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Review

Technical, Economic, Social and Regulatory Feasibility Evaluation of Dynamic Distribution Tariff Designs

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Abstract: The increasing number of distributed energy resources in the distribution grids creates the risk of grid congestion and the high cost of grid expansion. The implementation of the dynamic distribution grid tariffs can potentially avoid grid congestion. Meanwhile, the design and implementation of any distribution tariff need to consider and match the regional/national requirements. However, there is no sufficient evaluation method available to review and evaluate the feasibility of the dynamic distribution tariffs. Therefore, this paper introduces a feasibility evaluation method with four dimensions of technical, economic, social, and regulatory to review dynamic distribution tariffs. The literature on dynamic distribution tariffs is collected, and 29 dynamic distribution tariffs are selected and further categorized into five attributes of rationale, cost drivers, dynamics, events, and active demand. The evaluation results show that the time-of-use tariff is the most feasible dynamic distribution tariff, and the review of a proposed future distribution tariff model in Denmark verifies the evaluation method and results. The developed feasibility evaluation method for dynamic distribution tariffs can ensure the design and implementation of a dynamic distribution tariff to be feasible and applicable in a region.

Keywords: scoping review; dynamic distribution tariff; feasibility evaluation; technology readiness; participation cost; user convenience level; regulatory readiness

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1. Introduction

Due to the increasing number of Distributed Energy Resources (DERs) in the distribution grids, e.g., Electric Vehicles (EVs), batteries, heat pumps, PhotoVoltaic (PV), and the introduction of other smart technologies, the patterns of energy demand have been changing in the distribution network, both in Europe and worldwide [1]. From the demand side, these changes provide opportunities and benefits, such as using electricity when the price is low or financial gains by producing electricity [2]. However, from the distribution grid perspective, these changes create the risks of grid congestion and the high cost of grid expansion [3]. The DSO has to develop new tools for monitoring and controlling a more active distribution network with the use of sensors, such as smart meters. The tools should be based on real-time algorithms, online optimization solutions, forecasting systems, etc. [3]. One potential solution to avoid grid congestion is to implement dynamic distribution grid tariffs.

Dynamic Distribution Tariffs (DDTs) aim to motivate consumers to reduce or shift their flexible energy consumption and create incentives for consumers to participate in Demand Response (DR) programs [4]. Energy flexibility on the demand side refers to the possibility of increasing or reducing the energy consumption of a demanding process [5,6]. DR is defined by the European Commission as the intentional modification of normal consumption patterns by end-users in response to incentives from grid operators [7]. DR programs are expected to reduce the use of peak load generation and electricity cost, and improve system reliability [8]. DR programs aim to incentivize changes in the electricity consumption patterns in response to the varying electricity prices [9].

However, the design and implementation of DDTs have to comply with the national/regional regulations. Distribution grid tariffs are the main revenue stream for Distribution System Operator (DSOs) and are determined by a revenue frame regulation. The revenue via the DSO tariff is regulated to make sure reasonable tariffs to consumers. For instance, in Denmark, according to §73 in the Danish law of electricity supply [10], the determination of the electricity suppliers' service prices should be equitable, objective, and non-discriminative. According to §69 in the Danish law of electricity supply [10], the revenue from grid services for grid companies is determined by the supply authority once a year. Price differentiation for more efficient utilization of the electricity grid and security of supply is allowed. However, price differentiation based on geographical delimitation is only allowed in specific cases.

Although several DDTs, e.g., Real-Time Pricing (RTP), Time-of-Use (ToU), Critical Peak Pricing (CPP), etc., have been introduced and discussed in the literature, there is no systemic review of different DDTs. Meanwhile, the implementation potentials of any DDT need to consider and match the regional/national requirements. The regional/national requirements not only include the technological aspect, but also economic, and regulatory aspects [11–13]. However, such feasibility evaluation for DDTs is missing in the literature.

To fill this gap, this paper develops a feasibility evaluation method to evaluate DDT designs. The feasibility evaluation method includes four aspects: technical, economic, social, and regulatory feasibility. To introduce and demonstrate the developed feasibility evaluation method, this paper conducting a scoping review in the IEEE Xplore database. A total of 29 references were selected and further categorized into five attributes of rationale, cost drivers, dynamics, events, and active demand.

This paper firstly introduces the scoping review approach and the feasibility evaluation method in the Methodology section. Afterward, the DDTs found in the literature are analyzed and categorized into 16 combined attributes, and introduced in the Section of Analysis and evaluation of dynamic distribution tariffs. Furthermore, the evaluation results with the technical, economic, and regulatory aspects are also presented in the same section. In the Discussion section, a DDT potentially implemented in Denmark is discussed that demonstrates that the feasibility evaluation can ensure the selected DDTs to be potentially implemented in the region.

2. Methodology

2.1. Literature Search

To investigate various types of DDTs in the literature, this paper conducts a scoping review search. Compared to other review methods, such as narrative or traditional literature reviews that usually focus on a specific type of dynamic tariffs or specific purposes, the scoping review approach investigates all available literature under a designed scope with thorough literature analysis. Therefore, the scoping review approach not only can provide an overview of the related literature but also comprehensive search results and analysis of available dynamic tariffs in the literature.

Several databases, e.g., ACM digital library, IEEE Xplore, Web of Science, ScienceDirect have been considered, and the literature search is only conducted in the IEEE Xplore database because the publication in this database is more multi-disciplinary oriented, and the main purpose of the paper is to introduce the feasibility evaluation method and evaluate DDTs with five aspects.

The following search string is designed and initially searched in the IEEE Xplore database: *(Dynamic OR Variable OR (Day-ahead OR Day ahead) OR Changing) AND (Tariff OR Pricing OR Cost).*

The search string above resulted in many but not relevant results. Therefore, the search string is modified to be "(((“Document Title”:Dynamic) OR (“Document Title”:Variable)) AND ((“Document Title”:Tariff)))", and this results in 50 articles. After the duplication check and relevance check, 29 relevant articles with full text are selected for further categorization analysis (shown in Table 1).

Table 1. Literature on dynamic distribution tariffs.

