Group Project Description

Learning Objectives

The following learning objectives will be evaluated in this group project:

- Describe the fundamental principles of convex optimization and linear programming
- Formulate and explain the dual problem and optimality conditions of a linear and convex optimization problem
- Recognize the structure of various decision-making problems for power systems operation and planning (such as the economic dispatch, unit commitment, optimal power flow, strategic bidding, investment and capacity expansion problems) in terms of input data, decisions, objective and constraints, and formulate them as mathematical optimization problems
- Describe and identify the suitability of different solution algorithms for large-scale optimization problems, and apply them to solve efficiently specific decision-making problems in power systems
- Describe and compare the different methods of optimization under uncertainty in terms of input data, problem structure (objective, constraints, decision variables), and computational complexity
- Solve, analyze and interpret the solutions of specific decision-making problems in power systems
- Organize, plan, and carry out work collaboratively in a group
- Analyze, structure and present results to a broad audience

Instructions

Key tasks and stages of the project work include:

1. **Problem statement and motivation:**
    a. Define the boundaries of the decision-making problem considered, including the role and decisions of the stakeholders involved, time horizon, and geographical boundaries.
    b. Identify and discuss the trade-offs between different objectives of the stakeholders involved.
    c. Identify various constraints to be considered and discuss their relevance and impact on the problem considered.
    d. Identify the key challenges for the decision-making problem considered and derive a suitable approach to tackle them, including the potential sources of uncertainty and risk, and computational complexity.

2. **Optimization problem formulation and solution method:**
    a. Identify the required input data to solve the problem considered, and relevant datasets, and reflect on how this will impact your modelling choices and solution
    b. Formulate the decision-making problem considered as an optimization problem, by formulating its decision variables, objective function(s) and constraints
    c. Derive an approach to model the potential sources of uncertainty and risk associated with this decision-making problem
    d. Derive a suitable solution method to tackle the computational complexity of the decision-making problem considered
    e. Motivate your modelling choices and proposed solution methods based on your knowledge from this course as well as other relevant reading materials and references
    f. Critically discuss the benefits and limitations of the proposed approach

3. **Implementation and computational challenges:**
    a. Solve these optimization problems efficiently using a programming language of your choice
    b. Rigorously document the code and dataset used, such that it can be run by the TAs and your results are replicable.
    c. Discuss the computational complexity of the proposed approach

4. **Numerical results analysis:**
    a. Define a relevant case study
    b. Identify relevant datasets
    c. Perform a numerical validation of your approach
    d. Identify the relevant metrics to analyze and baselines to compare your chosen approach to
    e. Select the most relevant numerical results and analyze them in a clear and concise manner

Deliverables and deadlines

The following schedule includes i) formative feedback activities during class, including elevator pitches, and peer-feedback; ii) intermediary deliverables for formative assessment; and iii) final deliverable for summative assessment.

Time	**Deliverables & activities schedule**
Week 4	✓ Announcement of group projects

Week 5 **(Wednesday at 12pm)**	✓ Intermediary deliverable 1: Group contract
Week 6	
	AUTUMN BREAK
Week 7 **(Wednesday at 12pm)**	✓ Activity: Comparing project statement and plan to Chat GPT's proposal ✓ Intermediary deliverable 2: project statement and motivation
Week 8	
Week 9	
Week 10 **(Wednesday at 12pm)**	✓ Activity: Elevator pitch and peer-feedback ✓ Intermediary deliverable 3: Model formulation and solution method
Week 11	
Week 12	✓ Intermediary deliverable 4: implementation & computational challenges
Week 13 **(Wednesday at 12pm)**	✓ Activity: Elevator pitch and peer-feedback ✓ Intermediary deliverable 5: result analysis
Week 14 **(Friday at 6pm)**	✓ Final deliverable: report & code

Intermediary deliverable 1: Group contract

The students will form groups **of 3-4 students** and prepare a group contract. They will receive feedback from the teachers on their group contract. They can revise and resubmit this group contract.

