure 3. Typical DCPP grid tariff design applied to the individual household consumption pattern.](image)

![Figure 4. Typical load duration curve and ranges of relevance regarding peak definitions and impact on the redistributive effects of different household categories. The black dotted lines represent different trigger percentage levels.](image)
We, therefore, acknowledge that the very definition of peak hours in the load duration curve will be subject to changes based on how fast green technologies penetrate the system. Trigger percentages of up to 40% increase the range for policy-relevant design and follow the pricing rationale of the suggestions made by the Danish Chamber of energy suppliers, Green Power Denmark [28]. The more hours are defined as peak, the smoother and softer the redistribution across different consumer groups. The top 1%, 5%, 20% and 40% of the Danish national load-duration curve of 2017 trigger the DCPP for all residential consumers regardless of their consumption. A sensitivity study is necessary to account for the approximation of critical network conditions and to offer a broader range for the policy-relevant design of DCPP. Figure 4 shows a typical load-duration curve in blue and different trigger percentages ranging from the top 1% to the top 40%. While from 1% to 5% the yearly hours reflect peak conditions more accurately, the range up to the top 20% represents the uncertain future due to the electrification of heat and private transport [36].

3.2.3. Combining IPP with DCPP: Dynamic Individual Critical Peak Pricing (DCIPP)

Dynamic Individual Peak Pricing or DCIPP is a combination of IPP and DCPP, as it combines the allocative principles conveyed by the IPP with the flexibility of the DCPP. This scheme exclusively applies a higher tariff during system peak hours to households consuming above the threshold defined in the IPP.

As a result, DCIPP covers both design characteristics. At first, implementing the trigger percentage targets temporal flexibility and allows for high consumption when the network is not constrained. Second, higher grid tariffs are applied when the network is under stress to reduce congestion. DCIPP offers different characteristics by choosing thresholds and trigger percentages and thus offers to weigh both factors. Figure 5 visualizes the application of the DCIPP tariff design on household consumption.

![Figure 5. Typical DCIPP grid tariff design applied to the individual household consumption pattern.](image)

The investigations of DCIPP follow a sensitivity approach. All sixteen combinations of thresholds and trigger percentages yield different prominent effects on cost redistribution. We decided to show outcomes of the DCIPP design for one particular threshold of 2 kWh and four different trigger percentages to simplify the presentation.
Local characteristics vary significantly across regions, and political preferences are also different. Therefore, this study and the DCIPP designs offer a set of designs for grid tariff implementation and reveal their impact on households and technologies, but it does not aim to find an optimal design.

3.3. Case study: residential electricity consumers

The case study data cover Danish smart meter consumption in combination with socio-techno-economic data for 2017. After that, the mathematical model is presented, followed by the introduction of the investigated scenarios.

3.3.1. Danish electricity consumption data and socio-techno-economic categories

This study uses the comprehensive electricity consumption dataset analyzed in [37,38]. It covers approximately 1,565,856 Danish households in 2017. Households are aggregated into 90 different socio-techno-economic categories to comply with GDPR requirements with approximately 720,000 sufficient profiles. The used categories are dwelling type and area, and the occupancy and income of the household, and the connection of green technologies such as EV and HP following the same approach of [37]. Table 1 summarizes the division of the categories, using mainly median statistics.

### Table 1. Chosen socio-economic categories and their respective values.

| Characteristic name | Characteristics          |
|---------------------|--------------------------|
| Dwelling type       | AP: Apartment            |
|                     | H: House                 |
| Occupancy           | P1: 1 occupant           |
|                     | P2: 2 occupants          |
|                     | P3: 3-4 occupants        |
|                     | P5+: 5 or more occupants |
| Dwelling area       | AP: A1<66m²              |
|                     | A2<85m²                  |
|                     | A3                       |
|                     | H: A1<110m²              |
|                     | A2<146m²                 |
|                     | A3                       |
| Income level        | €1<240kDKK               |
| Electric vehicle    | EV0: No                  |
|                     | EV1: Yes                 |
| Heat pump           | HP0: No                  |
|                     | HP1: Yes                 |

The house dwelling type (H) includes stand-alone single-family houses and terraced houses. The occupancy category contains single households (P1), two-person households (P2), 3-4 person households (P3) and households with five or more occupants (P5+). Due to their fundamental differences in size, the dwelling-area categories are separated for both houses and apartments. Since apartments are mostly smaller, the lower third (A1) goes up to 66 sqm, whereas the lower third of houses reaches 110 sqm (A1). (€1-€3) represent the income groups determined by median statistics. An EV in a household is indicated by (EV1), whereas an HP is represented by (HP1). For purposes of simplification, broader averages across several categories are presented in the results.

3.3.2. Mathematical model to calculate grid tariff designs

The model for calculating the impacts of new grid tariff designs consists of a simple model. The constraint that the grid tariff retains the revenue-neutral total network income is its central component. The grid tariff with IPP, DCPP and DCIPP always consists of two parts: a base and a peak level. Before the optimization, the consumption of each consumer category is divided into the base consumption and peak consumption depending on the grid tariff design as an exogenous input. After that, the optimization determines the height of the IPP, DCPP and DCIPP peak tariffs. The following subsections present the constraints and initial values of the model.

3.3.2.1. Constraint to guarantee revenue-neutral redesign of the grid tariff design

To guarantee a clear view of the redistribution effects of the new grid tariff designs, the model calculates the total network income to be revenue-neutral. Equation (1) summarizes all the components of this constraint.
\[ R^S^O = \sum_G q^\text{peak,year}_g g^\text{peak,year}_T + q^\text{base,year}_g g^\text{base}_T r_{\text{recov}} \]  

\( R^S^O \) represents the total network income earned by the system operator. This value is calculated once with a basic volumetric tariff without peak pricing to determine the sum and is kept constant for all other grid designs. The yearly consumption \( q^\text{year}_g \) per consumer group G is divided into base consumption \( q^\text{base,year}_g \) and peak consumption \( q^\text{peak,year}_g \). The peak consumption is multiplied by the respective peak price \( g^\text{peak,year}_T \). Similarly, the base consumption is multiplied by the base grid tariff \( g^\text{base}_T \), which is a constant input. The right-hand side of the equation, however, is also multiplied by a third factor \( r_{\text{recov}} \). This represents the recovery factor for the base income. It is necessary to force the model to determine a difference between base and peak pricing and, therefore, to calculate a redistribution cost to maintain the total network income \( R^S^O \). With \( r_{\text{recov}} = 1 \) the variable \( g^\text{peak,year}_T \) has to equal \( g^\text{base}_T \) to maintain feasibility. The redistribution factor can be interpreted as a number that shows the part of the total network cost that will be recovered by the base consumption and implicitly how much will be recovered by the peak. With \( r_{\text{recov}} = 0.8 \), the total network income \( R^S^O \) will be 80% recovered by the base consumption and subsequently the remaining 20% by the peak consumption. This forces the model to find a \( g^\text{peak,year}_T \) that satisfies the revenue neutrality of the network’s income and further results in the needed height of the peak tariff depending on the design. The redistribution factor changes the size of the redistribution, but not the redistribution pattern across the different consumer groups. A sensitivity study on \( r_{\text{recov}} \) therefore does not offer groundbreaking results and is consequently not shown in this study.

