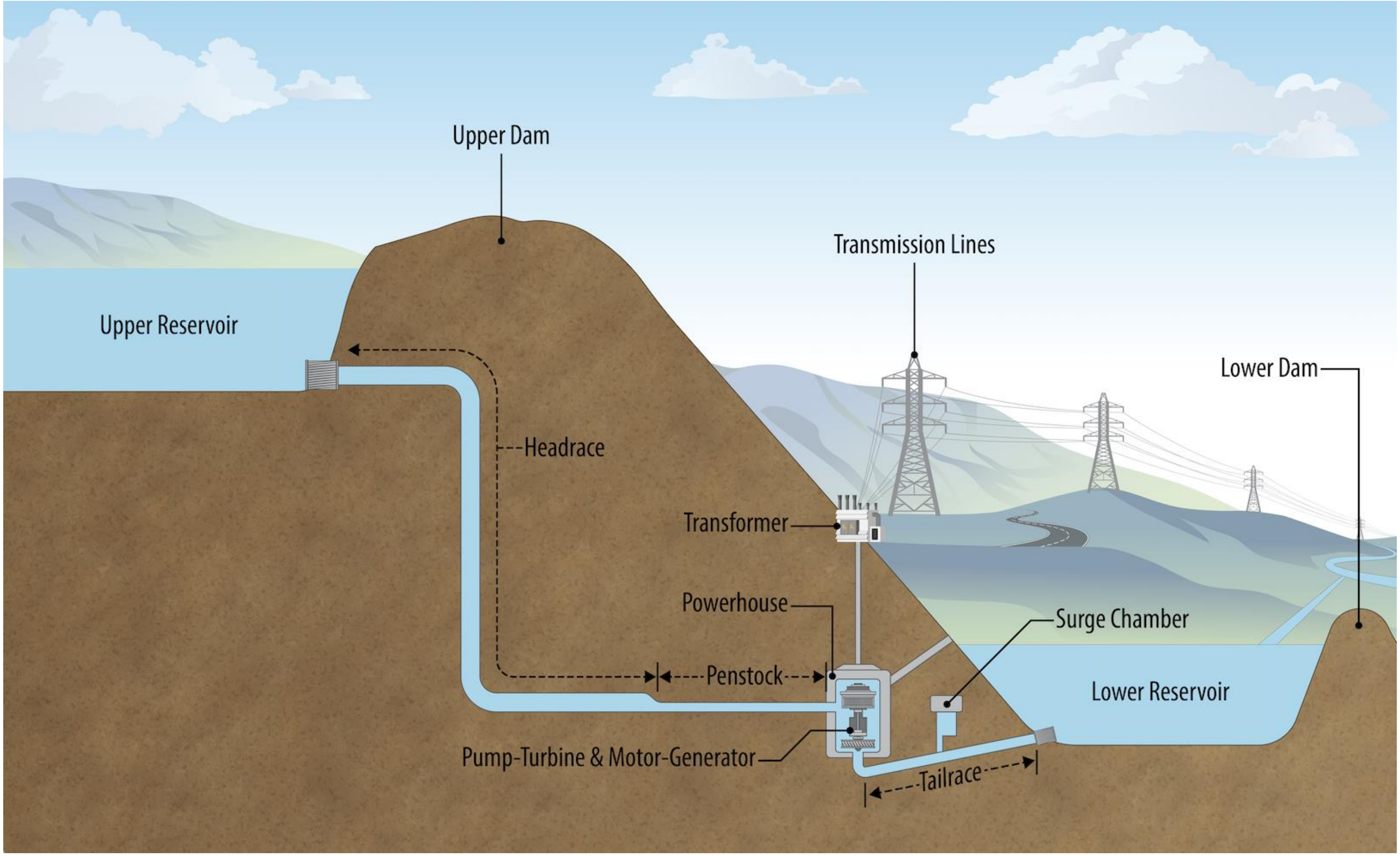
Supplemental Information: Modeling Greenhouse Gas Emissions from Closed-Loop Pumped Storage Hydropower

Annika Eberle, Aaron Vimont, Stuart Cohen, Leta Keane, Dylan Hettinger, Rebecca Hanes, Timothy Simon, Greg Avery, Garvin Heath, and Daniel Inman

This is supplemental information related to the Pumped Storage Hydropower Life Cycle Assessment website.

