e-Hydrogen Cost Optimizer
v.0.3.1

User Manual

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Introduction

The global transition toward sustainable energy demands innovative solutions to optimize renewable systems and maximize efficiency. The **e-Hydrogen Cost Optimizer** application addresses the complex challenges of managing integrated energy systems that produce hydrogen via water electrolysis powered by renewable sources, specifically solar and wind power.

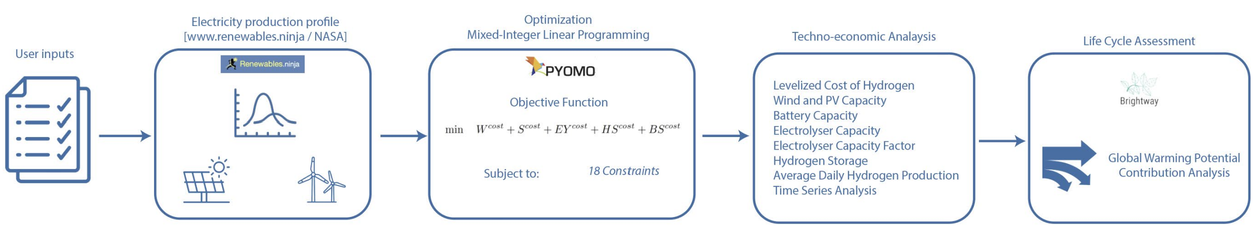
Leveraging cutting-edge mathematical modeling, this tool provides a robust framework for renewable energy planning. It focuses on optimizing the integration of: i) solar photovoltaics (PV), ii) wind turbines, iii) battery storage, iv) hydrogen storage, and v) electrolyzers.

The app streamlines resource allocation, minimizes the total system cost, and ensures reliable electrolytic hydrogen (e-hydrogen) supply through Mixed-Integer Linear Programming (MILP). This advanced optimization framework:

- Models dynamic interactions between energy sources, storage, and electrolyzers.
- Handles both continuous variables (e.g., energy flows) and discrete decisions (e.g., capacity sizing).
- Delivers precise, efficient solutions to complex energy system challenges.

Then an environmental assessment is performed in order to evaluate the greenhouse gas emissions of the project system proposed by the app.

This guide provides comprehensive instructions for operating the **e-Hydrogen Cost Optimizer**. Designed for professionals in energy system planning, design, and management (including researchers, engineers, and decision-makers) it details the application's features, functionality, and optimization processes to help you achieve your project objectives effectively.



Overall framework of the e-Hydrogen Cost Optimizer

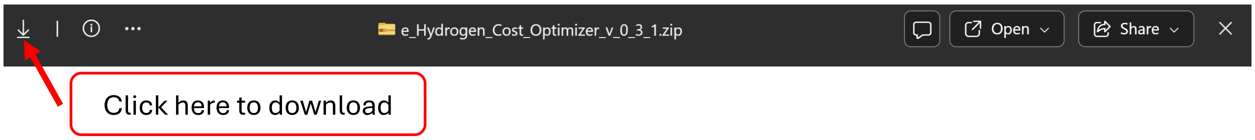
System Requirements

Before installing the **e-Hydrogen Cost Optimizer**, ensure that the system is running Windows OS and has a stable connection to the internet.

Installation

To use the **e-hydrogen Cost Optimizer** on Windows, download the zip-archive found here:

[e_Hydrogen_Cost_Optimizer_v_0_3_1.zip]