The electricity consumption inputs \( q^\text{peak,year}_g \) and \( q^\text{base,year}_g \) representing peak and base consumption are calculated as follows for the grid designs presented in section 3.2.:

**IPP:**
\[
q^\text{peak/base,year}_g = \begin{cases} 
q^\text{peak,year}_g = \sum_{t=1}^{T} q_{t,g} \text{ if } q_{t,g} \geq \text{Threshold} \\
q^\text{base,year}_g = \sum_{t=1}^{T} q_{t,g} \text{ if } q_{t,g} < \text{Threshold} 
\end{cases}
\]

**DCPP:**
\[
q^\text{peak/base,year}_g = \begin{cases} 
q^\text{peak,year}_g = \sum_{t=1}^{T} q_{t,g} \forall t \in T^\text{peak,trigger} \\
q^\text{base,year}_g = \sum_{t=1}^{T} q_{t,g} \forall t \in T^\text{base,trigger} 
\end{cases}
\]

**DCIPP:**
\[
q^\text{peak/base,year}_g = \begin{cases} 
q^\text{peak,year}_g = \sum_{t=1}^{T} q_{t,g} \forall t \in T^\text{peak,trigger} \land \text{if } q_{t,g} \geq \text{Threshold} \\
q^\text{base,year}_g = \sum_{t=1}^{T} q_{t,g} \forall t \in T^\text{base,trigger} \lor \text{if } q_{t,g} < \text{Threshold} 
\end{cases}
\]

where \( T^\text{peak,trigger} \) represents all hours that are the top load hours depending on the trigger percentage and \( T^\text{base,trigger} \) the hours that are below the trigger percentage.

3.3.2.2. Initial values for the model

Table 2 summarizes the initial values of the model. A representative grid area in Denmark was chosen, and its volumetric grid tariff for residential users (approx. 0.025€) was applied for 2017 [39]. The calculated total network income results as \( R^S^O \) which is kept constant through all grid tariff designs and corresponds to approximately 10.2 m€. The recovery of base consumption is set to 95% and therefore forcing the model to recover 5% of the total network income by the peak.

**Table 2. Initial starting values of the model**

| Input  | Value   | Unit       |
|--------|---------|------------|
| \( g^\text{base}_T \) | 18.25   | Øre/kWh   |
| \( R^S^O \)     | 75,740,979,438 | Øre       |
| \( r_{\text{recov}} \) | 0.95    | -         |

The initial values have only a limited effect on the redistribution of cost. A higher or lower initial value of the grid tariff or a different recovery factor only changes the magnitude of the design impact.
and cost redistribution. In contrast, groups are affected positively or negatively depending on their consumption patterns and the respective grid tariff design.

### 3.3.3. Scenarios and comparison of results

Overall, over 406 different scenarios were calculated for IPP, DCPP and DCIPP. This study presents twelve representative scenarios with four variations for each of the grid tariff designs for the sake of communication. Table 3 summarizes the scenarios shown in the results section.

**Table 3. Overview of presented scenarios**

| Scenario                  | Threshold | Trigger percentage |
|---------------------------|-----------|--------------------|
| IPP; 1kWh                 | 1kWh      | -                  |
| IPP; 1.5kWh               | 1.5kWh    | -                  |
| IPP; 2kWh                 | 2kWh      | -                  |
| IPP; 3kWh                 | 3kWh      | -                  |
| DCPP; 1%                  | -         | 1%                 |
| DCPP; 5%                  | -         | 5%                 |
| DCPP; 20%                 | -         | 20%                |
| DCPP; 40%                 | -         | 40%                |
| DCIPP; (2kWh;1%)          | 2kWh      | 1%                 |
| DCIPP; (2kWh;5%)          | 2kWh      | 5%                 |
| DCIPP; (2kWh;20%)         | 2kWh      | 20%                |
| DCIPP; (2kWh;40%)         | 2kWh      | 40%                |

The IPP design threshold varies between 1-3 kWh to show the sensitivity and allocative impact of different socio-economic households and technologies. DCPP scenarios vary across the trigger percentage between 1-40%, representing different pressure situations of the grid and also having allocative properties. DCIPP has both threshold and trigger percentages. The threshold is kept constant at 2kWh, while the trigger percentage varies from 1-40%. The results section focuses on the relative difference in total volumetric grid tariff costs compared to the flat volumetric tariffs in 2017. The resulting prices of $g_{peak, var}$ are not the main focus of this study because the level of the peak tariff is dependent on the local grid characteristics managed by the respective DSO. The peak tariff could vary across distribution systems in Denmark. However, the tendencies of the impacts on household categories and technologies stay the same.

### 4. Results

The results are presented in the following four subsections. The first three subsections present the relative differences in volumetric cost, focusing on dwelling type, size and technologies such as electric vehicles and heat pumps for IPP, DCPP and DCIPP. The results focus on the average yearly network bill of consumers and highlight allocative patterns. The fourth subsection compares the impact of all scenarios, highlighting the impact of the grid tariff designs depending on the household income characteristics and occupancy. The resulting peak prices $g_{peak, var}$ are summarized in Table A4 in Appendix A.2. and are occasionally referred to but are also presented in the respective subsections. The total redistribution of all ninety categories is summarized in Table A5 in Appendix A.2.

#### 4.1. Individual Peak Pricing (IPP): targetting high power and consumption demands at any time

Figure 6 shows the average relative cost redistribution compared to flat volumetric tariffs for households that do not own an EV or HP and that live in houses and apartments of different sizes. The average is calculated across all occupancy and income characteristics. Figure 7 shows the relative redistribution of grid cost with a technology focus. The figure focuses on a single-family house (H)
in the large dwelling area (A3) and income group (€3) owning an EV, HP, or neither (No-tech) to isolate the impact on technology ownership. The investigated IPP ranges from a 1 kWh to a 3 kWh threshold.

Figure 6. Average relative redistribution of volumetric grid cost with IPP on Apartments (Ap) and Houses (H) with different dwelling areas (A1-A3). No EVs or HPs are present in the households.

