ΠΟΛΥΤΕΧΝΕΙΟ ΚΡΗΤΗΣ / TECHNICAL UNIVERSITY OF CRETE

Design and optimization of hybrid energy systems using open-source computational tools

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Chania, July 2025

Abstract

The objective of this thesis is to present the capabilities of two free access software related to the design, and optimization of hybrid energy systems incorporating various technologies. The first one is called REopt and focuses on site-specific system optimization within the USA. It also emphasizes the integration of renewable energy sources into the grid and resilience of the system. The second software is called nPro and concentrates on the detailed design of district-level energy systems requiring a more sophisticated network modeling. Also, this software performs a building-based approach on how to design heat networks. To understand the functionality of these tools, several (non-comparable) case studies will be conducted regarding the sustainability of the analyzed systems and the efficiency of the software tools. Overall, the thesis is developed in the form of a user manual in order to understand the basic features of the two software tools.

In the first chapter, the evaluation concentrates on REopt software. A step-by-step tutorial is presented followed by three applications to emphasize the functionality of REopt. The first system is a PV-Battery-on grid; the location will be in Denver, USA, and the energy goals are cost-savings and clean energy production. The second application is a PV-Battery-CHP unit–on grid, the location will be based in San Francisco, USA and the energy goals are the same. Finally, a conclusion is made as to whether the foresaid hybrid systems minimize the life cycle cost of energy and are economically viable.

In the second chapter, a thorough technoeconomic analysis will take place by nPro software. Unlike REopt, nPro provides users with data from different locations throughout the world. First, demand profiles will be demonstrated followed by district energy systems classification. Then, a step-by-step guide will take place in which all the functions of the tool are described. Finally, a case study will be presented focusing on specific hybrid systems and their economic potential.

The location of the analysis will be in Chania, Greece in a specific district containing Nikolaou Skoula, Efedron Polemiston, Zimvrakakidon and Mathiou Milonogianni streets (as for all of the upcoming applications). The first three systems will focus only on their electricity demand and contain a PV-Wind-on grid system, a PV-Battery-Wind Turbines-off grid system and a Hydrogen-PV-Wind Turbines-off grid system. A comparison of them will be made recommending the optimal solution.

Focusing only on heat demand with nPRO, some other systems will be analyzed including a Geothermal Energy-Heat storage-on grid system and a Biomass CHP unit-Heat storage-on grid system. A comparison between them will follow proposing the optimal solution.

Key words: REopt, nPro, techno-economic analysis, optimization, Distributed Energy Resources (DERs), photovoltaics (PV), battery, gas emissions, Combined Heat and Power (CHP), district heating and cooling (DHC), demand profiles, hydrogen, hybrid systems, energy hub, investment cost, Net Present Value (NPV).

Περίληψη

Αντικείμενο της παρούσας διπλωματικής εργασίας είναι ο σχεδιασμός και η βελτιστοποίηση υβριδικών ενεργειακών συστημάτων μέσω της αξιολόγησης της απόδοσής , της οικονομικής αποδοτικότητας και του περιβαλλοντικού τους αποτυπώματος υπό διαφορετικές συνθήκες λειτουργίας. Για την τεχνοοικονομική ανάλυση αυτών των συστημάτων, χρησιμοποιούνται εξειδικευμένα λογισμικά. Το πρώτο είναι το REopt, το οποίο επικεντρώνεται στη βελτιστοποίηση συστημάτων σε συγκεκριμένες τοποθεσίες εντός των Ηνωμένων Πολιτειών της Αμερικής. Δίνει επίσης έμφαση στην ενσωμάτωση ανανεώσιμων πηγών ενέργειας στο δίκτυο και στην ανθεκτικότητα του συστήματος. Το δεύτερο εργαλείο είναι το nPro, το οποίο εστιάζει στον λεπτομερή σχεδιασμό ενεργειακών συστημάτων σε επίπεδο συνοικίας, απαιτώντας σύνθετη μοντελοποίηση δικτύων. Για την κατανόηση της λειτουργικότητας των εργαλείων αυτών, θα εκπονηθεί μια μεθοδολογία έρευνας (case study) που θα αξιολογεί τη βιωσιμότητα των εξεταζόμενων συστημάτων και την αποτελεσματικότητα των λογισμικών. Η πτυχιακή εργασία αναπτύσσεται συνολικά με τη μορφή ενός εγχειριδίου χρήστη, με σκοπό την κατανόηση των βασικών λειτουργιών των δύο λογισμικών εργαλείων.

Στο πρώτο κεφάλαιο, η αξιολόγηση επικεντρώνεται στο λογισμικό REopt. Παρουσιάζεται ένας αναλυτικός οδηγός χρήσης, ακολουθούμενος από τρεις εφαρμογές με στόχο την ανάδειξη της λειτουργίας του εργαλείου.

Το πρώτο σύστημα είναι ένα σύστημα φωτοβολταϊκών πάνελ, μπαταρίας τα οποία είναι συνδεδεμένα με το δίκτυο στην τοποθεσία Denver, Η.Π.Α. και έχοντας ως ενεργειακούς στόχους την εξοικονόμηση πόρων και την παραγωγή ενέργειας από ανανεώσιμες πηγές. Η δεύτερη εφαρμογή αφορά ένα σύστημα φωτοβολταϊκών πάνελ, μπαταρίας και μονάδας συμπαραγωγής ηλεκτρικής και θερμικής ενέργειας επίσης συνδεδεμένο με το δίκτυο, με τοποθεσία το San Francisco, Η.Π.Α. και τους ίδιους ενεργειακούς στόχους. Τέλος, εξάγεται το συμπέρασμα ως προς το κατά πόσον τα παραπάνω υβριδικά συστήματα μειώνουν το κόστος κύκλου ζωής της ενέργειας και είναι οικονομικά βιώσιμα.

Στο δεύτερο κεφάλαιο, εκπονείται τεχνοοικονομική ανάλυση μέσω του λογισμικού nPro. Σε αντίθεση με το REopt, το nPro παρέχει στους χρήστες δεδομένα για τοποθεσίες σε όλο τον κόσμο. Αρχικά, παρουσιάζονται τα προφίλ ενεργειακής ζήτησης, ακολουθούμενα από την κατηγοριοποίηση των συστημάτων ενέργειας σε επίπεδο συνοικίας. Στη συνέχεια παρατίθεται ένας αναλυτικός οδηγός που περιγράφει όλες τις λειτουργίες του εργαλείου. Τέλος, γίνεται μια έρευνα περίπτωσης (case study) επικεντρωμένη σε συγκεκριμένα υβριδικά συστήματα και την οικονομική τους προοπτική.

Η τοποθεσία της ανάλυσης είναι τα Χανιά, Ελλάδα, σε συγκεκριμένη περιοχή που περιλαμβάνει τις οδούς Νικολάου Σκουλά, Εφέδρων Πολεμιστών, Ζυμβρακάκηδων

και Μαθιού Μυλωνογιάννη (όπως ισχύει για όλες τις επόμενες εφαρμογές). Τα πρώτα τρία συστήματα επικεντρώνονται αποκλειστικά στις ανάγκες ηλεκτρικής ενέργειας των κτηρίων και περιλαμβάνουν: ένα σύστημα φωτοβολταϊκών-ανεμογεννητριών συνδεδεμένο με το δίκτυο, ένα σύστημα φωτοβολταϊκών-ανεμογεννητριών-μπαταρίας εκτός δικτύου και τέλος ένα σύστημα τεχνολογίας υδρογόνου-φωτοβολταϊκών-ανεμογεννητριών εκτός δικτύου επίσης. Θα γίνει σύγκριση των τριών προκειμένου να προταθεί η βέλτιστη λύση.

Στη συνέχεια, εστιάζοντας αποκλειστικά στις θερμικές ανάγκες των κτιρίων , αναλύονται τα εξής συστήματα: ένα σύστημα γεωθερμικής ενέργειας με συνάμα αποθήκευση θερμότητας συνδεδεμένο με το δίκτυο και ένα σύστημα μονάδας συμπαραγωγής από βιομάζα με ταυτόχρονη αποθήκευση θερμότητας, συνδεδεμένο με το δίκτυο. Ακολουθεί σύγκριση των δύο, με στόχο την πρόταση της βέλτιστης λύσης.

Λέξεις κλειδιά: REopt, nPro, τεχνοοικονομική ανάλυση, βελτιστοποίηση, Κατανεμημένοι Ενεργειακοί Πόροι, φωτοβολταϊκά (ΦΒ), μπαταρία, εκπομπές αερίων, Συμπαραγωγή Ηλεκτρισμού και Θερμότητας (ΣΗΘ), δίκτυο διανομής θέρμανσης και ψύξης, προφίλ ζήτησης, υδρογόνο, υβριδικά συστήματα, ενεργειακό κέντρο, επενδυτικό κόστος, Καθαρή Παρούσα Αξία (ΚΠΑ).

CHAPTER 1: Overview and implementation of the REopt Optimization Tool

1.1. Introduction

REopt is a web tool for techno-economic modeling and optimization of Distributed Energy Resources (NREL, 2025). Distributed Energy Resources (DERs) are small-scale power generation or storage technologies that are located close to where electricity is used, such as homes, businesses, or communities. Unlike centralized power plants, which generate electricity far from where it is consumed, DERs are decentralized and often renewable, offering greater flexibility, resilience, and efficiency to the energy grid. When a site is considering Distributed Energy Resources (DER's) there are a lot of factors to be addressed such as local renewable energy resource at our site, technology costs (capital costs, O&M costs) and incentives that might be available evaluating site and organizational goals and priorities. That concludes cost savings, resilience against grid outages, and clean energy goals for decarbonization and/or health related emissions in energy justice. Financial parameters contain not only the upfront costs but also the potential savings that the requested technology can provide throughout the technology life.

REopt helps co-optimize all of these different factors and help sites identify the cost optimal system sizing of DER assets that could meet their site or organization goals. The form of this chapter is to provide manual instructions on the user in order to understand the basic features of the REopt computational tool. It is suggested in a later stage (e.g. in the form of a new thesis) to provide examples that will be based on realistic scenarios and comparable to each other.

1.2. Tutorial

- To begin with, each user can access the REopt web tool interface at https://reopt.nrel.gov/tool/, and the following webpage will appear.

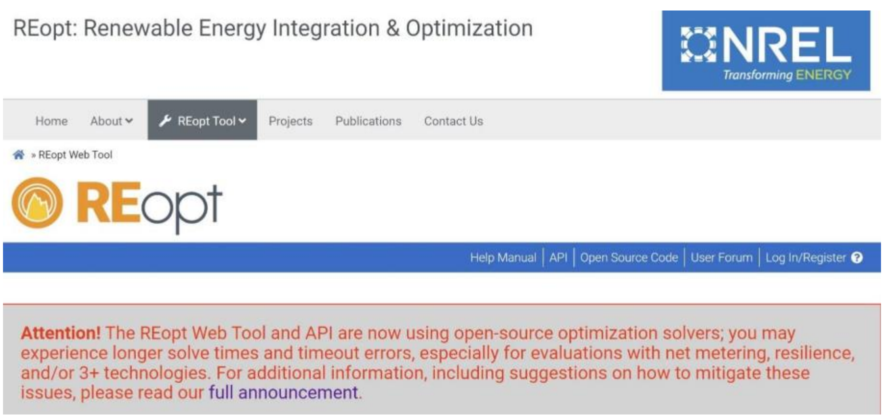


Fig. 1. *REopt Web Tool Interface*

● Then, from the blue menu bar that pops up, there is an option to Login/Register among other things.

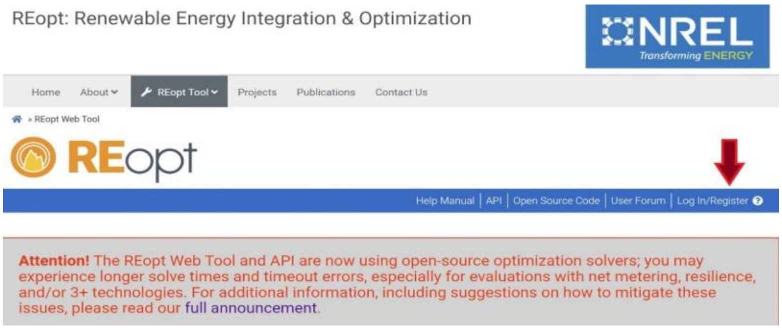


Fig. 2. *Log in / Register option*

● After using the above option, the tool provides the user with the choice of logging in either via Google or Facebook account. It is optional but very valuable, because users can access past evaluations, and also custom load profiles that have been uploaded, and any custom utility rates that's been modeled in REopt can be claimed (see **Fig. 3.**).

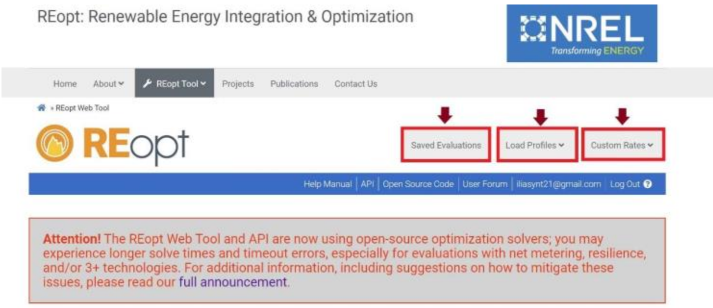
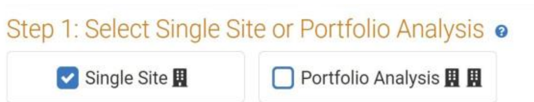


Fig. 3. *Saved evaluations/Load profiles/Custom Rates*

● To start the techno-economic analysis, there are a few steps that users have to consider.

Step 1: *Selecting Single Site or Portfolio analysis*

It allows users to choose either one site evaluation with REopt or a screening across multiple facilities. This option helps facilitate analysis across a number of buildings all at once and reduces the amount of time required for users that may not feel comfortable with their programming skills.



Step 2: *Choosing energy goals*

In this section, REopt allows users to select the goals during the analysis period. There are 3 kinds of energy goals: cost savings, resilience, and clean energy. Since REopt is always a cost savings or cost optimization tool, the option of cost savings cannot be unselected. Nevertheless, each user can choose optionally to toggle clean energy goals and/or resilience goals.

Fig. 4. *Cost savings-based analysis*

Fig. 5. *Cost savings and resilience-based analysis*

Step 3: *Determine technologies*

REopt provides some technologies that can be chosen for analysis by the user. These technologies are constituted by: **Photovoltaics (PV), Battery, Grid, Wind, CHP, Prime and emergency Generators, Chilled Water Storage and Geothermal Heat Pump.**

The images below show the technologies that are going to be chosen for optimization. The first example is composed of the default selected technologies from REopt and it is a PV-Battery-Grid connected system (**Fig. 6)**.

The second example shows the same system but with the addition of a CHP unit from a user (**Fig. 7)**. It is also notable that, when a user toggles the CHP technology an expansion pops up (red arrows) and requires two fields to be filled. As shown from the first arrow, the user selects whether the boiler generates hot water or steam in the drop-down menu. As for the second arrow, it shows the CHP technologies that the user can evaluate and need to be selected (either one or both).

Fig. 6. *PV, Battery, Grid are selected for the optimization*

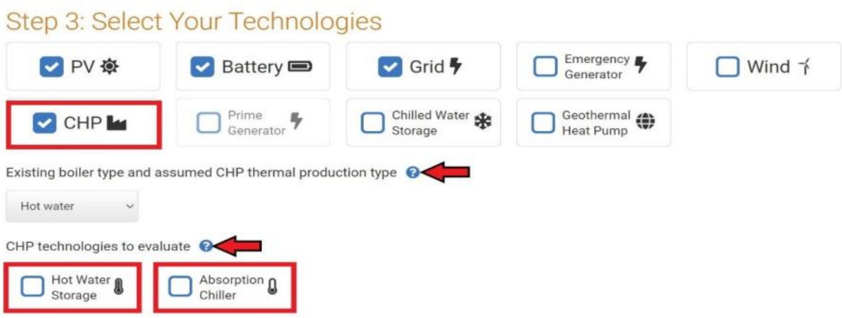


Fig. 7. *PV, Battery, Grid, CHP selected for the analysis*

Step 4: *Entering Site Data*

By scrolling down further, each user shall see a section entering more specific data about the site which is about to be analyzed. The first parameter is the site and utility partition. Toggling the small cross on the right, will cause a new drop-down menu to show and users shall enter not only their evaluation name to distinguish various sites and scenarios (optional input) but also the site's location and electricity rate (mandatory input).

***Fig. 8**. Site Data options*

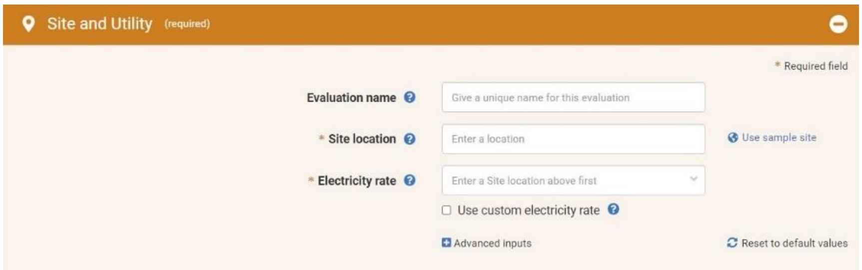


***Fig. 9**. Evaluation name, Site and Utility section*

Nation Energy Renewable Laboratory (NREL) maintains a utility rate database that summarizes a lot of utility rates available across the USA. It is not a 100% coverage of utility and utility rates and also not always a perfect representation of a given one , but it is a great starting point and also gives users the capability of inserting a custom electricity rate .This can be either a blended energy charge (total costs divided by total consumption) or if someone knows the split between the energy charges and demand charges (charges that apply to the peak demand within a month whereas energy charges are applied on the dollar per kilowatt hour basis). If these costs vary monthly, then monthly option can be toggled and users can enter inputs for each month, both energy and demand charges. There is also an option for detailed utility rate modeling, providing that users have logged in. This is an advanced capability that requires an in-depth understanding of how utility rates work. Utility Rate DataBase (URDB) label provides a rate that isn't available in the dropdown list for our selected location and corresponds to an unlisted rate. This label can be found in the URL for the URDB rate on the open EI website. Lastly, if the electricity rate varies on an hourly basis (and cannot be modeled using the "Detailed" custom rate option) the user can upload a custom file with time-varying energy rates.

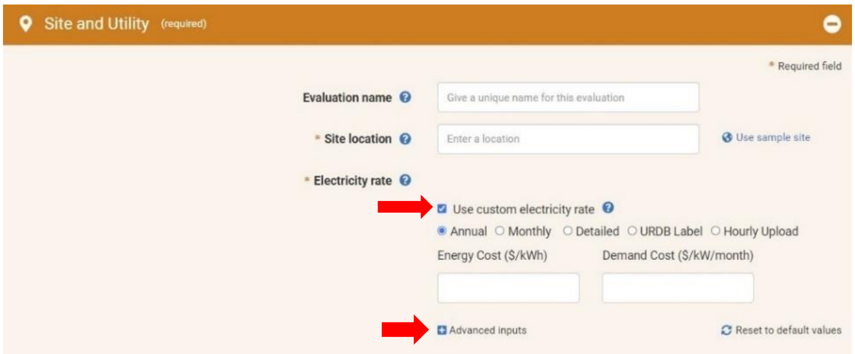


***Fig. 10**. Custom electricity rate*

The inputs required for the analysis have asterisks beside them. All the other inputs have default values that users can choose to override if desired but are not essential for the optimization to start.

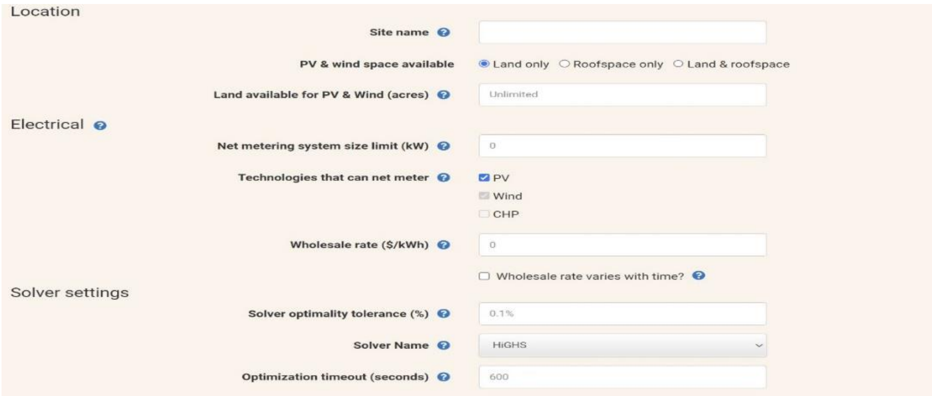


***Fig. 11.** Additional optional inputs*

Furthermore, we have the required input of load profiles. There are a couple of different options in this section. The user can simulate a building using DOE (Department of Energy) commercial reference building profiles. These are simulated representative load profiles for commercial reference buildings developed by DOE. It accounts for the climate zone of the building and the building type but doesn't cover all of them. Each user can choose one that best represents the usage patterns at the preferred site.

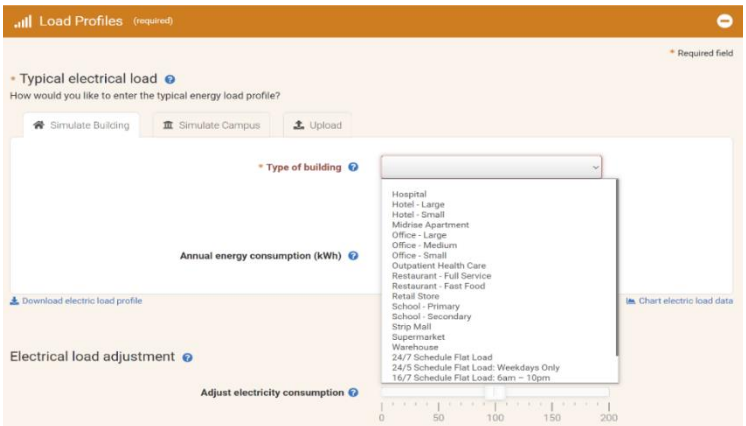


***Fig. 12**. Commercial reference buildings*

After selecting a building type, the user shall see the annual energy consumption for that DOE for commercial reference building. Alternatively, if annual or monthly consumption data is available for the site, it can be entered into the cell. That would scale the shape of the commercial reference building to the magnitude of the actual site. The image below shows an example used as a reference for building a hospital and the estimated annual energy consumption of it **(Fig. 8.2)**. The electrical load adjustment is if a user is interested in planning energy efficiency measures, for instance, and doesn't know exactly what impact they'll have. Then he could scale that load profile up or down.

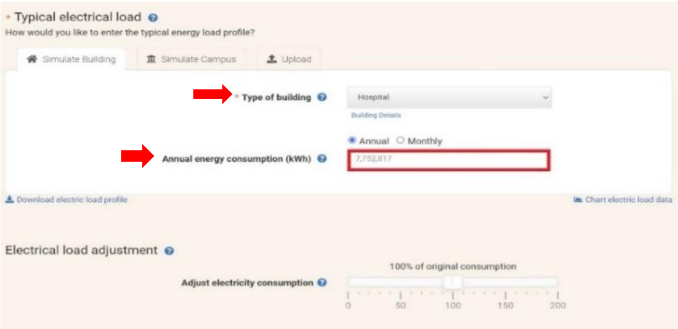


***Fig. 13**. Estimated annual energy consumption for specific building type*

It is also notable, the simulate campus option. If a user wants to modelling energy consumption at a campus that has multiple buildings or there is a multifunction building type (for instance: apartment upstairs and a restaurant downstairs), different types of buildings can be selected from the list and also the percentage of total energy consumption that is contributed by each one of them.

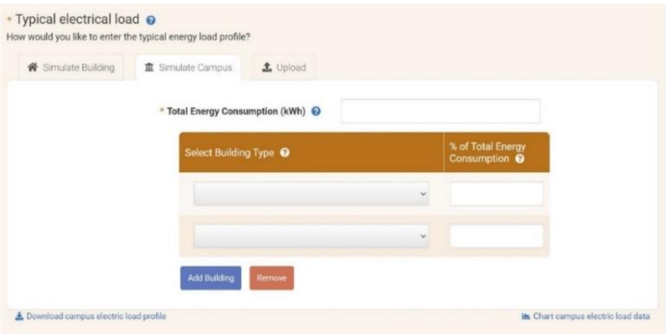


***Fig. 14**. Simulate Campus option*

Additionally, there is the financial assumption section. It contains the analysis period (in years), which by default is set to 25 years. Also, the host discount rate is presented, which is the site's discount rate, and its default value comes from NREL's annual technology baseline. Communities might use a lower value, but it varies, so each user can update that based on his organization. Electricity cost escalation rate is a projection of how much electricity costs might change year over year. By toggling the advanced inputs, each user should see two options that are not required for the analysis. The host effective tax rate is the percentage of income that goes to tax for the host. O&M cost escalation rate is the nominal expected annual rate of inflation over the financial life of the system.

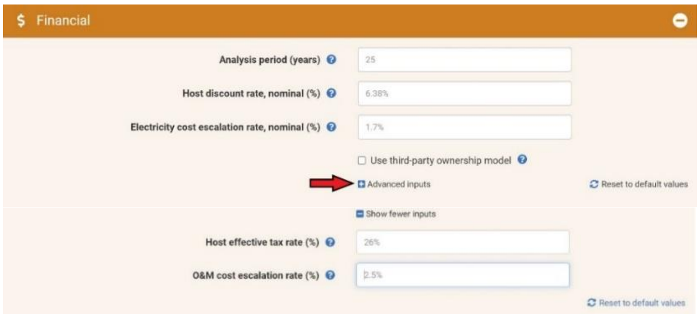


***Fig. 15**. Financial section*

Moving forward, there is a renewable energy and emissions section accounting (clean energy accounting). The climate (CO_{2e} or CO_2) emissions rates of grid electricity assumed in the analysis. If "Hourly" is selected, the analysis will use hourly CO_{2e} emissions data from NREL's Cambium database for grid-sourced electricity. This feature (Cambium) contains hourly emission metrics for a suite of forward-looking scenarios of the U.S. electricity sector, covering the contiguous United States through 2050. Users may modify the inputs on the hourly tab to tailor the Cambium emissions data used. If "Annual" is selected, a single annual grid emission factor (lbs/kWh), can be entered. These factors will be applied to grid-sourced electricity in each hour of the year. If "Upload" is selected, the user can upload one year of custom hourly CO_{2e} emissions factors.

Defaults: If the site location is within the contiguous United States, the default factors will be hourly long run marginal emissions rates from this feature (Cambium) for the state corresponding to the location. Default grid emission factors are inclusive of transmission and distribution losses. If the site location is outside the United States, any of the grid emission factor input options can be used. However, if no emission factor selection is made, there is no default value and emissions impact from the electricity grid will be assumed to be zero. Only one active tab (Hourly, Annual, or Upload) for specifying the emission factor will be applied to optimization. Emissions factors are not required for input.

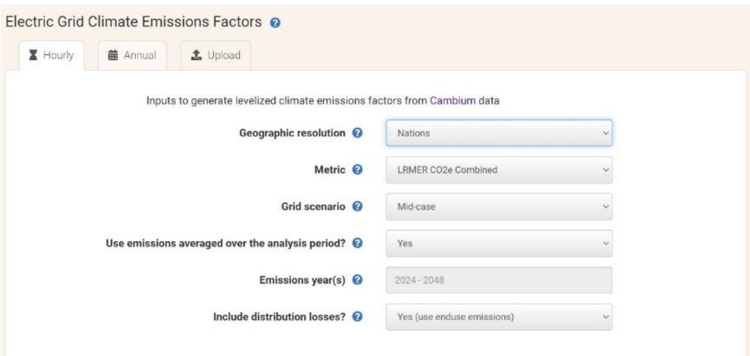


***Fig. 16.** Electric Grid Climate Emissions Factors*

i. **Geographic resolution** (NREL, 2025): Geographic unit at which grid emissions are determined. Based on the site location entered under "Site and Utility," the corresponding location will automatically be selected, at the geographic resolution selected here.

- **Nation:** Entire contiguous U.S.

- **GEA Regions:** These regions refer to the Grid Economic and Environmental Attributes (GEA) regions, which are geographic areas defined by the National Renewable Energy Laboratory (NREL) for the purpose of energy system modeling and analysis. These regions are used to aggregate and simplify regional energy data, such as grid emissions profiles, energy costs, and environmental attributes, to provide geographically relevant information for users in different parts of the country. By dividing the U.S. into different GEA regions, the tool can offer more accurate assessments for various geographic areas without requiring hyper-local data for every scenario.

- **States:** States within the contiguous U.S.

Note: *Users* can modify inputs to generate hourly levelized grid climate emissions factors from NREL's Cambium data sets, for locations in the USA.

ii. **Metric**: Emissions metric for grid-purchased electricity and explanation

AER vs. SRMER vs. LRMER: Their usage is to describe different levels of geographic or temporal resolution when evaluating emissions factors for electricity generation

- **AER**: Represents the average carbon emissions per unit of electricity consumed over a given period (usually a year) across an entire grid or region. It gives a broad view of the emissions intensity by averaging out both low- and high-emission sources of electricity generation.
  - **Use case**: AER is often used when high temporal precision is not needed or when considering long-term energy planning.
  - **Limitations**: Since it averages emissions over time, it doesn't capture the variations in grid emissions that occur throughout the day or in specific short timeframes (e.g., peak vs. off-peak hours).

- **SRMER**: Refers to the emissions produced by the last or "marginal" unit of electricity generation needed to meet demand in the short term. This is the most immediately responsive power source when demand changes, and it tends to be more carbon-intensive (e.g., natural gas or coal plants) compared to baseload or renewable sources.
  - **Use case**: SRMER is important for short-term decisions, such as when evaluating the emissions impact of adding or reducing load on the grid at a specific moment (e.g., charging a battery or using electricity during a peak hour).
  - **Advantage**: Provides a more precise understanding of the marginal environmental impact of electricity consumption at specific times.
  - **Limitations**: It can fluctuate widely over short periods, making it less stable for long-term planning or average assessments.

- **LRMER**: LRMER reflects the emissions associated with meeting additional demand over a longer period, considering future changes in the energy mix. This could include planned renewable energy projects or the retirement of fossil fuel plants.
    - **Use case**: It is used for long-term planning and forecasting, especially when evaluating how new energy technologies will affect grid emissions over time. It's relevant when planning large-scale renewable energy adoption or electrification projects that will influence grid demand over many years.
    - **Advantages:** It accounts for future shifts in the energy mix, providing a more forward-looking estimate of emissions impacts compared to AER or SRMER.
    - **Limitations:** LRMER involves assumptions about future grid conditions, so it may be less precise for short-term decisions.

CO_2 vs. CO_{2e}:

- CO_2: carbon dioxide
- CO_{2e}: CO_2 equivalent. Combined impact of CO_2, CH_4, and N_2O using 100-year global warming potential (GWP). This is very important for engineering groups.

Combustion vs. Combined:

- Combustion: Emissions from direct combustion.
- Combined: Precombustion (removing CO_2 from fossil fuels before combustion is completed) includes fuel extraction, processing, and transport and also the combustion emissions.

AER Generation vs. AER Load:

- Generation: Focuses on the emissions associated with producing electricity. It gives an overall picture of the emissions intensity of the power grid's electricity generation. It is useful for understanding the emissions profile of power plants and overall generation.
- Load: Focuses on the emissions associated with consuming electricity. It reflects the emissions impact of the electricity that is actually used by consumers. It is important for understanding the emissions impact from the perspective of electricity consumers, which can vary based on grid emissions at different times.

Note: Users can select from the metric dropdown menu the category that suits their needs for the analysis as explained above.

iii. **Grid scenario**: Future scenarios used to estimate out-year emissions.

IRA: The Inflation Reduction Act (*IRA)* represents a significant piece of legislation aimed at addressing climate change, reducing greenhouse gas emissions, and promoting clean energy. It includes a range of provisions related to energy, taxes, and environmental policy.

PTC: Production Tax Credit (*PTC*) provides tax credits for the production of renewable energy from sources like wind, geothermal, and biomass. It offers a per-kilowatt-hour tax credit for energy produced.
ITC: Investment Tax Credit (*ITC*) offers tax credits for investments in renewable energy projects, such as solar photovoltaic systems. It provides a percentage of the investment cost as a tax credit.