As detailed on the associated website, the National Renewable Energy Laboratory (NREL) developed the pumped storage hydropower life cycle assessment (PSH-LCA) tool—based on the methods outlined in Simon et al. (2023)—to allow users to choose PSH site characteristics at varying levels of detail and understand how different components, materials, and life cycle phases contribute to the overall life cycle greenhouse gas (GHG) emissions of a closed-loop PSH facility. Figure 1 illustrates the major components of a closed-loop PSH facility that can be modeled using this tool.

Figure 1. Components in a PSH facility that can be modeled using the PSH-LCA tool. *Modified from* Cohen, Ramasamy, and Inman (2023).



The PSH-LCA tool calculates GHG emissions for thirteen system components:

- Dam—The embankment structure used to hold back water and form a reservoir
- Headrace—The water conveyance tunnel from the upper reservoir to the penstock
- Penstock—The water conveyance tunnel from the headrace to the pump-turbine
- Anchor—The structural component used to secure the penstock
- Tailrace—The water conveyance tunnel from the outlet of the pump-turbine to the lower reservoir
- Powerhouse—The structure that houses the motor-generator and pump-turbine units
- Reservoir—The body of water used for energy storage, either at the upper (higher elevation) or lower (lower elevation) part of the PSH plant
- Surge chamber—A structure that helps maintain the flow conditions in the pump-turbine
- Stored electricity—The electricity that is used to operate the pumps and move water to the upper reservoir, which is then stored as the potential energy of water in the upper reservoir, minus losses
- Transformer—The device that converts electrical energy from a given input voltage to a different output voltage
- Transmission line—The electrical transmission line from the PSH plant to the closest high-voltage transmission interconnection
- Pump-turbine—The mechanical components that convert between pressure and mechanical energy to either move water from the lower to upper reservoirs by pumping or release water from the upper to lower reservoirs to drive the turbine-generator
- Motor-generator—The device that either converts rotational energy from the turbine into electrical energy or uses electrical energy to drive the pump.

There can be one or more of each of these components in a PSH facility (e.g., two dams are shown in Figure 1—one for the upper reservoir and one for the lower reservoir).

The tool combines the physical properties of those components with empirical curve fits to estimate twenty-two key material and product flows that are required to construct and operate a facility (Table 1). Table 2 defines the variables used in the equations shown in Table 3 for calculating the material and product flows. Table 4 includes additional assumptions used to complete the LCA calculations. These equations, along with the methods described in Simon et al. (2023), are embedded in the PCA-LCA tool to calculate GHG emissions for a wide range of potential PSH designs.

Table 1. List of Material and Product Flows Included in the LCA

Material/Product Flow	**Primary source(s) or use(s)**
Asphalt	Reservoir liner (if asphalt type is chosen)
Concrete	• Dam construction (if concrete, roller-compacted concrete, or concrete face types are chosen) • Tunnel construction (i.e., for the headrace and tailrace)
Copper	• Transmission line • Pump-turbine components • Transformer components
Diesel	Operation of on-site machinery for construction
Electricity, two types: • Used for construction • Used during operation (called "stored electricity")	Pump operation to move water to the upper reservoir
Explosives	Creation of new reservoirs
Direct GHG emissions	Emissions from the reservoir due to land use change
Lubricating oil	Maintenance of mechanical parts in the powerhouse
Polymer	Insulation in the transformer
Riprap	Slope protection for earthen dams
Sand and gravel	Slope reinforcement for rockfill dams
Steel, three types: • Chromium • Low alloy • Reinforcing	Reinforcement for structural components
Soil	Slope reinforcement for earthen dams
Sulfur hexafluoride	Used in electrical insulation and switches
Transmission line	Electrical infrastructure to connect the PSH facility to the power system
Transportation, three types: • Freight ship • Rail • Truck	Transportation of materials to the PSH construction site (prior to or as a part of construction)
Water	• Initial reservoir fill • Annual replenishment to account for operational and evaporation losses