Figure 6 shows that most households would benefit from IPP. The smaller the dwelling size, the larger the reduction of volumetric grid costs compared to flat tariffs. Consequently, apartments could save from IPP because the living areas are on average smaller than detached houses. Only large detached houses (H A3) would face increasing costs, and only in some scenarios.

Moving the threshold to higher levels has two further impacts on households. First, the higher the threshold, the greater the annual savings for a small apartment ranging from 3.46% to 4.72%. At the same time, when the dwelling area increase, the savings are reduced. A large apartment has savings of between 1.45% and 3.19%. The same tendency is also observed in houses, though on a different level depending on the dwelling area. Small houses (A1) have decreasing costs only rarely, being
almost unchanged between 0.68% and 1.7% with a 3 kWh threshold. Medium and large houses almost always pay more for IPP. A large house faces a rise of around 2.27% with a 3 kWh threshold.

![Diagram showing average relative redistribution of volumetric grid costs with IPP for a single-family house (H) with an occupancy of 3-4 (P3) in a high dwelling area (A3) and income group (€3) owning an HP, EV or not owning either.]

Figure 7. Average relative redistribution of volumetric grid cost with IPP for a single-family house (H) with an occupancy of 3-4 (P3) in a high dwelling area (A3) and income group (€3) owning an HP, EV or not owning either.

Figure 7 shows more extreme values compared to Figure 6. The higher the threshold, the higher the percentage change for HP and EV owners. HP owners pay an additional 7.56% or up to 31.13% depending on the applied threshold. EV users face an increase of up to 72.75% in volumetric grid costs, which can correspond to 133873 Øre/year (~180 €/year) see Table A5 in Appendix A.2. Also noticeable is the effect of increasing the thresholds on technologies. 1 kWh and 1.5 kWh result in a 7.56% and 13.16% increase in yearly volumetric grid costs for HPs, whereas EVs yield only 6.26% and 12.49%. At the highest threshold, the picture shifts drastically toward the higher penalization of EVs. At the same time, for households without technologies the situation remains almost unchanged.

Generally, IPP penalizes high consumption at all times. Smaller households, especially apartments, pay overall less than before, whereas owners of larger houses pay more. Raising the threshold reduces the number of hours and consumers falling under the new grid tariff. As the total network income of the peak remains the same, the leftover hours and households have to recover a larger share of the total network cost. Subsequently, the peak tariff (variable) increases to maintain Equation (1). Mostly EVs and a few large households or HP owners consume more than 3 kWh regularly, and therefore the main part of the DSO’s peak income is recovered by them ($q_{peak,year gt peak,year}$). In contrast, with a 1 kWh threshold, the redistribution is relatively flat across user groups.

IPP reduces grid costs for smaller households with lower occupancy rates at the expense of larger households with higher occupancy. Furthermore, the grid tariff design isolates the effect of high consumption, thereby increasing the grid costs of EVs in particular compared to HP. However, the design of IPP is inherently flawed due to its permanent application, which does not reflect the dynamics of congestion effects. This variability is tackled in the case of DCPP, as shown below.

4.2. Dynamic critical peak pricing: reacting to network congestion

DCPP is applied at four different levels of national load, starting from the top 1%, 5%, 20% and 40%. Rather than the actual numbers, the shape of the radar plots is more important in showing the redistribution across different categories. Figure 8 shows the average relative cost redistribution per dwelling type and area. Figure 10 zooms in on the redistribution of the DCPP for a household living...
in a single-family house in the large dwelling area and income group and owning either an EV, a HP or neither.

![Figure 8. Average relative redistribution volumetric grid cost with DCPP on Apartments (Ap) and Houses (H) with different dwelling areas (A1-A3). No EVs or HPs are present in the households.](image)

Although households in small apartments benefit the most from DCPP, as shown in Figure 8, this benefit shrinks the more hours are included in the DCPP (1% towards 40%), going from 0.54% to 0.22% in savings. The larger the dwelling size of the apartment, the smaller the savings. Large apartments pay slightly more, from 0.05% to 0.07%. Similarly, the larger the house, the higher the relative increase in grid costs. In contrast to the apartments, the more hours that are included in the DCPP, the fewer the large households have to pay in additional yearly network costs. Noticeably, a medium-sized house has to pay 0.11% more in the 1% DCPP scenario, while large houses are barely affected.
The new design yields for the HP are respectively 0.47%, 0.87%, 0.4% and 0.03% for the 1%, 5%, 20% and 40% DCPP scenario. Generally, differences in yearly grid costs are considerably small, with $f_{recov}=0.95$, but become more prominent with smaller recovery factors (see also Table A7 and Table A6 in Appendix A.2.). The reason for this lies in the consumption pattern of households. Only the share of consumption lying within the timing of the top percentages of national load determines the change in relative grid cost. At the same time, EV owners even save costs with DCPP. Their cost decreases by -0.6%, -0.84%, -0.76% and -0.62% in ascending order of all scenarios.

Like apartments and houses, the cost redistribution relating to HP and EV depends on the share of consumption in the top percentages of the yearly load duration curve or outside of it. However, EVs are not very present in the top 1% to 20%. Even though dynamic grid tariffs did not apply in Denmark in 2017, EV charging happened more during the night and outside of peak hours, showing flexibility to a certain degree [37]. The 40% DCPP scenario includes more hours of EV charging. Subsequently, the relative savings for EV owners decrease compared to the 20% DCPP scenario. Conversely, HP owners reach their highest relative cost increases in the 5% and 20% DCPP since HP consumption is especially high during hours of high national load [3,37]. As TOU tries to mimic a DCPP, EV owners are likely to save grid costs compared to simple flat volumetric tariffs. This may result in failing to apportion future grid reinforcement costs to the grid users with large peak-load patterns. At the same time, it is important to acknowledge the already flexible behavior of EV owners.

DCPP offers efficient solutions to the problem of reflecting grid constraints dynamically without differentiating between consumption levels that contribute to congestion. DCPP reallocates grid costs that are less strong than IPP across consumers. Generally, smaller apartments achieve savings in volumetric grid costs, medium-sized houses relatively more, even compared to houses with large living areas. While EVs pay significantly more with IPP, the DCPP design even reduces their grid expenses compared to flat volumetric tariffs at HP’s expense, which pay more. The next section combines the advantages of the previously tested designs with the DCIPP.

4.3. Dynamic Critical Individual Peak Pricing: reacting to network congestions and allocating network costs
DCIPP offers an opportunity to design the grid tariff freely. In particular, the triangle in Figure 7 and Figure 9 can be shaped based on preferences and previously named design objectives. Figure 10 and Figure 11 summarize the outcomes for apartments and houses of different dwelling areas and green technologies respectively.

