Time-of-Use Tariff with Local Wind Generation

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***Abstract*—Renewable energy, such as wind power, is known to significantly reduce system costs and carbon emissions. However, traditional Time of Use (ToU) tariffs fail to account for local energy generation. To overcome this limitation, we propose a mechanism for calculating new ToU tariffs that incorporates Agile ToU and local energy resources, such as a wind farm. By partially supplying local consumption, wind energy can reduce electricity costs for consumers and encourage load shifting towards peak renewable energy production periods. We demonstrate the effectiveness of the proposed mechanism by testing it on a case study of a residential area in Wales, UK, where electricity would be partially supplied by a nearby wind farm with 5 turbines through a Power Purchase Agreement (PPA). The results show that the new tariff significantly reduces electricity bills.**

***Index Terms*—Time-of-Use Tariff, Renewable Integration, Local Consumption, Power Purchase Agreement.**

I. Introduction

The increasing deployment of renewable energy sources in the electricity grid is driving the transition towards a sustainable and low-carbon energy system. However, the integration of these sources is not straightforward, and their variability and intermittency can pose significant challenges for grid operators. One way to mitigate these challenges is through the implementation of Time of Use (ToU) tariffs, which aim to incentivize consumers to shift their demand away from peak times when electricity prices are high [1].

ToU tariffs are widely used in the electricity industry, and their implementation can have a significant impact on grid stability, system costs, and consumer behavior. The basic idea behind ToU tariffs is to charge different prices for electricity consumption during different times of the day. Typically, these tariffs have higher prices during peak hours, which are usually in the morning and evening when the demand for electricity is high, and lower prices during off-peak hours [2].

The integration of renewable energy sources, such as wind and solar, can affect the implementation of ToU tariffs in several ways. One significant impact is on the market clearing price, which is the price at which the electricity market balances supply and demand. The penetration of renewables like wind can lead to a reduction in the market clearing price during the intervals when renewable energy is injected into the grid [3]. This reduction in price can make the implementation of ToU tariffs more challenging, as the price difference between peak and off-peak hours may become smaller, making it less attractive for consumers to shift their consumption.

However, the integration of local energy resources, such as a local wind farm, can also have a significant impact on the implementation of ToU tariffs. In these cases, the wholesale market price is not affected, but local generation can be bought by local consumers through contracts such as power purchase agreements (PPAs), creating a new ToU tariff for them.

In this paper, we focus on the impacts of local wind generation in an area in Wales, UK under a PPA. We present a mechanism based on Agile ToU to systematically calculate new ToU tariffs for local customers, which shows how customer costs can be reduced, and the load can be gradually shifted to periods when more electricity is produced by low-cost renewables. Our analysis is based on a wind farm with five turbines in a local area in Wales that partially supplies local consumption. The results show a significant reduction in tariffs, demonstrating the effectiveness of the Agile ToU mechanism in promoting the use of local renewable energy and improving the efficiency of the electricity system.

II. Time-of-Use Tariffs

A. Applications, Advanatgaes, and Disadvatages

Time-of-Use (ToU) Tariffs are a pricing mechanism for electricity where the cost varies depending on the time of day, the day of the week, and the season. ToU tariffs can incentivize energy consumers to shift their electricity consumption to periods of lower demand or higher renewable energy availability, which can reduce peak demand and enable the integration of more renewable energy into the grid. In this review, we will explore different types of ToU tariffs, their advantages and disadvantages, and provide examples of their applications in the UK.

There are different types of ToU tariffs, including time-varying, critical peak pricing, and real-time pricing. Time-varying ToU tariffs are the most common and involve setting different prices for electricity during different periods of the day or week. For example, a utility may charge a higher price during peak demand hours in the evening and a lower price during off-peak hours at night [4]. Critical peak pricing involves charging customers a much higher price during specific hours of the year when demand is highest [5]. Real-time pricing involves pricing electricity based on the wholesale market price, which fluctuates in real-time based on supply and demand [6].

