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A Framework for Assessing the Participation of Aggregated Flexible Loads in Power Markets

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***Abstract*-- This paper introduces a parametrized analyzing framework for facilitating power market participation of flexible loads specifically industrial through the aggregation of consumers. By combining flexible loads' potential, the demand response of the industrial sector can be mobilized and made available, particularly when the qualification limits cannot be met by single industrial plants. To aggregate the flexibility potential of flexible consumers, an analysis framework is necessary to streamline the calculation process for aggregators and plant owners to estimate their potential and prerequisites to participate in various power markets. This paper proposes a simplified approach to categorize the combination of flexible industries into parallel and series configurations. A set of calculations and assumptions is presented to obtain the values for the flexibility parameters of the aggregated industries. The results of this study provide insights into the potential benefits and challenges associated with aggregating industrial consumers in power markets.**

***Index Terms*— Demand response, flexibility aggregation analysis, industrial flexibility, power markets.**

I. Introduction

INTEGRATION of flexible consumers, particularly industrial consumers, into power markets, has gained increasing attention due to its potential to enhance effective operation and contribute to grid stability [1]. However, there are a number of obstacles in the way of these consumers participating effectively in the electricity market. Market regulations, which control the rules and principles of the market, are a significant barrier to industrial customers' participation. These regulations' complexity and constant evolution could lead to uncertainty and prevent potential participants from actively entering the industry. Moreover, the market qualifications are primarily designed for large-scale generators and suppliers, and the regulatory requirements may pose significant challenges for a solitary customer to fulfill.

To address these challenges, this study proposes an analytical framework tailored for operators of industrial clusters aiming to parameterize market regulations and participants' flexibility potential. Firstly, this framework enables estimating the feasibility of entering power markets. Subsequently, a novel method is introduced to identify the parameters influenced by aggregating multiple participants. This information empowers industrial plant owners to assess their flexibility and identify strategic investment areas for participation in various power markets. Additionally, this approach facilitates aggregators in targeting more potential customers.

The literature on demand response (DR) and flexible load integration in power markets reveals a growing interest in addressing the challenges in load aggregation. Various studies have explored methodologies to aggregate flexible loads effectively. In [2] an energy management system for aggregating controllable loads in the distribution system is proposed, considering uncertainties from local solar photovoltaic generation and the provision of ancillary services. Authors in [3] analyzed the role of resource aggregators in DR programs and their importance in maintaining the balance between power supply and demand, promoting energy conservation, and reducing emissions. The research paper [4] focuses on quantifying energy flexibility in buildings and proposes a standard for quantifying building energy flexibility and facilitating contractual agreements between stakeholders. Paper [5] also introduces a novel approach to analyze the operational flexibility of power systems, crucial for integrating high shares of variable renewable energy sources. Additionally, in [6] a robust active dynamic aggregation model for distributed integrated multi-energy systems is presented to act as virtual power plants. Lastly, in paper [7] a market-based virtual power plant model is introduced to address challenges posed by the growing penetration of distributed energy resources and the liberalization of electricity markets.

In summary, the literature highlights the crucial role of DR and aggregation in improving the integration of flexible loads, especially during the operational phase. However, the literature has limited research on the pre-operation mobilization of loads. One of the pioneering works in this domain is presented in [8], where the process-to-market mapping (P2MM) method is introduced as a parameterized approach for assessing the potential of industrial consumers in power markets.

The contributions of this paper are threefold. 1) The P2MM parameterized concept is harnessed to create a new structured and parameterized approach that categorizes load aggregation into two configuration methods, i.e., series and parallel for facilitating the aggregation of the flexible loads to participate in power markets. 2) The novel approach introduces the concept of categorizing flexibility parameters into two distinct classes: primary and secondary. This classification not only signifies the aggregability of consumers but also offers pre-operation insights to stakeholders, indicating the specific upgrades and adaptations required in their systems to achieve eligibility for participation in power markets. 3) The proposed framework simplifies the

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estimation of load flexibility by excluding operational conditions, allowing for straightforward pre-operation assessments. Lastly, the proposed aggregation method is tested in a case study with three industrial consumers.

