

# REVUB: User Manual

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1 The REVUB model (“Renewable Electricity Variability, Upscaling and Balancing”) was developed  
2 specifically to address the challenge of optimising hydro-solar-wind complementarity through smart  
3 hydropower operation and smart choice of solar-wind portfolios. We first explain the general principles  
4 of the REVUB model (Note 1), based on which the different modules of the model are explained one  
5 by one: hydropower plant classification (Note 2); simulation of hydropower generation and reservoir  
6 dynamics (Note 3); and simulation and optimisation of joint hydro-solar-wind operation (Note 3 to  
7 Note 5). An optional, additional assessment of pumped-storage potential with REVUB is described  
8 in Note 6. The possibilities of modelling interactions between hydropower plants in cascades are  
9 described in Note 7. Some notes on spinning reserve requirements are summarised in Note 8. An  
10 overview table of terms and symbols used in the model description is given in Note 9.

11 The most recent version of the REVUB code was written for Python environments and can be accessed  
12 via <https://github.com/VUB-HYDR/REVUB> and used under the MIT license. All equations given in  
13 this document are referenced in the code wherever relevant/used. The ways to prepare input, run  
14 the code, and interpret output are given in Note 10, Note 11 and Note 12. The manual ends with an  
15 overview of additional modelling tips in Note 13.

## 16 Note 1 Principles of REVUB

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

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

## 33 Note 2 Hydropower plant categorisation

34 In REVUB, hydropower plants are categorised into two groups, based on whether the average natural  
35 inflow would take more or less than one year to fill the reservoir; in other words, whether the reservoir  
36 is “large” or “small” compared to the inflow. For plants in the “large” category, rule curves can be  
37 designed to ensure outflow and power output are relatively stable from month to month<sup>3,4</sup>, enabling  
38 the plant to serve as baseload provider. Such rule curves typically boil down to parameterisations of  
39 required outflow as a function of lake level<sup>5</sup>. For hydropower plants in the “small” category, rule curves  
40 should additionally take into account that during the wet season(s), certain fractions of the received  
41 water need to be directly released from the reservoir without being stored, as reservoir capacity would  
42 be insufficient for this<sup>6</sup>. Small hydropower plants thus operate partly as run-of-river plants.  
43 In mathematical terms, the classification of hydropower plants as “large” or “small” is done by calcu-  
44 lating the dimensionless filling time  $\tau_{fill}$ :

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

45 where  $V_{max}$  is the reservoir volume (in m<sup>3</sup>),  $T_{year}$  is the number of seconds in a year, and  $Q_{in,nat}(t)$   
46 denotes natural reservoir inflow (in m<sup>3</sup>/s). By default, hydropower plants are classified by REVUB

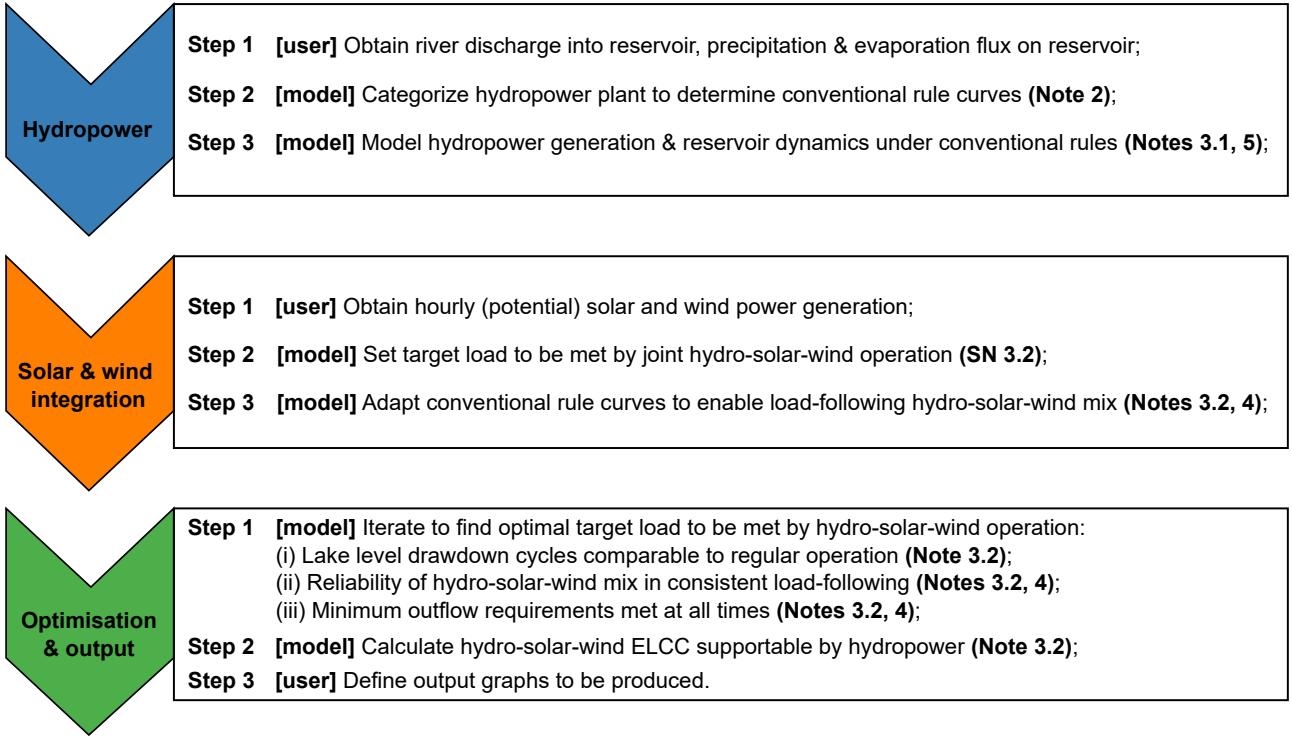


Figure S1: **Flowchart of the REVUB model approach**, explaining the steps taken in modelling hydro, solar and wind power and their integration. ELCC = Effective Load Carrying Capability. See also Note 10, Note 11 and Note 12 for the ways to prepare input, run the code, and interpret output.

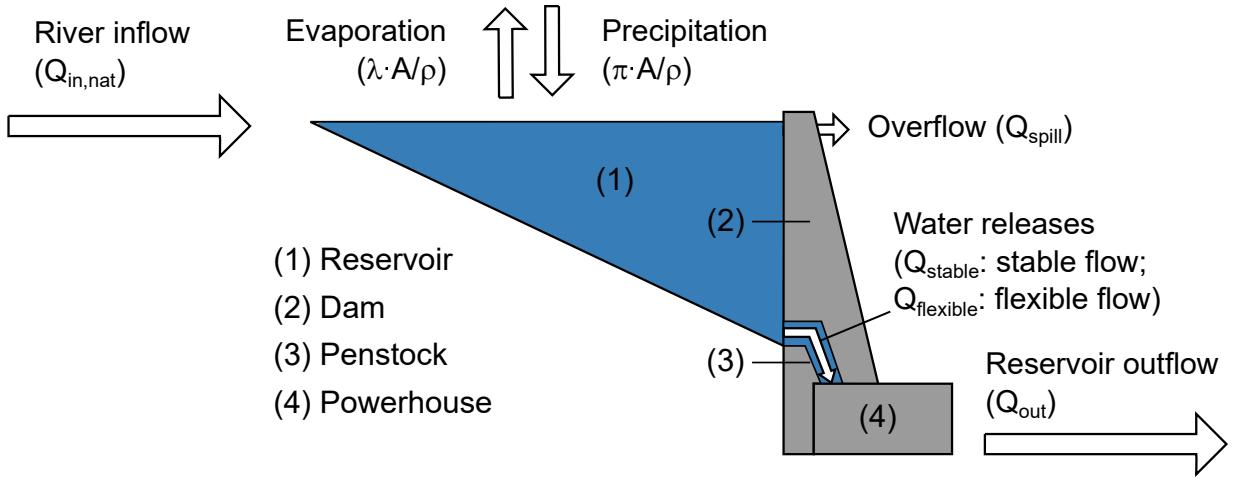
47 as large or small based on whether their  $\tau_{fill}$  is larger or smaller than unity, respectively; but this can  
48 be changed by the user.

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

56 Even for large hydropower plants, only part of the water intake can be allocated for flexible use,  
57 as a minimum stable outflow usually has to be guaranteed for at least four reasons (two technical  
58 reasons and two environmental reasons): (i) ensuring that turbines run in their high-efficiency range,  
59 which requires a certain minimum loading [*technical*]; (ii) safeguarding power system stability, since  
60 requirements for inertia impose having some synchronous capacity, such as from hydroturbine-driven  
61 generators, dispatched at all times<sup>7</sup> [*technical*]; (iii) safeguarding downstream ecological integrity  
62 through a minimum environmental outflow<sup>8</sup> [*environmental*]; and (iv) supplying irrigation water de-  
63 mand downstream [*environmental*].

