REVUB training dataset

Contents

NOTE

THIS TRAINING DATASET PERTAINS TO REVUB VERSION 1.0.4

UPDATES TO THE TRAINING DATASET WILL BE UNDERTAKEN AS SOON AS POSSIBLE FOLLOWING **REVUB** MODEL UPDATES, BUT DELAYS MAY OCCUR

THE TRAINING DATASET IS STILL USABLE TO LEARN THE BASICS UNDER ALL CIRCUMSTANCES

REVUB training dataset

Introduction

This exercise provides a hands-on practical introduction to working with the REVUB hydropower-VRE dispatch model. REVUB serves to examine the potential of individual hydropower plants with reservoir storage to support the "firming-up" of variable renewables (VRE), e.g. solar and wind power. This can be done by releasing more water from the reservoir during periods when VRE availability is low compared to demand, and retaining more water in the reservoir during periods when VRE availability is high.

In this example, an international financial institution named the Planet Bank has been approached by one of its member states, the Republic of Flexibar, concerning the financing of a planned hydropower dam at the site of the King Floribert Gorge.

The Bank is investigating the feasibility and economic attractiveness of this planned King Floribert Hydropower Project, a proposed 1250-MW scheme impounding a 14-billion m^3 storage reservoir (King Floribert Lake) on one of the country's principal rivers, requiring a 240-m high dam to be built in the Gorge.

Next to boosting the Republic's electricity generation, the project will also allow for a large-scale irrigation project to be developed downstream of the plant, receiving regulated water flow from the reservoir.

As part of its due diligence, and as part of its general interest in supporting the deployment of clean solar photovoltaic (PV) and wind power projects worldwide, the Bank asked the question to what extent the King Floribert Hydropower Project would be able to provide storage and flexibility services to support VRE deployment in the Republic, in particular floating solar on King Floribert Lake and wind power harvested on the mountain ridges surrounding the Gorge.

In this exercise, imagine you are the expert working for the Bank tasked with investigating this topic. The principal questions are:

(i) Given the information we have on the design of the hydropower project, how many MW of solar and/or wind could we deploy alongside the project so that the hybrid hydro-VRE complex could effectively operate as a single unit (from the point-of-view of the grid)?

(ii) How would the hybrid hydro-VRE plant function under extreme situations, e.g. droughts?

You have been given a set of initial data on the King Floribert Hydropower Project's proposed design. This data includes river flow, precipitation, evaporation, downstream irrigation requirements, solar and wind resource strength, electricity demand, and all sorts of technical data on the King Floribert Hydropower Plant design.

After looking for the right tool to use, you decide to use the REVUB model to investigate the above questions. This seems a good choice: the REVUB model allows to run simulations from hourly-to-decadal timescale to investigate how to optimise hydropower plant operation to support VRE hybridisation, and can provide insights on elements such as seasonal reservoir drawdown/refilling cycles, hour-to-hour peaking needs of the hydro turbines, and operational strategies under extreme events such as droughts.

The present training dataset is meant to show how to run an appropriate REVUB simulation from beginning to end, starting with the raw data provided.

The training consists of three parts: (1) data initialisation; (2) running a simulation and defining different scenarios; and (3) analysing results.

Part 1: Data initialisation

Task 1.1: Downloading REVUB and accompanying files

The REVUB model is provided as Python code. To run it, you need to have an environment installed for Python. In this training set, we use the Spyder environment. For ease of use, we recommend downloading the [Anaconda distribution](), which contains the Spyder application.

To set up REVUB on your system, you need to download its Python code and an Excel file to initialise simulations, referred to as the "master file". You also need to create a couple of data input files from your end and fill them with the required data. We will explain step by step how this works.

1. Create a folder on your system into which you download the Python code, found on the REVUB repository on https://github.com/VUB-HYDR/REVUB/tree/master/1_REVUB_code.

2. Also download the Excel files *parameters_simulation.xlsx* (the "master file") and *plotting_settings.xlsx* from https://github.com/VUB-HYDR/REVUB/tree/master/2_REVUB_control_files into the same destination folder as the code. Both Excel files have a pre-determined table structure. All basic parameters for the simulations and for the standard visualisation of outputs will be directly entered here.

3. Make sure you have nine empty Excel files in the same folder, which should carry the following names, following the pattern *data_(…).xlsx* according to the data they will host:
    a. *data_inflow.xlsx*. This file will be used to enter full hourly time series of reservoir inflow.
    b. *data_precipitation.xlsx*. This file will be used to enter full hourly time series of precipitation gains on the reservoir lake surface.
    c. *data_evaporation.xlsx*. This file will be used to enter full hourly time series of evaporation losses from the reservoir lake surface.
    d. *data_outflow_prescribed.xlsx*. This file will be used to enter full hourly time series of required outflow from the reservoir to meet downstream irrigation (and other) needs.

e. *data_CF_solar.xlsx*. This file will be used to enter full hourly time series of the capacity factor[1] of potential solar PV plants built at the envisaged site(s).
f. *data_CF_wind.xlsx*. This file will be used to enter full hourly time series of the capacity factor of potential wind power plants built at the envisaged site(s).
g. *data_load.xlsx*. This file will be used to enter full hourly time series of the electricity demand curve that the hybrid hydro-VRE plant will aim to meet; in other words, the production curve that the hydro-VRE plant will aim to provide to the grid.
h. *data_bathymetry.xlsx*. This file will contain data on the shape of the reservoir of the hydropower plant, so that REVUB can track changes in lake volume, area, and hydraulic head through time.

Task 1.2: Setting up the master file for simulation control

Open the file *parameters_simulation.xlsx*. As mentioned, this is the "master file"; we will keep this file open in the background throughout the data initialisation process, as it controls the links between the REVUB code and the *data_(…).xlsx* files mentioned above.

Go to the worksheet "*Hydropower plant parameters*". This sheet requires the user to specify all parameters listed in column A (*HPP_name*, *HPP_active*, etc.) for each separate hydropower plant that the user wishes to model. Column B explains the meaning of the parameters in column A. Columns C and onwards are empty, for the user to enter their data.

Each column (from C onwards) will thus contain the data for one specific run for an individual hydropower plant. This allows to rapidly run sensitivity tests for individual parameters: By copying data from a single column into the next column and changing one single parameter, for instance, a scenario for the same hydropower plant can be re-run with one parameter changed, without losing the setup of the initial run.

We will now start setting up the first simulation run for the King Floribert Hydropower Project.

1. Enter the name of the hydropower plant under investigation, e.g. "King Floribert HPP" or a similar name, in the top row ("*HPP_name*") of column C (see the screenshot below).
2. The parameter "*HPP_active*" should be set to 1 for King Floribert HPP, and (for now) to 0 for the other columns to the right (see below). In this way, any REVUB simulation will only consider column C and not the other columns.

	A	B	C	D	E
1	**HPP_name**	name of hydropower plant in simulation	***King Floribert HPP***	***[name 2]***	***[name 3]***
2	**HPP_active**	used to include (= 1) or exclude (= 0) plant from current run	1	0	0
3	**HPP_name_data_inflow**	name of corresponding worksheet in the "data" Excel sheets from which to pull data on reservoir inflow (hourly inflow in m^3/s; hours in rows, years in columns)			
4	**HPP_name_data_precipitation**	name of corresponding worksheet in the "data" Excel sheets from which to pull data (precipitation flux in kg/m^2/s; hours in rows, years in columns)			
		name of corresponding worksheet in the "data" Excel sheets			

Note: The worksheets "*General parameters*" and "*Simulation accuracy*" contain REVUB-wide parameters that apply across all simulated hydropower plants simultaneously (i.e. those with *HPP_active* = 1). We will come back to the required settings in these worksheets later.

Now that we specified *HPP_name* and *HPP_active* in the master file, we turn to the next rows of parameters (rows 3-10 in the worksheet "*Hydropower plant parameters*"). These link each hydropower plant in the master file to the corresponding data in the *data_(…).xlsx* files created under Task 1.1, which mostly contain time series (the one exception being the bathymetry file, which will be discussed later).

[1] The capacity factor of any power plant is taken to refer to the electricity that it generated over a certain time period (e.g. hour, day, season, year...) divided by the power that would have been generated if the plant had run at full capacity over that entire period. Here, the relevant time period is hourly.

The name of the *data_(…).xlsx* file to which each of the rows 3-10 in the worksheet "*Hydropower plant parameters"* of the master file refers, is given by the variable name (in column A) minus "*HPP_name_*". Thus, for instance, row 3 refers to the Excel file named *data_inflow.xlsx*.

These *data_(…).xlsx* files are currently still empty, so in the next steps, we will collect the required data, fill the *data_(…).xlsx* files with that data, and then link them to the master file by entering the name of the relevant worksheet in each *data_(…).xlsx* file into the appropriate cell in the master sheet. For instance, if the user creates a worksheet in *data_inflow.xlsx* to enter the inflow data for King Floribert HPP and calls the worksheet "*King Floribert*", they should input the string *King Floribert* into cell C3 of the master file afterwards. All of this is explained in detail in the next section.

Task 1.3: Setting up input data time series

All needed time series data needs to be entered in the empty Excel files in the following format: *all hours of the year* by row, and *all years of the simulation* by column. Usually, the limiting factor for the length that a simulation can span is the time spanned by river flow data series—most of the other parameters (e.g. evaporation, solar power yield, …) typically exhibit a lot less variability from year to year, so for those, it is usually sufficient to take a single year of data and apply it to all simulation years.

In this simple example, we have been given raw data on river inflow that spans a 26-year period (1980-2005). This data is provided in the file *raw_data.xlsx* (worksheet "*inflow*"), available in the same folder as this exercise: https://github.com/VUB-HYDR/REVUB/tree/master/5_Training_dataset. Accordingly, we will set up REVUB simulations that allow to span up to 26 years of inflow data.

In many cases, input data would not be available at full hourly resolution across multiple years[2]. Rather, it is typical for the data to come in either of the two following formats:

1) Monthly resolution, either for a single "typical" year, or for multiple years. This often applies to inflow, precipitation, and evaporation. In this case, the raw inflow data is given at monthly resolution for multiple years (12 values per year *x* 26 years = 312 values).

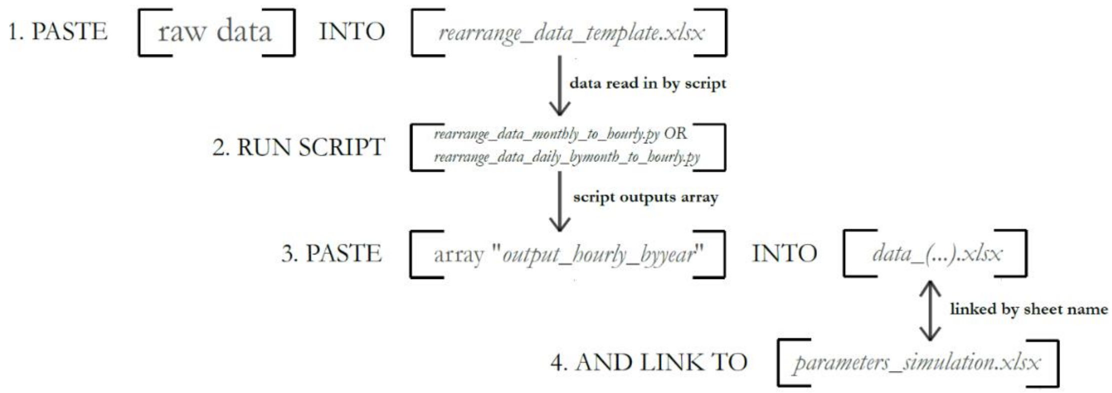
2) Hourly resolution (24-h format) for a "typical" day for each month. This may apply to solar PV and/or wind data; for instance, data downloaded from the Global Solar Atlas or Global Wind Atlas comes in this format. Downstream irrigation requirements may also be given at this resolution.