Table 2. Variable Definitions

Variable	Definition	Unit	Type of Variable
$R_{turbine}$	Average rated capacity of the turbine(s)	MW	User input
$R_{facility}$	Rated capacity of the facility	MW	User input
$G_{facility}$	Annual generation	GWh/year	User input
$E_{roundtrip}$	Ratio of energy discharged to the grid from a starting state of charge to the energy received from the grid to bring the system to the same starting state of charge (value is less than one due to losses in the pump-turbine, electromechanical, and other systems)	Unitless	User input (options include: 0.7, 0.75, 0.8, 0.85)
G_{mix}	Stored electricity grid mix (i.e., the composition of technologies used to provide charging energy for the PSH plant and how it changes over time; grid mixes are based on simulations conducted using NREL's Regional Energy Deployment System [ReEDS] model)	Unitless	User input[a]
L	Assumed physical life of the plant (from online date to decommissioning)	Year	User input (options include: 80, 100)
$N_{turbine}$	Number of turbines	Unitless	User input
$V_{reservoir}$	Volume of the reservoir	m^3	User input
$A_{reservoir}$	Surface area of the reservoir	m^2	User input
$D_{reservoir}$	Average depth of the reservoir = $\frac{V_{reservoir}}{A_{reservoir}} * [0.0348\ \text{m/ft}]$	m	Calculated value
$l_{powerhouse}$	Length of the powerhouse (for rectangular powerhouse)	m	User input
$w_{powerhouse}$	Width of the powerhouse (for rectangular powerhouse)	m	User input
$h_{powerhouse}$	Height of the powerhouse	m	User input
$d_{powerhouse}$	Diameter of the powerhouse (for cylindrical powerhouse)	m	User input
l_{dam}	Length of the dam along its crest	m	User input

Variable	**Definition**	**Unit**	**Type of Variable**
h_{dam}	Average height of the dam along its crest	m	User input
V_{dam}	Volume of the dam	m^3	User input
a	Multiplier to modify the dam concrete requirements, specific to the type of dam (equal to 0.99 if the dam type has a concrete face, 0.95 if roller-compacted concrete, and 0 for other types of dams)	Unitless	Constant
b	Multiplier that varies with the type of dam (equal to 1 for dams that are rockfill or rockfill with a concrete face and 0 for all other types of dams)	Unitless	Constant
c	Multiplier that varies with the type of dam (equal to 1 for dams that are earthen or earthen with a concrete face and 0 for all other types of dams)	Unitless	Constant
$l_{headrace}$	Length of the headrace tunnel	m	User input
$d_{headrace}$	Diameter of the headrace tunnel	m	User input
$l_{tailrace}$	Length of the tailrace tunnel	m	User input
$d_{tailrace}$	Diameter of the tailrace tunnel	m	User input
$l_{penstock}$	Length of the penstock tunnel	m	User input
$d_{penstock}$	Diameter of the penstock tunnel	m	User input
ρ_{liner}	Density of the liner material, which varies with the type of material (2322 for asphalt, 1700 for clay, and 0.5 for geomembrane)	kg/m^3	Constant
k	Multiplier to scale the liner material requirements by the material type (equal to 1 for geomembrane, 0.375 for concrete and asphalt, and 0.25 for clay)	Unitless	Constant
l_{line}	Length of the transmission line	m	User input
$d_{transport}$	Average transportation distance (varies by mode of transport)	km	Based on methods outlined in Simon et al. (2023) (Table 4)