Their group contract should formalize the expectations of group members and contain the following:

- Group members' names and contact information

- Expectations (ground rules) regarding preparation for and attendance at group meetings, frequency and duration of meetings, and communication. The contract should focus on behaviors that will be expected of all group members and should only include those behaviors that are crucial to the group's effectiveness. Groups could aim for five to seven ground rules.
- Assignment of specific tasks, roles, and responsibilities along with due dates. The group can itemize the tasks to be completed for the project and provide a space for each group member to sign up for that task.
- Outline of the specific process for dealing with unmet expectations or other problems that might arise.
- An agreed-upon method for peer feedback during the project so that problems can be addressed before the project ends.
- A place for each group member to sign, indicating their agreement to the contract.
- A place for group members to sign once the project is completed to indicate whether or not they agree that all group members contributed as expected and, therefore, earn the group grade.

The group contract should be prepared using the following instructions and template: https://sheridancollege.libguides.com/groupwork/managing-group-projects/writing-a-group-contract

Intermediary deliverable 2: Problem statement and motivation

Each group can submit a short intermediary report (max 4 pages, 1 column, 12pt), summarizing their problem statement and plan of action to tackle this problem. They will receive feedback on their report from the teachers and will be able to address this feedback in their final report.

Intermediary deliverable 3: Model formulation and solution method

Each group can submit a short intermediary report (max 4 pages, 1 column, 12 pt), presenting their mathematical model formulation and solution method. They will receive feedback on their report from the teachers and will be able to address this feedback in their final report.

Intermediary deliverable 4: Implementation and computational challenges

Each group can submit a short intermediary report (max 4 pages, 1 column, 12 pt), presenting the implementation and computational challenges related to the implementation of their approach. They will receive feedback on their report from the teachers and will be able to address this feedback in their final report.

Intermediary deliverable 5: Results analysis

Each group can submit a short report (max 4 pages, 1 column, 12 pt) highlighting and analyzing their key results. They will receive feedback on their report from the teachers and will be able to address this feedback in their final report.

Final deliverable

Each group should submit:

- A final group report (max 20 pages + references and appendix, 1 column, 12pt) summarizing and motivating their problem statement, model formulation and solution method, analyzing and critiquing their numerical results.
- A working code (properly documented) along with their report.
- A table summarizing the individual participation (in %) of each group member to each category of the project.
- A signed group contract.

Solely the final deliverable (report & submitted code) will be graded (summative assessment). Although the intermediary deliverables are not mandatory, they provide an opportunity for you to receive feedback on your progress (formative assessment).

Evaluation criteria and grading scale

Four categories of the project work will be evaluated, namely:

1. **Problem statement and motivation (10% of final grade)**
2. **Optimization problem formulation and solution method (30% of final grade)**
3. **Implementation (25% of final grade)**
4. **Numerical validation (35% of final grade)**

These categories will be evaluated separately in the final report (grade between 0 – 100%), based on the abovementioned instructions (a detailed grading table will be provided), and will count towards the final grade based on their respective weights (see above). The clarity and quality of the presentation will be evaluated in each category.

In addition, the individual participation of each student in the group work will be accounted for in your individual grade. Each group is expected to work collaboratively on each task. Hence, each student is expected to have a minimum participation ratio in each evaluation category (the participation ratio of all students in each category should sum to 100%). If a student falls below these minimum ratios in any category, their final grade will be adjusted proportionally. These minimum participation % and the corresponding adjustment factors for each category are listed below:

Individual participation %	**Adjustment of grade**
[***b***%, 100%]	No adjustment
[***a***%, ***b***%[	grade*(individual participation %)/***b***
[0%, **a**%[	Fail (overall)

Where, the values of the thresholds ***a*** and ***b* (in %)** are given below, depending on the size of the group:

Group size	***a* (in %)**	***b* (in %)**
4	10	18
3	13	24
2*	20	37

* not recommended, only allowed if one or more group members drop out of the course after the group formation

Each student will receive a grade between 0-100%, which will then be converted into the 7-scale grading system as follows:

[92% - 100%] → Grade 12 (pass)
[84% - 92%) → Grade 10 (pass)
[68% - 84%) → Grade 7 (pass)
[60% - 68%) → Grade 4 (pass)
[50% - 60%) → Grade 2 (pass)
[20% - 50%) → Grade 0 (fail)
[0% - 20%) → Grade -3 (fail)

Group project topics

Below you are given different options for your group project topics. You should only choose *one topic* per group.