To enable a REVUB simulation, we must first convert such data to full hourly format to correctly fill the *data_(…).xlsx* files.

This can be done through the auxiliary codes *rearrange_data_monthly_to_hourly.py* (for data format "1" above) or *rearrange_data_daily_bymonth_to_hourly.py* (for data format "2" above), and its data read-in template, *rearrange_data_template.xlsx*, which has two worksheets corresponding to data formats 1 (worksheet "*monthly_series*") and 2 (worksheet "*daily_bymonth_series*"). All of these files are available on https://github.com/VUB-HYDR/REVUB/tree/master/3_Auxiliary_scripts.

A schematic of the data flow that is needed, from raw data to REVUB input, is shown in the below figure. These steps are explored in detail in the next section.

[2] But whenever it is, that is great, as it can then be directly pasted into the *data_(…).xlsx* files and most of the following steps can be ignored.



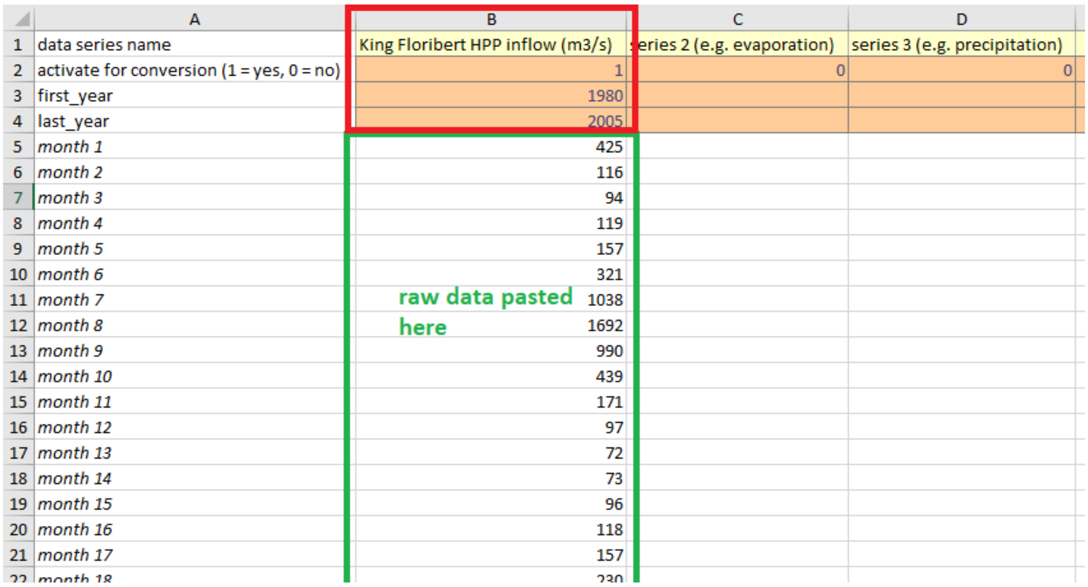
Working with data in format "1" (monthly averages)

Let us start this process for the inflow data. As you see in the file *raw_data.xlsx*, worksheet "*inflow*", this data is only available in the monthly format, but spans multiple years (1980-2005). We are thus dealing with data of format "1" above.

We must thus use the worksheet "*monthly_series*" of the read-in template *rearrange_data_template.xlsx*. Here, we can paste the raw data series into one of the dedicated columns. We must also accurately specify the first and last year, so that the presence of leap years is automatically correctly accounted for.

Thus, specify 1980 as *first_year* (row 3), 2005 as *last_year* (row 4), and copy+paste the monthly inflow data from the file *raw_data.xlsx* (312 values) into the rows below (row 5 and onwards), as in the screenshot below.

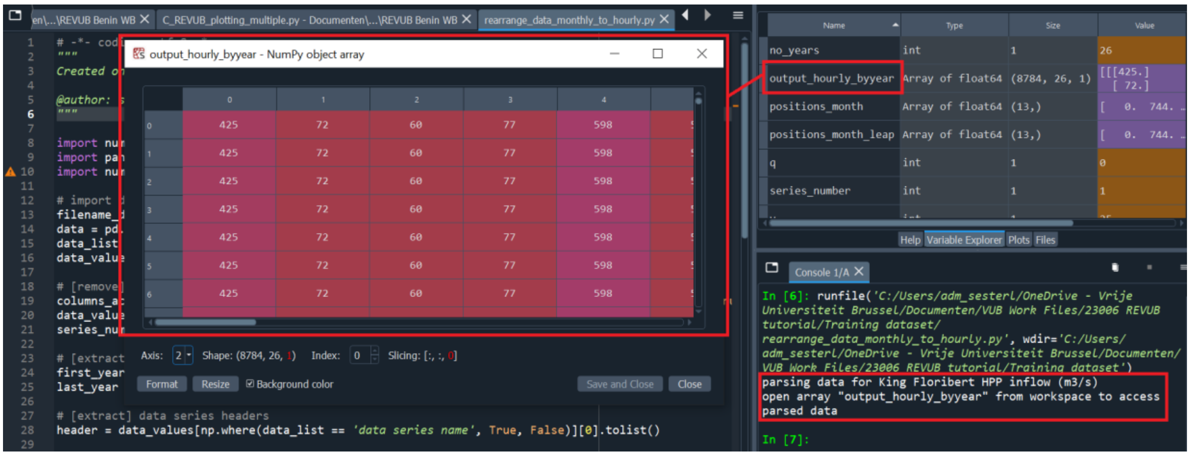
You need to also make sure the column is activated by specifying "1" in *activate for conversion* (row 2), and to avoid confusion with future data conversions, give it an appropriate *data series name* (row 1).



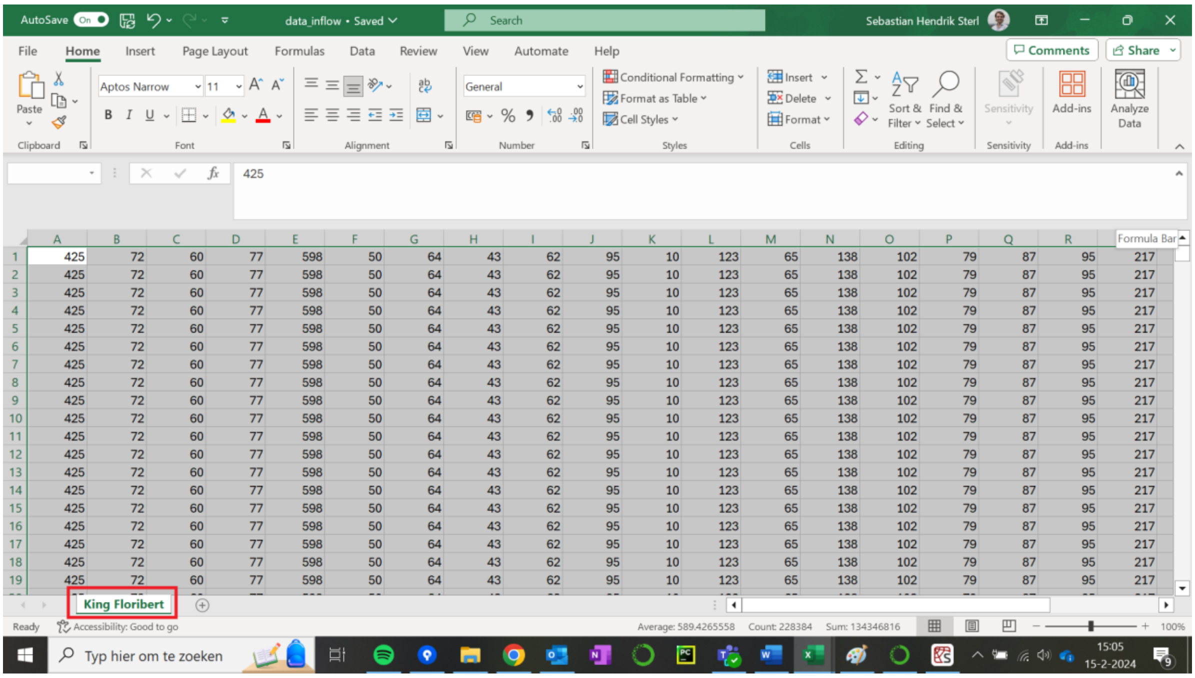
	A	B	C	D
1	data series name	King Floribert HPP inflow (m3/s)	eries 2 (e.g. evaporation)	series 3 (e.g. precipitation)
2	activate for conversion (1 = yes, 0 = no)	1	0	0
3	first_year	1980		
4	last_year	2005		
5	*month 1*	425		
6	*month 2*	116		
7	*month 3*	94		
8	*month 4*	119		
9	*month 5*	157		
10	*month 6*	321		
11	*month 7*	1038		
12	*month 8*	1692		
13	*month 9*	990		
14	*month 10*	439		
15	*month 11*	171		
16	*month 12*	97		
17	*month 13*	72		
18	*month 14*	73		
19	*month 15*	96		
20	*month 16*	118		
21	*month 17*	157		
22	*month 18*	230		

Now, we are ready to run the format conversion file. To do this, all you need to do is run the Python script *rearrange_data_monthly_to_hourly.py* in the same folder as the read-in template *rearrange_data_template.xlsx*.

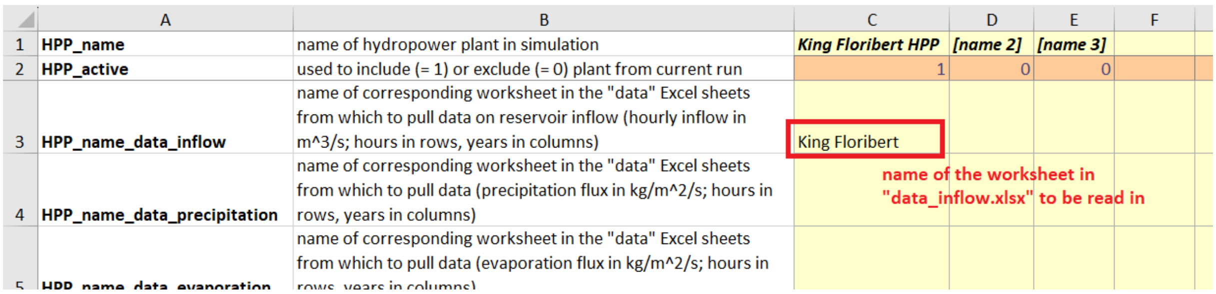
Running the file successfully will give a number of outputs; you need to copy the contents of the output array "*output_hourly_byyear*" along its first two dimensions ([*number of hours in a year*] x [*number of simulation years*]), which is the data series in the required full hourly format for REVUB. See the following screenshot for a visualisation.



Thus, this array can be pasted directly into a worksheet in the destination Excel file, in this case *data_inflow.xlsx*, as shown below.



Last, the worksheet into which the data was pasted requires an identifier as name (e.g. "*King Floribert*" in the screenshot above); this identifier will then be used in the relevant row in the master file (picture below). This way, the hydropower plant we are simulating is linked correctly to its inflow data.



