REVUB: User Manual

Sebastian Sterl

Vrije Universiteit Brussel (VUB), Brussels, Belgium
Contact: sebastian.sterl@vub.be

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Contents

The REVUB model ("Renewable Electricity Variability, Upscaling and Balancing") was developed specifically to address the challenge of optimising hydro-solar-wind complementarity through smart hydropower operation and smart choice of solar-wind portfolios. We first explain the general principles of the REVUB model (Note 1), based on which the different modules of the model are explained one by one: hydropower plant classification (Note 2); simulation of hydropower generation and reservoir dynamics (Note 3); and simulation and optimisation of joint hydro-solar-wind operation (Note 3 - Note 5). An optional, additional assessment of pumped-storage potential with REVUB is described in Note 6. Some notes on spinning reserve requirements are summarised in Note 7. An overview table of terms and symbols used in the model description is given in Note 8. The REVUB code exists for Python and MATLAB environments and can be accessed via `https://github.com/VUB-HYDR/REVUB` and used under the MIT license. All equations given in this document are referenced in the code wherever relevant/used. The ways to prepare input, run the code, and interpret output are given in Note 9, Note 10 and Note 11. Examples of REVUB use in literature are enumerated in Note 12.

Note 1 Principles of REVUB

The basic idea of REVUB is to assess the potential of reservoir hydropower to assist in the grid integration of variable power generation, e.g. from solar PV and wind power. Since reservoir hydropower can be flexibly dispatched, the premise is that every hydropower plant can help compensate for part of the variability of the pooled solar/wind resources on the same grid[1,2]. This requires adaptations, down to hourly resolution, of the conventional reservoir rule curves applied to keep reservoir water levels within acceptable ranges on seasonal and multiannual time scales.

REVUB calculates the adapted rule curves required for balancing a given solar/wind mix, and optimises the amount of solar/wind power whose variability each hydropower plant can compensate, based on three criteria: (i) reservoir lake levels must remain stable under the new rule curves, comparably to conventional reservoir operation, on seasonal and multiannual time scales; (ii) the resulting hydro-solar-wind power mix must be reliable, i.e. capable of consistently meeting a certain load from hour to hour, month to month and year to year without failure (unless, in rare cases, extreme droughts force hydropower curtailment); and (iii) downstream environmental flow constraints are never to be violated. An overview of the calculation steps performed by REVUB is given in Fig. S1. The steps outlined in this chart are described in more detail in the next sections, as indicated.

Note 2 Hydropower plant categorisation

In REVUB, hydropower plants are categorised into two groups, based on whether the average natural inflow would take more or less than one year to fill the reservoir; in other words, whether the reservoir is "large" or "small" compared to the inflow. For plants in the "large" category, rule curves can be designed to ensure outflow and power output are relatively stable from month to month[3,4], enabling the plant to serve as baseload provider. Such rule curves typically boil down to parameterisations of required outflow as a function of lake level[5]. For hydropower plants in the "small" category, rule curves should additionally take into account that during the wet season(s), certain fractions of the received water need to be directly released from the reservoir without being stored, as reservoir capacity would be insufficient for this[6]. Small hydropower plants thus operate partly as run-of-river plants.

In mathematical terms, the classification of hydropower plants as "large" or "small" is done by calculating the dimensionless filling time τ_{fill}:

$$\tau_{fill} = \frac{V_{max}/T_{year}}{\overline{Q_{in,nat}(t)}}, \tag{S1}$$

where V_{max} is the reservoir volume (in m^3), T_{year} is the number of seconds in a year, and $Q_{in,nat}(t)$ denotes natural reservoir inflow (in m^3/s). By default, hydropower plants are classified by REVUB as large or small based on whether their τ_{fill} is larger or smaller than unity, respectively; but this can be changed by the user.

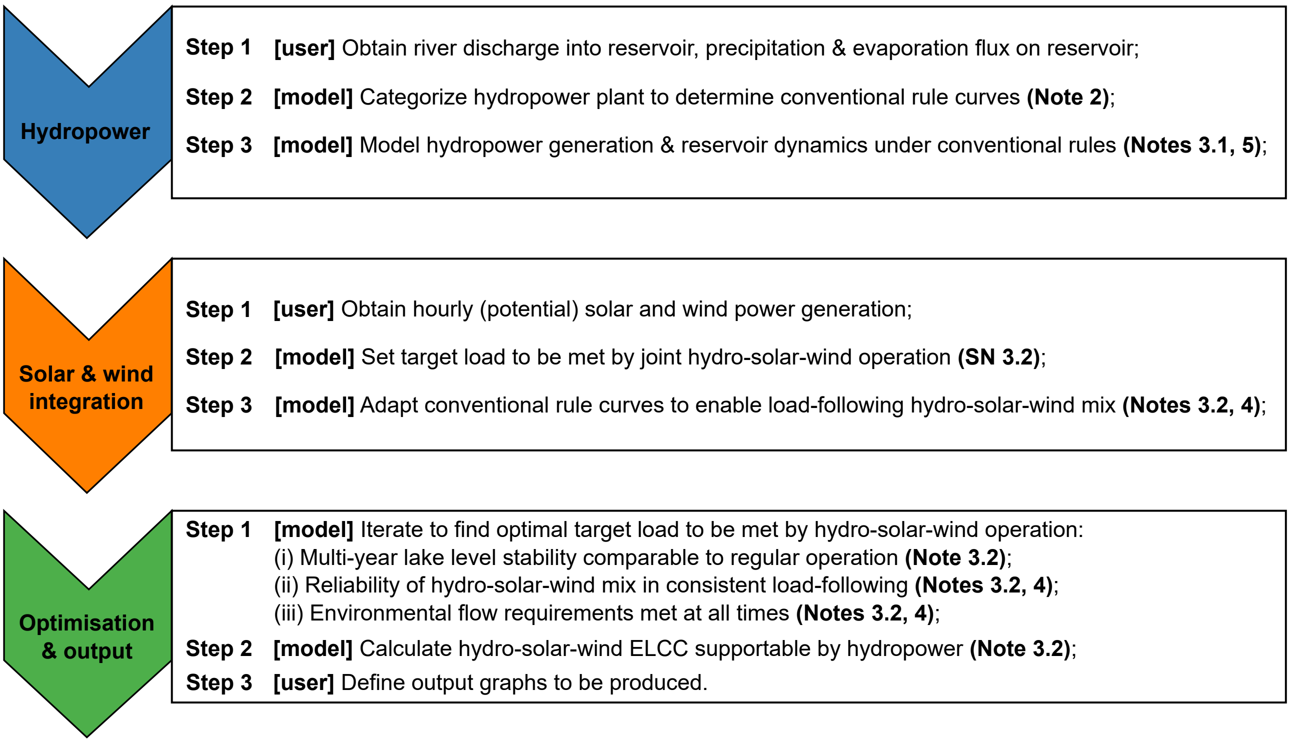

Figure S1: **Flowchart of the REVUB model approach**, explaining the steps taken in modelling hydro, solar and wind power and their integration. ELCC = Effective Load Carrying Capability. See also Note 9, Note 10 and Note 11 he for the ways to prepare input, run the code, and interpret output.

Regardless of whether a plant is classified as large or small, it could be operated according to alternative rule curves with similar seasonal to multiannual outcomes as those resulting from conventional operation, but with additional patterns in water release from sub-daily to seasonal timescales, designed for balancing supply with demand in a power mix with a high share of variable renewable electricity (RE). This would mean allocating a portion of the inflowing water for flexible use and releasing it to generate extra power whenever needed to meet a certain load, such as during evening and night hours when solar PV output is low or zero.

Even for large hydropower plants, only part of the water intake can be allocated for flexible use, as a minimum stable outflow usually has to be guaranteed for at least two reasons: (i) safeguarding power system stability, since requirements for inertia impose having some synchronous capacity, such as from hydroturbine-driven generators, dispatched at all times[7]; and (ii) safeguarding downstream ecological integrity[8]. Thus, reservoir outflow must have a stable and a flexible component, which are denoted respectively $Q_{stable}(t)$ and $Q_{flexible}(t)$ (both in m^3/s). Overall flexibility can be increased by reducing $Q_{stable}(t)$ in favour of $Q_{flexible}(t)$. Essentially, to allocate a certain amount of water for flexible use, the stable outflow will have to be reduced by a comparable amount such that the overall water budget remains unchanged.

Total reservoir outflow may have two other components: a seasonal ("run-of-river") component, denoted $Q_{RoR}(t)$, for small hydropower plants; and an overflow-prevention component[5] $Q_{spill}(t)$, representing the release of water via spillways when filling levels approach critical values, e.g. during extremely wet periods. Thus, total reservoir outflow $Q_{out}(t)$ is, in general, given by

$$Q_{out}(t) = Q_{stable}(t) + Q_{flexible}(t) + Q_{RoR}(t) + Q_{spill}(t), \tag{S2}$$

for both large and small hydropower plants. Correspondingly, hydropower generation consists of components $P^{hydro}_{stable}(t)$, $P^{hydro}_{flexible}(t)$ and $P^{hydro}_{RoR}(t)$ (in MW) [i].

[i]It is assumed that overflow prevention releases are never used for power generation, to avoid damaging turbine equipment and because such high flows would normally exceed turbine capacity anyway.

