42002: Second assignment

Modelling of Residential Hybrid Renewable Energy System

General information

The assignment is handed out on November 5th 2021 at 17:00. The poster presentation of the results is in person on December 3rd at DTU from 8:00-12:00. The report must be submitted on Learn.Inside (https://learn.inside.dtu.dk/) on December 6th before 23:59. Since it is part of the exam, the assignment must be solved and handed in by each group, and identical assignments are not accepted (plagiarism check is applied).

For the scientific poster presentation, you need to design and print your research posters with your motivation, objectives, methodology, results, and implications in the most common poster size DIN A0 or DIN A1. While the posters need to be presented on December 3rd, please also upload them as a pdf file under "Course Content / Assignments" and "Group Assignment - Poster Assignment". Furthermore, a report of a maximum of 9-10 (A4) pages (1 title page (including abstract), 1 content table page, 1 contribution page, 1-2 nomenclature pages, maximum of 3-4 research pages, 1 page for a figure about the model) needs to be uploaded before December 6th. Pleasure upload only one .pdf file with all necessary sections. At the same time, every group is required to upload the GAMS code. Please be aware that the system only keeps the most recent submission.

Additionally, the groups should give each other feedback with respect to the code but also to the general idea. Two groups should sit down (e.g., in the weekly exercise session) and present their ideas to each other and give each other feedback. After a 10-15 minutes discussion between the groups, feedback should be explained orally, but also recorded in writing. Please sit together and provide feedback to each other until 20th of November before 23:59. There is an extra submission for the feedback where you have to note down a maximum of seven aspects.

Motivation of the final project

In recent years, households have been adopting low-carbon technologies (LCTs), such as on-site storage and small-scale generation facilities. Most European countries have support policies for these technologies in place, which include stipulations about self-consumption. At the same time, there is an ongoing discussion about the cost-effectiveness of taxes on self-consumption, which has resulted in quite different approaches to policy design. This means regulation that accommodates self-consumption must consider both technical (for example, building, technology, demand) and socio-economic (for example, income, electricity prices, behaviour patterns) criteria of efficiency and equity. The group project aims to evaluate the optimal investment regarding cross-sectional LCTs (for example, photovoltaic systems, battery systems, electrical boiler, gas boiler, heat pumps, heat storage systems) at different tariff options (for example, flat and variable with and without tax schemes) for diverse socio-economic groups or rather different household archetypes (for example, high-income and low-income households, large and small dwelling areas).

You are asked to develop a mixed-integer linear program (MILP) for residential buildings to assess the optimal investment decision-making regarding electrical and thermal LCTs. The decision variables are the investment decisions of the households by minimising the total energy system costs for the respective households over the lifetime. Thereby, various technologies and their investment costs, as well as fuel and electricity prices, should be taken into account.

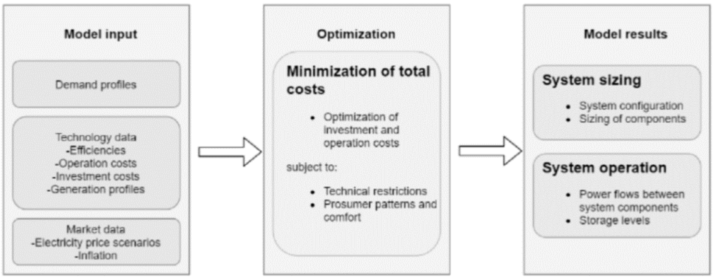
Based on household data for a Danish case study, the model needs to be applied to several household and LCT configuration archetypes under multiple policy framework conditions or tariff options. The results should include costs and revenue streams for households under different policy regimes and technology adoption. The impact of different tax configurations and levels will be assessed based on these results. We show that a comprehensive revision of current regulation can support prosumers' integration and address equity concerns by avoiding cross-subsidisation from poorer to richer households. From here, policy recommendations will be derived about the most cost-effective and equitable combinations of measures to be targeted towards specific household groups.

Our variables are the investment decisions of the households by minimizing the costs of energy.

Description of the general model

Formulate a model for residential energy system investment mathematically and implement it in GAMS. The objective function should minimise the energy purchase cost of the respective household. The electricity and heat demand of the household need to be covered at all the time. The model should include binary variables for each unit that may be invested. The main purpose of this assignment is to develop a model and assess this model. An overview of the general model concept is given in Figure 1:

Figure 1: Model concept: the objective of the model is to minimise the energy consumption cost while covering the required electricity and heat demand in every time step. The model results give an insight into the optimal energy system configuration.