	A	B	C	D	E	F
1	HPP_name	name of hydropower plant in simulation	King Floribert HPP	[name 2]	[name 3]	
2	HPP_active	used to include (= 1) or exclude (= 0) plant from current run	1	0	0	
3	HPP_name_data_inflow	name of corresponding worksheet in the "data" Excel sheets from which to pull data on reservoir inflow (hourly inflow in m^3/s; hours in rows, years in columns)	King Floribert			
4	HPP_name_data_precipitation	name of corresponding worksheet in the "data" Excel sheets from which to pull data (precipitation flux in kg/m^2/s; hours in rows, years in columns)	name of the worksheet in "data_inflow.xlsx" to be read in			
5	HPP_name_data_evaporation	name of corresponding worksheet in the "data" Excel sheets from which to pull data (evaporation flux in kg/m^2/s; hours in rows, years in columns)				

You have now successfully parsed the inflow data in the correct format, and linked the simulation setup of the King Floribert plant to the same inflow data series. Well done! Now we will follow a similar principle to repeat the process for a few other time series parameters that come in similar raw formats.

Applying the same principle is possible for the following other parameters given in the file *raw_data.xlsx*, all of which come in format "1":

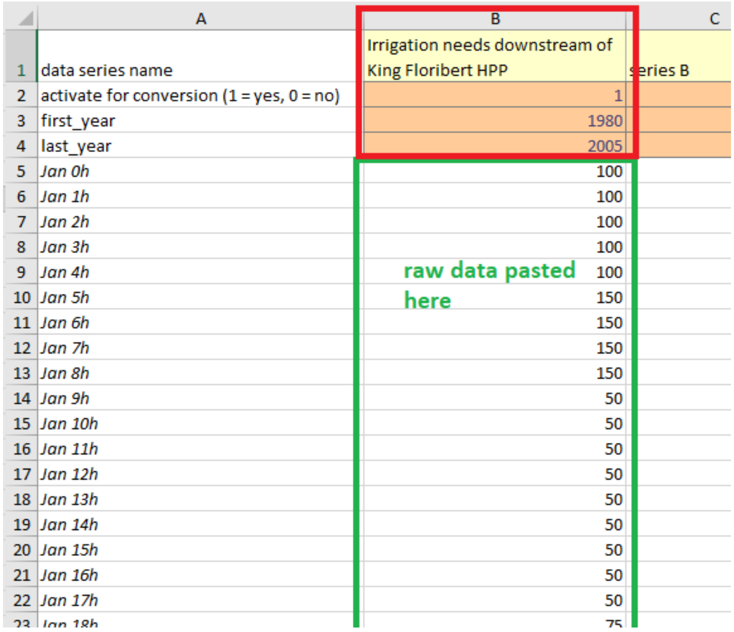
- To fill *data_precipitation.xlsx*: use the worksheet "*precipitation*" in the file *raw_data.xlsx*. This data is also given at monthly resolution for the period 1980-2005, and hence the exact same procedure can be applied as for the inflow. Note that you do not have to delete any previously pasted time series from the read-in template *rearrange_data_template.xlsx*. You can simply add columns to paste new data, and toggle the activate/disactivate option in the second row.

- To fill *data_evaporation.xlsx*: use the worksheet "*evaporation*" in the file *raw_data.xlsx*. For evaporation, unfortunately, you only have data for a "typical year" at your disposal. Thus, our best option is to assume that this data more or less holds for every year. The solution is thus to repeat this time series 26 times first (corresponding to 26 years in the period 1980-2005) and then carry out the same procedure as above for the inflow and precipitation.

Working with data in format "2" (typical hourly curves by month)

Now, let us have a look at the file *raw_data.xlsx*, worksheet *"outflow_prescribed*". This sheet shows estimated downstream irrigation requirements for agricultural activities that will be developed alongside the King Floribert hydropower plant, given by hour of the day for each month of the year (each month has different irrigation needs, in function of the crops' seasonal cycles; and nighttime irrigation is deemed more efficient than daytime irrigation).

Since this data is given in format "2" (see above), we must parse the data into the worksheet "*daily_bymonth_series"* of the read-in template *rearrange_data_template.xlsx* (as shown in the picture below) and subsequently run the auxiliary script called *rearrange_data_daily_bymonth_to_hourly.py*, as before.



	A	B	C
1	data series name	Irrigation needs downstream of King Floribert HPP	series B
2	activate for conversion (1 = yes, 0 = no)	1	
3	first_year	1980	
4	last_year	2005	
5	Jan 0h	100	
6	Jan 1h	100	
7	Jan 2h	100	
8	Jan 3h	100	
9	Jan 4h	100	
10	Jan 5h	150	
11	Jan 6h	150	
12	Jan 7h	150	
13	Jan 8h	150	
14	Jan 9h	50	
15	Jan 10h	50	
16	Jan 11h	50	
17	Jan 12h	50	
18	Jan 13h	50	
19	Jan 14h	50	
20	Jan 15h	50	
21	Jan 16h	50	
22	Jan 17h	50	
23	Jan 18h	75	

Once the script is run, we can once again copy the contents of the output array "*output_hourly_byyear*" along its first two dimensions, which is the data series in the required full hourly format for REVUB. Its contents can then be passed into the Excel sheet *data_outflow_prescribed.xlsx*, and the worksheet linked to the master file according to the same procedure as explained above.

There are a few other raw data series that also come in format "2" and for which you can fill the relevant Excel files using the same procedure outlined above:

- To fill *data_CF_solar.xlsx* and *data_CF_wind.xlsx*: use the worksheet "*solar power*" and "*wind power*", respectively, in the file *raw_data.xlsx*. This sheet provides estimates of the hourly capacity factor of solar panels and wind turbines for each month of the year, i.e. format "2". Such data can be readily obtained from e.g. the Global Solar Atlas and Global Wind Atlas.

- To fill *data_load.xlsx*: use the worksheet "*load*" (electricity demand) in the file *raw_data.xlsx*. Again, this data comes in format "2". Typically, such data should actually be available in full hourly format (8760-8784 data points per year), but in this instance, the electric utility of the Republic of Flexibar declined to make full data available and instead released a typical curve for each month. Thus, we can repeat the same procedure as for irrigation outflow and solar/wind CF above.

Task 1.4: Setting up bathymetry series

The last sheet that needs to be linked with the master file is *data_bathymetry.xlsx*, which needs to contain data on the shape of the reservoir.

Using geospatial analysis, engineers from the Republic of Flexibar have estimated this reservoir shape (volume-area-head relationship). The raw data is given in the sheet "*bathymetry*". This data simply needs to be pasted into the empty Excel file *data_bathymetry.xlsx*, with lake volume in the first column, lake area in the second, hydraulic head in the third, and no headers.

The more granular the dataset, the more accurate the REVUB simulations will be in terms of reservoir dynamics. However, it is not strictly necessary to use a highly detailed (1000-point) dataset such as the one in this example. One could run a simulation with only a fraction of the provided data points.

Note that the *hydraulic head* of the lake is of far higher importance to the eventual simulation outcomes than the *lake area*. This is because the power generated scales linearly with the hydraulic head, whereas the lake area is only important to calculate the correct total amount of lake surface evaporation and/or captured precipitation, which is usually a small fraction of the overall water budget of the reservoir.

Again, as with all Excel files mentioned above, the worksheet with the data in *data_bathymetry.xlsx* requires an identifier (e.g. "Lake Floribert"), which then needs to be reflected in the master file.

After having completed all tasks up to here, the sheet "*Hydropower plant parameters*" of your master file should look something like this, with the identifiers you chose for each data series reflected in the appropriate row:

	A	B	C	D	
1	**HPP_name**	name of hydropower plant in simulation	***King Floribert HPP***	***[name 2]***	***[na***
2	**HPP_active**	used to include (= 1) or exclude (= 0) plant from current run	1	0	
3	**HPP_name_data_inflow**	name of corresponding worksheet in the "data" Excel sheets from which to pull data on reservoir inflow (hourly inflow in m^3/s; hours in rows, years in columns)	King Floribert		
4	**HPP_name_data_precipitation**	name of corresponding worksheet in the "data" Excel sheets from which to pull data (precipitation flux in kg/m^2/s; hours in rows, years in columns)	King Floribert		
5	**HPP_name_data_evaporation**	name of corresponding worksheet in the "data" Excel sheets from which to pull data (evaporation flux in kg/m^2/s; hours in rows, years in columns)	King Floribert		
6	**HPP_name_data_outflow_prescrib**	name of corresponding worksheet in the "data" Excel sheets from which to pull data on prescribed (environmental/irrigation) outflow (hourly in m^3/s; hours in rows, years in columns)	King Floribert		
7	**HPP_name_data_CF_solar**	name of corresponding worksheet in the "data" Excel sheets from which to pull data (hourly solar CF as fraction/percentage; hours in rows, years in columns)	Solar near King Floribert		
8	**HPP_name_data_CF_wind**	name of corresponding worksheet in the "data" Excel sheets from which to pull data (hourly wind CF as fraction/percentage; hours in rows, years in columns)	Wind near King Floribert		
9	**HPP_name_data_load**	name of corresponding worksheet in the "data" Excel sheets from which to pull data (hourly load normalised to a mean of unity)	Flexibar		
10	**HPP_name_data_bathymetry**	name of corresponding worksheet in the "data" Excel sheets from which to pull data (first column: volume in m^3; second: surface area in m^2; third: head in m)	Lake Floribert		
11	**c_solar_relative**	fraction of solar in the solar/wind portfolio			

Task 1.5: Specifying technical and operational hydropower plant data

Now that we have set up all input data series, we need to specify further technical and operational parameters of the hydropower plant and its hybridisation with VRE.

These include important numbers such as the installed capacity of the plant (MW); the number of installed turbines; the maximum operationally achievable volume/surface/head (note that these may lay somewhere on the bathymetry curve from Task 1.5 that is not necessarily the curve's endpoint), and others.

A full list of these parameters, pertaining to the King Floribert hydropower plant (and including various numbers which you, as expert in the field, deemed appropriate for a first simulation), is given in the worksheet "*other technical parameters*" of *raw_data.xlsx*.

These data need to be copied and pasted into the appropriate cells in the worksheet "*Hydropower plant parameters*" in the master file, as in the picture below. (In *raw_data.xlsx*, they are already given in the right order to simply copy+paste them all at once).

	A	B	C	D	E
1	**HPP_name**	name of hydropower plant in simulation	*King Floribert HPP*	*[name 2]*	*[name 3]*
2	**HPP_active**	used to include (= 1) or exclude (= 0) plant from current run	1	0	0
11	**c_solar_relative**	fraction of solar in the solar/wind portfolio	1		
12	**h_max**	maximum head in m	219		
13	**A_max**	maximum lake area in m^2	2.0E+08		
14	**V_max**	maximum lake volume in m^3	1.4E+10		
15	**V_initial_frac**	initial filling fraction of lake volume	0.8		
16	**P_r_turb**	installed capacity in MW	1250		
17	**Q_max_turb**	maximum discharge (total of all turbines) in m^3/s	1000		
18	**no_turbines**	number of turbines (units)	4		
19	**eta_turb**	turbine efficiency as fraction	0.8		
20	**dP_ramp_turb**	turbine ramp rate in % of full capacity / min	0.03		
21	**f_stop**	fraction of lake volume at which production stops	0.1		
22	**f_restart**	fraction of lake volume at which production restarts after stopping	0.2		
23	**f_opt**	optimal filling fraction f_opt (eq. S4, S5)	0.8		
24	**f_spill**	fraction f_spill beyond which spilling starts (eq. S7)	0.95		

Task 1.6: Setting simulation parameters and accuracy

To finalise the initialisation of the simulation, we now just need to specify a few more generic parameters related to the simulation and its calculation accuracy.

First, on the sheet "*General parameters*" of the master file, we will set the parameters *year_start* and *year_end* to define the years we want to include in the simulation. Eventually, we will want to use the full set of input data years (*year_start* = 1980; *year_end* = 2005), but it is often wise to start with a shorter time span to test whether the simulation was set up correctly and gives sensible outputs.