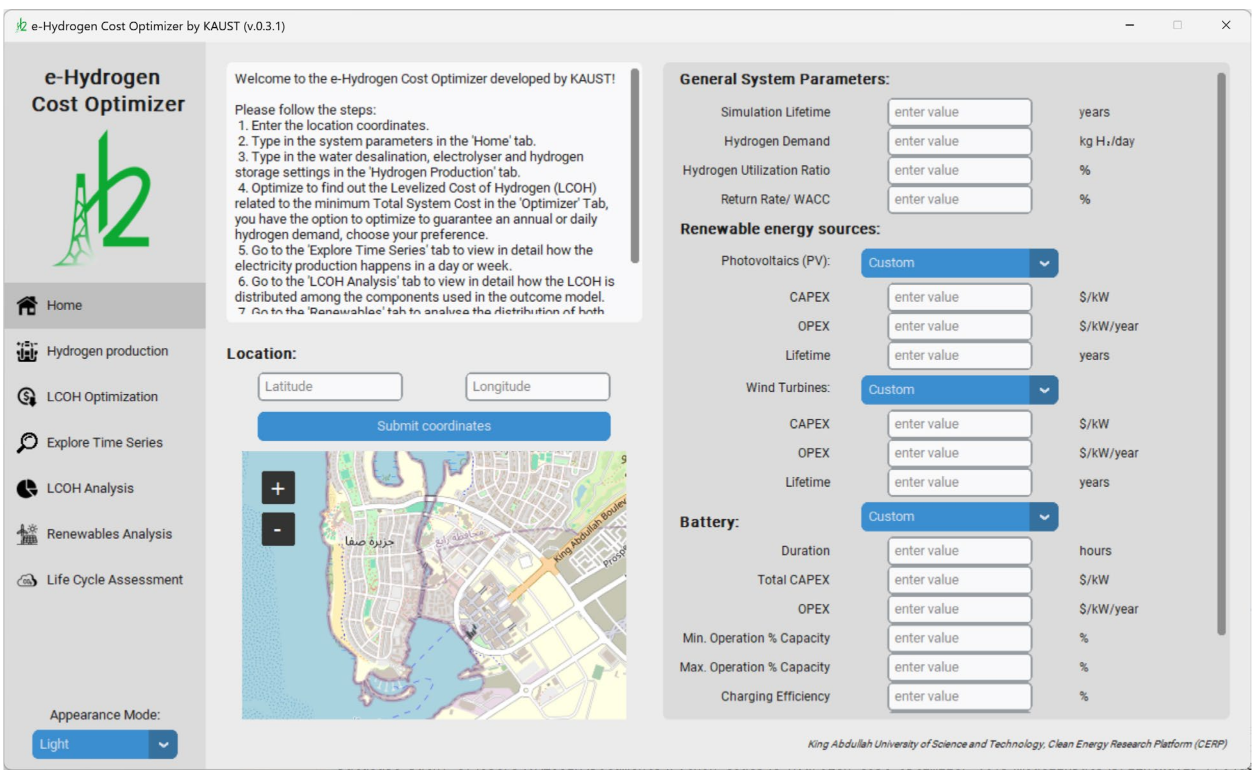
Unzip the archive and start `e_Hydrogen_Cost_Optimizer_v_0_3_1.exe`

If you want to change the executable file to another directory, you must move the entire folder `e_Hydrogen_Cost_Optimizer_v_0_3_1` containing both the executable file and the folder named `_internal`. Also, you can create a shortcut of the executable file and place it wherever you want (e.g., desktop).

To uninstall it, delete the created folder.

Running e-hydrogen Cost Optimizer

When you launch the **e-Hydrogen Cost Optimizer**, it does not contain any data. On the left side, you see a Navigation sidebar. On the right, you see the Home page.



Home page

The Navigation sidebar shows, in order of appearance, the pages that should be filled and explored in order to get an optimized result for the desired input scenario. The user shall follow the order proposed. In the following sections, each page is described. Moreover, an example case study is provided.

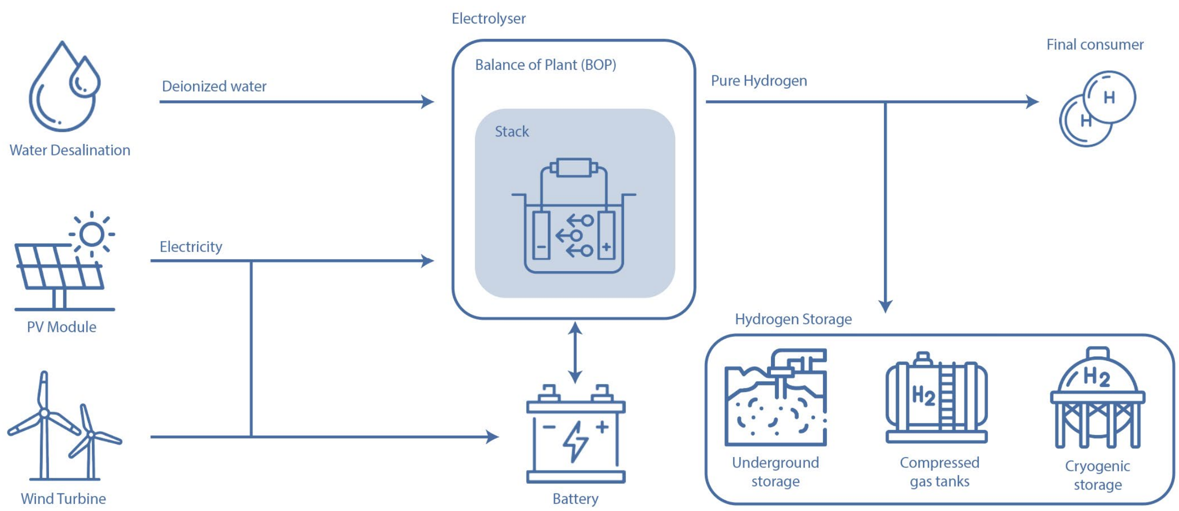
Home page

The Home page provides a quick guide for users explaining in brief how the application works, a Location frame and a System Parameters frame.

In the Location frame, first, the user must set the location of interest in decimal degrees (coordinates).

After entering the values of latitude and longitude, the user must click “Submit coordinates” to confirm if the location of interest is displayed. The user can zoom in and zoom out the map embedded and can explore the surroundings by dragging the map.