Figure 10. Average relative redistribution volumetric grid cost with DCIPP for Apartments (Ap) and Houses (H) with different dwelling areas (A1-A3). No EVs or HPs are present in the households.

Figure 10 shows that this arrangement of DCIPP has very stable impacts across the different scenarios. Differences between the scenarios with a fixed threshold (2 kWh) and varying trigger percentages (1-40%) range in second to third-digit percentages. Small, medium and large dwelling-size apartments save respectively 4.3%, 4.1% and 2.3% in yearly volumetric network costs. Small houses save about 1.1%, whereas medium houses pay up to 0.29% more. Large households pay, on average, a 1.85% higher grid bill.

Figure 11. Average relative redistribution volumetric grid cost with DCIPP for a single-family house (H) with an occupancy of 3-4 (P3) of the high dwelling area (A3) and income group (€3) owning an HP, EV or not owning either.
Unlike Figure 9, where the tariff transfers more of the grid costs to the owners of electric cars, DCIPP has a more balanced impact on the owners of electric cars and e-vehicles. At the same time, households without these devices are only marginally affected. Both technologies face higher costs. The triangle leans towards HP owners. With higher percentages included in DCPP part of DCIPP, the additional relative costs are 15.3%, 19.91%, 18.1% and 16.75% for each scenario. Similar to the outcomes of Error! Reference source not found., the 5% scenario yields the highest redistribution. Nevertheless, DCPP doubles the difference between the 1% and 5% scenarios, whereas the DCIPP results in less harsh developments. The highest cost increase is 42691 Øre/year (~57 €/year) for a specific household category using a heat pump (see Table A5 in the appendix A.2.). Regarding EV owners, the effects of the scenarios are closer to the IPP, with steadily increasing costs. Ultimately, the four scenarios yield more minor additions of 7.91%, 7.94%, 9.86% and 12.21% compared to IPP.

The combined tariff design targets timing and consumption, and thus implicitly power usage as well. Determining the high load hours allows for consumption during hours without congestion or close to it, while the threshold targets only consumers who exceed certain limits. Consequently, only large consumption during hours of higher network constraints is penalized. In addition, DCIPP triggers the flexibility to shift consumption or limit it to the bare minimum without causing too much distortion across different households. Small households, especially apartments, have limited flexibility, as their appliances cover a greater share of basic needs. With DCIPP, they are protected against higher grid charges that would ultimately affect their essential consumption needs.

The DCIPP allows for a smooth redesign of the grid tariff. Small households benefit at the expense of larger ones. Depending on the chosen power threshold, the triangle of Error! Reference source not found. can be modeled relatively freely based on preferences. The higher the threshold that is chosen, the more the triangle leans towards the EV user. HP owners are stronger penalized between 5% and 20%. Triggering flexibility be reflecting the grid costs is only one of the possible preferences that enter into rate-making. Another area of rising concern is fairness in grid-cost allocation. The next section offers a detailed view of the tested tariffs’ impact on the different income groups.

4.4. Limiting redistributive effects on poor households for an inclusive transition

This section zooms in on the effect of DCIPP on different income groups. Figure 12 shows the average relative cost change for households of all dwelling types, sizes and occupancies and for the three income groups €1 to €3, all without EVs or HPs. Figure 13 shows the households with technologies.
The relative changes in grid-cost distribution are primarily linked to income and occupancy. The single households in the lowest income group benefit with around a 3.6% reduction in their average yearly grid bill. In the single household of the highest income group, the savings range between 2.28% and 1.66% depending on the scenario. The relative cost reduction shrinks with occupancy, turning into additional costs in the three to four person households (P3) of all income groups. Large households with five or more occupants (P5+) show a small contrast, with the low-income group being more negatively affected than the high-income group. However, the poorer the household in the P5+ category, the higher the occupancy level (5.6 occupants in the low-income group against 5.1 occupants in the high-income group). Yet, this occupancy group faces 4% and 6.44% higher fees across all income groups.
Figure 13 adds to income and occupancy the ownership of HPs and EVs. The more people living in a household, the more rooms are usually heated, and consequently the larger the electricity consumption and grid tariff payments. A tendency to increase grid costs with higher incomes and occupancy is also visible in this figure. Only the two-person households are present in all three income groups with an HP. Differences across income groups are present with a 12.1% over 18.25% to 20.61% rise in grid costs in the (2 kWh, 5%) scenario. The difference between the three to four occupancy compared to P5+ is marginal (up to 2% higher cost). Some single household categories using an HP, such as single households living in small apartments and with a yearly income corresponding to the lowest group, show a reduction in their grid bill. A yearly reduction of 1366 Øre/year is observed, whereas the largest households using heat pumps might pay up to 66310 Øre/year (~89 €/year) more in volumetric charges. EV households pay consistently less than HP households, but still have around 10% higher grid costs than with flat volumetric tariffs.

In contrast to IPP and DCPP, the DCIPP design increases mostly volumetric grid costs the higher the income and occupancy of a household. This pattern is also maintained when adding technologies such as EV or HP to households. DCIPP offers to model a grid tariff design that distributes costs depending on preferences and maintains outcomes dependent on income level and occupancy.

5. Discussion
In the following, we first present a critical review of the assumptions and address the method’s shortcomings. Afterwards, we propose an in-depth discussion on grid tariff characteristics and how to design them.

5.1. Critical review of the assumptions

We rely on four key assumptions that affect our results. First, we assume inelastic residential demand, which impacts on the changes in yearly network bills. Consumers are generally cost-averse; therefore, increasing tariffs in specific periods triggers the demand response from them [40], especially when also equipped with smart controllers [41,42]. However, the flexibility of technologies and consumers cannot be directly assessed from the demand data. At the same time, EV consumption in this study already indicates a degree of flexibility, as is shown by an average reduction in grid costs when applying DCPP (see Figure 9). Consumers in Denmark could already decide on real-time spot-pricing in 2017, and shifted EV charging is thus present in the dataset [37,43]. The direct reason for the shift in EV charging remains unknown. Thus, the interaction between the system operator and the consumer is dynamic. It requires yearly updates of grid tariff levels and potential designs, discussion of which would go beyond the scope of this study.

Second, we use a proxy for grid congestion in peak hours given by the load duration curve. The definition of congestion in distribution systems is a local challenge. It depends on the local grid infrastructure, consumer behavior and connected technologies. Consequently, the investigated grid tariffs require as detailed a geographical and temporal resolution as possible [44].