We will start the initial test here with *year_start* = 1980 and *year_end* = 1983, i.e. using only the first four years. The other parameters can be left as they are, as in the picture below.

	A	B	C
1	year_start	1980	reference start year used in the simulation
2	year_end	1983	reference end year used in the simulation
3	column_start	1	index of column (first column = 1) corresponding to year_start in time series Excel sheets (this needs to be the same across all Excel sheets)
4	rho	1000	density of water (kg/m^3) (introduced in eq. S3)
5	g	9.81	gravitational acceleration (m/s^2) (introduced in eq. S8)
6	T_fill_thres	1	represents number of years of filling as threshold for determining f_reg if left unspecified by user (see sheet "Hydropower plant parameters"). Default/recommended is unity, so f_reg represents the fraction of annual mean inflow that would take exactly one year to fill reservoir.
7	LOEE_allowed	0	allowed Loss of Energy Expectation as percentage of yearly ELCC
8	option_storage	0	wish to activate pumped storage module (Note 7) for at least one hydropower plant or not? (0 = no, 1 = yes)

Next and last, we can set a few parameters related to the simulation's accuracy in the sheet "*Simulation accuracy*". The precise meaning of each of these is given in the REVUB manual (https://github.com/VUB-HYDR/REVUB/tree/master/4_Manual) ; they all relate to the accuracy with which the algorithm searches for the most suitable solution for hydro-VRE operation. The values as shown in the picture below permit a relatively light simulation, so we will use them as shown.

	A	B	C
1	N_ELCC	1000	This number defines the amount of discrete steps between 0 and max(E_hydro + E_solar + E_wind)
2	psi_min_threshold	0	When min(Psi) (eq. S21) is lower than this threshold, no further refinement loops are performed
3	f_init_BAL_start	0	These values are used to get a good initial guess for the range of the ELCC for BAL. This is the lower value in the guessed range
4	f_init_BAL_step	0.2	These values are used to get a good initial guess for the range of the ELCC for BAL. This is the step size in the guessed range
5	f_init_BAL_end	1	These values are used to get a good initial guess for the range of the ELCC for BAL. This is the upper value in the guessed range
6	N_refine_BAL	2	Number of refinement loops for equilibrium search for min(Psi) in BAL (see eq. S21)
7	X_max_BAL	2	Number of loops for iterative estimation of P_stable,BAL (see eq. S9 & explanation below eq. S19)

Part 2: Running a simulation

Task 2.1: The principles of running REVUB and obtaining output

With your data sheets and master file set up, it is time to run a first simulation for the King Floribert hydropower plant.

Open a console in your preferred environment (as said, here, we use Spyder) from which you can run the REVUB model. Make sure that the REVUB scripts *A_REVUB_initialise.py*, *B_REVUB_main_code.py* and *C_REVUB_plotting_individual.py* are located in the same folder as the data files and the master file.

First, run script *A_REVUB_initialise.py*. This script serves to read in all the data you parsed into their sheets in Part 1. In case any formatting errors occurred in this process, you will notice here.

If the code runs without error, your data have been correctly read in.

Next, open the script *B_REVUB_main_code.py*. It needs to be run from the same console; make sure the settings are appropriate for this (e.g. in Spyder, after opening the script, click *Run* → *Configuration per file* → *Run file with custom configuration* → check "*Execute in current console*" and "*Run in console's namespace instead of an empty one*").

Now run the script. You will see a progress counter in the console window to show how far along you are in the simulation, as in the picture below. **The simulation should take around 2-3 minutes at most.**

```
HPP 1 / 1 : King Floribert HPP
(i) simulating CONV
Note: Average spilling in CONV equal to 3.22 % of average
inflow.
done
(ii) finding optimal BAL solution
C_OR =  89.7 %
refinement step 1 / 2 > scanning: 16.0 %
refinement step 1 / 2 > scanning: 33.0 %
refinement step 1 / 2 > scanning: 50.0 %
refinement step 1 / 2 > scanning: 66.0 %
refinement step 1 / 2 > scanning: 83.0 %
refinement step 1 / 2 > scanning: 100.0 %
refinement step 2 / 2 > scanning: 4.0 %
refinement step 2 / 2 > scanning: 9.0 %
refinement step 2 / 2 > scanning: 13.0 %
```

Once you see the text "*simulation finished*" appear in the console, the simulation has completed successfully.

To test that we obtained sensible results, we will run a quick visualisation of the outcomes using the script *C_REVUB_plotting_individual.py*, the plotting code for individual hydropower plant results.[3]

Before running the plotting script, we need to specify a few plotting parameters in the Excel file *plotting_settings.xlsx* which you downloaded in Task 1.1. In its worksheet "*Plot power output (single HPP)*", we need to specify the correct name of the hydropower plant for which we want to plot results; it needs to match exactly the name in the master file. See below for an example.

	A	B	C
1	plot_HPP	King Floribert HPP	exact name of hydropower plant to plot
2	plot_year	2	for monthly and hourly graphs: choose which simulation year to take (1 = first year; 2 = second year; etc.)
3	plot_month	4	for hourly graph: choose month to plot (1 = Jan; 2 = Feb; etc.)
4	plot_day_month	12	for hourly graph: choose day of the month that the plot starts with
5	plot_num_days	4	for hourly graph: number of days to show, starting at *plot_day_month*

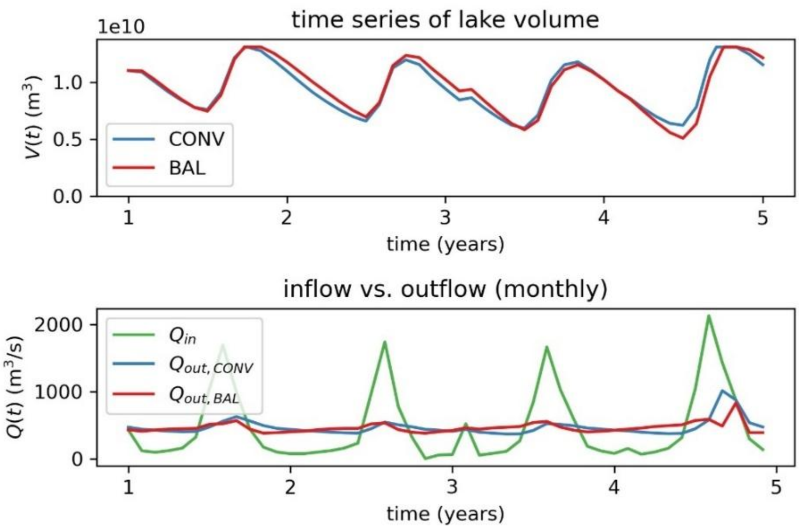
The numbers in the picture given above correspond to the following plotting parameters: sub-annual (month-by-month) results will be shown for year 2 (*plot_year* = 2); and hourly results will be shown for the same year for month 4 (*plot_month* = 4) starting at day 12 of that month (*plot_day_month* = 12) and for 4 consecutive days (*plot_num_days* = 4). In the above case, this translates to: sub-annual results will be shown for the year 1981; and hourly results for the period April 12th till 15th in the year 1981.

Feel free to use alternative numbers while testing the visualisations. This also applies to the numbers on the worksheet "*Plot release rules (single HPP)*".

When done, run the script *C_REVUB_plotting_individual.py* (again, in the same console/workspace as the previous scripts).

The script will produce a set of figures that will appear in the same folder from which the script was run, named "*King Floribert HPP_Fig[X]*".

For instance, Figure 3 shows time series of lake volume and of inflow vs. outflow under regular operation ("CONV") and under hydro-VRE hybridization ("BAL", for "balancing"). If run correctly, your results in Figure 3 should look like this:

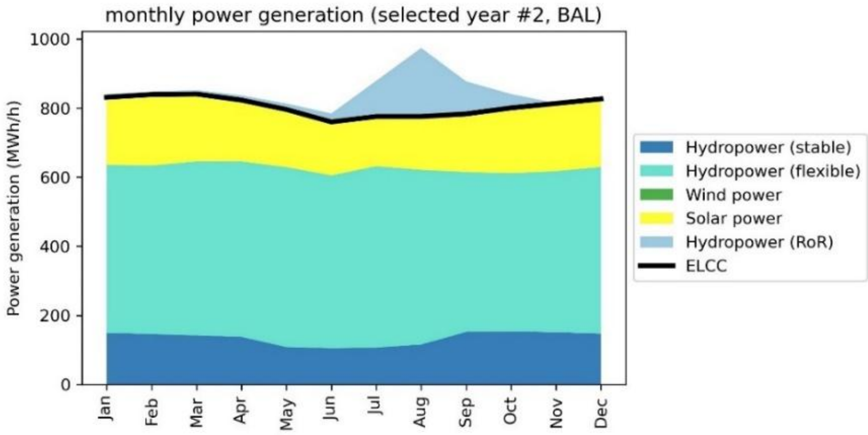


Note that the point of "CONV" series is to serve as a reference for how the operation of the hydropower plant would likely look in the absence of any need for solar/wind balancing, i.e. "traditional" hydropower operation. This reference is necessary to know what a realistic seasonal drawdown and refilling cycle for the plant should look like, so that the operation for hydro-VRE hybridisation can be optimised to result in a

[3] There is also another script *C_REVUB_plotting_multiple.py* in which results for multiple hydropower plants included in the simulation (those with *HPP_active* = 1 in the master file) can be added together, but we will not use it in this training dataset.

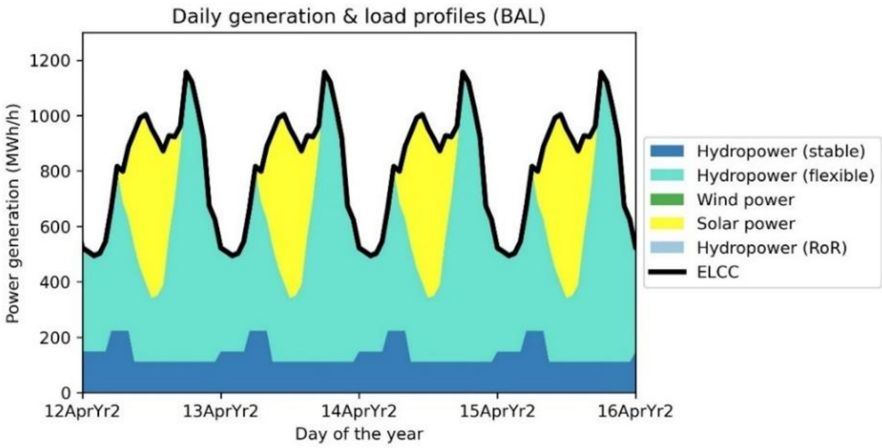
similar drawdown-refilling cycle (i.e. an operation which neither underutilises nor overdraws the water budget).

Figure 4 shows the seasonal distribution of power generation of the hydro-VRE mix for the selected year (*plot_year* = 2), as well as of the demand followed by the mix[4], and should look as below. The seasonal cycles of load and solar power potential are clearly visible. We also see the impact of the seasonality of the irrigation demand, which translates into higher "fixed" (stable) outflow during the period Sept-April. Further, it can be seen that the reservoir cannot store all the incoming water; in the wet season (June-Sept), the inflow peak of the (very seasonal) river has to be partially turbined directly without being stored (the "*RoR*" component) to prevent reservoir overflow.



An example of the actual hour-to-hour hydropower and VRE generation in the mix for the chosen example period is shown in Figure 5. It can be seen how hydropower is allowed to ramp down during daytime, when solar power can meet large parts of the demand.