- Mid-case (**without** tax credit phaseout): expected value for inputs such as technology costs, fuel prices, and demand growth. No nascent technologies. IRA's PTC and ITC are assumed to not phase out.
- Mid-case (**with** tax credit phaseout): the same set of base assumptions as the first scenario, but where IRA's PTC and ITC start phasing out in 2038.
- Low Renewable Energy and Battery Costs (**without** tax credit phaseout): same set of base assumptions as the first scenario, but where renewable energy and battery costs are assumed to be lower. IRA's PTC and ITC are assumed to not phase out.
- Low Renewable Energy and Battery Costs (**with** tax credit phaseout): the same set of base assumptions as the first scenario, but where renewable energy and battery costs are assumed to be lower. IRA's PTC and ITC start phasing out in 2033.
- High Renewable Energy and Battery Costs (phaseout threshold not reached): the same set of base assumptions as the first scenario, but where renewable energy and battery costs are assumed to be high. The emission threshold specified in IRA is not reached in this scenario, and consequentially, the PTC and ITC do not phase out, and there is no corresponding scenario with a phaseout.
- Electrification (phaseout threshold not reached): the same set of base assumptions as the first scenario, but where demand growth is assumed to average 1.99% from 2022 through 2050, representing higher rates of electrification than the base assumption. The emission threshold specified in IRA is not reached in this scenario, and consequentially, the PTC and ITC do not phase out, and there is no corresponding scenario with a phaseout.
- Low Natural Gas Price (phaseout threshold not reached): the same set of base assumptions as the first scenario, but where natural gas prices are assumed to be lower. The emission threshold specified in IRA is not reached in this scenario, and consequentially, the PTC and ITC do not phase out, and there is no corresponding scenario with a phaseout.
- High Natural Gas Price (without tax credit phaseout): the same set of base assumptions as the first scenario, but where natural gas prices are assumed to be high. IRA's PTC and ITC are assumed to not phase out.
- Mid-case with 95% Decarbonization by 2050 (without tax credit phaseout): the same set of base assumptions as the first scenario, but nascent technologies are included and there is a national electricity sector decarbonization constraint that linearly declines to 5% of 2005 emissions on net by 2050. IRA's PTC and ITC are assumed to not phase out.
- Mid-case with 100% Decarbonization by 2035 (without tax credit phaseout): the same set of base assumptions as the first scenario, but nascent technologies are included

and there is a national electricity sector decarbonization constraint that linearly declines to zero on net by 2035. IRA's PTC and ITC are assumed to not phase out.

Note: Each user can select- from grid scenario dropdown menu – one of the ten scenarios that project the possible evolution of the electricity sector through 2050.

iv. **Use emissions averaged over the analysis period?** Whether to account for the projected evolution of the grid or utilize a single year's emissions factors.

Yes: Utilize grid emissions factors that are averaged over the analysis period in order to capture the emissions impact of the identified technologies throughout the planning horizon. (Note: The analysis period can be modified under the "Financial" section.

No (use a single year's emissions): Assume that grid emissions factors for a chosen year remain the same throughout the analysis period. Users can specify this year by entering a specific "Emissions year" between 2024 and 2050.

Note: By default, REopt will utilize grid emissions factors that are averaged over the analysis period in order to capture the emissions impact of the suggested technologies throughout the planning horizon. The analysis period can be modified under the "Financial" accordion***.*** If a user selects No (use a single year's emissions), the reported emissions metrics will assume that emissions throughout the analysis period are the same as the chosen year. Users can specify this year below by entering a specific "Emissions year" between 2024 and 2050.

v. **Emissions year(s)**: The year(s) of the climate emissions data used to calculate the emissions impact of the suggested technologies. Depends on input "Use emissions averaged over the analysis period".

• If "Yes" is selected for "Use emissions averaged over the analysis period?", then this input field will not be modifiable, and will display the range of years used to calculate the average hourly emissions profile (starting in current year and extending for the analysis period.

• If "No (use a single year's emissions)" is selected for "Use emissions averaged over the analysis period", then this field will be modifiable, and users can enter a year between 2024 and 2050. In this case, REopt's calculated emissions impacts will assume that each year of the analysis period has the electric grid climate emissions factors of the year entered here.

vi. **Include distribution losses?** Whether distribution losses are included in the calculated emissions factors.

Busbar: A busbar is a metallic strip or conductor used to collect and distribute electrical power in a power system. It serves as a central point where multiple electrical circuits are connected and where electrical current is routed. The main purpose of a busbar is to facilitate the distribution of electricity from a single source to various loads or circuits. It helps in managing and directing electrical flow within electrical panels, substations, or distribution boards. Emissions rates do not include distribution losses.

End-use: End-use refers to the point at which energy or resources are utilized by the final consumer for specific purposes. This is the ultimate consumption of energy or materials, as opposed to their generation or transmission. End-use includes all activities and appliances that consume energy or resources, such as heating, cooling, lighting, transportation, and industrial processes. This concludes emissions rates at the point of consumption, including distribution losses and will be higher than busbar emissions rates.

Note: Based on the above analysis, users can choose from the menu whether they want to use end-use emissions (**Yes**) or busbar emissions (**No**)

Moreover, there is an electric grid health emissions factors section. Electric Grid Health Emissions Factors include various elements that impact the efficiency and environmental performance of the power grid. By focusing on factors such as generation mix, transmission losses, grid reliability, and energy efficiency, stakeholders can work towards reducing emissions and improving the overall health of the electric grid. Implementing strategies to enhance renewable energy integration, modernize infrastructure, and manage demand can significantly contribute to a cleaner and more efficient power system. The health-related (NOx, SO2, PM2.5) emissions rates of grid electricity assumed in the analysis.

If “Hourly” is selected, hourly marginal emission data for NOx, SO2, and PM2.5, which is acquired from US EPA AVERT for the US region selected, will be applied to each hour of grid-sourced electricity. If “Annual” is selected, single annual grid emission factors for NOx, SO2, and PM2.5, in lbs/kWh, can be entered. These factors will be applied to grid-sourced electricity in each hour of the year. If “Upload” is selected, the user can upload one year of custom hourly emissions factors.

For site locations in the United States, if no emission factor selection is made, default health emission factors will be used. If the site location is within the continental United States, the default factors used will be hourly marginal emissions from the US EPA AVERT for the region corresponding to the location, which is listed below the dropdown menu box. If the site is in Hawaii or Alaska, the default annual emissions factors used in the evaluation come from the EPA eGrid database and will be listed on the “Annual” tab. Default grid emission factors are inclusive of transmission and distribution losses.

If the site location is outside the United States, any of the grid emission factor input options can be used. However, if no emission factor selection is made, there is no default value and emissions impact from the electricity grid will be assumed to be zero.

Only one active tab (Hourly, Annual, or Upload) for specifying the emission factor will be applied to optimization. Emissions factors are not required for input.

Inputs to generate levelized health emissions factors from data

- **EPA's AVERT Region:** For site locations in the contiguous United States, the default grid emissions factors for NOx, PM2.5, and SO2 are for the US EPA AVERT region corresponding to the site location, which is listed below the dropdown menu box. A different region than the default can be selected. For sites in Hawaii and Alaska, use the "Annual" tab. Emission factors for grid electricity are inclusive of transmission and distribution losses. Emission factors are not required for input.

- **Projected annual percent decrease in grid health emissions factors (%/year):** Year over year, a percentage decrease in the total annual emissions rate of the grid for health-related emissions. A positive value indicates an annual decrease, and a negative value indicates an annual increase. The default value is calculated based on the national average rate of decrease of long-run marginal CO2e emissions, as reported by Cambium for the Mid-Case Scenario**.**

Proceeding further, we have the technology models that are chosen for the analysis. For solar we have the default system capital cost based on the US national average from NREL's annual technology baseline. If there is an existing PV system on site, the user can enter that information on the appropriate cell. By toggling the advanced inputs, a new menu pops up.

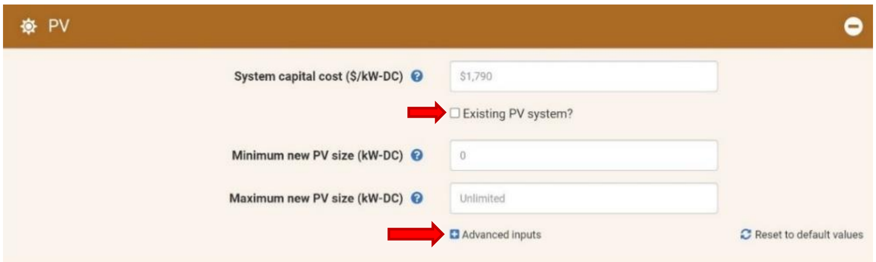


Fig. 17*. PV system general information*

As mentioned before, this section contains advanced inputs for users to enter, if necessary (such as Operation and Maintenance costs, which direction the PV system is facing etc.), but in this example, we'll use the default values that REopt already has.

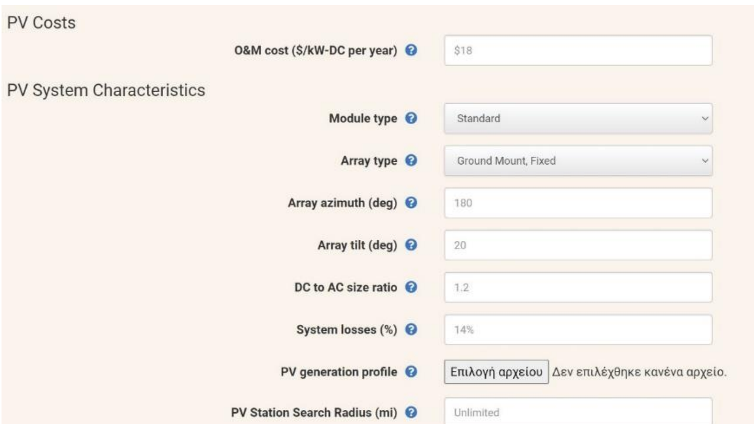


Fig. 18. *PV costs and system characteristics*

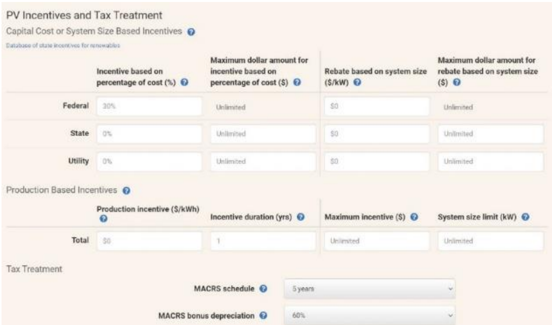


Fig. 19. *PV incentives and tax treatment*

The same pattern goes for the **battery** properties that the system will contain. With that being said, we have general information first and then more advanced inputs for the user if desired.

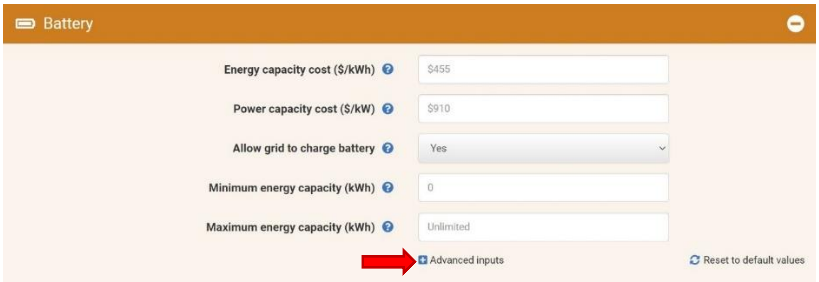


Fig. 20. *General information for battery capacity*

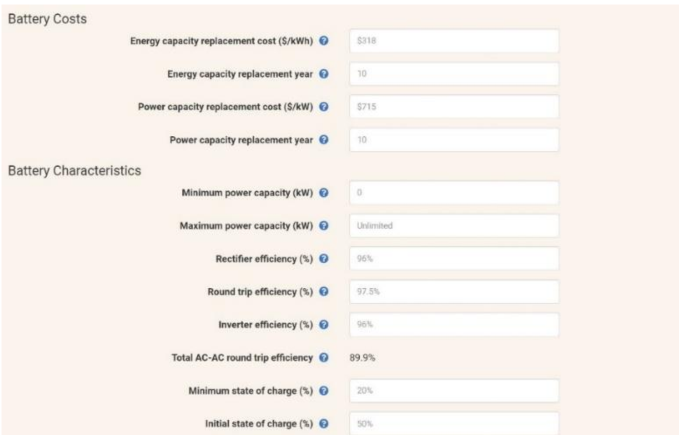


Fig. 21. *Battery costs and characteristics*

Fig. 22. *Battery incentives and tax treatment*

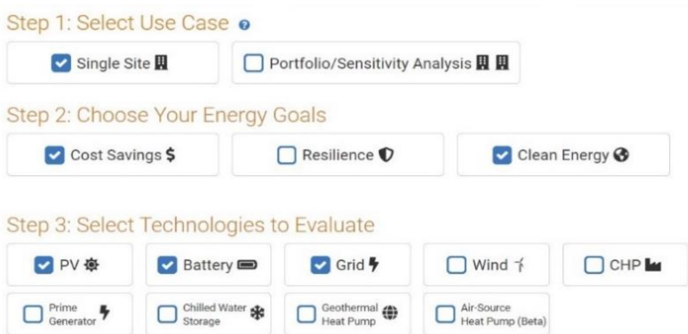
To sum up, the inputs that are going to be modified for the analysis to start are the site location, the electricity utility rate, and the building type. Despite everything that's presented, these three inputs are the necessary ones for optimization. So, the site location we are selecting is Denver, Colorado, US, electricity rate is the **Intermountain Rural Elec Assn - Commercial Demand Metered Time of Use (B-TOU)** and the type of building is **Office-Medium.** Also, our energy goals will focus on cost-savings and clean energy.

1.3. Results

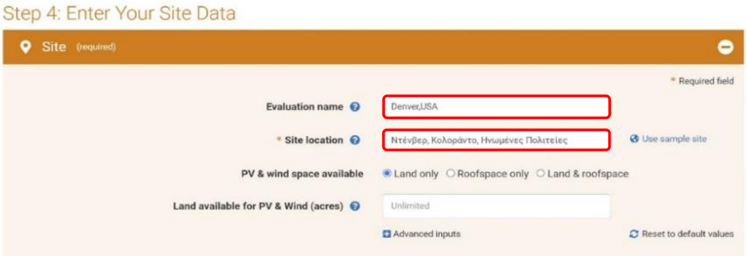
In this final chapter, the user shall see a step-by-step guide of the inputs that are necessary for the analysis to begin. With the form of some precise examples, this will be more intuitive (NREL, 2025).

- PV-Battery system inputs

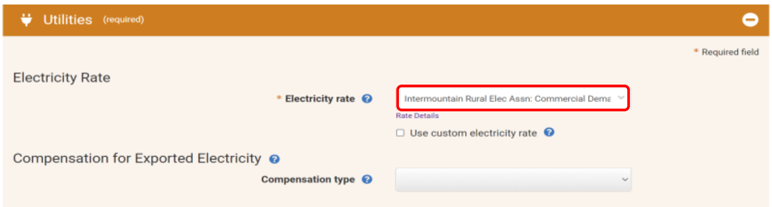
As mentioned before, each user shall toggle the highlighted parts as shown in the figure below for this specific system. (**blue checkboxes**)



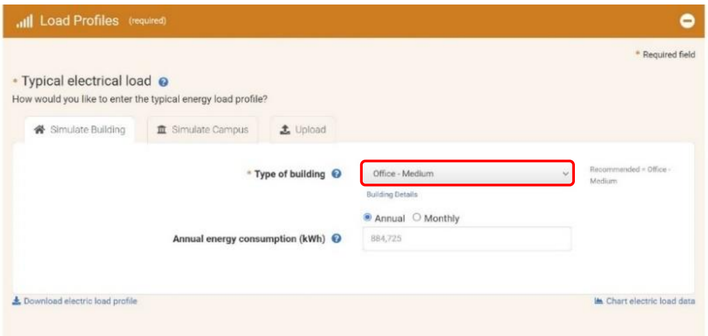
Next, the user can optionally name the evaluation (for example Denver, USA) and type the first mandatory selection referring to the site location. In this section we type **Denver,** and from the dropdown menu that pops up, we pick **Denver, Colorado, USA**.



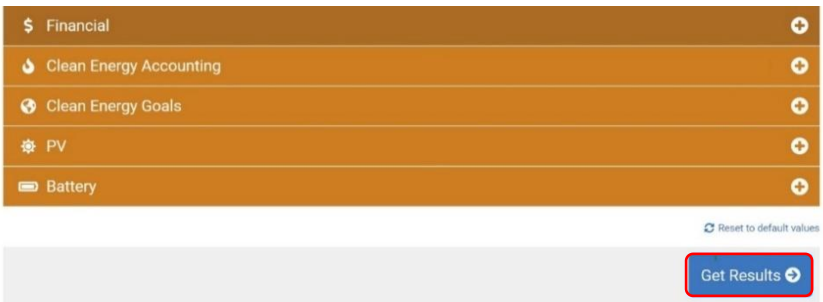
Proceeding further, when user types a location, some **electricity rates** will load automatically, and this will be the second mandatory selection. From the drop-down menu, we can pick a rate for this location. In this example, we 've picked the first that pops up.



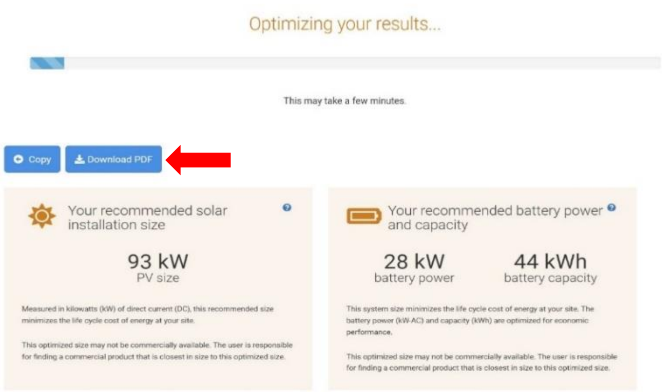
After electricity rate selection, there is the final mandatory pick so that the optimization can start and contains the **type of building**. From the list that pops up and for this particular example, we picked **Office-Medium.**



These three inputs are the necessary ones for optimization to begin. As mentioned before, based on data each user has, some sections and advanced inputs can be modified. The techno-economic analysis can start by toggling **Get Results.**



Typically, it can take a few minutes to solve depending on the complexity of the optimization process. When the loading time of the optimization is done, the user shall look at the types of results that REopt outputs.



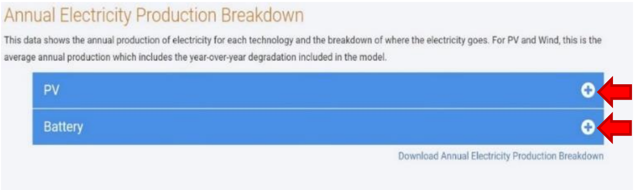
By toggling **Download PDF,** each user can have the evaluation report summary as pdf file.

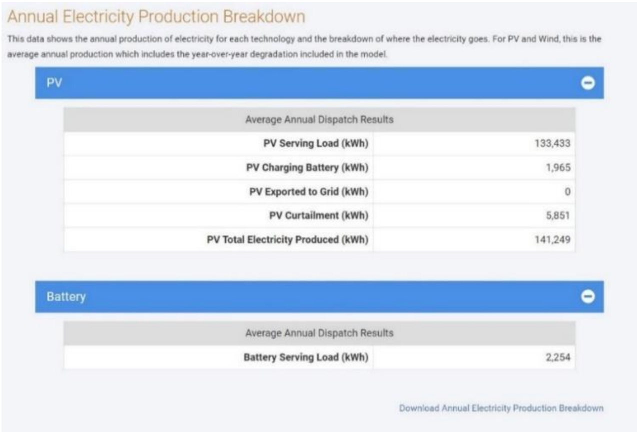
Firstly, the results show that PV and battery are cost effective. For this site, approximately 93 kW of PVs and 28 kW of battery is needed (the capacity is 44kWh based on the respective voltage).

In this system, REopt has identified the opportunity of providing 14,053 $ in net present value or life cycle cost savings. This is the present value of the net savings after accounting for things like capital costs, incentives, O&M costs, and bill savings.

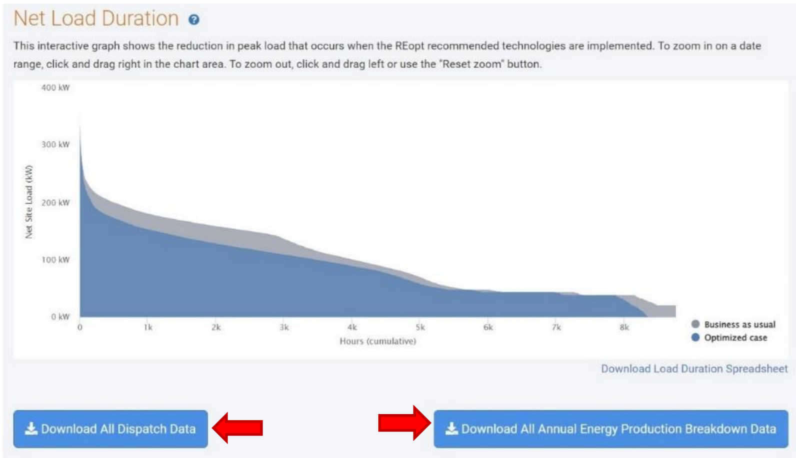
By scrolling down, the user shall see the **system performance** in the example year. Zooming out (as pointed by the red arrow), provides also the chance to see how PV and battery are supporting the load.

Moving forward into results, there is also data that shows the **annual production of electricity** for each technology and where the electricity goes. By toggling the cross for each technology this data pops up.





Additionally, the user should see the **net load duration graph**. The Net Load Duration graph represents the potential reduction in utility electric load in every hour of the year that the recommended technologies would provide, if implemented. It is also notable that the hourly dispatch and all annual energy production data can be downloaded.



The **Results Comparison** section below shows how doing business as usual compares to the optimal case. In the first column user can see the business-as-usual case, the financial outputs in column two and then the savings in column tree.

Moving forward, users can see the system sizing, how much energy the PV system is generating, the annual renewable energy percentage that this PV system is contributing to the electric load and emissions impacts. There is also a breakdown of energy and demand charge savings, and the user can see the year one costs in the business-as-usual case, the same costs in the optimized scenario and then savings which are presented by negative values. Similarly, we also have the life cycle cost breakdown which contains capital costs after incentives, O&M costs, and total utility costs. Finally, there are some summary financial metrics including capital costs before incentives, year one O&M costs, total life cycle costs, net present value, simple payback period, internal rate of return and the PV levelized cost of energy.

Results Comparison

Results Comparison

These results show how doing business as usual compares to the optimal case.

	Business As Usual	Financial	Difference
System Size			
PV Size	0 kW	93 kW	93 kW
Battery Power	0 kW	28 kW	28 kW
Battery Capacity	0 kWh	44 kWh	44 kWh
Energy Production and Fuel Use			
Average Annual PV Energy Production	0 kWh	141,249 kWh	141,249 kWh
Average Annual Energy Supplied from Grid	884,726 kWh	749,569 kWh	-135,157 kWh
Renewable Energy Metrics			
Annual Renewable Electricity (% of electricity consumption)	0%	15%	15%
Climate Emissions			
Avoided CO_2e Emissions throughout Analysis Period	N/A	388 tonnes	388 tonnes
Health Emissions			
Avoided NO_x Emissions throughout Analysis Period	N/A	1.08 tonnes	1.08 tonnes
Avoided SO_2 Emissions throughout Analysis Period	N/A	0.71 tonnes	0.71 tonnes
Avoided $PM_{2.5}$ Emissions throughout Analysis Period	N/A	0.04 tonnes	0.04 tonnes

Fig. 22. *System sizing, energy production, renewable energy metrics, climate and health emissions results*

Year 1 Utility Electricity Cost — Before Tax			
Utility Export Benefit	$0	$0	$0
Utility Energy Cost	$56,295	$47,695	-$8,600
Utility Demand Cost	$39,370	$33,508	-$5,862
Utility Fixed Cost	$480	$480	$0
Utility Minimum Cost Adder	$0	$0	$0
Total Year 1 Utility Cost - Before Tax	$96,145	$81,683	-$14,462
Life Cycle Cost Breakdown			
Technology Capital Costs + Replacements, After Incentives	$0	$123,263	$123,263
O&M Costs	$0	$19,721	$19,721
Total Utility Electricity Cost	$1,044,020	$886,982	-$157,037
Cost of Climate Emissions throughout Analysis Period (If Included in Objective)	$0	$0	$0
Cost of Health Emissions throughout Analysis Period (If Included in Objective)	$0	$0	$0
Summary Financial Metrics			
Total Upfront Capital Cost Before Incentives	N/A	$211,239	$211,239
Year 1 O&M Cost, Before Tax	$0	$1,667	$1,667
Total Life Cycle Costs	$1,044,020	$1,029,967	-$14,053
Net Present Value	$0	$14,053	$14,053
Payback Period	N/A	12.02 yrs	12.02 yrs
Internal Rate of Return	N/A	7.0%	7.0%
PV Levelized Cost of Energy	N/A	$0.060/kWh	$0.060/kWh

Fig. 23. *Year 1 energy cost before tax, life cycle cost breakdown, financial metrics*

Additionally, there are also results that show emissions outcomes in a little bit more detail than in the summary table.

Renewable Energy & Emissions Metrics

Renewable Energy & Emissions Metrics

These results show emissions outcomes for the business as usual and optimized cases. If marginal grid emissions rates are utilized (the default inputs), users should focus on avoided emissions, rather than emissions totals. Note for all emissions outputs, "t" (as in, "t CO_2e") represents metric tons (tonnes).

	Business As Usual	Financial	Difference
Renewable Energy			
Annual Renewable Electricity (% of electricity consumption)	0%	15%	15%
Climate & Health Emissions Costs			
Cost of Climate Emissions throughout Analysis Period	$146,778	$131,471	-$15,307
Cost of Health Emissions throughout Analysis Period	$83,207	$70,420	-$12,787
Climate Emissions, CO_2e			
Average Annual Emissions (t CO_2e)	149	133	-16
Average Annual Emissions from Grid Purchases (t CO_2e)	149	133	-16
Average Annual Emissions from Onsite Fuel Burn (t CO_2e)	0	0	0
Total Emissions throughout Analysis Period (t CO_2e)	3,718	3,330	-388
Emissions from Grid Purchases throughout Analysis Period (t CO_2e)	3,718	3,330	-388
Emissions from Onsite Fuel Burn throughout Analysis Period (t CO_2e)	0	0	0
Percent Reduction in CO2 Emissions from BAU (%)	N/A	10.43%	10.43%
Breakeven Cost of CO_2e Emissions Reduction ($/t CO_2e)	N/A	N/A	N/A

Fig. 24. *Climate emissions costs*

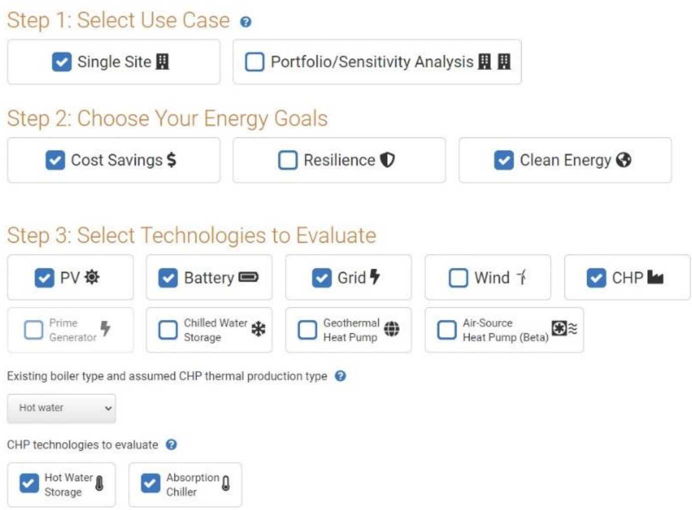
Health Emissions, NO_x			
Average Annual Emissions (t NO_x)	0.28	0.24	-0.04
Average Annual Emissions from Grid Purchases (t NO_x)	0.28	0.24	-0.04
Average Annual Emissions from Onsite Fuel Burn (t NO_x)	0.00	0.00	0.00
Total Emissions throughout Analysis Period (t NO_x)	7.01	5.93	-1.08
Emissions from Grid Purchases throughout Analysis Period (t NO_x)	7.01	5.93	-1.08
Emissions from Onsite Fuel Burn throughout Analysis Period (t NO_x)	0.00	0.00	0.00
Health Emissions, SO_2			
Average Annual Emissions (t SO_2)	0.18	0.15	-0.03
Average Annual Emissions from Grid Purchases (t SO_2)	0.18	0.15	-0.03
Average Annual Emissions from Onsite Fuel Burn (t SO_2)	0.00	0.00	0.00
Total Emissions throughout Analysis Period (t SO_2)	4.55	3.84	-0.71
Emissions from Grid Purchases throughout Analysis Period (t SO_2)	4.55	3.84	-0.71
Emissions from Onsite Fuel Burn throughout Analysis Period (t SO_2)	0.00	0.00	0.00
Health Emissions, $PM_{2.5}$			
Average Annual Emissions (t $PM_{2.5}$)	0.01	0.01	-0.00
Average Annual Emissions from Grid Purchases (t $PM_{2.5}$)	0.01	0.01	-0.00
Average Annual Emissions from Onsite Fuel Burn (t $PM_{2.5}$)	0.00	0.00	0.00
Total Emissions throughout Analysis Period (t $PM_{2.5}$)	0.25	0.21	-0.04
Emissions from Grid Purchases throughout Analysis Period (t $PM_{2.5}$)	0.25	0.21	-0.04
Emissions from Onsite Fuel Burn throughout Analysis Period (t $PM_{2.5}$)	0.00	0.00	0.00

Download Hourly Grid Emissions Factors

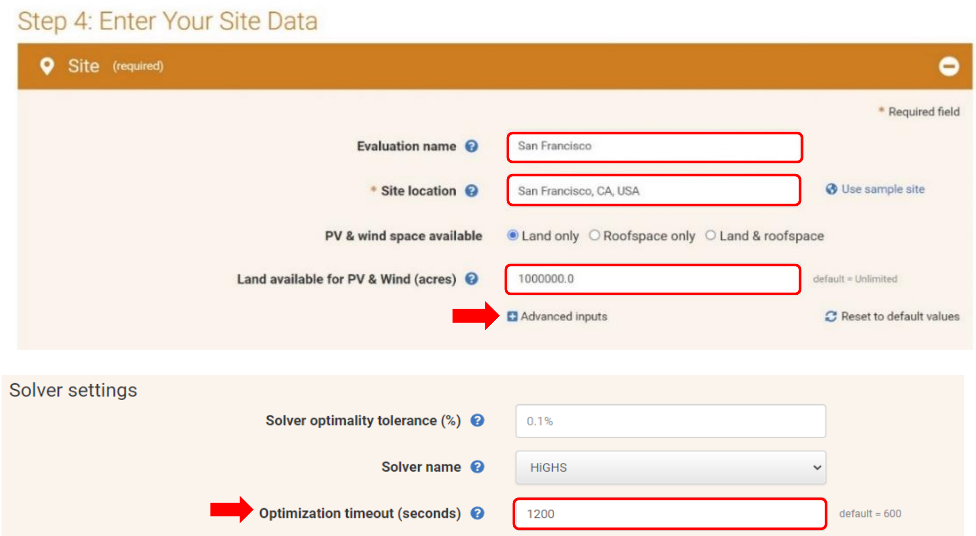
***Fig. 25**. Health emissions*

- PV-Battery-CHP system inputs

As mentioned before, each user can toggle the highlighted parts -as shown in the image below- for this specific system. **(blue checkboxes)**

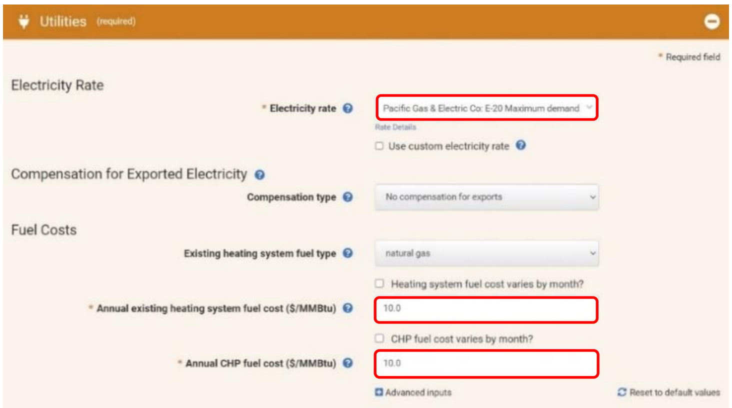


On this second example, the optimization will focus on a PV-Battery-Grid system as the previous example <u>but with the addition of a CHP unit</u>. As for energy goals, cost savings and electricity from renewable resources (clean energy) are the main ones.