64 Thus, regulated reservoir outflow must have a stable and a flexible component, which are denoted  
65 respectively  $Q_{stable}(t)$  and  $Q_{flexible}(t)$  (both in m<sup>3</sup>/s).  $Q_{stable}(t)$  can be further split up into a technical  
66 component  $Q_{stable}^{tech}(t)$  and its environmental/irrigation component  $Q_{stable}^{env/irr}(t)$ . These components are  
67 not mutually exclusive, as one can contribute to the other; thus, in general,  $Q_{stable}(t)$  is not the sum  
68 of both components, but simply the maximum value of both (the one that takes precedence over the  
69 other, thereby automatically fully covering the other).

70 Overall flexibility can be increased by reducing  $Q_{stable}(t)$  in favour of  $Q_{flexible}(t)$ . Essentially, to  
71 allocate a certain amount of water for flexible use, the stable outflow will have to be reduced by a  
72 comparable amount such that the overall water budget remains unchanged. Since  $Q_{stable}^{env/irr}(t)$  is usually



**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.

prescribed externally, in practice, this means that allocating more water to flexibility implies reducing  $Q_{stable}^{tech}(t)$ .

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<sup>5</sup>  $Q_{spill}(t)$ , 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

$$\begin{aligned} Q_{out}(t) &= Q_{stable}(t) + Q_{flexible}(t) + Q_{RoR}(t) + Q_{spill}(t) \\ &= \max \left[ Q_{stable}^{tech}(t), Q_{stable}^{env/irr}(t) \right] + Q_{flexible}(t) + Q_{RoR}(t) + Q_{spill}(t). \end{aligned} \quad (\text{S2})$$

for both large and small hydropower plants. Correspondingly, hydropower generation consists of components  $P_{stable}^{hydro}(t)$ ,  $P_{flexible}^{hydro}(t)$  and  $P_{RoR}^{hydro}(t)$  (in MW)<sup>i</sup>.

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

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

where  $\pi(t)$  and  $\lambda(t)$  are respectively precipitation and evaporation flux ( $\text{kg/m}^2/\text{s}$ ; see Methods);  $A(t)$  is the surface area of the reservoir lake ( $\text{m}^2$ );  $\rho$  the density of water (taken to be  $1000 \text{ kg/m}^3$ ); and  $\Delta t$  is the simulation time step (one hour is the default in REVUB). Seepage losses, which are usually very small in reservoirs<sup>6,9</sup>, 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

<sup>i</sup>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.

97 how  $Q_{stable}(t)$  and  $Q_{flexible}(t)$ , and the corresponding power generation components  $P_{stable}^{hydro}(t)$  and  
98  $P_{flexible}^{hydro}(t)$ , are modelled for balancing-oriented operation.

### 99 Note 3.1 Conventional (baseload-oriented) operation

100 We denote conventional, baseload-oriented operational rules with the abbreviation “CONV”. By defi-  
101 nition,  $Q_{flexible,CONV}(t)$  and  $P_{flexible,CONV}^{hydro}(t)$  are zero. The default way of modelling  $Q_{stable,CONV}(t)$   
102 in REVUB is based on logarithmic-exponential release rules<sup>4,10</sup>, which works well in case conven-  
103 tional operational rules are unknown, and can be determined on the basis of long-term average inflow  
104  $\overline{Q_{in,nat}(t)}$ <sup>ii</sup>. Under the assumption that environmental/irrigation outflow  $Q_{stable}^{env/irr}(t)$  is prescribed at  
105 all times, approximate rules used in REVUB are:

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

106 where  $d_{min}$  is the fraction of yearly average inflow required as minimum stable outflow;  $V_{max}$  is the  
107 maximum reservoir storage capacity;  $f_{opt}$  is the optimal filling fraction; and  $\kappa$ ,  $\phi$  and  $\gamma$  are constants.  
108  $\kappa$  and  $\phi$  are given<sup>4</sup> by

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

109 and

$$\phi = \alpha \tau_{fill}^{1/2}. \quad (\text{S6})$$

110 Recommended default values are  $f_{opt} = 80\%$ ,  $\alpha = 2/3$ , and  $\gamma = 10$  based on generalised reservoir  
111 operation rules<sup>4,10</sup>; for  $d_{min}$ , values may be chosen based on requirements for minimum turbined  
112 flow to prevent turbines running at low efficiency, and/or generalised environmental flow rules<sup>8</sup> (the  
113 former will usually take precedence over the latter). It is possible (and arguably desirable when  
114 running scenarios for the first time) for the user to not specify a value for  $d_{min}$ , and instead provide a  
115 value of minimum required load  $f_{min}$  on one single turbine (expressed as fraction of maximum turbine  
116 throughput), reflecting the lower bound of the turbine’s operating range, based on which REVUB  
117 will calculate and work with a default value of  $d_{min}$ <sup>iii</sup>. All the preceding parameters can be changed  
118 by the user in the process of calibration to historical data.

119 The overflow prevention component  $Q_{spill,CONV}$  is modelled as

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

120 where  $f_{spill}$  is the filling fraction at which the overflow prevention starts<sup>iv</sup>, and  $\mu$  represents a small  
121 fraction such that lake levels are brought below critical levels  $f_{spill}V_{max}$  as quickly as possible without  
122 releasing unnaturally high flows downstream; recommended values are  $f_{spill} = 95\%$  and  $\mu = 0.1$ , but  
123 these can be changed by the user.

124 To simulate minimum drawdown levels when facing drought-like situations, one further rule is added  
125 to equation (S4): outflow, and with it hydropower production, is automatically curtailed<sup>5,11</sup> if the  
126 volume levels  $V_{CONV}(t)$  dip below critical levels  $f_{stop}V_{max}$ , and only restarted once volumes have  
127 recovered to  $f_{restart}V_{max}$ . The values  $f_{stop}$  and  $f_{restart}$  must be specified by the user, ideally based on  
128 reservoir bathymetry (see Note 3.3).

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<sup>ii</sup>By default, REVUB considers this average to be across the entire modelled period, but the user can alternatively select a specific part of the input period on which to base the average.

<sup>iii</sup>The calculation is as follows:  $d_{min}^{default} = (f_{min}Q_{turb}^{max}/N_{turbines})/\overline{Q_{in,nat}(t)}$ , where  $N_{turbines}$  is the number of turbines (units) of the plant. The term  $f_{min}Q_{turb}^{max}/N_{turbines}$  represents the minimum flow in m<sup>3</sup>/s required to keep one turbine running within its operating range.

<sup>iv</sup>Note that every hydropower plant has a certain safety level, i.e. the dam is always somewhat higher than the maximum water level<sup>5</sup>, 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.

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

$$P_{stable,CONV}^{hydro}(t) = \min \left[ Q_{stable,CONV}(t); Q_{turb}^{max} \right] \eta_{turb} \rho g h_{CONV}(t), \quad (\text{S8})$$

130 where  $\eta_{turb}$  is the turbine efficiency (%)<sup>v</sup>,  $g$  the gravitational acceleration (9.81 m/s<sup>2</sup>), and  $h(t)$  the  
 131 hydraulic head (m), i.e. the difference in water level between the headwater behind the dam and the  
 132 tailwater at the turbines. The value of  $\eta_{turb}$  should be user-defined, ideally based on knowledge of the  
 133 plant's turbines<sup>vi</sup>. The calculation of  $h(t)$  is explained in Note 3.3.  $Q_{turb}^{max}$  is the maximum turbine  
 134 throughput (at which the power generating capacity of the turbine is fully used). If this value cannot  
 135 be found, it can be approximated with  $Q_{turb}^{max} \approx P_{turb}^r / (\eta_{turb} \rho g h_{max})$ , where  $P_{turb}^r$  is the rated power  
 136 capacity of the hydropower plant and  $h_{max}$  is the maximum hydraulic head.

137 With these rules, results are mostly independent of arbitrary initial conditions (convergence to the  
 138 same time series happens typically within 2 simulation months). REVUB uses the initial condition  
 139  $V_{CONV}(0) = f_{init} V_{max}$  (and the corresponding lake area and water level; see Note 3.3) where the user  
 140 can specify  $f_{init}$ .

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

### 144 Note 3.2 Balancing-oriented operation

145 Reservoir operation oriented towards balancing solar and wind power variability is denoted with the  
 146 abbreviation “BAL”. For reservoirs of large hydropower plants, BAL operation is modelled as follows.  
 147 First, the needs for sub-daily to seasonal dispatching patterns must be established. The load difference  
 148  $P_d(t)$  between total inflexible power generation (stable hydropower, solar power, and wind power) and  
 149 power demand is calculated as:

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

150 Here,  $c_{solar}$  and  $c_{wind}$  represent a certain amount of solar PV and wind power capacity, respectively  
 151 (in MW), whose value is to be optimised by REVUB;  $CF_{solar}(t)$  and  $CF_{wind}(t)$  represent the solar  
 152 and wind capacity factor for each time step, respectively; and  $L(t)$  represents a certain target load  
 153 profile that is to be followed<sup>vii</sup>.

