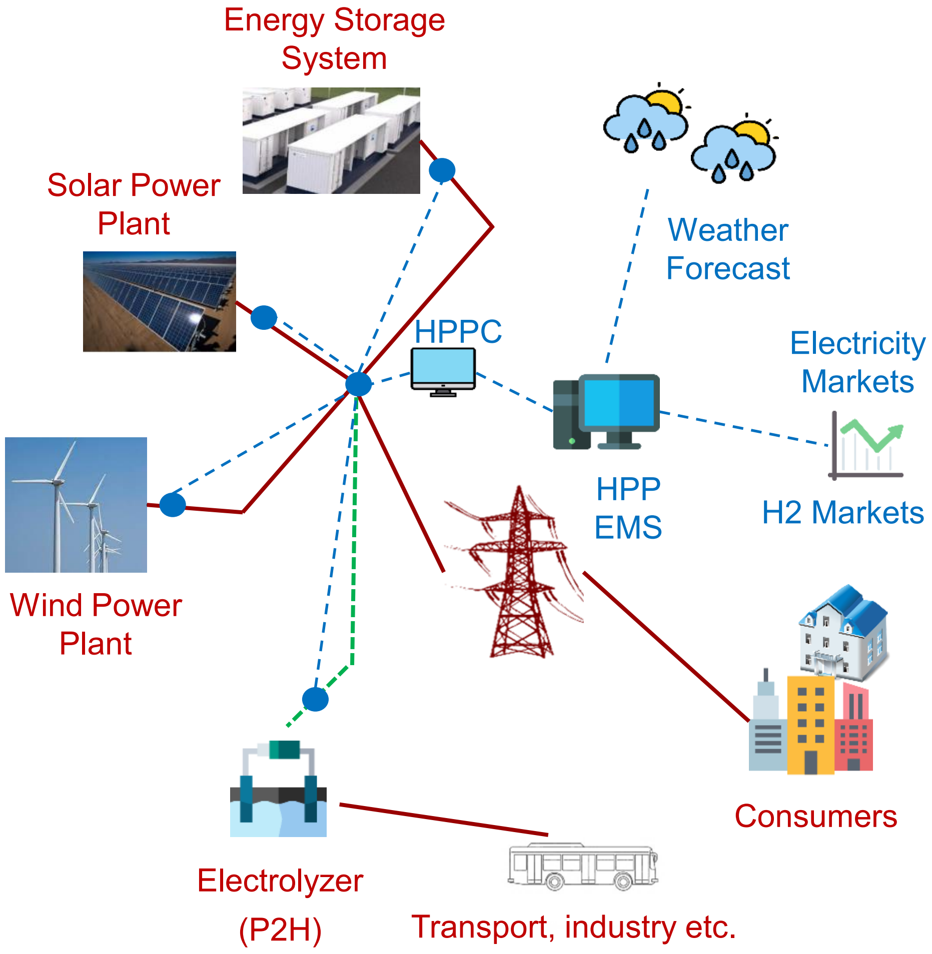
Hybrid Power Plant & HyDesign

Megha Gupta, DTU Wind (gupta@dtu.dk)

Hybrid Power Plant – Utility scale

Multi-technology, co-located and grid connected

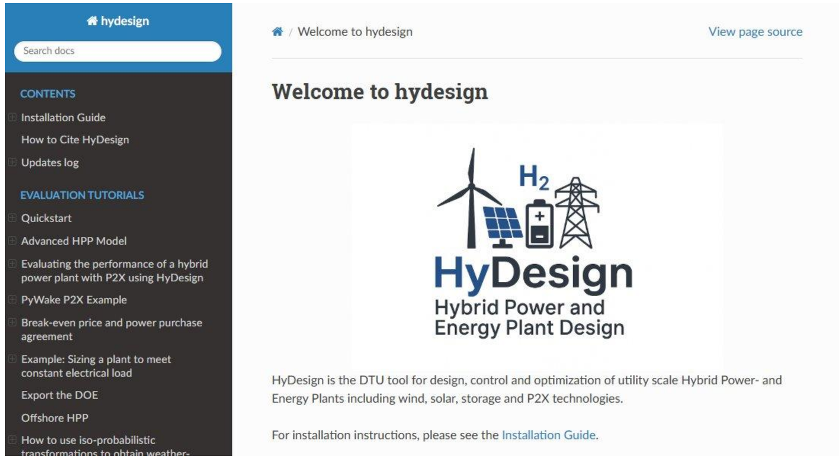


General Features	More than one generation sources involved
	All assets are owned by same company so higher controllability
	More RES integration with same grid connection