The rest of the paper is structured as follows: Section II describes an analyzing method to assess the power market participation potential of flexible consumers. In section III, the proposed aggregation system and related configurations are explained. Then in section IV, the functionality of the proposed framework over several case studies is discussed and the paper's conclusion is presented in section V.

II. Analysis of power market participation potential

A. Introduction to market participation challenges

In assessments of DR, it is often assumed that market regulations are easily fulfilled. However, complex market requirements act as a discouraging point for industrial consumers to participate in the market. The evolving nature of market rules in tandem with the development of electricity systems creates uncertainty for potential participants. Consequently, there is a need for clearer information for plant owners and operators to determine their eligibility for market participation before assessing the potential benefits. The P2MM method suggested in [8] aims to address this gap. It aims to determine the technical and regulatory eligibility of industrial consumers to take part in various power markets, serving as a pre-selection step before the aggregation analysis and then conducting economic evaluations to determine whether participation is justified.

B. Process-to-Market Mapping (P2MM) method

This method aims to assess the viability of entering different markets by considering specific criteria for market participation. The goal is to identify feasible power markets and screen out infeasible ones. The methodology consists of several evaluation steps. In summary, the process involves identifying power market options that are assumed to be Nordic power markets in this paper, defining market and process parameters, testing compatibility, and selecting suitable market options for industrial processes. The overall process is as follows:

Step 1: Market parameter identification

Consumers in power markets must obey particular regulations to be allowed to attend the markets that can be presented as market parameters. This study uses general parameters from [8] as power market regulations according to the Danish electricity market regulations and European Commission guidelines [9]. These regulations are categorized into bidding and operational requirements as follows:

Bidding requirements:

Bidding Time (M1): This parameter refers to the time scale at which bids are submitted to the market.

Bidding Frequency (M2): It indicates the frequency at which bids are shared with the market.

Bidding Due (M3): This parameter specifies the deadline by which bids must be transmitted.

Minimum Bid Size (M4): It represents the minimum size or threshold that a bid must meet to be accepted in the market.

Operational requirements:

Activation Speed (O1): This parameter defines the maximum time span allowed to reach the required power level.

Symmetricity (O2): It refers to the ability to change the consumption equally in either up or down directions based on the requirements.

Response Time (O3): This parameter signifies the minimum time span during which the power level must be maintained at the required level obtained in the market clearing.

Auto Activation (O4): It indicates the capability of the system to automatically adjust power consumption based on built-in control and measurement devices.

Information Sharing Rate (O5): This parameter denotes the minimum frequency of measurement and communication of power consumption to ensure efficient grid operation.

Step 2: Process parameter identification

Parameters to evaluate the operational flexibility of consumers are identified in this step based on operational criteria and assigning suitable values. This study uses three categories of features suggested in [8] to define the flexibility level of an industry including load, time, and organizational flexibilities. The considered process parameters are as follows:

Load flexibility:

Total Capacity (A1): This parameter shows the greatest amount of power that can be consumed, indicating the maximum amount that can be offered in the market.

Utilization Factor (A2): It describes the average percentage of the maximum capacity utilized during rigid operation and offers information on how the load is typically utilized.

Minimum/Maximum Power Deviation Range (A3): It specifies the range in which load consumption may be changed while still adhering to the limitations established by the process, equipment, or facility. $A3_{up}$ stands for the upper bound, and $A3_{down}$ for the lower bound.

Time flexibility:

Maximum Time Shift (B1): The longest period before which a load deviation must be made up.

Ramp Time (B2): This parameter represents the amount of time needed to transition a process to a new operating load level, accounting for load modifications.

Maximum Load Variation Frequency (B3): To maintain the intended process output quality during flexible operations, this value specifies the maximum frequency or minimum time interval for load changes.

Maximum DR Duration (B4): To provide flexibility in load operation, this parameter indicates the longest time the load can diverge from the baseline.

