Design and analysis of a grid-connected residential rooftop PV system

The purpose of this exercise is to gain experience in using SAM for designing a PV system and performing a basic financial analysis of the project. You will need to design a rooftop-mounted PV system for a house or apartment located in your hometown. It can be your own family house, and annex to your house (garage, barn), rooftop of an apartment building, or you can design the PV system for a new house (in which case you will design the PV array with optimal orientation). **However, do not simulate the same PV system (system size & components) used in the lecture examples.**

You will need to estimate the annual energy consumption of the household, and design a PV system that will generate solar electricity to cover 80% of the yearly consumption. If 80% is not economically feasible, you can lower it and redesign your system for minimizing the electricity bill and having a positive NPV after 25 years. However, you need to justify your decision.

You will need to size the system based on PV panels and inverters available for sale in your country. Thereafter, you will analyze the performance of the system in terms of monthly and annual energy yield, capacity factor, performance ratio, etc. Last, you will need to analyze the cost and revenue of your system, based on local PV component and electricity prices, and calculate financial metrics such as LCOE, NPV, and payback period.

Finally, draw conclusions about the financial feasibility, challenges and opportunities for rooftop PV systems in your country.

Report

You have considerable freedom in designing your PV system however, you will need to document each step of your PV system design and analysis process in the report, which will be evaluated on its **technical quality, clarity** and **the insight/justification** you provide for each choice you make in the design process**.**

When you write your report results, create sections which have the same letter and name as the steps bellow, and document the tasks results requested in the bullet points below.

The length of the report including figures and tables should **not exceed 12 pages** (without references and appendix) with the use of standard margins and font size. You can add appendix pages as you want with extra results & figures, but the main methods, results, and conclusions need to be presented and summarized in the 12 pages.

The design steps to be documented in your report:

Part 1. System design and performance estimation

a) Estimation of the yearly household energy consumption.

You will need to estimate your yearly and monthly energy consumption.

- ○ Document and justify your choice for calculating the **yearly and monthly household consumption.**
- ***Hint****: You can use your monthly energy bills if available*
  - ▪ *Or an energy consumption calculator such as:*
    - *https://www.rapidtables.com/calc/electric/energy-consumption-calculator.html*

        - *Or publication on average residential consumption for your country*
        - *Or another (better) method of your choice.*

b) The solar resource at the location.

- Calculate/Include the daily average horizontal insolation **H** [kWh/m^2/d] for each month of the year.
- *Use PVGIS (https://ec.europa.eu/jrc/en/pvgis) to download TMY weather data for your location.*

c) Tilt, orientation and mounting of the PV array.

- **Document the tilt, orientation and module standoff (for BAPV/BIPV systems) of your PV array and justify your selection.**
- *If you are designing a PV system for an existing house, then use the tilt and orientation of the rooftop side you plan to install the system. Justify why you have chosen that specific roof side[1].*
- *If you are designing a PV system for a new house, then determine and use the optimal tilt and orientation for that location. You can use the SAM parametric simulation to determine that, after you made a rough model of your system.*
- *Find an appropriate mounting system for your roof, and document:*
    - *including image, link to buy, price, technical specs, mentioning the type of roof it is designed for, how it will be attached to the roof and the panels, standoff to roof.*
    - *Also attach its datasheet to the appendix*

d) Shading losses.

- **Model the shading by choosing one of the options below, and document the monthly shading either using the SAM output or the sunpath diagram with shadings:**
- ***OPTION A***
    - ***Use the 3D shade modelling** tool in SAM to model your building and PV array, and any obstructions (tree, buildings) that will shade your PV system.*
    - ***This shading will affect your PV system in the following calculations.***
    - *Include a screenshot of the 3D model and of the month-by-hour beam irradiance shading loss*
    - ***Hint**: Watch the SAM Webinar on how to use the 3D shade modeling tool*
    - *https://www.youtube.com/watch?list=PLjWUCCbi7ZQGaKWztGRLadL90Y0a75hyx&v=Fp505oNJSfw&feature=emb_title*
- ***OPTION B***
    - *Use one of the Solar Pathfinder horizon shading measurements you made in Lecture 6 instead, and assume this is the shading at your location of choice.*
    - ***This shading will affect your PV system in the following calculations.***
    - *Include the traced Solar pathfinder horizon image and of the month-by-hour beam irradiance shading loss implemented in SAM.*

e) Preliminary sizing of the system using manual calculations.