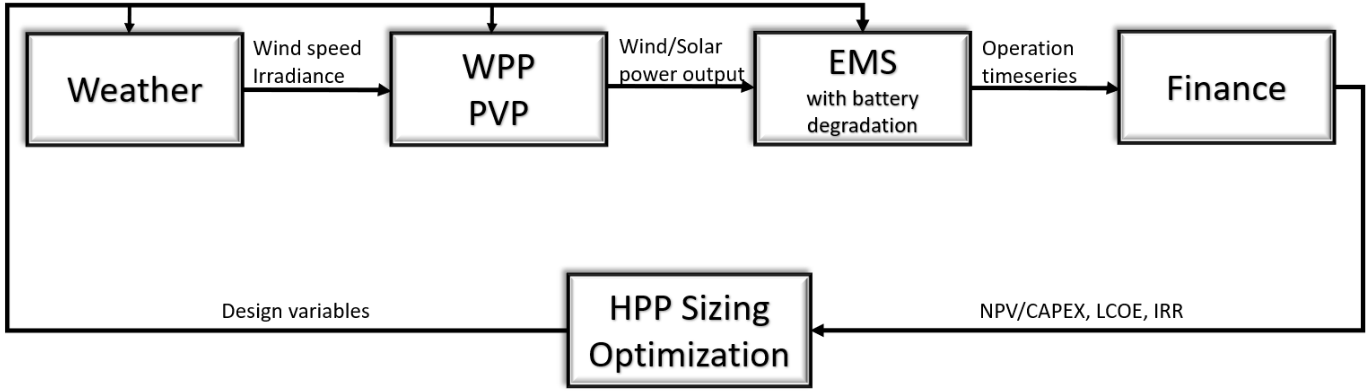
Motivation	To reduce cost/ maximize revenue from different energy markets
	One common energy management system
	Reduced curtailment means more value of RE
	Optimal utilization of land
	More flexibility allows for decommissioning of fossil fuel-based generators

HyDesign: Python-based open-source tool

- HyDesign is a software platform for design and operation of utility-scale hybrid power plants
- Can be used for:
    1. sizing optimization of HPP
    2. evaluation of a specific plant design
- Objective function is user specified (min LCOE, max NPV/CAPEX…)
- Key components: wind, solar, battery, hydrogen, grid-connection
- Multi-disciplinary optimization problem implemented in OpenMDAO



https://topfarm.pages.windenergy.dtu.dk/hydesign/



Optimal sizing methodology of HPP

Inputs
- Electricity prices
- H2 price and demand
- Site location for weather data
- Technologies cost

Optimization

Output (Design Variables)				Output
Wind	**Solar**	**Battery**	**P2H**	**Finance model**
Rotor diameter, hub height	AC power	Power rating	Electrolyzer capacity	NPV/CAPEX
Area of land	Surface tilt angle	Energy storage Capacity	H2 storage capacity	IRR
Rated power	Surface azimuth angle			LCOE, LCOH
Number of wind turbines				AEP, AHP
Wind power density				Number of batteries

Instructions to install HyDesign

You can follow these steps. Be mindful of a space between e and . in step 5. It throws crazy errors otherwise.

The instructions for HyDesign installation are as follows:
https://topfarm.pages.windenergy.dtu.dk/hydesign/installation.html (reference link)

Pre-requisite: Anaconda installed (reference link: https://docs.anaconda.com/free/anaconda/install/)
Installation on Laptop through Anaconda terminal:
----
1. git clone https://gitlab.windenergy.dtu.dk/TOPFARM/hydesign.git
2. cd hydesign
3. conda env create --file environment.yml
4. conda activate hydesign
5. pip install -e .

If Step 1 doesn’t work, you may need to do this first-> conda install git

Let’s see how HyDesign looks, and how it works……..

- Gitlab repository: https://gitlab.windenergy.dtu.dk/TOPFARM/hydesign

- At the bottom -> link to documentation -> https://topfarm.pages.windenergy.dtu.dk/hydesign

Start – working with a notebook
To evaluate a HPP design

Advanced HPP Model

Evaluating the performance of a hybrid power plant using HyDesign

HyDesign is an open-source tool for design and optimization of utility scale wind-solar-storage based hybrid power plants.

In this notebook we will evaluate a hybrid power plant design in a specific location.

A hybrid power plant design consists on selecting the following parameters:

Wind Turbine design:

1. Clearance [m] (`clearance`): Height from the ground to rotor tip at lowest postion. This parameter controls the wind turbine hub height
2. Specific power of the wind turbine [MW/m2] (`sp`): Defined as `sp = p_rated / ( pi * R^2 )`, it controls the turbine rotor size for a g power produce more power at lower wind speeds, but are more expensive.
3. Rated power of the wind turbine [MW] (`p_rated`)

Wind Plant design:

4. Number of wind turbines in the wind plant [-] (`Nwt`)
5. Wind power installation density [MW/km2] (`wind_MW_per_km2`): This parameter controls how closely spaced are the turbines, which in t

- Open the example notebook '**Advanced_hpp_model.ipynb**' (in the folder …\hydesign\docs\notebooks) – evaluating the performance of HPP.
- Run the cells to evaluate a given plant design and calculate the econometrics.

