

The Cost and Geographic Impact of Inflexibility Facing Time-based tariff

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Abstract— This study presents the status of time-of-use grid tariff adoption in Denmark. It identifies trends in tariff transformation from distribution grid operators, examines how the ongoing transformation rebalances grid cost recovery from fixed subscription charge to variable volumetric fee, and explores the consequences for households. We carried out a thorough review and analysis of the progressive transformations of the tariff structure over the 2017-2024 period, crossed with key characteristics of the 36 Danish DSOs under study. We evaluated the impact of tariff transformations in heterogeneous households' grid bill using high-resolution smart meter data. Our findings offer near-real-time insights into the reallocative impacts of tariff transformations, highlighting significant implications for both less and highly electrified households, and revealing the challenges and disparities among different DSO sizes in adapting to these changes.

Index Terms— Electricity Grid Tariff; Electrification Grid cost recovery; Households; Time-of-Use.

I. INTRODUCTION

Since the introduction of the Clean Energy Package in Europe in 2019, Distribution System Operators (DSOs) have been obliged to offer cost-reflective tariff structures and to move away from traditional flat tariffs. Since then, there has been a burgeoning of pricing initiatives, led by time-of-use (ToU) pricing. ToU tariffs are energy-based tariffs that apply two or more daily block rates, setting different per kWh fees to reflect the aggregated level of grid use, and are accompanied by a fixed subscription payment. They are broadly used by households [1], [2], [3] and are offered in 21 out of 28 EU countries [4]. Their wide adoption is due to their simplicity of implementation and transparency regarding how the block rates are set and when prices vary, which supports acceptance and adoption from the grid users [5]. It is also because ToU tariffs provide a relatively conservative risk/reward profile for grid users, which facilitates political acceptance when deployed to residential users [6].

This success builds on the deployment of smart meters allowing advanced billing. Today, about half of European households and businesses have a smart meter [7]. 22 EU member states have established a legal framework for their rollout, and 16 have committed to full deployment [8]. In four

countries, including Denmark, an independent data hub has been created to manage all metering data for the electricity market. But although there is noticeable progress in smart meters rollout, this deployment is far from being even in Europe, including within countries. Zooming in at the country level sometimes reveals striking differences in the way, speed and extent to which time-based tariffs are implemented, especially in countries covered by multiple DSOs or with low support from central administration, as is the case in Germany, Belgium or the Czech Republic [9], [10]. The survey realized by [9] over 56 European DSOs of different sizes and supply areas further reveals geographical disparities associated with the level of communication and automation reached by different types of DSOs. In particular, DSOs serving large sparsely populated areas often fall behind in these aspects.

In Denmark, smart meters were successfully deployed by 2020. This technological advancement has facilitated the introduction of ToU tariffs as part of the *Tarifmodel 3.0* framework, which aims to incentivize flexibility. However, the adoption of ToU tariffs has progressed heterogeneously across Denmark's 36 DSOs, each responsible for different territorial coverage and consumer bases [11] [12].

Existing literature extensively examines the impact of ToU pricing on consumer load shifting and energy costs. However, a research gap remains regarding the modalities of progressive ToU deployment across multiple DSOs within a national framework. Specifically, it is unclear how the restructuring of grid pricing affects households with varying consumption patterns. This study addresses this gap by empirically analyzing ToU tariff implementation across Danish DSOs, with a focus on grid cost recovery strategies and their redistributive effects on households. We aim to:

- Examine the strategies employed by different DSOs to recover grid costs
- Assess the dynamic redistribution of grid costs across heterogeneous households and geographic areas; and
- Estimate the cost of inflexibility for various household types.

By leveraging empirical data on smart meter consumption, geospatial DSO coverage, and historical tariff structures, this study provides near-real-time insights into the reallocative impacts of grid cost recovery mechanisms. The findings contribute to a broader understanding of tariff design

implications, informing both policymakers and grid operators on the socioeconomic and equity dimensions of ToU tariff deployment in multi-DSO regulatory environments.