Variable	Definition	Unit	Type of Variable
$M_{transport}$	Multiplier for transportation (varies by mode of transport)	Unitless	Constant (Table 4)
T_{steel}	Total mass of steel used in the transformer	kg	Calculated value (Table 3)
T_{copper}	Total mass of copper used in the transformer	kg	Calculated value (Table 3)
$Q_{material}$	Quantity of all materials except concrete	kg	Calculated value (Table 3)
$Q_{concrete}$	Quantity of concrete	m^3	Calculated value (Table 3)

[a] Definitions for stored electricity grid mix: the mid case is from the NREL *2021 Standard Scenarios* Report; 95% reduced grid CO_2 emissions by 2035 is based on the “95% by 2035” scenario in the NREL *2021 Standard Scenarios* Report; and 95% reduced grid CO_2 emissions by 2050 is based on the “95% by 2050” scenario in the NREL *2021 Standard Scenarios* Report.

MW = megawatt; GWh = gigawatt-hour; m = meter; ft = foot; kg = kilogram; km = kilometer.

Table 3. Equations Used To Estimate Material and Product Flows for a Closed-Loop PSH System

Component	Material/Product Flow	Equation/Assumption	Unit	Source
Anchor	Concrete	Assumed to equal 40	m^3	NWRED (2012)
Entire PSH system	Copper	$\left((1.5632\,R_{turbine} - 64.605) + (3.1895\,R_{turbine} - 101.32)\right)N_{turbine}\dfrac{0.3672}{0.00110231\,\frac{ton}{kg}}$	kg	Curve fit derived from data in Flury and Frischknecht (2012), Torres (2011), Krüger et al. (2018), and Kapila et al. (2019)

Component	Material/Product Flow	Equation/Assumption	Unit	Source
	Diesel	$0.916\, V_{reservoir} + 30{,}000{,}000$	L	Curve fit derived from data in Flury and Frischknecht (2012), Krüger et al. (2018), and Kapila et al. (2019)
	Electricity, construction	$72{,}900\, R_{turbine} * N_{turbine}$	kWh	Industry consultation
	Electricity, stored (operational)	$\frac{G_{facility}}{E_{roundtrip}} * \frac{1{,}000{,}000 \text{ kWh}}{\text{GWh}}$	kWh/year	Unit conversion of user input
	Transportation for all materials except concrete (varies by mode—freight ship, rail, or truck—and by material)	$\frac{d_{transport} * M_{transport} * Q_{material}}{907.185 \frac{\text{kg}}{\text{ton}}}$	t-km	Based on Simon et al. (2023) (see Table 4 for details)
	Transportation for concrete (varies by mode—freight ship, rail, or truck)	$d_{transport} * M_{transport} * Q_{concrete} * 2.4 \frac{\text{tons of concrete}}{\text{m}^3}$	t-km	Based on Simon et al. (2023) (see Table 4 for details)
	Water, initial fill	$V_{reservoir}$	m^3	Geometric relationship
	Water, refill due to operational losses	$A_{reservoir} * \frac{33.2 \text{ cm}}{\text{year}} * \frac{0.01 \text{ m}}{\text{cm}}$	m^3/year	Based on an average evaporation rate calculated from Sanford and Selnick (2013)