Advanced_hpp_model.ipynb

```
examples_sites = pd.read_csv(f'{examples_filepath}examples_sites.csv', index_col=0, sep=';')
examples_sites
```

	case	name	longitude	latitude	altitude	input_ts_fn	sim_pars_fn
0	India	Indian_site_good_wind	77.500226	8.334294	679.803454	India/GWA2/input_ts_Indian_site_good_wind.csv	India/hpp_pars.yml
1	India	Indian_site_good_solar	68.542204	23.542099	29.883557	India/GWA2/input_ts_Indian_site_good_solar.csv	India/hpp_pars.yml
2	India	Indian_site_bad_solar_bad_wind	77.916878	17.292316	627.424643	India/GWA2/input_ts_Indian_site_bad_solar_bad_...	India/hpp_pars.yml
3	Europe	France_good_solar	4.229736	44.422011	204.000000	Europe/GWA2/input_ts_France_good_solar.csv	Europe/hpp_pars.yml
4	Europe	France_good_wind	-0.864258	48.744116	302.000000	Europe/GWA2/input_ts_France_good_wind.csv	Europe/hpp_pars.yml
5	Europe	France_bad_solar_n_wind	2.167969	47.428087	140.000000	Europe/GWA2/input_ts_France_bad_solar_n_wind.csv	Europe/hpp_pars.yml
6	Europe	Germany_bad_solar_n_wind	10.766602	49.310798	442.000000	Europe/GWA2/input_ts_Germany_bad_solar_n_wind.csv	Europe/hpp_pars.yml
7	Europe	Germany_good_wind	7.873535	53.287111	5.000000	Europe/GWA2/input_ts_Germany_good_wind.csv	Europe/hpp_pars.yml
8	Europe	Denmark_good_solar	11.813965	55.397760	42.000000	Europe/GWA2/input_ts_Denmark_good_solar.csv	Europe/hpp_pars.yml
9	Europe	Denmark_good_wind	8.594398	56.227322	85.000000	Europe/GWA2/input_ts_Denmark_good_wind.csv	Europe/hpp_pars_BM.yml

```
name = 'Denmark_good_wind'
ex_site = examples_sites.loc[examples_sites.name == name]
```

Select example site of interest and change the name as per the list.

Advanced_hpp_model.ipynb

In this cell, enter the design of HPP of your interest

- Select the size of HPP:
  - wind plant size in MW in terms of number of WT and rated power of WT: Nwt * P_rated;
  - solar_MW;
  - battery size
    - b_P: battery power in MW
    - b_E_h: battery energy hours

```
start = time.time()

clearance = 10
sp = 350
p_rated = 5
Nwt = 70
wind_MW_per_km2 = 7
solar_MW = 80
surface_tilt = 50
surface_azimuth = 180
solar_DCAC = 1.5
b_P = 50
b_E_h  = 3
cost_of_batt_degr = 10
```

Advanced_hpp_model.ipynb

The output of the HPP model evaluation:

Objective function: maximize NPV/CAPEX

NPV: Net present Value

IRR: Internal rate of return

LCOE: Levelized cost of electricity

CAPEX: Total capital expenditure

OPEX: Total operational expenditure

AEP: Annual energy production

GUF: Grid utilization factor

Grid [MW]: grid capacity

Total curtailment [GWh]: for 25 years

Total curtailment with deg [GWh]: for 25 years considering the impact of degradation

```
NPV_over_CAPEX: 0.207
NPV [MEuro]: 78.996
IRR: 0.078
LCOE [Euro/MWh]: 47.474
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Batt OPEX [MEuro]: 0.000
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Shared OPEX [MEuro]: 0.000
penalty lifetime [MEuro]: 0.000
AEP [GWh]: 733.508
GUF: 0.279
grid [MW]: 300.000
wind [MW]: 350.000
solar [MW]: 100.000
Battery Energy [MWh]: 150.000
Battery Power [MW]: 50.000
Total curtailment [GWh]: 337.661
Total curtailment with deg [GWh]: 152.556
Awpp [km2]: 50.000
Apvp [km2]: 1.226
Plant area [km2]: 50.000
Rotor diam [m]: 134.867
Hub height [m]: 77.434
Number of batteries used in lifetime: 2.000
Break-even PPA price [Euro/MWh]: 31.519
Capacity factor wind [-]: 0.202
```
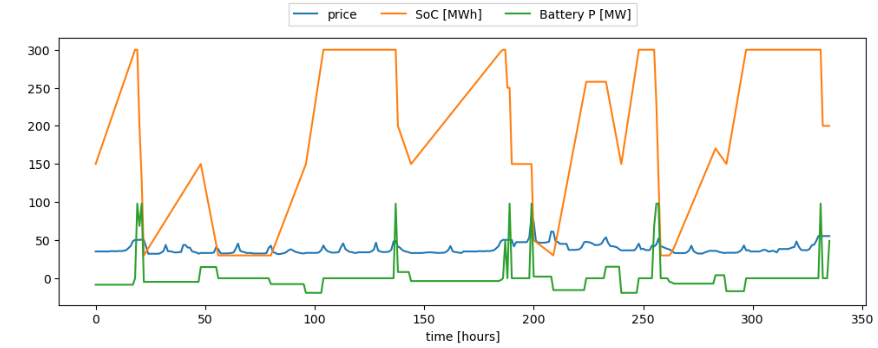
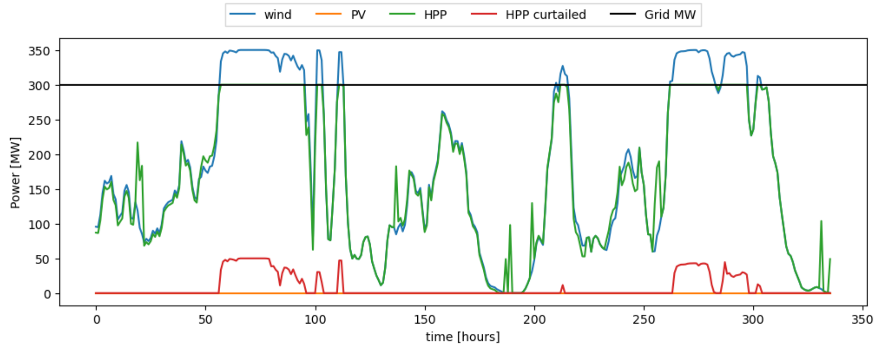