While we provide you with some recommended sources for data that might help build case studies for the models you develop, you are free (and encouraged) to find other sources too.

Each topic formulation has a problem description that describes what you might want to consider when you formulate your optimization models. We do not expect you to include everything suggested in the different texts, but you should make sure that you include at least one source of uncertainty, consider the scalability of the problem and(or) apply a method that relies on KKTs/duality theory when relevant. Remember to refer back to the learning objectives.

We do not provide forecasts and realizations or scenarios/distributions for sources of uncertainty. Based on the data you have available you should make assumptions to obtain scenarios/distributions yourself. Please argue why you make the assumptions you do. If in doubt you can discuss your assumptions with the teaching team.

Further, some relevant literature is listed for your *inspiration*. You can use this to help understand and formulate your models as well as gain insight into potential useful data. You can also use these works as references when you write your final assignments. We encourage you to also look for helpful literature yourself.

Option 1: Optimal grid expansion problem

Objective

In this project, you will explore the problem of optimal grid expansion from the perspective of a Transmission System Operator (TSO) or Distribution System Operator (DSO). Your task is to develop an approach to identify and assess the most effective investments in grid expansion to accommodate growing energy demand and increased use of variable renewable energy sources, while accounting for both technical and economic factors as well as the impact of long-term uncertainty.

Problem description

The grid expansion problem aims to find the optimal investments to reinforce or expand the transmission and/or distribution power grid, to adapt to the changing (increasing) power demand and increasing share of variable power sources. The transmission and distribution capacity of the grid is often a limiting factor in power systems already today, and large investments into the grid are needed.

At the transmission level, it is typical that the geographical regions with high shares of renewable power resources are different from regions with high demand for power, thus efficient transmission of power is important. At the distribution level, the growing energy demand and bidirectional flows resulting from rising shares of distributed energy resources (DERs) and prosumers, i.e. consumers with flexible loads (e.g. electric vehicles, heat-pumps, batteries) and power production units (e.g. rooftop PV) already pose significant challenges for DSOs.

The TSO or DSOs' objective is to run the grid as efficiently and safely as possible. This means that they aim to provide a stable supply of energy, i.e. minimizing the unserved loads while accounting for potential disturbances and/or contingencies in the system, at the lowest possible cost, i.e. maximize the social welfare across their planning horizon. Therefore, to solve the optimal grid expansion problem, the TSO and DSOs must account for the investments costs that incur when expanding any line capacity or building a new line, as well as the costs of operating the (new) system over the chosen time horizon.

When expanding the grid, there are certain constraints the TSO or DSOs should comply with. There could e.g. be political or geographical restrictions on where they are allowed to build new lines (e.g. areas where grid expansion is not allowed or too expensive). Furthermore, they might be limited by budget restrictions, or technical constraints on the maximum number of lines that they can upgrade and/or build at the same time. Finally, they might be constrained by technical and safety requirements, such as limits on the losses in the system and reliability of the power delivered under various potential disturbances and/or contingencies.

In addition, several years might pass between the time a new (or enhanced) line is planned and its construction is completed. Therefore, the TSO and DSOs must take investment decisions now for an uncertain future generation mix and demand profile. This requires accounting for long-term uncertainty and associated risks.

Generally, solving investment problems with long-term uncertainty is computationally challenging. To be able to find a solution to this optimization problem in a tractable time, decomposition techniques might be necessary, as well as the use of scenario reduction techniques and representative hours/days/years.

Finally, the TSO and DSOs might want to consider how their investments impact electricity prices and thus producers and prosumers' behavior. For instance, if a new line would lead to higher energy prices in a region, this could lead to more demand response from prosumers and increased supply in that region. To do so, they should anticipate the impact of their investment decisions on future energy market clearing using complementarity modelling.