154 The time series  $L(t)$ , by default, is set as follows:

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

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

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

158 where  $p_i(x)$  denotes the  $i^{th}$  percentile of a variable  $x$ . Here,  $i$  thus represents the percentile of  $P_{inflexible}$   
 159 not exceeding  $P_{load}$ ; in other words, the percentage of time during which RE generation should not

---

<sup>v</sup>Hydropower plants usually produce reactive power next to active power (i.e. the power factor is less than unity). For purposes of REVUB, representing the power factor can be done through this same efficiency factor. For instance, to represent a conversion efficiency of 95% (a turbine quantity) and a power factor of 80% (an electric circuit quantity), one could set  $\eta = 95\% \times 80\% = 76\%$ .

<sup>vi</sup>The efficiency of hydroturbines depends on the effective turbined flow at each moment, but is typically above 80% in realistic ranges of the latter<sup>12,13</sup>. As explained above, the value  $d_{min}$  should at least reflect the fact that at any given moment, at least one of the  $N_{turbines}$  turbines of a given plant must be active and running at a certain minimum partial load to allow consistent operation at high efficiency.

<sup>vii</sup>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).

160 exceed the average load to be followed. Generally, the lower  $i$ , the higher the amount of allowed excess  
 161 production (overproduction) as compared to  $L(t)$ .

162 In REVUB, the time series  $CF_{solar}(t)$  and  $CF_{wind}(t)$  must be provided as model input by the user.  
 163 These could represent power generation from single locations, or weighted averages across the locations  
 164 for on-grid solar or wind power selected for the region under scrutiny, to simulate the feed-in of solar  
 165 and wind power from various locations into the same power grid. In case of the latter, we recommend  
 166 assuming that the total capacity is distributed across locations within the region according to site-  
 167 specific weight factors  $w_{solar}^n$  and  $w_{wind}^n$ . Then,  $CF_{solar}(t)$  and  $CF_{wind}(t)$  would be given by

$$CF_{solar}(t) = \frac{\sum_{n=1}^{N_{solar}} CF_{solar}^n(t) w_{solar}^n}{\sum_{n=1}^{N_{solar}} w_{solar}^n}; \quad CF_{wind}(t) = \frac{\sum_{n=1}^{N_{wind}} CF_{wind}^n(t) w_{wind}^n}{\sum_{n=1}^{N_{wind}} w_{wind}^n}, \quad (\text{S12})$$

168 with  $CF_{solar}^n(t)$  and  $CF_{wind}^n(t)$  the capacity factors of solar PV or wind power for each time step,  
 169 respectively, at each individual site with index  $n$ ; and  $N_{solar}$  and  $N_{wind}$  the number of sites for solar PV  
 170 or wind power generation, respectively. The weight factors  $w_{solar}^n$  and  $w_{wind}^n$  represent preferences for  
 171 certain sites over others for the development of solar PV and wind parks. To determine the site-specific  
 172 weight factors, one could take e.g. the available area for deployment in each different site and assume  
 173 it scales linearly with potential capacity deployment, as per ref.<sup>14</sup>. Another approach is that of ref.<sup>15</sup>,  
 174 which took a site's weight factor to be equal to the multi-year average capacity factor for solar PV or  
 175 wind power at that site, reflecting a preference for sites with higher yield:

$$w_{solar}^n = \overline{CF_{solar}^n(t)}; \quad w_{wind}^n = \overline{CF_{wind}^n(t)}. \quad (\text{S13})$$

176 The capacity ratio  $c_{solar} : c_{wind}$  should also be user-defined; it represents the relative share of solar  
 177 and wind capacity to be deployed by the model. Sensitivity tests to find an optimal ratio can then be  
 178 performed by running the model for several values of the capacity ratio.

179 Second, in BAL operation,  $Q_{stable}(t)$  is reduced in favour of  $Q_{flexible}(t)$  such that  $L(t)$  can be met  
 180 by the combination of stable hydropower, flexible hydropower, solar power and wind power. In the  
 181 REVUB code, the default approach (which could be adapted by the user in the code) is to take  
 182  $Q_{stable,BAL}^{tech}(t)$  as a fraction of the average inflow<sup>viii</sup>:

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

183 Here, the fraction  $C_{OR}$  denotes the “operating reserve coefficient”<sup>16</sup>, and determines the amount of  
 184 water available for flexible use. Theoretically, as  $C_{OR} \rightarrow 1$ , the hydropower plant in question would  
 185 operate near-completely flexibly and provide almost no minimum stable load, beyond the “coinci-  
 186 dental” one from the environmental and irrigation outflow. This would also imply that the outflow  
 187 of the dam could become extremely low for prolonged periods; for instance, when solar/wind power  
 188 generation is high and/or demand is low. Such operation would likely violate inertia requirements  
 189 and minimum load constraints of the plant. As default, REVUB therefore uses an upper bound of  
 190  $C_{OR}^{max} = 1 - d_{min}$ , such that the minimum outflow under BAL is always consistent with that under  
 191 CONV. The selection of the optimal  $C_{OR}$  for each hydropower plant is explained in Note 4.

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

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

193 Third, the necessary amount of flexible outflow  $Q_{flexible,BAL}(t)$  and corresponding flexibly produced  
 194 power  $P_{flexible,BAL}^{hydro}(t)$  are determined for the instances when  $P_{inflexible}(t)$  cannot meet  $L(t)$ , i.e. when  
 195  $P_d(t) < 0$ . The following rule then applies for  $P_{flexible,BAL}^{hydro}(t)$  to maximize the followed load under  
 196 peak capacity constraints and ramping constraints<sup>17</sup>:

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

<sup>viii</sup>As for the CONV rules, by default this average is taken across the entire modelling period, but the user can alternatively select a part of that period as basis for the average.

197 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 ( $\Delta P_d(t) \geq 0$ );  $\Delta P_{turb}^{ramp}$  is the maximum ramp rate of the plant (in MW per time step);  
 198 and  
 199

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

200 This gives a flexible outflow

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

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

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

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

204 Since one needs the hydraulic head  $h_{BAL}(t)$  to calculate  $P_{stable,BAL}^{hydro}(t)$  from equation (S15), but  $h_{BAL}(t)$   
 205 follows only from the overall operation, which requires knowledge of  $P_{stable,BAL}^{hydro}(t)$  to calculate  $P_d(t)$   
 206 according to equation (S9), this problem is solved iteratively by REVUB with an initial guess of  
 207  $P_{stable,BAL}^{hydro}(t) = (1 - C_{OR})P_{stable,CONV}^{hydro}(t)$ , repeated until convergence (typically, 2-3 iterations suffice).  
 208 The calculation of  $h(t)$  is the same as for CONV and is explained in Note 3.3.

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

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

215 where

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

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

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

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

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

---

<sup>ix</sup>The length of periods when hydropower production is forced to stop, is important for due diligence planning and reflects in parameters such as the  $P_{guaranteed}^{90}$  power (MW), i.e. the power that is guaranteed 90% of the time. Integration of VRE will generally improve such parameters, since VRE can continue producing even when hydropower is temporarily stopped and despite the fact that the flexibility from hydropower is lost in those periods. REVUB calculates  $P_{guaranteed}^{xx}$  for a user-defined percentile  $xx$  for both CONV and BAL scenarios to showcase this.

<sup>x</sup>Or a user-selected part of that simulation period, in line with the CONV and BAL rules.

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

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

233 The ELCC thus represents the total yearly load followed by each hydropower plant in combination with  
 234 the solar and wind power whose variability it can compensate, under the optimal solution. The aggregate  
 235 of ELCC across all hydropower plants represents the total followable load when all hydropower  
 236 plants optimally contribute to compensating solar-wind variability; it is abbreviated  $\text{ELCC}_{tot}$  here-  
 237 after.