Advanced_hpp_model.ipynb – plotting results – EMS operation

```python
n_days_plot = 14
plt.figure(figsize=[12,4])
plt.plot(price_t[:24*n_days_plot], label='price')
plt.plot(b_E_SOC_t[:24*n_days_plot], label='SoC [MWh]')
plt.plot(b_t[:24*n_days_plot], label='Battery P [MW]')
plt.xlabel('time [hours]')
plt.legend(loc='upper center', bbox_to_anchor=(0.5, 1.15),
           ncol=3, fancybox=0, shadow=0)

plt.figure(figsize=[12,4])
plt.plot(wind_t[:24*n_days_plot], label='wind')
plt.plot(solar_t[:24*n_days_plot], label='PV')
plt.plot(hpp_t[:24*n_days_plot], label='HPP')
plt.plot(hpp_curt_t[:24*n_days_plot], label='HPP curtailed')
plt.axhline(grid_MW, label='Grid MW', color='k')
plt.xlabel('time [hours]')
plt.ylabel('Power [MW]')
plt.legend(loc='upper center', bbox_to_anchor=(0.5, 1.15),
           ncol=5, fancybox=0, shadow=0)
```





Save EMS results

```python
results_1year = {'Electricity Price':price_t[:8760], 'Wind Power': wind_t[:8760],'Solar Power': solar_t[:8760],'HPP Power': hpp_t[:8760],'Curtailed Power': hpp_curt_t[:8760] ,'Battery SOC': b_E_SOC_t[:8760],'Battery Power': b_t[:8760]}
df = pd.DataFrame(results_1year)
df.to_csv('EMS_out_DK_good_solar.csv')
```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More input files

Additionally, there are 2 input files used:

- For technologies cost - **‘hpp_pars.yml’** in the folder …\hydesign\hydesign\examples\Europe
- For weather data – select the file corresponding to the selected location – **‘input_ts_xxxxx’** in the folder …\hydesign\hydesign\examples\Europe\GWA2

The data represents wind speed (WS) and wind direction (WD) at different hub heights, direct normal irradiance (DNI), diffused horizontal irradiance (DHI), global horizontal irradiance (GHI) and spot market electricity prices – with an hourly resolution for one year.

Note: the weather data and electricity prices are user inputs and can be updated in this file.

	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P
1		WS_1	WS_50	WS_100	WS_150	WS_200	WD_1	WD_50	WD_100	WD_150	WD_200	temp_air_1	ghi	dni	dhi	Price
2	1/1/2012 0:00	2.803428	6.289076	8.109687	8.777118	10.33508	163.2749	166.8879	170.5735	179.0672	181.6893	276.7673	0.035121	0	0.035121	35.171
3	1/1/2012 1:00	2.791624	6.275261	8.093319	8.910806	10.40799	166.335	170.3653	174.4807	181.7799	184.4725	277.3744	0.01756	0	0.01756	35.171
4	1/1/2012 2:00	3.036807	6.656427	8.54771	9.467695	10.865	168.6747	172.2646	175.9297	181.4956	184.1347	278.0159	0	0	0	35.171
5	1/1/2012 3:00	3.405581	7.233561	9.23767	10.43509	11.79302	176.7051	179.3924	182.1396	185.4649	187.9601	278.6559	0	0	0	35.171
6	1/1/2012 4:00	3.649363	7.54244	9.584774	10.86428	12.08176	188.3958	190.483	192.6083	195.2514	197.9662	279.2908	0	0	0	35.171

Input file – hpp_pars.yml

examples > Europe > ! hpp_pars.yml

```yaml
# ---------------------------------------------------------------------------------
# HPP Global
# ---------------------------------------------------------------------------------
G_MW: 300 # Grid capacity
year: '2012' # Single representative year
N_life: 25

# ---------------------------------------------------------------------------------
# Wind
# ---------------------------------------------------------------------------------
wind_turbine_cost: 640_000  # [Euro/MW] for reference turbine
wind_civil_works_cost: 260_000  # [Euro/MW]
wind_fixed_onm_cost: 12_600  # Wind fixed O&M cost per year [Euro/MW /year]
wind_variable_onm_cost: 1.35 #[EUR/MWh_e] Danish Energy Agency

d_ref: 145
hh_ref: 100
p_rated_ref: 5.0 #[MW]

# Degradation
wpp_efficiency: 1
wind_deg_yr: [0, 25]
wind_deg: [0, 0.25] #25yr * 1%/yr
share_WT_deg_types: 0.5

# ---------------------------------------------------------------------------------
# PV
# ---------------------------------------------------------------------------------
solar_PV_cost: 110_000   # [Euro/MW DC]
solar_hardware_installation_cost: 100_000  # [Euro/MW DC]
solar_inverter_cost: 20_000 #[Euro/MW]
solar_fixed_onm_cost: 4_500  # Solar O&M cost per year [Euro/MW] DC
land_use_per_solar_MW: 0.01226 # Danish energy agency
```