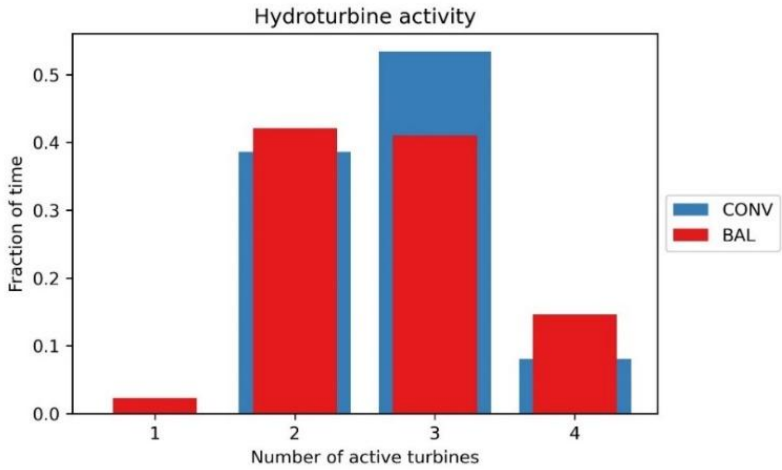
Nevertheless, there are restrictions imposed on hydropower flexibility to (i) keep at least one turbine running at minimum load and (ii) meet downstream irrigation requirements, which vary within a day. Both of these are reflected in the stable hydropower component in the figure below. It can be seen that the irrigation component (cf. the curve you used in Task 1.3) is higher than the minimum load component during the night and morning hours, but not during the rest of the day when the minimum load component automatically covers the irrigation requirements.



Switching from a conventional operation scheme to a hydro-VRE hybridisation scheme would change the typical use profiles of the plant's four turbines. This is shown in the produced Figure 8 (below). Under

[4] The demand followed by the mix is designated "ELCC", or "Effective Load Carrying Capability". It refers to the guaranteed load that the hydro-VRE plant can meet from hour to hour.

conventional operation, three turbines would be active simultaneously more than half of the time, whereas under hydro-VRE hybridization, a more varied use profile is required with many more moments when all four turbines are active simultaneously, but also many more moments where only a single turbine is active.



Together, these figures seem to imply that (i) the King Floribert HPP could substantially stabilise the seasonal inflow of the river, with only a relatively small flood peak left during the wettest months, and would (ii) have the potential to provide substantial support to solar PV. However, achieving this would require (iii) adapting the operational scheme adequately so that the flexibility potential is harnessed.

To analyse outcomes of the scenario in greater detail, we should now run a full simulation based on the entire input data series (1980-2005), since a data series of four years (1980-1983) is generally too short to have accurate statistics on extremes in inflow and other input parameters. These could substantially affect the most suitable operation mode of the hydropower plant with VRE.

However, since the short test simulation we ran above appears to make sense and gives no errors, we can be confident that a long simulation will provide us with answers to some of the initial questions.

Task 2.2: Creating alternative scenarios

Having confirmed that the simulation runs, let us take this opportunity to define another scenario in which the VRE portfolio contains wind next to solar as well. We can then run both scenarios across their full time horizon together.

To define the scenario with solar and wind, all we need to do in the master file is copy the King Floribert HPP column in the worksheet "*Hydropower plant parameters*", rename it (parameter *HPP_name*), activate it (parameter *HPP_active*), and leave all other parameters equal except for *c_solar_relative*.

In this scenario, we will change the latter from 1 to 0.5, representing a scenario in which the installed capacity of solar PV and wind keep pace with each other (for each unit of solar PV installed, a unit of wind power capacity is also installed).

The screenshot below shows how to correctly set up this second run of the King Floribert plant. None of the other parameters and/or Excel files need to be adapted, as we assume everything else will remain equal between the two scenarios.

	A	B	C	D	E
1	HPP_name	name of hydropower plant in simulation	King Floribert HPP	King Floribert HPP with wind	[name 3]
2	HPP_active	used to include (= 1) or exclude (= 0) plant from current run	1	1	0
3	HPP_name_data_inflow	name of corresponding worksheet in the "data" Excel sheets from which to pull data on reservoir inflow (hourly inflow in m^3/s; hours in rows, years in columns)	King Floribert	King Floribert	
4	HPP_name_data_precipitation	name of corresponding worksheet in the "data" Excel sheets from which to pull data (precipitation flux in kg/m^2/s; hours in rows, years in columns)	King Floribert	King Floribert	
5	HPP_name_data_evaporation	name of corresponding worksheet in the "data" Excel sheets from which to pull data (evaporation flux in kg/m^2/s; hours in rows, years in columns)	King Floribert	King Floribert	
6	HPP_name_data_outflow_prescri	name of corresponding worksheet in the "data" Excel sheets from which to pull data on prescribed (environmental/irrigation) outflow (hourly in m^3/s; hours	King Floribert	King Floribert	
7	HPP_name_data_CF_solar	name of corresponding worksheet in the "data" Excel sheets from which to pull data (hourly solar CF as fraction/percentage; hours in rows, years in columns)	Solar near King Floribert	Solar near King Floribert	
8	HPP_name_data_CF_wind	name of corresponding worksheet in the "data" Excel sheets from which to pull data (hourly wind CF as fraction/percentage; hours in rows, years in columns)	Wind near King Floribert	Wind near King Floribert	
9	HPP_name_data_load	name of corresponding worksheet in the "data" Excel sheets from which to pull data (hourly load normalised to a mean of unity)	Flexibar	Flexibar	
10	HPP_name_data_bathymetry	name of corresponding worksheet in the "data" Excel sheets from which to pull data (first column: volume in m^3; second: surface area in m^2; third: head in m)	Lake Floribert	Lake Floribert	
11	c_solar_relative	fraction of solar in the solar/wind portfolio	1	0.5	
12	h_max	maximum head in m	219	219	
13	A_max	maximum lake area in m^2	2.0E+08	2.0E+08	
14	V_max	maximum lake volume in m^3	1.4E+10	1.4E+10	
15	V_initial_frac	initial filling fraction of lake volume	0.8	0.8	
16	P_r_turb	installed capacity in MW	1250	1250	
17	Q_max_turb	maximum discharge (total of all turbines) in m^3/s	1000	1000	
18	no_turbines	number of turbines (units)	4	4	
19	eta_turb	turbine efficiency as fraction	0.8	0.8	

We now just need to change *year_end* to 2005 (instead of 1983) in the worksheet "*General parameters*" to allow running the simulation across the full time horizon:

	A	B	C
1	year_start	1980	reference start year used in the simulation
2	year_end	2005	reference end year used in the simulation
3	column_start	1	index of column (first column = 1) corresponding to year_start in time series Excel sheets (this needs to be the same across all Excel sheets)
4	rho	1000	density of water (kg/m^3) (introduced in eq. S3)
5	g	9.81	gravitational acceleration (m/s^2) (introduced in eq. S8)

We can now re-run scripts A, B and C to obtain results for both scenarios.

Using a time span of 26 years instead of 4, the simulation will accordingly take longer. 26 years is a relatively long period to use for REVUB, so a simulation may last up to 30 minutes per scenario/plant. (In practice, this is usually why you would wait until all parameters and scenario definitions are fully set up and agreed upon with the clients / target groups before running scenarios over long time periods. All debugging and refining should be done, as much as possible, on scenarios with shortened periods such as under Task 2.1.)

As you activated both scenarios by setting *HPP_active* = 1, script B will run both successively.

```
HPP 1 / 2 : King Floribert HPP
(i) simulating CONV
Note: Average spilling in CONV equal to 6.99 % of average
inflow.
done
(ii) finding optimal BAL solution
C_OR =  82.8 %
refinement step 1 / 2 > scanning: 16.0 %
refinement step 1 / 2 > scanning: 33.0 %
refinement step 1 / 2 > scanning: 50.0 %
```

```
HPP 2 / 2 : King Floribert HPP with wind
(i) simulating CONV
Note: Average spilling in CONV equal to 6.99 % of average
inflow.
done
(ii) finding optimal BAL solution
C_OR =  82.8 %
refinement step 1 / 2 > scanning: 16.0 %
refinement step 1 / 2 > scanning: 33.0 %
refinement step 1 / 2 > scanning: 50.0 %
```

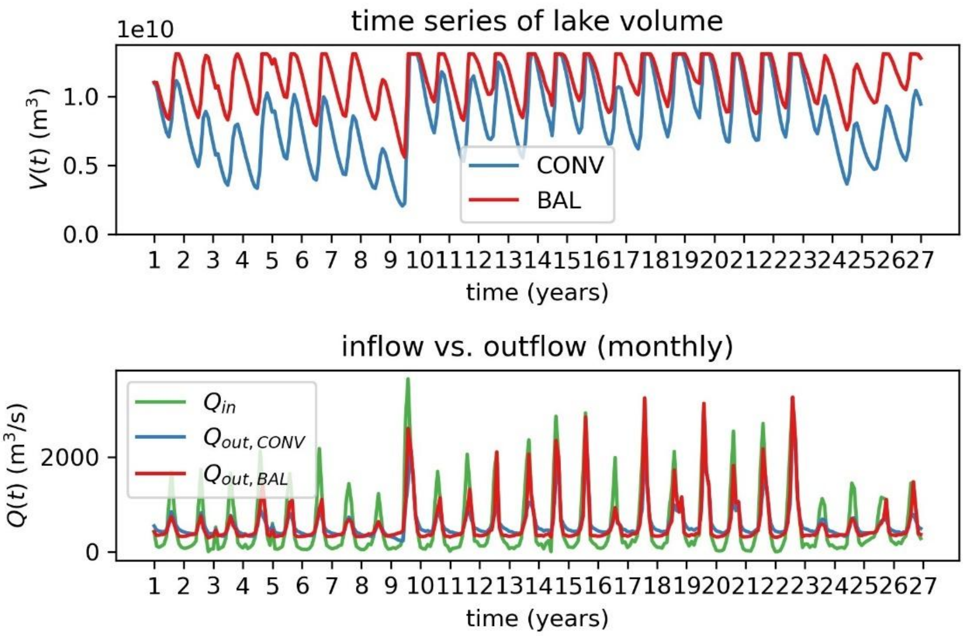
Once the simulation is done for both scenarios, given the time elapsed, it is advisable to save the entire workspace (e.g. into a *.spydata* file) so it can be loaded later to have all results at hand, without having to re-run REVUB.

Part 3: Analysing results

Task 3.1: Analysing scenario outcomes

Visualising results for either scenario works as discussed before in Task 2.1, with the note that we always need to specify the plotting parameters in the Excel file *plotting_settings.xlsx*, in particular the name of the plant/scenario (reflecting the name in the master file) in its worksheet "*Plot power output (single HPP)*".