---

[1] *(For Danish locations building data might be extractable from https://skraafoto.kortforsyningen.dk/oblivisionjsoff/index.aspx?project=Denmark&lon=10.2027929&lat=56.1277927 and https://www.weblager.dk/ (digitalized building archive))*

In this part of the exercise, you will need to do a manual calculation of the number of panels necessary and monthly AC energy production of your system, similarly to the exercise in lecture 8.

- Calculate:
    - The number panels necessary n_{panels}
    - The monthly and yearly AC energy E_{AC} produced by the system [kWh]
    - The daily average final yield of the system Y_F [h/d] for each month
- *You will later compare these preliminary values with the ones calculated from SAM.*
- *Use a R(β,γ) slant factor to calculate the plane of array irradiance, from Table A.3.2 in Appendix A (page 646) in [1].*
- *Use the same monthly shading losses as in point d.*
- *Assume* $\boldsymbol{k_T}$ *and* $\boldsymbol{k_G}$ *from Tables 8.2 and 8.3 in Chapter 8 in [1], from locations that have a similar climate profile as your location.*
- *Use the same panel that you will use in point h.*

f) Plane-of-array insolation calculation using SAM/transposition models.

- Calculate and document the daily average plane-of-array insolation $\mathbf{H_G}$ **[kWh/m²/d]** normalized reference yield $\mathbf{Y_r}$ **[h/d]** for each month of the year using SAM.
- *Create a PVWatts, Residential model, import your TMY file, set the correct tilt and azimuth of your roof and perform a Simulation to calculate the plane-of-array irradiance (You don't need to set the other model parameters for just calculating POA). Go to Results->Monthly data->Plane of array irradiance to get the data.*
- *You will then need to divide by the number of days in the month to get to a daily value.*

g) Other losses.

Document the losses that you are assuming in the simulation.

- *Start from the default losses and adapt them to your specific, location, system and module type.*
    - *Use the default values in SAM.*
    - *Use 0.5%/year degradation.*
- *You will get extra point here if you analyze the possible losses for your system, assume realistic losses and document/justify your choices accordingly.*
    - *For example if you live in countries with less rain you can assume more soiling losses. Similar with snow losses.*
    - *If you are installing thin film modules, the yearly degradation rate might be higher.*
- *Use references to motivate your choice. For example papers with statistics on snow and soling losses for different regions of the globe.*

h) Sizing of the PV array.

- **Size the PV array such that the PV system will cover 80% of the yearly consumption.**
- **Calculate and document the number of panels in the array n_{panels} and PV array STC rating P_{Go}**
- **Document the datasheet parameters for your chosen panel as well as the price, and for option A link of where to buy, and for option B how you estimated the price.**
- **Justify you choice.**
- ***OPTION A***
    - *Select a commercial PV panel type that is appropriate for your application; it must be available for sale in your country.*

- *OPTION B*
    - *Select one of the PV panel you have designed in Assignment 2.*
    - *Estimate the price per panel based on retail prices of panels of similar rating and cell type.*
  - *In SAM use the "CEC Performance model with user entered specifications"*
  - ***Use the following temperature related parameters:***

Isc	*Voc*	*Pmp*	*NOCT*
0.048 %/°C	*-0.29 %/°C*	*-0.35 %/°C*	*45°C*

https://jinkosolarcdn.shwebspace.com/uploads/Cheetah%20JKM325-345M-60H-(V)-A4-EN-F30.pdf