Recommended data

- Future renewable generation and electricity demand: https://2024.entsos-tyndp-scenarios.eu/download/
- Existing grid: Ordoudis, C., Pinson, P., Morales González, J. M., & Zugno, M. (2016). *An Updated Version of the IEEE RTS 24-Bus System for Electricity Market and Power System Operation Studies*. Technical University of Denmark. (Or any IEEE test system)
- Costs on grid expansions: Look in literature

Recommended research papers & books

N. Alguacil, A. L. Motto and A. J. Conejo, "Transmission expansion planning: a mixed-integer LP approach," in *IEEE Transactions on Power Systems*, vol. 18, no. 3, pp. 1070-1077, Aug. 2003, doi: 10.1109/TPWRS.2003.81489.1 Available at: 10.1109/TPWRS.2003.814891

S. de la Torre, A. J. Conejo and J. Contreras, "Transmission Expansion Planning in Electricity Markets," in *IEEE Transactions on Power Systems*, vol. 23, no. 1, pp. 238-248, Feb. 2008, doi: 10.1109/TPWRS.2007.913717. Available at: 10.1109/TPWRS.2007.913717

Shrestha, G. B., & Fonseka, P. A. J. (2004). "Congestion-driven transmission expansion in competitive power markets". IEEE Transactions on Power Systems, 19(3), 1658–1665. https://doi.org/10.1109/TPWRS.2004.831701. Available at: 10.1109/TPWRS.2004.831701

Ruiz, C., & Conejo, A. J. (2015). "Robust transmission expansion planning". European Journal of Operational Research, 242(2), 390–401. https://doi.org/10.1016/J.EJOR.2014.10.030. Available at: 10.1016/j.ejor.2014.10.030

Conejo, A. J., Baringo, L., Kazempour, J., & Siddiqui, A. S. (2016). "Investment in Electricity Generation and Transmission: Decision Making Under Uncertainty". Springer. https://doi.org/10.1007/978-3-319-29501-5. Available at: https://link.springer.com/book/10.1007/978-3-319-29501-5

Roald, L. A., Pozo, D., Papavasiliou, A., Molzahn, D. K., Kazempour, J., & Conejo, A. (2023). Power systems optimization under uncertainty: A review of methods and applications. Electric Power Systems Research, 214, 108725. https://doi.org/10.1016/J.EPSR.2022.108725

Morales, J. M., Conejo, A. J., Madsen, H., Pinson, P., & Zugno, M. (2014). Integrating renewables in electricity markets - Operational problems. Springer, 205, 429. https://doi.org/10.1007/978-1-4614-9411-9 (TEXTBOOK)

Option 2: Strategic investment problem for power plant operators

Objective

In this project, you will explore the problem of strategic investment from the perspective of power plant operators. Your task is to develop an approach to identify and assess the most effective investments in generation capacity, focusing on how to optimize the timing, location, and type of new power plants, while accounting for both market and regulatory factors, as well as the impact of long-term uncertainty in fuel prices, demand, and market conditions.

Problem description

The strategic investment problem for generators aims to determine the optimal investment decisions for expanding or upgrading power generation capacity, in a highly competitive and evolving electricity market. Power generators must make critical decisions on where, when, and what type of generation assets (e.g., renewable, thermal, storage units, or synchronous generators) to invest in, to maximize profits and ensure long-term competitiveness, while also adhering to environmental and evolving market regulations.

Power plant operators must decide whether to invest in traditional (e.g., gas, coal) or renewable generation (e.g., wind, solar, hydro) based on market incentives, fuel price projections, and policy-driven goals like carbon reduction. Investments in renewables offer long-term benefits but come with uncertainties in generation due to variability and intermittency. When solving the strategic investment problem, generators must balance investment (e.g., capital costs of new plants), operational and maintenance costs with projected revenue streams from selling electricity and capacity into the electricity market. Accurately modelling these (uncertain) future profits require accurately modelling the investment costs, operational costs and constraints, and maintenance needs and costs of the various technologies considered.