Title	Reference	DDT Type	Paper Scope
Electric Vehicle (EV) Charging Management with Dynamic Distribution System Tariff	[14]	RTP	Proposes a smart charging algorithm with the dual objectives of minimizing charging costs and preventing grid congestion. EVs are charged according to individual user requirements while respecting the constraints of the local distribution grid. A day-ahead DDT scheme is proposed to avoid congestion on the local distribution system from the day-ahead planning perspective.
The Impact of Dynamic Electricity Tariff on Long-Run Incremental Cost	[15]	RTP	Investigates the effect of DDT and flexible demand on Long run incremental cost and network investment decisions are deeply analyzed and discussed.
Dynamic Tariff Method for Congestion Management in Distribution Networks	[16]	RTP	This paper puts forward a congestion management way for distribution networks considering electric vehicles and heat pumps.
Grid Expansion Costs Considering Different Price Control Strategies of Power-to-X Options Based on Dynamic Tariffs at the Low-Voltage Level	[17]	RTP	This paper examines grid extensions caused by different control strategies of Power-to-X options. The focus is on a price-controlled control strategy that dynamizes fees and levies to improve the integration of high PV feed-in.
Dynamic Tariff-Subsidy Method for PV and V2G Congestion Management in Distribution Networks	[18]	RTP	This paper proposes a dynamic tariff-subsidy method for congestion management in distribution networks with high penetration of PV, heat pumps, and EVs with vehicle-to-grid function.
Optimal Reconfiguration-Based Dynamic Tariff for Congestion Management and Line Loss Reduction in Distribution Networks	[19]	RTP	This paper presents an optimal reconfiguration-based DDT method for congestion management and line loss reduction in distribution networks with high penetration of electric vehicles.
Uncertainty Management of Dynamic Tariff Method for Congestion Management in Distribution Networks	[20]	RTP	This paper demonstrates the efficacy of the uncertainty management of the dynamic tariff method. Uncertainty management is required for the decentralized dynamic tariff method because the dynamic tariff is determined based on optimal day-ahead energy planning with forecasted parameters such as day-ahead energy prices and energy needs which might be different from the parameters used by aggregators
Long Term Incentives for Residential Customers Using Dynamic Tariff	[21]	RTP	This paper reviews several DDT schemes, including flat tariff, time-of-use, time-varying tariff, demand charge, and dynamic tariff, from the perspective of the long-term incentives.
Dynamic Power Tariff for Congestion Management in Distribution Networks	[22]	RTP	This paper proposes a dynamic power tariff, a new concept for congestion management in distribution networks with high penetration of electric vehicles, and heat pumps.
Distributed Optimization-Based Dynamic Tariff for Congestion Management in Distribution Networks	[23]	RTP	This paper proposes an optimization-based DDT method for congestion management in distribution networks with high penetration of electric vehicles and heat pumps.
Efficient Prediction of Dynamic Tariff in Smart Grid Using CGP Evolved Artificial Neural Networks	[24]	RTP	A smart electricity price forecasting mechanism is proposed which when incorporated in the smart grid can be quite beneficial in informing the user of the electricity price during the next hour. Two models have been evolved using the Neuro Evolutionary Cartesian Genetic Programming Evolved Artificial Neural Network algorithm to estimate the electricity prices for the next hour
Demand Response Program for Shiftable Modes in Variable Tariff Zones of an Utility	[25]	RTP	This investigation presents a logical shifting algorithm for shiftable modes of operations of schedulable loads of users. In this approach, we have considered a washing machine and dishwasher of residential shiftable loads due to its multiple modes of operation. A day-ahead zonal forecasting pricing data of New York City is taken from the website for the proposed algorithm illustration.

Table 1. *Cont.*

Title	Reference	DDT Type	Paper Scope
Building Control and Storage Management with Dynamic Tariffs for Shaping Demand Response	[26]	RTP	The results from a proof-of-concept study combining modern building automation systems (BAS) with DDTs are presented. The use of a building automation system that optimizes the electricity demand of a retail end-consumer while managing a local battery unit and respecting all comfort constraints, e.g., on room temperature, illuminance, and indoor air quality, is proposed.
An Infrastructure of Dynamic Tariff Management and Demand Response applied to Smart Grids using Renewable Energy Resources and Energy Storage Systems	[27]	RTP	This paper presents a proposal for a management infrastructure for DDTs and DR to support the consumer in an environment of smart grids, in the presence of renewable energy sources and energy storage systems.
Real Time Emulation of Dynamic Tariff for Congestion Management in Distribution Networks	[28]	RTP	This paper presents the real-time evaluation of the dynamic tariff method for alleviating congestion in a distribution network with high penetration of DERs. The dynamic tariff method is implemented in a real-time digital testing platform that emulates a real distribution network.
Dynamic Electricity Tariff Definition Based on Market Price, Consumption and Renewable Generation Patterns	[29]	RTP	In this paper, a method for determining the tariff structures has been proposed, optimized for different load regimes. Daily DDT structures were defined and proposed, on an hourly basis, 24 h day-ahead from the characterization of the typical load profile, the value of the electricity market price, and considering the renewable energy production.
Sensitivity Analysis of Dynamic Tariff Method for Congestion Management in Distribution Networks	[30]	RTP	The dynamic tariff method is designed for the DSO to alleviate the congestions that might occur in a distribution network with high penetration of DERs. This paper conducts three case studies to demonstrate the impact of small and big changes of parameters on the line loading profiles and the effectiveness of the dynamic tariff method.
Comprehensive Congestion Management for Distribution Networks Based on Dynamic Tariff, Reconfiguration, and Re-Profiling Product	[31]	RTP	This paper proposes a comprehensive scheme for day-ahead congestion management of distribution networks with high penetration of DERs. In the proposed scheme, the DDT, network reconfiguration, and re-profiling products are integrated, which combines the advantages of these methods.
Towards Variable End-Consumer Electricity Tariffs Reflecting Marginal Costs: A Benchmark Tariff	[32]	RTP	This paper proposes a tariff scheme as a benchmark for studying the DR of end-consumer. The tariff concept is applied to the situation in the city of Zurich, Switzerland, using time series of the Swiss EEX power market spot prices and Zurich's yearly electricity load profile.
Time-Optimized Dynamic Two-Step Tariffs for CHP Operation	[33]	ToU	This work proposes and improves a simplified dynamic two-step tariff for end-consumers based on the course of the EEX day-ahead electricity market.
Dynamic Tariff Design for a Robust Smart Grid Concept: An Analysis of Global vs. Local Incentives	[34]	ToU	Encouraged by the importance of finding a cost-efficient and robust approach for flexible appliances, a proposed structure for a simplified dynamic tariff is analyzed in this study. The tariff is designed to enable selective shifting of load and decentralized generation.
The Use of Dynamic Tariff by The Utilities to Counter act The Influence of Renewable Energy Sources	[35]	ToU	In this research, a new DDT strategy was developed which will make electricity prices from the utility to be cheaper during the times when there are solar resources.
Modeling the Effects of Variable Tariffs on Domestic Electric Load Profiles by Use of Occupant Behavior Submodels	[36]	ToU	This paper presents a stochastic bottom-up model designed to predict the change in domestic electricity profile invoked by consumer reaction to electricity unit price, with submodels comprising user behavior, price response, and dependency between behavior and electric demand.
Effective Dynamic Tariffs for Price-Based Demand Side Management with Grid-Connected PV Systems	[37]	ToU	In this work, a new tool for the optimization of DDTs is developed. This is based on a statistical analysis of the consumption profiles and optimization procedures, aiming to derive the most appropriate ToU tariffs.
Dynamic Network Tariffs: Are They the Most Efficient Way to Match Peak Consumption and Network Incremental Costs?	[38]	CPP	The purpose of this paper is to present the main results of the ongoing analysis of applying dynamic network access tariffs in Portugal.