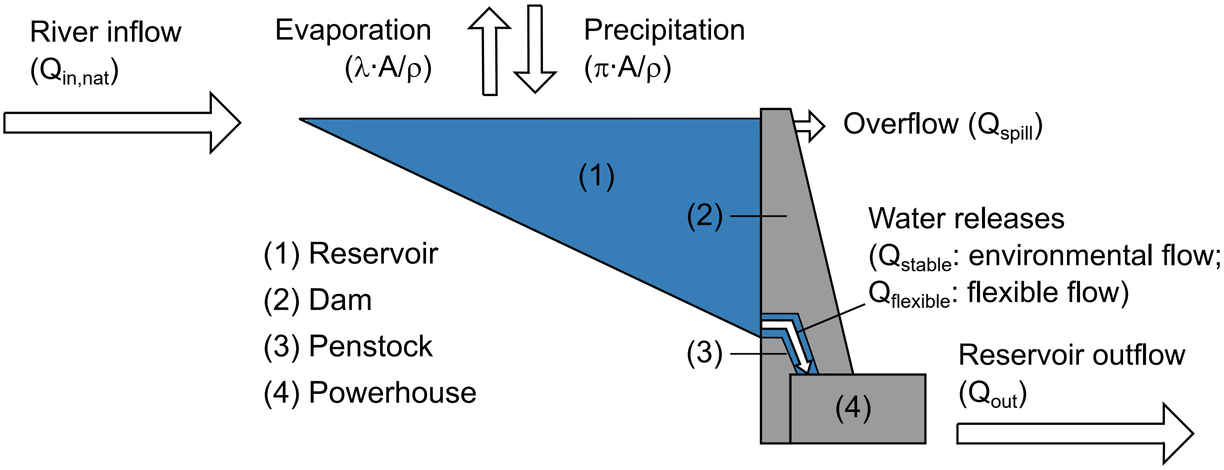

Figure S2: **Flowchart of the water gains and losses of a large hydropower plant as modelled in REVUB.** Gains consist of river discharge and lake surface precipitation; losses consist of reservoir outflows and lake surface evaporation.

In the next sections, the simulations in REVUB of flexibility provision by large and small hydropower plants are discussed in detail. Note 3 and Note 4 deal with large plants (which are the exception rather than the rule; but starting with these is informative as the mathematics are somewhat simpler); Note 5 extends the principles to small plants.

Note 3 Reservoir simulation for large hydropower plants

The volume of water $V(t)$ contained in a large hydropower plant's reservoir is given by the recursive relation

$$V(t+\Delta t) = V(t) + \left[Q_{in,nat}(t) - Q_{stable}(t) - Q_{flexible}(t) - Q_{spill}(t) + [\pi(t) - \lambda(t)]\,\frac{A(t)}{\rho}\right]\Delta t, \tag{S3}$$

where $\pi(t)$ and $\lambda(t)$ are respectively precipitation and evaporation flux (kg/m^2/s; see Methods); $A(t)$ is the surface area of the reservoir lake (m^2); ρ the density of water (taken to be 1000 kg/m^3); and Δt is the simulation time step (one hour is the default in REVUB). Seepage losses, which are usually very small in reservoirs[6,9], are neglected in the REVUB code (but could be included e.g. via a correction factor to total inflow). A schematic diagram of the involved water fluxes is given in Fig. S2.

Note 3.1 explains how $Q_{stable}(t)$ and the corresponding power generation $P_{stable}^{hydro}(t)$ are modelled for conventional, baseload-oriented operation, in which the flexible components are zero. Simulating conventional operation is necessary to have a reference time series of long-term lake volume fluctuations, based on which the balancing-oriented operation can be calibrated. Subsequently, Note 3.2 explains how $Q_{stable}(t)$ and $Q_{flexible}(t)$, and the corresponding power generation components $P_{stable}^{hydro}(t)$ and $P_{flexible}^{hydro}(t)$, are modelled for balancing-oriented operation.

Note 3.1 Conventional (baseload-oriented) operation

We denote conventional, baseload-oriented operational rules with the abbreviation "CONV". By definition, $Q_{flexible,CONV}(t)$ and $P_{flexible,CONV}^{hydro}(t)$ are zero. The default way of modelling $Q_{stable,CONV}(t)$ in REVUB is based on logarithmic-exponential release rules[4,10], which works well in case conventional operational rules are unknown, and can be determined on the basis of long-term average inflow:

$$Q_{stable,CONV}(t) = \left\{ \begin{array}{ll} \overline{Q_{in,nat}(t)}\left[d_{min} + \ln\left(\kappa\left[\frac{V_{CONV}(t)}{V_{max}}\right]^{\phi} + 1\right)\right], & \text{for } V_{CONV}(t)/V_{max} < f_{opt} \\ \overline{Q_{in,nat}(t)}\left[\exp\left(\gamma\left[\frac{V_{CONV}(t)}{V_{max}} - f_{opt}\right]^{2}\right)\right], & \text{for } V_{CONV}(t)/V_{max} \geq f_{opt} \end{array} \right\}, \tag{S4}$$

where d_{min} is the fraction of yearly average inflow required as minimum stable outflow; V_{max} is the maximum reservoir storage capacity; f_{opt} is the optimal filling fraction; and κ, ϕ and γ are constants. κ and ϕ are given[4] by

$$\kappa = f_{opt}^{-\phi} \left[\exp\left(1 - d_{min}\right) - 1\right], \tag{S5}$$

and

$$\phi = \alpha \tau_{fill}^{1/2}. \tag{S6}$$

Recommended default values are $f_{opt} = 80\%$, $\alpha = 2/3$, and $\gamma = 10$ based on generalised reservoir operation rules[4,10]; for d_{min}, values may be chosen based on generalised environmental flow rules[8] and/or requirements for minimum turbined flow to prevent turbines running at low efficiency. The overflow prevention component $Q_{spill,CONV}$ is modelled as

$$Q_{spill,CONV}(t) = \left\{ \begin{array}{ll} 0, & \text{for } V_{CONV}(t)/V_{max} < f_{spill} \\ \max\left[0, \left(Q_{in,nat}(t) + [\pi(t) - \lambda(t)] \frac{A_{CONV}(t)}{\rho}\right)(1+\mu) - Q_{stable,CONV}(t)\right], & \text{for } V_{CONV}(t)/V_{max} \geq f_{spill} \end{array} \right\}, \tag{S7}$$

where f_{spill} is the filling fraction at which the overflow prevention starts[ii], and μ represents a small fraction such that lake levels are brought below critical levels $f_{spill}V_{max}$ as quickly as possible without releasing unnaturally high flows downstream; default values are $f_{spill} = 95\%$ and $\mu = 0.1$, but these can be changed by the user.

To simulate minimum drawdown levels when facing drought-like situations, one further rule is added to equation (S4): outflow, and with it hydropower production, is automatically curtailed[5,11] if the volume levels $V_{CONV}(t)$ dip below critical levels $f_{stop}V_{max}$, and only restarted once volumes have recovered to $f_{restart}V_{max}$. The values $f_{stop} = 10\%$[11] and $f_{restart} = 20\%$ are defaults in REVUB, but can be changed by the user.

The corresponding stable power output $P^{hydro}_{stable,CONV}(t)$ can then be calculated as

$$P^{hydro}_{stable,CONV}(t) = \min\left[Q_{stable,CONV}(t); Q^{max}_{turb}\right] \eta_{turb} \rho g h_{CONV}(t), \tag{S8}$$

where η_{turb} is the turbine efficiency (%), g the gravitational acceleration (9.81 m/s^2), and $h(t)$ the hydraulic head (m), i.e. the difference in water level between the headwater behind the dam and the tailwater at the turbines. The efficiency of η_{turb} should be user-defined[iii]. The calculation of $h(t)$ is explained in Note 3.3. Q^{max}_{turb} is the maximum turbine throughput (at which the power generating capacity of the turbine is fully used), which is approximated with $Q^{max}_{turb} \approx P^{r}_{turb}/(\eta_{turb}\rho g h_{max})$, where P^{r}_{turb} is the rated power capacity of the hydropower plant and h_{max} is the maximum hydraulic head. With these rules, results are mostly independent of arbitrary initial conditions (convergence to the same time series happens typically within 2 simulation months). The initial condition $V_{CONV}(0) = f_{opt}V_{max}$ (and the corresponding lake area and water level; see Note 3.3) are defaults in REVUB, but can be changed by the user.

We note that, in case the user wishes to include their own conventional reservoir rules, this is possible by correspondingly adapting the default REVUB code by adapting the lines referring to the above equations.

Note 3.2 Balancing-oriented operation

Reservoir operation oriented towards balancing solar and wind power variability is denoted with the abbreviation "BAL". For reservoirs of large hydropower plants, BAL operation is modelled as follows. First, the needs for sub-daily to seasonal dispatching patterns must be established. The load difference

[ii]Note that every hydropower plant has a certain safety level, i.e. the dam is always somewhat higher than the maximum water level[5], to mitigate flood risk. Because of this safety level, should the overflow procedure fail for any reason, the dam would not immediately overflow. However, flooding would occur along the shores of the lake, which is why it is always prudent to prevent straining the safety level.