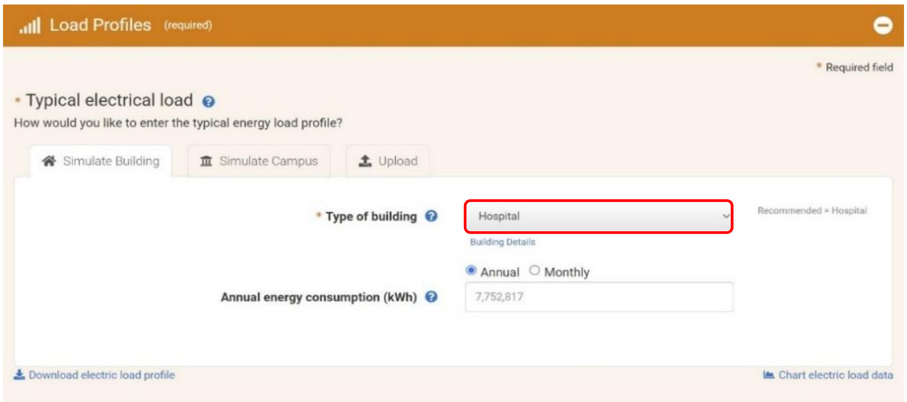


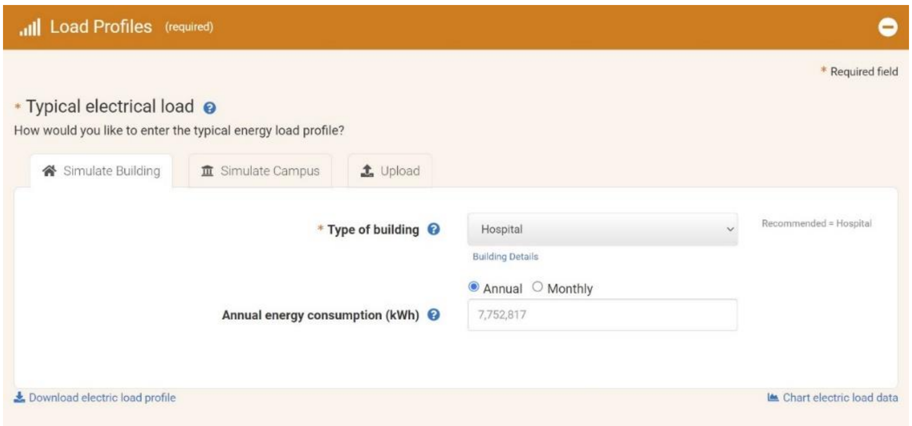
So, again as the previous example we named the new evaluation **(San Francisco)** changed the location to San Francisco, USA and set a land for PV and Wind of 1,000,000 acres (1562.5 miles). In this particular site, due to its large size, we came across some problems with the solver and optimization of loading time. Therefore, there was a change in the **optimization timeout** section and instead of 600 seconds **(default)** we made it 1200 seconds. This can be found in the Advanced inputs below **Land available for PV and Wind** cell.

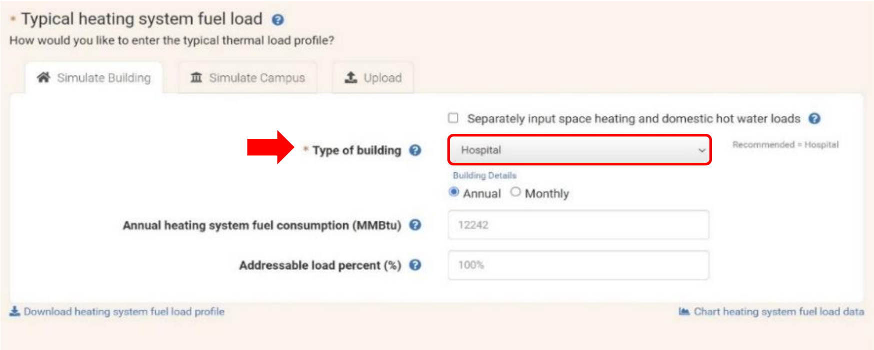
As for the utilities section, we have picked an electricity rate form the dropdown menu: **Pacific Gas & Electric Co - E-20 Maximum demand of (1000 KW or more) (Secondary)** and set the other two required inputs from this section which are *the annual existing heating system fuel cost* and *the annual CHP fuel cost.*

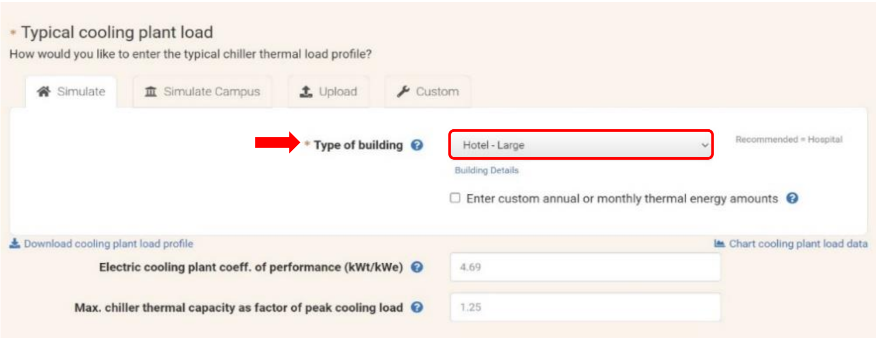


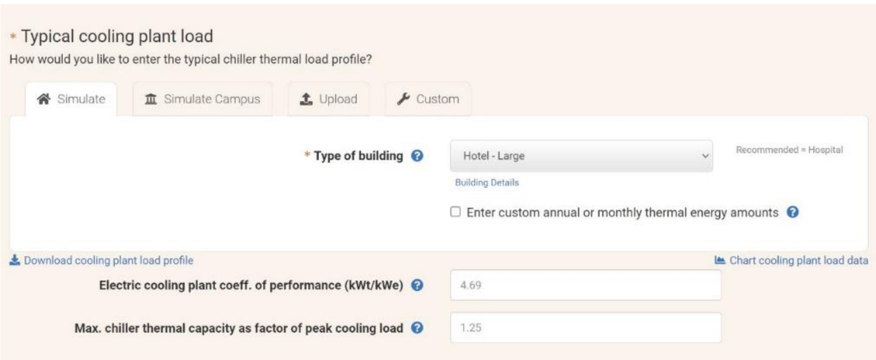
In the load profile section, as type of building we picked **hospital** from the list, for the simulation of typical heating system fuel load a **hospital** is selected again and at last for the cooling plant load we picked a **hotel large simulation**.











These were the necessary inputs for this system optimization to start. If some information or any other metrics are needed for the site, the user can modify the cells REopt provides. Toggling Get Results and waiting a couple of minutes will result in the illustration of a recommended site.

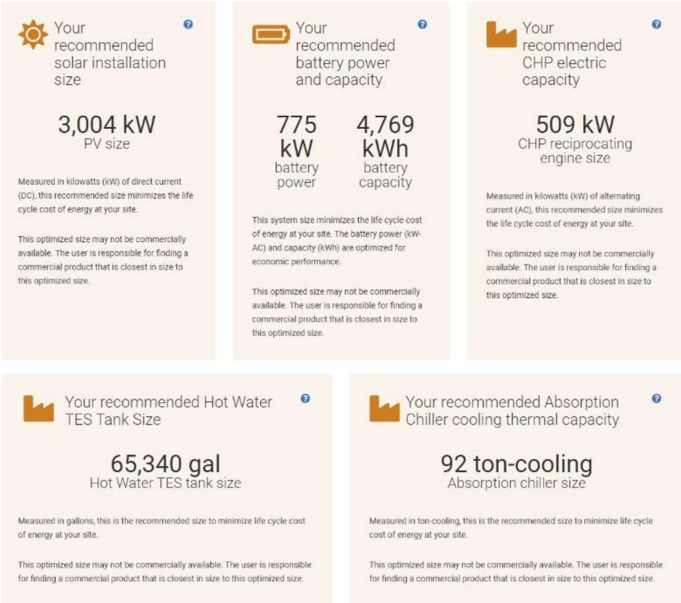
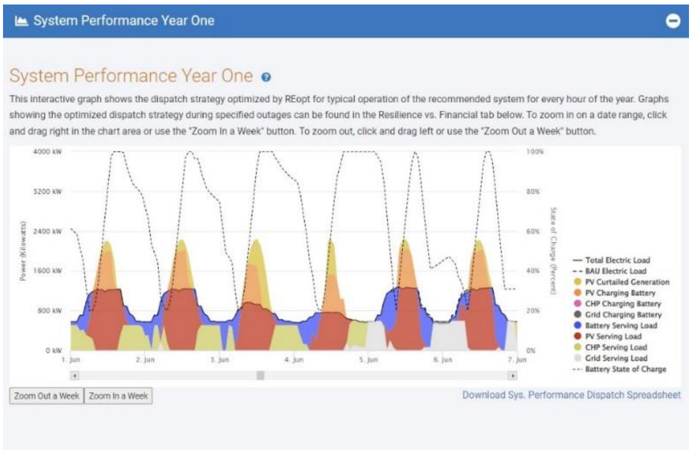


Fig. 26. *Summary of the recommended technologies for optimization of the selected site*

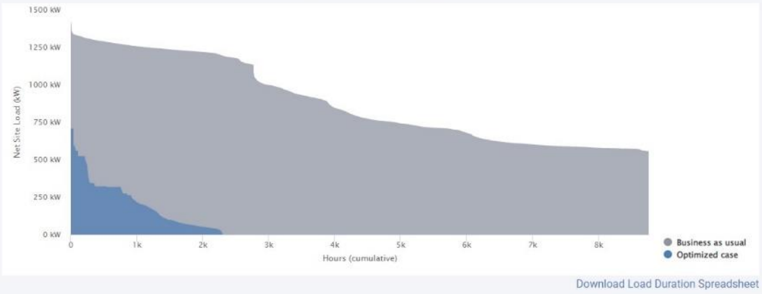


Cooling Thermal Dispatch

This interactive graph shows the cooling thermal dispatch strategy optimized by REopt. To zoom in on a date range, click and drag right in the chart area. To zoom out, click and drag left or use the "Reset zoom" button.

Net Load Duration

This interactive graph shows the reduction in peak load that occurs when the REopt recommended technologies are implemented. To zoom in on a date range, click and drag right in the chart area. To zoom out, click and drag left or use the "Reset zoom" button.



Results Comparison

Results Comparison

These results show how doing business as usual compares to the optimal case.

	Business As Usual	Financial	Difference
System Size			
PV Size	0 kW	3,004 kW	3,004 kW
Battery Power	0 kW	775 kW	775 kW
Battery Capacity	0 kWh	4,769 kWh	4,769 kWh
CHP Size	N/A	509 kW	509 kW
Hot Water Storage Tank Size	N/A	65,340 gal	65,340 gal
Absorption Chiller Size	N/A	92 ton	92 ton
Energy Production and Fuel Use			
Average Annual PV Energy Production	0 kWh	4,493,589 kWh	4,493,589 kWh
CHP Electric Production	N/A	3,062,782 kWh	3,062,782 kWh
CHP Thermal Production	N/A	13,465 MMBtu	13,465 MMBtu
CHP Fuel Used	N/A	30,292 MMBtu	30,292 MMBtu
Electric Chiller Cooling Production	1,482,734 ton-hr	1,242,198 ton-hr	-240,536 ton-hr
Electric Chiller Electric Consumption	1,111,845 kWh	931,476 kWh	-180,368 kWh
Absorption Chiller Cooling Production	N/A	240,536 ton-hr	240,536 ton-hr
Absorption Chiller Thermal Used	N/A	4,589 MMBtu	4,589 MMBtu
Absorption Chiller Electricity Used	N/A	59,995 kWh	59,995 kWh
Average Annual Energy Supplied from Grid	7,752,817 kWh	496,784 kWh	-7,256,033 kWh
Heating System Thermal Production	9,794 MMBtu	951 MMBtu	-8,843 MMBtu
Heating System Fuel Used	12,242 MMBtu	1,189 MMBtu	-11,053 MMBtu

Fig. 27. *System sizing, energy production and fuel use*

Renewable Energy Metrics			
Annual Renewable Electricity (% of electricity consumption)	0%	53%	53%
Annual Renewable Energy (% of electric + heat consumption)	0%	34%	34%
CHP Total Efficiency (% HHV-basis)	N/A	78%	78%
CHP Electric Efficiency (% HHV-basis)	N/A	34%	34%
CHP Thermal Utilization (% of max)	N/A	100%	100%
CHP Electric Capacity Factor	N/A	69%	69%
Climate Emissions			
Avoided CO_2e Emissions throughout Analysis Period	N/A	-17,701 tonnes	-17,701 tonnes
Health Emissions			
Avoided NO_x Emissions throughout Analysis Period	N/A	-2.85 tonnes	-2.85 tonnes
Avoided SO_2 Emissions throughout Analysis Period	N/A	2.53 tonnes	2.53 tonnes
Avoided $PM_{2.5}$ Emissions throughout Analysis Period	N/A	1.24 tonnes	1.24 tonnes

Fig. 28. *Renewable energy metrics, climate and health emissions results*

Year 1 Utility Electricity Cost – Before Tax			
Utility Export Benefit	$0	$0	$0
Utility Energy Cost	$1,139,797	$71,969	-$1,067,828
Utility Demand Cost	$960,053	$192,335	-$767,718
Utility Fixed Cost	$41,015	$41,015	$0
Utility Minimum Cost Adder	$0	$0	$0
CHP Standby Charges	N/A	$0	$0
Total Year 1 Utility Cost - Before Tax	$2,140,865	$305,319	-$1,835,546
Year 1 Utility Fuel Cost – Before Tax			
Heating System Fuel Cost	$122,423	$11,889	-$110,534
CHP Fuel Cost	N/A	$302,917	$302,917
Life Cycle Utility Fuel Cost – After Tax			
Heating System Fuel Cost	$1,301,768	$126,420	-$1,175,347
CHP Fuel Cost	N/A	$3,221,022	$3,221,022
Life Cycle Cost Breakdown			
Technology Capital Costs + Replacements, After Incentives	$0	$6,109,456	$6,109,456
O&M Costs	$0	$1,420,222	$1,420,222
CHP Standby Charges	$0	$0	$0
Total Utility Electricity Cost	$23,247,311	$3,315,409	-$19,931,902
Non-Outage Fuel Costs	$1,301,768	$3,347,443	$2,045,675
Cost of Climate Emissions throughout Analysis Period (If Included in Objective)	$0	$0	$0
Cost of Health Emissions throughout Analysis Period (If Included in Objective)	$0	$0	$0
Summary Financial Metrics			
Total Upfront Capital Cost Before Incentives	N/A	$10,066,924	$10,066,924
Year 1 O&M Cost, Before Tax	$0	$120,082	$120,082
Total Life Cycle Costs	$24,549,079	$14,192,530	-$10,356,549
Net Present Value	$0	$10,356,549	$10,356,549
Payback Period	N/A	4.24 yrs	4.24 yrs
Internal Rate of Return	N/A	20.0%	20.0%
PV Levelized Cost of Energy	N/A	$0.062/kWh	$0.062/kWh

Fig. 29. *Year 1 energy and fuel cost before tax, life cycle cost breakdown, financial metrics*

1.4. Comparison

What we wanted to succeed in during this techno-economic analysis was an estimation of a cost optimal system that minimizes the life cycle cost of energy in our site. Based on the technologies we picked for the evaluation (**PV-Battery** in example 1 and **PV-Battery-CHP** in example 2) and reviewing some results we got, we see that these technologies are cost effective. Another asset that should be addressed is the net present value. It is a financial metric used to evaluate the profitability of an investment by comparing the present value of its expected cash inflows to the present value of its cash outflows. In our first site (PV-Battery based), net present value is +14,053$ (savings), so our project has the potential of being financially attractive. As for our second (PV-Battery-CHP with hot and chilled water storage tanks), the net present value stands at +10,356,549$, which makes it again profitable. Proceeding a bit further, we can see the results comparison between business-as-usual cases and the optimal one. As shown in **Fig. 22.** -in **example one**- there is a 141,249-kWh average annual PV energy production compared to business as usual which is 0kWh. This has an important footprint in the average supplied energy from grid (749,569 kWh than 884,726 when in business as usual) and also a 15% of electricity consumption comes from renewable sources rather than what he had before (0%). Furthermore, an optimal case scenario provides less climate emissions by avoiding 388 tons of carbon dioxide and various greenhouse gases. Additionally, as we can see in the year 1 utility electricity cost (**Fig. 23**) evaluation, the optimal system has an 81,683$ cost rather than 96,145$ that we have in business-as-usual cases. There is a difference of 14,462$ which makes the optimal system more cost effective. As for the **second example**, there is 4,493,589 kWh average annual PV energy production compared to business-as-usual cases (**Fig. 27**). Additionally, with a big amount of energy coming from PV and a smaller from CHP unit (3,062,782 kWh), grid supplies 496,784 kWh electricity than 7,752,817 kWh that provided under normal circumstances. Furthermore, due to the CHP utilization (absorption and electric chiller combined), the expected energy produced by the existing boiler will be 951 MMBtu compared to 9,794 MMBtu. The portion of total electricity consumption that is derived from on-site renewable resource generation in a single year is 53%. In the optimal case scenario, there are also 17,701 tons less emissions containing carbon dioxide and greenhouse gases (**Fig. 28**). Moreover, year 1 total utility cost is 2,140,865$ in business-as-usual case than 305,319 $ in the optimal case scenario.

As we continue to review the results in the table, we see the total utility electricity cost. On the **first example**, in business-as-usual case it is 1,044,020 $ and in optimal scenario-with the addition of technologies capital costs and O&M costs- is 886,982$. That provides us with a difference of 157,037$ that we could save during the life cycle. Last but not least, here is a summary of year 1 costs and the comparison of both scenarios gives a 14.053$ savings that we can get, following our estimated cost optimal system. Also, the estimated payback period of the investment is 12 years followed by a 7% internal rate of return. On the **second example,** when reviewing the same metrics as the first, we have 23,247,311 $ life cycle cost of all utility electricity costs in business-as-usual case and a 3,315,409 $ for the optimal case (**Fig. 29**). Even though there is total upfront capital cost of the new technologies for the estimated optimal system (10,066,924 $) before incentives and O&M cost (1,420,222 $) than the business as usual case, the present value of costs-after taxes and incentives associated with the project- will approximately be 24,549,079 $ (business as usual) and $14,192,530 $ (optimal case). This provides us with a net present value of making the project financially attractive. Lastly, the estimated payback period of the investment will be 4.24 years with an internal rate of return standing at 20%.

Table 1. Optimal systems summary

Category	***San Francisco***	***Denver***	***Unit***
Technologies			
Photovoltaics (PV)	3,004	93	kW DC
Battery	775	28	kW AC
Battery Capacity	4,769	44	kWh
CHP	509	-	kW AC
Hot Water Storage	65,340	-	gallons
Absorption Chiller	92	-	tons
Economic results			
Year 1 Cost	305,319	81,683	$
Total 25-year Cost	14,192,530	1,029,967	$
Payback period	4.24	12.02	years
Net savings	10,356,549	14,053	$
Energy Production			
PV Generation	4,493,589	141,249	kWh
Grid Energy Usage	496,784	749,569	kWh
Environmental Benefits			
CO_2 Emissions Reduction	17,701	388	tons
NO_x Emissions Reduction	2.85	1.08	tons
SO_2 Emissions Reduction	2.53	0.71	tons

In the table above, we summarize the most important factors for the systems that have been optimized. Comparing the two systems, users can come to some additional conclusions. The system in **San Francisco** is designed for a ***larger* scale**, with significantly higher PV capacity (3,004 kW compared to 93 kW in Denver). The large size reflects **higher energy demands** and **ambitious target*s*** serving as a result of large-scale facilities (e.g. hospitals). In **Denver**, we have a **smaller system** in scale that is most suitable for medium-sized buildings (e.g. office spaces). As for the economic metrics, in **San Francisco's** site there is a **higher initial cost** (14,192,530$ over 25 years), but it delivers significantly ***greater savings***(10,356,549$).Also, due to **high energy efficiency** and savings from CHP and energy storage utilization there is a **short payback period** (4.24 years).On the other hand, the site in **Denver** has ***lower initial cost*** (1,029,967$ over 25 years), but also lower savings (14,053$).Additionally , there is a ***longer payback period*** (12.02 years) as a result of the **smaller scale** and **fewer available technologies**. Energy wise, in **San Francisco** the exceptionally high PV production (4,493,589 kWh/year), significantly **reducing reliance on the grid**. Also, the battery system (4,769 kWh) and CHP **maximize energy utilization**. As for the site in Denver, much lower PV production (141,249 kWh/year), resulting in **greater reliance on the grid**. Moreover, the smaller battery capacity (44kWh) **limits efficiency and energy autonomy**. Finally, for the environmental benefits, in **San Francisco** there Is a significant reduction of CO_2 emissions (17,701 tons in 25 years), as well as NO_x and SO_2. Due to multiple technologies and large scale, we have an impressive impact on clean energy. In **Denver**, there is a smaller reduction in CO_2 (388 tons), reflecting limited use of renewable energy sources. That is why this system is suitable for a smaller environmental impact without a significant infrastructure upgrade.

Caution: This model provides an estimate of the techno-economic feasibility of solar, wind, battery, and/or CHP, so investment decisions should not be made on REopt results alone. These results assume perfect prediction of solar irradiance, wind speed, and electrical and thermal loads. In practice, actual savings may be lower based on the ability to accurately predict solar irradiance, wind speed, and load, and the control strategies used in the system.

CHAPTER 2: Overview and implementation of the nPRO software

2.1. Introduction

NPro is an advanced software tool meant to design and plan buildings and district heating networks (nPro Energy, 2025). It provides features like demand simulation, district heating network design, renewable energy integration, and system optimization using AI. Each user can generate load profiles, design complex energy systems, optimize costs, and compare scenarios. The tool is intuitive, collaborative and validated with real-world data, targeting engineers, utilities, and consultants.

Additionally, it is a modular, flexible tool that simplifies and accelerates the manual planning process of quarters. NPro has been developed especially for the early planning phase, when only a little information about district and energy systems is available. The form of this chapter is to provide manual instructions on the user in order to understand the basic features the nPRO computational tool. It is suggested in a later stage (e.g. in the form of a new thesis) to provide examples that will be based on realistic scenarios and comparable to each other.

2.2. Key features

- **Demand profiles**
  - Automatically generate hourly energy demand profiles for *heating*, *cooling*, and electricity using an extensive database.
  - Supports diverse building types, including residential and commercial setups.
- **District heating and cooling systems**
  - Simulates traditional and 5th-generation district heating and cooling (5GDHC) systems.
  - Optimizes network parameters like temperature profiles and pipe dimensions for cost and energy efficiency.
- **Technology integration**
  - Models' renewable energy sources, hydrogen technologies, heat pumps, energy storage systems and other technologies.
  - Supports simulation of energy hubs and microgrids.

- **Optimization engine**
  - Identifies the most economical system configurations and sizes of components for optimal performance.
  - Provides sensitivity analysis for CO_2 pricing impacts.
- **Collaborative and Intuitive**
  - Cloud-based collaboration tools allow teams to share and update project data seamlessly.
  - Designed for ease of use without requiring extensive prior training.

- ***Demand profiles***

For the planning of districts, the correct estimation of demand profiles is crucial. This helps identify peak demands, assess system capacity needs, optimize cost and energy efficiency, which is critical for designing sustainable energy solutions like district heating or renewable integration.

Depending on the planned energy system, different demand or load profiles are important for district planning (nPro Energy, 2025). These include:

Heating demand

- ***Space heating***: It represents the largest energy demand in the district. The total demand depends -to a large extent - on the insulation standard of the buildings and is characterized by strong seasonality. The energy required to provide space heat is directly dependent on the weather. In years with severe, cold winters, heating demands are higher than in years with mild winters. To determine an average annual heating demand, measured consumption data can be subjected to a weather adjustment, which is usually based on day degree figures.

- ***Domestic hot water:*** The heat demand for domestic hot water preparation does not directly depend on weather conditions. Therefore, for demand calculations, it is often assumed that the demand for domestic hot water remains constant throughout the year and between different ones. However, analysis shows that the demand for domestic hot water varies seasonally and is slightly higher in winter than in summer. Due to the demand for domestic hot water, districts have a constant demand for heat throughout the year. This is of great importance for district energy systems. On the one hand, it must be considered that with a central heat supply (with district heating) the relative heat losses in summer can be very high. On the other hand, waste heat from cooling demands in summer can be used to cover domestic hot water demands. This is particularly promising for 5GDHC networks, as low-cost air conditioning (space cooling) can be provided at low cost.

- ***Process heat:*** In addition to space heat and domestic hot water, process heat is a demand type relevant for specific building types including industrial and commercial buildings. The temperature requirement ranges from 30 - 300 °C. Typical examples are bakeries, which require up to 50% of their heat for baking processes. But laundries, restaurants or hospitals also have a relevant share of process heat. A large proportion of these additional heat demands results in increased electricity demands for the building. In the nPro tool, process heat requirements that are covered electrically are added to the electricity requirement, since these do not have to be provided via a heating network.

Cooling demand

- ***Space cooling:*** In commercial buildings, such as office buildings, the installation of systems for air conditioning has become more and more standard. Especially for businesses with customer contact, air conditioning is a key factor in increasing customer satisfaction. Banks, hotels or shopping centers, for example, must have air conditioning. Shopping centers in particular have high internal loads, which leads to considerable cooling loads in summer but also in the transitional period. In the residential sector, on the other hand, air conditioning is still rarely encountered, and when that happens, it is often implemented via decentralized mono-split units. With increasingly frequent and more pronounced periods of heat, as well as an increased need for appealing living comfort, the demand for air conditioning solutions is becoming more and more important. Large glass facades in new buildings also increase the heat loads in the summer. With the move away from fossil heat generators (gas or oil boilers) to low-temperature solutions, especially heat pumps, there are new synergy effects for the provision of heating and cooling in the residential sector.

Cooling technologies: Refrigeration technology can be electrically or thermally driven. For small refrigeration applications, electrically driven units are more common. In industrial applications with high thermal capacities, thermally driven chillers are also used. In these systems, for example, heat from combined heat and power units (CHP) is converted into cooling in absorption chillers, allowing efficient use of CHP heat even in summer operations.

- *Compression chiller:* The electrical supply is compression chillers (also called split and multi-split units). This technology uses a refrigeration cycle to extract heat from a system, primarily for air conditioning or industrial cooling applications. It operates by compressing refrigerant gas, which absorbs heat from the environment when evaporated and releases it when condensed. Compression chillers are energy-efficient, scalable, and commonly used in large commercial or industrial setups. They come in various types, including air-cooled and water-cooled systems, depending on the application and available resources.
- *Absorption chiller:* Thermally driven refrigeration technology involves absorption of chillers. It uses a heat source (like natural gas, solar thermal energy, or waste heat) instead of electricity to drive the refrigeration cycle. Heat energy drives the refrigerant from a solution, and the refrigerant evaporation removes heat from the desired space or process. Absorption chillers are particularly suited for energy-efficient applications where waste heat or renewable energy is available, such as in combined heat and power (CHP) systems.

- ***Process cooling:*** Process cooling includes cooling demands such as server cooling, food refrigeration, or cooling demands in industrial processes. As a result of increasing digitization, commercial buildings are increasingly being provided with dedicated areas for IT infrastructure. In new office buildings in particular, there are server rooms in which large cooling loads occur in a small area. These cooling loads must be dissipated via refrigeration technology, whereby waste heat from IT infrastructure can also be reused to cover heat demands of the same building, for example. A very efficient approach is, for example, centrally installed heat pumps, which can provide heating and cooling for a building at the same time. In this way, they can generate space heat as well as server cooling.

Electricity demand

The estimation of electricity demands is a prerequisite for holistic, energy-efficient planning of districts. Electricity demands primarily include plug loads and charging power of e-mobility.

- ***Plug loads:*** Plug loads are the electric load consumed by **household appliances** for general use or lighting. Household appliances in residential buildings include, for example, computers, stovetops, washing machines, televisions, and refrigerators. The consumption profile and total annual consumption are largely determined by the user behavior of the building's occupants. The electricity demand used for lighting is subject to seasonal fluctuations: In winter, this is greater than in summer due to the shorter days. The control of the building lighting (manual, central, presence-dependent by means of motion sensors) also has an influence on annual consumption. Standby losses account for a significant portion of the total electricity demand.

- ***E-mobility:*** The expected increase in electric cars in the future will lead to an increased demand for electricity in both residential and commercial districts. Electric storage concepts and smart charging management are needed to ensure that electricity generation from renewable energies and the demand for the charging infrastructure for e-mobility occur at the same time. Only in this way can decentral generated electricity from photovoltaic or wind power plants be used directly on site without putting too much strain on the distribution grid infrastructure. Smart load management can use demand-side management to reduce charging power at times of low renewable electricity production or, conversely, increase charging power at times of high renewable electricity production and exploit the battery capacities of electric vehicles to smooth out demand peaks. Here, the load profiles that need to be considered for neighborhood planning vary greatly depending on the building type. In residential neighborhoods, the peak load is expected to occur primarily in the late afternoon and evening hours when residents return from work. Unless smart charging management is installed, the electric vehicle is charged immediately upon arrival and, depending on the maximum charging power, the charging power drops in the subsequent hours through the night. In the case of office buildings, substantially different load profiles are expected. Here, the highest charging power occurs primarily in the morning after the employees arrive. In commercial buildings, load management is more complex, since the charging management system does not know when the employee will leave work again and therefore charges the vehicle with the maximum possible power.

❖ *District energy systems*

To decarbonize districts, district energy systems are a proven approach to exploit synergies between different energy sectors (electricity, heating, cooling and mobility) and achieve a sustainable, zero-emission energy supply.

Unlike decentralized energy systems for buildings, district energy buildings are networked with each other and can thus exchange energy. This includes electricity as well as the heating and cooling sectors. By connecting buildings, synergies can be exploited in terms of energy storage, load shifting, and balancing of heating and cooling loads. Furthermore, setting up a centralized heating and cooling supply instead of many decentralized producers can be more cost-effective.

- Microgrid

A common element in districts is microgrids (A. Cagnano, E. De Tuglie & P.Mancarella, 2020). These are electricity grids that are not part of the public electricity grid and that the district operator can use to exchange electricity between buildings and energy hubs. The advantage of microgrids is that their operation is subject to fewer regulations than the public power grid. For example, there are fewer or no grid fees if a building with a photovoltaic system supplies electricity to another building. A microgrid thus enables the interconnection of regenerative generators such as photovoltaics or wind energy, with electrical storage (district battery) and consumers.

- District heating and cooling

District heating or district cooling networks can be constructed to thermally connect buildings for a central heating and cooling supply. These networks enhance energy efficiency, reduce carbon emissions, and provide cost-effective solutions for residential, commercial, and industrial applications.

A third network type are 5GDHC networks, which can provide both heat and cold to buildings and additionally shift surplus waste heat from one building with high cooling demands to another building with high heating demands. 5GDHC networks are therefore particularly suitable for districts with miscellaneous consumer structure (districts with different types of buildings).

- Hydrogen

Hydrogen technologies can also be an interesting addition for districts. The use of hydrogen enables the long-term storage of surplus electricity (for example from photovoltaic or wind power plants). Here, an electrolyzer converts electricity into hydrogen, which can then either be stored or fed into the natural gas grid. Stored hydrogen can be converted back into heat and electricity in a fuel cell or in a suitable combined heat and power (CHP) unit. The waste heat from the conversion of hydrogen into electricity in a fuel cell or a CHP unit can then be distributed to buildings with district heating networks.