Component	**Material/Product Flow**	**Equation/Assumption**	**Unit**	**Source**
Dam	Concrete	$a\frac{(2+0.003\,h_{dam})(1.64\,h_{dam})\,l_{dam}}{2}$	m³	Geometric relationship
	Riprap	$2*20*l_{dam}*2500\frac{\text{kg of riprap}}{\text{m}^3}$	kg	Geometric relationship
	Sand and gravel	$b\frac{\left(V_{dam,center}+2*V_{dam,side}\right)}{0.00110231\frac{\text{ton}}{\text{kg}}}90.4\ \frac{\text{tons of soil}}{\text{m}^3\text{ of soil}}$	kg	Geometric relationship
	Soil	$c\frac{\left(V_{dam,center}+2*V_{dam,side}\right)}{0.00110231\frac{\text{ton}}{\text{kg}}}59.3\ \frac{\text{tons of soil}}{\text{m}^3\text{ of soil}}$	kg	Geometric relationship
	Steel, reinforcing	$(1-a)\left[\frac{(2+0.003\,h_{dam})(1.64\,h_{dam})\,l_{dam}}{2}\right]*7.85\frac{\text{tons of reinforcing steel}}{\text{m}^3}*\frac{1}{0.00110231}\frac{\text{kg}}{\text{ton}}$	kg	Geometric relationship
Generator	Copper	$\frac{0.34975\,N_{turbine}(3.1895\ *\ R_{turbine}-\ 101.32)}{0.00110231\frac{\text{ton}}{\text{kg}}}$	kg	Curve fit derived from data in Flury and Frischknecht (2012), Torres (2011), Krüger et al. (2018), and Kapila et al. (2019)
	Steel, low alloy	$\frac{2.1502\,N_{turbine}(3.1895\ *\ R_{turbine}-\ 101.32)}{0.00110231\frac{\text{ton}}{\text{kg}}}$	kg	Curve fit derived from data in Flury and Frischknecht (2012), Torres (2011), Krüger et

Component	Material/Product Flow	Equation/Assumption	Unit	Source
				al. (2018), and Kapila et al. (2019)
Headrace	Concrete	$\pi\left[\left(\frac{d_{headrace}}{2}\right)^2 - \left(\frac{d_{headrace}}{2} - 0.667\right)^2\right] l_{headrace}$	m³	Geometric relationship
	Steel, reinforcing	$0.01 * \pi\left[\left(\frac{d_{headrace}}{2}\right)^2 - \left(\frac{d_{headrace}}{2} - 0.667\right)^2\right] l_{headrace} * 7.85 \frac{\text{tons of reinforcing steel}}{\text{m}^3} * \frac{1}{0.00110231}\frac{\text{kg}}{\text{ton}}$	kg	Geometric relationship
Penstock	Steel, low alloy	$\pi\left[\left(\frac{d_{penstock}}{2}\right)^2 - \left(\frac{d_{penstock}}{2} - 0.1148\right)^2\right] l_{penstock} * * 7.85 \frac{\text{tons of reinforcing steel}}{\text{m}^3} * \frac{1}{0.00110231}\frac{\text{kg}}{\text{ton}}$	kg	Geometric relationship

Component	**Material/Product Flow**	**Equation/Assumption**	**Unit**	**Source**
Powerhouse	Concrete	For rectangular powerhouse: $1.089\left[h_{powerhouse} * w_{powerhouse} * l_{powerhouse} - \left\{\left(h_{powerhouse} - 1\right) * \left(w_{powerhouse} - 1\right) * \left(l_{powerhouse} - 1\right)\right\}\right]$ For cylindrical powerhouse: $1.089\,\pi\left\{h_{powerhouse}\left(\frac{d_{powerhouse}}{2}\right)^2 - \left[\left(h_{powerhouse} - 1\right)\left(\frac{d_{powerhouse}}{2} - 1\right)^2\right]\right\}$	m^3	Geometric relationship
	Steel, reinforcing	For rectangular powerhouse: $0.011\left[h_{powerhouse} * w_{powerhouse} * l_{powerhouse} - \left\{\left(h_{powerhouse} - 1\right) * \left(w_{powerhouse} - 1\right) * \left(l_{powerhouse} - 1\right)\right\}\right] * 7.85\,\frac{\text{tons of reinforcing steel}}{\text{m}^3} * \frac{1}{0.00110231}\,\frac{\text{kg}}{\text{ton}}$ For cylindrical powerhouse: $0.011\,\pi\left\{h_{powerhouse}\left(\frac{d_{powerhouse}}{2}\right)^2 - \left[\left(h_{powerhouse} - 1\right)\left(\frac{d_{powerhouse}}{2} - 1\right)^2\right]\right\} * 0 * 7.85\,\frac{\text{tons of reinforcing steel}}{\text{m}^3} * \frac{1}{0.00110231}\,\frac{\text{kg}}{\text{ton}}$	kg	Geometric relationship
Reservoir	Explosives	$2.5\left(R_{turbine} * 1000\,\frac{\text{kW}}{\text{MW}}\right) * N_{turbine}$	kg	Derived from data in Flury and Frischknecht (2012), Guo et al. (2020), Krüger et al. (2018), Torres (2011), and