It is often easier to start with a simple model. In this regard, you should start step by step. For example, first create a model that determines the costs without investing in the energy supply. Test this model and see whether the results are more or less in line with reality. Then you can add individual technologies one after the other and test the extended model. It is important to test extensively, at least at the beginning, under which conditions are invested in a technology. At the end, the main model should comprise the following:

- Formulate the model for energy system investment mathematically and implement it in GAMS. The model should include investments in both conventional electricity and heat technologies. To focus on the interactions between various technologies, the model should have an hourly time resolution. In principle, the time horizon of the model could be a year or a number of years. However, to facilitate computations, consider only a small number of representative weeks in a year, for example, an average week during each season. Justify any other model assumptions you make.
- The household is always able to cover the electricity demand with electrical energy from the grid. For the coverage of the heat demand, the household should be equipped in the basic scenario with a natural gas boiler that can cover the demand in every time step.
- Construct a data set for the technologies included in the model. You can rely on the given table and can add data when you think this is necessary and helpful for your analysis. Note that if the time horizon is a year, investment costs can be annualized, and operations costs can be multiplied by the number of weeks in a year, a representative week covers (for an average week during each season, approximately 13).
- Solve the model to find the optimal residential system configurations for varying assumptions on tariffs and technology prices. You may, for instance, solve the model with prices increased and decreased by 10%. A major objective of this group project should be the economic comparison

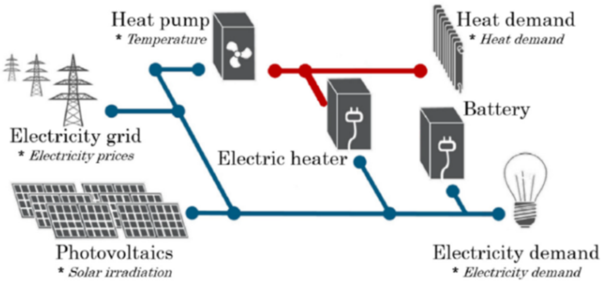
of the basic model (electric demand can be covered by consuming electricity from the grid and heat demand can be covered by a natural gas boiler) with an optimal system (the system should choose an optimal solution for the given electricity and heat demand).

- Before you continue with the extensions, remember to check the results with the help of sensitivities: How does the technology mix change when prices are changed? Does the model invest in any of the technologies? If not, you could think about policy schemes or subsidy payments for LCTS.

- The main result is the yearly energy purchase cost (electricity and heat) for the respective household. How is the yearly energy purchase cost changing with and without LCT investments? Are your results valid? What are the average prices for a comparable household in Denmark? How are the energy purchase cost changing with different tariff schemes? Is it worthwhile to invest in LCTs under the given circumstances?

An overview of a potential configuration is given in Figure 2:

Figure 2: System overview: residential energy supply system for electricity and heat. Design variables are battery size, PV plant size, heat pump size, and electric heater size. The asterisk indicates the time-varying input data sets that are used in the clustering process



The decisive parameters could be, for example, the following:

- spot market prices for purchasing energy (time-dependent),
- feed-in tariffs (or the spot market price for selling excess energy) (time-dependent or not time-dependent),
- constant, variable, and peak related grid tariffs for utilising grid but also self-produced energy (time-dependent or not time-dependent),
- tax schemes and policy frameworks related to the tariffs (not time-dependent),
- electricity demand of the household archetypes (time-dependent),
- heating demand of the household archetypes (time-dependent),
- technologies and their (annual) investment costs (not time-dependent),

- maximum production capacity of each technology or for each household archetype (not time-dependent),
- investment budget of the household archetypes (not time-dependent).

Energy system models frequently have a high computational burden wherefore it often is needed to solve the model for only a representative set of time segments. Aggregating the time domain is a simplification and therefore the aim is to find a good balance between amount of time slices considered and the resulting solution quality. Representative time segments can be chosen in many different ways. In this context, you can choose freely between different approaches as long you take important aspects of the general model into account. Possible approaches are as follows:

- Solve the main model without any reduction in the time domain - solve it with 1 year of hourly resolution.
- Define the alternative aggregation strategies (ways of selecting hours). The strategies do not have to be advanced, but you should aim at making different selections. An idea is also to consider different numbers of hours and to see how the size of the aggregated time-domain influences the results.
- Construct the resulting data sets and make a small analysis of the different data sets. This could be, for example, mean values, standard deviation, variance and/or general plots of the different time series.
- Solve the main model for the different aggregated sets to obtain the optimal investments in the power system for each aggregation.