Organizational flexibility:

Planning Deadline (C1): This parameter indicates the deadline for load planning operations and reflects the earliest possible period for modifying the loads to ensure successful process operation.

Operating Times (C2): It provides details regarding the period of time that the process can be operated.

Data Sharing Interval (C3): the lowest period at which consumption is measured and regulated.

Automatic Activation Rights (C4): It defines if unplanned load activations are acceptable and specifies if automatic load adjustments are allowed.

External Activation/Monitoring/Scheduling (C5): This parameter highlights the potential engagement of external parties in load activation, monitoring, and scheduling and represents the acceptance of external entities engaging in consumption data monitoring and scheduling activities.

Step 3: Domain Mapping

In this method, the process-to-market matrix is drawn and the connections between process parameters and market parameters are evaluated based on the corresponding relations. For that purpose, a matrix is created for each power market, where the process parameters are assumed as rows and the market parameters create columns. For each cell in the matrix, it is determined if there is a connection between the corresponding process parameter and the market parameter. This is done by asking the question: "Would a modification in the process parameter impact the consumer's capacity to meet the specified power market regulations?" In case of an affirmative response, establish a link between the two parameters in the cell and mark it with a color. This indicates that there is an influence or dependency between them. Table 11 in [8] shows the matrix constructed with the process parameters and market parameters. The cells crossed with relevant parameters in the table are filled with the corresponding relationship in this matrix that shows the mapping instructions. The mentioned matrix is called the 'mapping instruction matrix' in this paper.

Stage 4: Color-coded scoring system

There are different types of scoring systems in the P2MM method. In this paper, each crossed cell linking a flexibility parameter and a market parameter is colored green or yellow. It is assumed that if a cell related to the flexibility parameter meets the market requirements of the corresponding power market is colored "green". Otherwise, the color would be "yellow".

If all the crossed cells become green, the intended industry is technically eligible to attend the power market. However, if some cells of the matrix get yellow, the industry needs advancements in equipment or facility to be qualified to attend the intended power market solitarily. Offering an aggregated product to the power market by mobilizing other plants to a single load can also influence specific cells in the matrix. In this paper, aggregating flexible loads, its impact on the flexibility parameters in the P2MM method, and a framework to facilitate the aggregation analysis of industrial loads is proposed which is described in the next section.

III. The Proposed Aggregation Analysis Method

Aggregation of two or multiple industries makes the DR of the industrial section more feasible. That means, if the P2MM for an individual industry does not validate the qualification of the industry, a part of the qualification barrier might be resolved by combining the industry with another industry. However, to aggregate the flexibility potential of industries, an analysis system is required to simplify the calculations of the gained process parameters of the combined industries. To this aim, in this paper, the combination of flexible industries is simply divided into parallel and series. Then, a set of calculations and assumptions are presented to obtain the values for the flexibility parameters of the new aggregated industries. It is essential to note that the proposed analysis method is simplified by excluding operational conditions such as the rebounding effect. This simplification enables a straightforward pre-operation estimation for industrial plant owners and operators. They can identify specific areas where investments are required to qualify for participation in power markets or being aggregated. It can also help aggregators simply identify loads with qualifiable parameters for plants with potential for integration into their portfolios.

A. *Parallel combination*

The parallel combination of flexible loads in this paper refers to the activation of two or multiple flexible loads simultaneously, as illustrated in Fig. 1 for two industries. Fig. 1 demonstrates the load profiles of two flexible loads. Subsequently, the "aggregated profile" is generated by combining these two profiles in parallel. The aggregated profile, depicted in the figure, takes the form of a polygon with various characteristics. However, for conducting potential analysis on the participation of a product in power markets, a simplified final product is required. This simplified product should encompass all the constituent profiles and be presented with predefined parameters. In Fig. 1, the simplified product is demonstrated considering the abovementioned conditions that has specific parameters as one solitary product.