➢ ***Microgrid system analysis***

i. Key components of a microgrid

- **Distributed Energy Resources (DERs)**
  - Renewable energy sources: Solar PV, wind turbines, hydro, biomass
  - Non-renewable sources: Diesel generators, microturbines, fuel cells
- **Energy Storage Systems (ESS)**
  - Batteries (Lithium-ion, Lead-acid, Flow batteries)
  - Supercapacitors and flywheels

- Thermal Energy Storage (*TES*)
- **Loads**
  - Critical loads (hospitals, emergency services)
  - Non-critical loads (residential, commercial, industrial)
- **Power Conversion Systems**
  - Inverters, converters, transformers for AC/DC power management
- **Microgrid Control & Management System**
  - Supervisory Control and Data Acquisition (*SCADA*)
  - Energy Management System (*EMS*) for load balancing
  - Protection and fault detection mechanisms

ii. Operating Modes of a microgrid

- **Grid-Connected Mode**
  - Microgrid operates with the main grid
  - Imports or exports power as needed
  - Provides ancillary services like frequency regulation
- **Islanded Mode (Off-Grid Operation)**
  - Operates independently when disconnected from the main grid
  - Relies on local generation and storage
  - Requires advanced control for voltage and frequency stability

Microgrid Control Strategies

- **Centralized Control** – Single controller manages power flow
- **Decentralized Control** – Distributed control using local decision-making
- **Hierarchical Control**

Primary Control – Manages voltage/frequency stability
Secondary Control – Restores system parameters
Tertiary Control – Optimizes energy dispatch

iii. Benefits and challenges of microgrid systems

Aspect	Advantages	Disadvantages
Energy reliability	Provides backup power during grid failures and enhances resilience	Requires advanced control for stable operation in islanded mode
Sustainability	Reduces carbon footprint by integrating renewable energy sources	Renewable sources like solar/wind are intermittent and need storage
Cost Efficiency	Lowers electricity costs through local generation and demand-side management	High initial investment in infrastructure, storage, and control systems
Grid Independence	Can operate autonomously in remote or disaster-prone areas	Regulatory barriers and grid interconnection challenges
Power Quality	Advanced control systems improve voltage and frequency stability	Variability in renewable energy sources can cause power fluctuations
Scalability	Can be expanded based on energy demand and available resources	Requires careful planning and integration to match load requirements
Energy Management	AI-based forecasting and load balancing optimize performance	Complex control algorithms require skilled personnel and cybersecurity measures

- ***Heating and cooling networks***

District heating networks consist of a **supply and return pipe**, which are usually installed in the ground and transport hot water from a **heating center (energy hub)** to buildings (nPro Energy, 2025). In heat exchangers, hot water is used to provide space heating or domestic hot water. The water is cooled down in heat exchangers and flows back to the energy hub, where it is heated again. **District cooling networks** operate in a similar way: Cold water (usually below 10 °C) is transported in a supply pipe to the buildings and used for air conditioning or process cooling. The slightly heated water then flows back to a **cooling center or energy hub**, where it is again cooled down to the supply temperature. In the energy hub, the water is cooled down by **compression chillers or absorption chillers.**

Heating networks are often subdivided into different generations: The first heating networks were steam networks (**1st generation**), which transported hot steam in pipes from an energy hub to the buildings. Nowadays, this type of heat network is not installed anymore, because high heat losses occur in the pipe network due to the high steam temperatures. However, this type of heating network is still in operation in some cities, such as New York City. During the 20th century, more and more heating networks with pressurized water at temperatures of around 100 °C (**3rd generation**) have been installed. These networks are still in operation today and in some cases are still being constructed. A modern generation of heat networks are **4th generation district heating networks** (low-temperature district heating). These operate at lower temperatures of around 70 °C. Lowering the flow temperature enables new heat sources, such as solar thermal, to be integrated and reduces distribution losses. The latest developments are so-called **5th generation district heating and cooling networks (5GDHC)**, which are also known as **anergy networks**. They do not have a defined flow and return pipe but consist only of a warm and cold pipe. The advantage of these heating networks is that they can provide both heat and cold with just one network (2 pipes). Furthermore, they enable the use of ambient heat, such as heat from river water, near-surface geothermal energy, or wastewater. There are also **alternative classifications** of heating and cooling networks.

i. Key components of heating and cooling networks

Component	Description
Heat sources	Combined Heat and Power (CHP), geothermal energy, solar thermal, biomass, industrial waste heat
Cooling sources	Absorption chillers, electric chillers, free cooling (using ambient air or water)
Thermal Storage	Hot water tanks, phase change materials (PCM), underground thermal energy storage (UTES)
Distribution System	Insulated pipelines that transport hot or cold fluids to buildings
Control System	SCADA-based real-time monitoring, AI-based demand forecasting, and peak load management

ii. Benefits and challenges of microgrid systems

Aspect	Advantages	Disadvantages
Energy efficiency	Utilizes waste heat and centralized production for higher efficiency	Requires extensive infrastructure and planning
Cost savings	Reduces heating/cooling costs through economies of scale	High initial capital investment
Environmental benefits	Supports renewable integration, reducing CO_2 emissions	Biomass and CHP systems may produce emissions if not optimized
Reliability	Provides stable heating/cooling independent of electric grid fluctuations	Vulnerable to pipeline failures and maintenance issues
Scalability	Can expand to serve new buildings and industries	Limited application in areas without centralized infrastructure

- ***Hydrogen technologies***

Hydrogen is emerging as a key player in **clean energy transition**, offering solutions for energy storage, transportation, and industrial applications (A. Kovac, M. Paranos & D. Marcius, 2021). As a **zero-emission fuel**, hydrogen can be integrated into microgrids, district energy systems, and power generation to enhance sustainability

i. Types of Hydrogen Production

Type	Process	Advantages	Disadvantages
Green Hydrogen	Electrolysis using renewable energy (solar, wind, hydro)	Zero carbon emissions, sustainable	High cost, limited infrastructure
Blue Hydrogen	Natural gas reforming with carbon capture (CCS)	Lower emissions than grey hydrogen	CCS technology is still expensive
Grey Hydrogen	Natural gas steam reforming (no CCS)	Low-cost production	High CO_2 emissions
Turquoise Hydrogen	Methane pyrolysis producing solid carbon	No CO_2 emissions, emerging tech	Still in early development

ii. Hydrogen Applications in Energy Systems

Application	Description	Benefits
Energy Storage	Hydrogen can store excess renewable energy via electrolysis and be used later for power generation	Long-term energy storage, grid balancing
Fuel Cells for Microgrids	Hydrogen fuel cells provide electricity and heat for decentralized energy systems	Clean, efficient, reliable backup power
Hydrogen in District Heating	Hydrogen can be blended with natural gas or used directly for heating networks	Low-carbon heating alternative
Transportation	Hydrogen fuel cells power buses, trains, trucks, and ships	Zero emissions, fast refueling
Industrial Use	Used in steelmaking, ammonia production, and chemical industries	Decarbonizes heavy industry

iii. Benefits and Challenges of Hydrogen Technologies

Aspect	Positives	Negatives
Sustainability	Green hydrogen is 100% renewable with zero emissions	Production costs are still high.
Energy Storage	Provides long-duration storage, complementing renewables	Requires large-scale infrastructure
Versatility	Can be used for electricity, heating, and transportation	Hydrogen handling requires advanced safety measures
Scalability	Hydrogen technologies can be expanded to various sectors	Hydrogen transport and distribution are challenging

2.3. First interaction with nPro

- Each user can initially access nPro software tool interface at https://app.npro.energy/en (nPro Energy, 2025).

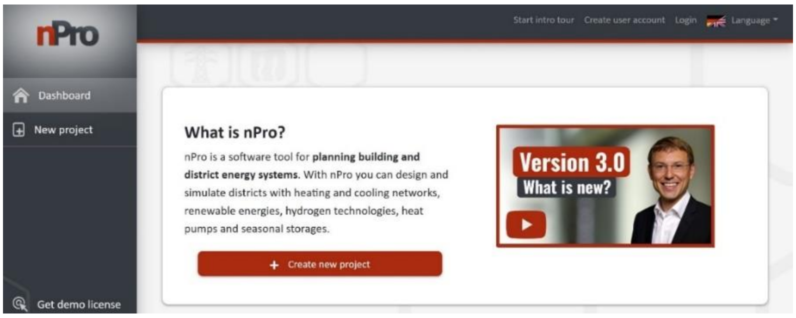
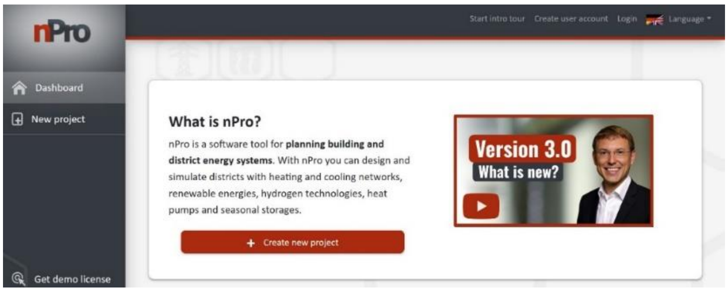


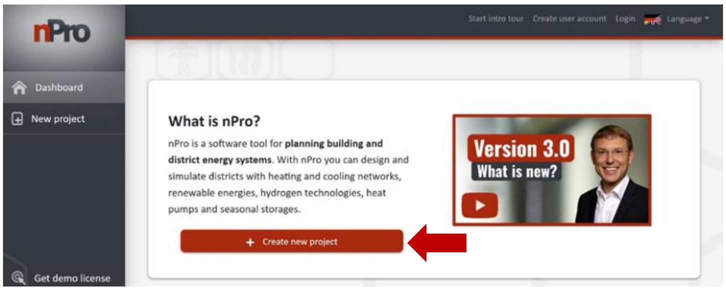
Fig. 30. nPro webtool ***interface***

- From the menu list, there is an optional choice of **creating an account**. This turns out to be very helpful in saving for various projects. Users can select whether a demo license, academic, or commercial will be used. *The demo license* is free of charge but with limited functionality and lasts three weeks before the account is deactivated. *Academic* is also free of charge, tool functions to its full potential but can be used only by faculty, students or staff of a recognized degree-granting academic institution. Lastly, *commercial license* is for already purchased nPro licenses by a company/organization.



- To start techno-economic analysis, there are a few steps that users need to take.

STEP 1: *Create new project*



By clicking *create new project* (red arrow above), an overview of the section is presented. Users can then select a name for the project, the type of it, country and city of interest, and also the energy supply solution. For those that may select a different type of registration (e.g. demo or academic), a similar window will appear to be used.

STEP 2: *Inserting project data*

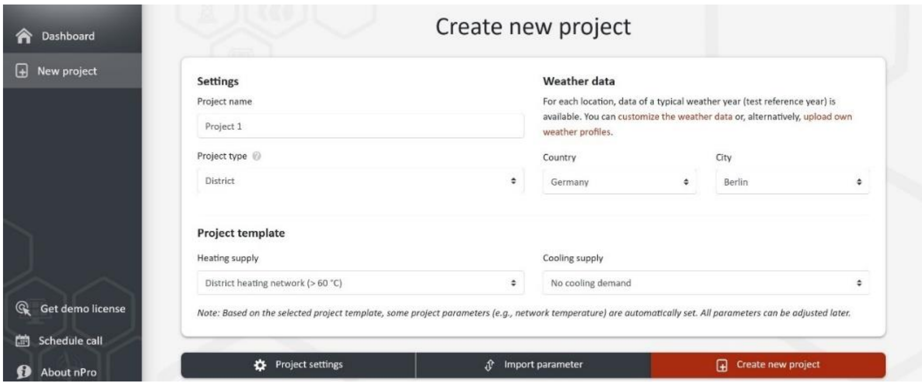


Fig. 11. *Project* ***overview***

✓ ***Project type***: By toggling this section, a drop-down menu pops up, which shows whether a district, building, or an energy hub will be selected for the analysis. ***District*** will be buildings – heat network -energy hub, the ***building*** will be just a single building with the evaluation of some demand profiles, usage zones and energy hub and at last user can select the ***energy hub*** module if load profiles are available.

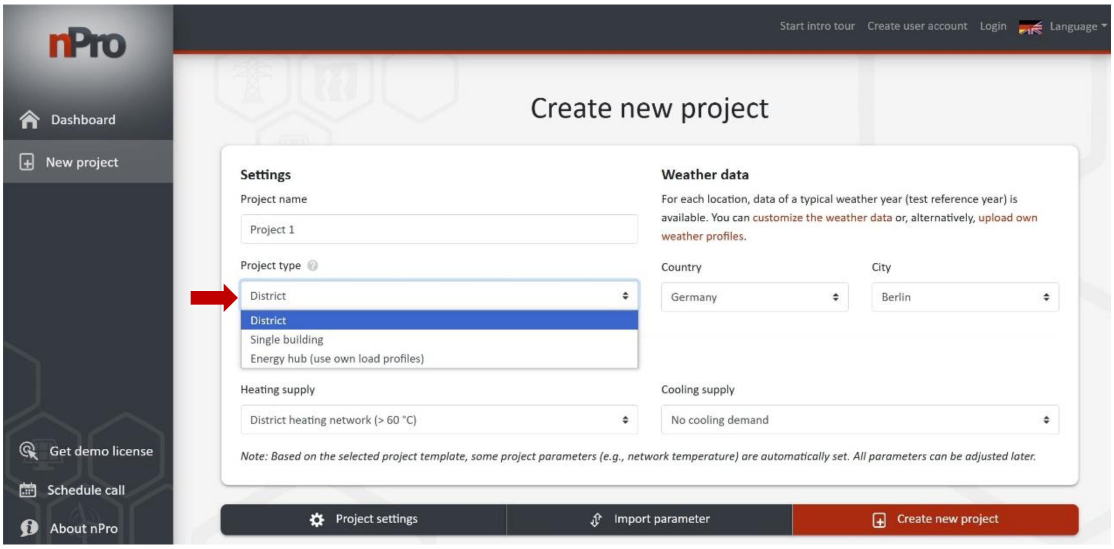


Fig. 22. *Selecting* ***project type***

✓ **Project template configuration**: In this session, nPro gives the user the chance to define heating and/or cooling supply preferences. A thorough analysis of the favored district network is followed starting with *heating supply* selection and then continuing to the *cooling supply* (**page 21**).

Heating supply configuration: In the case of the ***district,*** there are a few more options that the user can select for what kind of network will be in the analysis. Normal *district heating network (>60 °C), low-ex heat network (35-60 °C) with decentral hot water heating,**5**th **G**eneration **D**istrict **H**eating and **C**ooling (**5GDHC**) network (0-35 °C, anergy network), decentral air-/ground source heat pumps (no heat network)* and also *microgrid (electricity-based system, no heat network)*.

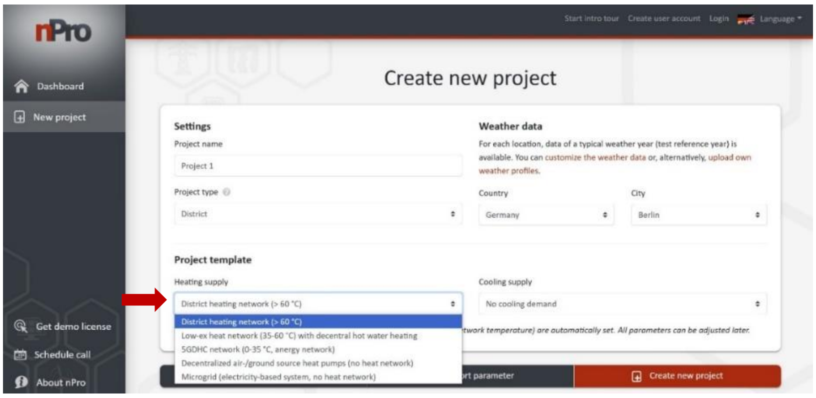


Fig. 33. *Heating supply choice*

- ❖ **District heating network (>60 °C)**: centralized system that distributes heat to multiple buildings through a network of insulated pipes (Wirtz, 2023). These networks typically supply hot water or steam from a central heat source to meet space heating and domestic hot water demands.

For **high-temperature district heating** (above 60 °C), common temperature ranges include:

- **Traditional high-temperature systems**: 80–120 °C (older networks, industrial use)
- **Modern systems**: 70–90 °C (common for urban heating)
- **Low-temperature systems**: 50–70 °C (increasingly used for efficiency and sustainability)

Heat sources for district heating (>60 °C)

i. *Combined Heat and Power (**CHP**)* Plants
ii. *Fossil Fuel Boilers* – Natural gas, coal, or oil-fired boilers (gradually being phased out)
iii. *Waste-to-Energy Plants* – Utilize municipal solid waste for heat production
iv. *Industrial Waste Heat* – Recovered heat from factories, steel plants, and refineries
v. *Biomass and Biogas Plants* – Sustainable heat generation using wood chips, pellets, or anaerobic digestion
vi. *Geothermal Energy* – High-temperature geothermal sources for base-load heating
vii. *Large-Scale Solar Thermal – Solar collectors* supplying hot water to the network

Key Components of a District Heating Network

i. *Heat Production Plant* – Central facility generating heat at >60°C
ii. *Heat Exchangers* – Transfer heat efficiently between the primary network and building systems
iii. *Pumping Stations* – Maintain pressure and flow rate in the distribution system
iv. *Supply and Return Pipes* – Insulated underground pipelines distribute heat (e.g., supply at 80°C, return at 50°C)
v. *Heat Substations* – Located in buildings to regulate heat delivery via heat exchangers

Table 1. ***High temperature District Heating Advantages and Disadvantages***

Category	Advantages	Disadvantages
Scalability	Ideal for cities, industrial parks, and residential complexes	Requires extensive infrastructure investment
Energy Efficiency	Efficient use of **waste heat** and **CHP** (Combined Heat & Power)	Higher **heat loss** in long-distance distribution
Fuel Flexibility	Integrates **renewables, waste heat, and fossil fuels**	Transitioning from **fossil-based sources** to **green energy**
Carbon Emissions	Lower emissions when using **low-carbon energy sources** (biomass, geothermal, etc.)	Requires **decarbonization efforts** to phase out natural gas
Reliability & Cost	Centralized maintenance reduces **operational costs**	**Upfront costs** for infrastructure and modernization
Legionella Prevention	Ensures **safe domestic hot water** without additional treatment	**Energy waste** if temperatures are unnecessarily high
Seasonal Heat Storage	Compatible with **large-scale thermal energy storage** (TES)	Needs integration with **modern building heating systems**

❖ **Low-Exergy (Low-Ex) Heat Network (35–60°C) with Decentralized Hot Water Heating:** A Low-Exergy (Low-Ex) district heating network operates at 35–60°C, significantly reducing energy losses and allowing for greater integration of renewable and waste heat sources (nPro Energy, 2025). Unlike traditional high-temperature district heating (>80°C), Low-Ex networks focus on using heat at the lowest possible temperature while still meeting heating demands efficiently.

In this system, domestic hot water is generated locally (decentralized) at each building or apartment, rather than directly supplied by the network. This approach enhances system efficiency and minimizes heat losses in distribution.

Key Features of a Low-Ex District Heating Network

i. *Low Supply Temperature (35–60°C)*
   - Reduces heat loss in pipes, increasing efficiency
   - Enables direct integration of low-temperature renewable heat sources
ii. *Decentralized Domestic Hot Water Production*
   - Uses **local heat exchangers** or **small heat pumps** in each building/unit
   - Prevents **Legionella risks**, as water is heated on demand
   - Reduces the need for high-temperature water storage
iii. *Utilization of Renewable & Waste Heat Sources*
   - **Geothermal (low-temp reservoirs)**

- **Solar thermal energy**
- **Industrial & data center waste heat**
- **Larger-scale air/water heat pumps**
- **Wastewater heat recovery**

iv. *Sector Coupling & Smart Control*

- Can integrate with **electric heat pumps** to boost temperatures if needed
- Enables **demand-side management** via smart meters and thermal storage

System Components

i. ***Centralized Low-Temperature Heat Source***

- Geothermal, solar, waste heat, or heat pumps provide **35–60°C** heat
- Large-scale heat pumps can upgrade waste heat when needed

ii. ***Distribution Network***

- **Well-insulated supply & return pipes** to minimize heat losses
- Lower temperature allows for more efficient pipe materials

iii. ***Building-Level Decentralized Hot Water Production***

- **Instantaneous Water Heaters (Heat Exchangers)**: Use district heat directly
- **Boosting Heat Pumps**: Local small heat pumps increase temperature to >60°C if needed

iv. ***Smart Monitoring & Control***

- **Demand-responsive heating**: Optimizes heat distribution
- **Heat storage tanks in buildings**: Reduce peak load on the grid

Table 2. Low-Ex District Heating Advantages and Challenges

Category	Advantages	Disadvantages
Efficiency	Lower **distribution losses** than high-temperature networks	Some **heat losses still exist**, especially in long networks
Renewable Integration	Ideal for **heat pumps, geothermal, solar thermal, and waste heat**	Requires **optimized system design** to maximize renewable use
Legionella Risk Reduction	**Decentralized DHW** means no stagnant water at risky temperatures	Requires **local water heating solutions** (e.g., booster heat pumps)
Cost-Effectiveness & Scalability	Easier network expansion – buildings can **gradually integrate**	**Initial investment** in decentralized systems for DHW
Comfort & Reliability	**Optimized local control** ensures sufficient heating & hot water	Decentralized DHW requires **reliable and efficient local heat exchangers**
Existing Building Compatibility	Works well with **modern low-temperature heating systems**	**Older buildings** may need **larger radiators or underfloor heating** for efficiency
Heat Storage Needs	Thermal energy storage (TES) helps manage **peak demand** efficiently	Additional **storage tanks or phase change materials (PCM)** may be required

❖ **5th Generation District Heating and Cooling (5GDHC) – Anergy Networks (0–35°C):** A 5th Generation District Heating and Cooling (**5GDHC**) network, also known as an **anergy network**, operates at ultra-low temperatures (0–35°C) (Kaori Company, 2025). It is a decentralized, bidirectional, and demand-driven system that allows both **heating and cooling** within the same network. Unlike traditional district heating, which relies on high-temperature water, 5GDHC focuses on **thermal energy exchange** rather than centralized heat supply.

Key Characteristics of 5GDHC Systems

i. *Ultra-Low Temperature (0–35°C)*
   - Reduces heat losses to almost zero
   - Suitable for direct heat exchange with the environment (groundwater, lakes, waste heat)

ii. *Bidirectional & Decentralized Heat Exchange*
   - Buildings can **both extract and inject heat**, creating a **balanced energy loop**
   - Waste heat from cooling processes can be reused for heating elsewhere

iii. *Local Heat Pumps for Final Temperature Boost*
   - Each building uses **small heat pumps** to raise the temperature for space heating (e.g., 45–55°C) and domestic hot water (>60°C)
   - Energy-efficient as the heat pump only needs to make a **small temperature jump**

iv. *Renewable & Waste Heat Integration*
   - Uses low-grade heat sources like:
     - ✓ Geothermal (shallow boreholes, aquifers, lakes)
     - ✓ Industrial or data center waste heat
     - ✓ Sewage/wastewater heat recovery
     - ✓ Solar thermal collectors

v. *No Dedicated Supply & Return Pipes*
   - Unlike traditional **two-pipe** systems, 5GDHC often has a **single loop** were energy flows in multiple directions
   - Buildings contribute excess heat to the network when cooling is needed

System Components

i. *Ambient Temperature Network (0–35°C)*
   - Underground insulated pipes circulate water at near-environmental temperature
   - Water can be sourced from geothermal wells, aquifers, or surface water

ii. *Heat Pumps in Buildings*
   - Extract heat from the network and upgrade it for space heating & DHW
   - In summer, the same system provides cooling by rejecting excess heat

iii. *Thermal Energy Storage (TES)*
   - Seasonal storage in underground aquifers (ATES – Aquifer Thermal Energy Storage) or borehole systems (BTES)
   - Stores summer heat for winter use and backwards

iv. *Smart Energy Management & Control*
   - AI-driven optimization of heat flows
   - Demand-response integration for grid balancing

Table 3. 5GDHC Advantages and Challenges

Category	Advantages	Challenges
Efficiency and Distribution Loss Reduction	Near-zero **distribution losses** as water moves at ambient temperature.	Requires **efficient building-side heat pumps** to extract useful heat.
Simultaneous Heating & Cooling	Enables **energy-efficient thermal balancing** by redistributing waste heat.	**Balancing heat supply & demand** requires advanced system design.
Renewable Energy Integration	100% **renewable-ready** – compatible with solar, geothermal, and waste heat.	**Availability of low-grade heat sources** may vary by location.
Scalability and Decentralization	Works well for **mixed-use developments** (residential, commercial, industrial).	**Infrastructure investment** is needed for bidirectional heat exchange.
Future-Proofing	Compatible with **energy-positive buildings & smart grids**.	**Regulatory and technical frameworks** may need adaptation in some regions.
Building Compatibility	Works best with **low-temperature heating** (e.g., underfloor heating, fan-coils).	**Existing buildings with traditional radiators** may need retrofitting.

❖ **Decentralized Air/Ground Source Heat Pumps (No Heat Network):**

A **decentralized heating and cooling system** using **air-source (ASHP) or ground-source (GSHP) heat pumps** eliminates the need for a central heating network (Wirtz, 2023). Instead, each building or unit has its own **individual heat pump**, extracting renewable heat from the air or ground. This approach is highly flexible, energy-efficient, and suitable for new developments and retrofitted buildings.

Key Characteristics of Decentralized Heat Pump Systems

i. *No Centralized Heat Network*
- Each building generates its own heating and cooling
- No need for insulated district heating pipes, reducing infrastructure costs

ii. *Usage of Renewable Ambient Energy*
- **Air-source heat pumps (ASHPs):** Extract heat from outdoor air, even in cold climates
- **Ground-source heat pumps (GSHPs):** Use stable underground temperatures via boreholes or horizontal loops

iii. *All-Electric Heating*
- Reduces dependence on fossil fuels
- Can be integrated with **solar PV** for self-sustaining energy use

iv. *Works for Heating & Cooling*
- **Reversible heat pumps** provide both **heating in winter** and **cooling in summer**
- **Passive cooling** possible with GSHPs (using ground temperature directly)

v. *Flexible System Design*
- **Single-family homes:** Individual ASHP or GSHP
- **Apartment buildings:** Shared GSHP with multiple heat exchangers
- **Commercial/industrial buildings:** Large-scale heat pumps with **thermal storage**

System Components

i. *Heat Pump Unit (Air or Ground Source)*
   - **ASHPs:** Outdoor unit absorbs heat from the air
   - **GSHPs:** Pipes or boreholes extract heat from the ground

ii. *Heat Distribution System*
   - Works best with **low-temperature heating:**
     - ✓Underfloor heating
     - ✓Low-temperature radiators
     - ✓Fan-coil units

iii. *Domestic Hot Water (DHW) System*
   - Either **integrated in the heat pump** or **separate electric water heater**
   - Hot water storage tanks may be needed

iv. *Smart Energy Controls*
   - Sensors & weather compensation optimize efficiency
   - Integration with **solar PV & battery storage** enhances self-sufficiency

Table 4. Advantages, Challenges and Considerations of Decentralized Heat Pumps

Category	Advantages	Challenges
Infrastructure Costs	No **heat network costs** – avoids expensive pipe installation and maintenance.	**Higher initial investment** per building for individual heat pump units.
Renewable Energy Integration	100% **renewable-ready** – compatible with solar PV and wind power.	**Grid dependence increases**, requiring grid capacity upgrades.
Scalability & Flexibility	Each building can **independently optimize** heating and cooling needs.	**It is not ideal for dense urban areas** where space for GSHPs is limited.
Heating & Cooling Function	Provides **year-round comfort** with a single system.	**ASHP efficiency drops in cold weather**, requiring backup heating.
Future-Proofing	Compatible with **demand response** and **energy storage** solutions.	**GSHP requires groundwork** – boreholes or trenches need space and investment.

❖ Microgrid – Electricity-Based Energy System (No Heat Network):

A **microgrid** is a **localized, self-sufficient electricity network** that can operate independently or connect to the main grid (Wirtz, 2023). It integrates **renewable energy sources, energy storage, and smart control systems** to provide **reliable, resilient, and sustainable power** for buildings, campuses, or communities. Since this system is **electricity-based**, all heating and cooling needs are covered using **electric solutions** like **heat pumps, electric boilers, or resistance heating** instead of a heat network.

Key Characteristics of an Electricity-Based Microgrid

i. *Local Power Generation*

   - Uses **renewable energy sources:**
     - ✓Solar PV
     - ✓Wind turbines

✓Biomass generators
✓Small hydropower

ii. *Energy Storage for Stability*
- **Battery Storage (BESS)** for load balancing and peak shaving
- **Thermal Energy Storage (TES)** for heating applications
- **Vehicle-to-Grid (V2G)** integration with EVs

iii. *Smart Grid Management & Demand Response*
- AI-driven load management to **match supply & demand**
- Smart meters for real-time monitoring

iv. *Full Electrification for Heating & Cooling*
- **Heat pumps (air/ground/water source)** replace gas boilers
- **Electric boilers & infrared heating panels** for direct heating
- **Battery-powered or solar-assisted cooling** (chillers, ACs)

v. *Grid-Connected or Island Mode*
- Can function **independently (off-grid)** or connect to the main utility grid
- Provides **backup power** during blackouts

System Components

i. *Local Power Generation*
- **Solar PV panels** (rooftop & ground-mounted)
- **Wind turbines** (small to medium scale)
- **Biogas or biomass CHP plants** for additional baseload power

ii. *Energy Storage & Load Management*
- **Lithium-ion batteries** for short-term energy balancing
- **Flow batteries** or **hydrogen storage** for long-term backup
- **Thermal storage** (hot water tanks, phase change materials)

iii. *Electric Heating & Cooling Systems*
- **Air & Ground Source Heat Pumps** for high efficiency
- **Electric boilers** for peak demand periods
- **Passive heating & cooling solutions** to minimize demand

iv. *Smart Grid Infrastructure*
- **Microgrid controller** for intelligent energy management
- **Demand response** to optimize consumption
- **Blockchain-based energy trading** in decentralized grids

Table 5. Electric-based Microgrid Advantages and Challenges

Category	Advantages	Challenges
Resilience & Energy Independence	Reduces reliance on **centralized utilities** and enhances energy security.	Requires **backup solutions** for prolonged outages or extreme weather conditions.
Renewable Energy Integration	Enables **100% green energy** systems with solar, wind, and battery storage.	**Intermittency of renewables** requires energy storage and demand-side management
Efficient Electrification	Supports **net zero** heating and cooling through electric heat pumps.	**Peak demand periods** can strain the local microgrid without sufficient storage.
Lower Transmission Losses	Local energy use reduces **grid strain** and improves efficiency.	**Grid interconnection** can be complex due to **regulatory barriers**.
Scalability & Modularity	Can **expand easily** with additional storage and renewable sources.	**Advanced energy management systems** are needed for optimal load balancing.

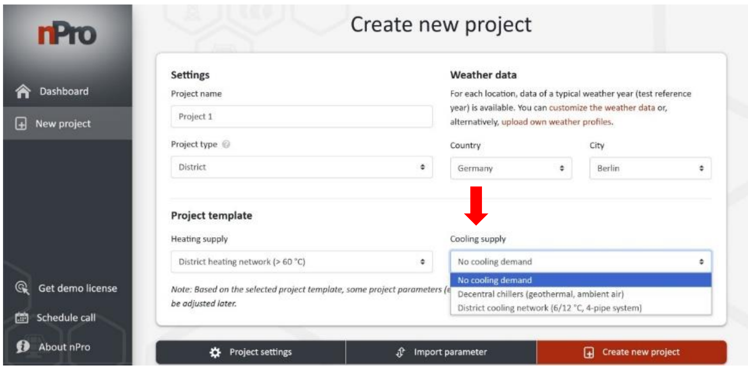


Fig. 34. *Selection of **cooling supply***

Cooling supply configuration***:*** If necessary, there are also options for the cooling demand containing *decentral chillers (geothermal, ambient air)* or *district cooling network (6/12 ◦C, 4-pipe system).*

❖ Decentralized chillers (geothermal, ambient air)

Decentralized chillers use either **geothermal energy** or **ambient air** to provide **localized cooling** for buildings. They operate independently, reducing reliance on large-scale district cooling networks.

System overview

- *Geothermal chillers (Ground coupled or water-cooled)*
  - Use **stable underground temperatures** for efficient cooling
  - Often integrated with **ground-source heat pumps (GSHPs)**
  - Can be **open-loop** (using groundwater) or **closed-loop** (circulating a heat transfer fluid through boreholes or horizontal loops)
- *Ambient air chillers (Air cooled systems)*
  - Extract heat from indoor spaces and reject it to the **outside air**

- Include **air-source chillers** and **hybrid chillers** with evaporative cooling
- Suitable for areas with **moderate to warm climates** where geothermal is not viable

Preferred utilization

- **Geothermal chillers**
  - Large buildings, campuses, or industrial sites with available **land for boreholes**
  - Areas with **high electricity costs** where efficiency savings matter
  - Locations with **seasonal cooling needs**, where geothermal storage can help
- **Ambient air chillers**
  - **Urban areas** with limited space for underground systems
  - Moderate climates where **ambient temperatures stay stable**
  - Projects with **budget constraints**, where lower upfront cost is needed

Table 6. Strengths and Weaknesses of Decentralized Chillers

Category	Geothermal chillers	Ambient air chillers
Energy Efficiency	✓ High COP (4.0–6.0) due to stable underground temperatures	⚠ Moderate COP (2.5–4.5): efficiency drops in hot climates
Climate Dependence	✓ Works **year-round** without major efficiency losses	⚠ Efficiency **decreases** in hot/humid weather
Water Usage	⚠ Can use **groundwater** or closed-loop systems	✓ **No water consumption**, unlike cooling towers
Installation Cost	✗ **High upfront costs** (drilling, ground loops)	✓ **Lower initial costs**, but may require larger units
Maintenance	✓ **Low maintenance:** underground components last **50+ years**	✗ **Higher maintenance** due to airflow and weather exposure
Scalability	⚠ Best for **large buildings & campuses,** due to the requirement of available land	✓ **Easier to install** in dense urban areas
Grid Load	✓ **Reduces peak electricity demand** via seasonal energy storage	✗ **Higher electricity consumption** in extreme temperatures
Sustainability	✓ Can be **100% renewable** when powered by green electricity	⚠ **Less sustainable** due to dependence on electricity demand

❖ District cooling network (6/12 °C,4 pipe system)

A **district cooling network** distributes **chilled water (6°C supply / 12°C return)** from a centralized plant to multiple buildings for space cooling. The **4-pipe system** allows simultaneous **cooling and heating**, making it ideal for mixed-use applications.

System operation

- *Central Chilled Water Production:* Chillers at the district cooling plant generate **6°C chilled water**
- *4-Pipe Distribution:*
  - **Two pipes** for chilled water supply & return (**6°C → 12°C**)
  - **Two pipes** for heating water supply & return (for integrated heating needs)

- *Building-Level Heat Exchangers:* Transfer cooling (or heating) without mixing fluids
- *Return Water Loop:* Warm water (12°C) returns to the plant for re-cooling

Table 7. Advantages and Challenges of a District Cooling Network (4 pipe system)

Category	Advantages	Challenges
Energy Efficiency	Centralized cooling is **30–50% more efficient** than standalone chillers	**Thermal losses** in long pipelines
Cost Savings	**Lower operational costs** due to economies of scale	**High initial investment** in infrastructure
Reliability	**Redundant cooling sources** improve system resilience	Requires **backup systems** for peak loads
Sustainability	Can integrate **waste heat, renewables, or thermal storage**	Dependent on **power grid** unless renewables are used
Flexibility	**4-pipe system allows simultaneous cooling & heating**	Requires **complex system balancing**
Maintenance	**Lower maintenance** compared to decentralized chillers	**Piping network needs regular upkeep**

Preferred utilization

- **Large Cities & Business Districts** – Skyscrapers, malls, hotels
- **Mixed-Use Developments** – Areas needing **both cooling & heating**
- **Industrial & Data Centers** – High cooling demand with stable loads
- **Universities & Hospitals** – Reliable, efficient cooling for large campuses

Step 3: *Designing district for data retrieval*

After inserting the basic inputs, the user shall toggle "**create new project**" on the bottom corner (Wirtz, 2023). By doing so, a new template will be shown that includes a geographical map of the area of interest, and the user can define the district heating network and also buildings for the analysis.