In the System Parameters frame, the user shall provide all the detailed information about the system that e-hydrogen production supply chain must follow.



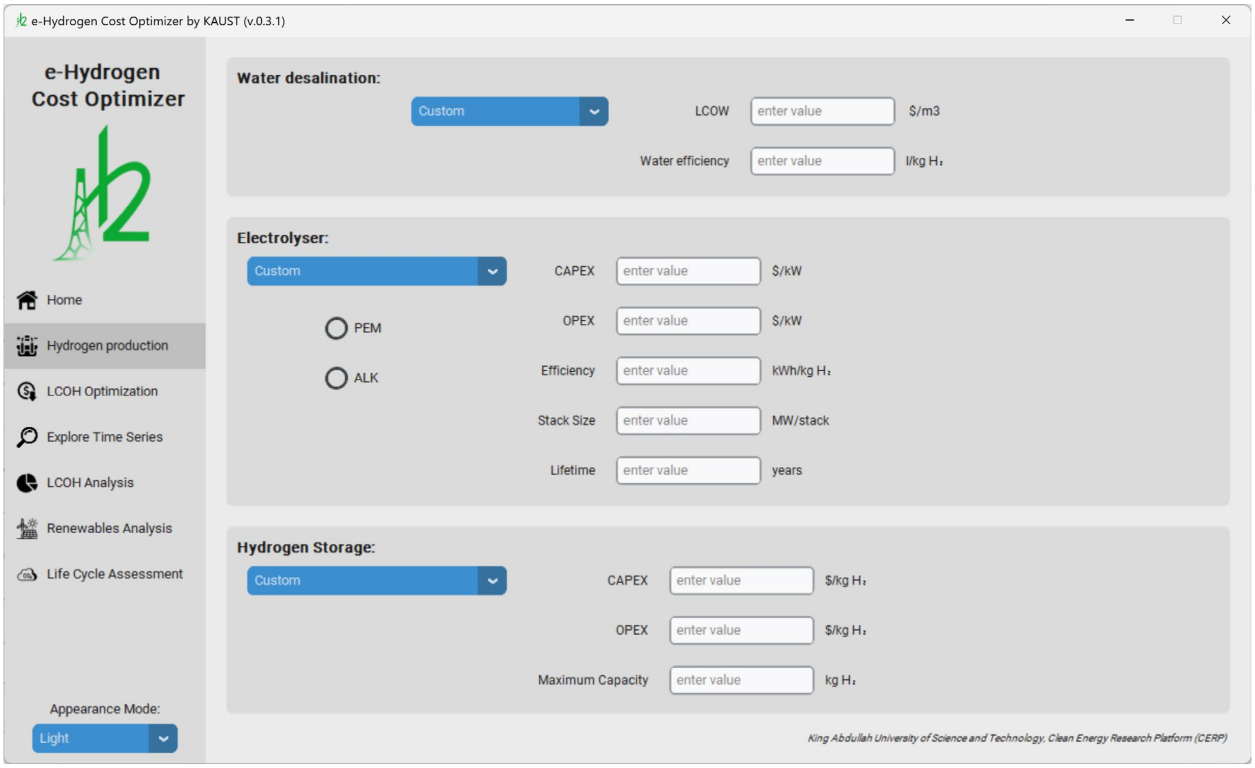
System scope of e-hydrogen production

Dropdown menus are available in order to facilitate the user entering some values regarding some components (i.e., photovoltaics (PV), wind turbines, and storage technologies). The sources from which these values were obtained are displayed, and each can be clicked to navigate directly to the corresponding reference.

If the user wants to enter any specific value related to the interested scenario to model, the user can either type in directly or modify a default value set when selecting an option from a dropdown menu.

Hydrogen Production page

The hydrogen production page lets the user provide the settings related to the cost of water desalination, electrolyzer and hydrogen storage parameters.



Hydrogen Production page

LCOH Optimization page

In the LCOH Optimization page, there are two main frames: the optimizer and results frame.

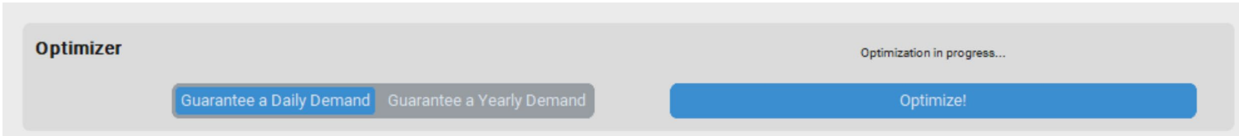
In the optimizer frame, the user can set whether to guarantee a daily or yearly demand, both values are based on the Hydrogen Demand input set in the Home page.

After the user has decided which kind of optimization should be run, the button “Optimize!” should be clicked.

If all the input values from the previous pages were correctly entered (no blank spaces or non-numeric characters) then a status of the optimizer is displayed.