Grid connection capacity

Wind turbine cost

Solar PV cost

Evaluate a HPP design with Power-to-Hydrogen

- Open the example notebook '**HPP_evaluation_P2X.ipynb** ' (in the folder …\hydesign\docs\notebooks) – evaluating the performance of HPP with hydrogen.

In this cell, enter the design of HPP with P2H.

- Select the size of HPP:
  - wind plant size in MW: Nwt * P_rated;
  - Solar plant size in MW: solar_MW;
  - battery size
    - b_P: battery power in MW
    - b_E_h: battery energy hours)
  - Electrolyzer size in MW: P_ptg_MW

Evaluating the HPP model

```
[ ]  start = time.time()

     clearance = 10
     sp = 353
     p_rated = 2
     Nwt = 145
     wind_MW_per_km2 = 5.02
     solar_MW = 50
     surface_tilt = 27.35
     surface_azimuth = 194.38
     DC_AC_ratio = 1.22
     b_P = 9
     b_E_h  = 8
     cost_of_batt_degr = 3.34
     ptg_MW = 100
```

Efficiency curve of electrolyzers

The efficiency curve parameter of different electrolyzer technologies used are:

- For technologies cost - **'Electrolyzer_efficiency_curves.csv'** in the folder …\hydesign\hydesign\examples\Europe …\hydesign\hydesign\examples\Europe

Note: the effeiciency and hydrogen production curve parameters are user inputs and can be updated in this file.

HPP_evaluation_P2X.ipynb – for HPP with hydrogen

The output of the HPP model evaluation:

Objective function: maximize NPV/CAPEX

NPV: Net present Value

IRR: Internal rate of return

LCOE: Levelized cost of electricity

CAPEX: Total capital expenditure

OPEX: Total operational expenditure

AEP: Annual energy production

GUF: Grid utilization factor

Grid [MW]: grid capacity

Total curtailment [GWh]: for 25 years

Annual_H2 [kg]: H2 production in one year

```
NPV_over_CAPEX: 0.090
NPV [MEuro]: 29.802
IRR: 0.066
LCOE [Euro/MWh]: 31.318
CAPEX [MEuro]: 330.666
OPEX [MEuro]: 11.200
penalty lifetime [MEuro]: 0.000
AEP [GWh]: 1155.963
GUF: 0.440
annual H2 [kg]: 1610665.418
grid [MW]: 300.000
wind [MW]: 290.000
solar [MW]: 50.000
PtG [MW]: 100.000
Battery Energy [MWh]: 72.000
Battery Power [MW]: 9.000
Total curtailment [GWh]: 0.000
Awpp [km2]: 57.769
Rotor diam [m]: 84.934
Hub height [m]: 52.467
Number_of_batteries: 1.000

exec. time [min]: 0.2549054265022278
```

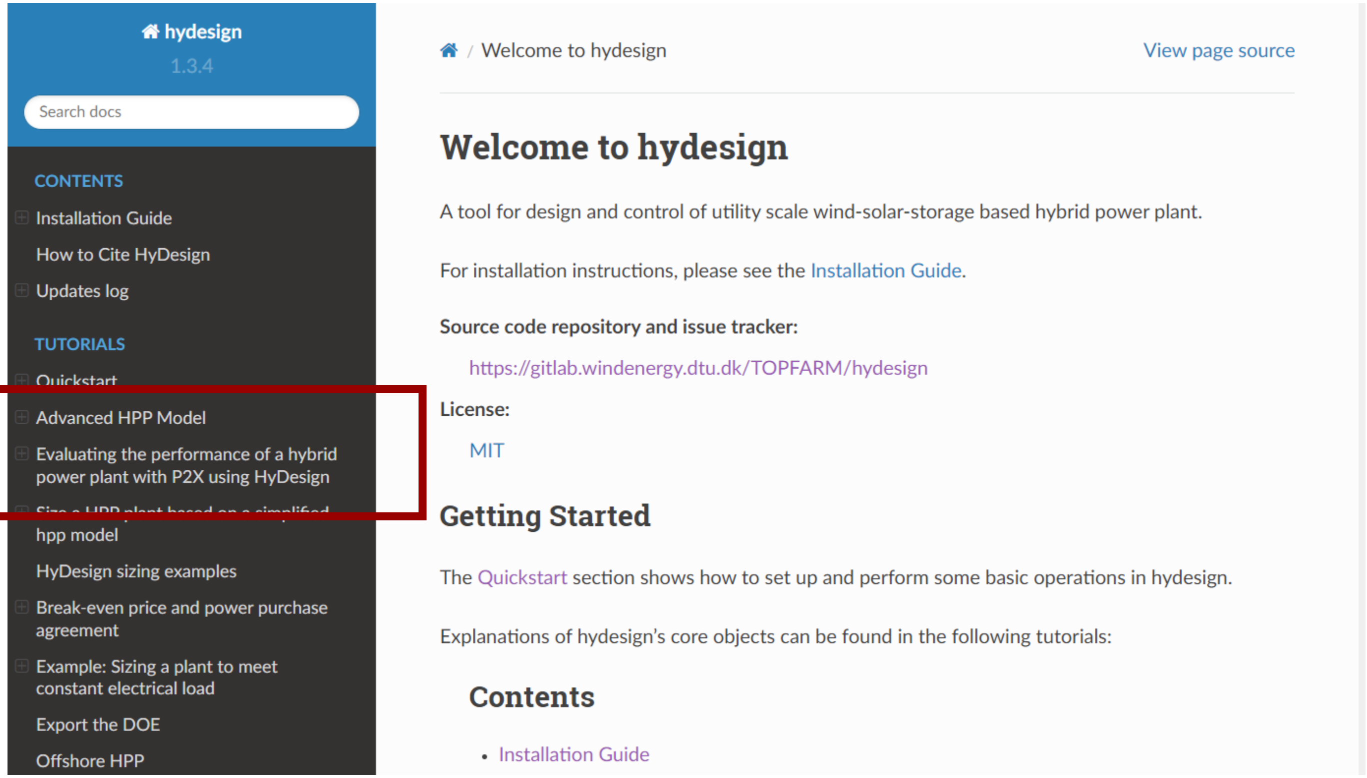
If HyDesign installation doesn’t work for you, then try the assignment with Google Colab.