Investment decisions may be influenced by various economic, geographical, technical and regulatory constraints. For instance, the power plant operators might be limited by budget constraints and the maximum number of new facilities they can build at the same time. Besides, the optimal investment strategies may be impacted by the regulatory frameworks, such as quotas on low-carbon energy sources, carbon pricing mechanisms, and potential subsidies for renewable projects. Power plant operators should model compliance costs related to emissions and consider how carbon pricing affects long-term profitability. Similarly, the geographical location of new power plants is critical. Locating generation near demand centers or in areas with strong renewable resources can increase profitability. However, locational decisions are often constrained by regulatory hurdles, land availability, and connection to the grid.

These investment decisions are further complicated by long-term uncertainty on fuel prices, demand growth, policy changes, and technological advancements, due to the increasing penetration of renewable energy sources, fluctuating demand, and regulatory changes aimed at decarbonizing the grid. As investments made today will impact the power plant's position in the market for decades, the power plant operators should account for long-term uncertainty in their optimal investment strategy. Scenario analysis, stochastic modeling, and risk-hedging strategies are critical for managing this uncertainty. Indeed, power plant operators face the challenge of ensuring their investments remain profitable over time, while accounting for the financial risks related to market price volatility, shifts in fuel costs, and competition from other market participants. Achieving a desirable trade-off between these various objectives depends on the individual attitude towards risk of a given power plant operator.

However, representing accurately these numerous sources of long-term uncertainty may result in computational challenges. Given the complexity and scale of this problem, generators often need to employ advanced optimization techniques, such as scenario reduction approaches as well as decomposition techniques.

Finally, strategic investments from large producers can affect the energy market dynamics. Indeed, generators with significant capacity may influence market prices through strategic bidding. Hence, large investments could shift the market dynamics, potentially allowing the generator to exercise market power. Strategic power plant operators can anticipate how their investment decisions will alter market dynamics by including market equilibrium models or complementarity modeling to simulate how the market will clear under different investment scenarios.

This project will require you to integrate technical, economic, and market perspectives, addressing the key challenges facing power generators as they seek to make long-term, profitable investments in an uncertain and evolving energy landscape.

Recommended data:

- Future renewable generation and electricity demand: https://2024.entsos-tyndp-scenarios.eu/download/
- Existing grid: Ordoudis, C., Pinson, P., Morales González, J. M., & Zugno, M. (2016). *An Updated Version of the IEEE RTS 24-Bus System for Electricity Market and Power System Operation Studies*. Technical University of Denmark. (Or any IEEE test system)
- Investment costs: Look in literature

Recommended research papers & books:

Conejo, A. J., Baringo, L., Kazempour, J., & Siddiqui, A. S. (2016). “Investment in Electricity Generation and Transmission: Decision Making Under Uncertainty”. Springer. https://doi.org/10.1007/978-3-319-29501-5. Available at: https://link.springer.com/book/10.1007/978-3-319-29501-5

Kazempour, J., Conejo, A. J., & Ruiz, C. (2013). Generation Investment Equilibria With Strategic Producers-Part I: Formulation. *IEEE Transactions on Power Systems*, *28*(3), 2613-2622. https://doi.org/10.1109/TPWRS.2012.2235467

L. Baringo and A. J. Conejo, "Offering Strategy of Wind-Power Producer: A Multi-Stage Risk-Constrained Approach," in *IEEE Transactions on Power Systems*, vol. 31, no. 2, pp. 1420-1429, March 2016, doi: 10.1109/TPWRS.2015.2411332.

Roald, L. A., Pozo, D., Papavasiliou, A., Molzahn, D. K., Kazempour, J., & Conejo, A. (2023). Power systems optimization under uncertainty: A review of methods and applications. Electric Power Systems Research, 214, 108725. https://doi.org/10.1016/J.EPSR.2022.108725

Morales, J. M., Conejo, A. J., Madsen, H., Pinson, P., & Zugno, M. (2014). Integrating renewables in electricity markets - Operational problems. Springer, 205, 429. https://doi.org/10.1007/978-1-4614-9411-9 (TEXTBOOK)

Option 3: Optimal scheduling and strategic offering problem in electricity markets

Objective

In this project, your group will explore how electricity market participants, particularly power producers, can derive optimal scheduling and/or strategic offering strategies. The focus is on understanding how these strategies impact both the profitability of the producer and the overall social welfare of the electricity market. You will analyze the role of uncertainty, market design, and market power.