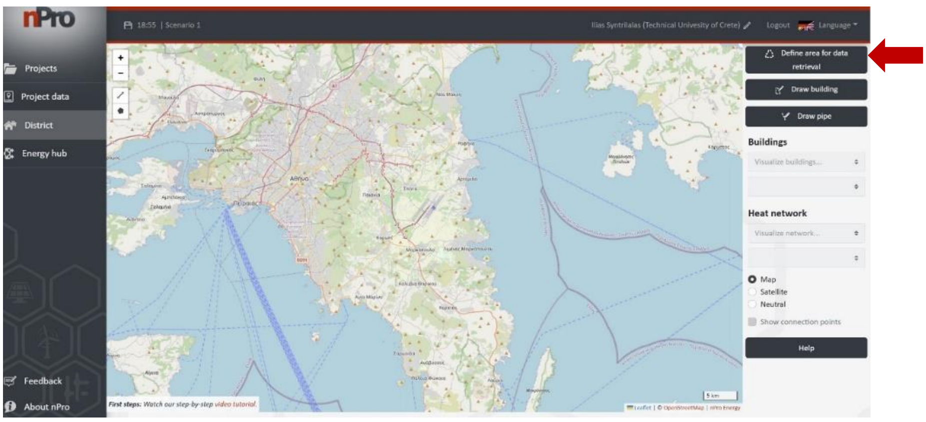
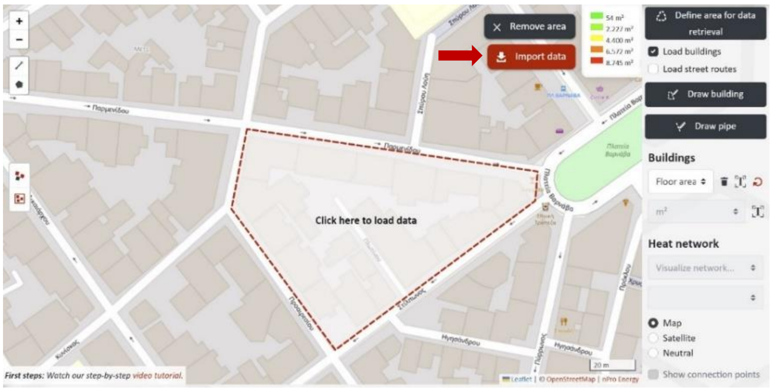
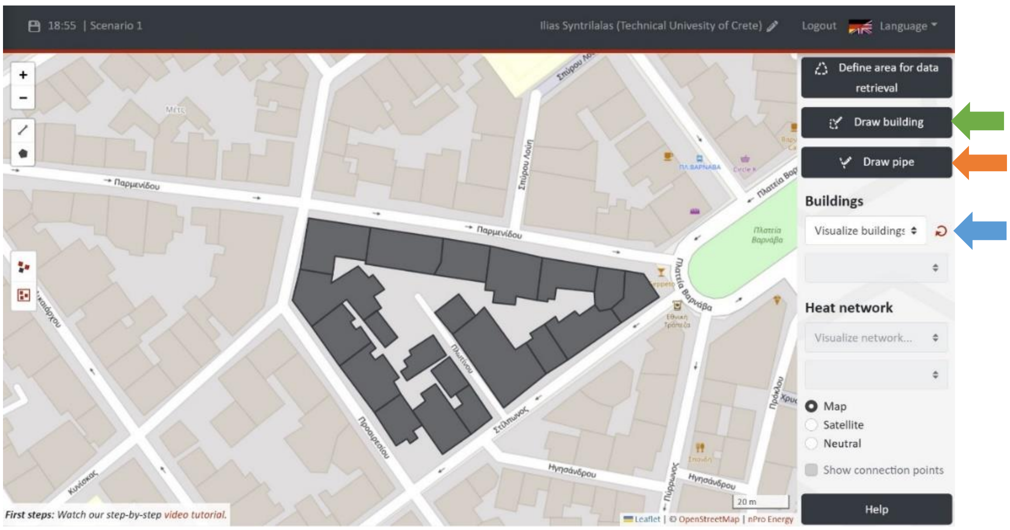


Fig. 4._Geographical Map of the Area for Data Retrieval_

By checking the *Define area for data retrieval* option (***Fig.6 red arrow***), user can draw the preferable area for the individual buildings data import. A necessary **zoom in** is needed for this designation. User can then start the drawing session, when a **cross point** will be shown on the map.

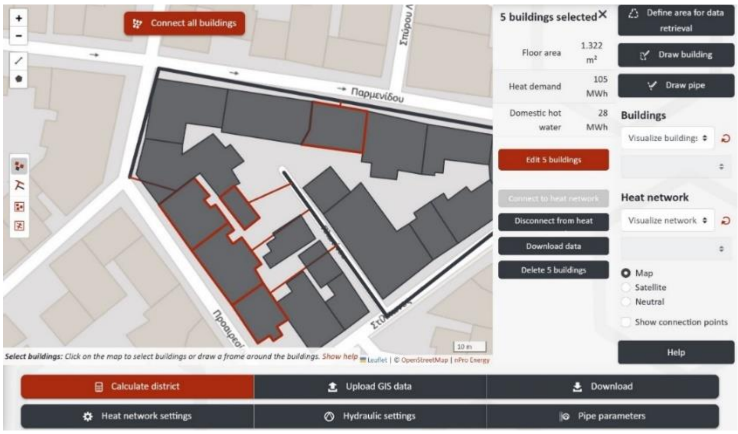


Toggling *Import data* gives the capability to visualize the district buildings, drawing some additional ones if necessary (green arrow) and changing also the view of the district buildings in the dropdown field below *Buildings* (blue arrow). Additionally, the user can draw the pipe network for the surrounding area by clicking *Draw pipe* (orange arrow). Providing that the project will be the **designation of a district heat network** and therefore heat, cold and/or electricity demands needs to be evaluated, these steps and the following ones are necessary for technoeconomic analysis. If the project will focus on electricity demands only excluding heating and/or cooling, pipe network design is not needed for optimization.

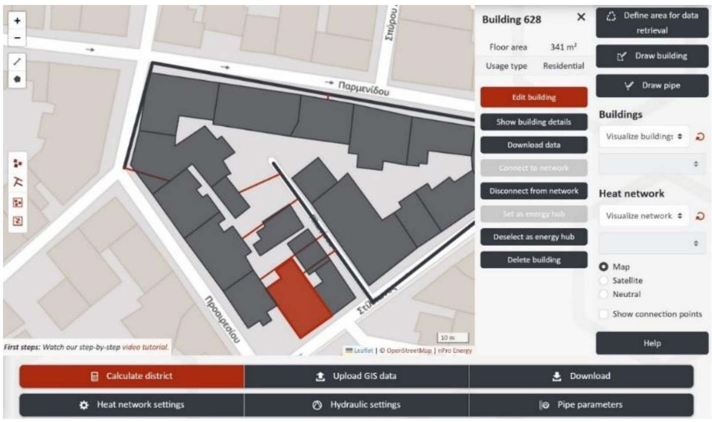


In this example we designed a pipe along the street and a piece of it in the district area, but different routes can also take place.

Afterwards, buildings need to be connected to the network. There is an option of connecting all buildings at once and when applied the tool connects them using the smallest distance possible. Users can also click into a single building and edit its parameters if necessary. This contains everything from the size of the floor area to the heat, cooling and/or electricity demands and even the way that heat, cold and/or electricity demands are covered.



From the designed district, a building shall be selected that will function as an energy hub. This can be done by clicking on a specific building and from the menu list click ***select as energy hub***.



It is also notable that users can upload building data and network sections using various formats for creating new buildings or even import data for existing ones (*upload GIS data* section). *Heat network settings*, *hydraulic* ones, and *pipe parameters* can be modified too.

Furthermore, the user can toggle ***Calculate district*** function. This will summarize the total energy demands of the selected district.

Step 4: *Energy hub*

In this section, the user shall decide on the appropriate energy generation and storage technologies for the energy system designation. This includes technologies such as heat pumps, boilers, photovoltaic systems, hydrogen technologies, and thermal storage units. It also gives the user the chance to define how these components interact within the energy system and consider factors like energy flows, control strategies, and integration with existing infrastructure.

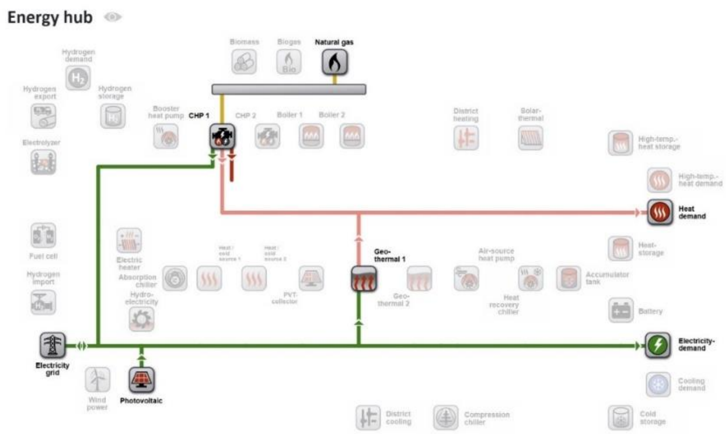
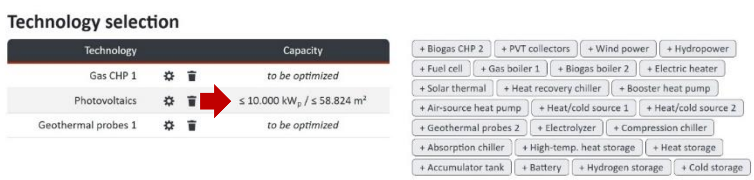


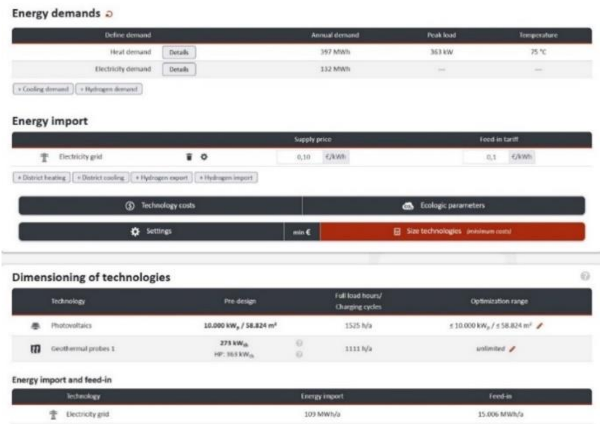
Fig. 36. *Configuration of the* ***energy hub***

Use can also define how these technologies will operate and put some additional constraints on them. To do so, the user shall click the gear for the preferred technology (as shown in the image below) and set for example for the *gas boiler* to operate when the ambient air is above 2 °C or even change the share of thermal and electric efficiency fraction.

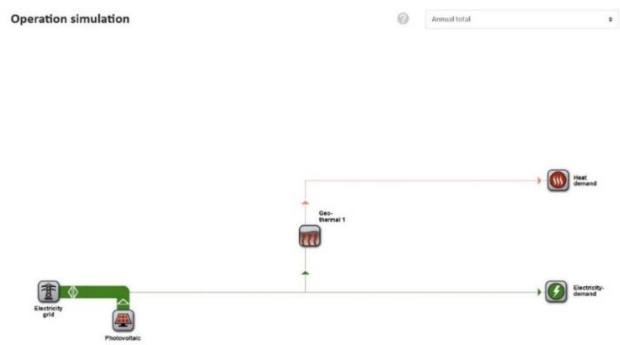


Users can then click *Size technologies* with a **minimum cost** goal for the optimization or change the target by toggling *Settings* and choosing a different one (for example CO_2 emissions).

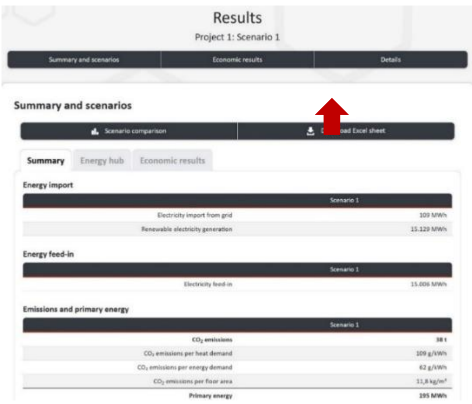
Dimensioning of technologies table shows the optimal design of the system. The capacities can be used to select **real available components.** For example, if the optimization suggests a boiler with 145kW, the next larger boiler size would be chosen, e.g. 150kW.If a storage has a **very small capacity**, the storage does not significantly impact the system efficiency in this case, the storage should be sized as a normal buffer storage. In addition, based on personal design preferences, design can be changed in the last column of the table.



Proceeding further, there is an option of ***Simulate system operation*** and by selecting this function a figure shows up. It describes the quantitative size of the energy flows generated and consumed, providing an initial overview of how much each component contributes to covering the demands. When clicking on a technology, the corresponding results are displayed below the graphic. In addition, when the mouse is moved over an energy flow (connection line), the amount of energy is displayed in MWh.



Toggling ***Go to result page*** button on the bottom footer, user can find all the economic results (cost shares, graphics and cash flow table) and see the costs of the energy system.



Cash flow

Year	Investment	Annual costs	Annual revenues	Annual sum	Net present value
0	-13.215.631 €	0 €	0 €	-13.215.631 €	-13.215.631 €
1	0 €	-126.530 €	1.565.675 €	1.439.145 €	-11.776.486 €
2	0 €	-120.505 €	1.491.119 €	1.370.614 €	-10.405.872 €
3	0 €	-114.767 €	1.420.113 €	1.305.347 €	-9.100.525 €
4	0 €	-109.302 €	1.352.489 €	1.243.187 €	-7.857.338 €
5	0 €	-104.097 €	1.288.085 €	1.183.988 €	-6.673.350 €
6	0 €	-99.140 €	1.226.747 €	1.127.608 €	-5.545.742 €
7	0 €	-94.419 €	1.168.331 €	1.073.912 €	-4.471.830 €
8	0 €	-89.923 €	1.112.696 €	1.022.773 €	-3.449.057 €
9	0 €	-85.641 €	1.059.711 €	974.070 €	-2.474.987 €
10	0 €	-81.563 €	1.009.248 €	927.686 €	-1.547.301 €
11	0 €	-77.679 €	961.189 €	883.510 €	-663.791 €
12	0 €	-73.980 €	915.418 €	841.438 €	177.647 €
13	0 €	-70.457 €	871.826 €	801.370 €	979.017 €
14	0 €	-67.102 €	830.311 €	763.209 €	1.742.226 €
15	0 €	-63.906 €	790.772 €	726.866 €	2.469.092 €
16	0 €	-60.863 €	753.116 €	692.253 €	3.161.345 €
17	0 €	-57.965 €	717.254 €	659.289 €	3.820.634 €
18	0 €	-55.205 €	683.099 €	627.894 €	4.448.528 €
19	0 €	-52.576 €	650.570 €	597.994 €	5.046.522 €
20	100.008 €	-50.072 €	619.591 €	669.526 €	**5.716.048 €**

The net present value after 20 years is positive (5.716.048 €).

Chapter 3: Hybrid systems in-depth tutorial using nPro

In this chapter, a step-by-step guide to hybrid systems design will be presented using nPro software. Firstly, the analysis will emphasize only the **electricity demand** of these systems suppressing their heat or cooling demands. Afterwards, a series of hybrid applications focusing only on **heat demand** is going to be displayed. Finally, there will be a comparison between them describing the **best options**. (IRENA, n.d.)

❖ Electricity Demand

3.1. Grid-PVs-Wind Turbines (CASE STUDY #1)

A Grid–PV–Wind Turbine Hybrid System is a power generation setup that integrates **Grid Power** (utility electricity), **Photovoltaic (PV) Solar Panels** and **Wind Turbines** to ensure a reliable and sustainable electricity supply (H. Azoug, H. Belmili & F. Bouazza, 2021).

System operation

i. **Power Generation**
   - **Solar PV Panels** generate DC electricity when sunlight is available
   - **Wind Turbines** generate AC (or DC depending on the type) from wind energy
   - Both sources may feed into a hybrid inverter or individual inverters, which convert the energy to usable AC for loads or to feed into the grid

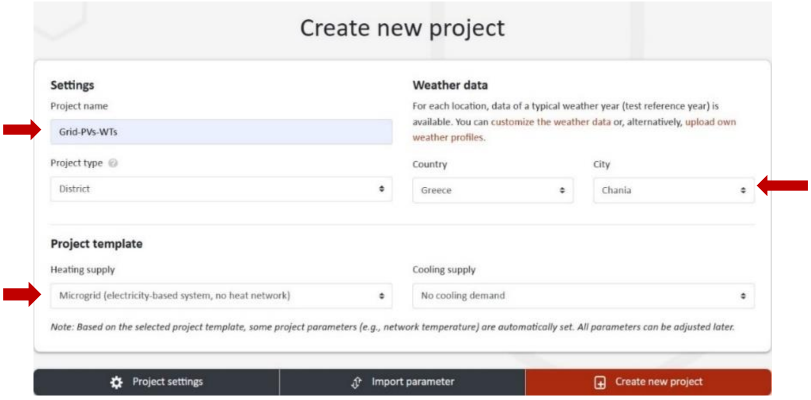
ii. **Power Management (Controller/Inverter role)**
   - A hybrid inverter or energy management system (EMS) monitors energy input from PV, wind, and grid
   - It prioritizes renewable sources to reduce grid dependency
   - If demand exceeds renewable generation, the system automatically draws power from the grid

iii. **Grid interaction**
   - If excess energy is produced, it can be stored in batteries (if present) or exported to the grid (if net metering or feed-in tariffs apply)
   - During low renewable output, the grid supplies the deficit

As mentioned before, after accessing nPro website user shall toggle the *create a new project* session for the analysis to start (before that the user should login in order to save the project and the respective results). Afterwards, each user should define the project type settings, the project template, and also the location of weather data retrieval. In our first application, the project type will be set as **district,** the country for weather data is going to be **Greece** and the city **Chania** (J. Vourdoubas, 2023)**.** As for the project template, neither heating nor cooling network will be evaluated and thus **microgrid** is going to be picked from the project template dropdown menu. See the screenshot below to add the data provided.

Inputs

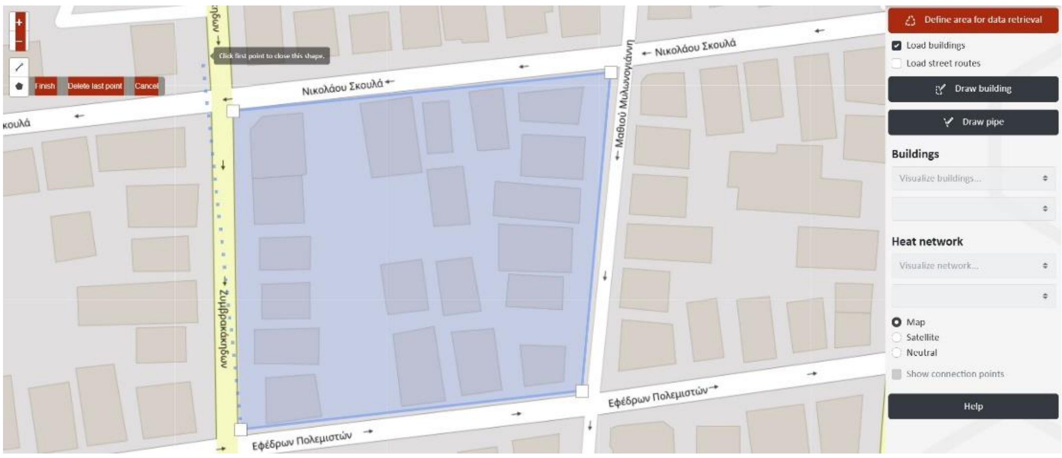
Step 1: *Basic inputs (press create new project when the following information is added)*



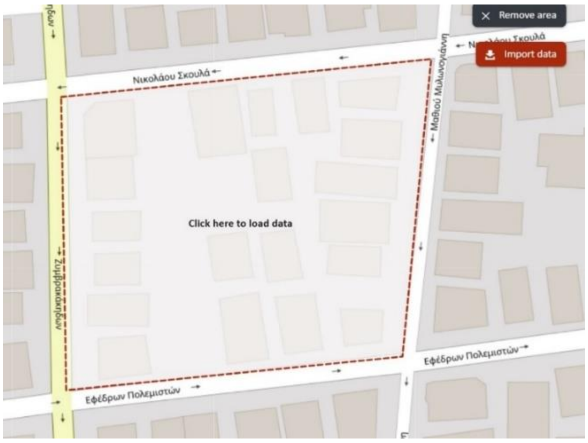
Step 2: *Designing the area of interest*

Toggling create new project once again after the basic inputs, the software will ask the user to **define the area for data retrieval (from the right)** by drawing it.

<u>Before</u> pressing the data retrieval button, the user should find the area of interest, consisting of the streets: Nikolaou Skoula, Efedron Polemiston, Zimvrakakidon and Mathiou Milonogianni (as shown in the picture below). The user should use the feature, find the area and use the +/-. After it finds the area, it presses the button define area for data retrieval (and not before).



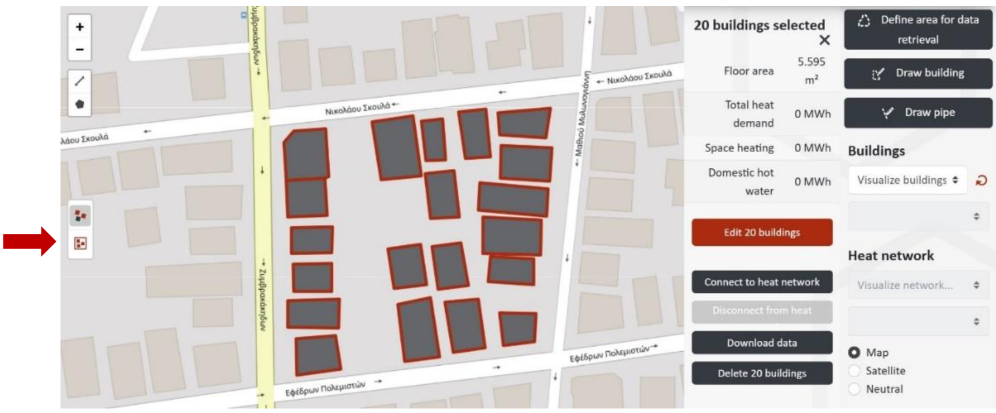
Step 3: *Import data*



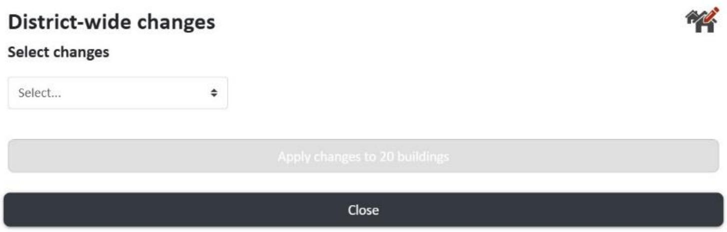
User shall then click ***Import data*** for the buildings individual energy demands

Step 4: *Activate/Deactivate energy demands*

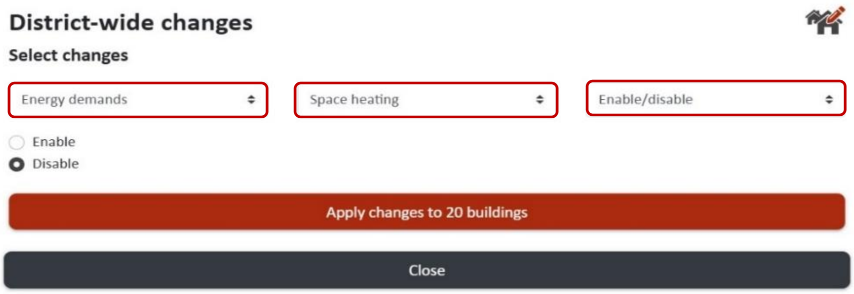
Due to the fact that this is an analysis based only on **electricity demand**, user should deactivate any unnecessary energy demand calculation.This can easily be done by toggling the *select all buildings* button (as shown with the red arrow below on the left of the picture).After that, user shall click ***edit 20 buildings*** then from the *drop-down menu* pick **energy demands**. **By default**, nPro has heat demand activated including *space heating* and *domestic hot water* needs.This selections needs to be deactivated by following the steps above.



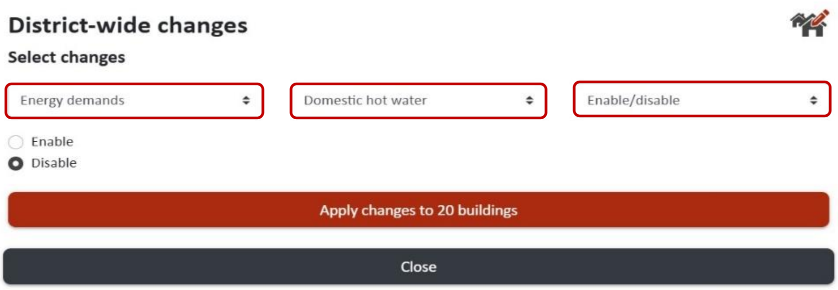
From the drop down menu, user shall pick *Energy demands*.



Then, from the next menu on the right select *Space heating* and the following one *Enable/Disable*.At last,user should click *Disable* and then **Apply changes to 20 buildings**.

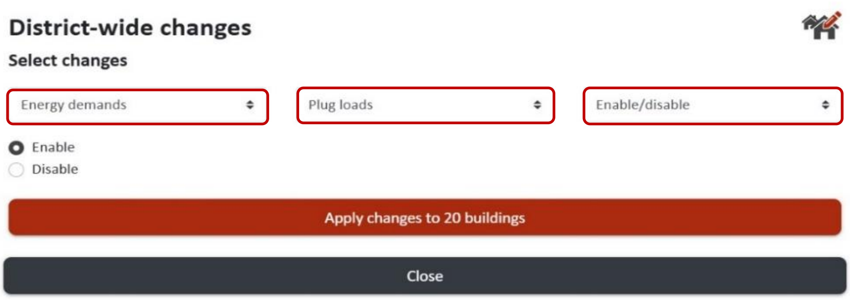


The same process will occur as for *Domestic hot water* demands.



It is notable that, nPro by default disabled the cooling demands sector (space cooling,process cooling) and therefore there is no need for user to change anything from these.

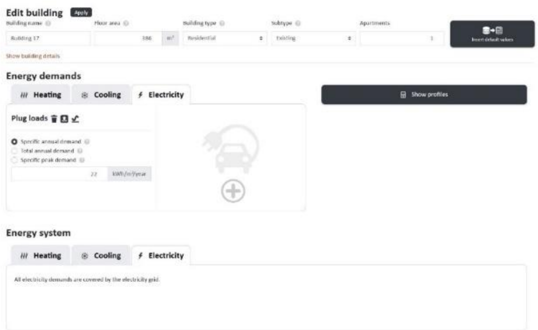
Furthermore, an other important modification needs to take part and it is the electricity demand activation. Same as before, user shall toggle *Energy demands*→*Plug loads*→*Enable/Disable* ,then select *Enable* and at last **Apply changes to 20 Buildings**.



There is also an option of *e-mobility* for the electricity demand session that can be activated, but in the analyzed systems coming that factor will be staying disabled as it is by default.

Additionally, tool gives user the opportunity to define values of the buildings when it comes to floor area, how many apartments are in a specific building, whether building is a residential type or for example a hospital and more importantly setting plug loads values of each one of them. If someone wants to make any kind of changes to a specific building information, this can be done by **toggling this building** , click **edit building** and apply any modifications.For the sake of this analysis, default values are used.

Step 1: *Edit building*



At first,user can change *building name*,*floor area*, *building type* (each building is linked to certain usage profiles and specific demand values), the *sub-type* (existing or new)of it and aslo the appartments that the specific building has.

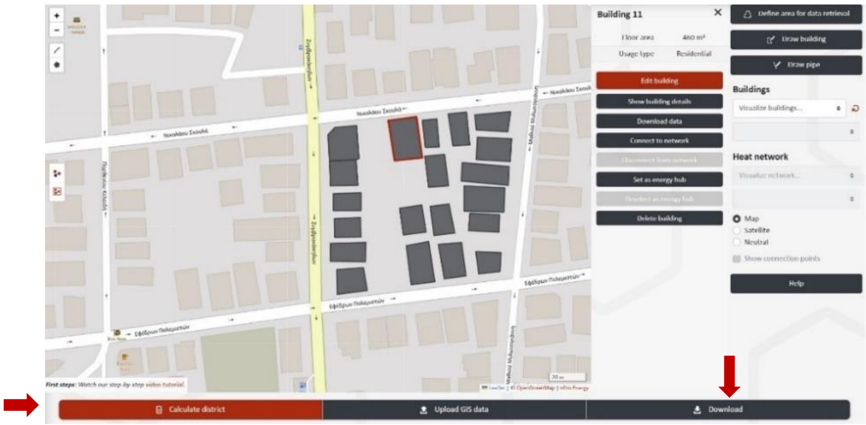
Step 2: *Energy demands*

User can optionally,modify the energy demands of an individual building based on the preferences. As mentioned before, energy demands can be enabled/disabled including heating, cooling or electricity ones. In this system, only electricity demand can optionally change because the other demands are disabled.

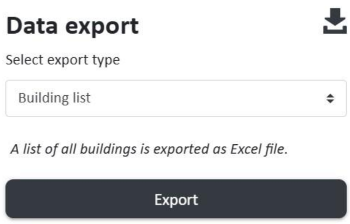
Step 3: *Energy system*

Due to the fact that this will be an **electricity only** demand analysis (cooling /heating demands are not included), any change to this sector is not needed.

After the necessary inputs, each user shall then click ***Calculate district*** for the tool to calculate the total electricity demand of the buildings.



User can **optionally** see a summary of the buildings, by clicking *Download* and from the drop-down menu that pops up picking *Building list*. An excel sheet will then be downloaded containing them.



The excel table below is an edited from the initial one, including the *number of the buildings*, *floor area* ,*floors* ,*apartments* and *plug loads* data.

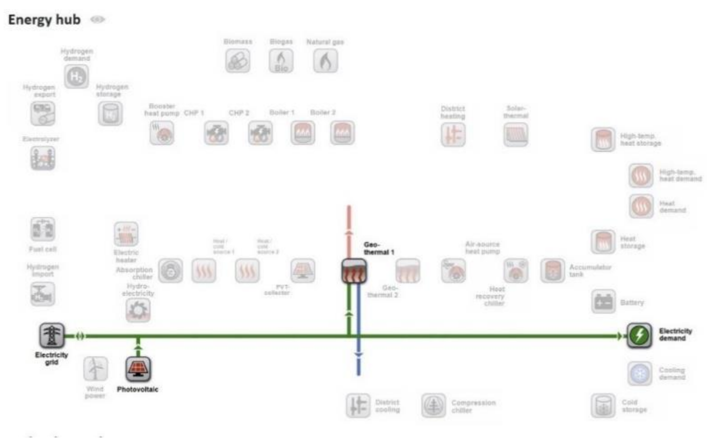
Building name	Building type	Floor area m²	Floors	Apartments	Plug loads MWh	Plug loads kW
Building 0	Residential	313	2	1	6,9	1,7
Building 1	Residential	352	2	1	7,7	2
Building 2	Residential	399	2	1	8,8	2,2
Building 3	Residential	214	2	1	4,7	1,2
Building 4	Residential	239	2	1	5,3	1,3
Building 5	Residential	235	2	1	5,2	1,3
Building 6	Residential	239	2	1	5,3	1,3
Building 7	Residential	193	2	1	4,2	1,1
Building 8	Residential	312	2	1	6,9	1,7
Building 9	Residential	378	2	1	8,3	2,1
Building 10	Residential	247	2	1	5,4	1,4
Building 11	Residential	460	2	1	10,1	2,6
Building 12	Residential	197	2	1	4,3	1,1
Building 13	Residential	201	2	1	4,4	1,1
Building 14	Residential	268	2	1	5,9	1,5
Building 15	Residential	278	2	1	6,1	1,5
Building 16	Residential	277	2	1	6,1	1,5
Building 17	Residential	386	2	1	8,5	2,1
Building 18	Residential	158	2	1	3,5	0,9
Building 19	Residential	249	2	1	5,5	1,4
Total		5595		20	123,1	

Fig. 36. *Exported excel table for building list*

It summarizes building types and their annual electricity demand that are picked for the analysis. All in all, the total floor area of the evaluation is 5,595 m^2 and the electricity demand of the entire district (sum of the electricity demands of all buildings plus the pump work for the heating network which is not included in the evaluation) is 123.1 MWh.

Step 1: *Selecting technologies*

Proceeding further, the user shall toggle the **Energy hub** session on the left side of nPro interface for manually selecting the technologies that are going to be optimized.