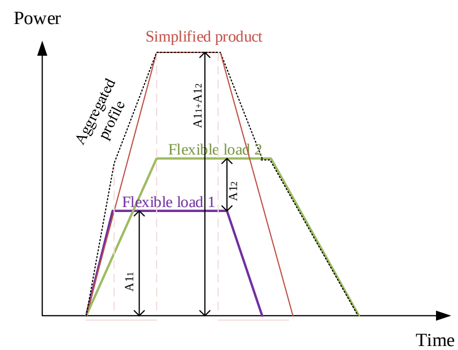

Fig. 1. Visual presentation of combining two industries in parallel

TABLE I

Calculation of the flexibility parameters obtained through the aggregation of *n* parallel industries

Total capacity (A1)	$\sum_{i=1}^{n} \mathbf{A1}_i$
Utilization factor (A2)	$\cup A2_i$
Power deviation range (A3)	$A3_{up} = \sum_{i=1}^{n} A3_{up,i}$ $A3_{down} = \sum_{i=1}^{N} A3_{down,i}$
Max time-shift (B1)	min $(B1_i)$
Ramp time (B2)	max $(B2_i)$
Max load variation frequency (B3)	max $(B3_i)$
Max DR duration (B4)	$\cap (B4_i)$
Planning deadline (C1)	max$(C1_i)$
Operating times (C2)	$\cap (C2_i)$
Data sharing interval (C3)	$\cap (C3_i)$
Automatic load activation (C4)	$C4 = True, if\ \forall C4_i = True$
Third-party data monitoring/ scheduling (C5)	$C5_{ext\ act,i} = True, if\ \forall\ C5_{ext\ act,i} = True$ $\cap (C5_{Monitoring/sch,i})$

Now, based on the definition of the parallel combination of flexible loads, TABLE I showcases the calculation of flexibility parameters obtained through the aggregation of *n* parallel industries. In the given formulations, the indices correspond to the industry number. Through the parallel aggregation of flexible loads, several parameters of the final product can be improved. These parameters include total capacity (A1), utilization factor (A2), and power deviation range (A3). For example, after aggregating two flexible loads, the value of total capacity parameter (A1) would be the summation of both loads. In this paper, these parameters are referred to as "enhancing parameters." However, the remaining parameters of flexible loads would be negatively impacted after aggregation which are termed "diminishing parameters." The enhancing parameters marked green and the diminishing red in the table.

B. Series combination

The series combination of industries in this paper is defined as activating two or multiple industries' DR one after another. It is assumed that each subsequent industry is activated before the preceding industry starts to ramp down, and this pattern continues for the remaining industries as illustrated in Fig. 2 for two flexible loads. The detailed aggregated profile of the combination of loads is also demonstrated. However, a simplified product profile is required to present into power markets. Therefore, the simplified product is also demonstrated in Fig. 2. The simplified product must incorporate all the individual profiles and be presented with predefined parameters that we assure to deliver. TABLE II presents the calculation of the flexibility parameters related to the simplified product obtained through the aggregation of *n* series industries. In the formulations, the indices indicate the industry number.

Through the series aggregation of flexible loads, several parameters of the final product can experience improvements. These parameters encompass maximum time shift (B1), maximum DR duration (B4), and operating times (C2). For instance, when aggregating two flexible loads in series, the total DR duration parameter (B4) would be enhanced based on the total duration of the aggregated product. Thus, these parameters are enhancing parameters and the rest of the parameters are diminishing parameters.