II. METHODOLOGY

We proceeded in four steps. First, we collected data about areas covered by Danish DSOs and matched it with municipality-level data to cluster DSOs. Second, we made an inventory of the yearly tariff structures and rates of each DSO between 2017 and 2024. Third, we used hourly smart meter data collected in Denmark in 2017 to build household archetypes combining dwelling type and heat pump and/or electric car ownership to, fourth, extrapolate grid bill values.

A. Geospatial composition of DSOs and classification

We consider geospatial information of municipalities in Denmark, taken from [13], as well as the corresponding number of households per municipality, taken from *Denmarks Statistics* [14]. The geospatial distribution of DSOs is overlapped with the geospatial distribution of municipalities. In case a municipality is served by two or more DSOs, we assume a proportional allocation of households respective to the area covered. As an example, if DSO A covers 60% of municipality X, and DSO B covers the remaining 40% of it, then 60% of the total households of municipality X are allocated to DSO A, etc. After allocating households to the different DSOs, we can classify them in terms of area covered and households supplied. Fig. 1 shows the relationship between the area served by each DSO and the number of households they supply. Each point represents a different DSO, showing the variation in coverage area and households supplied. Danish DSOs are grouped into four groups based on their supply area and number of connected households: very Large, Large, medium and small.

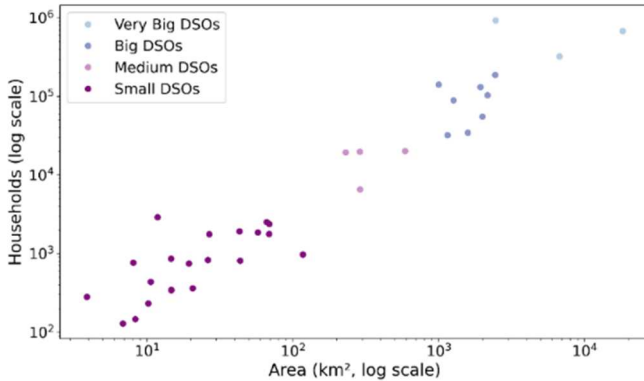


Figure 1. Clustering of DSOs

B. DSO tariff model and evolution between 2017 and 2024

In this study, we only consider the DSO grid tariff and disregard the other cost components included in the final consumption bill, meaning that we entirely disregard electricity prices, TSO tariff (also paid by households), and other taxes and levies. We collected yearly tariff data on all Danish DSOs over the period 2017-2024. 2017 corresponds to the year when the

smart meter rollout was nearly completed in Denmark. The data was collected from *Energidataservice* [15] and homogenized in their format across DSOs. The data includes the fixed monthly subscription, the per kWh volumetric fee, and, for the few DSOs not connected to the transmission grid but to another DSO, an additional 'overlying grid tariff' added to the volumetric component. This inventory allows us to track per DSO (and therefore geographically) the time points when DSO implement changes in their tariff structure, how many changes and thereby, the different steps they take to comply with the Danish Tariff 3.0 roadmap.

C. Household archetype consumption

We considered six household archetypes (Table 1). Each archetype corresponds to a combination of dwelling type (house or apartment) and "electrification" (heat pump and/or EV). We used observed hourly consumption data from the Danish TSO Energinet's *Energihub* to build archetype average yearly load profiles. Individual smart meter data was cross-featured with public registers from Denmark Statistics indicating the dwelling type and if the household owns an EV or a heat pump (for more details, see [16]). Due to the limited number of households owning both a heat pump and an EV in 2017, we built a synthetic load profile corresponding to this archetype building on observed data from house owners owning an EV and house owners using a heat pump. Fig. 2 displays the yearly load pattern of each archetype¹.