Table 1. *Cont.*

Title	Reference	DDT Type	Paper Scope
Design of Grid Tariffs in Electricity Systems with Variable Renewable Energy and Power to Heat	[39]	CPP	This paper compares two different grid tariff designs that facilitate more flexible energy demand of district heating operators.
Implementation of dynamic Tariffs in the Portuguese Eelectricity System—Preliminary Results of a Cost-Benefit Analysis	[40]	RTP, CPP, CPR	This paper reports the results obtained regarding the cost-benefit analysis. This analysis includes the identification of critical hours during which dynamic tariffs can be activated
Demand based Variable Electricity Tariff Meter	[41]	Consumption based ToU	Introduces demand-based variable electricity tariff meter with circuitry designed to tackle the problem of people consuming electricity for only essential purposes pays the same as people having luxurious consumption.
Variable Tariff Energy Meter with Automatic Power Flow Control	[42]	Consumption based RTP	This paper discusses a model and makes recommendations that would be useful in the current Indian scenario.

2.2. Categorization of DDTs in Literature

According to [4], six attributes can define the tariff schemes and a designed dynamic tariff is recommended to consider these six attributes. Each attribute contains several sections that a dynamic tariff design can consider selecting (shown in Table 2). For example, in a dynamic tariff design, the energy price can vary either by 'time of use' and/or by the 'current load at the household level'. This 'time of use' and 'load level' belong to the attribute of 'Rationale'.

Table 2. Six attributes of dynamic tariffs (modified from [4]).

Attribute	Explanation	Possible Sections in Each Attribute
Rationale	The price varies either by the time of use and/or by the current load at the household level.	• Time of use • Load level
Cost components	Reflect the value chain of energy, i.e., generation, transmission, distribution, and retail.	• Generation • Transmission and Distributions • Retail • Other charges
Cost drivers	The factors driving the costs. The independence of power and energy can be, e.g., metering cost driven by the number of customers connected	• Power (EUR/kW) • Energy (EUR/kWh) • Independent of power and energy (EUR)
Dynamics	Can be the number of time blocks in a day in the rate varies; Can be expressed as the price update frequency and the price spread, i.e., price differentials between blocks	• Number of time blocks • Price update frequency • Price spread
Events	Defined by their duration, occurrence (e.g., 10 times a year), and price spread. Be implemented to incentivize consumers to consume in events having lower prices or avoid events with high prices (e.g., in peak periods).	• Duration • Occurrence • Price spread
Active Demand	Consumers imposing dynamic tariffs may respond to price signals in a manual or automated way	• Manual • Automated

The attribute of cost components reflects the value chain of energy, i.e., generation, transmission, distribution, and retail. Since only distribution tariffs are considered in this paper, this attribute is neglected. According to the five attributes, the 29 relevant articles are analyzed and categorized.

2.3. Literature Evaluation

The literature evaluation aims to investigate the feasibilities of DDTs that can be implemented in an energy ecosystem. The feasibility evaluation is conducted with four dimensions: technical, economic, social, and regulatory.

2.3.1. Technical Feasibility Evaluation

The Technology Readiness Level (TRL) (described in Table A1 in Appendix A) [43] is used for the technical feasibility evaluation in this paper. TRL is originally designed by NASA for space exploration technologies, and TRLs measure the maturity level of a technology during its acquisition phase [44]. The TRL includes 9 levels, and the DDTs in the literature will be evaluated according to the description for each TRL level.

2.3.2. Economic Feasibility Evaluation

The majority of the literature regarding the economic feasibility evaluation focuses on the cost-benefit analysis of technologies or solutions, e.g., [45]. there is little literature for evaluating tariffs. According to the Cambridge dictionary, economic feasibility is 'the degree to which the economic advantages of something to be made, done, or achieved are greater than the economic costs'. Therefore, the cost can be the threshold for the economic feasibility of a DDT.

The economic feasibility evaluation in this paper is the monetary cost. This monetary cost is due to the acquisition of necessary devices or equipment for participation in a DDT program. The monetary participation cost scale has three level 1–3 is rated from low to high cost, that:

1. Low economic feasibility due to high cost to acquire new automatic solutions participation in the DDT program.
2. Medium cost for acquiring a device for participation in the DDT program, which typically for the continuous frequency measurement.
3. High economic feasibility due to little cost for participation in the DDT program requires no device or equipment.

2.3.3. Social Feasibility Evaluation

Distribution tariffs are part of the final electricity price that electricity consumers receive and DDTs aim to create incentives and motivate consumers to reduce or shift their energy consumption. Therefore, it is necessary to consider consumers' adoption of the DDT design. Various factors could influence consumers' adoption, and convenience is the most essential factor.

Therefore, this paper uses a user convenience level to evaluate the electricity consumers' response to the DDT price signals. There are three levels of user convenience:

1. Low convenience due to fully manual response with complex price signals (e.g., hourly prices)
2. Medium convenience due to fully manual response with easily understandable price signals (e.g., 2 price periods a day)
3. High convenience due to fully automatic response.

2.3.4. Regulatory Feasibility Evaluation

The regulatory feasibility in this paper is to evaluate whether the existing regulations allow the implementation of the State-of-the-Art solutions (DDTs in this paper), and if not, how likely the regulations will be realized in the future (regulatory readiness level). The

Danish law of electricity supply [10] is applied in the paper with four levels of regulatory readiness:

0 The required regulation is impossible to happen
1 The required regulation might happen in the long term
2 The required regulation will happen in the medium term
3 The required regulation can happen in the short term

3. Analysis and Evaluation of Dynamic Distribution Tariffs

The electricity tariffs are usually part of the electricity bills to consumers and cover the total cost for producing and supplying electricity [46]. The tariffs for supplying electricity are also called grid tariffs, and there are usually two types of grid tariffs: transmission tariffs for paying the Transmission System Operator and distribution tariffs for paying the local DSOs.

The DDTs discussed in the 29 selected articles can be categorized into: RTP, ToU, CPP, and Consumption-based tariffs. RTP is the most popularly discussed DDT in the literature (19 out of 29 references), and two consumption-based tariffs (consumption-based RTP and consumption-based ToU) are discussed separately in two articles. Furthermore, 29 selected articles are analyzed in detail based on six attributes of dynamic tariffs proposed by [4], and 16 combinations are identified based on the similarities and differences of DDTs' attributes in the literature (shown in Table 3).

3.1. Four Categories of Dynamic Distribution Tariffs

3.1.1. Real Time Pricing

RTP (also called dynamic rate) aims to adapt consumption to external variables, such as spot prices, grid overload, and DERs, etc. The characteristics of RTP in the literature are shown in Table 4. The prices for RTP in the literature all vary by time of use. In general, the cost driver for RTP is energy [4], but two cost drivers (energy and power) are found in the literature, and energy is the most common cost driver, and power is discussed only in [22]. The price spread is not specific in RTP DDT as it often depends on grid conditions. ToU DDTs' price spread is often specific defined as a price ratio between the different price periods typically between 2–4. Energy-based tariff is the most known price unit per consumed energy (DKK/kWh), whereas power is dependent on the size of the load as it is the price unit per power level per consumed energy (DKK/kW/kWh). For instance, charging an EV with 11 kW for a short period would be more costly than charging with 3.7 kW in a longer period, even though the energy consumed is the same.