As mentioned before, the system consists of **wind turbines**, **PVs**, it's an **on-grid system** and the optimization is focused on **electricity demand**. There is also an option for the user to change the capacities of the selected technologies costs, as seen in the figure below. Hence, the user should select only photovoltaics and wind power as shown in the figure below.

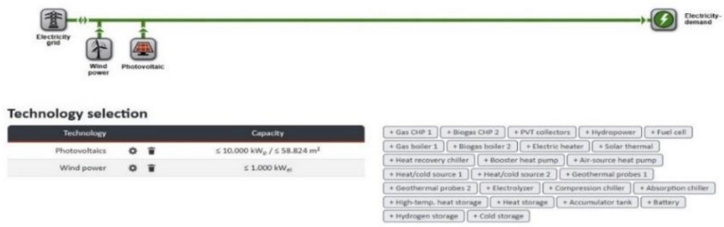


Fig. 37a. *Technologies selection*

Step 2: *Sizing technologies*

Additionally, as for the energy import, the supply price is set at 0.15€/kWh and the feed-in tariff on 0.05€/kWh. Users can also change the technology costs, the expected lifetime of the selected technologies (by default is set on 20 years) and the ecological parameters considering that energy imports increase the total CO_2 emissions and feed-ins decrease them. The optimization objective will focus on the feasibility of a cost-effective system.

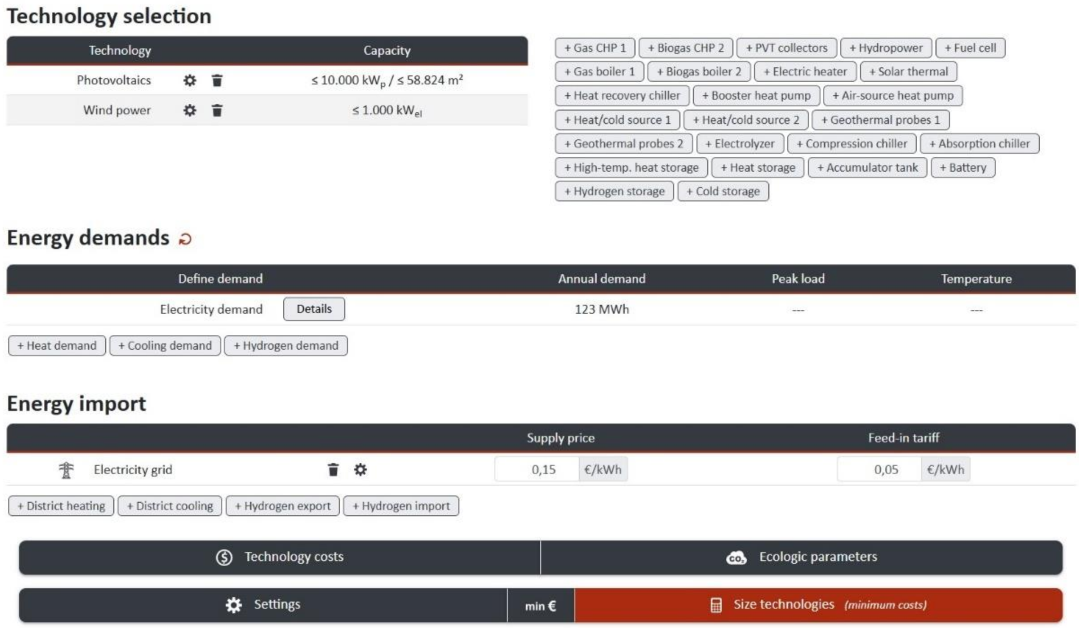
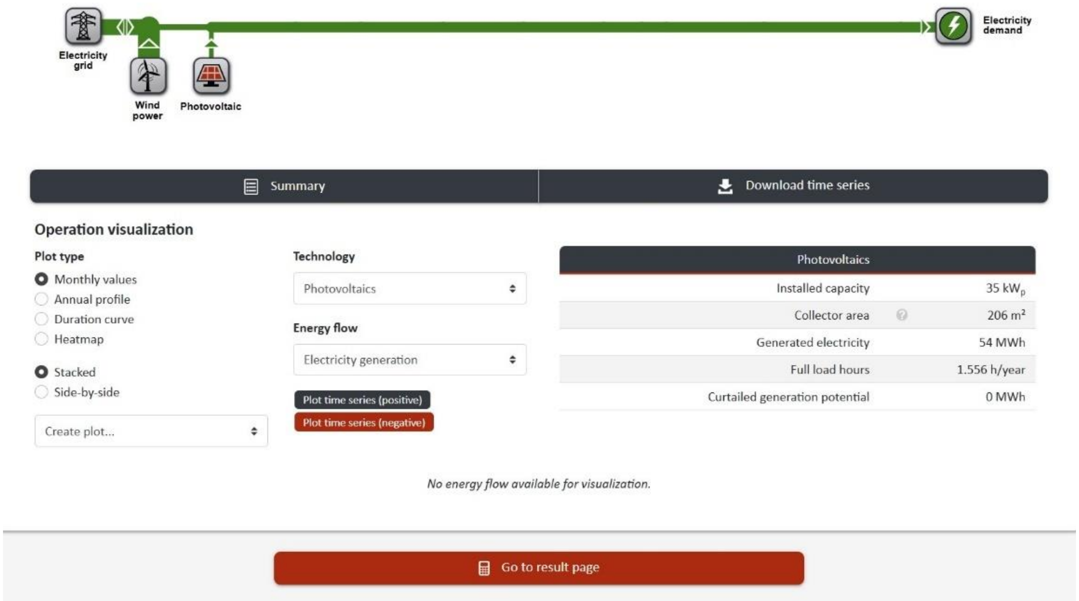


Figure 37b. *Energy demands and energy import*

Afterwards, the user should toggle ***Size technologies*** to allow software to calculate the design of the optimal system.

Step 3: *Simulate system operation*

After selecting ***Size technologies*** (bottom of the page at the right) and tool presenting the dimensioning of technologies, user can see the operation of the preferred system by toggling ***Simulate system operation (bottom of the page)***.



The figure above describes the quantitative size of the energy flows generated and consumed, providing an initial overview of how much each component contributes to covering demands. By clicking on a technology, the corresponding results are displayed below the graphic. In addition, when the mouse is moved over an energy flow, the amount of energy is displayed in MWh. After the simulation of the energy hub, there is a ***Go to result page*** function, so user can find a summary of all the results including especially the economic ones.

Results

Energy hub

The figures below show the optimal design of the system which is set at $35kW_p/58{,}824m^2$ for the PV and $127kW_{el}$ for the wind turbines. The capacities can be used to select **real available components**. Each one of the figures above can be exported through nPro after *Sizing technologies* and *Simulating system operation*. Users can then toggle *Go to result page* (bottom of the page) and select *create report* function. By clicking again *create report*, a .doc file will be downloaded which summarizes all results that the tool can provide, including the exported images below. If the **creating report** feature is not available due to software license issues (demo, academic, commercial), the following results can be summarized via the individual tabs that user can see after selecting **Go to result page**. The figures below show some selected results.

Summary | Energy hub | Economic results

Photovoltaics

	Scenario 1
Installed capacity	35 kW_p
Collector area	206 m^2
Generated electricity	54 MWh
Full load hours	1.556 h/year
Curtailed generation potential	0 MWh

Wind power

	Scenario 1
Installed capacity	127 kW_{el}
Generated electricity	258 MWh
Full load hours	2.029 h/year
Curtailed generation potential	0 MWh

Electricity generation and import

Technology	Annual sum	Share
Renewable electricity generation	**312 MWh**	**89,6 %**
Share photovoltaics	54 MWh	15,5 %
Share wind power	258 MWh	74,1 %
Electricity import from grid (energy hub)	36,3 MWh	10,4 %
Self-sufficiency (autarky) rate		70,6 %
Self-consumption rate		27,9 %

Emissions

	Spec. emissions		Annual sum		CO_2 emissions
Electricity import (energy hub)	350 g/kWh	×	36,3 MWh	=	12,7 t
Electricity feed-in	– 0 g/kWh	×	225 MWh	=	– 0 t
			Sum		**12,7 t**

Economic results

Annual balance

	Cash flow
Investment (annuity)	– 13.280 €/a
Energy costs	– 5.445 €/a
Maintenance costs	– 1.655 €/a
Lump sum costs (annuity)	– 1.328 €/a
Annual revenues	+ 48.177 €/a
Annual net profit	**+ 26.469 €/a**

i. **Investment**: Annuity of investments in all generation and storage plants, plus user-defined additional investments and retrofit measures. One-time connection fees are factored negatively

ii. **Energy costs**: Sum of energy purchase costs

iii. **Maintenance costs**: Sum of maintenance costs of all plants as well as the user-defined additional operating costs

iv. **Lump sum costs**: It is assumed that lump sum costs incurred together with the investments in the first project year (year 0)

v. **Annual revenues**: Total of all feed-in revenues (e.g. feed-in to the power grid), plus revenues for meeting the energy demands (heat, cold, electricity and hydrogen). One-time connection fees are not included (deducted from investments)

Economic KPIs

Net present value	+ 329.858 €
Amortization period	6 years
Internal rate of return	22,2 %
Levelized costs of energy	0,085 €/kWh
Energy costs per floor area	1,87 €/m²
Monthly energy costs per floor area	0,16 €/m²

i. **Net Present Value (NPV)**: It is the sum of all annual payments discounted at the beginning of the observation period. A positive NPV indicates that the investment is economically viable. A negative NPV signifies a not feasible investment
ii. **Amortization period**: It is the time for the investment to pay for itself
iii. **Internal Rate of Return (IRR):** It is the interest rate at which the NPV of all cash flows is zero. The IRR is a measure of the profitability of an investment
iv. **Levelized costs of energy**: Calculated as annual costs divided by all energy demands covered by the system (heat, cold, electricity, etc.)

Cash flow

Year	Investment	Annual costs	Annual revenues	Annual sum	Net present value
0	-182.050 €	0 €	0 €	-182.050 €	-182.050 €
1	0 €	-6.762 €	45.883 €	39.121 €	-142.929 €
2	0 €	-6.440 €	43.698 €	37.258 €	-105.671 €
3	0 €	-6.133 €	41.617 €	35.484 €	-70.187 €
4	0 €	-5.841 €	39.635 €	33.794 €	-36.393 €
5	0 €	-5.563 €	37.748 €	32.185 €	-4.208 €
6	0 €	-5.298 €	35.950 €	30.652 €	26.444 €
7	0 €	-5.046 €	34.238 €	29.192 €	55.636 €
8	0 €	-4.806 €	32.608 €	27.802 €	83.438 €
9	0 €	-4.577 €	31.055 €	26.478 €	109.916 €
10	0 €	-4.359 €	29.576 €	25.218 €	135.134 €
11	0 €	-4.151 €	28.168 €	24.017 €	159.151 €
12	0 €	-3.954 €	26.827 €	22.873 €	182.024 €
13	0 €	-3.765 €	25.549 €	21.784 €	203.808 €
14	0 €	-3.586 €	24.333 €	20.747 €	224.555 €
15	0 €	-3.415 €	23.174 €	19.759 €	244.314 €
16	0 €	-3.253 €	22.070 €	18.818 €	263.132 €
17	0 €	-3.098 €	21.019 €	17.922 €	281.054 €
18	0 €	-2.950 €	20.018 €	17.068 €	298.122 €
19	0 €	-2.810 €	19.065 €	16.255 €	314.377 €
20	0 €	-2.676 €	18.157 €	15.481 €	**329.858 €**

The net present value after 20 years is positive (329.858 €).

Cost and revenue details

Investments

	Investment	Annuity
Energy hub	165.500 €	13.280 €/a
Additional investments	0 €	0 €/a
Sum	**165.500 €**	**13.280 €/a**

Energy costs

	Price		Annual energy		Costs
Electricity	0,15 €/kWh	×	36,3 MWh/a	=	5.445 €/a
			Sum		**5.445 €/a**

Maintenance costs

	Costs
Energy hub	1.655 €/a
Additional operational costs	0 €/a
Sum	**1.655 €/a**

Lump sum costs

	Investments		Percentage		Costs
Planning costs	165.500 €	×	10 %	=	16.550 €
				Sum	**16.550 €**
				Annuity	**1.328 €/a**

Annual revenues

	Compensation		Quantity		Revenues
Electricity feed-in	0,05 €/kWh	×	225 MWh/a	=	11.250 €/a
Plug loads	0,3 €/kWh	×	123 MWh/a	=	36.927 €/a
			Sum		**48.177 €/a**

Energy hub

	Investment	Annuity	Maintenance costs
Photovoltaics	38.500 €	3.089 €/a	385 €/a
Wind power	127.000 €	10.191 €/a	1.270 €/a
Sum	**165.500 €**	**13.280 €/a**	**1.655 €/a**

3.2. Battery-PVs-Wind Turbines (CASE STUDY #2)

This system is designed to operate independently of the main electricity grid by generating and storing its own power (Q. Hassan, S. Algburi, A. Z. Sameen, H.M. Salman & M. Jaszczur, 2023).

System operation

i. **Power Generation**
- Solar PV Panels generate DC electricity during daylight
- Wind Turbine generates AC or DC electricity depending on design, based on wind speed
- Charge Controller(s) regulate voltage and current to prevent battery overcharging

ii. **Power Conversion and Management**
   - **a.** Hybrid Controller or MPPT Charge Controllers ensure power from both PV and wind and is optimally harvested and sent to charge batteries
   - **b.** If both sources are producing power, the system **combines or prioritizes** them for battery charging

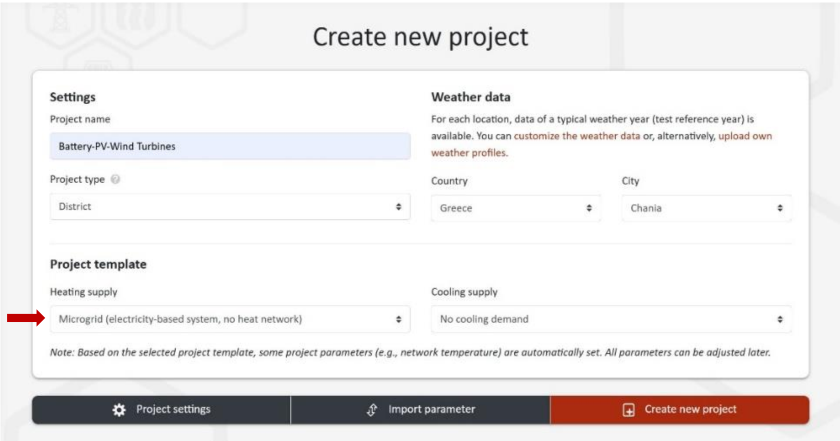
iii. **Energy storage**
   - a. Battery bank stores energy for use at night, during low solar/wind conditions and during high demand

iv. **Power supply to loads**
   - a. Inverter converts DC from batteries to AC for household or commercial use
   - **b.** System is sized so that the combination of generation + storage can meet demand even during several days of poor weather

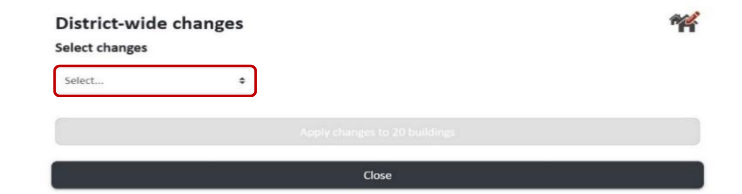
Inputs

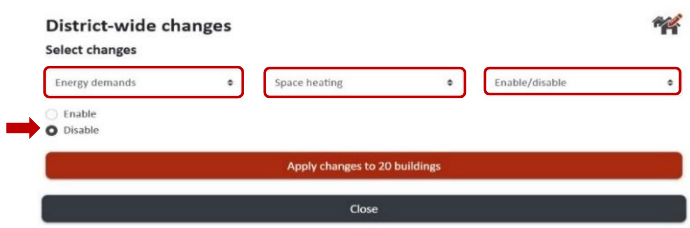
The area of the analysis will be the same as before, so the first steps will be the same as the previous system. After *creating new project* and *designing the location of interest* that mentioned previously, the user should pick the technologies in the *energy hub session*.

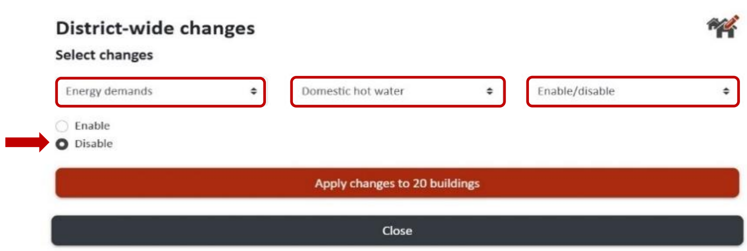
Same as the previous system, project type will be **district**, each user can optionally pick a name for the project, change *heating supply* to **microgrid**, country as Greece and city Chania.

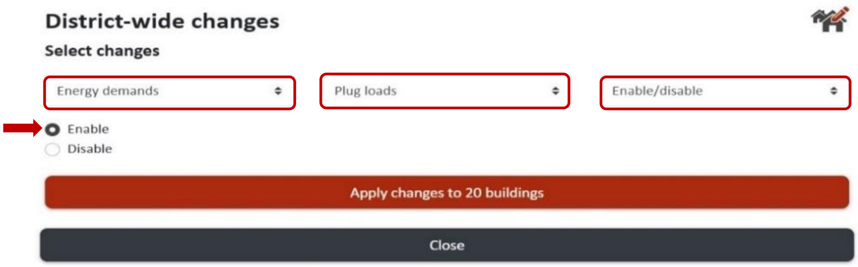


Afterwards, the user should toggle create new project for the drawing session to start. The same area- as the first system- for data retrieval will be set (**pages 66-68**). Again, due to the fact that the technoeconomic analysis will focus on electricity demand only, any needs for heating will be disabled (by default cooling demands has already been deactivated by nPro as mentioned before).





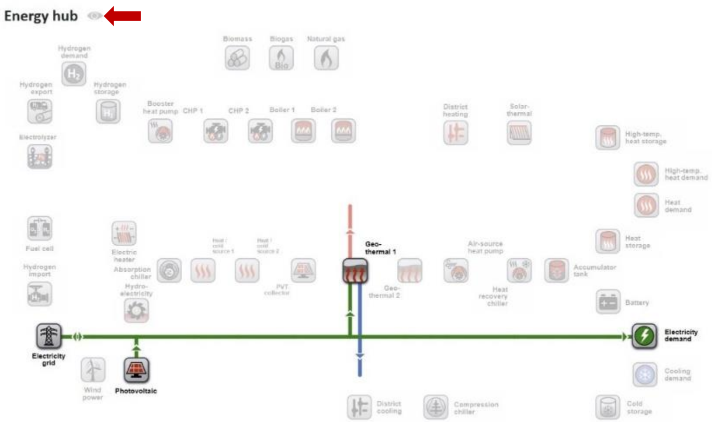




User shall then click again ***Calculate district***.

Step 1: *Selecting technologies*

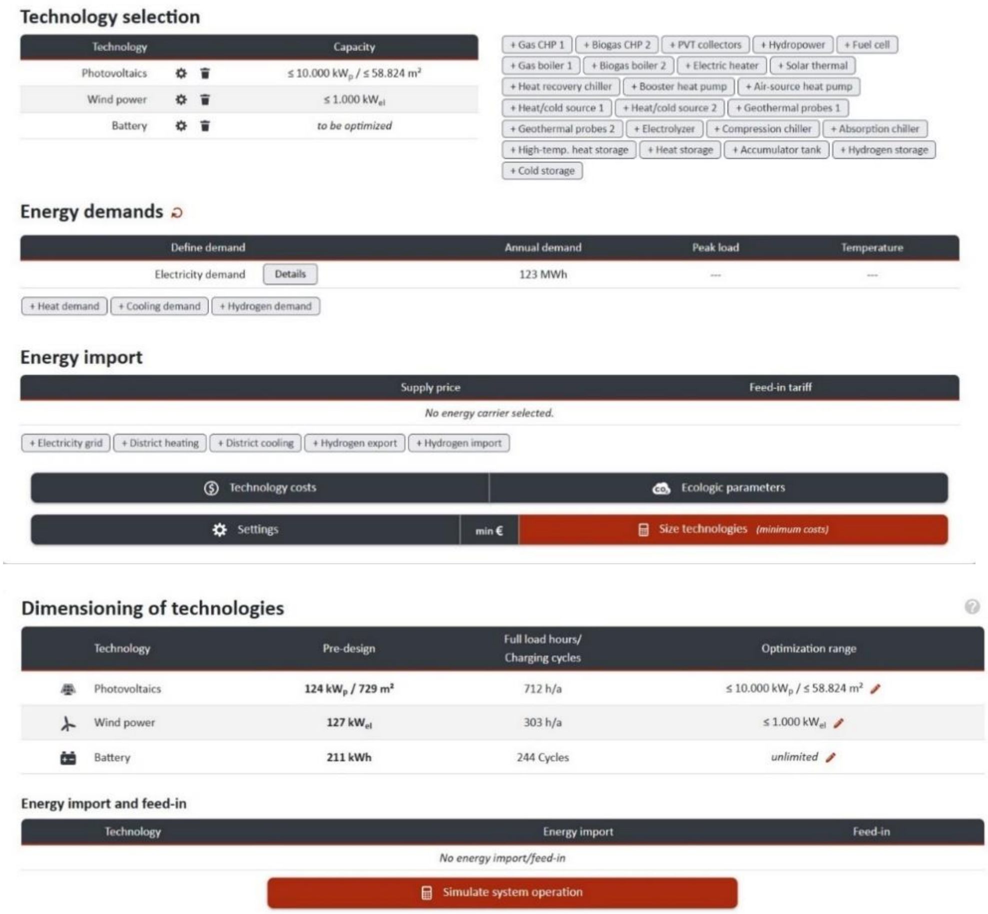
Proceeding further, the user shall toggle the **Energy hub** session on the left side of nPro interface for manually selecting the technologies that are going to be optimized.



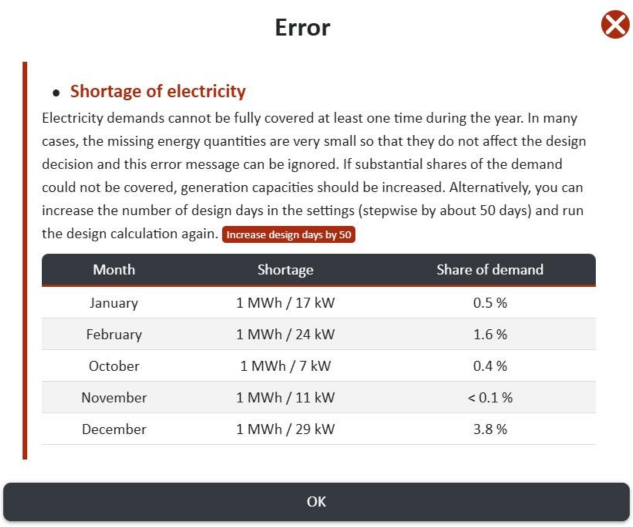
From the technologies above, the user shall ***choose*** **Wind Power, Photovoltaic and Battery** and ***unclick*** **Geothermal 1 and Electricity grid** that has nPro enabled by default. **Electricity demand** will also be needed, but it is enabled by default. Then each user can optionally hide the unselected technologies for a cleaner view (**red arrow above**).

The electricity demand of the district is set again at 123 MWh and in this case, there is not a supply price or feed-in tariff due to the fact that the hybrid system is an off-grid one.

After toggling *Size technologies (at the bottom of the page)*, the optimal design of the system is calculated, and the *dimensioning of technologies* are provided.



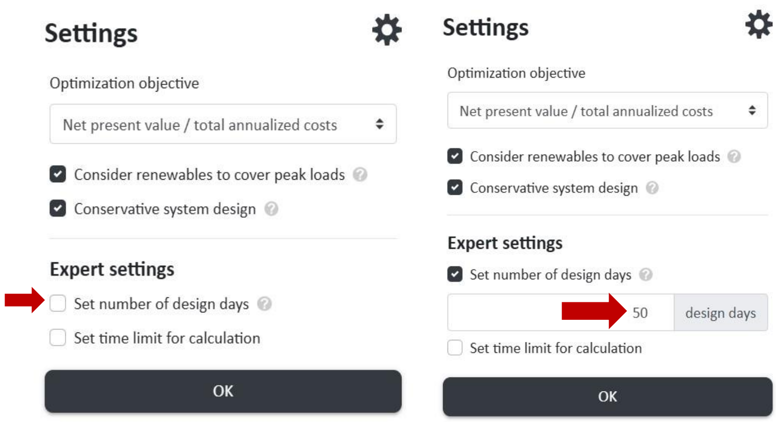
User can then click *Simulate system operation (bottom page)*, to see how this system will operate and how energy flow is shared within this system. After selecting this function, the user shall confront a system error. It is a shortage of electricity error in which electricity demands cannot be fully covered at least one time during the year.



The tool proposes some suggestions for fixing it (as shown in the picture above). In this particular case, an increase in the number of design days will be selected.

Step 1: User shall scroll up a little until finding **Settings**

Step 2: Then toggle the cog, select *Set number of design days*, *type 50* and *click ok.*

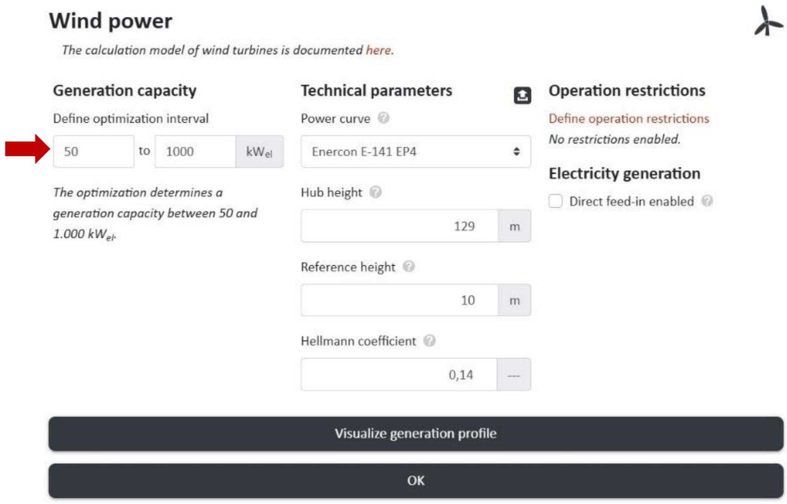


Step 3: Click *Size technologies* for the new dimensioning technologies to show.

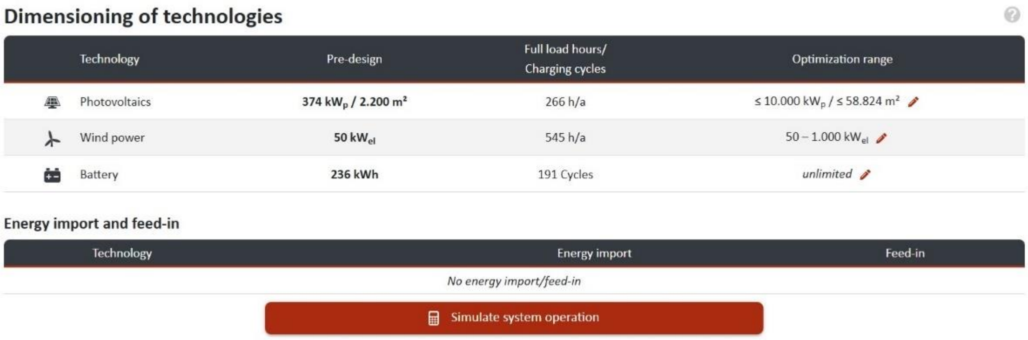
Now, as each user will see **wind power** is not taking part in the analysis. Since it is an interesting factor to address, users can manually adjust the optimization range for this technology.

Step 1**:** Select from wind power session the marker (as shown in the picture above)

Step 2: From the wind power menu that pops, change the **generation capacity** from **0 to 50**(red arrow below) and then click ok.



Step 3: Click once more ***Size technologies*.** New pre-design values should appear.


Dimensioning of technologies

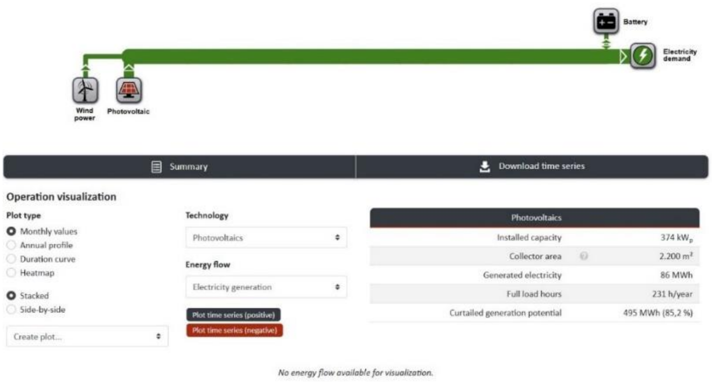
Technology	Pre-design	Full load hours/ Charging cycles	Optimization range
Photovoltaics	374 kW_p / 2.200 m^2	266 h/a	≤ 10.000 kW_p / ≤ 58.824 m^2
Wind power	50 kW_{el}	545 h/a	50 – 1.000 kW_{el}
Battery	236 kWh	191 Cycles	unlimited

Energy import and feed-in

Technology	Energy import	Feed-in
No energy import/feed-in		

Simulate system operation

Simulate system operation will show again the energy flows that are generated and consumed.



Same as before, ***Go to result page*** function will show a summary of all the results based on this specific hybrid system. There are 3 tabs a) summary, b) energy hub, c) economic results. The user clicks the 2nd tab “Energy Hub”.

Results

Energy hub

Photovoltaics

	Scenario 1
Installed capacity	374 kW_p
Collector area	2.200 m^2
Generated electricity	86 MWh
Full load hours	231 h/year
Curtailed generation potential	495 MWh

Wind power

	Scenario 1
Installed capacity	50 kW_{el}
Generated electricity	39,8 MWh
Full load hours	796 h/year
Curtailed generation potential	62 MWh

Battery

	Scenario 1
Storage capacity	236 kWh
Charging energy	39,2 MWh
Discharging energy	36,1 MWh
Full charging cycles	166

Fig. 38. *Sizing of the technologies in the energy hub*

Electricity generation and import

Technology	Annual sum	Share
Renewable electricity generation	**126 MWh**	**100 %**
Share photovoltaics	86 MWh	68,4 %
Share wind power	39,8 MWh	31,6 %
	Self-sufficiency (autarky) rate	100 %
	Self-consumption rate	100 %

Fig.39. *Electricity generation and import*

Economic results

The user should click Results (left side of the window) and then economic results tab.

Annual balance

	Cash flow
Investment (annuity)	– 61.032 €/a
Energy costs	– 0 €/a
Maintenance costs	– 6.502 €/a
Lump sum costs (annuity)	– 5.217 €/a
Annual revenues	+ 36.927 €/a
Annual net profit	**– 35.825 €/a**

Fig. 40. *Annual balance*

Economic KPIs

Net present value	– 446.448 €
Amortization period	---
Internal rate of return	---
Levelized costs of energy	0,591 €/kWh
Energy costs per floor area	13 €/m²
Monthly energy costs per floor area	1,08 €/m²

***Fig. 41**. Economic KPIs*

Cash flow

Year	Investment	Annual costs	Annual revenues	Annual sum	Net present value
0	-715.220 €	0 €	0 €	-715.220 €	-715.220 €
1	0 €	-6.192 €	35.168 €	28.976 €	-686.244 €
2	0 €	-5.898 €	33.494 €	27.596 €	-658.648 €
3	0 €	-5.617 €	31.899 €	26.282 €	-632.366 €
4	0 €	-5.349 €	30.380 €	25.030 €	-607.336 €
5	0 €	-5.094 €	28.933 €	23.839 €	-583.497 €
6	0 €	-4.852 €	27.555 €	22.703 €	-560.794 €
7	0 €	-4.621 €	26.243 €	21.622 €	-539.172 €
8	0 €	-4.401 €	24.993 €	20.593 €	-518.579 €
9	0 €	-4.191 €	23.803 €	19.612 €	-498.967 €
10	0 €	-3.992 €	22.670 €	18.678 €	-480.289 €
11	-110.387 €	-3.802 €	21.590 €	-92.599 €	-572.888 €
12	0 €	-3.621 €	20.562 €	16.942 €	-555.946 €
13	0 €	-3.448 €	19.583 €	16.135 €	-539.811 €
14	0 €	-3.284 €	18.650 €	15.367 €	-524.444 €
15	0 €	-3.128 €	17.762 €	14.635 €	-509.809 €
16	0 €	-2.979 €	16.917 €	13.938 €	-495.871 €
17	0 €	-2.837 €	16.111 €	13.274 €	-482.597 €
18	0 €	-2.702 €	15.344 €	12.642 €	-469.955 €
19	0 €	-2.573 €	14.613 €	12.040 €	-457.915 €
20	0 €	-2.451 €	13.917 €	11.467 €	**-446.448 €**

The net present value after 20 years is negative (-446.448 €).