Accessing notebooks through Google Colab

https://topfarm.pages.windenergy.dtu.dk/hydesign

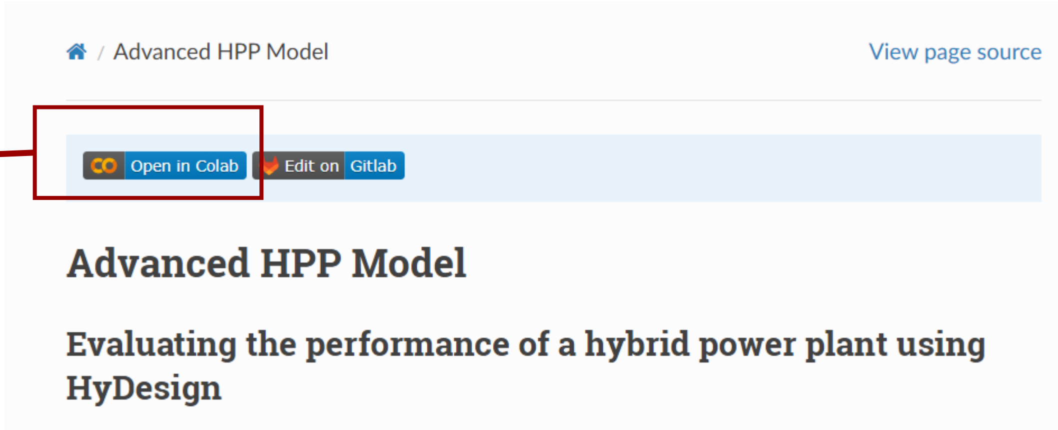
Notebook 1: Advanced HPP Model -> HPP size evaluation

Notebook 2: Evaluating the performance of a hybrid power plant with P2X using HyDesign -> HPP size evaluation with Power-to-Hydrogen



Accessing notebooks through Google Colab

Open the notebook in Google Colab



- Run each cell
- Check for the list of example sites (select the site of interest).
- Change the site name accordingly.

	case	name	longitude	latitude	altitude	
0	India	Indian_site_good_wind	77.500226	8.334294	679.803454	
1	India	Indian_site_good_solar	68.542204	23.542099	29.883557	
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5	Europe	France_bad_solar_n_wind	2.167969	47.428087	140.000000	
6	Europe	Germany_bad_solar_n_wind	10.766602	49.310798	442.000000	Eu
7	Europe	Germany_good_wind	7.873535	53.287111	5.000000	
8	Europe	Denmark_good_solar	11.813965	55.397760	42.000000	
9	Europe	Denmark_good_wind	8.594398	56.227322	85.000000	

```
[11] name = 'Denmark_good_wind'
     ex_site = examples_sites.loc[examples_sites.name == name]

     longitude = ex_site['longitude'].values[0]
     latitude = ex_site['latitude'].values[0]
     altitude = ex_site['altitude'].values[0]
```

Accessing notebooks through Google Colab

- In this cell, the evaluation of a HPP design is done
- Select the size of HPP:
  - wind plant size in MW: Nwt * P_rated;
  - solar_MW;
  - battery size
    - b_P: battery power in MW
    - b_E_h: battery energy hours)

Evaluating the HPP model

23s [13]

```
start = time.time()

clearance = 10
sp = 350
p_rated = 5
Nwt = 62
wind_MW_per_km2 = 7
solar_MW = 50
surface_tilt = 50
surface_azimuth = 180
solar_DCAC = 1.5
b_P = 20
b_E_h  = 3
cost_of_batt_degr = 5
```