One of the main advantages of ToU tariffs is that they can encourage consumers to shift their electricity consumption to times of the day when there is less demand or more renewable energy availability. This can reduce peak demand, which can help to lower the overall cost of electricity and reduce the need for additional power generation capacity. Furthermore, ToU tariffs can incentivize the adoption of energy-efficient technologies such as smart thermostats, which can automatically adjust the temperature of a home based on electricity prices.

However, there are also some disadvantages to ToU tariffs. For example, consumers may not have the ability to shift their electricity consumption to different times of the day, particularly if they work from home or have other constraints on their daily schedules. Additionally, ToU tariffs may be confusing or difficult to understand for some consumers, which could lead to dissatisfaction or distrust in the electricity market.

Table 1 below provides a comparison of different types of ToU tariffs based on their advantages, disadvantages, and applications.

Table 1 shows some of the main and common types of ToU Tariffs. Here are brief definitions for each of these ToU tariffs:

1) Time-varying: A time-varying tariff, also known as a time-of-use (ToU) tariff, is a pricing system that charges different rates for electricity usage based on the time of day [7]. Typically, these tariffs have higher prices during peak demand hours and lower prices during off-peak hours. This type of tariff encourages customers to shift their electricity usage to off-peak hours, thereby reducing strain on the electrical grid during peak demand times.

2) Critical peak: A critical peak tariff is a pricing system that charges customers a higher rate for electricity during certain times of the year when electricity demand is highest [8]. Typically, this type of tariff is used during periods of extreme heat or cold, when the demand for heating and cooling systems is at its highest. Customers who participate in a critical peak program are given advanced notice of when the higher rates will be in effect, and are encouraged to reduce their electricity usage during those times.

3) Real-time: A real-time tariff is a pricing system that charges customers for electricity based on the actual cost of producing and delivering the electricity at the time it is used [9]. This type of tariff can be more volatile than other types of tariffs, as the cost of electricity can fluctuate based on a variety of factors such as weather conditions, fuel prices, and demand. Customers who participate in a real-time program may be incentivized to shift their electricity usage to times when prices are lower, or to install renewable energy systems that can generate their own electricity.

In the UK, ToU tariffs are becoming more common as the country seeks to increase the integration of renewable energy into the grid. For example, in 2020, the UK government launched the Smart Export Guarantee (SEG) program, which requires energy suppliers to offer ToU tariffs to customers who generate their own renewable energy, such as solar PV or wind turbines [10]. Under the SEG program, energy suppliers must offer at least one ToU tariff that pays customers more for exporting electricity during peak demand hours and less for exporting electricity during off-peak hours.

Another example of ToU tariffs in the UK is the Octopus Agile tariff, which is a real-time tariff that reflects the wholesale market price of electricity [11].

B. *Octopus Agile Tariff*

Octopus Agile is a time-of-use (ToU) tariff offered by the UK-based energy supplier Octopus Energy. It is a flexible tariff that is designed to provide customers with more control over their energy consumption and bills [12]. The tariff is calculated based on wholesale energy prices, which changes every half hour. This allows customers to take advantage of periods of low energy prices and avoid using energy during periods of high prices. The Octopus Agile tariff is particularly attractive to customers who have smart meters installed in their homes. Smart meters allow customers to see their energy usage in real-time, which means that they can monitor their usage and adjust it according to the cost of energy [12]. This is particularly useful for customers who want to save money on their energy bills, as they can easily see when energy prices are low and adjust their usage accordingly. In addition to the real-time pricing, the Octopus Agile tariff also has a feature called "Agile Octopus," which provides customers with alerts when energy prices are particularly low. This allows customers to adjust their usage and take advantage of the low prices. One of the advantages of the Octopus Agile tariff is that it incentivizes customers to shift their energy usage away from peak periods, which can help to reduce the strain on the grid during periods of high demand. This is particularly important as the UK transitions to a more renewable energy system, which is more reliant on intermittent sources such as wind and solar. By encouraging customers to shift their energy usage to times when renewable energy sources are generating more energy, the Octopus Agile tariff can help to reduce the need for fossil fuel power plants to provide energy during periods of high demand. Another advantage of the Octopus Agile tariff is that it is a flexible tariff that allows customers to take control of their energy usage and bills [13]. By providing customers with real-time pricing information, the Octopus Agile tariff allows customers to make informed decisions about their energy usage and avoid using energy during periods of high prices. This can help to reduce energy bills and save customers money in the long run. While the Octopus Agile tariff is an innovative and flexible tariff, it may not be suitable for all customers. Customers who are on a fixed income or who are unable to shift their energy usage to off-peak periods may find that the tariff is not cost-effective for them. Additionally, customers