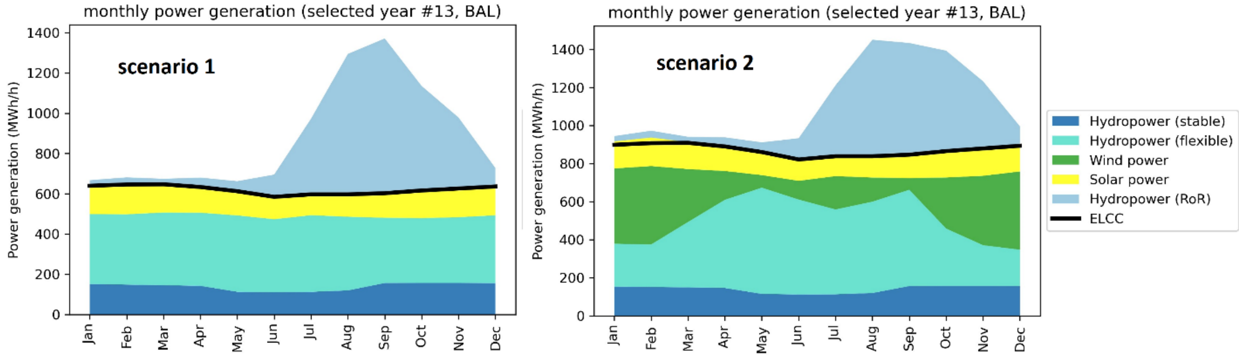
As an example, the below graph shows reservoir dynamics and inflow/outflow for the first scenario, where the VRE portfolio contains only solar:



Note that the simulation outcome is NOT simply the time series from the 4-year simulation before (Task 2.1) with results for the remaining 22 years appended. This is because REVUB finds the most suitable operational mode of hydropower *across the entire time horizon*, reflecting that the hydro-VRE portfolio should be as reliable as possible, subject to extremes in the long-term statistical properties of the inflow and other input data. Since the 4-year timespan we used in Task 2.1 does not accurately reflect all long-term statistical properties of these parameters, as can be clearly seen from the above graph (with various extremely wet and extremely dry years occurring in the years 5-26 of the simulation), the operation derived by REVUB from 4-year input would not necessarily be suitable across the entire 26-year horizon. In other words, simulating with all 26 years of data input will result in different operations for the first 4 years, as compared to just using the same 4 years.

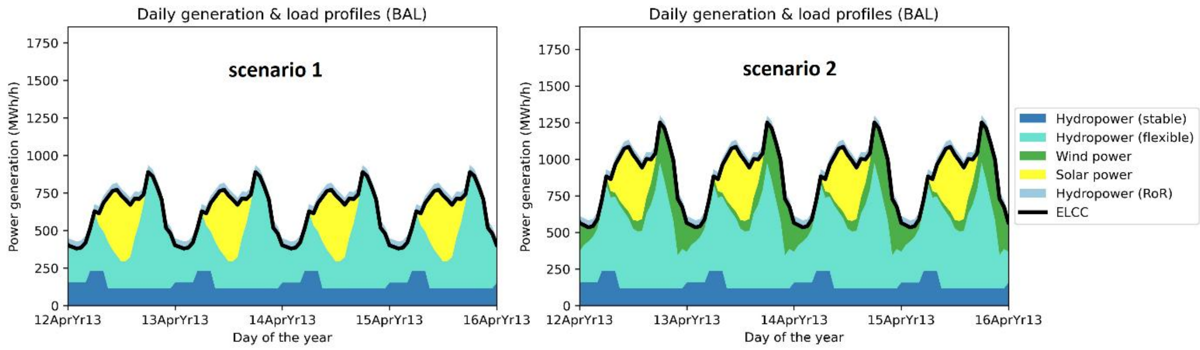
It can be seen that the time series of lake volume reach a minimum in year 9, which follows a consecutive 2-year dry period. To design the overall hydropower operation, REVUB takes into account the presence of such periods, and ensures that the hydro-VRE joint operation does not pose undue strain on reservoirs in already dry periods. Hence, the overall potential for VRE support from the hydro plant may result somewhat lower when running on the 26-year period, as compared to your initial 4-year run in Task 2.1 in which such consecutive dry periods are not present, as the 26-year period requires somewhat more conservative operation.

The monthly power generation for an example year (here, year 13) is shown below for both scenarios (Figure 4 in the produced output).



We observe that (i) the scenario with a solar-wind mix allows a higher load to be followed, and (ii) there appears to be good hydro-wind complementarity at seasonal level.

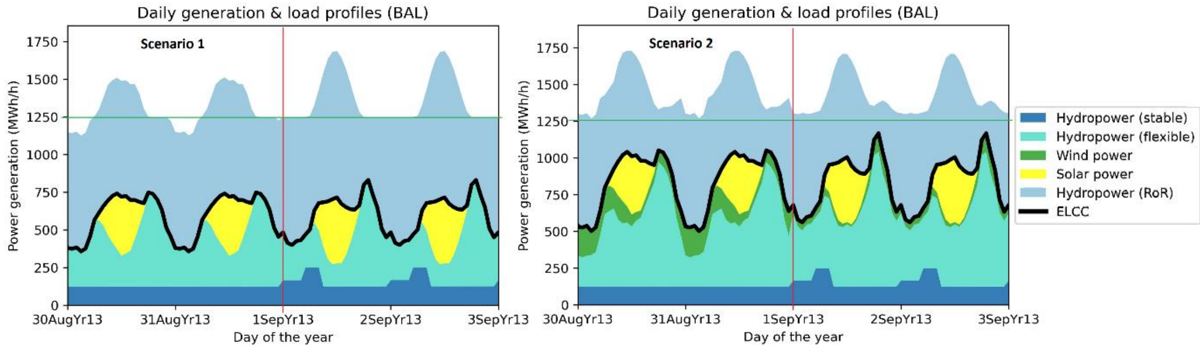
Observing the hourly dispatch graphs for both scenarios (Figure 6), we further see that there is also a day-night complementarity between solar PV and wind power in scenario 2. This reduces the burden on hydropower to provide balancing services during night and improves the overall load-following potential of the hydro-VRE portfolio.



This example of hourly dispatch pertains to April, which is one of the driest months of the year. Let us examine what happens in the wet months, when the seasonal (run-of-river) component of power output becomes important. This can be done by going back to the Excel file *plotting_settings.xlsx*, in whose worksheet "*Plot power output (single HPP)*" we can change *plot_month* to a wetter month, such as August (*plot_month* = 8).

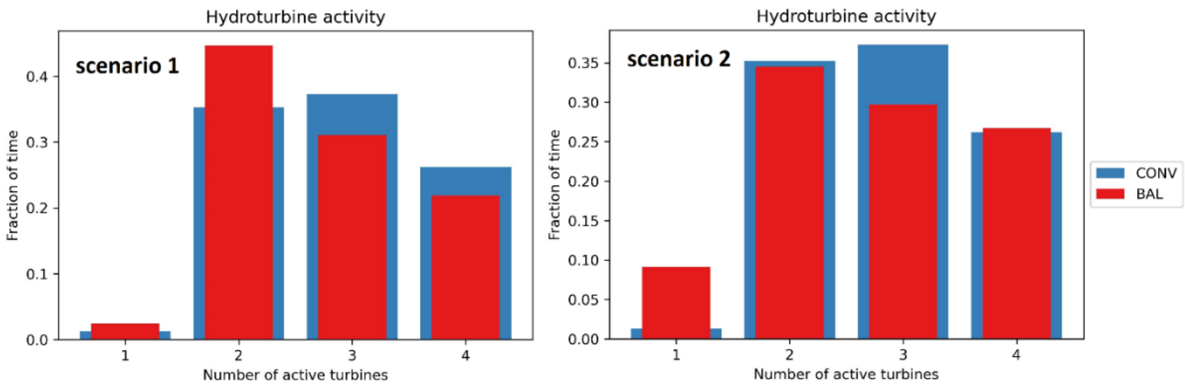
In the below figure, we consider the transition from August to September in year 13 (this can be done by choosing a day late in August to start the plot, e.g. *plot_day_month* = 30). Since we are using inflow at monthly resolution, results will show a corresponding change from August to September in the run-of-river component of power generation. In the figure, maximum hydropower generation from the King Floribert HPP (1250 MWh/h) is indicated with a green horizontal line.

In August, hydropower generation only reaches this maximum occasionally. In September, however, as the river reaches its maximum flow (see Figure 4 of the produced output), the hydroturbines get "maxed out" as a rule—there is so much water entering the reservoir that it all has to be turbined to prevent the reservoir from overflowing. This means that the hydropower plant operation reverts to a type of "baseload": the plant runs at 100% capacity factor during September, and cannot ramp up (because there is no upward capacity left) or down (because this would cause unwanted reservoir overflow) to provide flexibility. In such months, the hybrid hydro-VRE plant basically produces a flat hydropower profile with the solar PV and wind profiles on top.



Note that this has no effect on the guaranteed load (ELCC) that the hydro-VRE plant can meet during those wet months. However, it does mean that the hydro-VRE complex, during those months, does not act as a "single unit" from the point-of-view of the grid anymore—rather, the hydro output and VRE output become effectively decoupled during those months.

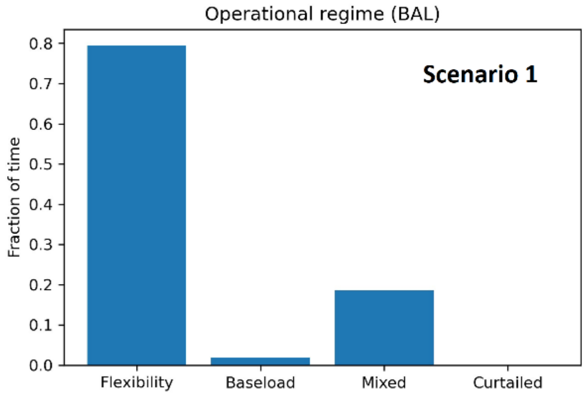
The histograms of hydroturbine activity (produced Figure 8), as before, show the distribution of the number of turbines active simultaneously. It can be seen that, when moving from a solar-only portfolio towards a 50/50 solar/wind portfolio, the extremes of the distribution increase. In other words, there are more moments with very low hydropower generation (only a single turbine active, often at minimum load), but also more moments with all turbines active (and in some cases, maxed out and reverting to "baseload" generation). This is because wind generation generally shows more volatility than solar generation, which is quite predictable between day and night. One of the implications is that while a solar/wind portfolio overall helps to lift the total load-following capability of the hydro-VRE complex, adding wind to the portfolio does introduce additional operational difficulties and would require a wider range of operation of the hydropower plant.

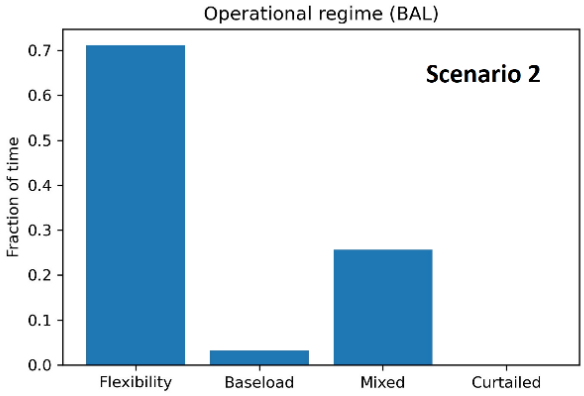


Lastly, Figure 9 of the produced output provides more details on the month-to-month type of operation that the hydropower plant can perform. The figure shows a bar chart in which four different modes of operation are shown:

- "*Flexibility*" (the hydropower plant can ramp up and down, as in the April example earlier);
- "*Baseload*" (the hydropower plant is temporarily running at 100% capacity factor and cannot provide flexibility, as in the September example above);
- "*Mixed*" (the hydropower plant is hovering close to 100% capacity factor and now and then the maximum is reached, as in the August example above); and
- "*Curtailed*" (when droughts force the hydropower plant to stop producing; this does not occur in the above example, but see Task 3.2).

For hybridised hydro-VRE operation, it would be ideal for the hydropower plant to be 100% in the "flexibility" range, so the hydro-VRE complex can act as a single unit (as seen by the grid) all the time. In reality, the physical characteristics of river flow, combined with the physical limitations of turbine capacity and reservoir size, often preclude this. Yet, in the example of King Floribert HPP, fed by an extremely seasonal river, the hydropower plant is able to act fully flexibly between 70% to 80% of the time, which is quite a satisfactory result.