[iii]The efficiency of hydroturbines depends on the effective turbined flow at each moment, but is typically above 80% in realistic ranges of the latter[12,13]; the value d_{min} can be chosen such as to reflect the fact that turbines should not run at too low partial loads, at which their efficiencies can drop considerably.

$P_d(t)$ between total inflexible power generation (stable hydropower, solar power, and wind power) and power demand is calculated as:

$$\begin{aligned} P_d(t) &= P^{hydro}_{stable,BAL}(t) + c_{solar} \cdot CF_{solar}(t) + c_{wind} \cdot CF_{wind}(t) - L(t) \\ &= P_{inflexible}(t) - L(t). \end{aligned} \tag{S9}$$

Here, c_{solar} and c_{wind} represent a certain amount of solar PV and wind power capacity, respectively (in MW), whose value is to be optimised by REVUB; $CF_{solar}(t)$ and $CF_{wind}(t)$ represent the solar and wind capacity factor for each time step, respectively; and $L(t)$ represents a certain target load profile that is to be followed[iv].
The time series $L(t)$, by default, is set as follows:

$$L(t) = P_{load} L_{norm}(t), \tag{S10}$$

with P_{load} a constant determining the average load to be followed and reflecting the constraints on overproduction, and $L_{norm}(t)$ the normalized ($\overline{L_{norm}(t)} = 1$) hour-to-hour load profile. P_{load} is calculated as

$$P_{load} = p_i(P_{inflexible}(t)), \tag{S11}$$

where $p_i(x)$ denotes the i^{th} percentile of a variable x. Here, i thus represents the percentile of $P_{inflexible}$ not exceeding P_{load}; in other words, the percentage of time during which RE generation should not exceed the average load to be followed. Generally, the lower i, the higher the amount of allowed excess production (overproduction) as compared to $L(t)$.
In REVUB, the time series $CF_{solar}(t)$ and $CF_{wind}(t)$ must be provided as model input by the user. These could represent power generation from single locations, or weighted averages across the locations for on-grid solar or wind power selected for the region under scrutiny, to simulate the feed-in of solar and wind power from various locations into the same power grid. In case of the latter, we recommend assuming that the total capacity is distributed across locations within the region according to site-specific weight factors w^n_{solar} and w^n_{wind}. Then, $CF_{solar}(t)$ and $CF_{wind}(t)$ would be given by

$$CF_{solar}(t) = \frac{\sum_{n=1}^{N_{solar}} CF^n_{solar}(t) w^n_{solar}}{\sum_{n=1}^{N_{solar}} w^n_{solar}}; \; CF_{wind}(t) = \frac{\sum_{n=1}^{N_{wind}} CF^n_{wind}(t) w^n_{wind}}{\sum_{n=1}^{N_{wind}} w^n_{wind}}, \tag{S12}$$

with $CF^n_{solar}(t)$ and $CF^n_{wind}(t)$ the capacity factors of solar PV or wind power for each time step, respectively, at each individual site with index n; and N_{solar} and N_{wind} the number of sites for solar PV or wind power generation, respectively. The weight factors w^n_{solar} and w^n_{wind} represent preferences for certain sites over others for the development of solar PV and wind parks. Given that sites with a higher yield would typically tend to be preferred, a simple approach would be to take a site's weight factor to be equal to the multi-year average capacity factor for solar PV or wind power at that site:

$$w^n_{solar} = \overline{CF^n_{solar}(t)}; \; w^n_{wind} = \overline{CF^n_{wind}(t)}. \tag{S13}$$

The capacity ratio $c_{solar} : c_{wind}$ should also be user-defined; it represents the relative share of solar and wind capacity to be deployed by the model. Sensitivity tests to find an optimal ratio can then be performed by running the model for several values of the capacity ratio.
Second, in BAL operation, $Q_{stable}(t)$ is reduced in favour of $Q_{flexible}(t)$ such that $L(t)$ can be met by the combination of stable hydropower, flexible hydropower, solar power and wind power. In the REVUB code, the default approach (which can be adapted by the user) is to take $Q_{stable,BAL}(t)$ as a fraction of the average inflow:

$$Q_{stable,BAL}(t) = (1 - C_{OR})\overline{Q_{in,nat}(t)}. \tag{S14}$$

Here, the fraction C_{OR} denotes the "operating reserve coefficient"[14], and determines the amount of water available for flexible use. Theoretically, as $C_{OR} \rightarrow 1$, the hydropower plant in question would

[iv]Note that for the terms in equation (S9), MW and MWh are interchangeable units, due to the hourly time step employed in REVUB. Similarly, CF could be interpreted both as actual power generation divided by maximum potential generation in each hour (dimensionless fraction), or as power generation per unit of capacity (in hours).

operate near-completely flexibly and provide almost no minimum stable load. This would also imply that the outflow of the dam could become zero for prolonged periods; for instance, when solar/wind power generation is high and/or demand is low. Such operation would violate (i) inertia requirements and minimum load constraints of the plant, and (ii) environmental flow requirements. As default, REVUB therefore uses an upper bound of $C_{OR}^{max} = 1 - d_{min} = 60\%$, such that the minimum outflow under BAL is always consistent with that under CONV. The selection of the optimal C_{OR} for each hydropower plant is explained in Note 4.

$P_{stable,BAL}^{hydro}(t)$ is calculated analogously to $P_{stable,CONV}^{hydro}(t)$ in equation (S8):

$$P_{stable,BAL}^{hydro}(t) = \min \Big[Q_{stable,BAL}(t); Q_{turb}^{max} \Big] \eta_{turb} \rho g h_{BAL}(t). \tag{S15}$$

Third, the necessary amount of flexible outflow $Q_{flexible,BAL}(t)$ and corresponding flexibly produced power $P_{flexible,BAL}^{hydro}(t)$ are determined for the instances when $P_{inflexible}(t)$ cannot meet $L(t)$, i.e. when $P_d(t) < 0$. The following rule then applies for $P_{flexible,BAL}^{hydro}(t)$ to maximize the followed load under peak capacity constraints and ramping constraints[15]:

$$P_{flexible,BAL}^{hydro}(t) = \left\{ \begin{array}{ll} 0, & \text{for } P_d(t) \geq 0 \\ \min \Big[Q_{turb,flexible}^{pot}(t) \eta_{turb} \rho g h_{BAL}(t); \min \Big[|P_d(t)|; P_{flexible,BAL}^{hydro}(t-1) + \Delta P_{turb}^{ramp} \Big] \Big], & \text{for } P_d(t) < 0 \;\&\; \Delta P_d(t) < 0 \\ \min \Big[Q_{turb,flexible}^{pot}(t) \eta_{turb} \rho g h_{BAL}(t); \max \Big[|P_d(t)|; P_{flexible,BAL}^{hydro}(t-1) - \Delta P_{turb}^{ramp} \Big] \Big], & \text{for } P_d(t) < 0 \;\&\; \Delta P_d(t) \geq 0 \end{array} \right\}, \tag{S16}$$

where $\Delta P_d(t) = P_d(t) - P_d(t-1)$ determines whether the hydropower plant should ramp up ($\Delta P_d(t) < 0$) or down ($\Delta P_d(t) \geq 0$); ΔP_{turb}^{ramp} is the maximum ramp rate of the plant (in MW per time step); and

$$Q_{turb,flexible}^{pot}(t) = \max \Big[0; Q_{turb}^{max} - Q_{stable,BAL}(t) \Big]. \tag{S17}$$

This gives a flexible outflow

$$Q_{flexible,BAL}(t) = \frac{P_{flexible,BAL}^{hydro}(t)}{\eta_{turb} \rho g h_{BAL}(t)}. \tag{S18}$$

Fourth, the overflow prevention component $Q_{spill,BAL}(t)$ is calculated analogously to equation (S7):

$$Q_{spill,BAL}(t) = \left\{ \begin{array}{ll} 0, & \text{for } V_{BAL}(t)/V_{max} < f_{spill} \\ \max \Big[0, \Big(Q_{in,nat}(t) + [\pi(t) - \lambda(t)] \frac{A_{BAL}(t)}{\rho} \Big) (1+\mu) - Q_{stable,BAL}(t) - Q_{flexible,BAL}(t) \Big], & \text{for } V_{BAL}(t)/V_{max} \geq f_{spill} \end{array} \right\}. \tag{S19}$$

As in CONV, to ensure that lake levels do not dip precariously low, $Q_{stable,BAL}$ and $Q_{flexible,BAL}$ are reduced to zero when $V_{BAL}(t) < f_{stop} V_{max}$ and restarted once $V_{BAL}(t) \geq f_{restart} V_{max}$.

Since one needs the hydraulic head $h_{BAL}(t)$ to calculate $P_{stable,BAL}^{hydro}(t)$ from equation (S15), but $h_{BAL}(t)$ follows only from the overall operation, which requires knowledge of $P_{stable,BAL}^{hydro}(t)$ to calculate $P_d(t)$ according to equation (S9), this problem is solved iteratively by REVUB with an initial guess of $P_{stable,BAL}^{hydro}(t) = (1 - C_{OR}) P_{stable,CONV}^{hydro}(t)$, repeated until convergence (typically, 3-6 iterations suffice). The calculation of $h(t)$ is the same as for CONV and is explained in Note 3.3.