TABLE I: Comparison of Different Time-of-Use Tariffs

Type of ToU Tariff	**Advantages**	**Disadvantages**	**Applications**
Time-varying	Easy to implement and understand, can incentivize consumers to shift demand away from peak hours	May not be effective if consumers cannot shift their electricity consumption, may not incentivize significant reduction in peak demand	Residential and small commercial customers
Critical peak	Can reduce peak demand significantly, can incentivize the adoption of energy-efficient technologies	May not be effective for customers who cannot shift their electricity consumption, may be confusing or difficult to understand for some customers	Large commercial and industrial customers
Real-time	Can reflect the actual cost of electricity and incentivize the adoption of renewable energy, can incentivize the adoption of energy-efficient technologies	Can be difficult for consumers to understand and manage, may not be effective for customers who cannot shift their electricity consumption	Large commercial and industrial customers

TABLE II: ToU based on Octopus Agile for load pricing.

Energy	Price per kWh
Midnight - 4pm	8.4p
4pm - 7pm	25.3p
7pm - 9pm	10.4p
9pm - midnight	8.4p

who are not comfortable with real-time pricing or who do not have a smart meter installed may find that the Octopus Agile tariff is too complex or confusing.

III. Proposed Model and Case Study

In our proposed model, the objective is to increase the proportion of renewable energy sources, particularly wind, in meeting power demands while simultaneously reducing costs for consumers.

Figure 1 shows the wholesale market price (p/kWh) in blue, the average wind profile in the region under study in green, and the Agile ToU tariff in red. The wholesale market price (£/MWh) is taken from EPEX Spot ([14]). The values are divided by 10 to convert to p/kWh. This is for the first day in March 2021. Due to a lack of yearly data, the Agile ToU tariff was utilized as the basis for developing the new ToU tariff. Wind and price data were sampled every 30 minutes, and the X-axis ranges from 1 to 48, corresponding to 00:30 to midnight.

Wind data was obtained by simulating wind generation from 5 wind turbines with a capacity of 2.5MW installed in south of Wales in the UK, using the platform Renewables.ninja [15]. Renewables Ninja is a web-based application that provides access to global weather and climate data, allowing users to estimate the hourly potential of solar and wind resources in specific locations. According to the average profile depicted in Figure 1, the average daily wind generation is estimated to be 4.72 MW.

Table II introduces the ToU Tariffs based on Octopus Agile for load pricing [16]. During the time frame between 10 am (the 20th time-step in Figure 1) to 4 pm (the 32nd time-step in Figure 1), the wind generation exceeds the average generation level. As a result, an additional time zone/interval is inserted in Table II, to produce a new table presented as Table III.

TABLE III: Adjusting the time periods throughout the day to incorporate peak wind times.

New ToU Time Periods	Price per kWh based on Agile
Midnight - 6am	8.4p
6am - 4pm	8.4p
4pm - 7pm	25.3p
7pm - 9pm	10.4p
9pm - midnight	8.4p

Time of Use Tariffs are typically developed to incentivize shifting of demand from peak times and, hence, reduce system costs. In the case of high penetration of renewable energy sources like wind, the market clearing price during the intervals of renewable power injection into the grid is expected to decrease. Our focus, however, is on evaluating the impact of local wind generation in the area under Power Purchase Agreement. As such, we assume that the wholesale market price will remain unchanged.

To represent ToU tariffs for local consumers whose corporate/aggregator enters into contracts with local renewables such as wind generators, two tariffs are utilized:

The ToU Electricity tariff (based on Octopus Agile Tariff) is applied only to grid supply (refer to Table III). The cost of wind power is incorporated as fixed tariffs for consumers at a rate of 35 £/MWh or 3.5p/kWh.