REVUB script C provides a number of readymade figures for immediate analysis and investigation, of which we have discussed a few above. Aside from this, a large number of other parameters and outputs can be extracted and/or derived from the output of script B in the workspace. Let us investigate some of the statistics of the hydropower-VRE complex from here. The below table provides an extract of some of the most important data (yearly data given as averages across the time horizon); please verify that you obtain the same numbers.

	Hybridised with solar only	**Hybridised with solar-wind mix**	**How to obtain/derive from REVUB parameter**
Hydropower capacity (MW)	1250	1250	n.a. (data input)
Average hydropower CF (%)	57%	58%	Taking the average of *CF_hydro_BAL_hourly* across its first two dimensions (hours, years) for the correct scenario (third dimension).
Solar PV capacity (MW) supported by the hydropower plant	636	642	Taking the average of *c_multiplier_BAL* across its first dimension (years) for the correct scenario (second dimension), and multiplying with this scenario's value of *c_solar_relative*.
Wind capacity (MW) supported by the hydropower plant	0	642	Idem, but using *c_wind_relative* instead of *c_solar_relative*.
Average hydropower generation (GWh/year)	6261	6315	Taking the average of *E_hydro_BAL_yearly* across its first dimension (years) for the correct scenario (second dimension), and dividing by 10^3 to convert MWh to GWh.
Average solar power generation (GWh/year)	1131	1144	Idem, but using *E_solar_BAL_yearly*.
Average wind power generation (GWh/year)	0	2045	Idem, but using *E_wind_BAL_yearly*.
Average total hydro-VRE generation E_{total} (GWh/year)	7393	9504	Sum of the three above
Total followed load (GWh/year), also known as Effective Load Carrying Capability (ELCC)	5433	7640	Taking the average of *ELCC_BAL_yearly* across its first dimension (years) for the correct scenario (second dimension), and dividing by 10^3 to convert MWh to GWh.
ELCC / E_{total}	73.4%	80.3%	The ratio of the two above lines

P_{90} guaranteed power (MW)	516	719	*P_BAL_total_guaranteed*
P_{90} guaranteed generation (GWh)	4520	6301	*P_BAL_total_guaranteed* multiplied by 8.76 (number of hours in a year divided by 10^3 to convert MWh to GWh)

What we learn from this exercise is that the hybridisation with solar and wind, as opposed to with solar only, has the following advantages:

- A small (1%) increase in hydropower generation from the plant, and in solar PV generation in the portfolio. This is because the seasonal complementarity between hydro and wind, which is much more pronounced than that between hydro and solar (albeit it exists too), allows to keep more water in the reservoir in the driest months of the year and requires higher releases in the wet season instead. This keeps lake levels more stable throughout the year, allowing higher hydraulic head. This higher hydraulic potential then, in turn, allows more solar PV integration too.

- A 29% increase in the total power generation in the hydro-VRE portfolio. The combination of hydro, solar and wind together gives a substantially larger portfolio than hydro-solar alone.

- A 41% increase in total followed load. The strong three-way complementarities at diurnal and seasonal scale allow for this substantial increase.

- A 39% increase in the P_{90} guaranteed power generation from the hydro-VRE portfolio.

We now have a tentative answer to the first research question posed at the start of this document:

(i) Given the information we have on the design of the hydropower project, how many MW of solar and/or wind could we deploy alongside the project so that the hybrid hydro-VRE complex could effectively operate as a single unit (from the point-of-view of the grid)?

Answer: *Depending on the precise mix of solar and wind resources to be hybridised with the hydropower plant, the hybridisable VRE capacity could be at least around 600 MW (solar-only) and potentially up to roughly 1300 MW (portfolio with 1:1 solar-wind mix). A side-note must be made that the hydro-VRE complex will be able to act as a "single unit" for about 70%–80% of the time, again depending on the precise mix of solar and wind, and the hydro plant will mostly revert to baseload operation during the remaining time (corresponding to the wettest months of the year, when the reservoir is at near-full capacity).*

As a next step, one could think of running REVUB tests for other solar:wind ratios and using various criteria to select an "ideal" solar:wind ratio. For instance the ratio at which ELCC/E_{total} reaches its maximum value, or the ratio at which the plant runs maximally in "flexibility" mode. (Of course, there may be non-REVUB-based criteria conceivable too, e.g. available land to host either solar PV or wind power plants.)

Task 3.2: Operation under extremes

In the previous section, we saw that the operation of King Floribert HPP would not have to undergo any curtailment resulting from drought. In this task, we want to investigate what would happen if an anomanously dry year were to ever occur, and how operation could be safeguarded against negative consequences in such cases.

You have not yet been given any data on such anomalous droughts occurring, but want to run a test nonetheless. You decide to go with an extreme example: let us assume that a single year happens in the 26-year series in which the river falls completely dry. This obviously represents an unrealistic situation, but can be instructive to understand how to potentially deal with trends towards more extremes.

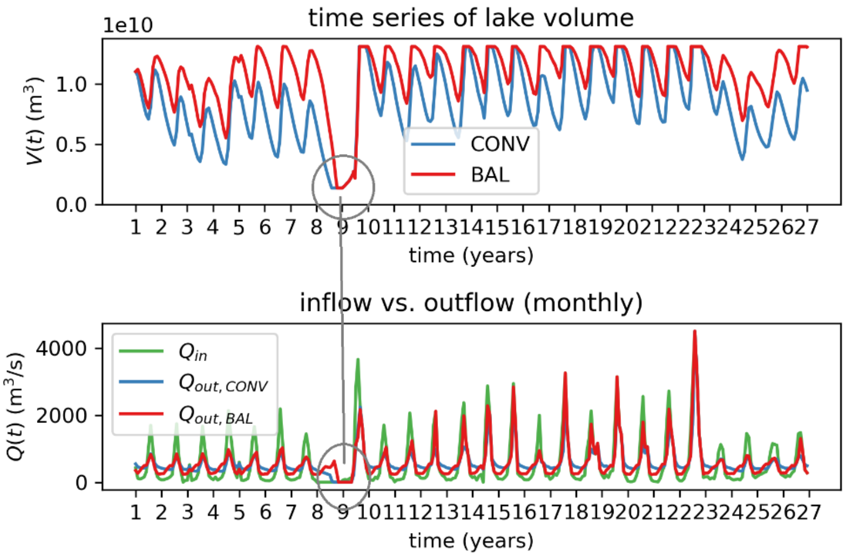
In the file file *raw_data.xlsx*, worksheet "*inflow (drought)*", an inflow dataset (data format "1"; see Task 1.3) has been prepared that contains such an anomalous year. The inflow dataset is identical to the one you used earlier, with two artificial changes: the entire inflow in the year 1987 has been set to 0, and the 1987 inflow has been added instead to the year 2001. (The latter is so that the long-term average flow across the entire data series remains unchanged, in the context of "all else being equal").

Using what you learnt above, through the read-in template *rearrange_data_template.xlsx* and the Python script *rearrange_data_monthly_to_hourly.py*, now set up an alternative inflow dataset for REVUB based on this *inflow (drought)* time series. Make sure to create a new worksheet, called e.g. "*King Floribert dry*", in the Excel file *data_inflow.xlsx* to host this dataset. In the master file, create a new scenario in which the inflow dataset is replaced by this new one, as shown below.

	A	B	C	D	E
1	HPP_name	name of hydropower plant in simulation	King Floribert HPP	King Floribert HPP with wind	King Floribert dry
2	HPP_active	used to include (= 1) or exclude (= 0) plant from current run	0	0	1
3	HPP_name_data_inflow	name of corresponding worksheet in the "data" Excel sheets from which to pull data on reservoir inflow (hourly inflow in m^3/s; hours in rows, years in columns)	King Floribert	King Floribert	King Floribert dry
4	HPP_name_data_precipitation	name of corresponding worksheet in the "data" Excel sheets from which to pull data (precipitation flux in kg/m^2/s; hours in rows, years in columns)	King Floribert	King Floribert	King Floribert
5	HPP_name_data_evaporation	name of corresponding worksheet in the "data" Excel sheets from which to pull data (evaporation flux in kg/m^2/s; hours in rows, years in columns)	King Floribert	King Floribert	King Floribert
6	HPP_name_data_outflow_prescrit	name of corresponding worksheet in the "data" Excel sheets from which to pull data on prescribed (environmental/irrigation) outflow (hourly in m^3/s; hours in rows, years in columns)	King Floribert	King Floribert	King Floribert
7	HPP_name_data_CF_solar	name of corresponding worksheet in the "data" Excel sheets from which to pull data (hourly solar CF as fraction/percentage; hours in rows, years in columns)	Solar near King Floribert	Solar near King Floribert	Solar near King Floribert
8	HPP_name_data_CF_wind	name of corresponding worksheet in the "data" Excel sheets from which to pull data (hourly wind CF as fraction/percentage; hours in rows, years in columns)	Wind near King Floribert	Wind near King Floribert	Wind near King Floribert
9	HPP_name_data_load	name of corresponding worksheet in the "data" Excel sheets from which to pull data (hourly load normalised to a mean of unity)	Flexibar	Flexibar	Flexibar
10	HPP_name_data_bathymetry	name of corresponding worksheet in the "data" Excel sheets from which to pull data (first column: volume in m^3; second: surface area in m^2; third: head in m)	Lake Floribert	Lake Floribert	Lake Floribert
11	c_solar_relative	fraction of solar in the solar/wind portfolio	1	0.5	0.5
12	h_max	maximum head in m	219	219	219

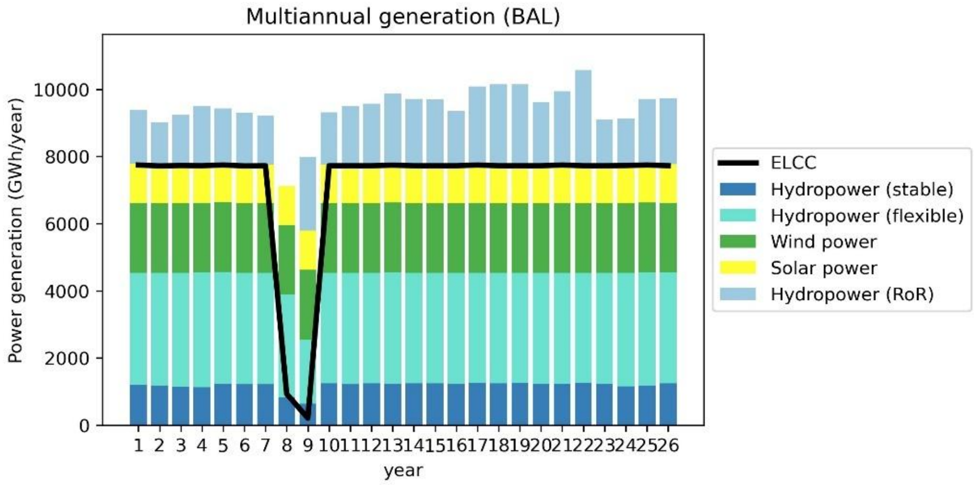
In this example, we will continue working with a solar:wind ratio of 1:1 for demonstration purposes, but feel free to test with 1:0 as well or instead.

Once you have run REVUB, one of the most important effects of the changed inflow time series is apparent in Figure 3 of the produced output. You should obtain a graph roughly like the below. It is apparent that the absent inflow in year 8 leads to a precipitous drop in lake levels.