There are three possible statuses:

1. Optimization failed.
2. Optimization in progress...
3. Optimization completed successfully!



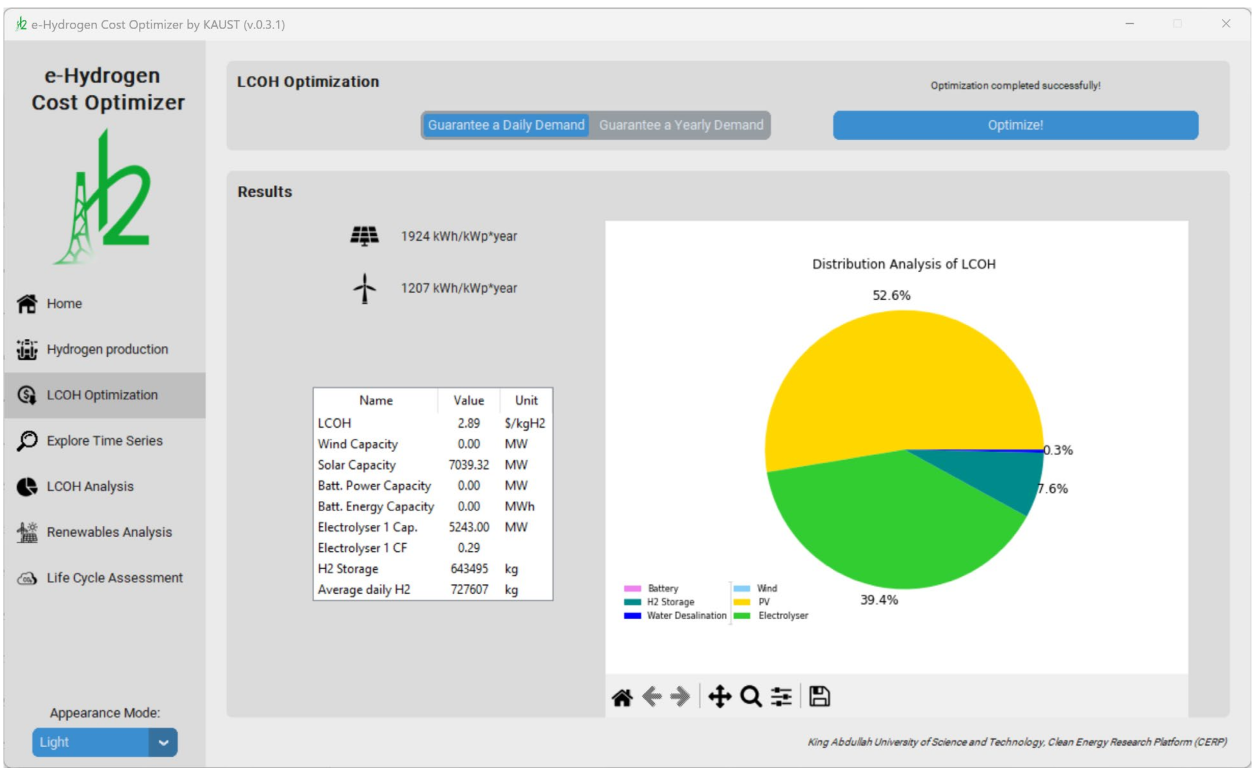
Optimizer frame

In the Results frame, results from the optimization model are presented.

First the electricity produced from solar PV and wind turbines are displayed in a kWh/kWp*year format. This data is extracted from the location provided (renewables.ninja).

Then a table containing the decision variables of the model and some other values are displayed.

Finally, a distribution analysis of the levelized cost of hydrogen (LCOH) is presented in a pie chart form.