- *You can deviate from the 80% of the yearly consumption target if you have a good reason, or you made a preliminary design and analysis of the system and came to the conclusion that 80% is not physically or economically feasible, and thus wish to optimize your PV system design and/or adjust it for the real-world constraints of your chosen location.*

i) **Sizing of the PV inverter.**
- **Size and select the inverter(s) for your system and justify your selection:**
- **You can deviate from the dc/ac ratio (SR_{AC}) determined at point e, if it makes sense to oversize the PV array**
- **Document the SR_{AC}, main inverter datasheet parameters (rating, efficiency, VMPP operation range, nighttime consumption) price, and link where to buy.**
- *Select a PV inverter that is appropriate for your application; it must be available for sale in your country (and for a Danish location it needs to be on the positive list)[i], and match the voltage and current ranges for your array.*
- *Check and document that the electrical parameters (Voc, Vmp, Isc, Imp, Pmax) of the PV array under extreme conditions match the electrical specs of the inverter, min/max current and voltage ratings, starting voltage, MPP range*
- *Explain how you determined the extreme conditions (irradiance and module temperature for your location)*

j) **Performance analysis**. Calculate and document the following performance parameters:
- Daily average reference yield Y_r [h/d] for each month
- daily average array yield Y_A [h/d] for each month.
- monthly and yearly AC energy E_{AC} produced by the system [kWh]
- daily average final yield of the system Y_F [h/d] for each month
- monthly and yearly DC full load hours of the system $t_{V\text{-}DC}$
- yearly DC capacity factor of the system CF [%]
- monthly and yearly performance ratio of the system PR [%]
- **Give insight on how well your system is performing.**
- **Compare the manual calculated values of Y_F and E_{AC} with the ones determined from Point e), comment on the differences. What did you miss in your preliminary calculation?**
- **You will get extra points for the correct interpretation of the performance parameters, if they are within the expected range, if not, what are the possible causes for the deviation. Support your analysis and with references.**
- **Compare the PR at least (CF and full load hours) with published PR values for residential systems in your country.**

- *Make a system simulation in SAM and justify that it is reasonable looking at the loss diagram and the AC energy.*

k) Loss analysis.

- Document the losses in your PV system and give insight on what are the main loss factors.
- Compare the losses with losses reported for similar system in your country or countries with similar climates.
- *Hint: Use the loss-diagram in SAM*

Part 2 Financial Analysis

Use the Distributed->Residential owner financial model to perform a financial analysis of your PV system.

l) **System costs.**

- **Estimate the direct Capital costs and document your sources for pricing.**
  - *Follow the SAM template.*
  - *Use and document the price values you have found for the panel. Inverter, mounting system in a table. Also document the total PV system cost per Wp and total price of the system*
  - *Use default values for other BOS components and labor. Or actual cost values for your country if you can find them. Example for US Table 2 in* [*https://www.nrel.gov/docs/fy22osti/80694.pdf*](https://www.nrel.gov/docs/fy22osti/80694.pdf)
  - *Remember to apply prices for you segment (residential).*
- ***Indirect capital costs:*** *Use default values.*
- ***Operation costs:*** *Use default values.*
- **IMPORTANT:** Validate the cost/Wp CAPEX of your system with published cost data for your country, or cost data from local installers. Cite your references and explain your assumptions as well as differences between the cost you calculated and what you found in the literature or online.

m) Parameters for financial modelling.

- **Determine incentives, electricity rates and Metering and Billing Scheme for your country (and include sources and explain how you found the data).**
- **Explain how you modelled it in SAM.**
  - ***Financial parameters:***
    - *Mortgage loan, debt fraction=100%, loan term=25 years;*
      - *loan rate=5%/year or determine specific loan rate for your country from IEA PVPS National reports*
        - [*https://iea-pvps.org/national-survey-reports/?year_p=&country=&order=DESC&keyword*](https://iea-pvps.org/national-survey-reports/?year_p=&country=&order=DESC&keyword)
    - *Analysis period=25 years*
    - *Inflation rate=2.5%/year*
    - *Real discount rate=3.5%/year*
    - *Rest of parameters are default.*
  - ***Incentives****:*
    - *No incentives, unless your country currently provides PV incentives*
    - *Extra points if you give a detailed explanation of how the incentives work and are awarded in your country + references.*
  - ***Electricity rates****:*