This paper finds that two types of price update frequencies (day-ahead forecast and the next hour forecast) have different objectives, and the day-ahead forecast is the most common in the literature. The main objective of the day-ahead forecast is to avoid grid congestions caused mainly by EV charging [14,16–23,28,30,31]. Different optimization methods and power flow calculations are discussed in the literature for congestion management. DR is an important objective discussed in the literature. For instance, for the demand side, peak loading reduction by automatically move load from appliances such as washing machine and dishwasher to low-cost time slots is discussed in [25], and a dynamic benchmark tariff design for assessing and evaluating the DR potential of price-responsive loads on the end-consumer side is proposed in [26,32]. The tariff is based on time-series of Swiss spot market prices (Swissix) as traded on the European Energy Exchange (EEX).

Table 3. Dynamic Distribution Tariffs in literature.

No.	DDT Type	Rationale	Cost Driver	Dynamics		Events		Price Spread	Active Demand	Objective	Reference
				Nr. of Time Blocks	Price Update Freq.	Duration	Occurrence				
1	RTP	Time of use	Energy	24/day (hourly)	1/day (Day-ahead forecast)			Considerable (dependent on the external variables) Often calculated by power flow calculations using different optimization methods.	Automatic	The objective is to avoid grid congestion—Congestion management.	[14,16–21,23,28,30]
										long-run incremental cost pricing in network charges under dynamic tariffs. The dynamic tariff is not in focus.	[15]
										used here as a dynamic benchmark tariff for assessing and evaluating the DR potential of price-responsive loads on the end-consumer side. It is based on time-series of Swiss spot market prices (Swissix) as traded on the European Energy Exchange (EEX)	[26,32]
										Calculated based on load profile, the value of electricity market price, and renewable energy production. Objective to promoting generation and consumption efficiency, while improving players' benefits.	[29]
2	RTP	Time of use	Power	24/day (hourly)	1/day (Day-ahead forecast)			Considerable (dependent on the external variables) Often calculated by power flow calculations using optimization methods.	Automatic	The objective is to avoid grid congestion—Congestion management.	[22]
3	RTP	Time of use	Energy	24/day (hourly)	24/day (forecasts the next hour)			Considerable (dependent on the external variables) Calculated by Artificial Neural Network	Not specified	Demand side management in smart grid environment informing the user of the electricity charge for the next hour	[24]
4	RTP	Time of use	Energy	24/day (hourly)	1/day (Day-ahead forecast)			Considerable (dependent on the external variables) Day-ahead market Locational based marginal pricing (LBMP) in New York city	Manual and/or automation (washing machines and dishwasher are shifted and could in theory be automated. It is not mentioned if it is automatic or manual)	shifting the high-cost time slot of appliance mode to a possible low-cost time slot in the tariff zone.	[25]

Table 3. *Cont.*

No.	DDT Type	Rationale	Cost Driver	Dynamics		Events		Price Spread	Active Demand	Objective	Reference
				Nr. of Time Blocks	Price Update Freq.	Duration	Occurrence				
5	RTP	Time of use	Energy	24/day (hourly)	1/day (Day-ahead forecast)			Considerable (dependent on the external variables)	Not specified	Through a dynamic tariff and DR management infrastructure, utilities will be able to deliver valuable consumer-focused information.	[27]
6	ToU	Time of Use	Energy	2 /day	Not specified (assumed to be 1/year)			Price ratio of high to low is 2.55	Manual	Shifting electricity demand for analyzing demand side management potential.	[36]
7	ToU	Time of use	Energy	2/day (higher prices in peak period)	1/year			Total cost is in theory the same as flat rate.	Manual	Named demand charge with the objective to shift electricity demand	[21]
8	ToU	Time of use	Energy	2/day	Not specified			Not specified	Not specified	Incentivize load shifting.	[33,34]
9	ToU	Time of use	Energy	2/day	2/year (winter/summer season)			Not specified	Not specified	17 h winter, 3.5 h high tariffs in summer.	[33]
10	ToU	Time of use	Energy	2/day	12/year (monthly based)			Not specified	Not specified	See reference for number of high tariff prices in each month.	[33]
11	ToU	Time of use	Energy	3/day	2/year (high demand period June-August and low demand period September-May)			Ratio of about 4.6 between the high and low price in high demand season and 2.3 in low demand season.	Manual	Incentivize consumers to consume electricity in periods with high electricity production from PVs.	[35]
12	ToU	Time of use	Energy	Optimization of blocks and time of blocks based on PV production and consumption as input	Not specified			A ratio of about 2 between highest and lowest price.	Manual	Develop optimal demand-side management using ToU dynamic tariffs (includes PV production)	[37]
13	CPP	Time of use	Energy			Last up to 8 h	Consumers are warned 1–2 days prior to the event.	Not specified	Manual	A pilot project testing dynamic tariffs on the network component.	[38]
14	CPP	Time of use	Energy			Reflect the local grid capacity constraints	When the load on the local grid is critical. Not specified further.	Not specified	Not specified	Improve business case for power to heat technologies and to induce more renewable energy in the system	[39]

Table 3. *Cont.*

No.	DDT Type	Rationale	Cost Driver	Dynamics		Events		Price Spread	Active Demand	Objective	Reference
				Nr. of Time Blocks	Price Update Freq.	Duration	Occurrence				
15	Consumption based ToU	Time of use and load level	Energy	5/day and 1 threshold load level of more than 5 units of power consumption (5 units is estimated to cover the essential devices, hence only luxury devices penalized)	Not specified			The ratio of 1.6 between lowest and highest base rates. Crossing the threshold increases the price by either 40, 50, 60, or 70%.	Not specified	Tackle the problem that consumers with only essential consumption purposes pay the same as consumers with luxury consumption.	[41]
16	Consumption based RTP	Time of use and load level	Energy	Not specified	Not specified			The suggested tariff structure allows a defined limit. Consuming more than the limit will increase the price by a ratio of 5.	Not specified	Cost = (50/f)∗Tariff∗ Energy. Where 50 is the frequency level in India (case) and f is the current frequency. Motivating consumers to consume more if the frequency is higher (hence, lower prices) and vice versa.	[42]

Table 4. The characteristics of RTP in the literature.