***Fig. 42**. Cash flow*

Cost and revenue details

Investments

	Investment	Annuity
Energy hub	650.200 €	61.032 €/a
Additional investments	0 €	0 €/a
Sum	**650.200 €**	**61.032 €/a**

Energy costs

Price	Annual energy	Costs
	Sum	**0 €/a**

Maintenance costs

	Costs
Energy hub	6.502 €/a
Additional operational costs	0 €/a
Sum	**6.502 €/a**

Lump sum costs

	Investments		Percentage		Costs
Planning costs	650.200 €	×	10 %	=	65.020 €
				Sum	**65.020 €**
				Annuity	**5.217 €/a**

Annual revenues

	Compensation		Quantity		Revenues
Plug loads	0,3 €/kWh	×	123 MWh/a	=	36.927 €/a
				Sum	**36.927 €/a**

Investments

Building energy systems

	Number	Investment	Annuity	Maintenance
Sum	**0**	**0 €**	**0 €/a**	**0 €/a**

Heat network

Spec. costs	Investment	Annuity	Maintenance
0 €/m	0 €	0 €/a	0 €/a

Energy hub

	Investment	Annuity	Maintenance costs
Photovoltaics	411.400 €	33.012 €/a	4.114 €/a
Wind power	50.000 €	4.012 €/a	500 €/a
Battery	188.800 €	24.008 €/a	1.888 €/a
Sum	**650.200 €**	**61.032 €/a**	**6.502 €/a**

3.3. Hydrogen -PVs-Wind Turbines system inputs (CASE STUDY #3)

A Hydrogen-PV-Wind Hybrid system integrates solar (PV), wind turbines, and hydrogen storage to provide reliable, off-grid, or grid-connected energy (H.A.Z. AL-bonrulah, M.J. Alshukri, L.M. Mikhaeel, N.N. AL-sawaf, K.Nesrine, M.V. Reddy & K.Zaghib, 2021). The system ensures energy availability even when solar and wind generation fluctuate. In this case, the analysis will focus on off-grid energy. (R. M. Ghoniem, A. Alahmer, H. Rezk & S. As'ad, 2023)

Component	Functionality
Photovoltaics (PVs)	Converts sunlight into electricity. Produces excess energy during sunny hours
Wind Turbines	Generate electricity from wind. More effective at night or during cloudy/windy conditions
Battery storage	Stores excess solar/wind energy for short-term use. Helps stabilize power supply
Electrolyzer	Uses excess electricity to split water (H_2O) into hydrogen (H_2) and oxygen (O_2)
Hydrogen storage	Stores hydrogen produced by the electrolyzer for later use
Fuel Cell	Converts stored hydrogen back into electricity when demand is high or solar/wind power is low
Power management system	Controls energy distribution between PV, wind, batteries, and hydrogen storage for efficient operation

System operation

i. **Energy generation**
   - PV panels generate electricity during the day
   - Wind turbines produce power based on wind availability
   - Surplus electricity is used for direct consumption or stored

ii. **Short-Term Energy Storage (Battery)**
   - Excess power first charges batteries
   - Batteries provide instant power when solar/wind energy is insufficient.

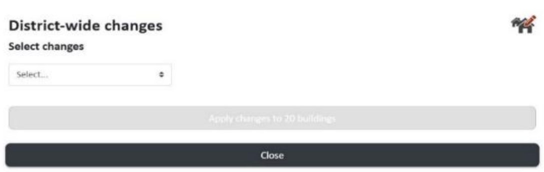
iii. **Long-Term Energy Storage (Hydrogen)**
   - When batteries are full, extra electricity powers the electrolyzer to produce hydrogen
   - Hydrogen is stored for long-term use

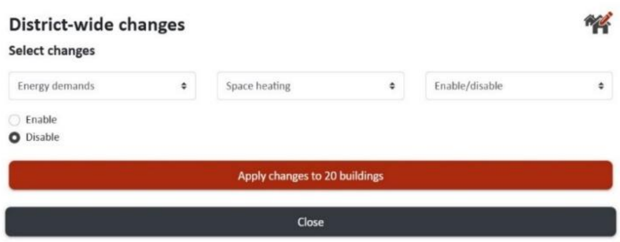
iv. **Power Supply During Low Renewable Generation**
   - If solar and wind energy are low, stored hydrogen is converted back to electricity via a **fuel cell** or **hydrogen generator**
   - This ensures a **continuous and stable power supply**

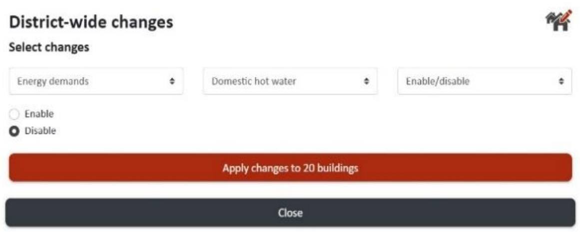
Inputs

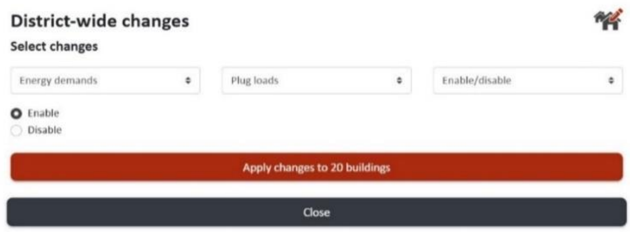
STEP 1: We follow the exact same steps as the previous case study 2. Nothing changes!

This system will be designed in the same location (Chania, Greece), the same area for data retrieval will be evaluated and as far buildings go (the user should follow the steps shown in pages 66-68), they will have also the same energy demands. Only electricity demands are necessary and therefore should be enabled.



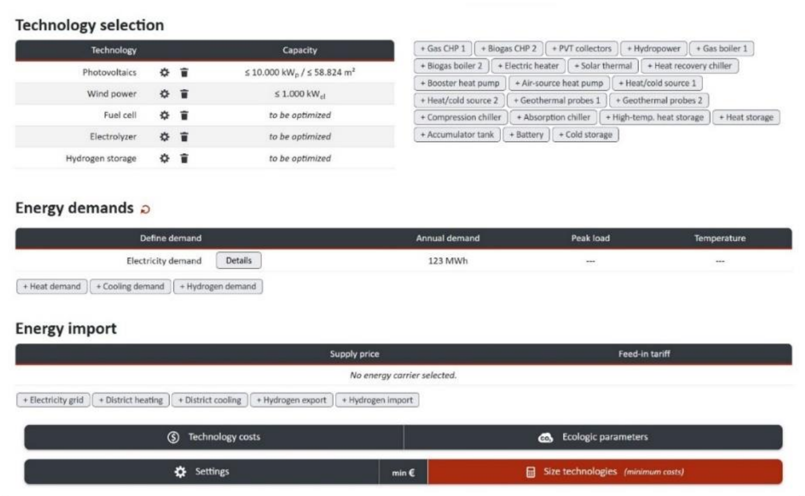


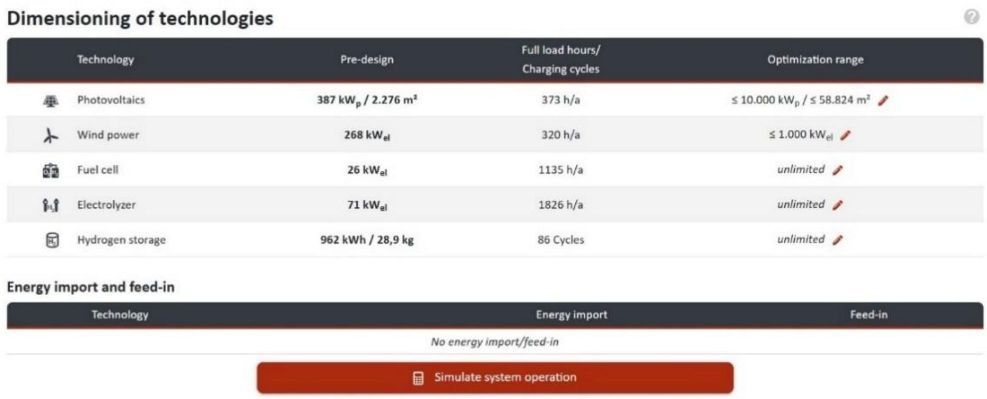




Proceeding further, the user shall pick the foresaid technologies for an off-grid system in the energy hub session (at the left).

After sizing technologies function, users shall see the optimal design of the system and also the dimensions of the picked technologies individually.





Dimensioning of technologies

Technology	Pre-design	Full load hours/ Charging cycles	Optimization range
Photovoltaics	387 kW$_p$ / 2.276 m²	373 h/a	≤ 10.000 kW$_p$ / ≤ 58.824 m²
Wind power	268 kW$_{el}$	320 h/a	≤ 1.000 kW$_{el}$
Fuel cell	26 kW$_{el}$	1135 h/a	*unlimited*
Electrolyzer	71 kW$_{el}$	1826 h/a	*unlimited*
Hydrogen storage	962 kWh / 28,9 kg	86 Cycles	*unlimited*

Energy import and feed-in

Technology	Energy import	Feed-in
No energy import/feed-in		

Simulate system operation

By toggling *Simulate system operation*, user should see the energy flows that is consumed and generated within the system and how each component is contributed to cover the energy demands.

Fig. 43. *System operation*

The results below are provided after the user presses the ***CREATE REPORT*** *section and downloads a file.*

Results

Energy hub

Technology	Dimensioning	Full load hours/Charging cycles
Hydrogen storage	962 kWh	75
Photovoltaics	387 kW$_p$	332 h
Wind power	268 kW$_{el}$	323 h
Fuel cell	26 kW$_{el}$	976 h
Electrolyzer	71 kW$_{el}$	1,572 h

Fig. 44. *Sizing of the technologies in the energy hub*

Storage capacity	962 kWh
Charging energy	73 MWh
Discharging energy	73 MWh
Storage capacity	28.9 kWh
Full charging cycles	75

Fig. 45. *Hydrogen storage*

Capacity	387 kW_p
Collector area	66
Generated electricity	129 MWh
Full load hours	332 h
Curtailed generation potential	473 MWh

Fig. 46. *Photovoltaics*

Capacity	268 kW_{el}
Generated electricity	87 MWh
Full load hours	323 h
Curtailed generation potential	457 MWh

Fig. 47. *Wind power*

Nominal electric capacity	26 kW_{el}
Generated electricity	25.4 MWh
Hydrogen demand	73 MWh
Full load hours	976 h

Fig. 48*. Fuel cell*

Nominal electric capacity	71 kW_{el}
Generated hydrogen	71 kW_{el}
Generated hydrogen	2.1 kW_{el}
Water consumption	19.2 kW_{el}
Water consumption	19.2 kW_{el}
Generated oxygen	17.1 kW_{el}
Electricity demand	112 MWh
Full load hours	1,572 h

Fig. 49. *Electrolyzer*

Technology	Annual energy	Share
Fuel cell	25.4 MWh	10.5 %
Renewable electricity generation	**216 MWh**	**89.5 %**
Share photovoltaics	129 MWh	53.4 %
Share wind power	87 MWh	36.0 %
	Self-sufficiency (autarky) rate	**100 %**
	Self-consumption rate	**100 %**

Fig. 50. *Electricity generation and import*

Economic results

	Cash flow
Investment (annuity)	– 141,817 €/a
Energy costs	0 €/a
Maintenance costs	– 36,697 €/a
Lump sum costs (annuity)	– 13,406 €/a
Annual revenues	+ 36,927 €/a
Annual net profit	**– 154,993 €/a**

Fig. 51. *Annual balance*

Net present value	– 1,931,571 €
Amortization period	-
Internal rate of return	-
Levelized costs of energy	1.559 €/kWh
Energy costs per floor area	34.3 €/m²
Monthly energy costs per floor area	2.86 €/m²

Fig. 52. *Economic KPIs*

Year	Investment	Annual costs	Annual revenues	Annual sum	Net present value
0	-1,837,770 €	0 €	0 €	-1,837,770 €	-1,837,770 €
1	0 €	-34,950 €	35,168 €	219 €	-1,837,551 €
2	0 €	-33,285 €	33,494 €	208 €	-1,837,343 €
3	0 €	-31,700 €	31,899 €	198 €	-1,837,145 €
4	0 €	-30,191 €	30,380 €	189 €	-1,836,956 €
5	0 €	-28,753 €	28,933 €	180 €	-1,836,776 €
6	0 €	-27,384 €	27,555 €	171 €	-1,836,605 €
7	0 €	-26,080 €	26,243 €	163 €	-1,836,442 €
8	0 €	-24,838 €	24,993 €	155 €	-1,836,287 €
9	0 €	-23,655 €	23,803 €	148 €	-1,836,139 €
10	0 €	-22,529 €	22,670 €	141 €	-1,835,998 €
11	0 €	-21,456 €	21,590 €	134 €	-1,835,864 €
12	0 €	-20,434 €	20,562 €	128 €	-1,835,736 €
13	0 €	-19,461 €	19,583 €	122 €	-1,835,614 €
14	0 €	-18,534 €	18,650 €	116 €	-1,835,498 €
15	0 €	-17,652 €	17,762 €	110 €	-1,835,388 €
16	-117,047 €	-16,811 €	16,917 €	-116,942 €	-1,952,330 €
17	0 €	-16,011 €	16,111 €	100 €	-1,952,230 €
18	0 €	-15,248 €	15,344 €	95 €	-1,952,135 €
19	-285,522 €	-14,522 €	14,613 €	-285,431 €	-2,237,566 €
20	305,909 €	-13,831 €	13,917 €	305,995 €	-1,931,571 €

Fig. 53. *Cash flow*

Cost and revenue details

	Investment	Annuity
Energy hub	1,670,700 €	141,817 €/a
Additional investments	0 €	0 €/a
Sum	**1,670,700 €**	**141,817 €/a**

Fig. 54. *Investment costs*

	Costs
Energy hub	36,697 €/a
Additional operational costs	0 €/a
Sum	**36,697 €/a**

Fig. 55. *Maintenance costs*

	Investments		Percentage		Costs
Planning costs	1,670,700 €	x	10 %	=	167,070 €
				Sum	**167,070 €**
				Annuity	**13,406 €/a**

Fig. 56. *Lump sum costs*

Compensation			Quantity		Revenues
Plug loads	0.3 €/kWh	x	123 MWh	=	36,927 €/a
			Sum		**36,927 €/a**

Fig. 57. *Annual revenues*

	Investment	Annuity	Maintenance
Hydrogen storage	721,500 €/a	61,410 €/a	14,430 €/a
Photovoltaics	425,700 €/a	34,159 €/a	4,257 €/a
Wind power	268,000 €/a	21,505 €/a	2,680 €/a
Fuel cell	78,000 €/a	7,554 €/a	4,680 €/a
Electrolyzer	177,500 €/a	17,189 €/a	10,650 €/a
Sum	**1,670,700 €/a**	**141,817 €/a**	**36,697 €/a**

Fig. 58. *Investment costs: Energy hub*

- ❖ Heat Demand

3.4. Grid-Geothermal Energy-Heat storage (CASE STUDY #4)

A **Geothermal Probes–Heat Storage–On-Grid System** is a hybrid energy system that combines **geothermal energy extraction**, **thermal storage**, and **grid electricity** to efficiently manage heating and cooling needs, typically for buildings or district energy systems.

System operation

- ✓ **Geothermal Probes (Borehole Heat Exchangers)**
  - **Vertical probes** are installed deep underground (typically 50–200 meters)
  - A **heat transfer fluid** (usually water or a glycol mix) circulates through these probes
  - In **winter**, the fluid absorbs heat from the ground
  - In **summer**, excess building heat is transferred into the ground (cooling effect)

  - Ground temperature is relatively stable year-round (~10–15°C in many regions), making this a reliable energy source

- ✓ **Heat pump system**
  - A **heat pump** extracts low-grade heat from the fluid and "upgrades" it to a usable temperature for space heating or domestic hot water
  - For cooling, the process is reversed (absorbs heat from building and dumps it into the ground)

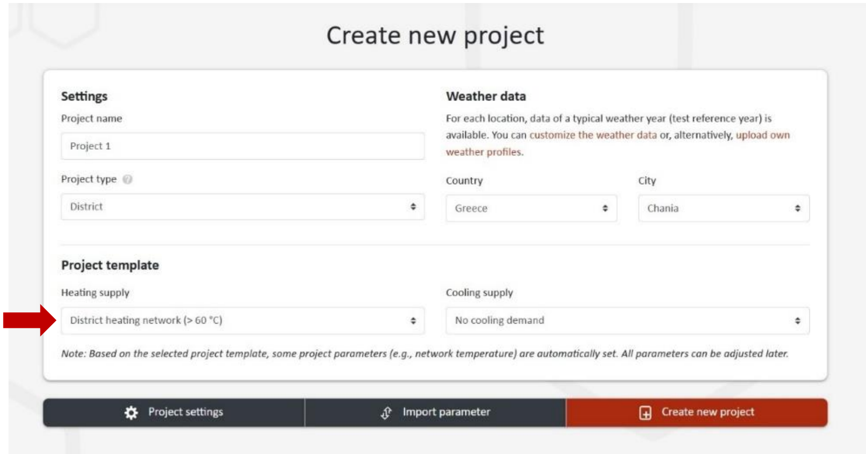
- ✓ **Heat Storage (Thermal Storage Tank or Borehole Thermal Energy Storage – BTES)**
  - **Short-Term Storage**: A hot water tank stores excess heat for daily load balancing
  - **Seasonal Storage**: Excess summer heat is stored underground in BTES fields or large insulated tanks and used in winter
  - **Cold storage** is also possible for chilled water or ice-based systems

- ✓ **Grid Connection (On-Grid)**
  - The **heat pump and system controls** run on grid electricity
  - The system may operate as:
    - **Grid-supported**, where power is always available from the grid
    - **Grid-interactive**, possibly combined with solar PV to reduce grid consumption
- ✓ **Smart Controls & Optimization**
  - Sensors monitor ground temperature, building load, and energy prices
  - The system can:
    - Shift heat pump operation to off-peak hours (time-of-use optimization)
    - Preheat or precool the building when electricity is cheaper or renewable power is abundant

Inputs

Step 1: *Setting the first basic inputs*

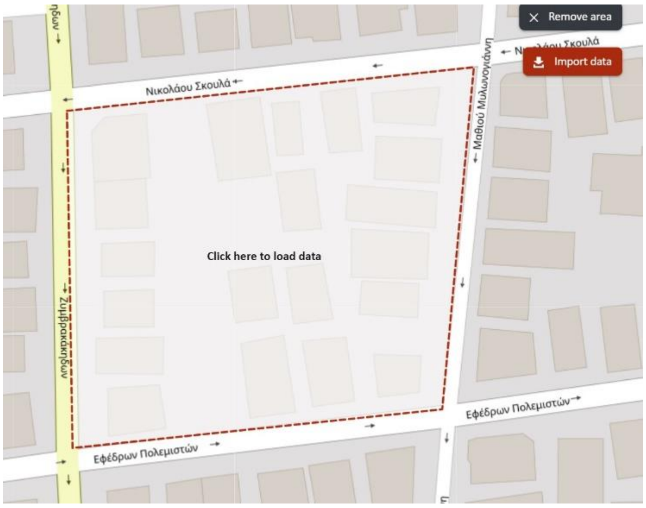
The only setting that changes here, is the ***heating supply*** which is now ***district heating network (>60 °C)***.



Step 2: *Designing the location*

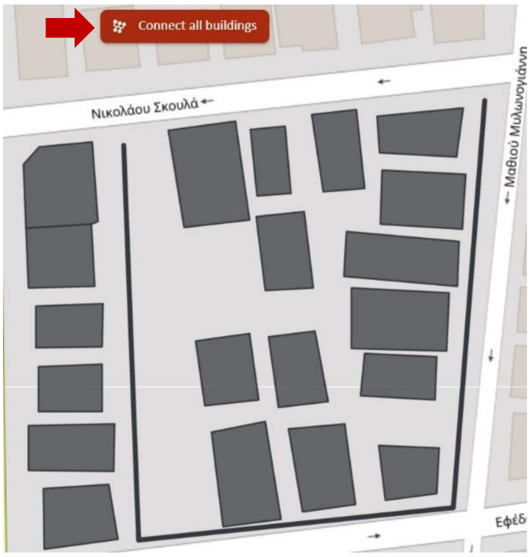
Again, the same process as the previous systems will be demonstrated. Zoom in and find the area of interest containing Nikolaou Skoula, Efedron Polemiston, Zimvrakakidon and Mathiou Milonogianni streets.

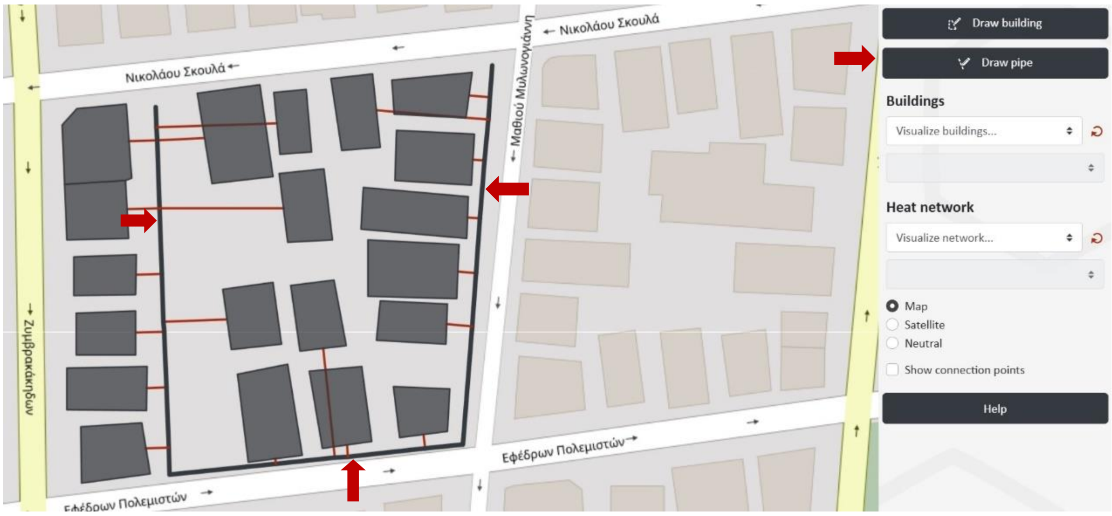
User shall then design the shape and click **import data.**



Step 3: *Configuring the pipe network*

Afterwards, the user should define the pipe system by clicking ***Draw pipe***. In this example, the pipe network will be installed into the boundary roads of Efedron Polemiston, Zimvrakakidon and Mathiou Milonogianni (red arrows). Another piece of the pipe will be placed inside the district area (blue arrow). User shall then toggle **connect all buildings**. The user will have to click the draw pipe option to add the lines.



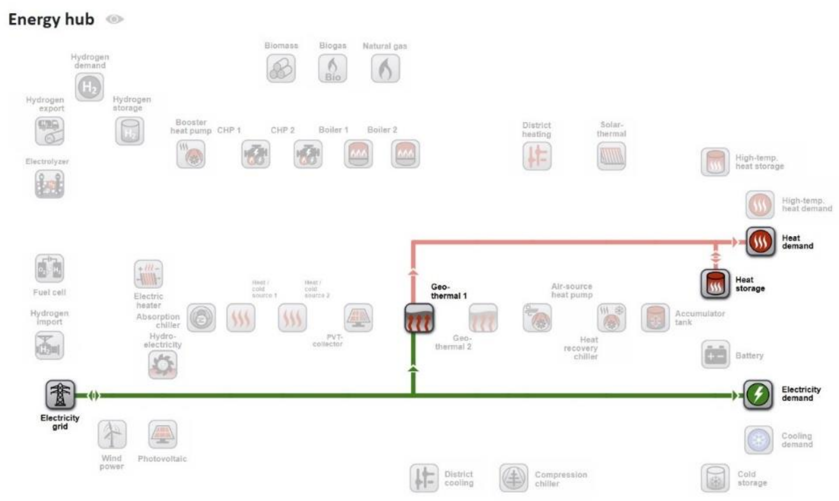


In addition, a building shall be picked to function as an energy hub. The **red** one, as shown in the image below, is toggling **select SET AS ENERGY HUB**.

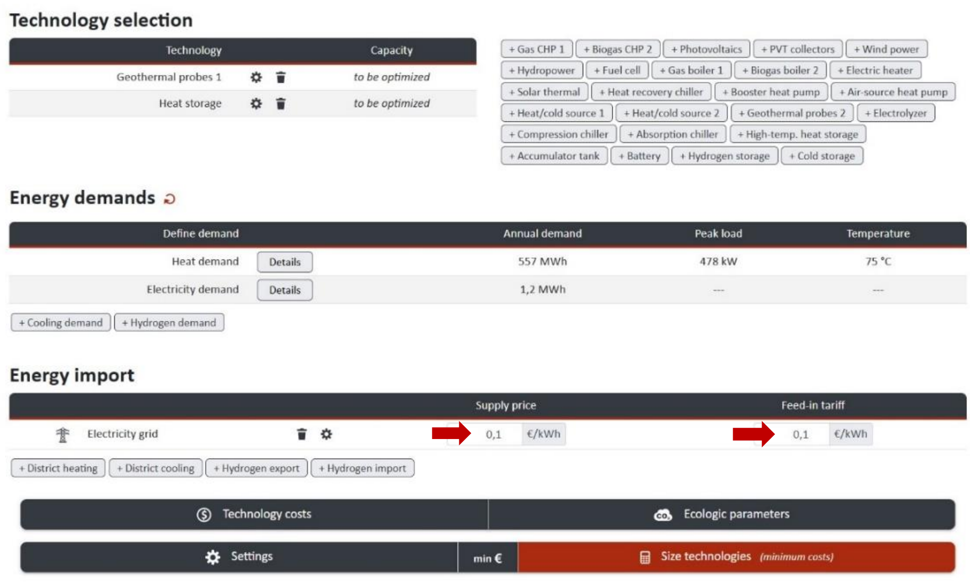
The tool has by default only heat demands activated and therefore there is no need to change anything in this particular session (neither cooling nor electricity demands activation). The user should press CALCULATE DISTRICT.

Step 4: *Selecting technologies*

In this segment, user should pick the technologies that are going to take part into the analysis containing **Geothermal**, **Heat Storage**, **Heat Demand**, **Electricity Grid** and **Electricity demand** (as shown in the picture below)

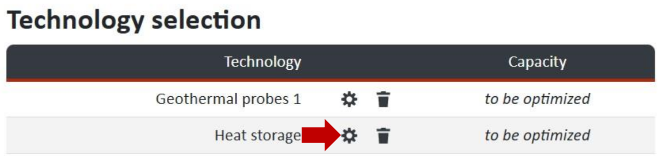


User shall change the supply price and also feed in tariff to 0.1 and then select **Size technologies.**

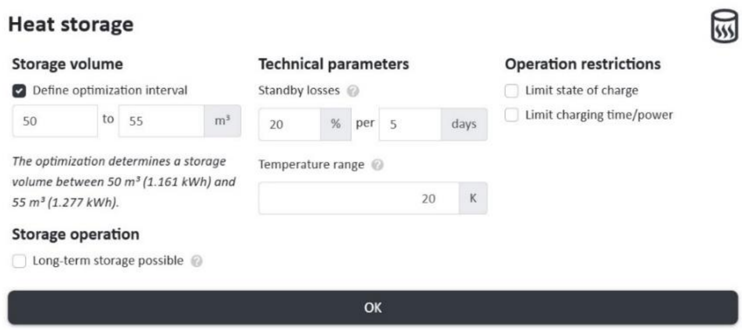


Pre-design section will appear, presenting the optimal design of the technologies. As for the heat extraction rate of the **geothermal source,** this will be set to 358 kW_{th} and as for the **heat storage** variable the tool does not include it into the optimization and is set to 0.

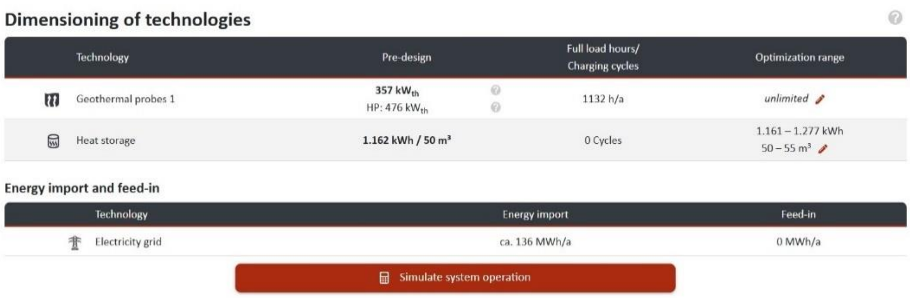
To change that, the user shall go to **technology selection** session and click **heat storage gear.**



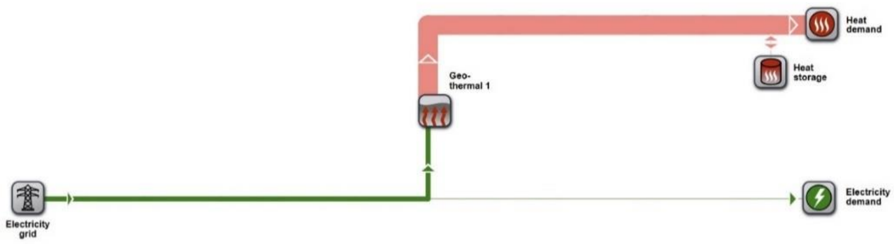
From the heat storage settings that pop up, user shall enable **define optimization interval**, determine a storage volume which in this application will be **50-55 m³** and then click ok.



After that, the user shall click again **Size technologies** and now a heat storage capacity should be included.

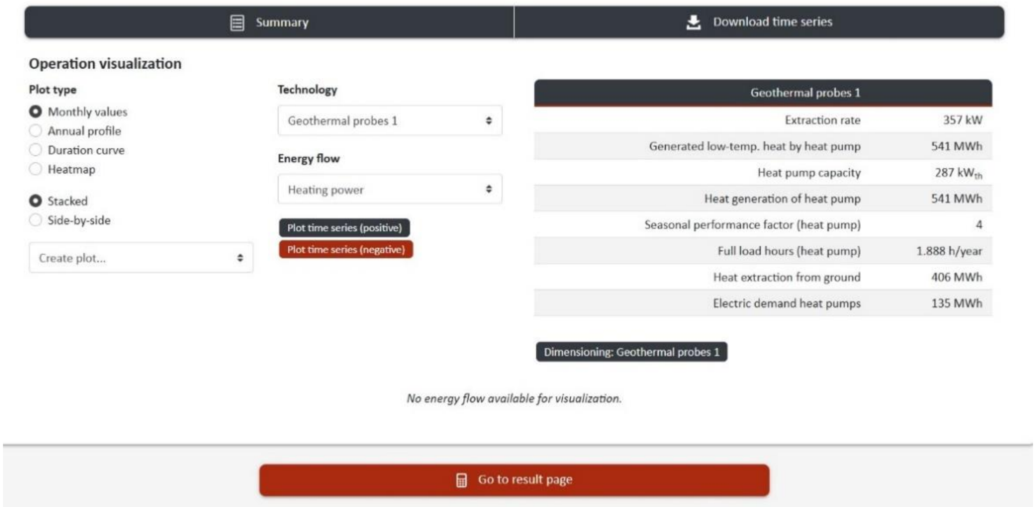


By toggling **simulate system operation**, user can see the quantitative size of the energy flows generated and consumed.



There is a section on the bottom page where users can see more detailed results for each technology and also visualize the operation profiles of the system.

Users can also click into **the Summary** section and there the most important KPIs of the system are generated.



Results

Energy hub

A summary of the technologies (with the form of screenshots) that have been utilized is following and user can see it after selecting **Go to result page→Summary and Scenarios→Energy hub (2nd tab)**.

Summary | Energy hub | Economic results

Geothermal probes 1

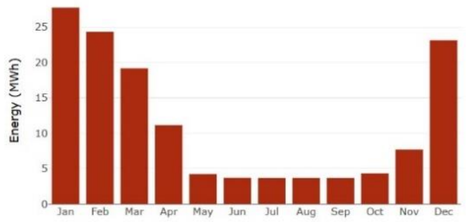
	Scenario 1
Extraction rate	357 kW
Generated heat	541 MWh
Heat pump capacity	287 kW_{th}
Electricity demand	135 MWh

Heat storage

	Scenario 1
Storage capacity	1.162 kWh
Charging energy	5,2 MWh
Discharging energy	5,1 MWh
Storage volume	50 m³
Full charging cycles	4

Electricity generation and import

Technology	Annual sum	Share
Electricity import from grid (energy hub)	136 MWh	100 %
Self-sufficiency (autarky) rate		0 %



Economic results

For economic analysis, the user shall pick the **Economic results** tab.