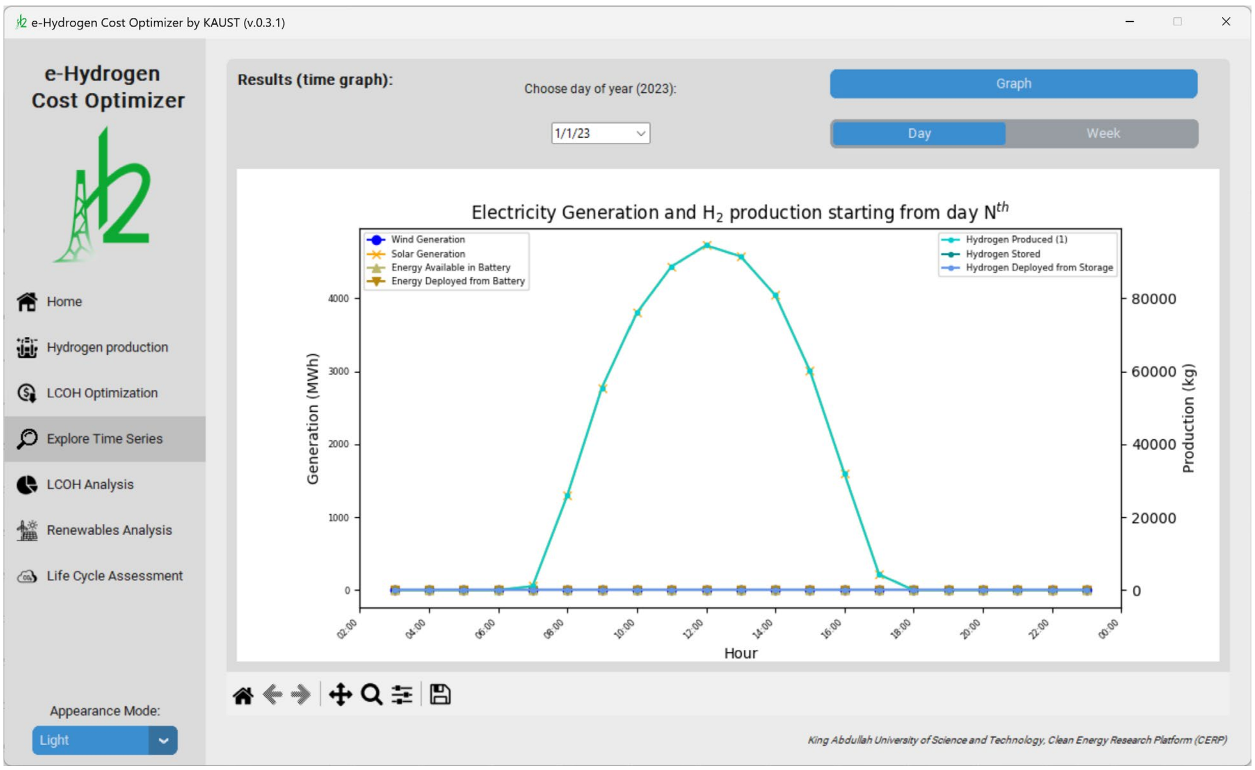
LCOH Optimization page

The MILP that was followed by the optimizer is explained in detail in the MILP formulation section.

Explore Time Series page

The Explore Time Series page lets the user observe the hourly system operation.

There are two main time periods to plot: day or week. It is also required to specify the day the plot should start. Once the user has defined this, when the “Graph” button is pressed a time series graph is displayed. The user can explore further the graph with the tool bar underneath.



Explore Time Series page

LCOH Analysis page

The LCOH Analysis page presents a horizontal bar chart where a further distribution analysis is performed of the levelized cost of hydrogen (LCOH) that the optimization obtained as a result.

The user shall click the "Graph" button in order to get the chart displayed. The user can explore further the graph with the tool bar underneath.

LCOH Analysis page

Renewable Analysis page

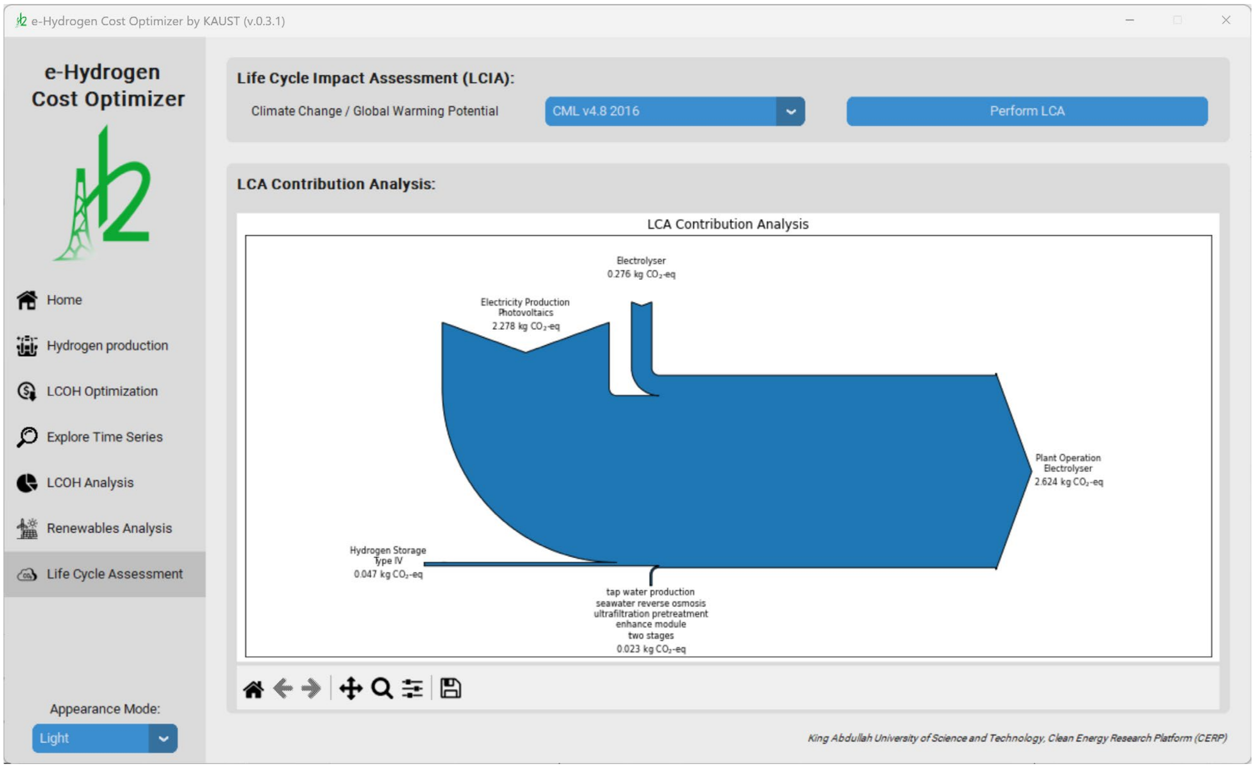
The Renewable Analysis page allows the user explore the distribution of electricity produced in the location selected of both solar PV and wind turbines. A boxplot is presented containing all the values of every month of the year.