DDT Type	RTP
Rationale	**Time of Use**
Cost driver	• Energy (is the most known when you pay per kWh) • Power (is dependent on the size of the load as it is paid by the kW/kWh)
No. of time blocks	24/day (hourly)
Price update freq.	• Day-ahead forecast • 24/day (forecasts the next hour)
Price spread	• Considerable (dependent on the external variables) • Calculated by power flow calculations using different optimization methods. • Day-ahead market Locational based marginal pricing (LBMP) in New York city • Calculated by artificial neural network (forecasts the next hour)
Active demand	• Automatic • Manual and/or automation (e.g., washing machines and dishwasher are time-shifted)

Meanwhile, the day-ahead forecast with the grid perspective is also discussed in the literature. In [27], dynamic tariff and DR management infrastructure are used by utilities to deliver valuable consumer-focused information, and an economically efficient approach for pricing network charges is discussed in [15] to identify the impacts of demand flexibility on the long-run incremental cost method. Furthermore, in [29], DDT is used to promote generation and consumption efficiency while improving players' benefits. The tariff is calculated based on load profile, the value of electricity market price, and renewable energy production.

Different from other literature, ref. [24] discusses the hourly forecasting, and proposes a CGP (Cartesian Genetic Programming) evolved artificial neural network algorithm to estimate the electricity prices for the next hour, and the algorithm is used for demand side management.

3.1.2. Time-of-Use Pricing

ToU pricing is to change end-users' routine behaviors. The main objective of using ToU pricing to provide incentives to local consumers and producers for load shifting. Reference [33] uses different ToU schemes to identify the best scheme considering the tariff complexity against flexibility potential and financial gains for the end-user. Reference [36] analyzes the demand-side management potential using ToU tariffs. Reference [21] incentivizes the end-users to shift demand using only economic benefits for the user. This is done by designing the scheme in a way that the users who do not change their consumption behavior will have the same costs as if they had a flat rate. In [35], ToU scheme is designed to shift consumption to periods with high electricity production from PVs. The objective of [37] is to enable high penetration of renewable energy sources by use of ToU tariffs. Reference [37] develops a tool for optimizing the ToU DDT identifying optimal periods and tariff rates.

The characteristics of ToU in the literature are shown in Table 5. Two times per day is the most common time block used in [21,33,34,36], and the price update frequencies are different, e.g., 1 time per year in [21], 2 times per year (winter/summer season) in [33], and monthly based in [33]. In [35], there are three time blocks in the ToU pricing and the price updates twice per year with the high demand period of June to August and the low demand period of September to May.

Table 5. The characteristics of ToU in the literature.

Rationale	Time of Use
Cost Driver	**Energy**
Number of time blocks	2/day 2/day (higher prices in peak period) 3/day Blocks and time of blocks are found using optimization taken PV production and consumption as input
Price update freq.	1/year 2/year (winter/summer season) 2/year (high demand period June-August and low demand period September–May) 12/year (monthly based)
Price spread	Price ratio of high to low is 2.55 Total cost is in theory the same as a flat rate. Ratio of about 4.6 between the high and low price in high demand season and 2.3 in low demand season. A ratio of about 2 between highest and lowest price.
Active demand	Manual

Contrastingly, optimal demand-side management using ToU dynamic tariffs (includes PV production) is discussed in [37]. The blocks and times of blocks are optimized based on PV production and consumption, therefore, there is no fixed number of time locks. With this method, the price spread is with a ratio of about 2 between the highest and lowest prices.

3.1.3. Critical Peak Pricing

CPP and Critical Peak Rebate (CPR) are two types of Critical Consumption Pricing (CCP). CPP aims to reduce critical peak demand that is usually to avoid grid overload. To avoid grid overload, CPP increases the electricity prices for the peak hours much higher than the regular price. CPR aims to increase demand when there is abundant electricity in the grid, e.g., high renewable non-dispatchable electricity production.

CPP is not popularly discussed as RTP and ToU, and only discussed in two articles. Ref. [38] presents a pilot project that tests CPP DDT on the network component. the CPP events last up to 8 h and consumers are warned 1–2 days prior to the event. The CPP discussed in [39] is to improve the business case for power to heat technologies and induce more renewable energy in the system. The CPP events in [39] are designed to reflect the local grid capacity constraints and are triggered when the local grid load is critical.

3.1.4. Consumption-Based ToU and RTP

The goals of consumption-based DDTs are energy-saving, a general load reduction, and consolidation at a certain load level [4]. Two consumption-based DDT are discussed in the literature: Consumption-based ToU and consumption-based RTP. The main objective of the consumption-based ToU is to tackle the problem that consumers with only essential consumption purposes pay the same as consumers with luxury consumption [41]. Comparatively, consumption-based RTP suggested by [42] aims to motivate consumers to consume more if the frequency is higher (hence, lower prices) and vice versa, and the RTP changes depend on the frequency based on the Equation (1).

$$\text{Dynamic Tariff} = (50/f) \times r_{\text{Tariff}} \times \text{Energy} \tag{1}$$

where f is the frequency in the grid and 50 is due to the Indian grid is operating with a frequency of 50 Hz. r_{Tariff} is the tariff rate and Energy is the consumed energy. If a certain threshold is reached then the price is multiplied by 5 (price spread ratio of 5), hence adding the consumption-based aspect to the RTP tariff.

The number of time blocks per day in the consumption-based DDTs is usually based on the share of consumption or the overall currently used load. For instance, in [41], there are 5 time blocks per day and 1 threshold load level of more than 5 units of power consumption (5 units is estimated to cover the essential devices, hence only luxury devices are penalized). The price spread has a ratio of 1.6 between the lowest and highest price periods, and when exceeding the threshold, a price spread ratio of 1.4–1.7 between the regular period price and the new penalized price.

3.2. Technical Feasibility of DDTs in Literature

The TRLs of the DDTs in the literature are shown in Table 6. All the RTP in the literature can be defined as at TRL 3- Experimental proof-of-concept because the proof-of-concept through simulation is conducted. However, a complex calculation of an hourly day-ahead DDT that can reflect forecasted operation costs and forecasts the next hour's price during the current hour is not yet technically validated in lab or relevant environment. For instance, DDT number 1 (from Table 3) uses a day-ahead DDT calculation based on expected consumption with differentiated prices dependent on the grid locations, but this DDT has not been implemented. Meanwhile, ref. [24] proofs the concept of DDT number 4 through simulation using data for New York City.

Table 6. Technology readiness level of identified DDTs.

DDT Type	DDT Number from Table 3	TRL	Explanation
RTP	1, 2, 3, 4, 5	3	Proof-of-concept through simulation is conducted.
ToU	6, 7, 8, 9, 10, 11, 12	9	A typical ToU pricing scheme is seen in operation today.
CPP	13, 14	9	A typical CPP pricing scheme is seen in operation today.
Consumption based ToU	15	3	Not yet implemented in practice.
Consumption based RTP	16	3	Not yet implemented in practice.

All ToU DDTs from the literature have a TRL 9 as all of the ToU schemes are reflecting ToU schemes already implemented in the real world today. There might be differences in the ratio and time blocks compared to what is implemented today, but all DDTs in the literature can be implemented today. For instance, DDT number 6 uses a ToU scheme with two price periods a day and the price spread is of ratio 2.55 between lowest and highest price.

CPP DDTs discussed in the two literature have TRL 9. For instance, the CPP DDTs are implemented for small, medium, and large business customers with 12 CPP events a year in [39], and a CPP pilot project is conducted in [38].