Research questions and objectives of the group work

During the group work you should answer the following research questions:

- **Basic Model:** What are the yearly energy costs (electricity and heat) for a representative Danish household for representative Danish households when covering the electricity demand by grid consumption and the heat demand by utilizing a natural gas boiler (this thermal technology can be taken for granted; no investment necessary)?
- **Optimal Model:** What is the optimal energy system layout / optimal investment for representative Danish households to cover electricity demand and heat demand while considering different LCT generation (photovoltaic system, heat pump) and storage technologies (battery storage system, heat storage)?
- **Economic Evaluation:** What are the energy savings or even the additional burdens for different households between the basic model and the

optimal model? How are the costs or revenues changing when different parameters are changed (please change only the costs of technologies and/or the purchase tariffs for the sensitivities; for better insights, it is sometimes helpful to concentrate on one parameter and not to change every parameter)?

- **Social Evaluation:** What implications can be derived for high- or low-income households when considering the different investment prices but also the savings or the additional burdens of the optimal vs. the basic energy system configuration?

Additionally, you can think about further impacts in terms of the energy triangle: environment and security of supply (or rather autonomy). For all the implications, you can define indicators to compare your results of the different scenarios or sensitivities.

Guidelines for designing the poster

Every group must design and present a scientific poster (DIN A0 or DIN A1). The focus of the poster should be on the scenario description and the model results. Search for academic poster examples or scientific poster examples for initial examples but also guidelines. The information must fit on one poster. Two posters are not wanted.

Main elements of a poster:

- Title (same as submitted in the report).
- Names and group numbers.
- Introduction and objectives.
- Methodology. Summarise your scenarios and sensitivities.
- Results. Carry information with wonderful figures and charts which allows compare the scenarios and allow insights into the main results.
- Visuals should be uncomplicated and bold. Leave out unnecessary details and ensure that visuals can 'stand alone' i.e. that graph axes are properly labelled, and that symbols are self-explanatory or explicitly explained.
- Discussion. State the main implications of your work.
- Blocks of text should not exceed three paragraphs and should be left-aligned; avoid centred and right-aligned text.
- Use dot points, lists or tables to increase clarity and quantity of information.
- References. References need to be stated like in any other scientific work.

- Font should be legible fonts like Times New Roman, Arial, Garamond.
- No smaller than 16 pt. font.
- All expected components are present, clearly laid out, and easy to follow in the absence of presenter.
- The figures and tables are appropriate and consistently labelled correctly.

Guidelines for writing the report

Every group must submit a report of a maximum of 9-10 (A4) pages (1 title page (including abstract), 1 content table page, 1 contribution page, 1-2 nomenclature pages, maximum of 3-4 research pages (more pages are not taken into account for the correction), 1 figure page for the system configuration). The focus of the report should be on the data and the mathematical description of the model. Every group must use the font Times New Roman, font size 12, at least 1.5 cm margin on the left, right, top and bottom, and line spacing of 1.5.

Essential title page information:

- Concise and informative title.
- Given group number.
- Author names and student numbers.
- Concise and factual abstract (maximum 300 words).

Before the main part of the report, please add one page where you mark clearly, who contributed with what:

- "We all contributed equally" is not enough.
- "XX contributed with: modelling of YY, writing section ZZ" is what I want to see.
- Table with the sections and the contribution of each group member is also possible.

In the main part of the report (maximum of 4 DIN A4 written pages - more pages are not accepted; + 1 additional page for the figure of the system configuration), you have the following sections:

- Describe briefly the overall problem: What is the overall problem you will analyse (objective)? Why is this interesting (motivation)? How will you analyse it? (methodology) Which results do you expect? Finish with three to five highlights as a major summary of your analysis (highlights are bullet points that capture the results of your research as well as the methods that you are using during the study. Think of them as the "elevator pitch" of your report. Don't try to capture all ideas, concepts or conclusions as highlights are meant to be short: 100 characters or fewer, including spaces.).