Problem description

Electricity markets aim to balance supply and demand efficiently, maximizing social welfare by clearing the market at prices that reflect the true marginal costs of production. However, in practice, power producers, including battery operators, renewable power producers, and synchronous generators, often seek to maximize their own profits across multiple market platforms, including the day-ahead and balancing electricity markets, and ancillary service (reserve) markets.

To model their costs and operating constraints accurately, each type of producer—renewable energy producers, battery operators, and synchronous generators—must consider both their specific technological characteristics and market conditions in different market platforms. Due to these specificities, different market platforms may be more or less profitable for various technologies.

The profit-maximizing scheduling and offering strategies of these producers may lead to strategic behavior. Under perfect competition, producers would submit bids based on their actual marginal costs, but real-world markets are rarely perfectly competitive. Producers may behave strategically, increasing their bids above their true marginal costs or withholding generation capacity to drive up prices, thereby boosting their own profits at the expense of market efficiency and social welfare. Modelling these price-making offering strategies requires anticipating the impact of the derived price-quantity bids on the market clearing outcomes, using complementarity modelling or Bertrand/Cournot oligopoly models.

In addition, both price-maker and price-taker strategic producers face significant sources of uncertainties since they do not know future energy prices, bids of other market players or the exact demand curves ahead of time. This uncertainty forces producers to balance the expected profits from their scheduling and offering strategies with the financial risks related to being over- or under-dispatched or facing unfavorable market conditions, depending on their individual attitude towards risk.

In addition to these strategic considerations, the integration of renewable energy, such as wind, introduces new challenges. Renewable energy is inherently variable, and power producers must account for this uncertainty when participating in ancillary services and day-ahead markets, where bids are submitted in advance of actual production. Any deviations from the scheduled production, caused by forecasting errors or the activation of reserves, may lead to financial penalties or rewards through imbalance prices.

Representing accurately these numerous sources of uncertainty may result in computational challenges, which can be tackled by using scenario reduction approaches as well as decomposition techniques.

Recommended data:

- Prices in various areas (SE and DK) for FCR-N and FCR-D (up and down): https://www.energidataservice.dk/tso-electricity/FcrNdDK2 or https://www.energidataservice.dk/tso-electricity/FcrReservesDK2 for data before June 2023.
- Scenarios for wind production in hourly resolution for the next day https://zenodo.org/records/1346213
- Or use from https://www.renewables.ninja/

Recommended research papers & books:

Conejo, A. J., & Baringo, L. (n.d.). Power Electronics and Power Systems Power System Operations. http://www.springer.com/series/6403 Chapter 8.

Lectures on "Renewables in Electricity Markets" by Pierre Pinson: https://pierrepinson.com/index.php/teaching/

J. M. Morales, A. J. Conejo and J. PÉrez-Ruiz, "Short-Term Trading for a Wind Power Producer," in *IEEE Transactions on Power Systems*, vol. 25, no. 1, pp. 554-564, Feb. 2010, doi: 10.1109/TPWRS.2009.2036810. Available at: https://ieeexplore.ieee.org/abstract/document/5373832

Morales González, J. M., Conejo, A. J., Madsen, H., Pinson, P., & Zugno, M. (2014). "Integrating Renewables in Electricity Markets: Operational Problems". Springer. International Series in Operations Research and Management Science Vol. 205 https://doi.org/10.1007/978-1-4614-9411-9. Available at: https://link.springer.com/book/10.1007/978-1-4614-9411-9

Roald, L. A., Pozo, D., Papavasiliou, A., Molzahn, D. K., Kazempour, J., & Conejo, A. (2023). "Power systems optimization under uncertainty: A review of methods and applications". Electric Power Systems Research, 214, 108725. https://doi.org/10.1016/J.EPSR.2022.108725. Available at: https://www.sciencedirect.com/science/article/abs/pii/S0378779622007842