Both consumption-based DDTs (the ToU combined with a consumption-based pricing scheme [41] and the RTP combined with a consumption-based pricing scheme [42]) are yet not implemented in practice and not validated in lab or relevant environment bringing the DDT on a TRL 3. Reference [41] proposes a concept formulation of the hardware and proofs the concept through real time calculations. The calculations are assumed to be done by a model. Reference [42] proposes a model/program for the consumption-based RTP DDT which shows the proof-of-concept.

3.3. Economic and Social Feasibility of DDTs in Literature

Each DDT is evaluated based on the users' actions, and the economic feasibility (participation monetary costs) and the social feasibility (user convenience levels) are identified based on the evaluation results (shown in Table 7). The participation cost is rated from 1 to

3 (1 is low cost and 3 is the high cost) and the user convenience levels (1–3) describe the convenience of end-users for responding to the DDT price signals.

Table 7. Economic and social feasibilities for each DDT.

DDT Type	DDT Number from Table 3	End-User's Actions	Economic Feasibility (Participation Monetary Cost Level)	Social Feasibility (User Convenience Level)
RTP	1	Users have to acquire automatic devices. Therefore, home appliances and other devices can be controlled automatically as a response to DDT signals. Afterward, the acquired devices can automatically consume electricity as cheaply as possible.	1	3
	2	This DDT uses automatic response but has power as a cost driver that it makes more inconvenient for end-users to decide when to and how much to consume.	1	3
	3	This solution calculates the next hour's price in the given hour and does not mention if the users respond automatically or manually to the DDT. However, either automatic or manual, this solution is very inconvenient as even automatic solutions will have difficulties prioritizing consumption in hours which is not known.	1	1
	4	Due to the unclear description in the literature, this solution is assumed to have a manual response to the DDT that users have to check the DDT every day and shift their use of washing machines and dishwashers.	3	1
	5	Due to the day-ahead RTP scheme, users have to check prices at least once a day.	3	1
ToU	6, 7, 8, 9	Since only 2 ToU periods are chosen per day, users can easily choose to consume or not in the high-price periods	3	3
	10	Prices are updated once each month and it is easy for users to understand only two price levels a day.	3	3
	11	Three price levels in one day are still considered as easily manageable for users	3	3
	12	This DDT calculates the ToU time blocks and their length based on PV production and consumption data. It is assumed to be done once a year based on the statistical data, resulting in a regular ToU tariff for users that the time blocks might be too many.	3	2
CPP	13	Users are warned 1–2 days before the CPP event.	3	3
	14	Users have to take fast load shifting/reduction actions as the CPP event in this DDT is based on the criticality of the local grid.	3	1
Consumption-based ToU	15	No actions are needed for users besides essential consumption. End-users with luxury consumption (e.g., air conditioning) should take shift load according to the ToU scheme.	3	3
Consumption-based RTP	16	Action based on the system's frequency and keeping the consumption below a limit	2	1

For instance, for DDT number 1, users have to acquire automatic devices that home appliances and other devices can be controlled automatically as a response to DDT signals. Afterward, the devices can automatically consume electricity as cheaply as possible. Therefore, the user convenience level is 3, and participation cost is high (3) due to the device acquisition.

In general, automatic consumer response requirement high investment costs to enable devices and systems to respond automatically. Therefore, RTP without automatic response solutions is rated 1- low convenience level as the user has to check the RTP tariff and manually react. ToU DDTs with less than 4 periods a day with a price update of a month or more are estimated to have high convenience as it is easy for users to understand and respond to different price periods.

3.4. Regulatory Feasibility of DDTs in Literature

The §73 in the Danish law of electricity supply [10] and article 18 in the European Union's electricity ordinance [47] are the most important laws to follow when designing a DDT in Denmark. The essential part of these laws is that the tariff has to be:

- Reasonable
- Non-discriminating
- Objective
- Reflecting the true costs
- Transparent
- Take grid security and flexibility into consideration

The regulatory readiness levels for DDTs in the literature (shown in Table 8) are identified based on the comparison of the realization requirements for DDTs in the literature and the Danish regulation requirements (bullet-points) above. Table 8 shows that all types of ToU DDTs have a regulatory readiness level of 3 (can happen in the short term) and are potentially implemented in Denmark.

Table 8. Required regulations for each relevant DDT scheme.

DDT Type	DDT Number	Required Regulations	Regulatory Readiness Level
RTP	1	This DDT scheme discriminates as the tariff is based on grid congestions in grid nodes. This means that neighbors theoretically pay different prices for electricity depending on the location in the grid. Price differentiating based on geographical delimitation is according to §73 in the Danish law of electricity supply only allowed in special cases.	1
	2	Power-dependent prices are a different way of settling the used electricity and are following the regulations. However, besides the power-dependent price, the scheme is similar to DDT number 1 and is rated the same.	1
	3	The tariff for the next hour in this RTP scheme determines this DDT is not transparent. It will not happen at all because even the automatic response cannot operate efficiently with only the next hour's information.	0
	4, 5	The transparency of this RTP scheme is determined by whether the day-ahead prices are already introduced from the electricity spot price. However, it is not considered to be transparent to end-users. Therefore, it doesn't follow the legal requirement.	1
ToU	6	This ToU DDT scheme reflects the true cost, as it uses a price ratio of 2.55. The price ratio is assumed to be adapted to the individual grid.	3
	7	As the price ratio for this ToU scheme reflects the flat rate if the consumption continues as normal, the realization level is high.	3
	8, 9, 10, 11	This ToU DDT scheme does not conflict with the regulations.	3
	12	It is assumed that the optimization in this ToU DDT scheme decides the number of time blocks and the length and is considered to match the transparency requirement (i.e., not too many time blocks).	3
CPP	13	If the price of the CPP event reflects true costs, it follows the regulations that give a warning 1–2 days. Therefore, this CPP is considered transparent.	3
	14	The CPP events occur when grid conditions are critical without warning the users in advance. Hence, it is not considered transparent and is given a low regulatory readiness level.	1

Table 8. *Cont.*

DDT Type	DDT Number	Required Regulations	Regulatory Readiness Level
Consumption-based ToU	15	This DDT discriminates the users with more than only essential appliances. This is not expected to happen in Denmark.	0
Consumption-based RTP	16	This DDT is not transparent as the tariff is dependent on the system frequency in real-time.	1

A CPP introduced in [38] also have a regulatory readiness level of 3, because this CPP is considered transparent (it follows the regulations as a warning 1–2 days before the event) and reflects true costs (if the price of the CPP event reflects true costs). Other DDTs in the literature have low regulatory readiness levels which indicate the difficulties be implemented in Denmark.

4. Discussion

The feasibility evaluation method for DDTs includes the technological, economic, social and regulatory dimensions, and each dimension includes several levels (as shown in Table 9). Table 9 shows that, for each dimension, a higher level/scale means higher feasibility this DDT has.