At given C_{OR} and given ratio $c_{solar} : c_{wind}$, REVUB optimises the above operation by identifying the time series $L(t) = L_{opt}(t)$, and the corresponding optimal $c_{solar} = c_{solar}^{opt}$ and $c_{wind} = c_{wind}^{opt}$, for which the resulting lake level time series is most comparable to what it would be under CONV operation. This optimisation is performed by finding the minimum of the relative deviation Ψ between the CONV and BAL lake levels across all time steps of an entire simulation period, as a function of c_{solar} and c_{wind}:

$$\Psi(c_{solar}, c_{wind}) = \frac{\overline{|(V_{BAL}(t) - V_{CONV}(t)|}}{\overline{V_{CONV}(t)}}; \tag{S20}$$

where

$$\min(\Psi) = \Psi(c_{solar}^{opt}, c_{wind}^{opt}). \tag{S21}$$

Note that the code could also be adapted to optimise lake levels compared to a certain mathematical rule curve, instead of to the outcome of "conventional" operational rules (Note 3.1). This would simply require exchanging $V_{CONV}(t)$ in equation (S20) by the corresponding rule curve of lake volume. Note furthermore that even when doing this, it is still useful to calculate the outcomes (hydropower generation and lake levels) resulting from conventional reservoir management, to verify (i) how well the rule curve can be followed *in general* under the given hydroclimate and occurrence of wet/dry years, and (ii) the extent to which the outcomes of flexible operation would differ from baseload-oriented operation.

REVUB assures that power droughts resulting from $V(t)$ dipping lower than $f_{stop}V_{max}$ can never be more severe under BAL operation than under CONV, by automatically discarding any solutions to equation (S21) where this would be the case.

Once the optimal solution is found, the Effective Load Carrying Capability (ELCC) of the hydro-solar-wind mix is calculated as follows. The maximum followable load $L_{followed}(t) = P_{followed}L_{norm}(t)$, which the hydro-solar-wind mix can meet without any load loss, is identified: this is the load at which the residual load ($L_{res}(t)$; the load minus the generation) has a maximum of zero. Thus, $P_{followed}$ is the value for which $\max\left[L_{res}(t)\right] = 0$, with $L_{res}(t)$ defined as:

$$L_{res}(t) = P_{followed}L_{norm}(t) - \left[P^{hydro}_{stable,BAL}(t) + P^{hydro}_{flexible,BAL}(t) + c^{opt}_{solar} \cdot CF_{solar}(t) + c^{opt}_{wind} \cdot CF_{wind}(t)\right]. \quad \text{(S22)}$$

The ELCC is then defined as the integral of $L_{followed}(t)$ over all time steps in a simulation year:

$$\text{ELCC} = \int_{year} L_{followed}(t)dt. \quad \text{(S23)}$$

The ELCC thus represents the total yearly load followed by each hydropower plant in combination with the solar and wind power whose variability it can compensate, under the optimal solution. The aggregate of ELCC across all hydropower plants represents the total followable load when all hydropower plants optimally contribute to compensating solar-wind variability; it is abbreviated ELCC_{tot} hereafter.

Ideally, $L_{followed}(t)$ should be equal to $L_{opt}(t)$ (and it usually is), but due to peaking constraints of hydropower plants (eq. (S17)), this is not guaranteed in every case. When $L_{followed}(t) < L_{opt}(t)$, the power plant's peaking capabilities are insufficient to meet all required peaks in $L_{opt}(t)$ together with solar and wind power. In such cases, the hydropower plant should run at somewhat lower flexibility, i.e. lower C_{OR}, at which a lower $L_{opt}(t)$ will apply that would put less strain on the plant's peaking capabilities, ensuring that $L_{followed}(t) \approx L_{opt}(t)$. This resimulation is done automatically by the REVUB code (Note 4).

The total contributions of hydro, solar and wind power to yearly electricity generation, denoted respectively $E^{hydro}_{reservoir}$, E_{solar} and E_{wind}, are obtained by integrating their respective power output across all time steps in a simulation year. First, $E^{hydro}_{reservoir}$ is equal to

$$E^{hydro}_{reservoir} = E^{hydro}_{stable} + E^{hydro}_{flexible} = \int_{year} \left(P^{hydro}_{stable}(t) + P^{hydro}_{flexible}(t)\right) dt. \quad \text{(S24)}$$

Second, E_{solar} and E_{wind} are obtained by multiplying c^{opt}_{solar} and c^{opt}_{wind} by $CF_{solar}(t)$ and $CF_{wind}(t)$, respectively, and integrating:

$$\begin{aligned} E_{solar} + E_{wind} &= \int_{year} \left(P_{solar}(t) + P_{wind}(t)\right)dt \\ &= \int_{year} \left(c^{opt}_{solar} \cdot CF_{solar}(t) + c^{opt}_{wind} \cdot CF_{wind}(t)\right)dt. \end{aligned} \quad \text{(S25)}$$

Note 3.3 Head-volume-area relationships

Calculating the hydraulic head $h(t)$ for each time step requires knowing the bathymetry and volume-area-depth relationship of each reservoir. Typical curves approximating such relationships need to be calibrated on a reservoir-to-reservoir basis. The user should provide bathymetric curves as input to each simulation. In case these are not available, we recommend using an archetypal reservoir shape function[16,17], modelling reservoirs' area-volume relationships with the equation

$$A(t) = A_{max}\left[\frac{V(t)}{V_{max}}\right]^{(1 - C_{reservoir})}, \quad \text{(S26)}$$

where $C_{reservoir} = V_{max}/(A_{max}z_{max})$ is the "reservoir coefficient", and A_{max} and z_{max} represent the maximum reservoir lake area and depth, respectively.

For any $V(t+\Delta t)$ calculated using equation (S3), the corresponding $A(t+\Delta t)$ can then be calculated using equation (S26). To obtain the hydraulic head $h(t+\Delta t)$ at each time step, the incremental change $\Delta h(t)$ is added to the head $h(t)$ of the previous time step, using the first-order approximation

$$\Delta h(t) \approx \frac{V(t+1) - V(t)}{A(t)}. \tag{S27}$$

When using equation (S26), before any simulation according to CONV or BAL in REVUB, a dummy simulation spanning all possible values of V, and thus of A and h, should be run to obtain a calibration (h, V) curve. In CONV and BAL simulations, the head $h(t+\Delta t)$ can then always be obtained from this calibration curve after $V(t+\Delta t)$ has been determined from equation (S3).

Note 4 Peaking suitability of large hydropower plants

Since hydropower plants differ in terms of peaking capabilities, operational strategies must be selected with care. If hydropower plants are operated at a too high C_{OR}, the corresponding peaks in flexible water release may exceed the maximum turbine throughput on a structural basis (cf. equation (S17)), meaning that the plant will be structurally unable to meet peak demand as well as leading to loss of spinning reserves (see Note 7). Typically, this would first occur in the seasons with highest peak demand and/or when water levels are at their lowest. Therefore, each hydropower plant's operation should happen at an optimised value $C_{OR} = C_{OR}^{opt}$ that ensures this is not the case, while maintaining adequate levels of flexibility. In REVUB, the default procedure (which can be changed by the user) is to define the turbine utilisation rate $k_{turb}(t)$ at each time step:

$$k_{turb}(t) = \frac{Q_{stable}(t) + Q_{flexible}(t)}{Q_{turb}^{max}}, \tag{S28}$$

and define hydropower plant operation (at given C_{OR}) as unsuitable for peaking purposes when $p_{99}(k_{turb})$, i.e. the 99^{th} percentile of k_{turb}, is unity (in other words, when turbine capacity is fully exhausted in at least one out of every 100 hours).
As default for each hydropower plant, REVUB uses $C_{OR}^{opt} = C_{OR}^{max}$, the maximum allowed operational flexibility. If operation is found to be unsuitable for peaking purposes at C_{OR}^{max}, the REVUB code automatically resimulates with incrementally reduced C_{OR}, until a value C_{OR}^{opt} is identified for which $p_{99}(k_{turb}) < 1$.