Component	Material/Product Flow	Equation/Assumption	Unit	Source
				Kapila et al. (2019)
	Liner (material type could be geomembrane, concrete, soil, or asphalt)	$2\pi\left\{\frac{1}{3}\left[\left[\left(\frac{A_{reservoir}}{\pi}\right)^2\right]^{1.6075} + 2\left[\left(\frac{A_{reservoir}}{\pi}\right)d_{reservoir}\right]^{1.6075}\right]\right\}^{\frac{1}{1.6075}} * 0.0381 * \rho_{liner} * k$	kg	Geometric calculation (using ellipsoidal calculation parameter of 1.6075)
	GHG emissions from reservoir	$\frac{512.926\ \mathrm{kg\ GHG\ emissions}}{\mathrm{acre\ of\ reservoir\ surface\ area}}\left(A_{reservoir} * \frac{1}{4046.86\,\frac{\mathrm{m}^2}{\mathrm{acre}}}\right)$	kg/year	Prairie et al. (2018)
Surge chamber	Concrete	$\left(80.524\ R_{facility} + 429.25\right) * 0.99$	m³	Empirical curve fit using data from Sandvag (2016)
	Steel, low alloy	$\left\{\left[\left(80.524\ R_{facility} + 429.25\right)^{1/3} + 0.0254\right]^3 - \left(80.524\ R_{facility} + 429.25\right)\right\} * 0.02832\,\frac{\mathrm{m}^3}{\mathrm{ft}^3} * 7.85\,\frac{\mathrm{tons\ of\ reinforcing\ steel}}{\mathrm{m}^3} * \frac{1}{0.00110231}\,\frac{\mathrm{kg}}{\mathrm{ton}}$	kg	Empirical curve fit using data from Sandvag (2016)

Component	Material/Product Flow	Equation/Assumption	Unit	Source
Tailrace	Concrete	$\pi\left[\left(\frac{d_{tailrace}}{2}\right)^2-\left(\frac{d_{tailrace}}{2}-0.667\right)^2\right]l_{tailrace}$	m³	Geometric relationship
	Steel, reinforcing	$0.01*\ \pi\left[\left(\frac{d_{tailrace}}{2}\right)^2-\left(\frac{d_{tailrace}}{2}-0.667\right)^2\right]l_{tailrace}*7.85\frac{\text{tons of reinforcing steel}}{\text{m}^3}*\frac{1}{0.00110231}\frac{\text{kg}}{\text{ton}}$	kg	Geometric relationship
Transmission network	Sulfur hexafluoride	$0.34\frac{G_{facility}}{E_{roundtrip}}*\frac{1\ \text{kg}}{1000\ \text{g}}$	kg	Vattenfall (2008)
	Transmission line	$l_{line}*\frac{1\ \text{km}}{1000\ \text{m}}$	km	Unit conversion of user input
Transformer	Copper	$T_{copper}=\frac{199.7\ N_{turbine}\ (0.0017\ R_{turbine}+0.1645)}{0.00110231\frac{\text{ton}}{\text{kg}}}$	kg	Curve fit derived from data in Flury and Frischknecht (2012), Torres (2011), Krüger et al. (2018), and Kapila et al. (2019)