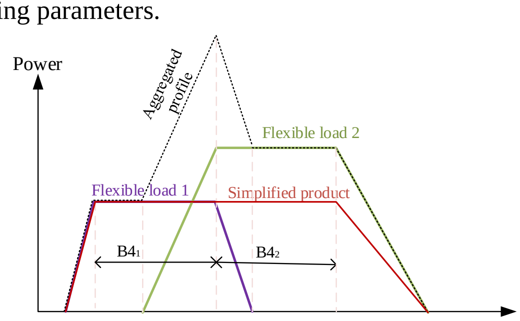

Fig. 2. Visual presentation of combining two industries in series

C. Aggregation analysis

So far, two types of load aggregation i.e., parallel and series are defined, then their corresponding simplified formulations are presented. As illustrated in previous subsections, both series and parallel combination types have their own diminishing and enhancing parameters. Diminishing parameters cannot be enhanced by aggregation. So, in order to attend to a power market, the voluntary flexible load must primarily meet all the required regulations related to their diminishing parameters (based on the mapping instruction matrix). The joint diminishing parameters between parallel and series combinations are B2, B3, C1, C3, C4 and C5. In this paper, these parameters are called 'primary parameters' which must meet the market regulations requirements. However, other parameters are called 'secondary parameters' which can be enhanced by either parallel or series aggregation of flexible loads.

TABLE II

Calculation of the flexibility parameters obtained through the aggregation of *n* series industries

Total capacity (A1)	$\boldsymbol{min\ (A1_i)}$
Utilization factor (A2)	$\cap A2_i$
Power deviation range (A3)	$A3_{up} = min(A3_{up,i})$ $A3_{down} = max(A3_{down,i})$ $A3_{continuous} = True, if\ \forall A3_{continuous,i} = True$
Max time-shift (B1)	$B1 = \sum_{i=1}^{n} B1_i \cap C_2$
Ramp time (B2)	$\cup B2_1$
Max load variation frequency (B3)	$max\ (B3_i)$
Max DR duration (B4)	$B4 = \sum_{i=1}^{n} B4_i$
Planning deadline (C1)	$max(C1_i)$
Operating times (C2)	$\cup (C2_i)$
Data sharing interval (C3)	$\cap (C3_i)$
Automatic load activation (C4)	$C4 = True, if\ \forall C4_i = True$
Third-party data monitoring/ scheduling (C5)	$\mathrm{C5_{Monitoring/sch} = True, if\ \forall\ C5_{Monitoring/sch} = True}$

IV. Case Study

In this section, technical and operational information of three industrial processes including greenhouse lighting, cement milling and food storage cooling systems based on [8] are used to show the functionality of the proposed analysis method. First, the P2MM results for these sample industries are solitarily demonstrated in Fig. 3 to Fig. 5 for the Nordic day-ahead regulatory system.

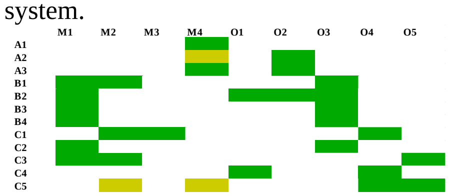

Fig. 3. P2MM result of the greenhouse lightning system for the day-ahead market

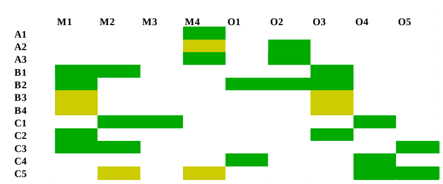

Fig. 4. P2MM result of cement milling system for the day-ahead market

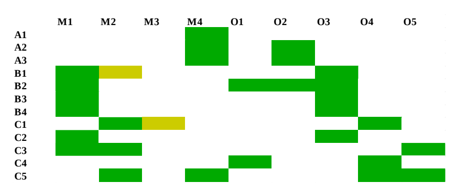

Fig. 5. P2MM result of the food storage cooling system for the day-ahead market

Then, to assess the aggregation of these processes, parallel and series pairwise aggregation of these processes are mapped to matrices in Fig. 6 to Fig. 11. In general, none of the processes and their aggregations are eligible to attend the day-ahead market since there are yellow cells in all matrices. However, we can observe how the series and parallel aggregation can affect the P2MM results.

Based on the figures, the related cells to the primary parameters (B2, B3, C1, C3, C4 and C5) after either series or parallel aggregation would not be enhanced and they are even reduced to the lowest level after aggregation. Hence, before aggregation, they must be advanced to meet the requirements.