Third, this study only investigates a snapshot of 2017 and does not assume any changes brought about by adopting EV and/or HP. Adopting these technologies changes the number of households present in each category and the grid-cost distribution between them. Updating grid tariffs requires anticipating future developments across the parameters and categorizations they are based on.

Finally, for reasons of simplicity, this study only focuses on a subset of twelve chosen scenarios among the 406 generated scenarios (showing different thresholds, trigger percentages, peak hours, one threshold and also two thresholds). The chosen scenarios are mostly edge cases to maximize the characteristics of the designs. Essentially, it is possible to argue that DCPP is the most efficient grid tariff design in terms of grid operation, while upgrading to DCIPP mostly improves the cost allocative characteristics and fairness principles at the expense of efficiency.

5.2. Comparing grid tariff design characteristics

Although the main objective of time-varying tariffs is to take advantage of demand-side flexibility, tariffs should not overlook relevant socio-economic issues. Grid tariffs are regulated prices that underlay several objectives. System operators and policymakers have to deal with the complexity of multiple objectives when choosing a design. With several overlaying objectives, it becomes implicitly challenging to balance the technical, economic and socio-economic factors, as they might cause opposing effects in the context of a rapidly changing environment. The new loads resulting from household electrification add and will continue adding to already existing electricity demand, potentially creating a competition effect across energy uses when the grid is congested. The higher grid charges triggered by, e.g., large simultaneous EV charging will also affect households not concerned by this charging, including the most vulnerable ones, those that only cover their basic needs. This local competition effect increases the relevance of including socio-economic considerations when designing grid tariffs.

The IPP tariff can avoid higher costs for basic electricity consumption, as it only charges higher tariffs for peak consumption beyond a set threshold (e.g. for electricity-intensive applications: EVs, HPs). This tariff mainly targets the power/energy contribution of each consumer. However, it does not consider the temporal component to utilize the available capacities. The marginal cost around the threshold incentivizes keeping consumption below the threshold. When exceeding the threshold,
consumers pay peak tariffs on their entire demand. The marginal grid cost of increasing the demand by one unit stays constant regardless of whether they consume just over the threshold or significantly more. In economic terms, the marginal cost of increasing consumption when exceeding the threshold is constant. One possibility for achieving a smoother and increasing marginal cost curve is to apply several thresholds with increasing peak tariffs. Regardless of the detailed design of the IPP, investments in technologies that allow for a net baseload and constant consumption are incentivized in the long run.

In contrast to IPP, DCPP is well suited to accurately reflecting grid congestion, regardless of consumers’ individual contributions. Dynamic prices are a well-suited economic tool with a constant marginal cost during peak hours. The constant marginal cost incentivizes consumers to reduce their entire consumption as much as possible when the network is congested. Marginal cost changes across the temporal dimension and thus induces an average effect that makes consumers invest in technologies that can shift loads across time. Despite the strong positive characteristics in terms of targeting congestion, DCPP comes with potential shortcomings in terms of tariff design objectives such as cost recovery and allocation, reflectivity, and non-discrimination (see subsection 3.1) [27].

DCIPP combines both IPP and DCPP to balance their characteristics. DCIPP offers the possibility to support fairness for vulnerable households that use electricity for their basic needs while transmitting to a chosen degree cost-reflective signals to the households causing congestions and associating grid-cost recovery with wealthier and larger households. The analysis shows that the higher the income in the same occupancy group, the more cost-sharing could be determined (see Figure 10). Also, smaller flats and houses pay less than larger ones (regardless of occupancy), which correlates with income. With DCIPP, households with higher incomes must pay slightly higher tariffs. In contrast, lower-income households benefit from this tariff design compared to the basic flat-tariff system that currently applies to most households. This characteristic is useful for policymakers wishing to increase the acceptability of changes to grid tariffs.

A similar tendency applies to households with heat pumps: households with higher incomes pay slightly more than with a flat rate. However, we did not find a significant pattern for households owning EVs. At the same time, based on our design, EV owners are less disadvantaged, even though they have high consumption. The reason for this could be that they mainly charge outside the times when the high tariff of the DCIPP applies.

The extent to which this design effectively shields vulnerable users against high grid costs depends on how the threshold is set and therefore refers to policy arbitrage, preferences and decisions and a sound definition of basic need. The threshold at which excess consumption is classified as peak consumption and charged at a higher tariff needs to be set carefully. A potential challenge is that large households are likely to surpass a threshold that is dimensioned to target mainly households with EVs. A balanced threshold needs to be found so that the DCIPP is still effective in shifting demand to off-peak hours and, on the other hand, does not penalize the most vulnerable groups for allowing an inclusive and fair transition. The threshold can potentially be set to available local capacities or local consumer characteristics and technologies in order to trigger grid-friendly behavior.

Finally, DCIPP allows grid costs to be allocated across different consumers and technologies. In contrast to fixed charges based on e.g. technologies, this tariff design only targets the impact of residential consumption on the grid at moments of congestion rather than penalizing household connection to the grid. Ultimately, the DCIPP design is a balance that adds allocative features at the expense of fully penalizing consumption during peak periods.

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1 Only for large households (category P5+) does this seem to be different. However, this must be handled cautiously, as the different income groups within P5+ are not comparable. The average occupancy in the low-income group is 5.6, and in the high-income group 5.1. See Section 3.3.
6. Conclusion and policy implications
This study aims to provide a detailed view of grid tariffs for residential electricity consumption and their distributional properties disaggregated into the socio-techno-economic categories of residential households. In order to address several tariff design objectives, such as congestion management, economic efficiency and allocative characteristics and fairness, we have developed and tested three grid tariff designs. First, Individual Peak Pricing (IPP) penalizes consumption above a certain threshold. Second, Dynamic Critical Peak Pricing (DCPP) penalizes consumption during hours of network congestion. Third, Dynamic Individual Critical Peak Pricing (DCIPP) combines the two. We calculate the redistribution of yearly volumetric grid costs under the assumption of the income neutrality of a distribution system operator that applies flat tariffs to around 1.56 million Danish households following the approach of [15].

IPP increases the volumetric grid costs mainly of large households and households owning an electric vehicle and heat pump. In contrast, small households benefit from this tariff in seeing a reduction of their grid bills. The higher the threshold of IPP, the more EV owners face higher volumetric costs. Although this tariff shifts more grid cost recovery on to households, effectively pulling grid expenditure up (i.e., EV owners), IPP is poorly suited to reflecting grid costs in the temporal dimension and thus alleviating system congestion. DCPP, on the other hand, corrects this shortcoming, as it applies higher rates when the network is congested. The design reduces the cost for apartments at the expense of medium-sized houses. Heat pump owners face higher network bills due to their consumption patterns. Conversely, electric vehicle owners pay even less than with flat volumetric tariffs, suggesting a certain flexibility but a lower contribution to total grid-cost recovery in Denmark. It is therefore important to review the volumetric grid-cost allocation on households from current TOU designs as well, as they might not allocate cost as policymakers potentially desire. DCIPP combines both allocative and temporal characteristics, offering a balanced design. Smaller consumers benefit from the new tariff design at the expense of larger households.