The user shall click the “Graph” button in order to get the charts displayed. The user can explore further the graph with the tool bar underneath.

Renewable Analysis page

Life Cycle Assessment page

The Life Cycle Assessment page lets the user assess the environmental performance of the project previously built in the LCOH Optimization page. In the Life Cycle Impact Assessment (LCIA) frame, the user can select the preferred LCIA method to calculate the Climate Change/Global Warming Potential per kilogram of e-hydrogen.



Life Cycle Assessment page

Results (xlsx file)

For users interested in exploring the detailed outputs of the e-Hydrogen Cost Optimizer, the results are conveniently stored in two files. This files contain comprehensive data generated from the optimization process, enabling deeper analysis and insights into the model's performance.

The `results.xlsx` and `lca_results.csv` files can be found in the following directory: `_internal/modelOutputs/`

This structured file of `results.xlsx` includes key information such as the operational profiles of energy sources, electrolyzer performance metrics, hydrogen production rates, storage utilization, and cost breakdowns. The `lca_results.csv` file contains a further breakdown of the environmental performance per subcomponent of the project built. Users can open both files with any spreadsheet application to review and analyze the results in detail.

By providing easy access to these outputs, the tool ensures transparency and flexibility for users who wish to further investigate or visualize the optimization results.

Case Study (example)

This section demonstrates how to use the **e-Hydrogen Cost Optimizer** with real-world data, specifically tailored to reflect planned projects in Saudi Arabia. To run the application for this case, input the provided values corresponding to renewable energy capacities, electrolyzer types, and hydrogen demand projections from the selected project. These values represent a close-to-realistic scenario based on the Kingdom's ambitious renewable energy targets and hydrogen production goals. By running the application with this dataset, users can explore insights such as cost structures, optimal system configurations, and performance metrics under local conditions. This example serves as a guide for users to adapt the tool to other regional projects or scenarios.

Parameter	Value	Units / Comments
Location	Duba [27.35 , 35.70]	Decimal coordinates [Longitude, Latitude]
Simulation Lifetime	30	years
Hydrogen Demand	600000	kg H_2 / day
Hydrogen Utilization Ratio	99	%
Return Rate / WACC	5	%
Photovoltaics (PV)	"Saudi Arabia 2023"	
Wind Turbines	"Onshore-Other Asia 2023"	
Storage	"LFP 2019 (60MW)-4h"	
Water Desalination	"Saudi Arabia 2023"	
Electrolyzer Parameters	"PEM Low Cost High Efficiency-2020"	
Hydrogen Storage	"Aboveground tanks-35bar"	

When running the **e-Hydrogen Cost Optimizer** with these input values, the optimizer shows a value of 2.89 $ / kg H_2 for a scenario when guaranteeing a daily demand and 2.67 $/kg H_2 for a scenario when guaranteeing a yearly demand.

If the user wants to understand more about the different results given for the same scenario, the results table can give some hints:

Name	Value	Unit
LCOH	2.89	$/kgH2
Wind Capacity	0.00	MW
Solar Capacity	7039.32	MW
Batt. Power Capacity	0.00	MW
Batt. Energy Capacity	0.00	MWh
Electrolyser 1 Cap.	5243.00	MW
Electrolyser 1 CF	0.29	
H2 Storage	643495	kg
Average daily H2	727607	kg

Case study results for a daily demand.

Name	Value	Unit
LCOH	2.67	$/kgH2
Wind Capacity	0.00	MW
Solar Capacity	5804.77	MW
Batt. Power Capacity	0.00	MW
Batt. Energy Capacity	0.00	MWh
Electrolyser 1 Cap.	4324.00	MW
Electrolyser 1 CF	0.29	
H2 Storage	0	kg
Average daily H2	600000	kg

Case study results for a yearly demand.