Table 9. The technological, economic, social, and regulatory feasibility evaluation method for dynamic distribution tariffs.

Dimension	Explanation	Feasibility Level	
Technical feasibility	Technology Readiness Level (TRL)	1	Basic principles observed
		2	Technology concept formulated
		3	Experimental proof of concept
		4	Technology validated in lab
		5	Technology validated in a relevant environment
		6	Technology pilot demonstrated in a relevant environment
		7	System prototype demonstration in an operational environment
		8	System complete and qualified
		9	The actual system is proven in an operational environment
Economic feasibility	Monetary cost is due to the acquisition of necessary devices or equipment for participation in a DDT program	1	Low economic feasibility due to high cost to acquire new automatic solutions participation in the DDT program.
		2	Medium cost for acquiring a device for participation in the DDT program, which typically for the continuous frequency measurement.
		3	High economic feasibility due to little cost for participation in the DDT program requires no device or equipment.
Social feasibility	user convenience for responding to DDT price signals.	1	Low convenience due to fully manual response with complex price signals
		2	Medium convenience due to fully manual response with easily understandable price signals
		3	High convenience due to fully automatic response.
Regulatory feasibility	Regulatory readiness for DDT implementation	0	The required regulation is impossible to happen
		1	The required regulation might happen in the long term
		2	The required regulation will happen in the medium term
		3	The required regulation can happen in the short term

The evaluation results of the DDTs in the literature are shown in Table 10. In Table 10, the column of total value (equals to the sum of the scores for all four feasibility dimensions) indicates the overall feasibility score for each DDT. Therefore, all six ToU get the highest score (18), and one CPP also gets 18.

Table 10. Overview of the evaluation grades, all above the bold line are top graded in all categories.

DDT Number	DDT Type	Technology Readiness Level	Economic Feasibility	Social Feasibility	Regulatory Readiness Level	Total Value
6	ToU	9	3	3	3	18
7	ToU	9	3	3	3	18
8	ToU	9	3	3	3	18
9	ToU	9	3	3	3	18
10	ToU	9	3	3	3	18
11	ToU	9	3	3	3	18
13	CPP	9	3	3	3	18
12	ToU	9	3	2	3	17
14	CPP	9	3	1	1	14
1	RTP	3	1	3	1	8
15	Consumption based ToU	3	3	3	0	9
2	RTP	3	1	3	1	8
4	RTP	3	3	1	1	8
5	RTP	3	3	1	1	8
16	Consumption based RTP	3	2	1	1	7
3	RTP	3	1	1	0	5

Note: the total value = SUM of scores for all four feasibility dimensions.

Therefore, according to the evaluation results, the most suitable DDT for implementation in Denmark. The ToU gets the highest score because it requires simple time schedules with differentiated tariffs. It is easy to understand for consumers and relatively easy to implement by the DSOs. The CPP (DDT No. 13) gets the highest score because it only requires a 1–2 day-ahead warning and it is easy for consumers to react to the events and the DSOs to implement compared to other CPPs.

Although the evaluation results in Table 10 show that the ToU pricing scheme has the most potentials to be implemented in Denmark, to realize and implement ToU into the Danish market, the ToU prices are required to reflect the real costs. Meanwhile, although the CPP DDT number 13 has the highest score in all evaluation categories, a qualified calculation of a true cost is needed to implement this CCP in Denmark, but such calculations are not available.

The RTP day-ahead scheme for congestion management has been the most discussed in the literature. However, the evaluation results show that it will not be realized in Denmark in the short term because it calculates DDT in each node in the grid. Therefore, two neighboring houses potentially can have different DDT prices which is difficult to be implemented in Denmark under the current or future regulations. Another main barrier for the DDTs to be implemented is due to the requirement of transparency to users.

Dynamic Distribution Tariff in Denmark

The developed feasibility evaluation method has reviewed dynamic distribution tariffs in the literature, and ToU is the most feasible DDT according to the evaluation result. However, there is much information in detail missing in the literature due to each article's scope. Therefore, to verify the evaluation method, this paper uses a proposal for the future distribution tariff in Denmark and a Danish DSO for the investigation.

In Denmark, the DSO's electricity customers are divided into segments based on the grid-level connection (shown in Table 11). Since 2015, Denmark has implemented a tariff model called "tarifmodel 2.0" (DDT 2.0) which has replaced the regular flat rate tariff and created incentives to shift consumption from peak hours. For example, for households (C-customers who are charged at the 0.4 kV level), the DDT 2.0 introduces a high-price tariff in 3 h from 5 to 8 PM during the winter period [48].

Table 11. Customer segmentation based on the grid-level connection [49].

Customer Segment	Grid-Level Connection
A0	132 kV
A—high	50 kV
A—low	50/10 kV transformer
B—high	10 kV
B—low	10/0.4 kV transformer
C	0.4 kV

A new tariff model called "tarifmodel 3.0" that extends the DDT 2.0 model was introduced in 2020 by Dansk Energi [49], and is expected to be in use in 2022. In the Tariff model 3.0, the distribution tariffs are time differentiated, the tariff in each time period equals the flat rate tariff 2021 multiplies the corresponded tariff scaling factor (as shown in Table 12). For instance, the new tariff for 0–6 am in winter is 3.85 Ore/kWh (=11.56 × 1/3) which is one-third of the flat rate tariff in 2021.

Table 12. Load periods and Tariff scaling factor in new distribution tariffs for households [49–51].

Hours	Winter		Summer		Flat rate Distribution Tariff **** in 2021 (Ore **/kWh)
	New Tariff * (Ore**/kWh)	Tariff Scaling Factor ***	New Tariff (Ore **/kWh)	Tariff Scaling Factor	
0-6	3.85	1/3	3.85	1/3	11.56
6-17	11.56	1	5.78	1/2	
17-21	34.68	3	15.03	1.3	
21–24	11.56	1	5.78	1/2	

* New tariff = Flat rate distribution tariff in 2021 multiplied by the Tariff scaling factor. ** 100 Ore = 1 Danish kroner ≈ 0.13 euro. *** Called "tarifskaleringsfaktor" in Danish. **** Each DSO in Denmark can decide their DSO tariff. The DSO tariff in this table is provided by a Danish DSO who is responsible for the distribution grid of the selected area.

Table 12 shows that this Tariff model 3.0 (DDT 3.0) uses a ToU pricing structure that has been implemented in many regions. There are three price levels in a day (similar to the DDT number 11 from Table 3) in this tariff model and it does not require electricity consumers to take any extra actions.

Meanwhile, this model is designed following §73 in the Danish law of electricity supply [10] and article 18 in the European Union's electricity ordinance [47]. According to Table 12, tariffs for winter and summer are different due to the grid operation cost is higher in winter; there are four time periods with three pricing levels to take flexibility into consideration; this tariff model is applied for all households under the same DSO. Therefore, this Tariff model 3.0 can be defined as: reasonable; non-discriminating; objective; reflecting the true costs; transparent; taking grid security and flexibility into consideration.