Fushuan Wen and A. K. David, "Optimal bidding strategies and modeling of imperfect information among competitive generators," in *IEEE Transactions on Power Systems*, vol. 16, no. 1, pp. 15-21, Feb 2001, doi: 10.1109/59.910776.

de la Torre, S., Aguado, J. A., & Sauma, E. (2023). "Optimal scheduling of ancillary services provided by an electric vehicle aggregator". Energy, 265, 126147. https://doi.org/10.1016/J.ENERGY.2022.126147. Available at: https://www.sciencedirect.com/science/article/pii/S036054422203033X

M. Shafie-khah, A. A. S. de la Nieta, J. P. S. Catalao and E. Heydarian-Forushani, "Optimal self-scheduling of a wind power producer in energy and ancillary services markets using a multi-stage stochastic programming," *2014 Smart Grid Conference (SGC)*, Tehran, Iran, 2014, pp. 1-5, doi: 10.1109/SGC.2014.7150712. Available at: https://ieeexplore.ieee.org/document/7150712

M. Zugno, J. M. Morales, P. Pinson and H. Madsen, "Pool Strategy of a Price-Maker Wind Power Producer," in *IEEE Transactions on Power Systems*, vol. 28, no. 3, pp. 3440-3450, Aug. 2013, doi: 10.1109/TPWRS.2013.2252633.

Option 4: Integrating Flexible Prosumers in Wholesale Electricity Markets

Objective

In this project, you will explore the problem of aggregating and integrating flexible consumers and prosumers into the electricity markets from the perspective of an energy community manager. Your task is to develop an approach to optimize the participation of flexible consumers and prosumers in electricity markets.

Problem description

The increasing decentralization of energy systems, coupled with the growing adoption of distributed energy resources (DERs) like rooftop solar panels, batteries, and electric vehicles (EVs), offers the opportunity for prosumers—individuals or entities that both produce and consume energy—to participate in wholesale electricity markets, such as day-ahead and balancing electricity markets and ancillary service markets.

Energy communities are legal entities, operated by a non-profit community manager, aiming at coordinating the participation of the flexible consumers and prosumers within it in wholesale electricity markets. The role of the energy community manager is to design incentives that optimize energy transactions and consumption within the community and encourage prosumers to shift their consumption to align their individual interests with the community's objectives. These objectives may include balancing supply and demand within the energy community, maximizing local consumption of renewable energy production and minimizing reliance on grid imports, reducing the energy procurement costs of the community members, or providing grid services to the transmission or distribution system operators. There are two primary mechanisms for enabling this coordination:

1. **Community-based local market:** The community manager organizes a local energy pool in which consumers and prosumers can buy and sell energy directly with one another through, which allows for more localized energy exchanges and reduced reliance on the central grid. The clearing of these local markets can be performed in a centralized manner by the community manager, or in a decentralized manner using decomposition techniques, in order to protect the privacy of the community members. In addition, the properties of these markets can be analyzed through equilibrium and complementarity modelling.

2. **Dynamic Pricing:** The community manager sets optimal hourly and locational prices to incentivize prosumers to adjust their energy consumption in line with community-level objectives. The community manager must model the impact of price signals on prosumers' behavior through complementarity and equilibrium modelling, ensuring that dynamic pricing schemes are designed to be both financially attractive and operationally effective.

To ensure the cost-effectiveness and reliability of the consumers and prosumers dispatch resulting from the proposed dynamic pricing or local market mechanisms, the community manager should account for various technical, economic, and regulatory factors. Firstly, they should accurately model the utility functions and operational constraints of the various types of consumers and prosumers. Indeed, prosumers with flexible loads, such as EVs, batteries, and heat pumps, have different levels of flexibility in terms of when and how they consume energy, and derive various utilities from their energy consumption. In addition, accurately accounting for the individual preferences of the community members (such as risk preferences) and ensuring the fair distribution of the profits among these prosumers is key to maintaining their participation in the community. Prosumers need to feel that they are fairly compensated for their contributions to the market, whether they are selling surplus energy or offering flexibility through reduced consumption. Finally, ensuring the feasibility of power flows within the community is essential to guarantee the operational effectiveness of the proposed market and dynamic pricing mechanisms.

