Designing a Power Grid

Fall 2025

Introduction

You own an engineering company. A foreign government comes to you and asks you to design their power grid. From scratch. Can you do it? Can you ensure the grid can safely supply electricity to everybody? And can you achieve the minimum environmental impact?

In this project, you will design a power system from scratch and perform several power flow simulations. The goal is to apply the fundamental methods and concepts from the lectures in a practical context. Along the way, you will face a number of design decisions and be guided by the central question: "How do renewables impact the power system if you were the grid operator?"

To explore this, you will begin by designing a conventional, robust transmission grid for a country or region of your choice. Then, you will gradually decarbonize the system by increasing the share of renewable energy sources (RES). The project can be structured into the following steps:

1) Step 1 (Task 1): Initial analysis and design of the baseline grid
2) Step 2 (Task 1) Implementation of the baseline grid in PowerFactory and analysis of the system
3) Step 3 (Task 2) Renewable expansion scenario
4) Step 4 (Task 3) RES reactive power supporty
5) Step 5 (Task 4) Time-series analysis

In this project you will become familiar with the software tool PowerFactory. You can find more details about PowerFactory on the course's Teams (accessed via DTU Learn). Note that our DTU version supports a maximum of 50 buses. Consider this limit when you plan your system and leave some reserve for possible later adjustments.

1 Task 1: Baseline grid

At the start of the project, we assume a grid with only conventional generation units, similar to how power grids operated for almost a century. This means that all generation is based on conventional sources, i.e., coal, oil, gas, nuclear, or hydro, and all use only synchronous generators. The requirements for the system (area, loads, number of nodes, transmission system, etc.) are described in detail in the following link: System Requirements. At this stage, you perform your initial analysis and investigation and determine the high-level characteristics of your system without using PowerFactory, i.e., decide the area, find the available resources, load distribution, etc.

Next, you need to build your system in PowerFactory. Your design should result in a system where you can run power flows for the following three scenarios and get acceptable system states (generator loadings, line loadings, and voltages). *Your system must be N-1 secure in the high load scenario.*

- Low load (2000 MW demand)
- Medium load (4000 MW demand)
- High load (6000 MW demand)

When simulating the above cases, you might need to make adjustments to your initial plants' sizing/location, as well as the grid. The result should be a robust baseline grid that delivers power in all these situations, respects all voltage and component limits, and is N-1 compliant for the high-load case. For the N-1 compliance analysis, you can use the N-1 sweep tool for outages of single generators and single lines.

Remember that your resulting baseline system must be the same across these 3 scenarios and can withstand all these events. In each scenario, you will need to adjust the power set-points of your generators, and possibly the voltage set-points and tap-changers of the transformers. You may use reactive power compensation units in moderation (consider their investment and operational cost) if necessary, making sure their sizes are realistic. Again, in each scenario, you may need to adjust the output of these units. For the N-1 case, loadings of up to 100% are permissible but should be avoided, and no part of your system should be islanded during any line loss.

2 Task 2: Operation with high shares of RES

Background: Over the past two decades, there has been a rapid increase in the share of renewable energy generation integrated into the electricity grid, primarily wind turbines and solar PV. Denmark has been at the forefront of these developments, operating an electricity grid with very large shares of RES. As a matter of fact, Denmark has been among the first countries to run its electricity grid on 100% RES for a full day (on Feb. 23, 2017). During the past years, Denmark has been covering up to 80% of the total electricity demand from RES (in 2022 and 2023). This does not mean that every day the share of RES is up to 80%. There are days when the share can be more than 100% (contributing to the export of electricity as well) and days when the total share of RES can be as low as 0%. Modern power grids are, therefore, exposed to very high variability in their generation mix and should be robust enough to handle electricity production from different sources and locations. This also includes the capability of reactive power generation, which is important for maintaining voltage within the permissible range.

Task: To study these developments in your project, in this part, you will operate under varying amounts of wind and solar generation in your system, and analyze the impact on the grid for the high load case (6000 MW). You don't need to perform the N-1 analysis in this task. First, you should install in total 6000 MW of RES (wind and solar) in addition to the already existing conventional generation. It is up to you to decide the mix between the two. For your decision, you shall also consider the relevant potential in the area you chose. After you decide the mix, you shall consider two operational scenarios which represent different weather conditions:

- 50% RES, i.e., 3000 MW.
- 80% RES, i.e., 4800 MW

Here, $\text{RES} = \text{MW}_{\text{wind}} + \text{MW}_{\text{solar}}$. Naturally, your baseline grid will need to be modified with new connections for the RES units. To highlight the challenges of RES integration, try to minimize the adjustments to your baseline grid, and consider only extra lines apart and the placement of new reactive power support units (SVC), but only when deemed necessary. Again, keep the cost of such units in mind and try to minimize them.