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

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

$$E_{reservoir}^{hydro} = E_{stable}^{hydro} + E_{flexible}^{hydro} = \int_{\text{year}} (P_{stable}^{hydro}(t) + P_{flexible}^{hydro}(t)) dt. \quad (\text{S24})$$

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

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

### 250 Note 3.3 Head-volume-area relationships

251 Calculating the hydraulic head  $h(t)$  for each time step requires knowing the bathymetry and volume-  
 252 area-depth relationship of each reservoir. Typical curves approximating such relationships need to be  
 253 calibrated on a reservoir-to-reservoir basis. The user should provide bathymetric curves as input to  
 254 each simulation. In case these are not available, we recommend using an archetypal reservoir shape  
 255 function<sup>18,19</sup>, modelling reservoirs' area-volume relationships with the equation

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

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

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

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

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

265 **Note 4 Peaking suitability of large hydropower plants**

266 Since hydropower plants differ in terms of peaking capabilities, operational strategies must be selected  
 267 with care. If hydropower plants are operated at a too high  $C_{OR}$ , the corresponding peaks in flexible  
 268 water release may exceed the maximum turbine throughput on a structural basis (cf. equation (S17)),  
 269 meaning that the plant will be structurally unable to meet peak demand as well as leading to loss  
 270 of spinning reserves (see Note 8). Typically, this would first occur in the seasons with highest peak  
 271 demand and/or when water levels are at their lowest. Therefore, each hydropower plant's operation  
 272 should happen at an optimised value  $C_{OR} = C_{OR}^{opt}$  that ensures this is not the case, while maintaining  
 273 adequate levels of flexibility. In REVUB, the default procedure (which can be changed by the user in  
 274 the code) is to define the turbine utilisation rate  $k_{turb}(t)$  at each time step:

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

275 and define hydropower plant operation (at given  $C_{OR}$ ) as unsuitable for peaking purposes when  
 276  $p_{99}(k_{turb})$ , i.e. the 99<sup>th</sup> percentile of  $k_{turb}$ , is unity (in other words, when turbine capacity is fully  
 277 exhausted in at least one out of every 100 hours).

278 As default for each hydropower plant, REVUB uses  $C_{OR}^{opt} = C_{OR}^{max}$ , the maximum allowed operational  
 279 flexibility. If operation is found to be unsuitable for peaking purposes at  $C_{OR}^{max}$ , the REVUB code  
 280 automatically resimulates with incrementally reduced  $C_{OR}$ , until a value  $C_{OR}^{opt}$  is identified for which  
 281  $p_{99}(k_{turb}) < 1$ .

282 **Note 5 Reservoir simulation for small hydropower plants**

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

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

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

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

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

296 Note that  $f_{reg}$  would normally be unity for the large (more-than-a-year storage) plants described in  
 297 the previous sections; nevertheless, the user is free to specify a value smaller than unity for such plants  
 298 when running REVUB. This could, for instance, reflect a requirement for a seasonal environmental  
 299 flow, or a safeguard against extremely dry years to prevent regular operating rules from overdrawing  
 300 the reservoir. In such a case, the operation of those plants, too, will follow what is described below,  
 301 rather than what is described in the previous sections.

302 Once  $f_{reg}$  chosen, the fraction  $Q_{in,frac}(t)$  is then assumed to be “storable” and, after accounting for the  
 303 imposed environmental and irrigation outflow  $Q_{stable}^{env/irr}(t)$ , usable for balancing. REVUB assumes that  
 304 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  
 305 reservoir without being stored, thus representing the seasonal “run-of-river” component  $Q_{RoR}(t)$ . Since  
 306  $f_{reg}$  can be calculated based on long-term average flow, such operation can be readily implemented as  
 307 long as accurate measurements of inflow are available.

308 For  $f_{reg} < 1$ ,  $d_{min}$  no longer represents the fraction of yearly average inflow required as minimum  
 309 stable outflow, but the fraction of yearly average *storable* flow required as minimum stable outflow.  
 310 The user must take this into account when specifying  $d_{min}$ . REVUB does this automatically when  
 311 calculating a default  $d_{min}$  in case the user does not wish to prescribe a value<sup>xi</sup>.  
 312 The term  $Q_{RoR}$  is appended in equation (S3) (and would be an additional entry under the “water  
 313 releases” arrows in Fig. S2):

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

314 and the corresponding seasonal power generation is then equal to

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

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

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

316 Dispatching such as described for large hydropower plants in the previous sections is done similarly  
 317 for small hydropower plants, with the following adaptations: (i) the component  $Q_{in,frac}(t)$  is used as  
 318 reference flow instead of  $Q_{in,nat}(t)$  in equation (S4); (ii) the rule is added that, as soon as reservoir  
 319 levels drop precariously low (in this case, below  $f_{restart}V_{max}$ ), the seasonal outflow (if nonzero) is  
 320 temporarily stopped and the operation reverts to that of large hydropower plants, using the full  
 321 inflow to stabilise water levels; and (iii) the seasonal power generation  $P_{RoR}^{hydro}(t)$  is not included in  
 322 equation (S9) as it is not expected to take part in the hour-to-hour load-following. Note, however,  
 323 that if river discharge would be regulated by other reservoirs upstream in a cascade-like configuration,  
 324 even  $P_{RoR}^{hydro}(t)$  could become relatively stable throughout the year.  
 325 Note that, for extremely seasonal rivers, it is possible that the run-of-river component of discharge  
 326 and power generation, after accounting for the stable and flexible components, fully “maxes out” the  
 327 turbine capacity. This would normally only happen during the periods in which the river discharge  
 328 reaches its natural peak. In those periods, the plant automatically acts as baseload provider (using  
 329 100% of its discharge capacity and/or rated power capacity) and only reverts to the flexible operation  
 330 once the inflow has somewhat reduced, freeing up operational reserves.

## 331 Note 6 Optional pumped-storage assessment

332 The REVUB code can also be used to assess the potential for increasing load-following potential  
 333 by refurbishing large hydropower plants to pumped-storage schemes<sup>17</sup>, such that excess production  
 334 (typically of solar PV during mid-day) can be used to pump water back up into the reservoir, enabling  
 335 the energy to be stored for use at a later stage. This would involve (i) building a downstream reservoir  
 336 with volume  $V_{lower,max} \ll V_{max}$  to store part of the released water, from which it can be pumped back  
 337 up into the reservoir, and (ii) ensuring the turbines can be operated in reverse mode and/or pumps  
 338 are installed.  
 339 The hydrological balance components then change as follows. First, since environmental and irrigation  
 340 flow constraints still have to be met, the component  $Q_{stable}^{env/irr}(t)$  has to be directly discharged  
 341 downstream and cannot be used for filling the lower reservoir. Only the component  $Q_{flexible}(t)$  and

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<sup>xi</sup>The calculation of this default, in a more generalised form for any  $f_{reg}$ , is as follows:  $d_{min}^{default} = (f_{min}Q_{turb}^{max}/N_{turbines} - (1 - f_{reg}) \min [Q_{in,nat}(t)])/(f_{reg}\overline{Q_{in,nat}(t)})$ . The term  $(1 - f_{reg}) \min [Q_{in,nat}(t)]$  represents the fact that the run-of-river component can contribute to the minimum load of the first turbine provided that it has a nonzero minimum throughout the year. For  $f_{reg} = 1$ , which is the case for “large” hydropower plants, this equation reduces to  $d_{min}^{default} = (f_{min}Q_{turb}^{max}/N_{turbines})/\overline{Q_{in,nat}(t)}$  as given earlier.

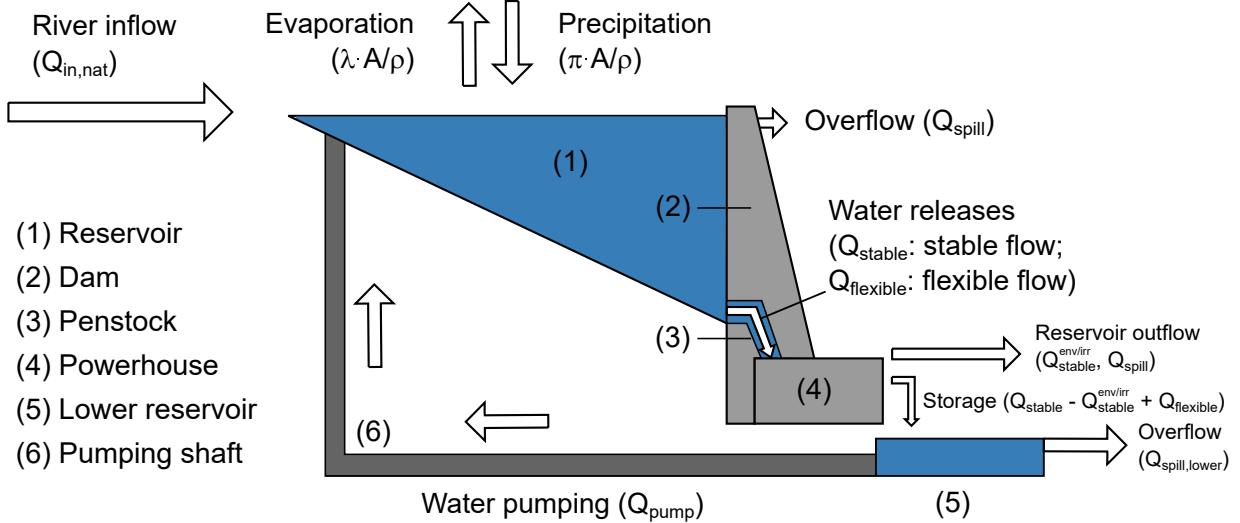


Figure S3: Flowchart of the water gains and losses of a large hydropower plant, including pumped storage. Water gains and losses of a hydropower plant modelled as pumped-storage plant, with an additional lower reservoir and a flow of water in the upstream direction for temporary energy storage.