Table 1: Denomination of household archetypes

Archetype	Notation
Apartments without EV or HP	NT AP
Houses without EV or HP	NT H
Apartments with HP but without EV	HP AP
Houses with HP but without EV	HP H
Houses with EV but without HP	EV H
Houses with both EV and HP	EV HP H

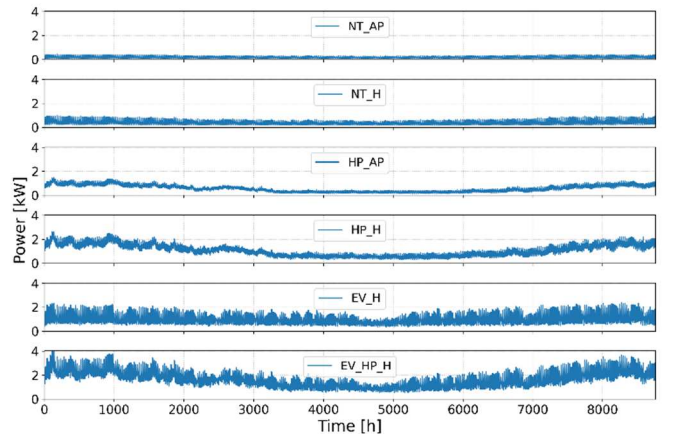


Figure 2. Average electricity profile for household archetypes

D. Household archetype yearly grid bill.

We consider that each DSO supplies electricity to all six archetypes. We multiplied the archetypes' hourly consumption

¹ as the data originates from 2017, most home charging is conducted at a power level of 3.7kW and smart charging was not usually applied

yet. Additionally, as the average is shown the load curve never exceeds 4kW.

with the tariff levels in the corresponding hour. The yearly fixed subscription is then added to determine the yearly grid bill for every archetype in all DSO areas.

III. RESULTS

A. Progressive implementation of TOU

Fig. 3 shows the progressive tariff transformations from 2017 to 2024. In 2017, most DSOs used a flat tariff except for Radius Elnet and Konstant Net (grouped as “Large” and “Very Large”, serving large urban areas), who had already implemented a two-block rate ToU.

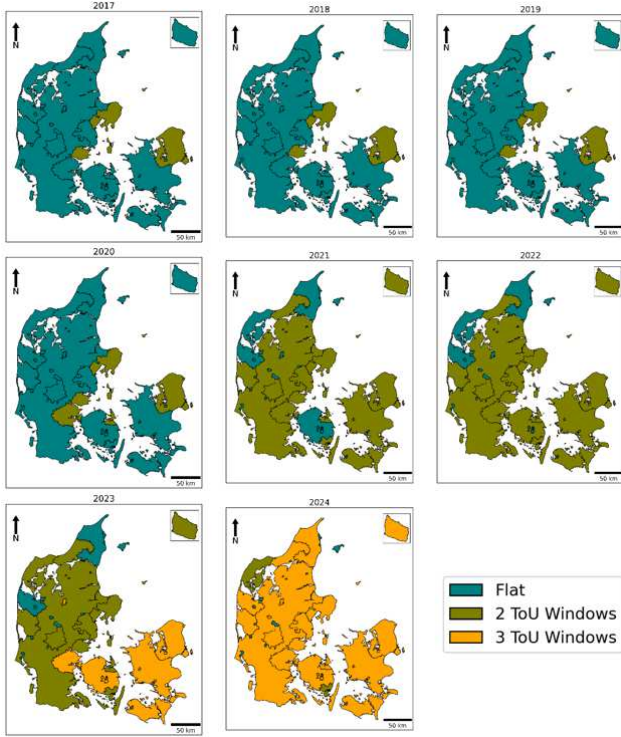


Figure 3. Gradual Implementation of ToU in Denmark

We see a three-phase expansion of ToU tariffs across Denmark. Until 2020, the picture remained largely unchanged before radically switching to two-time windows ToU in 2021 by all Large and very Large DSOs, most medium DSOs and several small DSOs. In the following years, we see the gradual adoption of a more complex three-time window ToU before another radical adoption of this tariff structure by virtually all DSOs in 2024. Zooming in, almost all Large and Very Large DSOs have implemented this tariff model within the first months of 2023 while smaller DSOs followed later that year and the next year. In 2024, 25 out of the 36 DSOs had implemented a three-time window ToU, two were still using a two-time window. Nine small DSOs still used a flat tariff².

B. Impact of tariff transformations on grid cost recovery

Fig 4. shows the relationship between the percentage of fixed and variable components in the yearly electricity bill of the two most contrasting household archetypes between 2017

and 2021, and between 2021 and 2024. Each point represents a combination of DSO size and year and indicates the relative share of the tariff components (e.g. 60% volumetric 40% fixed). The lines show the trajectory of the fixed/variable cost balance for each DSO type.