When the **e-Hydrogen Cost Optimizer** optimizes to guarantee a daily demand, it takes into account the worst day in terms of electricity production by solar PV and wind turbines. Therefore, the whole system usually is oversized to compensate for this minimal electricity input (i.e., hydrogen storage). On the other hand, when it optimizes to guarantee a yearly demand, the system can produce the hydrogen whenever it has available 'good' electricity production from solar PV and wind turbines. This variation can be seen in the Renewables Analysis tab.

MILP formulation

This section provides a detailed description of the mathematical model used by the e-Hydrogen Cost Optimizer to achieve the best total system cost. This model employs Mixed-Integer Linear Programming (MILP) to balance the complex interactions between renewable energy generation, storage systems, and hydrogen production. By defining variables such as system capacities, energy flows, and hydrogen production rates, the MILP framework identifies cost-optimal solutions while adhering to operational and technical constraints. This section serves as a comprehensive reference for users who wish to understand the underlying optimization process and its role in producing accurate and actionable insights.

This model is adapted and modified from [1].

The levelized cost of hydrogen (LCOH) is computed as:

$$LCOH = \frac{Total\ Lifetime\ Cost}{Total\ Lifetime\ H_2\ Production} = \frac{CAPEX + \sum_n^N \frac{OPEX_n}{(1+r)^n} + \sum_n^N \frac{Water\ cost}{(1+r)^n}}{\sum_n^N \frac{H_{prod}}{(1+r)^n}}$$

Due to the nature of the LCOH formula (i.e., a fractional function) it cannot be optimized by linear programming. Hence, the numerator becomes the objective function to minimize in the optimization model.

Objective function:

$$\min \ Total\ Lifetime\ Cost$$

$$\min \ W^{cost} + S^{cost} + EY^{cost} + BS^{cost} + HS^{cost} \tag{1}$$

The water cost is not included in the objective function because it does not have any decision variables to optimize, while the rest of the Total Lifetime Cost terms do. Please note that the decision variables are marked in blue along this section. Input parameters provide by the user within the application are marked in green. The data provided by the database from *renewables.ninja* are marked in purple. The one that are not marked in color is because they are defined within the constraints or are decisions variables from the previous timestep.

Where

$$W^{cost} = W^{Cap}\left(\sum_{j=0}^{\frac{n}{n^{RE}}} \frac{c^W}{(1+r)^{j\cdot n^{RE}}} + \sum_{t=0}^{n} \frac{o^W}{(1+r)^t}\right) \tag{2}$$

$$S^{cost} = S^{Cap}\left(\sum_{j=0}^{\frac{n}{n^{RE}}} \frac{c^S}{(1+r)^{j\cdot n^{RE}}} + \sum_{t=0}^{n} \frac{o^S}{(1+r)^t}\right) \tag{3}$$

$$EY^{cost} = s_i^{EY} EY_i^{Cap}\left(\sum_{j=0}^{\frac{n}{n^{EY}}} \frac{c^{EY}}{(1+r)^{j\cdot n^{EY}}} + \sum_{t=0}^{n} \frac{o^{EY}}{(1+r)^t}\right) \tag{4}$$

$$BS^{cost} = BS^{PCap}\left(\sum_{j=0}^{\frac{n}{n^{BS}}} \frac{c^{BS}}{(1+r)^{j\cdot n^{BS}}} + \sum_{t=0}^{n} \frac{o^{BS}}{(1+r)^t}\right) \tag{5}$$

$$HS^{cost} = HS^{Cap}\left(c^{HS} + \sum_{t=0}^{n} \frac{o^{HS}}{(1+r)^t}\right) \tag{6}$$

Constraints

General constraints for the whole system:

$$E_t^{Demand} = E_t^{Gen}, \quad \forall t \in T \tag{7}$$

$$E_t^{Demand} = e_i^{EY} EY_t^{Gen} + \frac{BS_t^{Store}}{\theta^{BStore}}, \qquad \forall t \in T \tag{8}$$

$$E_t^{Gen} = \theta_t^{Wind} W^{Cap} + \theta_t^{Solar} S^{Cap} + BS_t^{Deploy}, \qquad \forall t \in T \tag{9}$$

$$\sum_{t=0}^{T} \left(EY_t^{Gen} - HS_t^{Store} + HS_t^{Deploy}\right) = d, \qquad \forall t \in T \tag{10}$$

Constraints for electrolyzer operation:

$$EY_{i,t}^{Gen} \leq \frac{s_i^{EY}}{e_i^{EY}} EY^{Cap}, \qquad \forall t \in T \tag{11}$$