what remains of  $Q_{stable}^{tech}(t)$ , i.e. the part unaccounted for by  $Q_{stable}^{env/irr}(t)$ , can be used for filling the lower reservoir. Thus, the water balance of the lower reservoir is then given by

$$\begin{aligned} V_{lower}(t + \Delta t) &= V_{lower}(t) + [Q_{stable}(t) - Q_{stable}^{env/irr}(t) + Q_{flexible}(t) - Q_{pump}(t) - Q_{spill,lower}(t)] \Delta t \\ &= V_{lower}(t) + [\max [Q_{stable}^{tech}(t), Q_{stable}^{env/irr}(t)] - Q_{stable}^{env/irr}(t) + Q_{flexible}(t) - Q_{pump}(t) - Q_{spill,lower}(t)] \Delta t \\ &\equiv V_{lower}(t) + [Q_{in,lower}(t) - Q_{pump}(t) - Q_{spill,lower}(t)] \Delta t, \end{aligned} \quad (\text{S34})$$

where  $Q_{pump}(t)$  is the water pumped back up to the large reservoir for storage,  $Q_{spill,lower}(t)$  is the overflow component of the lower reservoir, and  $Q_{in,lower}(t)$  has been defined as the sum of the inflow into the lower reservoir from the upper reservoir for ease of notation. 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

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

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

$$Q_{out}(t) = Q_{stable}^{env/irr}(t) + Q_{spill}(t) + Q_{spill,lower}(t). \quad (\text{S36})$$

A schematic of this operation is shown in Fig. S3 (cf. Fig. S2). Note that this kind of pumped-storage operation is mostly applicable 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

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

where  $\Delta P_{pump}^{ramp}$  is the maximum ramp rate for pumping,  $\eta_{pump}$  is the pumping efficiency, and

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

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

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

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

$$Q_{spill,lower}(t) = \begin{cases} 0, & \text{for } (V_{lower,max} - V_{lower}(t)) / \Delta t \geq Q_{in,lower}(t) \\ Q_{in,lower}(t) - (V_{lower,max} - V_{lower}(t)) / \Delta t, & \text{for } (V_{lower,max} - V_{lower}(t)) / \Delta t < Q_{in,lower}(t) \end{cases}. \quad (\text{S40})$$

358 Since the pumping allows a certain fraction of the water to be recycled for power generation, the values  
 359  $c_{solar}^{opt}$  and  $c_{wind}^{opt}$  resulting from the optimisation described in Note 3.2 will end up higher as compared  
 360 to a situation without pumping component. In this way, pumped storage can help increase the load  
 361 that can be carried by the hydro-solar-wind combination.

362 The REVUB code includes an optional section to perform the above operations and the required  
 363 optimisation (this scenario is named “STOR” in the code, as opposed to “CONV” and “BAL”).

## 364 Note 7 Modelling cascade plants

365 The REVUB model includes provisions to allow modelling of cascaded plants, where two or more  
 366 plants directly downstream of each other interact. In particular, REVUB allows for the following  
 367 situations to be modelled:

- 368 • **A run-of-river-plant is located directly downstream of a reservoir plant.** In this case, the run-of-river plant needs only a very reduced amount of data input: installed capacity, hydraulic head, design discharge, number of turbines, and turbine efficiency. The upstream reservoir plant must be modelled with all the required parameters mentioned in the previous sections, and additionally it must be indicated that the upstream reservoir plant feeds the downstream one. In this way, the downstream plant will take the modelled outflow of the upstream one as inflow data, plus any unregulated lateral inflow. The CONV outflow from the upstream plant is used for this end<sup>xii</sup>.
- 376 • **A reservoir plant is located directly downstream of another reservoir plant; the upstream one is the main flexibility provider.** In this case, it is assumed that the operation of the upstream one is optimised based on its own reservoir capacity, and that the downstream one simply receives the resulting outflow of the upstream one and uses that for its own storage operation. The calculation is done as in the previous point, except that the downstream reservoir plant evidently needs the full set of parameters normally required for a REVUB simulation.
- 382 • **A reservoir plant is located directly downstream of another reservoir plant; the downstream one is the main flexibility provider.** In this case, it is assumed that the downstream plant uses the storage capacity of *both* reservoirs, denoted  $V_{down}$  (for the downstream plant) and  $V_{up}$  (for the upstream plant), respectively, to optimise its operation. Full sets of data for both plants must be entered, and the calculation is done as follows:

- 387 1. The simplified assumption is made that any change  $\Delta V$  in cumulatively stored volume  
 $V_{cumul}(t) = V_{down}(t) + V_{up}(t)$  across the reservoirs is proportionally divided over both, with a share that corresponds to each reservoir’s share in maximum total volume. Thus, if a total amount  $\Delta V$  of previously stored water is turbined by the downstream plant, it is assumed that this results in a change in storage of  $f_{down}\Delta V$  in the downstream reservoir, and  $f_{up}\Delta V$  in the upstream reservoir, with  $f_{down} + f_{up} = 1$  and  $f_{down/up} = V_{down/up}^{max}/V_{cumul}^{max}$ .
- 393 2. First, the simulation of the downstream reservoir plant is run. Any calculations involving overall storage volume, such as eq. (S3), are done using  $V_{cumul}(t)$ , and not  $V_{down}(t)$ , as basis. Based on the above logic, the amount of water stored in only the downstream reservoir is calculated as  $V_{down}(t) = f_{down}V_{cumul}(t)$ , and used to calculate the hydraulic head  $h_{down}(t)$  at any point in time, needed to calculate power output of the downstream reservoir. For calculating evaporation and precipitation losses/gains, the surface area of

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<sup>xii</sup>The logic for using CONV being that BAL outflow typically fluctuates strongly from hour to hour, but most run-of-river plants have some amount of “pondage” allowing to smoothen out such fluctuations.

both reservoirs is added to form  $A_{cumul}(t) = A_{down}(t) + A_{up}(t)$ , and any calculations involving overall area, such as again eq. (S3), are done with  $A_{cumul}(t)$ , and not  $A_{down}(t)$ , as basis. The regulation fraction  $f_{reg}$  is interpreted to represent the fraction of total flow into the downstream reservoir ( $Q_{in,down}(t)$ ) allocated for storage across the total available volume ( $V_{cumul}^{max}$ ). Lastly, the critical level of the “cumulative” storage is taken to be the maximum of  $f_{stop,down}$  and  $f_{stop,up}$  (and idem for  $f_{restart}$ ).

- 405 3. Second, the simulation of the upstream reservoir plant is run. Since its operation is dictated  
406 by the needs of the downstream plant (cf. the previous point), the calibration of its volume  
407 levels is slightly changed as compared to equation (S20): instead of using  $V_{CONV}(t)$  as  
408 calibration series, we use the volume curve for the upper reservoir implied by the previous  
409 point, i.e.  $V_{BAL,up}(t) = f_{up}V_{BAL,cumul}(t)$ . The  $f_{reg}$  parameter is imposed on the upstream  
410 reservoir, based on the value of the downstream reservoir and the ratio of respective average  
411 inflows:  $f_{reg,up} = f_{reg,cumul} \cdot f_{up} \cdot \overline{Q_{in,down}}/Q_{in,up}$ .

412 Since the REVUB model does not currently have detailed routing procedures for cascades with reser-  
413 voirs that lie relatively far apart, the application of the cascade module is currently limited to situations  
414 where downstream flow peak attenuation and flow delay between upstream and downstream reservoirs  
415 are small to negligible, i.e. where the reservoirs lie (more or less) directly downstream of one another.