Based on the Agile price algorithm, the ToU is simply obtained by (1):

$$\text{ToU} = \min(2.20W + P, 33.33) \tag{1}$$

Where W is the wholesale cost of electricity for that period in pence per kilowatt-hour (p/kWh) and P is he peak-time premium which is zero except for the time period between 4pm and 7pm where it has a fixed value of 12.00. The coefficient 2.20 accounts for distribution costs, which vary depending on the geographical location within the UK.

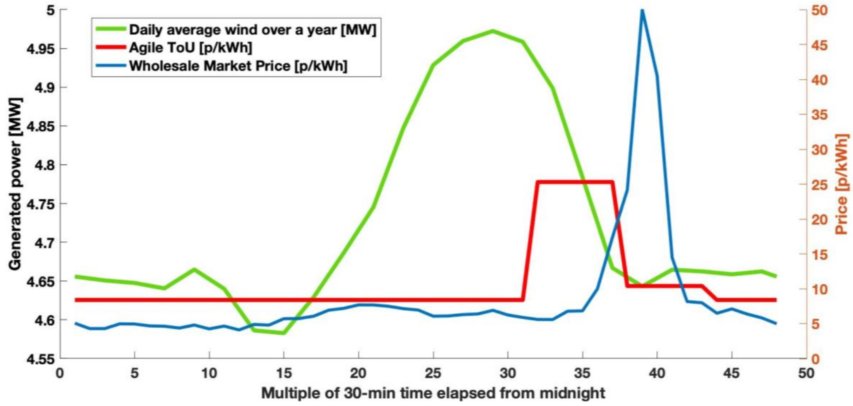

Fig. 1: Wind and price profiles.

Several parameters contribute to the definition of P, including transmission costs ($TNUoS$). As we aim to reduce the reliance of local loads on the national grid supply and leverage a local wind farm, $TNUoS$ is an important factor for our case. The cost of $TNUoS$ varies by region and only applies during peak periods (4-7pm), ranging from 2p/kWh to 7p/kWh. It is typically more expensive in the South due to the North-to-South transmission direction, with higher energy generation in the North and demand in the South of the UK. To simplify the model and demonstrate the procedure to introduce a new ToU, we use the average value of $TNUoS$, which is rounded up to 5p/kWh.

The value 33.33 is chosen to ensure the price is capped at 35p/kWh once VAT is added - this is a 2021 scenario.

As previously noted in this section, the cost of wind generation is assumed to be 3.5 p/kWh. However, to account for distribution costs using the Agile price algorithm formulated in (1), the product of the 2.20 coefficient and the 3.5 p/kWh wind cost is used. In this case, the peak-time premium (P) is applicable but the transmission network use of system charge (TNUoS) is not considered as the wind generation is from a local wind farm, and does not affect it. Hence, the Tariff for the portion of the load that is exclusively supplied by the local wind and procured through a PPA contract is set at a constant rate of 7.7 p/kWh over off-peak periods ($TPwind$).

The flowchart in Figure 2 presents a generalized procedure for modeling a new Time of Use (ToU) tariff that incorporates local wind generation under Power Purchase Agreement (PPA). This approach is not limited to a specific case and can be applied to similar scenarios with varying prices and parameters.

The inputs required for this model include the Agile ToU tariff or a similar ToU tariff with defined time intervals over 24 hours and fixed tariff for each period, the price for wind supply ($TPwind$), average load for each interval ($Dmean$) in MW, and the average wind generation for each interval ($TPwind$) in MW.

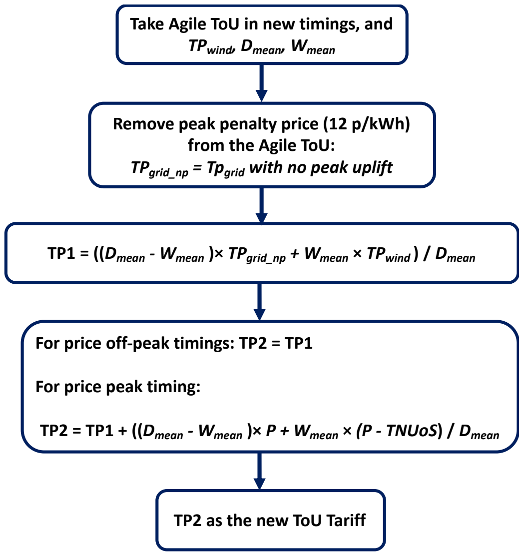

Fig. 2: Proposed price algorithm considering the local wind.