Accessing notebooks through Google Colab

The output of the HPP model evaluation:

Objective function: maximize NPV/CAPEX

NPV: Net present Value

IRR: Internal rate of return

LCOE: Levelized cost of electricity

CAPEX: Total capital expenditure

OPEX: Total operational expenditure

AEP: Annual energy production

GUF: Grid utilization factor

Grid [MW]: grid capacity

Total curtailment [GWh]: for 25 years

Total curtailment with deg [GWh]: for 25 years considering the impact of degradation

```
NPV_over_CAPEX: 0.207
NPV [MEuro]: 78.996
IRR: 0.078
LCOE [Euro/MWh]: 47.474
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PV CAPEX [MEuro]: 33.500
PV OPEX [MEuro]: 0.675
Batt CAPEX [MEuro]: 15.230
Batt OPEX [MEuro]: 0.000
Shared CAPEX [MEuro]: 65.982
Shared OPEX [MEuro]: 0.000
penalty lifetime [MEuro]: 0.000
AEP [GWh]: 733.508
GUF: 0.279
grid [MW]: 300.000
wind [MW]: 350.000
solar [MW]: 100.000
Battery Energy [MWh]: 150.000
Battery Power [MW]: 50.000
Total curtailment [GWh]: 337.661
Total curtailment with deg [GWh]: 152.556
Awpp [km2]: 50.000
Apvp [km2]: 1.226
Plant area [km2]: 50.000
Rotor diam [m]: 134.867
Hub height [m]: 77.434
Number of batteries used in lifetime: 2.000
Break-even PPA price [Euro/MWh]: 31.519
Capacity factor wind [-]: 0.202
```

Accessing notebooks through Google Colab

Open this notebook in Google Colab

Open in Colab | Edit on Gitlab

Evaluating the performance of a hybrid power plant with P2X using HyDesign

In this notebook we will evaluate a hybrid power plant design in a specific location.

- Run each cell
- Check for the list of example sites (select one test site).
- Change the site name accordingly.

	case	name	longitude	latitude	altitude	
0	India	Indian_site_good_wind	77.500226	8.334294	679.803454	
1	India	Indian_site_good_solar	68.542204	23.542099	29.883557	
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[11]
```
name = 'Denmark_good_wind'
ex_site = examples_sites.loc[examples_sites.name == name]

longitude = ex_site['longitude'].values[0]
latitude = ex_site['latitude'].values[0]
altitude = ex_site['altitude'].values[0]
```

Accessing notebooks through Google Colab

- In this cell, the evaluation of a HPP with P2H design is done
- Select the size of HPP:
  - wind plant size in MW: Nwt * P_rated;
  - Solar plant size in MW: solar_MW;
  - battery size
    - b_P: battery power in MW
    - b_E_h: battery energy hours)
  - Electrolyzer size in MW: P_ptg_MW

Evaluating the HPP model

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[ ]  start = time.time()

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     b_P = 9
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     cost_of_batt_degr = 3.34
     ptg_MW = 100
```

Accessing notebooks through Google Colab

The output of the HPP model evaluation:

Objective function: maximize NPV/CAPEX

NPV: Net present Value

IRR: Internal rate of return

LCOE: Levelized cost of electricity

CAPEX: Total capital expenditure

OPEX: Total operational expenditure

AEP: Annual energy production

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Grid [MW]: grid capacity

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PtG [MW]: 100.000
Battery Energy [MWh]: 72.000
Battery Power [MW]: 9.000
Total curtailment [GWh]: 0.000
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Rotor diam [m]: 84.934
Hub height [m]: 52.467
Number_of_batteries: 1.000

exec. time [min]: 0.2549054265022278
```

Changing input file data: Method 1

To change the input parameter,
Add the parameter in the HPP model definition as shown in the image.
For example, now the H2 price is set to 4 €/kg.

Initializing the HPP model

Initialize the HPP model (hpp_model class) with the coordinates and the necessary input files.

```
hpp = hpp_model(
        latitude=latitude,
        longitude=longitude,
        altitude=altitude,
        num_batteries = 3,
        work_dir = './',
        sim_pars_fn = sim_pars_fn,
        input_ts_fn = input_ts_fn,
        H2_demand_fn = H2_demand_fn,
        price_H2 = 4,
)
```

Changing input file data in Google Colab: Method 2

Download the input file ‘hpp_pars.yml’ -> contains technology (Wind, solar, battery, P2H, grid connection) costs value and other parameters