- Demonstrate the configuration of the model and the problem with the help of a self-explaining figure (+1 additional page only for the figure): What technologies are included in the problem? Which energy carriers are considered? What major input and output of the model is available?
- Formulate the model mathematically (the focus of the report): State and explain your model assumptions. State the mathematical model. Explain the objective and the constraints. All sets, parameters, variables need to be defined in the nomenclature.
- Data and data assumptions (the focus of the report): Describe the data. Include your data sources, i.e. remember references. Explain your data assumptions and any modifications to the data.
- Conclude with a short summary of the major model results (one figure can be used and explained to summarise the major results): What do the model results show? Was that what you expected? What does it tell you about the overall problem?

Additionally, the GAMS code needs to be uploaded. Make a zip file with all necessary code to run your model (including data files etc.) and upload it to Learn.Inside. The code must be executable without changes.

Guidelines for writing the feedback

Two (or three groups) should always sit down and explain their general ideas, problem formulation, GAMS code, and input assumptions, (and the first results, problems, bugs, difficulties) to each other (ca. 10-15 minutes). Please discuss with each other when you want to meet, where you want to meet, and in which way you want to present (I would recommend to use the exercise sessions for the feedback discussions). The GAMS code should be a substantial part of the discussion. Do not be afraid to reveal anything and use the option to discuss everything. During the discussion the groups should give each other some general and more detailled feedback about their idea, the coding structure, shortcomings or mistakes. At the end of the discussion, each group should write down the essential feedback in about 7 bullet points with two or three sentences. Even if the written feedback is to be kept short, you should address specific aspects with reference to the code and the lines or rather some equations of the other and not just write down general feedback. The feedback should only summarise the results of the oral discourse. Please provide not more than 7 specific aspects. The feedback needs to be discussed and submitted by each group until November 20th before 23:59.

The following groups should discuss their ideas, assumptions, and problems with each other (please let me know when some group is not answering your request for the feedback discussion; I will decide about a new constellation; you can not freely choose the other group):

- Group 1.1 and Group 1.2; Group 1.3 and Group 1.4; Group 1.5 and Group 1.6; Group 1.7 and Group 1.8; Group 1.9 and Group 1.10; Group 1.11 and Group 1.12; Group 1.13 and Group 1.14 and Group 1.15.
- Group 2.1 and Group 2.2; Group 2.3 and Group 2.4; Group 2.5 and Group 2.6;
- Group 3.1 and Group 3.2; Group 3.3 and Group 3.4; Group 3.5 and Group 3.6; Group 3.7 and Group 3.8; Group 3.9 and Group 3.10; Group 3.11 and Group 3.12; Group 3.13 and Group 3.14; Group 3.15 and Group 3.16; Group 3.17 and Group 3.18.
- Group 4.1 and Group 4.2;

Data input

Initial data input is provided in an additional excel sheet. At least the basic model should rely on the given data (you still have to look up, e.g., the network costs for the consumer tariffs and the solar radiation timeseries for Denmark). Please discuss your own collected data with other groups regarding the source and units. You do not need to find sources for the given data. However, please explain all other assumptions in detail.

Initial literature (there is much more and possibly more suitable literature)

1. McKenna, R., Merkel, E. and Fichtner, W., 2017. Energy autonomy in residential buildings: A techno-economic model-based analysis of the scale effects. Applied Energy, 189, pp.800-815.
2. Merkel, E., McKenna, R. and Fichtner, W., 2015. Optimisation of the capacity and the dispatch of decentralised micro-CHP systems: A case study for the UK. Applied Energy, 140, pp.120-134.
3. Teichgraeber, H., Lindenmeyer, C.P., Baumgärtner, N., Kotzur, L., Stolten, D., Robinius, M., Bardow, A. and Brandt, A.R., 2020. Extreme events in time series aggregation: A case study for optimal residential energy supply systems. Applied Energy, 275, p.115223.
4. Beck, T., Kondziella, H., Huard, G. and Bruckner, T., 2017. Optimal operation, configuration and sizing of generation and storage technologies for residential heat pump systems in the spotlight of self-consumption of photovoltaic electricity. Applied Energy, 188, pp.604-619.

5. Kaschub, T., Jochem, P. and Fichtner, W., 2016. Solar energy storage in German households: profitability, load changes and flexibility. Energy Policy, 98, pp.520-532.

6. Aniello, G., Shamon, H. and Kuckshinrichs, W., 2021. Micro-economic assessment of residential PV and battery systems: The underrated role of financial and fiscal aspects. Applied energy, 281, p.115667.