- Determine the electricity rates and direct PV support policies for your country from IEA PVPS national reports or other references.
  - https://iea-pvps.org/national-survey-reports/?year_p=&country=&order=DESC&keyword=
- *For example, in Denmark retail electricity prices for a residential household (greater Copenhagen (Andel spot)) are comprised of time dependent distribution tariffs and taxes shown in the table below[2]:*

Table 1. Electricity time dependent tarifs (in addition to the spot price and electricity tax)

Radius 2024 i øre/kWh	Winter tariff Oct-Marts	Summer tariff April-September	Average
Lavlast kl.00-06	15.19	15.19	15.19
Højlast kl. 06-17	45.56	22.77	34.16
Spidslast kl. 17-21	136.68	59.23	97.95
Højlast kl. 21-00	45.56	22.77	34.16

- *The **electricity tax** for 2024 is 76.1 øre per kWh[5]*
- *And a **monthly subscription** 59.5 DKK/Month. (All prices include VAT)*
- *So 1 kWh hour bought from the grid during summer in the cooking period cost 59.24 øre + electricity spotprice (e.g. 101.28 øre) + el tax (76.1 øre) =236.62 øre*
- *You can make an agreement with Vindstød so they buy you excess electricity: in the area of the DSO Radius the following trade costs are valid (no subscription to Vindstød)[3]:*

Trade costs	
Energinets feed-in tariff	-0,3750 øre/kWh
Energinets balance tariff	-0,1600 øre/kWh
Radius feed-in tariff	-0.54 øre/kWh
Vindstøds balance tariff	-1,0000 øre/kWh
Total subtraction from the spotprice	**- 2.075 øre/kWh**

*To model this electricity rate and direct support policy select **Net Billing** in the Metering and Billing section.*

- ***Use the fixed average electricity spotprice for 2023: 101.28 øre/kwh[4]***
- *For the Danish installation you can simplify by using the average tariffs stated in the most right column in the table for the whole year, but you need to implement the tariffs for the specific hours during the day (and remember both to implement the weekday and the weekend scheme in SAM). For other locations justify the scheme and optionally simplifications.*

---

[2] https://andelenergi.dk/kundeservice/aftaler-og-priser/nye-tariffer-for-el/
[3] https://www.vindstoed.dk/tilmelding-solcelle, https://radiuselnet.dk/elnetkunder/tariffer-og-netabonnement/
[4] https://ens.dk/sites/ens.dk/files/Statistik/elprisnotat_1_halvaar_2023.pdf
https://ens.dk/sites/ens.dk/files/Statistik/elprisnotat_2_halvaar_2023.pdf
[5] https://velkommen.dk/artikler/viden-om-el/elafgiften-2024/

- View the SAM Webinar on Electricity rates to gain a better understanding of the modelling process *https://www.youtube.com/watch?time_continue=1&v=yDzil9J8Qjc&feature=emb_logo*

  - ***Extra points will be given if you use better and more realistic cost, financial parameters, incentives (if any in your country), but you must document your reasoning and source for selecting them.***

n) **Electric load modelling**.
   - Use the 1 year load profile provided to you *SAM_Load_Data.csv*, and scale it with the actual monthly consumption of your house, using the **Adjust Load Profile to Monthly Usage** function in SAM
   - *If you only have annual energy consumption data, calculate average monthly values, and enter those into SAM.*
   - Plot the hourly load for 1 year.
   - Plot an average daily load profile for each season vs the average daily power output of your system. For example chose 4 days in the year (15 October, 15 July, 15 January, 15 March) and plot the hourly load and PV output for those days. You can also choose to calculate average daily profile for each season or these 4 months.
   - Calculate and comment on the degree of self consumption on these days.

o) **Financial analysis.**
   Calculate and document the following parameters:
   - LCOE (Nominal)
   - Electricity bill without system (year 1)
   - Electricity bill with system (year 1)
   - Net savings with system (year 1)
   - Net present value
   - Simple payback period
   - Discuss the financial performance of your system and how it could be improved.
   - Compare LCOE and payback time with published values for similar PV system in your country.

Use default values for parameters that have not been specified explicitly. Or if you change them, motivate your choice.

---

[i] PV inverters: Positivlister | Green Power Denmark