Important: For each scenario, you shall *turn off* as many of the conventional generators as possible, until you reach the scenario target. You will need to change the set-points of conventional generators and control of SVCs, the voltage set-points, and tap-changers with respect to the baseline grid modeling to achieve that. All renewable energy generation should be modeled with a power factor $\cos\varphi = 1$ in this task (no reactive power support). If you need more reactive power, then you may keep some conventional plants on, set their active power to 0, and set a maximum reactive power equal to $\pm 40\%$ of the machine's rated power.

The goals in this task are (i) to achieve the renewable energy source target, (ii) to keep bus voltages and line currents within the permissible limits. In your report, compare and discuss the system losses compared with the baseline grid (high-load scenario).

3 Task 3: Reactive Power Support from RES

Background: During several recent blackouts, including the one in Spain in 2025, the question of reactive power support from RES has been raised as one of the key contributors to the security of the grid. Several countries in Europe already require RES to offer reactive power to assist in severe overvoltages or undervoltages, which can lead to a blackout. In this task, you will need to examine how much the security of the power grid changes if you allow RES to offer reactive power support.

Task: You will work with the grid developed in Task 2 and consider again the high load case (6000 MW). Again, there are no N-1 considerations. Compare the losses across the three cases and discuss any differences.

- Case 1 is the 80% RES production with a fixed power factor and $\cos\varphi = 1$, taken from Task 2.
- Case 2, where you have 80% RES with a power factor that can vary between $0.95 \leq \cos\varphi \leq 1.0$ (lagging or leading).
- 100% RES with a power factor that can vary between $0.95 \leq \cos\varphi \leq 1.0$ (lagging or leading).

You are expected to answer these questions:

1. In Case 2, how many power plants providing reactive support (with P=0) could you switch off because you allowed a variable power factor in your RES plants?
2. Are you now able to run a power system with 100% RES (6000 MW)? For this case, your goal is to turn off all conventional generation units. If you cannot achieve this, you shall leave ON the minimum number of conventional units.

4 Task 4: Time series analysis

While building your power system, you used only instances to run power flows or test N-1 security, i.e., you made no considerations on performance with a realistic range of conditions. In this task, you will use time series of load, PV, and wind production from the country you chose over a whole year. The goal is to assess on a high level if your design could handle more realistic operational conditions and reflect on possible modifications that would be necessary. There are multiple sources available online for such data, and some guidelines/tips will be available in the course's accompanying website soon. You don't need to use PowerFactory or simulations for the following questions, but explain your answer based on the time series and system characteristics.

- Scale your load timeseries so that you obtain an average load of 4000 MW, equal to the mid-level scenario. What is the min and max load you observe and how does it relate to the low and high load of 2000 MW and 6000 MW we considered?
- In case these values are more strenuous than the ones used in Task 1, do you think your power system would handle them? Justify your answer and what possible modifications would be necessary.
- Consider now the case where you installed 6000 MW of RES. Use the net demand time-series, i.e., your load minus the RES production. Based on this, what is the highest and lowest rate of change of net-demand for two consecutive hours? Would your system (conventional units + interconnection) be able to handle such a sudden change? Consider some realistic ramp rates for your units based on the literature. What would need to adjust in your system to do so? Do you think your RES would allow you to decommission any conventional power plants?

For these questions, don't constrain yourselves to the project's requirements. Consider the system (with and without RES) that you developed and the above questions. You could think of various solutions such as storage, additional interconnections, RES curtailment, load curtailment (not very popular!), operating power plants at lower rates, having more flexible power plants, etc.

5 Report

As a general guideline for this report, try to be concise in your descriptions and show us your understanding of the system that you designed. Also, keep the context of this project in mind: "How does decarbonizing the grid (by adding more renewables) impact the power system from a grid operator's perspective?"

The report should provide details of the simulation, but a good report also abstracts from the simulations – for example, highlights trends, notes unexpected behavior, identifies why simulations fail, etc. Numbers are important, but only when put in context. Further down, you find a list of appendices that you need to attach to your report. This is the place for all the numerical details on the simulations, so that in the main body of the report you can focus on your analysis based on these numerical results. One additional item to add to the report is an exported file with your PowerFactory system model and the operational scenarios. Please note though that you cannot expect us to look at the PowerFactory model while reading the report – the report must be self-sufficient!

See below a short overview of the report sections, and please stick to the page limits of the sections. The report and the appendix must not exceed 10 and 12 pages, respectively.