Moreover, system operators and policymakers have the opportunity to balance the grid-cost allocation between electric vehicles and heat pump owners and incentivize either temporal or power flexibility more or less. Additionally, the grid tariff design can be adapted to local network capacities and consumer characteristics. DCIPP can also be adapted to both strong and weak grids, district heating areas or areas with dominant electric vehicle charging patterns. Our study further shows that DCIPP has characteristics that mostly reduce network bills in the smaller and the poorer households. Although not the primary objective, the results of DCIPP in terms of its impacts on household income groups offer policymakers and system operators a tool for increasing the acceptability of new grid tariff designs to tackle future challenges.

The DCIPP therefore offers a useful tariff design for policymakers and system operators to price network usage based on the basis of different preferences and local network characteristics. This is done by weighing the importance of allocative and fairness preferences against the characteristics affecting congestion management.

7. Patents

Author contributions.
Philipp Andreas Gunkel: conceptualization, methodology, software, analysis, writing
Claire-Marie Bergaentzlé: conceptualization, writing, supervision
Fabian Scheller: conceptualization, methodology, supervision
Dogan Keles: methodology, writing, supervision
Henrik Klinge Jacobsen: methodology, writing, supervision
All authors have read and agreed to the published version of the manuscript.
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Appendix A

A.1. Danish load-duration curve in 2017

![Figure A14 Load-duration curve of Denmark in 2017](image)

A.2. Additional results

Table A4. New grid tariffs for base and peak consumption per scenario from a flat volumetric tariff of 18.25 Øre/kWh (multiplied by a recovery factor of 0.95).

| Scenario          | Base [Øre/kWh] | Peak [Øre/kWh] |
|-------------------|----------------|---------------|
| IPP; 1kWh         | 17.34          | 20.29         |
| IPP; 1.5kWh       | 17.34          | 22.73         |
| IPP; 2kWh         | 17.34          | 26.80         |
| IPP; 3kWh         | 17.34          | 52.64         |
| DCPP; 1%          | 17.34          | 70.05         |
| DCPP; 5%          | 17.34          | 30.32         |
| DCPP; 20%         | 17.34          | 20.91         |
| DCPP; 40%         | 17.34          | 19.22         |
| DCIPP; (2kWh, 1%) | 17.34          | 273.33        |
| DCIPP; (2kWh, 5%) | 17.34          | 97.27         |
| DCIPP; (2kWh, 20%)| 17.34          | 43.11         |
| DCIPP; (2kWh, 40%)| 17.34          | 32.61         |
Table A5. Difference in total yearly cost paid per household on volumetric charges for each design in the respective household category in Ørefyr year compared to the base case of a flat volumetric design.