Note 5 Reservoir simulation for small hydropower plants

To assess the balancing potential of small hydropower plants (those with less than a year of storage), which are in reality much more ubiquitous than large hydropower plants, we define the alternative filling time $\tau_{fill,frac}$ corresponding to the amount of years it would take for a fixed fraction of the incoming flow, denoted $Q_{in,frac}(t)$, to fill the reservoir:

$$\tau_{fill,frac} = \frac{V_{max}/T_{year}}{Q_{in,frac}(t)}, \tag{S29}$$

where $Q_{in,frac}(t)$ is defined as

$$Q_{in,frac}(t) = f_{reg} Q_{in,nat}(t), \tag{S30}$$

with f_{reg} a suitable fraction, representing the fraction of incoming water available for storage and, therefore, flexible use. This fraction can be input in REVUB by the user. In case the user is unsure of a pertinent value, it can be left empty and REVUB defaults to a standard value determined by solving $\tau_{fill,frac} = 1$; that is, f_{reg} then represents the fraction of the incoming water that would take one year to fill the reservoir on average. Note that this default is very realistic for hydropower plants on rivers with extremely seasonal, unimodal discharge, but not necessarily as useful in bimodal-rainfall climates or in situations with relatively flat inflow profiles (e.g. in cases where a regulating dam is already present upstream).
Note that f_{reg} would normally be unity for the large (more-than-a-year storage) plants described in the previous sections; nevertheless, the user is free to specify a value smaller than unity for such plants

when running REVUB. This could, for instance, reflect a requirement for a seasonal environmental flow. In such a case, the operation of those plants, too, will follow what is described below, rather than what is described in the previous sections.
Once f_{reg} chosen, the fraction $Q_{in,frac}(t)$ is then assumed to be "storable" and usable for balancing. REVUB assumes that the remainder of the flow, given by $Q_{in,nat}(t) - Q_{in,frac}(t) = (1 - f_{reg})Q_{in,nat}(t)$, passes through the reservoir without being stored, thus representing the seasonal "run-of-river" component $Q_{RoR}(t)$. Since f_{reg} can be calculated based on long-term average flow, such operation can be readily implemented as long as accurate measurements of inflow are available.
The term Q_{RoR} is appended in equation (S3) (and would be an additional entry under the "water releases" arrows in Fig. S2):

$$\begin{aligned} V(t+\Delta t) &= V(t) + \left[Q_{in,nat}(t) - Q_{RoR}(t) - Q_{stable}(t) - Q_{flexible}(t) - Q_{spill}(t) + [\pi(t) - \lambda(t)] \frac{A(t)}{\rho} \right] \Delta t \\ &= V(t) + \left[Q_{in,frac}(t) - Q_{stable}(t) - Q_{flexible}(t) - Q_{spill}(t) + [\pi(t) - \lambda(t)] \frac{A(t)}{\rho} \right] \Delta t, \qquad \text{(S31)} \end{aligned}$$

and the corresponding seasonal power generation is then equal to

$$P_{RoR}^{hydro}(t) = \min \left[Q_{RoR}(t); \max \left[0; Q_{turb}^{max} - Q_{stable}(t) - Q_{flexible}(t) \right] \right] \eta_{turb} \rho g h(t). \qquad \text{(S32)}$$

Electricity generation from the hydropower component, denoted E_{RoR}^{hydro}, is then equal to

$$E_{RoR}^{hydro} = \int_{year} P_{RoR}^{hydro}(t)\ dt. \qquad \text{(S33)}$$

Dispatching such as described for large hydropower plants in the previous sections is done similarly for small hydropower plants, with the following adaptations: (i) the component $Q_{in,frac}(t)$ is used as reference flow instead of $Q_{in,nat}(t)$ in equation (S4); (ii) the rule is added that, as soon as reservoir levels drop precariously low (in this case, below $f_{restart}V_{max}$), the seasonal outflow (if nonzero) is temporarily stopped and the operation reverts to that of large hydropower plants, using the full inflow to stabilise water levels; and (iii) the seasonal power generation $P_{RoR}^{hydro}(t)$ is not included in equation (S9) as it is not expected to take part in the hour-to-hour load-following. Note, however, that if river discharge would be regulated by other reservoirs upstream in a cascade-like configuration, even $P_{RoR}^{hydro}(t)$ could become relatively stable throughout the year.

Note 6 Optional pumped-storage assessment

The REVUB code can also be used to assess the potential for increasing load-following potential by refurbishing large hydropower plants to pumped-storage schemes[15], such that excess production (typically of solar PV during mid-day) can be used to pump water back up into the reservoir, enabling the energy to be stored for use at a later stage. This would involve (i) building a downstream reservoir with volume $V_{lower,max} \ll V_{max}$ to store part of the released water, from which it can be pumped back up into the reservoir, and (ii) ensuring the turbines can be operated in reverse mode and/or pumps are installed.
The hydrological balance components then change as follows. First, since environmental flow constraints still have to be met, only the component $Q_{flexible}(t)$ can be used for filling the lower reservoir while the component $Q_{stable}(t)$ has to be directly discharged downstream. The water balance of the lower reservoir is then given by

$$V_{lower}(t+\Delta t) = V_{lower}(t) + [Q_{flexible}(t) - Q_{pump}(t) - Q_{spill,lower}(t)] \Delta t, \qquad \text{(S34)}$$

where $Q_{pump}(t)$ is the water pumped back up to the large reservoir for storage, and $Q_{spill,lower}(t)$ is the overflow component of the lower reservoir. The precipitation and evaporation terms are neglected here as the lower reservoir is assumed to have a much smaller surface area than the upper reservoir. The water balance of the large reservoir is then given (cf. equation (S3)) by

$$V(t+\Delta t) = V(t) + \left[Q_{in,nat}(t) - Q_{stable}(t) - Q_{flexible}(t) + Q_{pump}(t) - Q_{spill}(t) + [\pi(t) - \lambda(t)] \frac{A(t)}{\rho} \right] \Delta t, \qquad \text{(S35)}$$

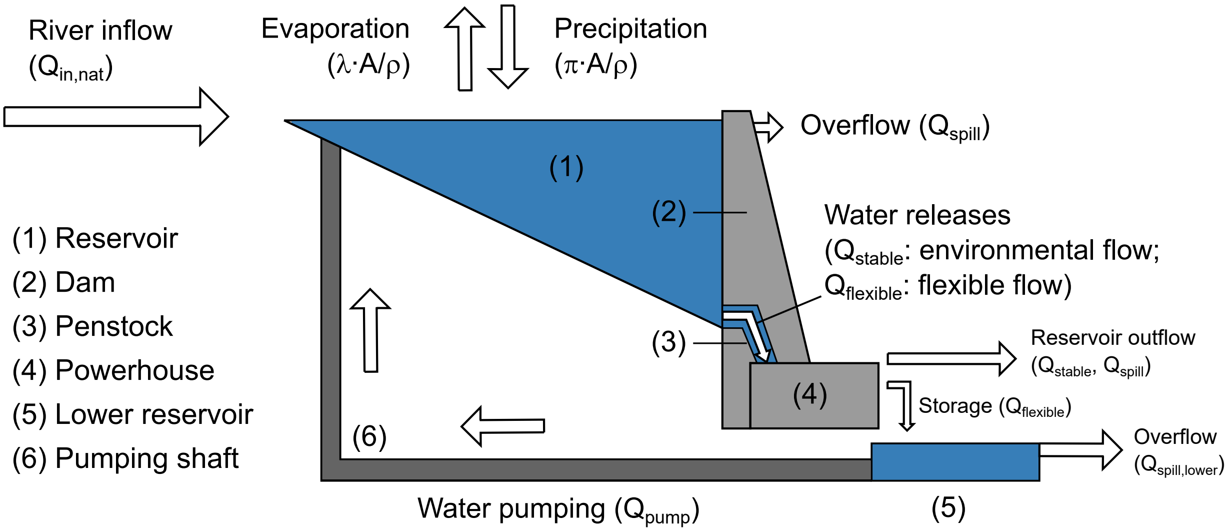

Figure S3: **Flowchart of the water gains and losses of a large hydropower plant, including pumped storage.** Water gains and losses of a hydropower plant modelled as pumped-storage plant, with an additional lower reservoir and a flow of water in the upstream direction for temporary energy storage.

and the net outflow of the pumped-storage plant is given (cf. equation (S2)) by

$$Q_{out}(t) = Q_{stable}(t) + Q_{spill}(t) + Q_{spill,lower}(t). \tag{S36}$$

A schematic of this operation is shown in Fig. S3 (cf. Fig. S2). Note that pumped-storage operation is only useful for large hydropower plants, as small plants have to continuously discharge during large parts of the year to prevent spillage, and pumping water back up would thus not serve a purpose.
The component $Q_{pump}(t)$ is calculated as follows. The power stored by pumping is given by

$$P_{pump}(t) = \left\{ \begin{array}{ll} 0, & \text{for } P_d(t) < 0 \\ \min\left[Q_{pump}^{pot}(t)\eta_{pump}^{-1}\rho g h(t); \min\left[P_d(t); P_{pump}(t-1) + \Delta P_{pump}^{ramp}\right]\right], & \text{for } P_d(t) \geq 0 \ \& \ \Delta P_d(t) \geq 0 \\ \min\left[Q_{pump}^{pot}(t)\eta_{pump}^{-1}\rho g h(t); \max\left[P_d(t); P_{pump}(t-1) - \Delta P_{pump}^{ramp}\right]\right], & \text{for } P_d(t) \geq 0 \ \& \ \Delta P_d(t) < 0 \end{array} \right\}, \tag{S37}$$

where ΔP_{pump}^{ramp} is the maximum ramp rate for pumping, η_{pump} is the pumping efficiency, and

$$Q_{pump}^{pot}(t) = \min\left[\frac{V_{lower}(t)}{\Delta t}; Q_{pump}^{max}\right] \tag{S38}$$

with Q_{pump}^{max} the maximum pump throughput. The flow pumped back into the reservoir then equals

$$Q_{pump}(t) = \frac{P_{pump}(t)}{\eta_{pump}^{-1}\rho g h(t)}. \tag{S39}$$

Finally, the overflow component of the lower reservoir is calculated as

$$Q_{spill,lower}(t) = \left\{ \begin{array}{ll} 0, & \text{for } \left(V_{lower,max} - V_{lower}(t)\right)/\Delta t \geq Q_{flexible}(t) \\ Q_{flexible}(t) - \left(V_{lower,max} - V_{lower}(t)\right)/\Delta t, & \text{for } \left(V_{lower,max} - V_{lower}(t)\right)/\Delta t < Q_{flexible}(t) \end{array} \right\}. \tag{S40}$$

Since the pumping allows a certain fraction of the water to be recycled for power generation, the values c_{solar}^{opt} and c_{wind}^{opt} resulting from the optimisation described in Note 3.2 will end up higher as compared to a situation without pumping component. In this way, pumped storage can help increase the load that can be carried by the hydro-solar-wind combination.
The REVUB code includes an optional section to perform the above operations and the required optimisation (this scenario is named “STOR” in the code, as opposed to “CONV” and “BAL”).