Regardless of the consumer type, the percentage of the grid cost recovery relying on fixed charges decreases over time, at the benefit of a larger reliance on volumetric ToU pricing. The magnitude of change in the fixed/variable balance differs significantly across DSO sizes, both in terms of the rate of change and the size of rebalancing. Very Large DSOs show a much more pronounced shift from fixed to variable cost composition over the first period of 2017-2021, while this change was less marked to marginal for the other DSOs, including Large DSOs, suggesting a clear cut in implementation strategies between the two. The paths of the remaining DSOs show less drastic, yet very different, rebalancing movements in the fixed/variable composition of their users’ bills in the middle years (2021) before accelerating this transformation until 2024, as a catch-up effect.

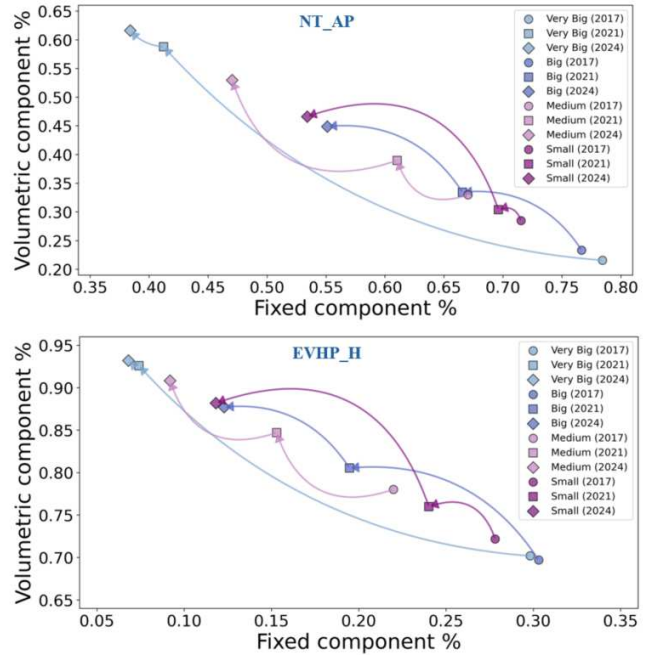


Figure 4. Movement of variable and fixed share per archetype (2017-2024)

This rebalancing of cost components impacts grid users in various proportions. In 2017, smaller consumers’ contribution to grid cost recovery was 67 to 80% based on subscriptions and 33 to 20% on volumetric fees, with the highest share of subscriptions from the largest DSOs. Today, this has transitioned to 40-55% subscription and 60-45% volumetric. For energy-intensive households, the transition in the subscription-volumetric ratio across the DSO types went from 23-31% to 6-13% subscription and from 77-69% to 94-87% volumetric, with the Very Large DSOs exposing large consumers with the highest volumetric exposure.

² However, as some of these DSOs are connected to another DSO, their users face some degree of time-varying component through the “overlying network tariff”.

Fig 5. Disaggregates the above results and shows the detail per DSO and user type over the period 2017-2024. Each row represents a DSO, ranked by its household connections (from the largest to the smallest); each column represents an archetype, ordered from the lowest to the highest consumption level. The left heat map captures the rebalancing of grid cost recovery from subscription to volumetric fee. E.g. In 2020, the contribution of an NT-A household connected to Radius to Radius' cost recovery was 40% more based on the volumetric fee than what it used to be in 2017. The right heat map shows the change in the total grid bill in Danish Krone. For an identical profile, the same NT-A household reduced its yearly bill by about 1,000 DKK (130 Eur) over the period.