According to the evaluation result, this Tariff model 3.0 has the highest levels of technical, economic, social, and regulatory feasibility, and is suitable for implementation in Denmark. Therefore, the developed feasibility evaluation method for DDTs can be proved useful not only for evaluating DDTs in literature but also in DDTs to be in practice.

5. Conclusions

This paper introduces a feasibility evaluation method with four dimensions of technical, economic, social, and regulatory. To introduce and demonstrate the developed feasibility evaluation method, a scoping review is conducted and 29 references are selected and further categorized into five attributes of rationale, cost drivers, dynamics, events, and active demand. The dynamic distribution tariffs in literature can be categorized into: Real-Time Pricing, Time-of-Use, Critical Peak Pricing, Consumption-based Time-of-Use, and Consumption-based Real-Time Pricing.

The dynamic distribution tariffs in literature are evaluated with the developed feasibility evaluation method, and the evaluation results show that the Time-of-Use tariff is the most feasible dynamic distribution tariff, although, Real-Time Pricing is the most popularly discussed in the literature.

To verify the evaluation method, a proposal for the future distribution tariff in Denmark and a Danish DSO are evaluated, and the result proves that the feasibility evaluation method can ensure dynamic distribution tariffs to be feasible and applicable in a region.

5.1. Contributions

The developed feasibility evaluation method for dynamic distribution tariffs can fill the research gap of no sufficient method available to review and evaluate dynamic distribution tariffs. This method not only can evaluate dynamic distribution tariffs, but also potentially evaluate any solution (e.g., technology, algorithm, or business model) in an energy ecosystem.

The developed feasibility evaluation method includes four dimensions that represent the technology readiness level, monetary participation cost, user convenience level, and the regulatory readiness level. Meanwhile, each dimension includes several levels and a higher level/scale means higher feasibility a DDT has. A total score that equals the sum of all four dimensions' scores can indicate the overall feasibility of a dynamic distribution tariff. It allows easy identification of the most feasible tariff to implement.

Moreover, except for the regulatory dimension, the other three are consumer-oriented. Fundamentally, the design of dynamic distribution tariffs needs to comply with the regulation. However, the implementation should consider electricity consumers' adoption potentials which the technical, economic, and social feasibility dimensions reflect on.

Although some dynamic distribution tariffs are promising for creating incentives for the consumers to reduce or shift their energy consumption in literature, e.g., Real-Time Pricing, they can not be implemented in practice not only due to the regulation constraints but also the low consumer adoption. Therefore, the developed feasibility evaluation method with four dimensions can ensure a given dynamic distribution tariff to match a targeted regional/national requirement.

5.2. Limitation and Future Works

The goal of dynamic distribution tariffs is to create incentives for consumers to reduce or shift their energy consumption and avoid grid congestion. However, the way in which the designed dynamic distribution tariffs will impact electricity consumer behaviors of energy use, especially with distributed energy resources, e.g., electric vehicle charging, is unknown. Meanwhile, whether the combination of dynamic distribution tariffs, hourly electricity pricing, DR programs, and smart algorithms can provide the sustainability and resilience of the distribution grids remains unclear.

Therefore, further works, e.g., simulations with various what-if scenarios and multi-objective optimization are recommended. Especially, agent-based simulations with the consideration from different stakeholders' perspectives are needed [52]. Meanwhile, besides Time-of-Use tariff, other types of dynamic distribution tariffs in the literature are recommended to be further investigated for understanding their impacts on the energy ecosystem [53]. The result can contribute to design the most suitable tariffs and justify regulations to support the sustainability and resilience of the whole energy ecosystem.

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Abbreviations

Term	Description
CCP	Critical Consumption Pricing
CPP	Critical Peak Pricing
CPR	Critical Peak Rebate
DDT	Dynamic Distribution Tariff
DER	Distributed Energy Resource
DR	Demand Response
DSO	Distribution System Operator
EV	Electric Vehicle
RTP	Real Time Pricing
ToU	Time-of-Use
TRL	Technology Readiness Level

Appendix A

Table A1. Technology Readiness Level scale [43].

TRL Level	Title	Description
1	Basic principles observed	• Identification of the new concept. • Identification of the integration of the concept. • Identification of expected barriers. • Identification of applications. • Identification of materials and technologies based on theoretical fundamentals/literature data. • Preliminary evaluation of potential benefits of the concept over the existing ones.
2	Technology concept formulated	• Enhanced knowledge of technologies, materials, and interfaces is acquired. • New concept is investigated and refined. • First evaluation of the feasibility is performed. • Initial numerical knowledge. • Qualitative description of interactions between technologies. • Definition of the prototyping approach and preliminary technical specifications for laboratory test.
3	Experimental proof of concept	• First laboratory scale prototype (proof-of-concept) or numerical model realized. • Testing at laboratory level of the innovative technological element (being material, sub-component, software tool, . . .), but not the whole integrated system. • Key parameters characterizing the technology (or the fuel) are identified. • Verification of the proof of concept through simulation tools and cross-validation with literature data (if applicable).
4	Technology validated in lab	• (Reduced scale) prototype developed and integrated with complementing subsystems at laboratory level. • Validation of the new technology through enhanced numerical analysis (if applicable). • Key Performance Indicators are measurable. • The prototype shows repeatable/stable performance (either TRL4 or TRL5, depending on the technology)

Table A1. *Cont.*

TRL Level	Title	Description
5	Technology validated in relevant environment	• Integration of components with supporting elements and auxiliaries in the (large scale) prototype. • Robustness is proven in the (simulated) relevant working environment. • The prototype shows repeatable/stable performance (either TRL4 or TRL5, depending on the technology). • The process is reliable and the performances match the expectations (either TRL5 or TRL6, depending on the technology). • Other relevant parameters concerning scale-up, environmental, regulatory and socio-economic issues are defined and qualitatively assessed.
6	Technology pilot demonstrated in relevant environment	• Demonstration in relevant environment of the technology fine-tuned to a variety of operating conditions. • The process is reliable and the performances match the expectations (either TRL5 or TRL6, depending on the technology). • Interoperability with other connected technologies is demonstrated. • Manufacturing approach is defined (either TRL6 or TRL7, depending on the technology). • Environmental, regulatory and socio-economic issues are addressed.
7	System prototype demonstration in operational environment	• (Full scale) pre-commercial system is demonstrated in operational environment. • Compliancy with relevant environmental conditions, authorization issues, local/national standards is guaranteed, at least for the demo site. • The integration of upstream and downstream technologies has been verified and validated. • Manufacturing approach is defined (either TRL6 or TRL7, depending on the technology).
8	System complete and qualified	• Technology experimented in deployment conditions (i.e., real world) and has proven its functioning in its final form. • Manufacturing process is stable enough for entering a low-rate production. • Training and maintenance documentation is completed. • Integration at system level is completed and mature. • Full compliance with obligations, certifications and standards of the addressed markets.
9	Actual system proven in operational environment	• Technology proven fully operational and ready for commercialization • Full production chain is in place and all materials are available • System optimized for full rate production

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