Note 7 Meeting spinning reserve requirements

In electricity networks, a certain reserve capacity, to be utilised in case of disruptions of supply, must always be available. The reserve capacity that is already online is denoted the spinning reserve, of which hydropower plants with reservoirs are typical providers. However, the flexible hydropower operation modeled by REVUB requires hydropower output to be increased during certain intervals to compensate for reductions in solar and/or wind power; thus, the remaining spinning reserves available to manage contingencies will consistently reach minimum values during those times.
The question is thus whether the hydropower plants could still respond to contingency events (e.g. failure of a transmission line leading to a solar power park temporarily being disconnected), despite being operated by flexible rule curves that lead to regular minima in the available spinning reserves. The spinning reserves $P_{spin}(t)$ from all hydropower plants within a certain geography can be calculated as

$$P_{spin}(t) = \sum_{\substack{\text{all hydro} \\ \text{plants}}} \left[1 - CF_{hydro}(t)\right] P^{r}_{turb}\Gamma(t), \tag{S41}$$

where $\Gamma(t)$ equals zero if the hydropower plant has temporarily undergone a drought-related shutdown, and unity otherwise; and $CF_{hydro}(t)$ is the capacity factor of each hydropower plant, calculated as

$$CF_{hydro}(t) = \frac{P^{hydro}_{stable}(t) + P^{hydro}_{flexible}(t) + P^{hydro}_{RoR}(t)}{P^{r}_{turb}}. \tag{S42}$$

To test the ability of hydropower to respond to supply disruptions of the added solar and wind power, the user should (ex-post) calculate the ratio (denoted ν) of $P_{spin}(t)$ to the total solar and wind power generation assumed to feed into the same grid. Typical benchmarks of spinning reserve needs for high-RE systems are in the order of $\nu \sim 10 - 20\%$ [18].

Note 8 Glossary

The table below provides an overview of all described parameters used in the REVUB model and its inputs and outputs. The symbol of each parameter is provided alongside its unit, a description of what it represents in the model, its data type (constant, variable, time series), its use in the model (as input, output, intermediate result, or used for preparing input), and its applicability across various components of the model. Here, "scenario" denotes a certain simulation setting: different scenarios may have different solar/wind mixes, different constraints on overproduction, different pools of hydropower plants contributing to flexibility, etc.

Symbol	Unit	Description	Type	Used as/for	Applicable to
$A(t)$	m^2	Reservoir lake surface area	Time series	Output	each hydropower plant & each scenario
A_{max}	m^2	Maximum reservoir lake surface area	Constant	Input	each hydropower plant
C_{OR}	-	Operating reserve coefficient: Fraction of yearly reservoir inflow available for flexible use	Variable	-	each hydropower plant
C^{max}_{OR}	-	Maximum allowed operating reserve coefficient taking into account environmental flow needs	Constant	Input	each hydropower plant
C^{opt}_{OR}	-	Optimal operating reserve coefficient	Constant	Output	each hydropower plant & each scenario
c_{solar}	MW	Installed capacity of solar panels	Constant	Output	each hydropower plant & each scenario
c^{opt}_{solar}	MW	Optimal installed solar power capacity needed to follow optimal load $L_{opt}(t)$	Constant	Output	each hydropower plant & each scenario
c_{wind}	MW	Installed capacity of wind turbines	Constant	Output	each hydropower plant & each scenario
c^{opt}_{wind}	MW	Optimal installed wind power capacity needed to follow optimal load $L_{opt}(t)$	Constant	Output	each hydropower plant & each scenario
$CF_{hydro}(t)$	-	Capacity factor of hydropower plants	Time series	Output	each hydropower plant & each scenario
$CF_{solar}(t)$	-	Weighted average capacity factor of solar panels across locations	Time series	Input	each scenario
$CF^{n}_{solar}(t)$	-	Capacity factor of solar panels in each location with index n	Time series	Input	each solar power site

Symbol	Unit	Description	Type	Used as/for	Applicable to
$CF_{wind}(t)$	-	Weighted average capacity factor of wind turbines across locations	Time series	Input	each scenario
$CF^n_{wind}(t)$	-	Capacity factor of wind turbines in each location with index n	Time series	Input	each wind power site
d_{min}	-	Percentage of average reservoir inflow required as minimum environmental outflow	Constant	Input	each hydropower plant
ΔP^{ramp}_{turb}	MW/min	Maximum ramp rate of hydropower plant	Constant	Input	each hydropower plant
ΔP^{ramp}_{pump}	MW/min	When simulating pumped-storage potential: Maximum ramp rate of pumps	Constant	Input	each large hydropower plant
$E^{hydro}_{reservoir}$	GWh/year	Total yearly hydropower generation	Yearly total	Output	each hydropower plant & each scenario
E^{hydro}_{stable}	GWh/year	Total yearly hydropower generation from stable reservoir outflow component	Yearly total	Output	each hydropower plant & each scenario
$E^{hydro}_{flexible}$	GWh/year	Total yearly hydropower generation from flexible reservoir outflow component	Yearly total	Output	each hydropower plant & each scenario
E^{hydro}_{RoR}	GWh/year	Total yearly hydropower generation from seasonal run-of-river outflow component	Yearly total	Output	each small hydropower plant & each scenario
E_{solar}	GWh/year	Total yearly solar power generation	Yearly total	Output	each hydropower plant & each scenario
E_{wind}	GWh/year	Total yearly wind power generation	Yearly total	Output	each hydropower plant & each scenario
ELCC	GWh/year	Effective Load Carrying Capability. Total yearly load followed by hydro-solar-wind without loss of load, ensuring long-term lake level stability, and meeting environmental flow requirements. Integral of $L_{followed}(t)$ over all time steps in a year.	Yearly total	Output	each hydropower plant & each scenario
ELCC_{tot}	GWh/year	Aggregate of ELCC across all power plants. Also called "total load-following potential" of hydro-solar-wind.	Yearly total	Output	each scenario
η_{turb}	-	Hydroturbine conversion efficiency	Constant	Input	each hydropower plant
η_{pump}	-	When simulating pumped-storage potential: Pumping efficiency	Constant	Input	each hydropower plant
f_{opt}	-	Optimal filling fraction of hydropower reservoir	Constant	Input	each hydropower plant
f_{spill}	-	Reservoir filling fraction at which overflow prevention via spillways is initiated	Constant	Input	each hydropower plant
f_{stop}	-	Low reservoir filling fraction at which hydropower generation is curtailed	Constant	Input	each hydropower plant
$f_{restart}$	-	Reservoir filling fraction at which hydropower generation is restarted after curtailment	Constant	Input	each hydropower plant
f_{reg}	-	Fraction of natural inflow that gives filling time equal to unity	Constant	Intermediate	each hydropower plant
g	m/s^2	Gravitational acceleration	Constant	Input	general
γ	-	Conventional reservoir rule parameter	Constant	Input	each hydropower plant
$\Gamma(t)$	-	Binary function indicating whether hydropower plant is operating (1) or not (0)	Time series	Output	each hydropower plant & each scenario
$h(t)$	m	Hydraulic head: Difference in water level between headwater (behind the dam) and tailwater (at the turbines)	Time series	Output	each hydropower plant & each scenario
h_{max}	m	Maximum hydraulic head of hydropower scheme	Constant	Input	each hydropower plant
$k_{turb}(t)$	-	Hydroturbine utilisation rate	Time series	Output	each hydropower plant & each scenario
κ	-	Conventional reservoir rule parameter	Constant	Input	each hydropower plant
$L(t)$	MW	Load to be followed	Time series	Intermediate	each scenario
$L_{opt}(t)$	MW	Optimal load to be followed by hydro-solar-wind mix, ensuring long-term reservoir lake level stability	Time series	Output	each hydropower plant & each scenario
$L_{followed}(t)$	MW	Actual followed load under optimal solution at zero loss of load (ideally equal to $L_{opt}(t)$)	Time series	Output	each hydropower plant & each scenario
$L_{res}(t)$	MW	Residual load: Difference between actual followed load and total hydro-solar-wind power generation	Time series	Intermediate	each hydropower plant & each scenario
$L_{norm}(t)$	-	Normalised load curve shape	Time series	Input	each scenario
$\lambda(t)$	$kg/m^2/s$	Evaporation flux on reservoir lake surface	Time series	Input	each hydropower plant
μ	-	Constant used in modelling overflow prevention via spillways	Constant	Input	each hydropower plant
n	-	Index for different locations of solar and wind power generation	Index	-	solar power and wind power sites
N_{solar}	-	Total number of solar power generation sites connected to the same power grid	Constant	Pre-input	each scenario
N_{wind}	-	Total number of wind power generation sites connected to the same power grid	Constant	Pre-input	each scenario
$\nu(t)$	-	Ratio of spinning reserves to total solar and wind power generation	Time series	Output	each hydropower plant & each scenario