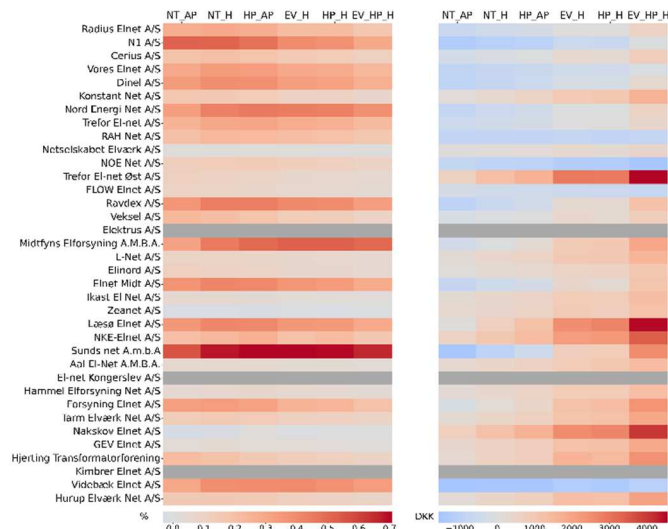


Figure 5. Change in tariff composition and yearly grid bill (2017-2024). The grey lines indicate missing tariff data in 2017

Consistent with Fig. 4, the red shades on the left map indicate that the relative share of the volumetric component in the final grid bill increased, especially for lower-consumption households from the largest DSOs. We observe several exceptions indicating that the tariff transformation process is not homogenous and reflects specific local or organizational specificities. Notably, we note cases where the largest consumers faced the largest tariff rebalancing (e.g. Midtlys Elforsyning), and we observe a handful of medium and small DSOs (e.g. Nakskov Elnet), where the subscription fee decreased over the period, following the termination of their smart meters' rollout.

With the shift from fixed subscription charges to volumetric fees, many households experienced a reduction in their overall annual electricity bills (blue shades on the right map). The magnitude of bill reductions varies between DSOs and household archetypes. The highest grid bill reductions were most often achieved by households connected to DSOs who implemented clear rebalancing between subscription and volumetric fees, suggesting the benefits of ToU tariffs outweighed the increased volumetric charges for a substantial portion of consumers. In addition, the smallest consumers appear to be clear beneficiaries from the tariff transformation, besides the fact that they are the least equipped for adjusting

their load. Higher-consumption households tend to experience grid bill increases if they do not adjust to tariff signals. In the case of Denmark, we see a clear difference in terms of grid bill impact based on whether electrification is associated with the dwelling type. ToU tariffs tend to increase substantially the grid bill for households combining either a heat pump or an EV to a house, while this impact is less marked for electrified homeowners in apartments.

Fig. 6 illustrates the impacts on the yearly grid bill (subscription + volumetric fee) in absolute values for each user type in 2017 and 2024³. E.g. NT_AP users supplied by Radius, on average, paid a grid bill of 1,720 DKK in 2017 against 1,093 DKK in 2024. Overall, we see a general increase in grid bills over the period marked by two trends: the size of the consumer and the size of the DSO she is connected to.

Larger consumers face a relatively higher grid bill increase compared to small consumers. To give an order of magnitude, a house owner with a heat pump and an EV who does not act flexibly pays, on average, 4,890DKK per year (1,300Eur) with the newest tariff, which is 46% higher than the same household's average grid bill eight years before. On the other hand, small-demand households pay, on average, 11% less at the country's level.

However, this impact is almost only observed among the small DSOs and half of the medium ones, which indicates that the size of the DSO and/or the time of implementation of the tariff matters the most when investigating mid-term tariff impact. The large majority of Very Large and Large DSOs show a decrease in grid bills across most consumer categories, including the highest-demand ones. Electrified users connected to Very Large and Large DSOs who experienced a grid bill increase during that period saw, on average, an increase three times smaller than that of similar households connected to Medium and Small DSOs (excluding outliers with exceptionally high grid bill impacts).