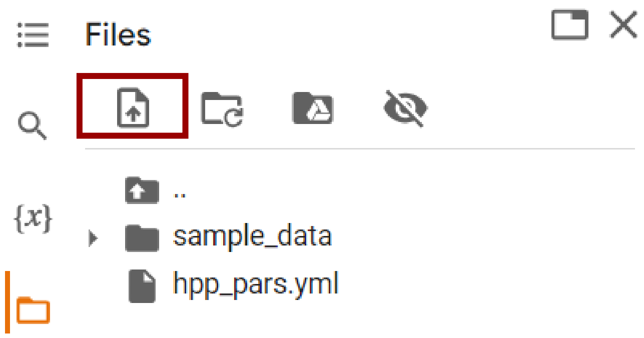
https://gitlab.windenergy.dtu.dk/TOPFARM/hydesign/-/blob/main/hydesign/examples/Europe/hpp_pars.yml

hpp_pars.yml 5.12 KiB Open in Web IDE Replace Delete

```yaml
# ------------------------------------------------------------------------------------------
# HPP Global
# ------------------------------------------------------------------------------------------
G_MW: 300 # Grid capacity
year: '2012' # Single representative year
N_life: 25

# ------------------------------------------------------------------------------------------
# Wind
# ------------------------------------------------------------------------------------------
wind_turbine_cost: 640_000  # [Euro/MW] for reference turbine
wind_civil_works_cost: 260_000  # [Euro/MW]
wind_fixed_onm_cost: 12_600  # Wind fixed O&M cost per year [Euro/MW /year]
wind_variable_onm_cost: 1.35 #[EUR/MWh_e] Danish Energy Agency

wpp_efficiency: 1.0
d_ref: 145
hh_ref: 100
p_rated_ref: 5.0 #[MW]

# ------------------------------------------------------------------------------------------
# PV
# ------------------------------------------------------------------------------------------
solar_PV_cost: 110_000   # [Euro/MW DC]
solar_hardware_installation_cost: 100_000  # [Euro/MW DC]
solar_inverter_cost: 20_000 #[Euro/MW]
solar_fixed_onm_cost: 4_500  # Solar O&M cost per year [Euro/MW] DC
pv_deg_per_year: 0.5e-2
land_use_per_solar_MW: 0.01226 # Danish energy agency
```

Changing input file data in Google Colab: Method 2

- Modify the input data in ‘hpp_pars.yml’ as desired. Upload the modified the input file ‘hpp_pars.yml’ in the current directory. (Note: The file name can be renamed as well)



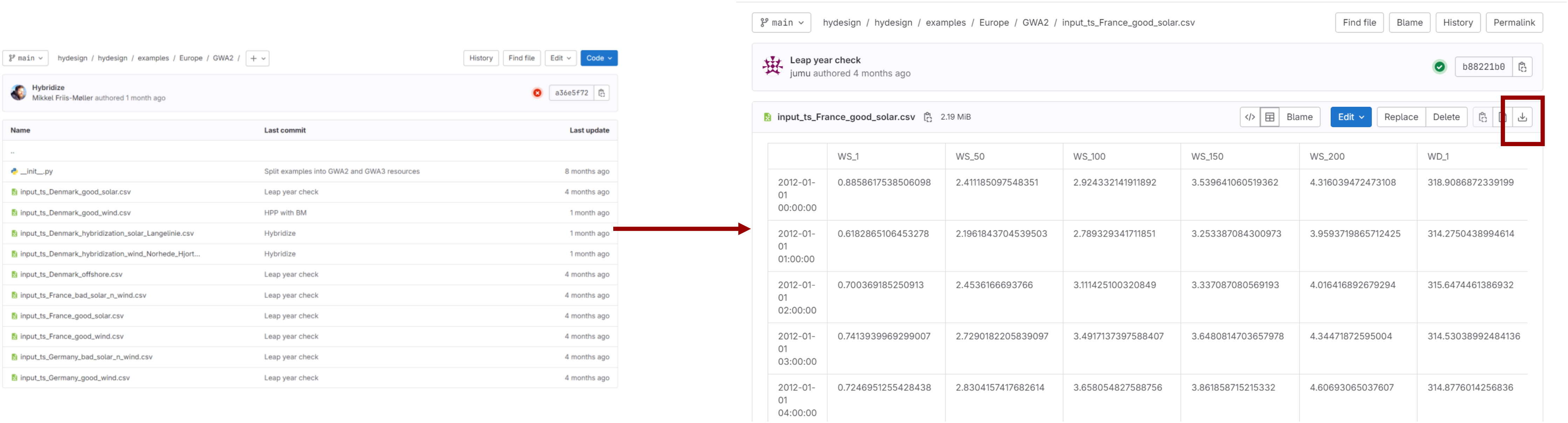

```python
name = 'France_good_wind'
ex_site = examples_sites.loc[examples_sites.name == name]

longitude = ex_site['longitude'].values[0]
latitude = ex_site['latitude'].values[0]
altitude = ex_site['altitude'].values[0]

input_ts_fn = examples_filepath+ex_site['input_ts_fn'].values[0]
sim_pars_fn = 'hpp_pars.yml'
```

- Rename the input file name in the notebook to point toward the modified set of inputs.
- Re-run the evaluation function and check for the results.

Accessing weather data file in Google Colab

Download the weather data file ‘input_ts_xxxxx.csv’ (xxxx corresponds to the site of interest) from the link below:

https://gitlab.windenergy.dtu.dk/TOPFARM/hydesign/-/tree/main/hydesign/examples/Europe/GWA2?ref_type=heads



The data represents wind speed (WS) and wind direction (WD) at different hub heights, direct normal irradiance (DNI), diffused horizontal irradiance (DHI), global horizontal irradiance (GHI) and spot market electricity prices – with an hourly resolution for one year.