The effect of this drop is so strong that the lake levels eventually reach critical levels at which hydropower production has to be curtailed. (This level is defined in the input data through the parameter *f_stop*; it should reflect the physical parameter of the level at which the "dead volume" of the hydropower reservoir is reached. For King Floribert Lake, the dead volume is 10% of its maximum volume according to the data which you were given (*f_stop* = 0.10; see Task 1.5), and after a drought occurrence, hydropower production only restarts once lake levels have recovered to 20% (*f_restart* =0.10).

As a result, starting in year 8 of the simulation, the hydropower generation gets curtailed for a while until lake levels recover in the following year. This is seen from Figure 5 of the produced output, which shows year-to-year generation and followed load:



Clearly, the extreme drought leads to a loss of hydropower generation and concurrent loss of load-following capabilities of the hydro-VRE complex in year 8, which takes until year 10 to fully recover from. (And we are not even talking of the irrigation scheme downstream yet, which will be deprived of river water for a similar period!)

The reason why this anomaly happens is because the overall operation scheme of hydro flexibility is based on long-term flow statistics, and does not *a priori* take into account the extremes that may occur (since this is impossible to do in real life, as such extremes cannot be predicted with certainty)[5]. If we want the hydropower operation to be more robust to such extremes, we have to be more prudent with certain operational parameters. Here, we will show one example of how this could be done.

The reservoir releases water in a regulated way for two reasons: (i) provision of minimum turbine load (as defined by the parameter "*min_load_turbine*"; see Task 1.5) and meeting downstream irrigation objectives, and (ii) provision of flexibility services to VRE to allow the hydro-VRE complex to operate as a single unit. Since (i) is considered a fixed outflow, and reducing it on purpose would harm downstream agriculture, we will focus only on (ii). If we lowered the flexibility services of the hydropower reservoir *on purpose*—i.e. lowering the amount of storage in active use, and reducing the size of the hybridisable VRE capacity—we might be able to prevent lake levels from dropping so fast during a failed rainy season, and thus more easily bridge very dry periods.

We can try this by changing one input parameter that we have not dealt with so far. It is the parameter *f_reg*, found in the sheet "*other technical parameters*" in the file *raw_data.xlsx*, where it was left empty. The parameter represents the fraction of total incoming water that is allocated for *regulated use*. Here, "regulated" encompasses both element (i) and element (ii) in the paragraph above.

In line with the file *raw_data.xlsx*, you have left this parameter empty in the master file until now, as REVUB usually calculates a default value based on the reservoir size (i.e. a determination of the amount of regulatable water flow based on the physical capabilities of the reservoir to store inflow). However, it is possible in

[5] We recall that the REVUB code is written to reject any solutions of hydro-VRE operation that would result in worse hydropower drought than what would happen under conventional hydropower operation. In other words: in terms of avoiding hydropower curtailment, REVUB solutions are always *at least as good* as what would have happened anyway under regular baseload-oriented hydropower operation without VRE.

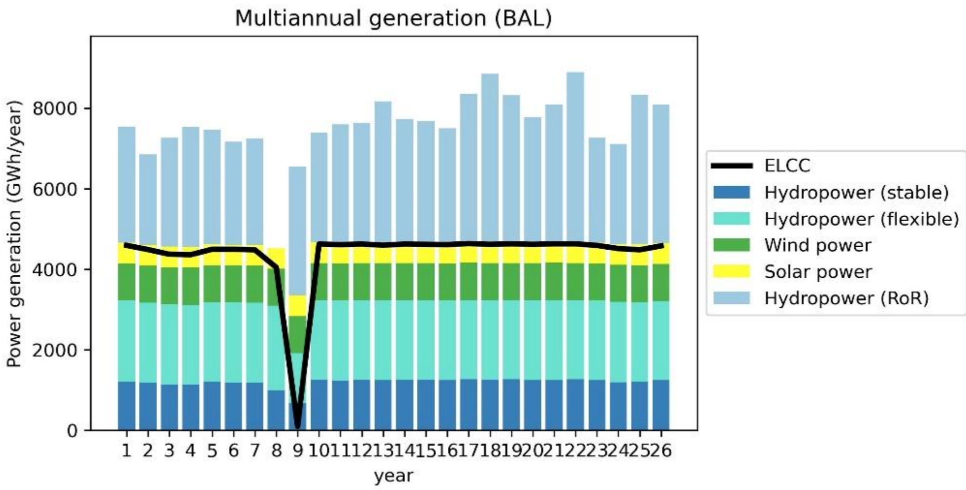
REVUB to override this default by providing your own value, which could be both higher or lower than the default, and based on any user-defined parameter (e.g. P_{90} flows).

In the scenarios you ran in Task 3.1, the value of *f_reg* was 0.74 (check the REVUB output to verify!). We will now run a scenario in which we reduce it on purpose to 0.50, meaning that we forego roughly one-third of the regulation capabilities of the reservoir on purpose. While this lowers the amount of hybridisable VRE, it also results in less strain on the reservoir during dry periods.

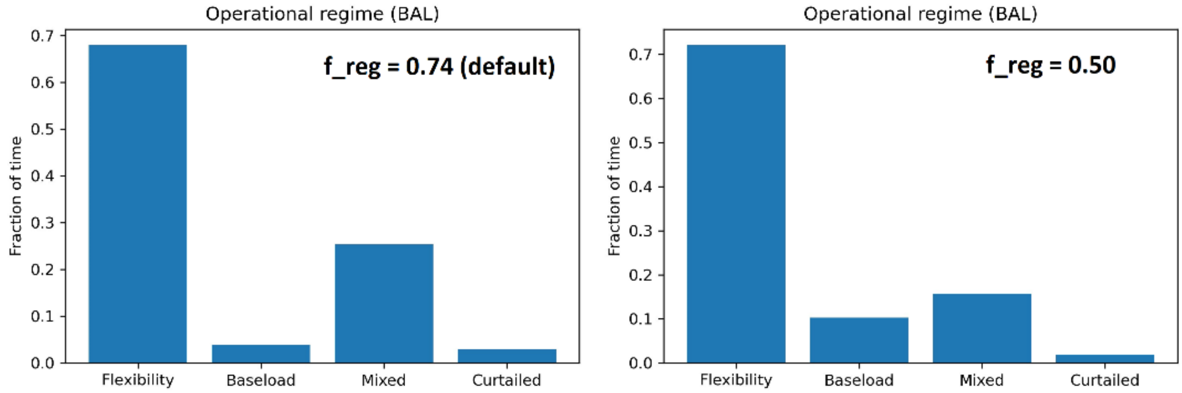
All you have to do is enter a value in the *f_reg* row in the master file, as in the example below, and re-run:

	A	B	C	D	E	F
1	**HPP_name**	name of hydropower plant in simulation	***King Floribert HPP***	***King Floribert HPP with wind***	***King Floribert dry***	***King Floribert dry mitigate***
2	**HPP_active**	used to include (=1) or exclude (=0) plant from current run	0	0	0	1
9	**HPP_name_data_load**	which to pull data (hourly load normalised to a mean of unity)	Flexibar	Flexibar	Flexibar	Flexibar
10	**HPP_name_data_bathymetry**	name of corresponding worksheet in the "data" Excel sheets from which to pull data (first column: volume in m^3; second: surface area in m^2; third: head in m)	Lake Floribert	Lake Floribert	Lake Floribert	Lake Floribert
11	**c_solar_relative**	fraction of solar in the solar/wind portfolio	1	0.5	0.5	0.5
12	**h_max**	maximum head in m	219	219	219	219
13	**A_max**	maximum lake area in m^2	2.0E+08	2.0E+08	2.0E+08	2.0E+08
14	**V_max**	maximum lake volume in m^3	1.4E+10	1.4E+10	1.4E+10	1.4E+10
15	**V_initial_frac**	initial filling fraction of lake volume	0.8	0.8	0.8	0.8
16	**P_r_turb**	installed capacity in MW	1250	1250	1250	1250
17	**Q_max_turb**	maximum discharge (total of all turbines) in m^3/s	1000	1000	1000	1000
18	**no_turbines**	number of turbines (units)	4	4	4	4
19	**eta_turb**	turbine efficiency as fraction	0.8	0.8	0.8	0.8
20	**dP_ramp_turb**	turbine ramp rate in % of full capacity / min	0.03	0.03	0.03	0.03
21	**f_stop**	fraction of lake volume at which production stops	0.1	0.1	0.1	0.1
22	**f_restart**	fraction of lake volume at which production restarts after stopping	0.2	0.2	0.2	0.2
23	**f_opt**	optimal filling fraction f_opt (eq. S4, S5)	0.8	0.8	0.8	0.8
24	**f_spill**	fraction f_spill beyond which spilling starts (eq. S7)	0.95	0.95	0.95	0.95
25	**f_reg**	***[leave empty if unsure - default determined by storage size will be used]*** which fraction of the incoming water is allocated for regulated use				0.5
26	**min_load_turbine**	minimum load on one single turbine to ensure high-efficiency range (fraction)	0.3	0.3	0.3	0.3
		[leave empty if unsure - default determined by minimum turbine				

Once you have run the REVUB simulation, you will see in the output that this strategy has indeed alleviated the consequences of the mega-drought. For instance, Figure 5 of the output shows that this time, the hydropower plant recovers from the drought within the same year, instead of spanning two years as in the earlier example with default *f_reg*. This comes at the price of a higher overall allocation of water to the run-of-river component, leaving less for the flexibility component and thus lowering the amount of hybridisable VRE. In this case, the size of the VRE component hybridisable with King Floribert HPP drops from roughly 1300 MW at *f_reg* = 0.74 (default) to roughly 600 MW at *f_reg* = 0.5 (in both cases, made up of 50% solar and 50% wind).



The effect of lowering *f_reg* is furthermore visualised by Figure 9 of the produced output. Comparing between both scenarios, it is clear that lowering *f_reg* reduces the amount of time the plant has to spend inactive due to the megadrought.



This example shows how the standard operation of the hydropower plant could be adapted to preclude, or at least reduce, the impact of anomanously dry events happening. The example used is very drastic and would never occur in reality, but it is instructive in showing how various model elements interact.

We note that—whether anomalously dry years appear or not—one could also do the opposite: boost *f_reg* on purpose to increase the potential for providing flexibility services, and thus reaching a higher VRE capacity to integrate in the hydro-VRE complex. This would come at the cost of increased risk of curtailment by overdrawing the reservoir in relatively dry years. Depending on reliability criteria of the hydropower plant—as e.g. according to P_{90} reliability indicators—this might be an acceptable risk to take.

We are now ready to answer our second question, posed at the start of the document:

(ii) How would the hybrid hydro-VRE plant function under extreme situations, e.g. droughts?

Answer: *Depending on the severity of the drought, the hydropower reservoir might not refill in time and hydropower might have to be curtailed, in which case the hydro-VRE hybrid plant reverts to a VRE-only plant for the time it takes to reactivate the reservoir. The hydropower plant operators could reduce the severity of such events by downsizing the VRE added to the hybrid plant on purpose and accordingly adapting the flexible hydropower operation. Whether this is a sensible idea or not depends on the overall criteria for reliability placed on the hydropower plant.*

Conclusion

Congratulations, you have successfully run various scenarios of hybrid hydro-VRE operation for the King Floribert Hydropower Plant, and the Bank is happy about the information you have provided.

They are particularly intrigued by (i) the high difference that a balanced solar-wind portfolio makes, as compared to solar-only, and (ii) are happy to know that the reservoir would still have sufficient regulation capabilities even if operation is designed in a prudent way to alleviate the effect of potential megadroughts.

You are encouraged to explore more scenarios and dive into more of the outputs provided by REVUB. This training dataset only showed a selection of the possibilities.

Acknowledgements

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Any comments or suggestions for improvements in the training dataset are appreciated and may be communicated to the author at sebastian.sterl@vub.be.