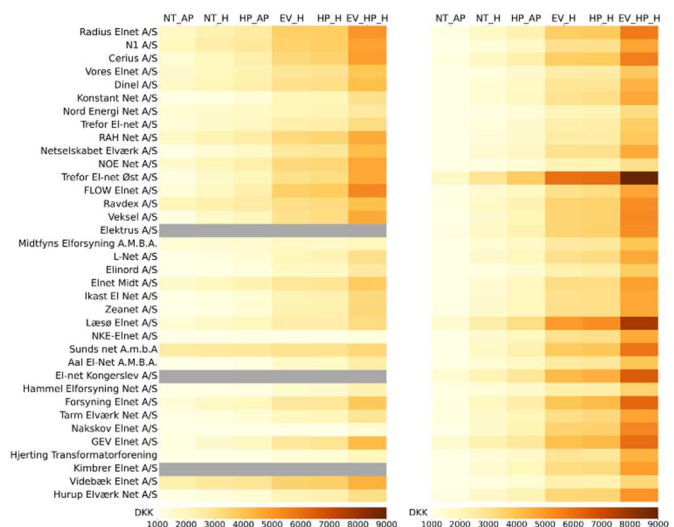


Figure 6. Total average bill per DSO and archetype (2017-left; 2024-right)

Medium-sized DSOs exhibit mixed effects: half follow grid bill reduction patterns similar to larger DSOs, while the other

³ The impact of inflation is not considered

half show more significant bill increases, including for small consumers, resembling the impact patterns of Small DSOs. With few exceptions, Small DSOs experience the steepest cost increases, especially for high-demand consumers, with extreme spikes surpassing 100% in some cases. The smallest consumers connected to Small DSOs (and excluding outliers) pay, on average, 30% more in 2024 than in 2017 and the largest consumers about 60% more. The overall picture is far from being homogenous throughout, as shown by the different outliers. Within the Small DSO category, a few households also benefitted from a grid bill reduction (Elnet Midt, Sunds Net and Videbæk Elnet). The gains spanned from the NT_AP to the EV_HP_H depending on the DSO. Finally, the change of tariffs by two DSOs, Trefor El-net Øst and Læsø Elnet, which are both DSOs operating on islands give additional insights. EV_HP_H users supplied by these DSOs respectively face an 88% and 58% higher annual grid bill than the mean for the corresponding archetype, indicating extra cost for grids in remote islands.

IV. DISCUSSION AND CONCLUDING REMARKS

In this work, we investigated the impact of tariff changes on inflexible consumer archetypes with a special focus on DSO type. We show that the size of the DSO appears to be a significant factor in determining the extent to which the shift to variable pricing has been successful. Very Large DSOs serving large densely populated areas are “early movers”, both in terms of grid tariff transformation and complexification, and tend to embrace a much more substantial change in their cost balance structure, drifting away from fixed components. Although late movers are catching up with early movers, the accelerated implementation of ToU tariffs does not necessarily lead to a catch-up effect in terms of the final grid bill enjoyed by consumers connected to Very Large networks. Significant tariff discrepancies across Danish regions, especially remote areas like islands, were also identified, potentially contributing to varying rates of electrification across the territory, particularly on Danish islands. This disparity highlights potential equity concerns and heterogeneous uptake of electrification in countries where multiple DSOs modify their tariff structure. Policies supporting the transition to ToU tariffs might need to consider DSO size and tailor their approaches to ensure that the benefits and impacts are fairly distributed.

The net stepwise rebalancing of grid cost components in the final bill from all the DSOs directly reflects the implementation of the requirements for cost-reflectiveness set forth in the Clean Energy Package. This results in a decreased reliance on subscription charges and an increased reliance on volumetric fees to recover grid cost, which may result in revenue uncertainty and new cash flow risk for grid operators.

One common source of uncertainty is the extent to which end users adjust their consumption in response to ToU block rates. In this study, we assume a constant load profile throughout the year. However, recent empirical analyses indicate that Danish households do make load adjustments in response to ToU pricing, though these adjustments are primarily observed among large consumers, particularly those with electric cars. In contrast, heat pump owners show lower levels of flexibility, while the smallest consumers exhibit very limited flexibility, as they generally lack the electrical equipment necessary for meaningful adjustments. As a result, the main trends we

identify for the smallest consumers remain valid. More broadly, our findings underscore the cost of non-flexibility. In Denmark, all else being equal, this cost translates into an additional 27% in grid spending by the residential sector. This highlights the importance of clear, transparent, and accessible communication about tariff designs to enhance their effectiveness, encourage flexibility, and prevent new tariffs from inadvertently driving up energy costs for consumers.