Firstly, the peak penalty price should be removed from the Agile ToU to obtain the price to be paid to the grid main supplier without wind and uplift of peak penalty ($TPgrid-np$). An initial ToU price ($TP1$) representing the new off-peak price can be then calculated using the equation (2). Then, the ToU pricing model for the peak period is determined using equation (3). This equation takes into account the peak-time premium (P), while excluding the transmission network use of system charge (TNUoS), as the wind farm is located in a local area.

$$TP_1 = \frac{(D_{\text{mean}} - W_{\text{mean}}) \times TP_{\text{grid}-np} + W_{\text{mean}} \times TP_{\text{wind}}}{D_{\text{mean}}} \quad (2)$$

TABLE IV: ToU Tariffs considering the local wind generation and transmission costs.

Timings	Agile ToU	D_{mean}	W_{mean}	TP_{wind}	TP_{grid_np}	TP1	**TP2 (Final ToU)**
Midnight - 6am	8.40	10.84	4.65	7.70	8.40	8.10	**8.10**
6am - 4pm	8.40	10.84	4.84	7.70	8.40	8.05	**8.05**
4pm - 7pm	25.30	10.84	4.81	7.70	13.30	10.82	**20.60**
7pm - 9pm	10.40	10.84	4.65	7.70	10.40	9.24	**9.24**
9pm - midnight	8.40	10.84	4.66	7.70	8.40	8.10	**8.10**

$$TP_2 = TP_1 + \frac{(D_{\text{mean}} - W_{\text{mean}}) \times P + W_{\text{mean}} \times (P - TNUoS)}{D_{\text{mean}}} \tag{3}$$

The variables used in the equations are defined as follows: TP represents the Time of Use Price (i.e., the new tariff); $TPwind$ is the price to be paid solely for wind supply (i.e., 7.7 p/kWh in the case study); $TPgrid$ is the price to be paid for grid supply (i.e., wind deducted) that is obtained from Agile ToU; $TPgrid - np$ is the price to be paid for grid supply (with wind and peak penalty prices deducted); $Wmean$ denotes the average wind generation in each timing [MW]; $Dmean$ represents the average load in each timing (the total annual consumption in the study area is 95 GWh, hence $Dmean$ is calculated as 95000/(365*24), which equals 10.84 MW); P denotes the peak-time premium price of 12 p/kWh; and $TNUoS$ represents the transmission network use of system charge (5 p/kWh in the case study).

Table IV provides a summary of the calculations and presents the final results of the Time of Use price ($TP2$) for the case study.

IV. Conclusion

This paper proposes a mechanism for calculating new Time of Use (ToU) tariffs for local customers based on Agile ToU, which considers the integration of local energy resources such as a wind farm. The new ToU, which incorporates the cost of a local wind by Power Purchase Agreement (PPA), is demonstrated to be lower compared to the original ToU. Specifically, at peak time, the new ToU is reduced from 25.30 p/kWh to 20.60 p/kWh. The results of the case study show that wind energy can reduce electricity costs for consumers and encourage load shifting to times of high renewable energy production. Future research could explore the incorporation of different load values for varying time periods of the day. Additionally, the accuracy of the model could be improved by incorporating the exact projections of wind generation for the day on which the wholesale market prices are given. It is worth noting that the impact of local renewable generation on ToU is distinct from that of integrating renewables into the transmission grid, such as offshore wind farms. Therefore, further investigations into the impact of local renewable generation on ToU are necessary and should be modeled in future studies. Overall, the proposed mechanism offers an effective approach to encouraging demand shifting during peak periods and integrating local energy generation into ToU tariffs.

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