#### 416 Note 8 Meeting spinning reserve requirements

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

$$P_{spin}(t) = \sum_{\text{all hydro plants}} [1 - CF_{hydro}(t)] P_{turb}^r \Gamma(t), \quad (\text{S41})$$

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

$$CF_{hydro}(t) = \frac{P_{stable}^{hydro}(t) + P_{flexible}^{hydro}(t) + P_{RoR}^{hydro}(t)}{P_{turb}^r}. \quad (\text{S42})$$

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

#### 434 Note 9 Glossary

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

Symbol	Unit	Description	Type	Used as/for	Applicable to
$A(t)$	$\text{m}^2$	Reservoir lake surface area	Time series	Output	each hydropower plant & each scenario
$A_{max}$	$\text{m}^2$	Maximum reservoir lake surface area (reached at maximum filling level $V_{max}$ )	Constant	Input	each hydropower plant
$A_{down}(t)$	$\text{m}^2$	Estimated surface area of water of <i>downstream</i> reservoir in a cascade	Time series	Output	each cascade & each scenario
$A_{up}(t)$	$\text{m}^2$	Estimated surface area of water of <i>upstream</i> reservoir in a cascade	Time series	Output	each cascade & each scenario
$V_{cumul}(t)$	$\text{m}^3$	Cumulative surface area of water in reservoirs in a cascade. Equal to $A_{down}(t) + A_{up}(t)$	Time series	Output	each cascade & each scenario
$C_{OR}$	-	Operating reserve coefficient: Fraction of yearly reservoir inflow available for flexible use	Variable	-	each hydropower plant
$C_{OR}^{max}$	-	Maximum allowed operating reserve coefficient taking into account environmental flow needs	Constant	Input	each hydropower plant
$C_{OR}^{opt}$	-	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
$c_{solar}^{opt}$	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
$c_{wind}^{opt}$	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
$CF_{solar}^n(t)$	-	Capacity factor of solar panels in each location with index $n$	Time series	Input	each solar power site
$CF_{wind}(t)$	-	Weighted average capacity factor of wind turbines across locations	Time series	Input	each scenario
$CF_{wind}^n(t)$	-	Capacity factor of wind turbines in each location with index $n$	Time series	Input	each wind power site
$d_{min}$	-	Fraction of average storable reservoir inflow required as minimum outflow	Constant	Input	each hydropower plant
$d_{min}^{default}$	-	Default value of $d_{min}$ used by REVUB in case of non-specification by user	Constant	Input	each hydropower plant
$\Delta P_{turb}^{ramp}$	MW/min	Maximum ramp rate of hydropower plant	Constant	Input	each hydropower plant
$\Delta P_{pump}^{ramp}$	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
$E_{RoR}^{hydro}$	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
$\eta_{turb}$	-	Hydroturbine conversion efficiency (note: can be used to include representation of power factor)	Constant	Input	each hydropower plant
$\eta_{pump}$	-	When simulating pumped-storage potential: Pumping efficiency	Constant	Input	each hydropower plant
$f_{down}$	-	Fraction of downstream reservoir volume in cumulative storage volume in a cascade	Constant	Input	Each cascade
$f_{up}$	-	Fraction of upstream reservoir volume in cumulative storage volume in a cascade	Constant	Input	Each cascade
$f_{opt}$	-	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

Symbol	Unit	Description	Type	Used as/for	Applicable to
$f_{restart}$	-	Reservoir filling fraction at which hydropower generation is restarted after curtailment	Constant	Input	each hydropower plant
$f_{reg}$	-	Fraction of yearly average natural inflow allocated to flexible use	Constant	Input	each hydropower plant
$g$	$\text{m}/\text{s}^2$	Gravitational acceleration	Constant	Input	general
$\gamma$	-	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 (reached at maximum filling level $V_{max}$ )	Constant	Input	each hydropower plant
$k_{turb}(t)$	-	Hydroturbine utilisation rate	Time series	Output	each hydropower plant & each scenario
$\kappa$	-	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
$\lambda(t)$	$\text{kg}/\text{m}^2/\text{s}$	Evaporation flux on reservoir lake surface	Time series	Input	each hydropower plant
$\mu$	-	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
$N_{turbines}$	-	Total number of turbines (units) of a single hydropower plant	Constant	Pre-input	each hydropower plant
$\nu(t)$	-	Ratio of spinning reserves to total solar and wind power generation	Time series	Output	each hydropower plant & each scenario
$P_{turb}^r$	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
$P_{guaranteed}^{xx}$	MW	Guaranteed power (based on user-defined exceedance percentile $xx$ ) across simulation horizon	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
$\phi$	-	Conventional reservoir rule parameter	Constant	Input	each hydropower plant
$\pi(t)$	$\text{kg}/\text{m}^2/\text{s}$	Precipitation flux on reservoir lake surface	Time series	Input	each hydropower plant
$\Psi$	-	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
$Q_{in,frac}(t)$	$\text{m}^3/\text{s}$	Part of natural inflow assumed to be storable, equal to $f_{reg}$ times the natural inflow	Time series	Intermediate	each small hydropower plant

Symbol	Unit	Description	Type	Used as/for	Applicable to
$Q_{in,nat}(t)$	$\text{m}^3/\text{s}$	Natural river discharge into reservoir	Time series	Input	each hydropower plant
$Q_{in,lower}(t)$	$\text{m}^3/\text{s}$	Upper reservoir discharge into lower reservoir for pumped-storage plants, consisting of the non-environmental/irrigation component of stable outflow as well as flexible outflow	Time series	Input	each hydropower plant & each scenario
$Q_{out}(t)$	$\text{m}^3/\text{s}$	Total reservoir outflow, consisting of stable, flexible, run-of-river and spilling components	Time series	Output	each hydropower plant & each scenario
$Q_{stable}(t)$	$\text{m}^3/\text{s}$	Stable component of reservoir outflow	Time series	Output	each hydropower plant & each scenario
$Q_{stable}^{tech}(t)$	$\text{m}^3/\text{s}$	Technologically required part (related to minimum stable turbine load and need for active synchronous capacity) of stable component of reservoir outflow	Time series	Output	each hydropower plant & each scenario
$Q_{stable}^{env/irr}(t)$	$\text{m}^3/\text{s}$	Environmentally/irrigation-wise required part of stable component of reservoir outflow	Time series	Output	each hydropower plant & each scenario
$Q_{flexible}(t)$	$\text{m}^3/\text{s}$	Flexible component of reservoir outflow	Time series	Output	each hydropower plant & each scenario
$Q_{RoR}(t)$	$\text{m}^3/\text{s}$	Seasonal run-of-river component of reservoir outflow (zero for large hydropower plants)	Time series	Output	each small hydropower plant
$Q_{spill}(t)$	$\text{m}^3/\text{s}$	Spilling component of reservoir outflow	Time series	Output	each hydropower plant & each scenario
$Q_{turb}^{max}$	$\text{m}^3/\text{s}$	Maximum hydroturbine throughput	Constant	Input	each hydropower plant
$Q_{turb,flexible}^{pot}(t)$	$\text{m}^3/\text{s}$	Maximum potential outflow available for flexible hydropower generation, before accounting for needs and ramping constraints	Time series	Intermediate	each hydropower plant & each scenario
$Q_{pump}(t)$	$\text{m}^3/\text{s}$	When simulating pumped-storage potential: Pumped flow	Time series	Output	each large hydropower plant & each scenario
$Q_{pump}^{max}$	$\text{m}^3/\text{s}$	When simulating pumped-storage potential: Maximum pumping throughput	Constant	Input	each large hydropower plant
$\rho$	$\text{kg}/\text{m}^3$	Density of water	Constant	Input	general
$t$	hours	Time	Variable	-	general
$T_{year}$	seconds	Number of seconds in a year	Constant	Input	general
$\tau_{fill}$	-	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
$V(t)$	$\text{m}^3$	Volume of water in reservoir	Time series	Output	each hydropower plant & each scenario
$V_{max}$	$\text{m}^3$	Maximum reservoir volume	Constant	Input	each hydropower plant
$V_{down}(t)$	$\text{m}^3$	Estimated volume of water in downstream reservoir in a cascade	Time series	Output	each cascade & each scenario
$V_{up}(t)$	$\text{m}^3$	Estimated volume of water in upstream reservoir in a cascade	Time series	Output	each cascade & each scenario
$V_{cumul}(t)$	$\text{m}^3$	Cumulative volume of water in reservoirs in a cascade. Equal to $V_{down}(t) + V_{up}(t)$	Time series	Output	each cascade & each scenario
$V_{lower}(t)$	$\text{m}^3$	When simulating pumped-storage potential: Volume of lower reservoir	Time series	Output	each large hydropower plant & each scenario
$V_{lower,max}$	$\text{m}^3$	When simulating pumped-storage potential: Maximum volume of lower reservoir	Constant	Input	each large hydropower plant
$w_{solar}^n$	-	Weight factor for capacity in each solar power site	Constant	Pre-input	each solar power site
$w_{wind}^n$	-	Weight factor for capacity in each wind power site	Constant	Pre-input	each wind power site
$z_{max}$	m	Maximal reservoir depth	Constant	Pre-input	each hydropower plant

## 442 Note 10 Running the model: Input (A)

443 The initialisation of the REVUB simulation is done through the file `A_REVUB_initialise`. All  
 444 parameters to be defined by the user can be controlled using the Excel file `simulation_parameters`,  
 445 hereafter the “control file”. This includes various types of data:

- 446 • *Hydropower-plant specific parameters*, which are constants specific to each hydropower plant.  
 447 These quantities are set in the worksheet “**Hydropower plant parameters**” of the control file.  
 448 In this worksheet, it is also possible to turn on/off individual hydropower plants for simulation  
 449 inclusion (parameter `HPP_active`); thus, the worksheet can serve as overall database to collect  
 450 hydropower plant data.