Constraints for battery operation:

$$BS_t^{Avail} = BS_{t-1}^{Avail} + BS_{t-1}^{Store} - \frac{BS_{t-1}^{Deploy}}{\theta^{BSDeploy}}, \qquad \forall t \in T \tag{12}$$

$$BS^{ECap} \leq BS^{Duration} * BS^{PCap}, \qquad \forall t \in T \tag{13}$$

$$BS_t^{Avail} \leq u^{BS}\ BS^{ECap}, \qquad \forall t \in T \tag{13}$$

$$BS_t^{Avail} \geq m^{BS}\ BS^{ECap}, \qquad \forall t \in T \tag{14}$$

$$BS_t^{Store} \leq BS^{ECap} - BS_t^{Avail}, \qquad \forall t \in T \tag{15}$$

$$BS_t^{Store} + \frac{BS_{t-1}^{Deploy}}{\theta^{BSDeploy}} \leq BS^{PCap}, \qquad \forall t \in T \tag{16}$$

$$BS_t^{Store} \leq \theta_t^{Wind} W^{Cap} + \theta_t^{Solar} S^{Cap}, \qquad \forall t \in T \tag{17}$$

$$BS^{PCap} \leq maxBS^{PCap}, \qquad \forall t \in T \tag{19}$$

$$\frac{BS_t^{Deploy}}{\theta^{BSDeploy}} \leq BS_t^{Avail}, \qquad \forall t \in T \tag{20}$$

Constraints for hydrogen storage operation:

$$HS_t^{Avail} = HS_{t-1}^{Avail} + HS_{t-1}^{Store} - \frac{HS_{t-1}^{Deploy}}{\theta^{HSDeploy}}, \qquad \forall t \in T \tag{21}$$

$$HS_t^{Avail} \leq HS^{Cap}, \qquad \forall t \in T \tag{22}$$

$$HS_t^{Store} \leq HS^{Cap} - HS_t^{Avail}, \qquad \forall t \in T \tag{23}$$

$$\frac{HS_t^{Deploy}}{\theta^{HSDeploy}} \leq HS_t^{Avail}, \qquad \forall t \in T \tag{24}$$

$$HS_t^{Store} \leq EY_t^{Gen}, \qquad \forall t \in T \tag{25}$$

$$HS^{Cap} \leq maxHS^{Cap}, \qquad \forall t \in T \tag{26}$$

Sets

T set of timesteps t that the model will optimize for

Decision variables

W^{Cap} total nameplate wind turbine capacity to build (MW)

S^{Cap} total nameplate solar PV capacity to build (MW)

EY^{Cap} total number of model stacks to build (integer)

BS^{PCap} total battery power capacity to build (MW)

HS^{Cap} total hydrogen storage capacity to build (kg of H2)

EY_t^{Gen} amount of H2 to produce from stacks of EY at timestep t

BS_t^{Avail} amount of energy available in battery at end of timestep t

BS_t^{Store} amount of energy to store at timestep t

BS_t^{Deploy} amount of energy to release into electrolyzer grid at timestep t

HS_t^{Avail} amount of hydrogen available in hydrogen storage at end of timestep t

HS_t^{Store} amount of hydrogen to store at timestep t

HS_t^{Deploy} amount of hydrogen to release into demand at timestep t

Parameters

d demand for hydrogen (depending on the case is set by day or by year)

θ_t^{Wind} capacity factor for wind energy source at timestep t

θ_t^{Solar} capacity factor for solar PV source at timestep t

θ^{BStore} efficiency of storing energy in battery

$\theta^{BSDeploy}$ efficiency of deploying energy from battery

$\theta^{HSDeploy}$ efficiency of deploying hydrogen from hydrogen storage

c^W CAPEX cost for wind technology generation

c^S CAPEX cost for solar technology generation

c^{EY} CAPEX cost for electrolysis

c^{BS} CAPEX cost for battery storage

c^{HS} OPEX cost for hydrogen storage

o^W OPEX cost for wind technology generation

o^S OPEX cost for solar technology generation

o^{EY} OPEX cost for electrolysis

o^{BS} OPEX cost for battery storage

o^{HS} OPEX cost for hydrogen storage

e^{EY} energy usage per unit (MWh) output of H2 in electrolyzer model i per kg of H2 (MWh/kgH2)

s^{EY} stack size capacity for electrolyzer (MW)

n plant lifetime (years)

n^{RE} renewable technology lifetime (years)

n^{EY} electrolyzer technology lifetime (years)

n^{BS} battery technology lifetime (years)

r discount rate on an annual basis

u^{BS} upper bound of battery energy level (0-1)

m^{BS} lower bound of battery energy level (0-1)

$BS^{Duration}$ maximum discharge time for battery (hours)

Bibliography

[1] J. Florez, M. AlAbbad, H. Vazquez-Sanchez, M. G. Morales, and S. M. Sarathy, "Optimizing islanded green ammonia and hydrogen production and export from Saudi Arabia," *Int J Hydrogen Energy*, vol. 56, pp. 959–972, Feb. 2024, doi: 10.1016/j.ijhydene.2023.12.075.