REFERENCES

- [1] R. Carmichael, R. Gross, R. Hanna, A. Rhodes, and T. Green, “The Demand Response Technology Cluster: Accelerating UK residential consumer engagement with time-of-use tariffs, electric vehicles and smart meters via digital comparison tools,” *Renewable and Sustainable Energy Reviews*, vol. 139, p. 110701, Apr. 2021, doi: 10.1016/J.RSER.2020.110701.
- [2] M. L. Nicolson, M. J. Fell, and G. M. Huebner, “Consumer demand for time of use electricity tariffs: A systematized review of the empirical evidence,” *Renewable and Sustainable Energy Reviews*, vol. 97, pp. 276–289, Dec. 2018, doi: 10.1016/J.RSER.2018.08.040.
- [3] TREFOR, “Tarif og abonnement - Forbrugskunder og egenproducenter.”
- [4] ACER, “Report on Distribution Tariff Methodologies in Europe,” no. February, p. 88, 2023, [Online]. Available: https://documents.acer.europa.eu/Official_documents/Acts_of_the_Agency/Publication/ACER_Report_on_D-Tariff_Methodologies.pdf
- [5] F. El Gohary, M. Nordin, P. Juslin, and C. Bartusch, “Evaluating user understanding and exposure effects of demand-based tariffs,” *Renewable and Sustainable Energy Reviews*, vol. 155, p. 111956, Mar. 2022, doi: 10.1016/J.RSER.2021.111956.
- [6] A. Faruqi, “Ten lessons in rate design: A meditation,” *Electricity Journal*, vol. 35, no. 10, p. 107223, 2022, doi: 10.1016/j.tej.2022.107223.
- [7] European Commission, “EU action plan on digitalising the energy system. Questions and Answers: EU action plan on digitalising the energy system,” https://ec.europa.eu/commission/presscorner/detail/en/QANDA_22_6229, no. October, 2022.
- [8] European Commission, “REPORT FROM THE COMMISSION Benchmarking smart metering deployment in the EU-27 with a focus on electricity.,” *Brussels, 17.6.2014*, vol. COM(2014), pp. 1–10, 2014.
- [9] A. Meletiou, J. Vasiljevaska, G. Pretico, and S. Vitiello, “Distribution System Operator Observatory 2022. Managing innovation and RES grid connection for a carbonneutral Europe,” 2023. doi: 10.2760/90495.
- [10] C. Cambini, A. Meletiou, E. Bompard, and M. Masera, “Market and regulatory factors influencing smart-grid investment in Europe: Evidence from pilot projects and implications for reform,” *Util Policy*, vol. 40, pp. 36–47, 2015, doi: 10.1016/j.jup.2016.03.003.
- [11] Energitilsynet, “ANALYSE AF KONKURRENCEN PÅ DETAILMARKEDET FOR EL,” 2012.
- [12] Energistyrelsen, “Download GIS-filer.” Accessed: Feb. 15, 2024. [Online]. Available: <https://ens.dk/service/statistik-data-noegletal-og-kort/download-gis-filer>
- [13] IGISMAP, “Download Denmark Administrative Boundary Shapefiles – Regions, Municipalities, Postal Areas and More.” Accessed: Apr. 26, 2024. [Online]. Available: <https://www.igismap.com/download-shapefile-of-denmark-country-boundary-polygon/>
- [14] StatBank Denmark, “People.” Accessed: Feb. 15, 2024. [Online]. Available: <https://www.statbank.dk/3415>
- [15] Energi Data Service, “Datahub Price List.” Accessed: Oct. 25, 2024. [Online]. Available: <https://www.energidataservice.dk/tso-electricity/DatahubPricelist>
- [16] P. Andreas Gunkel, H. Klinge Jacobsen, C. M. Bergaentzlé, F. Scheller, and F. Møller Andersen, “Variability in electricity consumption by category of consumer: The impact on electricity load profiles,” *International Journal of Electrical Power and Energy Systems*, vol. 147, May 2023, doi: 10.1016/j.ijepes.2022.108852.