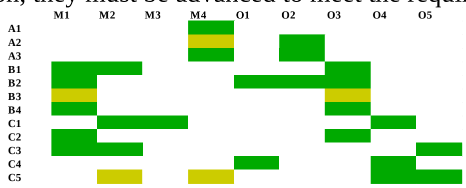

Fig. 6. P2MM result of the series aggregation of greenhouse lightning system and cement milling for the day-ahead market

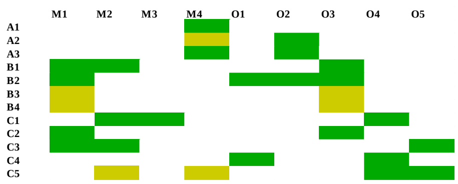

Fig. 7. P2MM result of the parallel aggregation of greenhouse lightning system and cement milling for the day-ahead market

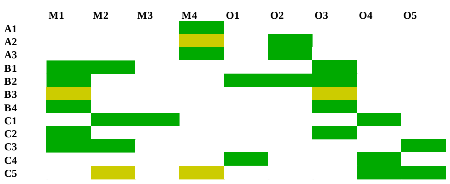

Fig. 8. P2MM result of the series aggregation of cement milling and food storage cooling system for the day-ahead market

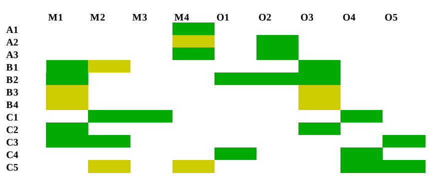

Fig. 9. P2MM result of the parallel aggregation of cement milling and food storage cooling system for the day-ahead market

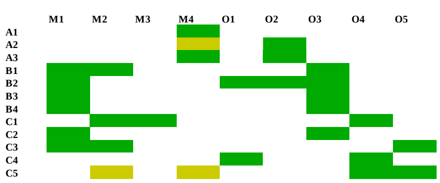

Fig. 10. P2MM result of the series aggregation of greenhouse lightning system and food storage cooling system for the day-ahead market

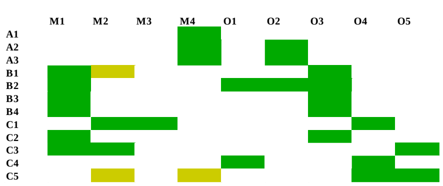

Fig. 11. P2MM result of the parallel aggregation of greenhouse lightning system and food storage cooling system for the day-ahead market

Secondary parameters on the other hand can be enhanced after aggregation. These parameters for parallel combination are A1, A2, and A3. As can be observed in Fig. 11, the A2-M4 cell is not fulfilled by the greenhouse process, and after aggregating that with the cooling process, the cell becomes green. Besides, secondary parameters for series aggregation are B1, B4, and C2. As Fig. 4 and Fig. 5 demonstrate, the cells related to B4 in cement milling and B1 in the cooling system are not fulfilled individually for the day-ahead market. But after series aggregation as shown in Fig. 6, Fig. 8, and Fig. 10, all of the series secondary parameters are fulfilled. That means the series aggregation helped enhance parameter B1 in the cooling process and B4 in cement milling to be accomplished.

V. Conclusion

This paper introduces a parametrized analyzing framework to evaluate the potential of industrial consumers to participate in power markets through the aggregation of flexible loads. The proposed approach categorizes the aggregation strategies into parallel and series configurations, offering insights into potential benefits and challenges for plant owners and aggregators. It highlights the importance of aggregation in meeting specific market requirements for an effective demand response and also emphasizes particular parameters that cannot be enhanced by aggregation. Besides, the proposed framework by disregarding operational constraints and using parameterized basis provides a simplified estimation for potential analysis and investment points of industrial plants that can be flexibly updated under various market rules. The proposed aggregation strategy is evaluated on pairwise aggregation of three industrial processes. The results prove the functionality of the introduced primary and secondary parameters in the parallel and series configurations.

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