5.1 Introduction – max: 3/4 page

Provide a brief introduction to the project and the report. By reading this part, the reader should clearly understand the key questions the report addresses and why these questions are important (note: stating that the project is part of a course is not a valid reason). Ideally, the introduction sets out the goal of your analysis, which you then answer in the conclusion. Together, these two sections should give the reader a comprehensive overview of what has been done in the report and prepare them for the detailed technical content that follows.

Simulation tasks and analysis - max: 6 pages + 2 additional pages with figures

This section forms the center of your report and should present the power system analysis; once more, abstracting from the simulations is the goal. You can structure it as you wish but please stick to the page limit. The following questions can provide you with some ideas for the content:

- Task 1: What role does the geography and the distribution of the demand play for the grid design? How close are demand and generation located to each other? Do you have any long-distance lines and are there any challenges with that? Did your N-1 consideration lead you to change your grid?
- Tasks 2 and 3: Where there reinforcements necessary? What are typical problems? What was your design and analysis approach when the

results were not satisfactory? What are the challenges when including more renewable sources and what strategies are needed? How do renewable sources impact the reactive power balance in the grid?

5.2 Conclusion – max: 3/4 page

This section shall answer the questions posed in the introduction and give a brief overview of the technical results that you obtained. This could include:

- A short and high-level summary of the analysis setup (no need to go into a lot of details here).
- The main conclusions from the tasks, e.g., how did the grid perform, what are strengths and weaknesses of the grid, how did renewables affect your grid design and performance.
- Future work: provide perspective on aspects that could be improved if you were to continue the project.

5.3 Lessons learned – max: 1/2 page

In this section, you are asked to reflect upon the process of how you conducted the project – this can be about technical decisions, managing the project, working in a group, etc. What are your main takeaways from this project? Please mention 3-6 takeaways. Include at least 1 takeaway for the design process, at least 1 takeaway for the part of your work related to Powerfactory, and at least 1 takeaway that is not related to technical matters, i.e., it can be about how you shall manage your work as a group, how you shall structure a report, what questions you shall ask when you start a project, etc. The takeaways shall be the key points emerging from your involvement in this project that you would like to remember for the next 5 years.

5.4 Workload distribution

Please give an overview of who in the group was responsible for which sections of the report. Make sure that everyone is involved in at least one section that involves power flow computation and analysis.

5.5 Timeline

- Project kick-off: Sep 5
  Introduction to the project, formation of groups
- Introduction to PowerFactory: Sep 12
- Introduction to mid-term presentation format: Sep 26
- Preliminary presentation - Oct 10
  Present your initial power system design with lines, generating units, loads, sizes, etc. Ideally have started implementing the system in PF, and show preliminary results/challenges with Task 1
- Introduction to final presentation format - Nov 14
- Final presentation - Nov 25
  At this point it's beneficial to have finalized and present most tasks so that you get more complete feedback
- Final report - Dec 4

Appendices

Grid layout

Show a schematic of the grid with the placements of the nodes and a clear naming. This can be an export of PowerFactory display (make sure it is legible) or some other graphic representation. Ideally, it serves as an orientation for the reader when going through your report (you can refer to it throughout the report). Show the layout of the baseline grid and also the grid accommodating RES.

Component summary

List all components and their parameters as used in the grid, i.e., generators, loads, lines, cables, transformers, reactive power compensation units. Together with the grid layout, it should be possible to reconstruct the grid. For lines, cables, and transformers, you can refer to the project description unless you used other values.

Scenarios dispatch

Provide one or multiple tables with all the active and reactive power dispatches for your generators in all scenarios (3 in Task 1 + 2 in Task 2 + 2 in Task 3). Make sure to also include the dispatch of the reactive power compensation units where relevant.

N-1 analysis

Simply export the results window from the N-1 analysis (make sure it's legible).

PowerFactory model

Export your PowerFactory model – please test if you can import it.

Grading scheme

Category	Weighing	Criteria
Formal layout	10%	Overall impression, page limit, plot legibility, legends, units
Language	5%	Understandable, well presented, correct use of technical terms, concise
Quality of analysis	10%	Connect concepts with lecture, present results in a meaningful way, being critical towards your own work
PowerFactory model	5%	Model included
Task 1	20%	Modeling assumptions for size and locations of generation & demand, requirements fulfilled, 3 load scenarios and N-1 analysis
Task 2	20%	2 load scenarios, discussion of required grid changes, role SVCs and reactive power support, losses comparison
Task 3	15%	2 scenarios, discussion of role of reactive power support from RES, losses comparison, discussion of the status of conventional power plants
Task 4	15%	Justification of answers, connection between real-world challenges and your system limitations
Overall	100%	-

Table 1: Grading scheme