Economic results

Settings

Annual balance

	Cash flow
Investment (annuity)	– 80.210 €/a
Energy costs	– 13.600 €/a
Maintenance costs	– 9.867 €/a
Lump sum costs (annuity)	– 9.436 €/a
Annual revenues	+ 118.893 €/a
Annual net profit	**+ 5.780 €/a**

Economic KPIs

Net present value	+ 72.041 €
Amortization period	20 years
Internal rate of return	5,6 %
Levelized costs of heat	0,238 €/kWh
Levelized costs of energy	0,238 €/kWh
Heating cost per floor area	20,22 €/m²
Monthly heating cost per floor area	1,68 €/m²

Cash flow

Year	Investment	Annual costs	Annual revenues	Annual sum	Net present value
0	-1.293.498 €	0 €	0 €	-1.293.498 €	-1.293.498 €
1	0 €	-22.350 €	113.232 €	90.882 €	-1.202.616 €
2	0 €	-21.286 €	107.840 €	86.554 €	-1.116.062 €
3	0 €	-20.272 €	102.704 €	82.432 €	-1.033.630 €
4	0 €	-19.307 €	97.814 €	78.507 €	-955.123 €
5	0 €	-18.387 €	93.156 €	74.769 €	-880.354 €
6	0 €	-17.512 €	88.720 €	71.208 €	-809.146 €
7	0 €	-16.678 €	84.495 €	67.817 €	-741.329 €
8	0 €	-15.884 €	80.472 €	64.588 €	-676.741 €
9	0 €	-15.127 €	76.640 €	61.512 €	-615.229 €
10	0 €	-14.407 €	72.990 €	58.583 €	-556.646 €
11	0 €	-13.721 €	69.514 €	55.793 €	-500.853 €
12	0 €	-13.068 €	66.204 €	53.137 €	-447.716 €
13	0 €	-12.445 €	63.052 €	50.606 €	-397.110 €
14	0 €	-11.853 €	60.049 €	48.196 €	-348.914 €
15	0 €	-11.288 €	57.190 €	45.901 €	-303.013 €
16	0 €	-10.751 €	54.466 €	43.716 €	-259.297 €
17	0 €	-10.239 €	51.873 €	41.634 €	-217.663 €
18	0 €	-9.751 €	49.403 €	39.651 €	-178.012 €
19	0 €	-9.287 €	47.050 €	37.763 €	-140.249 €
20	176.325 €	-8.845 €	44.810 €	212.290 €	**72.041 €**

The net present value after 20 years is positive (72.041 €).

Cost and revenue details

Investments

	Investment	Annuity
Building energy systems	118.736 €	7.732 €/a
Heat network	485.300 €	31.603 €/a
Energy hub	672.662 €	47.462 €/a
Additional investments	0 €	0 €/a
Sum	**1.276.698 €**	**86.798 €/a**

Maintenance costs

	Costs
Heat network	3.885 €/a
Energy hub	5.982 €/a
Additional operational costs	0 €/a
Sum	**9.867 €/a**

Lump sum costs

	Investments		Percentage		Costs
Planning costs	1.175.907 €	×	10 %	=	117.591 €
				Sum	**117.591 €**
				Annuity	**9.436 €/a**

Annual revenues

	Compensation		Quantity		Revenues
Electricity feed-in	0,1 €/kWh	×	0 MWh/a	=	0 €/a
Heat demand	0,25 €/kWh	×	476 MWh/a	=	118.893 €/a
			Sum		**118.893 €/a**

Investments

Building energy systems

	Number	Investment	Annuity	Maintenance
Heat network connection	20	118.736 €	7.732 €/a	0 €/a
Sum	**20**	**118.736 €**	**7.732 €/a**	**0 €/a**

Heat network

Spec. costs	Investment	Annuity	Maintenance
883 €/m	388.549 €	25.303 €/a	3.885 €/a

Energy hub

	Investment	Annuity	Maintenance costs
Geothermal probes 1	357.000 €	22.169 €/a	0 €/a
Heat storage	25.019 €	2.008 €/a	250 €/a
Heat pump (geothermal energy 1)	286.603 €	22.998 €/a	5.732 €/a
Sum	**668.622 €**	**47.175 €/a**	**5.982 €/a**

3.5. Grid-Biomass CHP unit-Heat storage (CASE STUDY #5)

A hybrid system combining an **on-grid biomass CHP unit** with **heat storage** operates as a flexible and sustainable energy solution, supplying **heat and electricity** to buildings or districts while interacting with the power grid (EPA, 2025).

System operation

- ✓ **Biomass CHP Unit (Combined Heat and Power)**
  - Fuel: Uses biomass (wood chips, pellets, agricultural residues)
  - Electric Output: Supplies electricity to local loads and/or exports to the grid
  - Thermal Output: Provides heat for space heating, domestic hot water, or industrial processes
  - Efficiency: ~25–35% electrical, ~50–60% thermal → total system efficiency ≈ 80–90%
- ✓ **Thermal Energy Storage (TES)**
  - Stores excess heat generated during periods of low demand
  - Discharges stored heat during peak demand or when the CHP is not operating
  - Typically, a hot water tank or larger buffer storage, possibly stratified
- ✓ **On-Grid Connection**
  - Allows electricity export (if generation > local demand)
  - Allows grid import during CHP downtime or maintenance
  - Helps optimize operation based on electricity prices (Time-of-Use)

♦ *Operation scenarios*

- ✓ **Winter (High Chat Demand)**
  - Biomass CHP runs at high load to meet thermal demand
  - Excess heat is stored in TES for use during off-periods or peak hours
  - Electricity is used locally or exported to the grid

- ✓ **Shoulder Seasons (Low to Moderate Demand)**
  - CHP runs intermittently or at reduced load
  - TES absorbs surplus and discharges as needed
  - Grid may supplement electricity when CHP is off
- ✓ **Maintenance or Fuel Supply Issues**
  - Grid electricity supports the load
  - TES discharges stored heat until biomass CHP is restored

♦ *Control strategy*

- ✓ A **central Energy Management System (EMS)** balances:
  - CHP operation based on thermal load priority
  - TES charge/discharge strategy
  - Electricity flow: self-consumption vs. export vs. grid import
  - Possibly includes forecasting (weather, demand, prices)

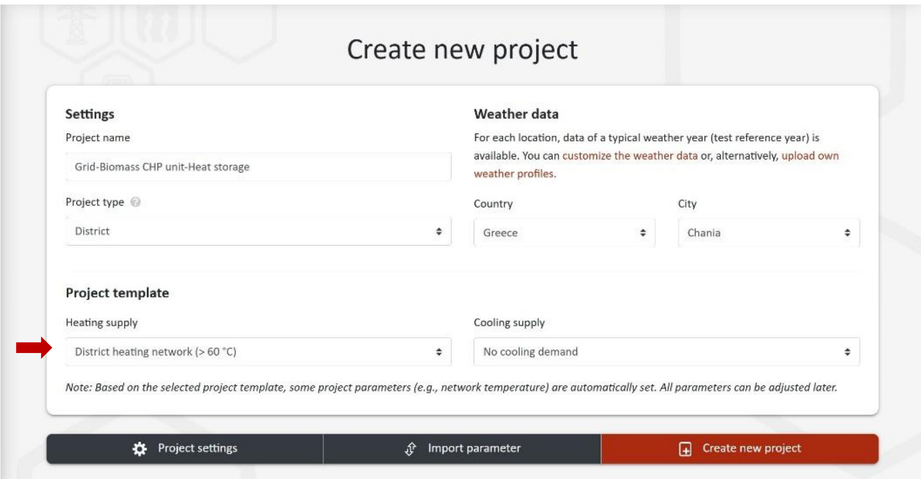
♦ *Benefits*

- ✓ **High efficiency:** Cogeneration improves fuel use efficiency
- ✓ **CO_2 Reduction:** Biomass is renewable and carbon-neutral (if sustainably sourced)
- ✓ **Grid Flexibility:** Can export surplus electricity or import when needed
- ✓ **Thermal Load Matching:** Heat storage bridges generation and demand gaps
- ✓ **Economic Optimization:** Can operate based on peak electricity prices

Inputs

Step 1: *Setting the first basic inputs* **(**THIS CASE STUDY IS 100% SIMILAR WITH CASE STUDY 4)

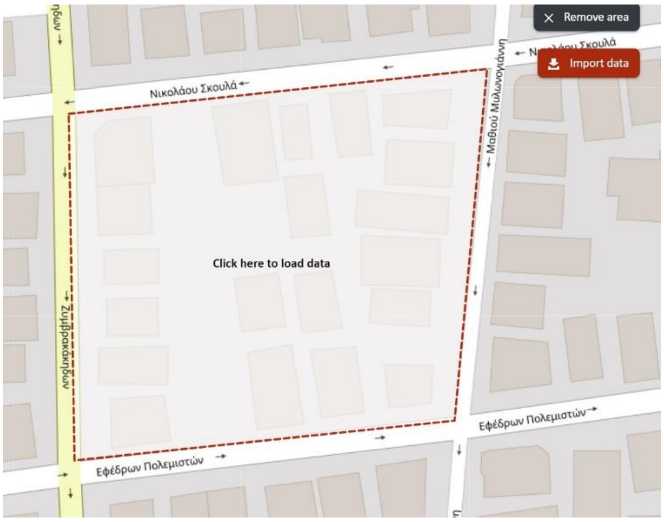
As mentioned before, the only setting that changes here, is the ***heating supply*** which is now ***district heating network (>60 °C)***.



Step 2: *Designing the location*

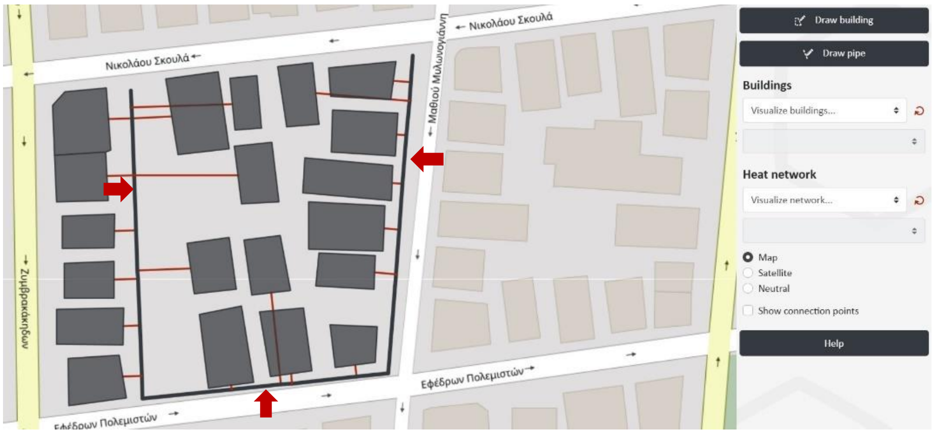
Again, the same process as the previous systems will be demonstrated. Zoom in and find the area of interest containing Nikolaou Skoula, Efedron Polemiston, Zimvrakakidon and Mathiou Milonogianni streets.

User shall then design the shape and click **import data.**



Step 3: *Configuring the pipe network*

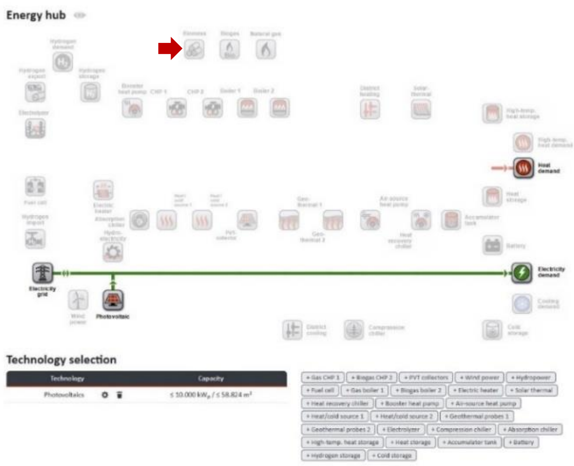
Afterwards, the user should define the pipe system by clicking ***Draw pipe***. In this example, the pipe network will be installed into the boundary roads of Efedron Polemiston, Zimvrakakidon and Mathiou Milonogianni (red arrows). Another piece of the pipe will be placed inside the district area (**blue arrow**). User shall then toggle **connect all buildings**.



In addition, a building shall be picked to function as an energy hub. The highlighted red one, as shown in the image below, is picked toggling **select as energy hub**.

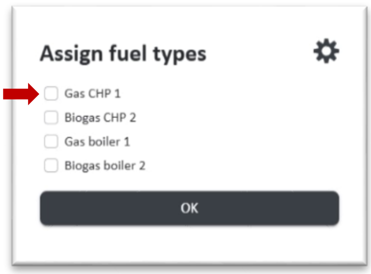
The tool has by default only heat demands activated and therefore there is no need to change anything in this particular session (neither cooling nor electricity demands activation).

Step 4: **Selecting technologies**

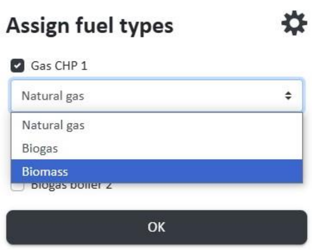


In this segment, users should again pick the technologies that are going to take part in the analysis containing **Biomass CHP unit**, **Heat Storage**, **Heat Demand**, **Electricity Grid** and **Electricity demand.** Some of the foretold technologies/demands are enabled by default right after selecting the energy hub tab. For *enabling the biomass CHP unit* user shall do the following steps:

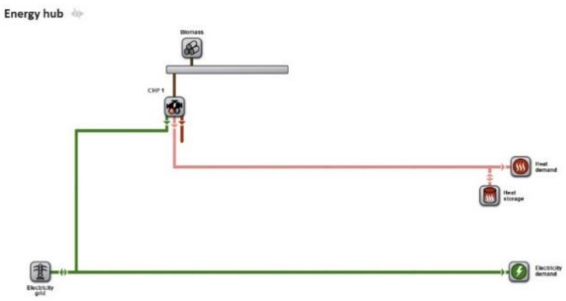
- At first, click the biomass technology (as shown with the red arrow above)
- Then, from the list pick the **Gas CHP 1**



- At last, from the drop-down menu select **biomass** and click ok



Afterwards, the user should pick the foresaid technologies, hide (optionally) the unnecessary ones and the following energy hub will be revealed.



Proceeding further, the user should see the **energy demands** of this system and **energy import** which will again have some of its parameters changed (*supply price* and *feed-in tariff* will be set as 0.1). Also, the biomass import supply price will be set as 0.05. By clicking *Size technologies,* the tool will provide the user with the optimal **dimensioning of technologies** to minimize the cost of the system.

Energy demands

Define demand		Annual demand	Peak load	Temperature
Heat demand	Details	543 MWh	476 kW	75 °C
Electricity demand	Details	1,3 MWh	---	---

+ Cooling demand | + Hydrogen demand

Energy import

	Supply price	Feed-in tariff
Electricity grid	0,1 €/kWh	0,1 €/kWh
Biomass import	0,05 €/kWh	No feed-in

+ District heating | + District cooling | + Hydrogen export | + Hydrogen import

Technology costs | Ecologic parameters

Settings | min € | Size technologies (minimum costs)

Dimensioning of technologies

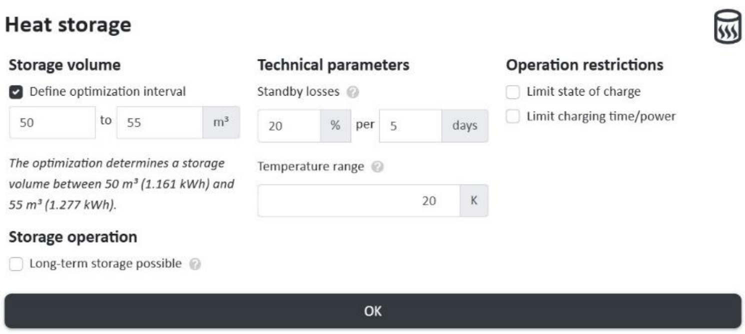
Technology	Pre-design	Full load hours/ Charging cycles	Optimization range
Biomass CHP 1	334 kW_{el} / 477 kW_{th}	1131 h/a	unlimited
Heat storage	0 kWh / 0 m^3	0 Cycles	unlimited

Due to the fact that heat storage will again not be evaluated in the analysis, user shall go to **technology selection** session (above **energy demands**) and click the **heat storage gear.**

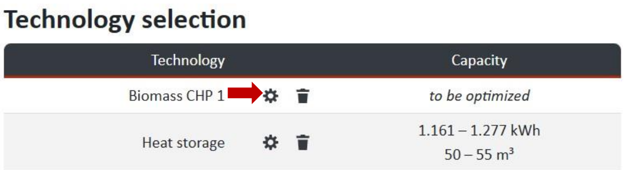
Technology selection

Technology	Capacity
Biomass CHP 1	to be optimized
Heat storage	to be optimized

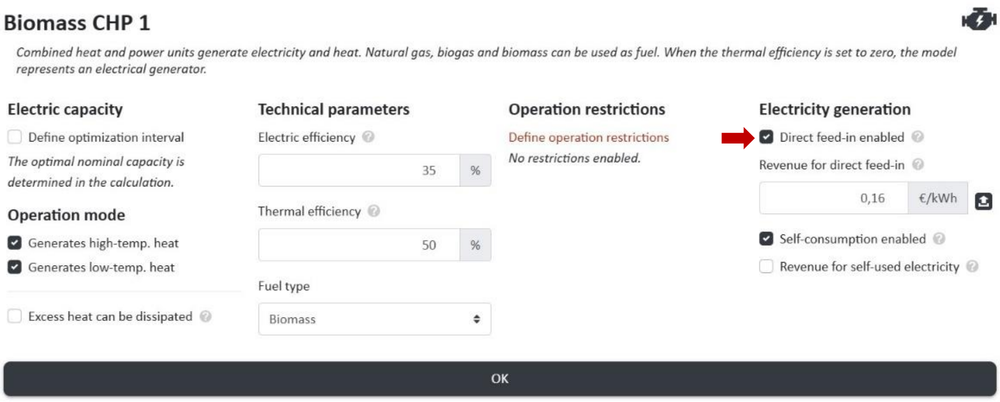
From the heat storage settings that pop up, user shall enable **define optimization interval**, determine a storage volume which in this application will be **50-55 m^3** and then click ok.



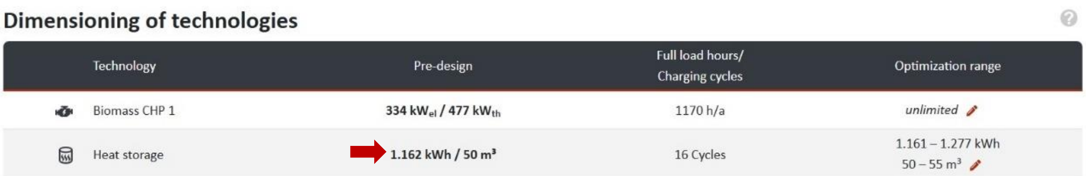
Another parameter that will be changed is biomass CHP direct feed-in setting. Even though the system is an off grid one, a sort of electricity is needed for the pump work, control systems, auxiliary loads (lights, emergency devices etc.).



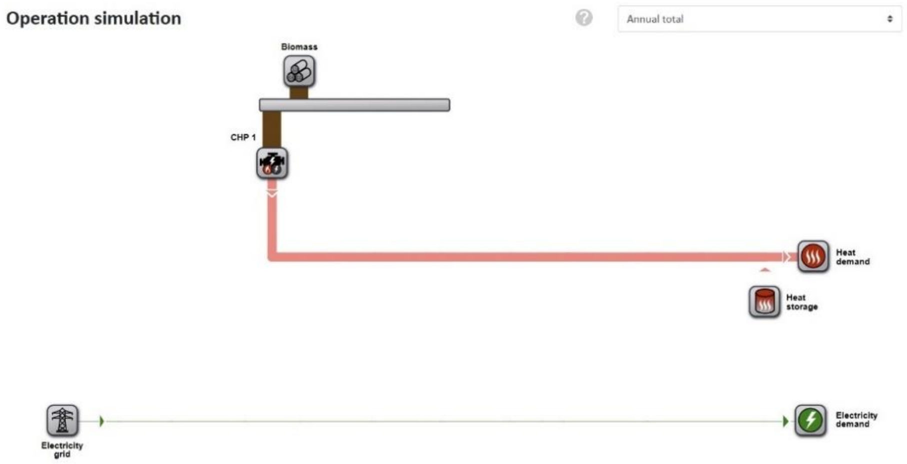
User should enable from electricity generation tab, the direct feed-in feature. A default value of 0,16 €/kWh will show, then the user can click ok.



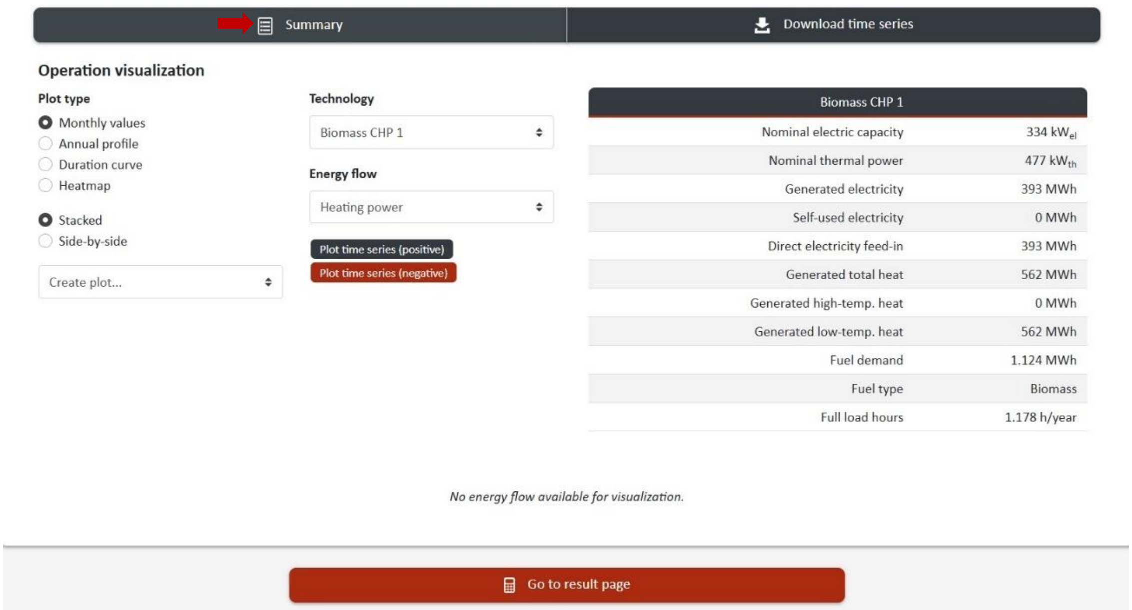
After that, the user shall click again **Size technologies** and now a heat storage capacity should be included.



By toggling **to simulate system operation**, users can see the quantitative size of the energy flows generated and consumed.



There is a section on the bottom page where users can see more detailed results for each technology and also visualize the operation profiles of the system. Users can also click into **Summary** section and there the most important KPIs of the system are generated.



Results

Energy hub

A summary of the technologies (with the form of screenshots) that have been utilized is following and user can see it after selecting **Go to result page→ Energy hub**.

Summary | Energy hub | Economic results

Biomass CHP 1

	Scenario 1
Nominal electric capacity	334 kW_{el}
Generated electricity	0 MWh
Generated heat	562 MWh
Fuel demand	1.124 MWh
Fuel type	Biomass
Full load hours	1.178 h/year

Heat storage

	Scenario 1
Storage capacity	1.162 kWh
Charging energy	18,9 MWh
Discharging energy	0 MWh
Storage volume	50 m^3
Full charging cycles	16

For economic analysis, the user shall pick the **Economic results** tab.

Economic results

Settings

Annual balance

	Cash flow
Investment (annuity)	– 78.103 €/a
Energy costs	– 56.395 €/a
Maintenance costs	– 39.027 €/a
Lump sum costs (annuity)	– 7.880 €/a
Annual revenues	+ 181.773 €/a
Annual net profit	**+ 368 €/a**

Economic KPIs

Net present value	+ 4.584 €
Amortization period	20 years
Internal rate of return	5 %
Levelized costs of heat	0,249 €/kWh
Levelized costs of energy	0,249 €/kWh
Heating cost per floor area	21,18 €/m²
Monthly heating cost per floor area	1,77 €/m²

Cash flow

Year	Investment	Annual costs	Annual revenues	Annual sum	Net present value
0	-1.080.254 €	0 €	0 €	-1.080.254 €	-1.080.254 €
1	0 €	-90.878 €	173.117 €	82.239 €	-998.015 €
2	0 €	-86.551 €	164.874 €	78.323 €	-919.692 €
3	0 €	-82.429 €	157.023 €	74.594 €	-845.098 €
4	0 €	-78.504 €	149.545 €	71.041 €	-774.057 €
5	0 €	-74.766 €	142.424 €	67.659 €	-706.398 €
6	0 €	-71.205 €	135.642 €	64.437 €	-641.961 €
7	0 €	-67.815 €	129.183 €	61.368 €	-580.593 €
8	0 €	-64.585 €	123.031 €	58.446 €	-522.147 €
9	0 €	-61.510 €	117.173 €	55.663 €	-466.484 €
10	0 €	-58.581 €	111.593 €	53.012 €	-413.472 €
11	0 €	-55.791 €	106.279 €	50.488 €	-362.984 €
12	0 €	-53.135 €	101.218 €	48.084 €	-314.900 €
13	0 €	-50.604 €	96.398 €	45.794 €	-269.106 €
14	0 €	-48.195 €	91.808 €	43.613 €	-225.493 €
15	0 €	-45.900 €	87.436 €	41.536 €	-183.957 €
16	-198.912 €	-43.714 €	83.272 €	-159.353 €	-343.310 €
17	0 €	-41.632 €	79.307 €	37.675 €	-305.635 €
18	0 €	-39.650 €	75.531 €	35.881 €	-269.754 €
19	0 €	-37.762 €	71.934 €	34.172 €	-235.582 €
20	207.621 €	-35.964 €	68.508 €	240.166 €	**4.584 €**

The net present value after 20 years is positive (4.584 €).

Cost and revenue details

Investments

	Investment	Annuity
Building energy systems	118.736 €	7.732 €/a
Heat network	404.094 €	26.315 €/a
Energy hub	459.219 €	44.056 €/a
Additional investments	0 €	0 €/a
Sum	**982.049 €**	**78.103 €/a**

Energy costs

	Price		Annual energy		Costs
Electricity	0,15 €/kWh	×	1,3 MWh/a	=	195 €/a
Biomass	0,05 €/kWh	×	1.124 MWh/a	=	56.200 €/a
			Sum		**56.395 €/a**

Maintenance costs

	Costs
Heat network	4.041 €/a
Energy hub	34.986 €/a
Additional operational costs	0 €/a
Sum	**39.027 €/a**

Lump sum costs

	Investments		Percentage		Costs
Planning costs	982.049 €	×	10 %	=	98.205 €
				Sum	**98.205 €**
				Annuity	**7.880 €/a**

Annual revenues

	Compensation		Quantity		Revenues
Electricity feed-in	0,1 €/kWh	×	0 MWh/a	=	0 €/a
CHP 1 (direct feed-in)	0,16 €/kWh	×	393 MWh/a	=	62.880 €/a
Heat demand	0,25 €/kWh	×	476 MWh/a	=	118.893 €/a
			Sum		**181.773 €/a**

Investments

Building energy systems

	Number	Investment	Annuity	Maintenance
Heat network connection	20	118.736 €	7.732 €/a	0 €/a
Sum	**20**	**118.736 €**	**7.732 €/a**	**0 €/a**

Heat network

Spec. costs	Investment	Annuity	Maintenance
882 €/m	404.094 €	26.315 €/a	4.041 €/a

Energy hub

	Investment	Annuity	Maintenance costs
Biomass CHP 1	434.200 €	42.048 €/a	34.736 €/a
Heat storage	25.019 €	2.008 €/a	250 €/a
Sum	**459.219 €**	**44.056 €/a**	**34.986 €/a**

Chapter 4: Comparison of the hybrid systems

4.1. Electricity demands focused systems

System	***Grid-PV-Wind***	***Battery-PV-Wind***	***Hydrogen-PV-Wind***
Supply price	0.15€/kWh	-	-
Feed-in tariff	0.05€/kWh	-	-
Investment Cost	-182.050 €	-715.220 €	-1.837.770 €
Maintenance Cost	-1.655 €/year	-6.502 €/year	-36.697 € /year
Net Present Value (NPV)	**+329.858 €**	**-446.448 €**	**-1.931.571 €**
Annual Revenues	+48.177 €/a	+ 36.927 €/a	+ 36.927 €/a
Internal Rate of Return (IRR)	22.2%	-	-
Amortization period	6 years	-	-

Our goal of this study was to analyze the capabilities of the nPRO software. In this sense, the thesis delved into developing some case studies related to the design (sizing) and economic evaluation of hybrid systems. From the systems that have been evaluated, only the **PV-Wind Turbines-on grid** system was financially viable and provided with a positive NPV. The low investment cost, grid stability, and revenue from feed-in tariffs are some facts making this system the optimal solution.

Battery-PV-Wind-off grid hybrid system could be viable by reducing the Capital Expenditure (usage of smaller/cheaper batteries). Additionally, grid interconnection to earn feed-in tariffs could be helpful and also direct financial contributions (by government usually) for these kinds of activities. Unfortunately, even though it can provide the cleanest energy.

Hydrogen-PV-Wind-off grid hybrid system is not viable under current assumptions. There is a very high upfront cost, no additional revenue beyond electricity offset can be generated, and also there is no monetization of the hydrogen that is produced.

4.2. Heat demands focused systems

System	***Geothermal-Heat storage***	***Biomass-Heat storage***
Supply price	0.1€/kWh	0.1€/kWh
Feed-in tariff	0.1€/kWh	0.1€/kWh
Investment Cost	-1.293.498 €	-1.080.254 €
Maintenance Cost	– 9.867 €/year	– 39.027 €/a
Net Present Value (NPV)	**+72.041 €**	**+4.584 €**
Annual Revenues	+ 118.893 €/a	+ 181.773 €/a
Internal Rate of Return (IRR)	5,6%	5%
Amortization period	20 years	20 years

Both of the systems that have been evaluated provide a positive NPV and therefore are economically feasible. In this particular comparison, the **Geothermal-Heat storage (A)** system will be the optimal solution. Although the investment cost is higher 1.293.498 € to 1.080.254 € for the **Biomass-Heat storage (B)** system, the NPV is also higher 72.041€ to 4.584 €. With Profitability Index (PI), the Capital Efficiency[1] can be measured.

$$PI_A = \frac{NPV}{Investment\ Cost} = \frac{72.041}{1.293.498} = 0{,}055$$

$$PI_B = \frac{NPV}{Investment\ Cost} = \frac{4.584}{1.080.254} = 0{,}0042$$

Even though Biomass generates more revenue annually, it delivers much less value over its lifetime. All in all, a higher PI for the **Geothermal-Heat storage** system, followed by a better IRR makes it a more suitable candidate for optimal choice.

[1] Capital efficiency is about how effectively a project uses the money you invest to generate value. The Profitability Index (PI) is often used to measure it.

Chapter 5: Conclusions

The work presented in this thesis has demonstrated the value of two free access computational software -REopt and nPro- for the design, optimization, and comparative evaluation of hybrid systems. Both tools offer complementary capabilities that can guide engineers in tailoring renewable energy solutions to specific contexts.

REopt provides a site-level, techno-economic optimization framework, with features that include: automated integration of solar, battery storage, and combined heat and power (CHP) assets, configurable energy goals spanning cost savings, clean energy goals, and resilience against grid disruptions Also, straightforward scenario analysis for single sites or portfolios of buildings and last but not least generation of detailed outputs such as optimal system sizing, dispatch strategies, and aggregated economic and emissions indicators.

This software was used to develop two on-grid systems: a **PV-Battery** configuration, illustrating the baseline benefits of solar and storage integration for a commercial load and a more advanced **PV-Battery-CHP** configuration, showcasing how the addition of a small heat engine can enhance both economic and resilience objectives.

nPro, by contrast, is tailored to district-scale planning and excels at: generating hourly demand profiles for electricity, heating, and cooling based on diverse building typologies, modeling microgrids, district heating and cooling networks, and energy hubs that interconnect multiple buildings. Furthermore, it supports a broad range of technologies – including wind, geothermal, biomass, CHP, hydrogen infrastructure, and thermal storage – with a unified, GIS (Geographic Information System)-aware environment. Lastly, this software employs an optimization engine that balances capital and operating costs across multiple energy vectors and spatially distributed loads.

Using nPro, five neighborhood-level systems were constructed and compared: a **grid-tied PV-Wind** system, an **off-grid PV-Wind-Battery microgrid** and an **off-grid PV-Wind-Hydrogen microgrid** (electricity focused systems). Focused on heat demand, a district heating scheme based on **geothermal energy** coupled with **thermal storage** and a **biomass CHP plant** integrated with heat storage is presented.

These case studies highlight how REopt and nPro address different scales: REopt streamlines building-level optimization while nPro captures the complexity of inter-building energy flows and network design. Both tools support the rapid design of hybrid systems that combine renewables, storage, and dispatchable sources. Early-stage design facilitated by REopt and nPro significantly reduces uncertainty in system sizing, technology mix, and financial viability, thus informing more confident investment decisions. In conclusion, REopt and nPro collectively provide a powerful, data-driven toolkit for advancing the deployment of hybrid renewable energy systems—whether for a single facility seeking cost savings and resilience, or for a whole district aiming for integrated, multi-vector decarbonization.

The form of the overall thesis was to provide manual instructions on the user in order to understand the basic features REopt and nPRO computational tools have. It is suggested in a later stage (e.g. in the form of a new thesis) to provide examples that will be based on realistic scenarios and comparable to each other.

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