Symbol	Unit	Description	Type	Used as/for	Applicable to
P_{turb}^{r}	MW	Rated hydroturbine capacity	Constant	Input	each hydropower plant
$P_{stable}^{hydro}(t)$	MW	Power generated by stable component of reservoir outflow	Time series	Output	each hydropower plant & each scenario
$P_{flexible}^{hydro}(t)$	MW	Power generated by flexible component of reservoir outflow	Time series	Output	each hydropower plant & each scenario
$P_{RoR}^{hydro}(t)$	MW	Power generated by seasonal run-of-river component of reservoir outflow	Time series	Output	each small hydropower plant & each scenario
$P_{inflexible}(t)$	MW	Inflexible power generation (stable hydro + solar + wind)	Time series	Intermediate	each hydropower plant & each scenario
$P_{solar}(t)$	MW	Solar power generation	Time series	Output	each hydropower plant & each scenario
$P_{wind}(t)$	MW	Wind power generation	Time series	Output	each hydropower plant & each scenario
$P_{followed}$	MW	Average actual followed load under optimal solution	Constant	Output	each hydropower plant & each scenario
P_{load}	MW	Average load to be followed	Constant	Intermediate	each hydropower plant & each scenario
$P_{spin}(t)$	MW	Spinning reserves available from all hydropower plants	Time series	Output	each hydropower plant & each scenario
$P_{pump}(t)$	MW	When simulating pumped-storage potential: Power used for pumping	Time series	Output	each large hydropower plant & each scenario
$P_{d}(t)$	MW	Difference between total inflexible power generation (stable hydro + solar + wind) and to-be-followed load	Time series	Output	each hydropower plant & each scenario
ϕ	-	Conventional reservoir rule parameter	Constant	Input	each hydropower plant
$\pi(t)$	kg/m^2/s	Precipitation flux on reservoir lake surface	Time series	Input	each hydropower plant
Ψ	-	Relative deviation between simulated lake levels under balancing-oriented and conventional operation, respectively	Function of c_{solar}, c_{wind}	Intermediate	each hydropower plant & each scenario
$Q_{in,frac}(t)$	m^3/s	Part of natural inflow that gives filling time equal to unity	Time series	Intermediate	each small hydropower plant
$Q_{in,nat}(t)$	m^3/s	Natural river discharge into reservoir	Time series	Input	each hydropower plant
$Q_{out}(t)$	m^3/s	Total reservoir outflow, consisting of stable, flexible, run-of-river and spilling components	Time series	Output	each hydropower plant & each scenario
$Q_{stable}(t)$	m^3/s	Stable component of reservoir outflow	Time series	Output	each hydropower plant & each scenario
$Q_{flexible}(t)$	m^3/s	Flexible component of reservoir outflow	Time series	Output	each hydropower plant & each scenario
$Q_{RoR}(t)$	m^3/s	Seasonal run-of-river component of reservoir outflow (zero for large hydropower plants)	Time series	Output	each small hydropower plant
$Q_{spill}(t)$	m^3/s	Spilling component of reservoir outflow	Time series	Output	each hydropower plant & each scenario
Q_{turb}^{max}	m^3/s	Maximum hydroturbine throughput	Constant	Input	each hydropower plant
$Q_{turb,flexible}^{pot}(t)$	m^3/s	Maximum potential outflow available for flexible hydropower generation, before accounting for needs and ramping constraints	Time series	Intermediate	each hydropower plant & each scenario
$Q_{pump}(t)$	m^3/s	When simulating pumped-storage potential: Pumped flow	Time series	Output	each large hydropower plant & each scenario
Q_{pump}^{max}	m^3/s	When simulating pumped-storage potential: Maximum pumping throughput	Constant	Input	each large hydropower plant
ρ	kg/m^3	Density of water	Constant	Input	general
t	hours	Time	Variable	-	general
T_{year}	seconds	Number of seconds in a year	Constant	Input	general
τ_{fill}	-	Filling time: number of years it takes (on average) to fill reservoir with natural inflow	Constant	Intermediate	each hydropower plant
$\tau_{fill,frac}$	-	Filling time: number of years it takes (on average) to fill reservoir with fraction f_{reg} of natural inflow	Constant	Intermediate	each small hydropower plant
$V(t)$	m^3	Volume of water in reservoir	Time series	Output	each hydropower plant & each scenario
V_{max}	m^3	Maximum reservoir volume	Constant	Input	each hydropower plant
$V_{lower}(t)$	m^3	When simulating pumped-storage potential: Volume of lower reservoir	Time series	Output	each large hydropower plant & each scenario
$V_{lower,max}$	m^3	When simulating pumped-storage potential: Maximum volume of lower reservoir	Constant	Input	each large hydropower plant
w_{solar}^{n}	-	Weight factor for capacity to be installed in each solar power site	Constant	Pre-input	each solar power site
w_{wind}^{n}	-	Weight factor for capacity to be installed in each wind power site	Constant	Pre-input	each wind power site
z_{max}	m	Maximal reservoir depth	Constant	Pre-input	each hydropower plant

Note 9 Running the model: Input (A)

The initialisation of the REVUB simulation is done through the file `A_REVUB_initialise_minimum_example`. In this file, all parameters that should be defined by the user (through accompanying Excel files) are indicated by `[Set by user]`. This includes various types of data:

- *Time-related parameters* and *model parameters* referring to the length of the time series to simulate, and to various quantities used in the hydropower modelling, according to the equations introduced in this Manual which are all referenced to their equation number in the code. These quantities are the same across all hydropower plants to be modelled;
- *Static parameters*, which are constants specific to each hydropower plant, and thus to be entered as 1-dimensional arrays with length equal to the number of hydropower plants for which to run a simulation, with each element representing the corresponding value for the corresponding hydropower plant;
- *Time series* of important parameters whose value needs to be known for each time step before a simulation can be performed, namely reservoir inflow, evaporation, precipitation, solar/wind power capacity factor, and the shape of the electricity demand profile. These values should be read in by the code as 3-dimensional matrices, with the following dimensions[v]: *[number of time slices (default: hours) per year; number of years covered by the simulation; number of hydropower plants included in the simulation]*.[vi]
- *Bathymetric relationship* for the modelled hydropower plants. These values should be read in by the code as an array with three columns and a user-determined number of rows; the first column should represent reservoir volume, and the second and third column the corresponding area and hydraulic head values.

Note 10 Running the model: Core code (B)

The actual core code of REVUB is contained in the file `B_REVUB_main_code`. Once the input data has been loaded using the file `A_REVUB_initialise_minimum_example`, the user can principally run this core code directly. The first lines of this code contain parameters related to accuracy and speed of computation denoted `[Set by user]`, which can be tuned (through an accompanying Excel file):

- `N_ELCC` determines the accuracy (the number of discrete steps between zero and maximum power generation) with which the zero-crossing of L_{res} in equation (S22) is determined.
- `f_init_BAL_start`, `f_init_BAL_step` and `f_init_BAL_end` determine the range (start, step size, and end) of $E_{solar} + E_{wind}$ (cf. equation (S25)), expressed as a fraction of $E^{hydro}_{reservoir,CONV}$ (cf. equation (S24)), in which the REVUB code starts searching for the solution to equation (S21). Note that the code gives a warning message to the user in case this range turns out to be inadequate (i.e. if no global minimum in Ψ is found). The same ranges should also be given for STOR scenarios (`f_init_STOR_start`, `f_init_STOR_step` and `f_init_STOR_end`) in case the user wishes to model these.

[v] Note that these technically refer to minimum dimensions. The user can, for instance, enter data for a higher amount of columns (years) than there are years in the simulation as specified by the time-related parameters above; REVUB will ignore those extra columns. This feature may be used to run initial tests using a limited number of years to speed up simulation time, before running with all years once satisfied with simulations settings.

[vi] Note that the REVUB code is designed to take into account the extra days occurring in leap years; for the purposes of preparing these data sets, if the simulation period contains leap years, the number of elements along the first dimension of these matrices should thus reflect the number of time slices (hours) in a leap year, and the data for non-leap years should be appended with *nan* values to reach the same length.

- `N_refine_BAL` determines the accuracy with which the solution to equation (S21) is determined. After the initial search for this minimum in the range [`f_init_BAL_start` : `f_init_BAL_step` : `f_init_BAL_end`] (see previous point), the REVUB model can zoom in to the range around this minimum to identify its value with increased accuracy, using a step size reduced by a factor of ten. The number of times with which this is done is determined by `N_refine_BAL`. Thus, `N_refine_BAL` = 1 means that the initial search is deemed accurate enough, whereas each +1 in `N_refine_BAL` increases the accuracy of identification of the minimum in Ψ by one digit. Accordingly, each +1 also increases computation time proportionally. For users wishing to model STOR scenarios, the same principle applies to `N_refine_STOR`.

- `psi_min_threshold` is zero by default, but can be set higher to speed up computation time in case the search for the minimum in Ψ takes too long. This parameter ensures that the zooming-in to higher accuracies (see previous point) is stopped as soon as $\min(\Psi)$ ends up below `psi_min_threshold`. It can thus be a compromise for users wishing to have high accuracy of determining $\min(\Psi)$ (i.e. setting `N_refine_BAL/STOR` > 1) but not at a high cost of computational speed.