- 451 • *Bathymetric relationship* for the modelled hydropower plants. These values should be read in  
 452 by the code as an array with three columns and a user-determined number of rows; the first  
 453 column should represent reservoir volume, and the second and third column the corresponding  
 454 area and hydraulic head values. The relationships are set in the Excel file `data_bathymetry`  
 455 and linked to the worksheet “**Hydropower plant parameters**” of the control file. This linking  
 456 is done through the parameter `HPP_name_data_bathymetry` on that worksheet.
- 457 • *Time series* of important parameters whose value needs to be known for each time step before  
 458 a simulation can be performed, namely reservoir inflow, evaporation, precipitation, solar/wind  
 459 power capacity factor, and the shape of the electricity demand profile. These values should be  
 460 read in by the code as two-dimensional matrices for each hydropower plant, with the following  
 461 dimensions<sup>xiii</sup>: *[number of time slices (default: hours) per year; number of years covered by the  
 462 simulation]*.<sup>xiv</sup> These quantities are set in the other Excel files `data_xxx.xlsx` and linked to the  
 463 worksheet “**Hydropower plant parameters**” of the control file. This linking is done through  
 464 the parameters `HPP_name_data_xxx` in that worksheet.
- 465   ◊ Note that hydrological time series (inflow, precipitation, evaporation) may often only  
 466 be available at monthly timescale, not hourly, as opposed to solar/wind capacity factors and load. The REVUB repository contains a monthly-to-hourly data converter code  
 467 (`rearrange_data_monthly_to_hourly`, under “*data/auxiliary scripts*”) that parses user-specified  
 468 monthly time series (to be entered in columns in the data collection file `rearrange_data_template.xlsx`, sheet `monthly_series`) into the matrix format required for RE-  
 469 VUB. Running the converter code provides a matrix named `output_hourly_byyear` that  
 470 can be copy-pasted into the relevant `data_xxx.xlsx` files.
- 471   ◊ Similarly, time series for downstream irrigation needs may typically only be available at  
 472 hourly (or different sub-daily) timescale for separate months of the year. The same may  
 473 be the case for e.g. simplified solar/wind CF input data in which only the basic sub-daily  
 474 and seasonal dynamics are represented. The REVUB repository also contains a second  
 475 data converter code (`rearrange_data_daily_bymonth_to_hourly`, under “*data/auxiliary  
 476 scripts*”) to parse user-specified 24-h series given separately for each month (to be entered  
 477 in columns in the file `rearrange_data_template.xlsx`, sheet `daily_bymonth_series`) into the  
 478 matrix format required for REVUB. Here, too, running the converter code provides a ma-  
 479 trix named `output_hourly_byyear` that can be copy-pasted into the relevant `data_xxx.xlsx`  
 480 files.
- 481 • *Indications* of which hydropower plant is in a cascade with which other one, either downstream  
 482 or upstream. This is done through the parameters `HPP_cascade_upstream` (indicating the name  
 483 of reservoir plants upstream) and `HPP_cascade_downstream` (indicating the name of reservoir  
 484 or RoR plants downstream) in the worksheet “**Hydropower plant parameters**” of the control  
 485 file.
- 486 • *Simulation accuracy parameters* specific to each hydropower plant. These quantities are set in  
 487 the worksheet “**Hydropower plant parameters**” of the control file. They are the following:
- 488   ◊ `f_init_BAL_start`, `f_init_BAL_step` and `f_init_BAL_end` determine the range (start, step  
 489 size, and end) of  $E_{solar} + E_{wind}$  (cf. equation (S25)), expressed as a fraction of  $E_{reservoir,CONV}^{hydro}$

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<sup>xiii</sup>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.

<sup>xiv</sup>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.

492 (cf. equation (S24)), i.e. the solution space in which the REVUB code starts searching  
493 for the solution to equation (S21). Note that the code gives a warning message to the  
494 user in case this range turns out to be inadequate (i.e. if no global minimum in  $\Psi$  is  
495 found). The same ranges should also be given for STOR scenarios (`f_init_STOR_start`,  
496 `f_init_STOR_step` and `f_init_STOR_end`) in case the user wishes to model these.

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

- 507 • *General modelling parameters* not specific to individual hydropower plants. These quantities  
508 are set in the worksheet “**General parameters**” of the control file. They refer to the length of  
509 the time series to simulate; to physical, invariant quantities used in the hydropower modelling  
510 according to the equations introduced in this Manual; and a few overall simulation accuracy  
511 parameters:

512  $\diamond$  `N_ELCC` determines the accuracy (the number of discrete steps between zero and maximum  
513 power generation) with which the zero-crossing of  $L_{res}$  in equation (S22) is determined.  
514  $\diamond$  `psi_min_threshold` is zero by default, but can be set higher to speed up computation time  
515 in case the search for the minimum in  $\Psi$  takes too long. This parameter ensures that the  
516 zooming-in to higher accuracies (see previous point) is stopped as soon as  $\min(\Psi)$  ends  
517 up below `psi_min_threshold`. It can thus be a compromise for users wishing to have high  
518 accuracy of determining  $\min(\Psi)$  (i.e. setting `N_refine_BAL/STOR` > 1) but not at a high  
519 cost of computational speed.  
520  $\diamond$  `X_max_BAL` determines the amount of iterative loops employed by the model to get a con-  
521 verged estimate of  $P_{stable,BAL}^{hydro}$  (cf. equation (S9) and the explanation below equation (S19)).  
522 Each +1 also increases computation time proportionally. For users wishing to model STOR  
523 scenarios, the same principle applies to `X_max_STOR`.

## 524 Note 11 Running the model: Core code (B)

525 The actual core code of REVUB is contained in the file `B_REVUB_main_code`. Once the input data has  
526 been loaded using the file `A_REVUB_initialise`, the user can principally run this core code directly.

## 527 Note 12 Running the model: Output graphics (C)

528 The results of the REVUB simulation are post-processed with two separate scripts, which generate  
529 several standardised figures based on the input and output of the model. The two scripts serve a  
530 somewhat different purpose:

- 531 • The script `C_REVUB_plotting_individual` is used to plot simulation results pertaining to a  
532 single (user-selected) hydropower plant.  
533 • The script `C_REVUB_plotting_multiple` is used to aggregate simulation results pertaining to (a  
534 user-selected set of) all hydropower plants. Based on a user-defined total electricity demand,  
535 it shows how much of this total demand can be met by hydro-solar-wind power on all involved  
536 timescales, and how much would remain to be met by other power sources.

537 **Note 12.1 Results for individual power plants**

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

- 539 • Figure 1 shows (a) the  $(h, V)$  and (b) the  $(A, V)$  bathymetric calibration curves used as input  
540 to the model.
- 541 • Figure 2 shows (a) the full time series of hydraulic head  $h(t)$  under CONV, BAL and (if mod-  
542 elled) STOR, (b) the frequency spectrum of these hydraulic head curves such that e.g. specific  
543 temporal signatures, such as diurnal dispatch in solar-heavy systems, can be discerned, and (c)  
544 the monthly median and interquartile ranges of natural inflow  $Q_{in,nat}(t)$  and outflow  $Q_{out}(t)$   
545 (equation (S2)) under CONV, BAL and (if modelled) STOR.
- 546 • Figure 3 shows (a) the full time series of lake volume  $V(t)$  under CONV, BAL and (if modelled)  
547 STOR, and (b) the monthly average time series of natural inflow  $Q_{in,nat}(t)$  and outflow  $Q_{out}(t)$   
548 under CONV, BAL and (if modelled) STOR.
- 549 • Figure 4 shows the monthly average composition of the hydro-solar-wind mix supported by the  
550 selected hydropower plant, under the BAL scenario and for a user-defined year (see below).  
551 The figure indicates hydropower generation (by stable, flexible and RoR components) and the  
552 optimal solar and wind power contribution identified by REVUB. The achieved ELCC, whose  
553 profile reflects that of  $L_{norm}(t)$ , is also indicated. In case a STOR scenario was simulated, a  
554 corresponding extra figure will be produced for that scenario, additionally indicating the pump-  
555 stored part of solar/wind power generation.
- 556 • Figure 5 is analogous to Figure 4, but at yearly resolution and reflecting the entire simulated  
557 time series.
- 558 • Figure 6 is analogous to Figure 4, but at hourly (full) resolution for a user-defined time slice  
559 (see below).
- 560 • Figure 7 shows approximated reservoir release rules in the BAL scenario for a user-defined hour  
561 of the day during a user-defined month. The plot shows the median and interquartile range  
562 of needed reservoir release (minus the RoR and spill components, i.e.  $Q_{stable} + Q_{flexible}$ ) versus  
563 the median hydraulic head, with each data point denoting results from one simulation year. A  
564 linear fit to these data points is also shown.
- 565 • Figure 8 shows statistics of turbine use over the simulated period. Based on the number of units  
566 installed (part of the input in the worksheet “**Hydropower plant parameters**” of the Excel file  
567 `parameters_simulation.xlsx`; see above), the amount of time in which a specific number of those  
568 is active is extracted from the hourly profiles of power generation and plotted in a bar chart.
- 569 • Figure 9 shows statistics of the operational regime in the BAL scenario, divided into four options:  
570 flexibility (the regular operation modeled with REVUB), baseload (when the turbine capacity  
571 is fully maxed out; see Note 5), mixed (the border regime where the plant oscillates between  
572 the flexibility regime and baseload regime; this occurs when total outflow oscillates near the  
573 maximum discharge capacity of the turbines), and curtailed (when droughts force hydropower  
574 curtailment).