| Category | IPP: 1 kWh | IPP: 1,5 kWh | IPP: 2 kWh | IPP: 3 kWh | DCIPP: 1% | DCIPP: 5% | DCIPP: 40% |
|----------|-------------|--------------|-----------|----------|------------|-----------|-----------|
|          |             |              |           |          | (2 kWh)    | (2 kWh)   | (2 kWh)   |
|          |             |              |           |          |            |           |           |
| Ap_P1_A1_E2_EV0_HP0 | -820 | -902 | -971 | -1028 | -156 | -120 | -85 | -62 | -975 | -967 | -966 | -968 |
| Ap_P1_A1_E1_EV0_HP1 | 1744 | 1395 | 296 | -1366 | 522 | 1071 | 629 | 107 | 1436 | 2480 | 1489 | 716 |
| Ap_P1_A2_E2_EV0_HP0 | -768 | -860 | -934 | -1010 | -189 | -179 | -132 | -92 | -968 | -951 | -940 | -939 |
| Ap_P1_A3_E2_EV0_HP1 | 1955 | 1559 | 731 | -1 | 522 | 948 | 523 | 26 | 1816 | 2529 | 1725 | 1086 |
| Ap_P1_A3_E1_EV0_HP0 | -651 | -780 | -950 | -999 | -237 | -208 | -139 | -98 | -971 | -972 | -963 | -963 |
| Ap_P2_A2_E1_EV0_HP0 | -872 | -964 | -1047 | -1123 | -112 | -64 | -38 | -26 | -1057 | -1046 | -1038 | -1040 |
| Ap_P2_A1_E2_EV0_HP1 | 2795 | 3086 | 1832 | 409 | 719 | 1363 | 847 | 221 | 4124 | 5836 | 4118 | 2819 |
| Ap_P2_A2_E2_EV0_HP0 | -812 | -917 | -1031 | -1146 | -165 | -151 | -110 | -76 | -1047 | -1043 | -1030 | -1030 |
| Ap_P2_A2_E1_EV0_HP1 | 1960 | 1242 | 222 | -793 | 677 | 1187 | 640 | 89 | 1479 | 1970 | 1076 | 635 |
| Ap_P2_A3_E2_EV0_HP0 | -765 | -880 | -993 | -1145 | -236 | -187 | -129 | -87 | -1069 | -1059 | -1032 | -1018 |
| Ap_P2_A3_E1_EV0_HP1 | -912 | -1020 | -1130 | -1221 | -92 | -33 | -13 | -8 | -1169 | -1138 | -1120 | -1123 |
| Ap_P2_A1_E1_EV0_HP1 | 4160 | 6294 | 6914 | 8524 | 846 | 1574 | 981 | 264 | 8116 | 11830 | 9314 | 7352 |
| Ap_P2_A3_E2_EV0_HP0 | -830 | -958 | -1108 | -1238 | -166 | -128 | -88 | -62 | -1176 | -1149 | -1121 | -1116 |
| Ap_P2_A3_E2_EV0_HP1 | 4840 | 7216 | 8567 | 14427 | 1128 | 1677 | 899 | 134 | 10222 | 13068 | 10120 | 8355 |
| Ap_P2_A3_E3_EV0_HP0 | -796 | -967 | -1172 | -1451 | -270 | -183 | -115 | -84 | -1271 | -1243 | -1189 | -1178 |
| Ap_P2_A1_E1_EV0_HP0 | -765 | -918 | -1077 | -1215 | -38 | -42 | -17 | 2 | -1076 | -1072 | -1070 | -1070 |
| Ap_P2_A1_E1_EV0_HP1 | 3195 | 3481 | 2248 | 964 | 998 | 1390 | 800 | 217 | 5184 | 5833 | 4197 | 3136 |
| Ap_P2_A2_E2_EV0_HP0 | -710 | -871 | -1071 | -1283 | 42 | -2 | 7 | 23 | -1021 | -1033 | -1045 | -1051 |
| Ap_P2_A2_E2_EV0_HP1 | 3029 | 3760 | 3574 | 4181 | 760 | 1169 | 714 | 207 | 5429 | 6543 | 5511 | 4497 |
| Ap_P2_A2_E3_EV0_HP0 | -694 | -862 | -1057 | -1240 | 9 | -31 | -19 | 1 | -1048 | -1049 | -1045 | -1042 |
| Ap_P2_A2_E3_EV0_HP1 | -787 | -957 | -1174 | -1364 | -3 | -31 | -6 | 14 | -1144 | -1178 | -1168 | -1161 |
| Ap_P2_A2_E1_EV0_HP1 | 5011 | 6927 | 7527 | 8975 | 914 | 1352 | 798 | 191 | 9145 | 10481 | 9302 | 8086 |
| Ap_P2_A2_E2_EV0_HP0 | -767 | -967 | -1222 | -1477 | 88 | 33 | 36 | 43 | -1157 | -1195 | -1190 | -1192 |
| Ap_P2_A2_E2_EV0_HP1 | 3924 | 4968 | 4632 | 3757 | 910 | 1426 | 887 | 320 | 7369 | 9271 | 7368 | 6022 |
| Ap_P2_A3_E2_EV0_HP0 | -711 | -916 | -1172 | -1445 | 16 | -33 | -13 | 8 | -1107 | -1158 | -1143 | -1146 |
| Ap_P2_A3_E2_EV0_HP1 | -676 | -815 | -1053 | -1310 | -3 | -7 | 21 | 32 | -1093 | -1057 | -1030 | -1031 |
| Ap_P2_A3_E1_EV0_HP1 | 4241 | 7281 | 9594 | 17762 | 640 | 1096 | 630 | 160 | 8627 | 12653 | 11134 | 9526 |
| Ap_P2_A3_E2_EV0_HP0 | -701 | -920 | -1226 | -1563 | 106 | 97 | 93 | 81 | -1207 | -1185 | -1170 | -1177 |
| Ap_P2_A3_E2_EV0_HP1 | 6033 | 9840 | 11896 | 13881 | 1236 | 1991 | 1272 | 466 | 14273 | 20033 | 16720 | 13719 |
| Ap_P2_A3_E3_EV0_HP0 | -419 | -572 | -926 | -1352 | 61 | 72 | 67 | 51 | -902 | -860 | -841 | -858 |
| Ap_P2_A3_E3_EV0_HP1 | 6618 | 11028 | 14098 | 20067 | 1025 | 1645 | 940 | 237 | 14945 | 19848 | 17012 | 14721 |
| Ap_P3_A3_E3_EV0_HP0 | 270 | 328 | -78 | -765 | 242 | 45 | 42 | 78 | 240 | -70 | -42 | 7 |
| H_P1_A1_E1_EV0_HP1 | 4827 | 6494 | 6515 | 7311 | 589 | 1485 | 828 | 73 | 7616 | 11487 | 8534 | 6478 |
| H_P1_A2_E2_EV0_HP0 | -730 | -896 | -972 | -1182 | -222 | -157 | -124 | -109 | -1155 | -1053 | -1032 | -1033 |
| H_P1_A2_E2_EV0_HP1 | 6318 | 8673 | 8560 | 9213 | 384 | 1214 | 620 | -90 | 8241 | 11717 | 9221 | 7563 |
|                   |                        |                        |                        |                        |                        |
|-------------------|------------------------|------------------------|------------------------|------------------------|------------------------|
| **H_P1_A1_e3_EVO** | **H_P2_A1_e1_EVO**    | **H_P3_A3_e1_EVO**    | **H_P4_A3_e1_EVO**    | **H_P5_A3_e1_EVO**    | **H_P6_A3_e1_EVO**    |
|                   |                        |                        |                        |                        |                        |
| **H_P1_A1_e3_HP0** | **H_P2_A1_e1_HP0**    | **H_P3_A3_e1_HP0**    | **H_P4_A3_e1_HP0**    | **H_P5_A3_e1_HP0**    | **H_P6_A3_e1_HP0**    |
|                   | **H_P1_A2_e1_HP0**    | **H_P2_A2_e1_HP0**    | **H_P3_A3_e1_HP0**    | **H_P4_A3_e1_HP0**    | **H_P5_A3_e1_HP0**    |
|                   |                        | **H_P1_A2_e1_HP1**    | **H_P2_A2_e1_HP1**    | **H_P3_A3_e1_HP1**    | **H_P4_A3_e1_HP1**    |
|                   | **H_P1_A2_e2_HP0**    | **H_P2_A2_e2_HP0**    | **H_P3_A3_e2_HP0**    | **H_P4_A3_e2_HP0**    | **H_P5_A3_e2_HP0**    |
|                   |                        | **H_P1_A2_e2_HP1**    | **H_P2_A2_e2_HP1**    | **H_P3_A3_e2_HP1**    | **H_P4_A3_e2_HP1**    |
|                   | **H_P1_A2_e3_HP0**    | **H_P2_A2_e3_HP0**    | **H_P3_A3_e3_HP0**    | **H_P4_A3_e3_HP0**    | **H_P5_A3_e3_HP0**    |
|                   |                        | **H_P1_A2_e3_HP1**    | **H_P2_A2_e3_HP1**    | **H_P3_A3_e3_HP1**    | **H_P4_A3_e3_HP1**    |
|                   | **H_P1_A3_e1_HP0**    | **H_P2_A3_e1_HP0**    | **H_P3_A3_e1_HP0**    | **H_P4_A3_e1_HP0**    | **H_P5_A3_e1_HP0**    |
|                   |                        | **H_P1_A3_e1_HP1**    | **H_P2_A3_e1_HP1**    | **H_P3_A3_e1_HP1**    | **H_P4_A3_e1_HP1**    |
|                   | **H_P1_A3_e2_HP0**    | **H_P2_A3_e2_HP0**    | **H_P3_A3_e2_HP0**    | **H_P4_A3_e2_HP0**    | **H_P5_A3_e2_HP0**    |
|                   |                        | **H_P1_A3_e2_HP1**    | **H_P2_A3_e2_HP1**    | **H_P3_A3_e2_HP1**    | **H_P4_A3_e2_HP1**    |
|                   | **H_P1_A3_e3_HP0**    | **H_P2_A3_e3_HP0**    | **H_P3_A3_e3_HP0**    | **H_P4_A3_e3_HP0**    | **H_P5_A3_e3_HP0**    |
|                   |                        | **H_P1_A3_e3_HP1**    | **H_P2_A3_e3_HP1**    | **H_P3_A3_e3_HP1**    | **H_P4_A3_e3_HP1**    |
|                   | **H_P2_A3_e3_HP1**    | **H_P3_A3_e3_HP1**    | **H_P4_A3_e3_HP1**    | **H_P5_A3_e3_HP1**    | **H_P6_A3_e3_HP1**    |
|                   | **H_P2_A3_e3_HP0**    | **H_P3_A3_e3_HP0**    | **H_P4_A3_e3_HP0**    | **H_P5_A3_e3_HP0**    | **H_P6_A3_e3_HP0**    |
|                   | **H_P2_A3_e3_HP1**    | **H_P3_A3_e3_HP1**    | **H_P4_A3_e3_HP1**    | **H_P5_A3_e3_HP1**    | **H_P6_A3_e3_HP1**    |
|                   | **H_P2_A3_e3_HP0**    | **H_P3_A3_e3_HP0**    | **H_P4_A3_e3_HP0**    | **H_P5_A3_e3_HP0**    | **H_P6_A3_e3_HP0**    |
|                   | **H_P2_A3_e3_HP1**    | **H_P3_A3_e3_HP1**    | **H_P4_A3_e3_HP1**    | **H_P5_A3_e3_HP1**    | **H_P6_A3_e3_HP1**    |
|                   | **H_P2_A3_e3_HP0**    | **H_P3_A3_e3_HP0**    | **H_P4_A3_e3_HP0**    | **H_P5_A3_e3_HP0**    | **H_P6_A3_e3_HP0**    |
|                   | **H_P2_A3_e3_HP1**    | **H_P3_A3_e3_HP1**    | **H_P4_A3_e3_HP1**    | **H_P5_A3_e3_HP1**    | **H_P6_A3_e3_HP1**    |
|                   | **H_P2_A3_e3_HP0**    | **H_P3_A3_e3_HP0**    | **H_P4_A3_e3_HP0**    | **H_P5_A3_e3_HP0**    | **H_P6_A3_e3_HP0**    |
|                   | **H_P2_A3_e3_HP1**    | **H_P3_A3_e3_HP1**    | **H_P4_A3_e3_HP1**    | **H_P5_A3_e3_HP1**    | **H_P6_A3_e3_HP1**    |
|                   | **H_P2_A3_e3_HP0**    | **H_P3_A3_e3_HP0**    | **H_P4_A3_e3_HP0**    | **H_P5_A3_e3_HP0**    | **H_P6_A3_e3_HP0**    |
|                   | **H_P2_A3_e3_HP1**    | **H_P3_A3_e3_HP1**    | **H_P4_A3_e3_HP1**    | **H_P5_A3_e3_HP1**    | **H_P6_A3_e3_HP1**    |
### Table A6. Sensitivity study on $f^{\text{red}}$ in the IPP scenario with a threshold of 1 kWh. The numbers show the relative change to the flat volumetric tariff.