- `X_max_BAL` determines the amount of iterative loops employed by the model to get a converged estimate of $P^{hydro}_{stable,BAL}$ (cf. equation (S9) and the explanation below equation (S19)). Each +1 also increases computation time proportionally. For users wishing to model STOR scenarios, the same principle applies to `X_max_STOR`.

Note 11 Running the model: Output graphics (C)

The results of the REVUB simulation are post-processed with two separate files, named `C_REVUB_plotting` and `C_REVUB_plotting_multiple`, which generate several standardised figures based on the input and output of the model. The two files serve a somewhat different purpose:

- The file `C_REVUB_plotting_individual` is used to plot simulation results pertaining to a single (user-selected) hydropower plant.

- The file `C_REVUB_plotting_multiple` is used to aggregate simulation results pertaining to (a user-selected set of) all hydropower plants. Based on a user-defined total electricity demand, it shows how much of this total demand can be met by hydro-solar-wind power on all involved timescales, and how much would remain to be met by other power sources.

Note 11.1 Results for individual power plants

The figures generated by the file `C_REVUB_plotting_individual` are described below.

- Figure 1 shows (a) the (h, V) and (b) the (A, V) bathymetric calibration curves used as input to the model.

- Figure 2 shows (a) the full time series of hydraulic head $h(t)$ under CONV, BAL and (if modelled) STOR, (b) the frequency spectrum of these hydraulic head curves such that e.g. specific temporal signatures, such as diurnal dispatch in solar-heavy systems, can be discerned, and (c) the monthly median and interquartile ranges of natural inflow $Q_{in,nat}(t)$ and outflow $Q_{out}(t)$ (equation S2) under CONV, BAL and (if modelled) STOR.

- Figure 3 shows (a) the full time series of lake volume $V(t)$ under CONV, BAL and (if modelled) STOR, and (b) the monthly average time series of natural inflow $Q_{in,nat}(t)$ and outflow $Q_{out}(t)$ under CONV, BAL and (if modelled) STOR.

- Figure 4 shows the monthly average composition of the hydro-solar-wind mix supported by the selected hydropower plant, under the BAL scenario and for a user-defined year (see below). The figure indicates hydropower generation (by stable, flexible and RoR components) and the optimal solar and wind power contribution identified by REVUB. The achieved ELCC, whose profile reflects that of $L_{norm}(t)$, is also indicated. In case a STOR scenario was simulated, a corresponding extra figure will be produced for that scenario, additionally indicating the pump-stored part of solar/wind power generation.

- Figure 5 is analogous to Figure 4, but at yearly resolution and reflecting the entire simulated time series.
- Figure 6 is analogous to Figure 4, but at hourly (full) resolution for a user-defined time slice (see below).
- Figure 7 shows approximated reservoir release rules in the BAL scenario for a user-defined hour of the day during a user-defined month. The plot shows the median and interquartile range of needed reservoir release (minus the RoR and spill components, i.e. $Q_{stable} + Q_{flexible}$) versus the median hydraulic head, with each data point denoting results from one simulation year. A linear fit to these data points is also shown.

At the beginning of the code, a few parameters denoted `[Set by user]` are loaded from an Excel file, where they can be changed to adapt the data to be plotted. These are as follows:

- `plot_HPP` is the index of the hydropower plant for which to plot results in all Figures.
- `plot_year` is the index of the simulation year for which to plot results in Figures 4 and 6.
- `plot_month` is the month in which to start the time slice in Figure 6.
- `plot_day_month` is the day of the month defined by `plot_month` on which to start the time slice in Figure 6.
- `plot_num_days` is the number of days for which to plot results in Figure 6.
- `plot_rules_month` is the month(s) of the year for which to plot results in Figure 7. This can be an array, e.g. [1, 4] would denote that the curves in Figure 7 are plotted both for January and for April.
- `plot_rules_hr` is the hour(s) of day during the month defined by `plot_rules_month` for which to plot results in Figure 7. This can be an array, e.g. [8, 20] would denote that the curves in Figure 7 are plotted both for 8 a.m. and 8 p.m.

Note 11.2 Results for multiple power plants

The file `C_REVUB_plotting_multiple` serves to show to what extent the investigated hydropower, solar power and wind power plants could contribute to the overall power mix of a given territory. The principle of this file is as follows:

- To run the file, the user must first define an overall electricity demand curve, denoted `P_total_hourly` (see below).
- The file then plots the aggregate power generation from all investigated hydro, solar and wind plants under BAL and STOR, and compares it to `P_total_hourly`.
- Any shortfalls in renewable power generation are then assumed to be filled up by thermal power plants. This reflects the assumption of a priority of dispatch for renewables.
- When renewable power generation exceeds `P_total_hourly` by a certain amount, this amount is assumed to be curtailed.

In this way, the file allows to calculate the total power mix (hydro/solar/wind/thermal) suggested by the streamlined hydro-solar-wind operation as simulated by REVUB.
The figures produced by the file are described below.

- Figure 1 shows the monthly average composition of the hydro-solar-wind mix under the BAL scenario for a user-defined year (see below). The figure indicates the total power demand `P_total_hourly`, and how this power demand is met by the aggregate hydropower generation (by stable, flexible and RoR components) from all hydropower plants, the aggregate of all solar and wind power, and the necessary other (thermal) power generation. Any curtailed solar/wind power is shown as such. The curve representing ELCC_{tot} is also included. In case a STOR scenario was simulated, a corresponding extra figure will be produced for that scenario, additionally indicating the pump-stored part of solar/wind power generation. (In this case, small hydropower plants for which no STOR scenario is available (cf. section Note 6) are included according to their BAL results.)
- Figure 2 is analogous to Figure 1, but at yearly resolution and reflecting the entire simulated time series.
- Figure 3 is analogous to Figure 1, but at hourly (full) resolution for a user-defined time slice (see below).

At the beginning of the code, a few parameters denoted `[Set by user]` are loaded from an Excel file, where they can be changed to adapt the data to be plotted. These are as follows:

- `plot_HPP_multiple` is an array containing the indices of the hydropower plants whose results are to be aggregated in the Figures. The user can thus select all, or a selection of, the simulated hydropower plants.
- `plot_year_multiple` is the index of the simulation year for which to plot results in Figures 1 and 3.
- `plot_month_multiple` is the month in which to start the time slice in Figure 3.
- `plot_day_month_multiple` is the day of the month defined by `plot_month` on which to start the time slice in Figure 3.
- `plot_num_days_multiple` is the number of days for which to plot results in Figure 3.
- `P_total_hourly` is the total power demand (for all time steps of the simulation) against which the hydro-solar-wind power generation is compared. We recommend that this is taken to be equal to $P^{av}_{total} L_{norm}(t)$ (cf. equation (S10)), with P^{av}_{total} the average total power demand (in MW), to be specified by the user.

Note 12 Examples of model use

The REVUB model has so far been used in, and/or inspired the methods of, the following publications/documents:

- S. Sterl, I. Vanderkelen, C.J. Chawanda, D. Russo, R.J. Brecha, A. van Griensven, N.P.M. van Lipzig, and W. Thiery. Smart renewable electricity portfolios in West Africa. *Nature Sustainability* **3**, 710–719 (2020). `https://doi.org/10.1038/s41893-020-0539-0`.
- S. Sterl, P. Donk, P. Willems, and W. Thiery. Turbines of the Caribbean: Decarbonising Suriname's electricity mix through hydro-supported integration of wind power. *Renewable and Sustainable Energy Reviews* **134** (2020) 110352. `https://doi.org/10.1016/j.rser.2020.110352`.
- P. Donk, S. Sterl, W. Thiery, and P. Willems. REVUB-Light: A parsimonious model to assess power system balancing and flexibility for optimal intermittent renewable energy integration—A study of Suriname. *Renewable Energy* **173**, 57–75 (2021). `https://doi.org/10.1016/j.renene.2021.03.117`.

- S. Sterl, D. Fadly, S. Liersch, H. Koch, and W. Thiery. Linking solar and wind power in eastern Africa with operation of the Grand Ethiopian Renaissance Dam. *Nature Energy* **6**, 407–418 (2021). `https://doi.org/10.1038/s41560-021-00799-5`.
- S. Sterl, A. Devillers, C.J. Chawanda, A. van Griensven, W. Thiery, and D. Russo. A spatiotemporal atlas of hydropower in Africa for energy modelling purposes. *Open Research Europe* **1**, 29 (2021). `https://doi.org/10.12688/openreseurope.13392.3`.
- S. Sterl and W. Thiery. La faisabilité du solaire PV pour remplacer la centrale hydroélectrique de Koukoutamba en Guinée: Étude quantitative. Vrije Universiteit Brussel, Brussels, Belgium (2022). `http://dx.doi.org/10.13140/RG.2.2.26548.83848`.
- P. Donk, S. Sterl, W. Thiery, and P. Willems. A policy framework for power system planning towards optimized integration of renewables under potential climate change – The Small Island Developing States perspective. *Energy Policy* **177** (2023). `https://doi.org/10.1016/j.enpol.2023.113526`.

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