Component	Material/Product Flow	Equation/Assumption	Unit	Source
	Polymer	$(T_{copper} + T_{steel})$	kg	Proxy value derived from total material quantities for other materials
	Steel, low alloy	$T_{steel} = \frac{765\ (0.0017\ R_{turbine} + 0.1645)}{0.00110231\ \frac{\text{ton}}{\text{kg}}}$	kg	Curve fit derived from data in Flury and Frischknecht (2012), Torres (2011), Krüger et al. (2018), and Kapila et al. (2019)
Turbine	Copper	$\frac{0.34975\ N_{turbine}\ (1.5632\ R_{turbine} - 64.605)}{0.00110231\ \frac{\text{ton}}{\text{kg}}}$	kg	Curve fit derived from data in Flury and Frischknecht (2012), Torres (2011), Krüger et al. (2018), and Kapila et al. (2019)
	Lubricating oil	$36.76 \frac{G_{facility}}{E_{roundtrip}} * \frac{1\ \text{kg}}{1000\ \text{g}}$	kg/year	Vattenfall (2008)
	Steel, chromium	$\frac{2.15\ N_{turbine}\ (1.5632\ R_{turbine} - 64.605)}{0.00110231\ \frac{\text{ton}}{\text{kg}}}$	kg	Curve fit derived from data in Flury and Frischknecht (2012), Torres

Component	**Material/Product Flow**	**Equation/Assumption**	**Unit**	**Source**
				(2011), Krüger et al. (2018), and Kapila et al. (2019)
	Steel, low alloy	$$\frac{2.5\ N_{turbine}\ (0.5474\ R_{turbine} + 8.4211)}{0.00110231\ \frac{\text{ton}}{\text{kg}}}$$	kg	Curve fit derived from data in Flury and Frischknecht (2012), Torres (2011), Krüger et al. (2018), and Kapila et al. (2019)
m = meter; kg = kilogram; L = liter; kWh = kilowatt-hour; GWh = gigawatt-hour; t-km = tonne-kilometer; cm = centimeter; kW = kilowatt; MW = megawatt; ft = foot; g = gram; km = kilometer.				

Table 4. Transportation Assumptions (Based on the Methods Described in Simon et al. [2023])

Mode of Transport	**Type of Material**	**Modeling Assumptions**[a]
Truck	Sand and gravel	• $d_{transport}$ = 63.8 km • $M_{transport}$ = 2
	Steel, chromium	
	Concrete	
	Copper	
	Steel, low alloy	
	Steel, reinforcing	
	Riprap	
	Soil	
Rail	Steel, chromium	• $d_{transport}$ = 659.9 km • $M_{transport}$ = 2
	Concrete	
	Copper	
	Steel, low alloy	
	Steel, reinforcing	
Freight ship	Steel, chromium	• $d_{transport}$ = 10203.7 km • $M_{transport}$ = 1
	Copper	
	Steel, low alloy	
No transport	GHG emissions from reservoir	• No transportation modeled for these materials
	Water	
	Diesel	
	Electricity	
	Explosives	
	Geomembrane	
	Lubricating oil	
	Sulfur hexafluoride	

[a] Transportation modeling assumptions are based on the methods described in the Supporting Information for Simon et al. (2023), which identifies specific site locations for all current and proposed PSH facilities in the United States and then estimates transportation distances for all sites using the locations of existing material and manufacturing facilities for each material/product (in the United States and abroad via publicly available routing maps tools [e.g., SeaRates for freight ship, Google Maps for truck, and Aberdeen Carolina & Western Railway's Class I Freight Carrier Map for North America for rail]). Transportation distances in the PSH-LCA tool use an average of all site distances computed for all types of materials for each mode of transport using the methods developed by Simon et al. (2023).

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