| Dwelling type | Dwelling area | $f^{\text{red}}=0.95$ | $f^{\text{red}}=0.9$ | $f^{\text{red}}=0.8$ |
|---------------|---------------|-----------------------|----------------------|----------------------|
| Ap            | A1            | 0.9654                | 0.9308               | 0.8615               |
| Ap            | A2            | 0.9686                | 0.9373               | 0.8745               |
| Ap            | A3            | 0.9855                | 0.9709               | 0.9419               |
| H             | A1            | 0.9932                | 0.9864               | 0.9728               |
| H             | A2            | 1.0032                | 1.0065               | 1.0129               |
| H             | A3            | 1.0139                | 1.0277               | 1.0554               |

### Table A7. Sensitivity study on $f^{\text{red}}$ in the DCPP scenario with a trigger percentage of 1%. The numbers show the relative change to the flat volumetric tariff.

| Dwelling type | Dwelling area | $f^{\text{red}}=0.95$ | $f^{\text{red}}=0.9$ | $f^{\text{red}}=0.8$ |
|---------------|---------------|-----------------------|----------------------|----------------------|
| Ap            | A1            | 0.9946                | 0.9891               | 0.9782               |
| Ap            | A2            | 0.9973                | 0.9947               | 0.9894               |
| Ap            | A3            | 1.0005                | 1.0009               | 1.0019               |
| H             | A1            | 0.9999                | 0.9998               | 0.9996               |
| H             | A2            | 1.0011                | 1.0022               | 1.0044               |
| H             | A3            | 1.0002                | 1.0005               | 1.0010               |

### Table A8. Sensitivity study on $f^{\text{red}}$ in the DCIPP scenario with a threshold of 1 kWh and a trigger percentage of 1%. The numbers show the relative change to the flat volumetric tariff.

| Dwelling type | Dwelling area | $f^{\text{red}}=0.95$ | $f^{\text{red}}=0.9$ | $f^{\text{red}}=0.8$ |
|---------------|---------------|-----------------------|----------------------|----------------------|
| Ap            | A1            | 0.9675                | 0.9350               | 0.8701               |
| Ap            | A2            | 0.9718                | 0.9436               | 0.8872               |
| Ap            | A3            | 0.9887                | 0.9773               | 0.9546               |
| H             | A1            | 0.9945                | 0.9889               | 0.9778               |
| H             | A2            | 1.0049                | 1.0099               | 1.0198               |
Table A9. Sensitivity on $f^{\text{red}}$ and the resulting base and peak prices per scenario.

| Scenario      | $f^{\text{red}}=0.95$ | $f^{\text{red}}=0.9$  | $f^{\text{red}}=0.8$  |
|---------------|------------------------|------------------------|------------------------|
| Base          | 17.34                  | 16.43                  | 14.60                  |
| IPP 1kWh      | 20.29                  | 22.34                  | 26.43                  |
| DCPP 1%       | 70.05                  | 121.84                 | 225.44                 |
| DCIPP (1kWh, 1%) | 116.08                | 213.92                 | 409.58                 |

A.3. Income redistribution across IPP and DCPP

Figure A15. Average relative change in cost with IPP for households without EV and HP across all dwelling sizes and types.

Figure A16. Average relative change in cost with DCPP for households with EV and HP across all dwelling sizes and types.

Figure A17. Average relative change in cost with IPP for households with EV and HP across all dwelling sizes and types.

Figure A18. Average relative change in cost with DCPP for households with EV and HP across all dwelling sizes and types.

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