575 To produce the figures, a few parameters need to be user-defined in the worksheets “**Plot power**  
576 **output (single HPP)**” and “**Plot release rules (single HPP)**” of the file `plotting_settings.xlsx`,  
577 where they can be changed to adapt the data to be plotted. These are as follows:

- 578 • `plot_HPP` is the index of the hydropower plant for which to plot results in all Figures.
- 579 • `plot_year` is the index of the simulation year for which to plot results in Figures 4 and 6.
- 580 • `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.
- The user can further choose to include or exclude the RoR-component of hydropower in the graphs, to include or exclude the plotting of the ELCC as a line, and to turn the production of each individual figure on and off.

### 593 Note 12.2 Results for multiple power plants

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

- To run the file, the user must first define several parameters to construct 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, insofar as user-defined available thermal capacity permits. This reflects the assumption of a priority of dispatch for renewables. Any shortfalls unable to be met by this thermal capacity are assumed to be unsatisfied.
- When renewable power generation exceeds `P_total_hourly` by a certain amount, this amount is assumed to be curtailed.

607 In this way, the file allows to calculate the total power mix (hydro/solar/wind/thermal) suggested by  
 608 the streamlined hydro-solar-wind operation as simulated by REVUB.

609 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 power (going beyond the user-defined overall demand) or unsatisfied power (unable to be met due to insufficient thermal capacity) is shown as such. 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).

- 624 • Figure 4 shows average ramping envelopes of the hydro and thermal capacity across the same  
 625 user-defined year as in Figure 1, for a user-defined range of hours. It contains two sub-figures,  
 626 one of the ramping needs in absolute terms (left) and one of the ramping needs expressed as  
 627 fraction of total capacity per hour (right).

628 To produce the figures, a few parameters need to be user-defined in the worksheet “Plot power  
 629 output (multi HPP)” of the file *plotting\_settings.xlsx*, where they can be changed to adapt the data  
 630 to be plotted. These are as follows:

- 631 • `plot_HPP_multiple` is an array containing the indices of the hydropower plants whose results  
 632 are to be aggregated in the Figures. The user can thus select all, or a selection of, the simulated  
 633 hydropower plants.
- 634 • `choose_demand_type` is a boolean operator, where 0 should be chosen to use the same (static)  
 635 demand time series for every year, and 1 signifies the user wishes to show changes (dynamic) in  
 636 annual demand levels.
- 637 • `P_total_av` and `P_r_total_thermal` represent the static values for average power demand and  
 638 available thermal capacity, respectively, for the case `choose_demand_type = 0`.
- 639 • `P_total_av_series` and `P_r_total_thermal_series` represent the dynamic values (one for each  
 640 year) for average power demand and available thermal capacity, respectively, for the case  
 641 `choose_demand_type = 1`.
- 642 • `plot_year_multiple` is the index of the simulation year for which to plot results in Figures 1  
 643 and 3.
- 644 • `plot_month_multiple` is the month in which to start the time slice in Figure 3.
- 645 • `plot_day_month_multiple` is the day of the month defined by `plot_month` on which to start the  
 646 time slice in Figure 3.
- 647 • `plot_num_days_multiple` is the number of days for which to plot results in Figure 3.
- 648 • `plot_ramping_range` is the number of hours across which ramping envelopes should be calcu-  
 649 lated.
- 650 • `chosen_load` is the name of the target load curve to be used in the plotting (found in the Excel  
 651 file *data\_load.xlsx*).
- 652 • `plot_ELCC_line_multiple` allows the user to choose to include or exclude the plotting of the  
 653 ELCC as a line.

### 654 Note 13 Supplementary tips for model use

655 This section provides a few additional hints that may help to ease the use of the REVUB model in  
 656 practice.

- 657 • As mentioned in sections Note 3.1 and Note 3.2, the default is to use the entire simulation  
 658 period as reference for several processes in REVUB, such as the calculation and use of long-  
 659 term average flow statistics (cf. eq. (S4), eq. (S14)) and the optimisation of lake level dynamics  
 660 of BAL/STOR versus CONV (eq. (S20)). The user can change this by manually setting the  
 661 parameters `year_calibration_start` and `year_calibration_end` in the sheet “Hydropower  
 662 plant parameters” of the control file *simulation\_parameters.xlsx*. This can be useful, for in-  
 663 stance, when simulating extreme events such as unforeseen droughts hitting a hydropower plant:  
 664 in that case, one would select the calibration period to not include that extreme year, forcing  
 665 the model to be “myopic” in relation to the extreme dry period. Leaving the parameter fields  
 666 empty will revert the model to the default of using the entire simulation period.

- 667 • In order to check several basic outcomes of the model (such as lake levels, outflow statistics, etc.),  
 668 it is instructive to first run a CONV scenario without bothering with the BAL/STOR optimi-  
 669 sations, allowing to easily identify obvious errors in the input data. For this reason, it is recom-  
 670 mended to first run a “calibration” scenario with only CONV by setting `calibration_only` to  
 671 zero in the worksheet “General parameters” in the control file. This will skip the BAL/STOR  
 672 optimisation entirely.
- 673 • One could conceivably wish to investigate how a hydropower plant performs flexibly (BAL)  
 674 compared to baseload-like (CONV), but *without* any contribution from solar and/or wind power,  
 675 i.e. solely to meet a certain target load without hybridisation with other power sources. This  
 676 can be simulated by simply not linking any solar and wind timeseries to the simulation (leaving  
 677 `HPP_name_data_CF_solar` and `HPP_name_data_CF_wind` empty in the sheet “Hydropower plant  
 678 parameters” of the control file), in which case REVUB will run the simulation without solar  
 679 and wind. In that case, the code uses an alternative for eq. (S11), namely

$$P_{load} = P_{turb}^r \cdot f_{reg} \cdot c_{dummy}, \quad (\text{S43})$$

680 with  $c_{dummy}$  a dummy variable analogous to  $c_{solar}$  and  $c_{wind}$  from eq. (S9), so that eq. (S21)  
 681 becomes

$$\min(\Psi) = \Psi(c_{dummy}^{opt}). \quad (\text{S44})$$

- 682 • For simplicity, if the user wishes to ignore precipitation and evaporation effects in the simulation  
 683 (usually second-order effects), they can simply choose to not link any precipitation or evaporation  
 684 time series to the hydropower plants in question. This is done in the sheet “Hydropower plant  
 685 parameters” of the control file by leaving the parameters `HPP_name_data_precipitation` and  
 686 `HPP_name_data_evaporation` empty. The same goes for the prescribed outflow, through the  
 687 parameter `HPP_name_data_outflow_prescribed`.
- 688 • Although REVUB is primarily designed to simulate reservoir hydropower plants, it can be used  
 689 in “simplified” mode to simulate run-of-river plants. In this case, most of the input parame-  
 690 ters can be ignored as they are not relevant to plants without reservoirs. The only remaining  
 691 parameters of importance are the inflow (`HPP_name_data_inflow` in the sheet “Hydropower  
 692 plant parameters” of the control file, linking to the correct inflow time series), rated ca-  
 693 pacity (`P_r_turb`), hydraulic head (`h_max`), design discharge (`Q_max_turb`), number of turbines  
 694 (`no_turbines`), and turbine efficiency (`eta_turb`). All other fields in the sheet “Hydropower  
 695 plant parameters” can be left empty. In case the run-of-river plant is part of a cascade with  
 696 reservoir plants upstream, even the inflow parameter can be left empty as the plant will receive  
 697 the outflow of the upstream plant as inflow (cf. Note 7).

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