In addition, various sources of uncertainty complicate the decision-making problem of the community manager for the integration of flexible loads and prosumers in wholesale electricity markets, including variability in renewable energy generation (e.g. PV production), unpredictable prosumer behavior and load patterns (e.g. EV charging), fluctuations in market prices, and external factors like weather conditions. To ensure the cost-effective and reliable dispatch of the flexible consumers and prosumers within the community, the community manager should account for these sources of uncertainty. Given the uncertainty in prosumer behavior and renewable energy generation, scenario analysis is critical for robust and risk-aware decision-making. The community manager can use stochastic models to account for different future states of energy supply and demand.

This project requires you to design and model a system that optimizes the integration of flexible loads and prosumers within an energy community through P2P (peer-to-peer) trading or dynamic pricing. You will need to address technical, economic, and regulatory challenges to achieve the community's goals.

Recommended data

- Data on demand development from different sectors (e.g. households) over years per EU country: https://tyndp.entsoe.eu/resources/d-1
- Data from 11 households in Germany: https://data.open-power-system-data.org/household_data/
- Predicted load profiles https://www.eac.com.cy/EN/RegulatedActivities/Distribution/agorailektrismou/Pages/ConsumerTypicalLoadProfiles.aspx (From Cyprus and all files are in Greek)

Recommended articles & book chapters

Roald, L. A., Pozo, D., Papavasiliou, A., Molzahn, D. K., Kazempour, J., & Conejo, A. (2023). Power systems optimization under uncertainty: A review of methods and applications. Electric Power Systems Research, 214, 108725. https://doi.org/10.1016/J.EPSR.2022.108725

Morales, J. M., Conejo, A. J., Madsen, H., Pinson, P., & Zugno, M. (2014). Integrating renewables in electricity markets - Operational problems. Springer, 205, 429. https://doi.org/10.1007/978-1-4614-9411-9 (TEXTBOOK)

Gkatzikis, L., Koutsopoulos, I., & Salonidis, T. (2013). The role of aggregators in smart grid demand response markets. IEEE Journal on Selected Areas in Communications, 31(7), 1247–1257. https://doi.org/10.1109/JSAC.2013.130708

Crowley, B., Kazempour, J., & Mitridati, L. (2023). How Can Energy Communities Provide Grid Services? A Dynamic Pricing Mechanism with Budget Balance, Individual Rationality, and Fair Allocation. https://arxiv.org/abs/2309.05363v3

Jia, L., & Tong, L. (2012). Optimal pricing for residential demand response: A stochastic optimization approach. 2012 50th Annual Allerton Conference on Communication, Control, and Computing, Allerton 2012, 1879–1884. https://doi.org/10.1109/ALLERTON.2012.6483451

Dorini, G. F., Pinson, P., & Madsen, H. (2013). Chance-constrained optimization of demand response to price signals. *IEEE Transactions on Smart Grid*, *4*(4), 2072-2080. https://doi.org/10.1109/TSG.2013.2258412

Sousa, T., Soares, T., Pinson, P., Moret, F., Baroche, T., & Sorin, E. (2019). Peer-to-peer and community-based markets: A comprehensive review. Renewable and Sustainable Energy Reviews, 104, 367–378. https://doi.org/10.1016/J.RSER.2019.01.036

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Tushar, W., Member, S., Saha, T. K., Yuen, C., Smith, D., & Vincent Poor, H. (2020). Peer-to-Peer Trading in Electricity Networks: An Overview. https://arxiv.org/pdf/2001.06882

de la Torre, S., Aguado, J. A., & Sauma, E. (2023). Optimal scheduling of ancillary services provided by an electric vehicle aggregator. Energy, 265, 126147. https://doi.org/10.1016/J.ENERGY.2022.126147

Option 5: Custom topic (to be approved by course responsible)