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Hybrid energy storage system using post-mining infrastructure (HESS)

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Life cycle assessment (LCA) of the HESS

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1 Life Cycle Assessment of Hybrid Energy Storage System (HESS)

Life cycle assessment (LCA) is widely recognized as one of the most comprehensive methodologies for evaluating the environmental impacts associated with industrial processes and technological systems. It considers the entire life cycle of a product or installation, encompassing raw material extraction, component manufacturing, construction, operation, and end-of-life decommissioning. LCA is defined as a systematic process for assessing the environmental burdens associated with a product, process, or activity by identifying and quantifying the consumption of energy and materials, as well as the emissions and waste generated throughout its life cycle. By adopting a holistic perspective, LCA enables the identification of the life cycle stages responsible for the greatest environmental impacts and supports the development of improvement strategies while avoiding the transfer of environmental burdens between life cycle stages, impact categories, or geographical regions.
The Hybrid Energy Storage System (HESS), developed within the HESS project, is an integrated multi-carrier energy storage concept that utilizes existing post-mining infrastructure, particularly mine shafts and underground excavations, as key functional elements of the storage facility. The concept is based on the adaptation of selected components of former or active mining infrastructure for energy storage applications, thereby reducing the demand for new large-scale civil engineering works while promoting the reuse of industrial assets as part of the energy transition.
In the proposed HESS configuration, energy is stored and converted in three complementary forms: gravitational potential energy, pressure energy, and thermal energy. The system integrates three interoperable storage subsystems, each designed to provide a minimum energy storage capacity of 10 MWh, enabling flexible and coordinated operation within a single hybrid energy storage installation, i.e.:

- pumped Storage Hydropower (PSH), using mine shafts to create hydraulic head and store energy in the form of water potential energy;
- compressed Gas Energy Storage, implemented as CAES using the air or CCES using carbon dioxide as the working medium;
- thermal Energy Storage (TES), used to recover, store and reuse heat generated or required during gas compression and expansion.

The project investigates two alternative operating scenarios for the Hybrid Energy Storage System (HESS). In the first scenario, the system operates as an adiabatic compressed air energy storage (ACAES) configuration, with air serving as the working fluid. In the second scenario, carbon dioxide is used as the working medium, resulting in a compressed carbon dioxide energy storage (CCES) configuration. Comparing these two configurations enables a comprehensive assessment of their respective environmental impacts.
Regardless of the selected configuration, it is assumed that all electricity required for the operation of the individual HESS subsystems, and consequently the integrated HESS installation, is supplied from the public electricity grid. Likewise, all electricity generated during the discharging phase is exported to the grid and is not used to satisfy the internal energy demand of the storage system.
The reference case considered in this study is based on the hard coal Budryk mine in Upper Silesia, Poland, with Shafts II and III selected for the implementation of the HESS concept. Shaft II is repurposed to accommodate the Pumped Storage Hydropower (PSH) subsystem, whereas Shaft III is adapted as a high-pressure storage vessel for either the Adiabatic Compressed Air Energy Storage (ACAES) or the Compressed Carbon Dioxide Energy Storage

(CCES) subsystem, together with the associated Thermal Energy Storage (TES) installation. The integrated HESS operates as a single coordinated energy storage facility, storing electricity during periods of surplus power generation and releasing it in response to demand from the National Power System (NPS). The operation of all subsystems is coordinated by a central intelligent energy router, which optimizes charging and discharging processes while ensuring safe and efficient system performance.

1.1 Goal and scope

This research used the LCA methodology to compare two HESS systems based on various forms of pressure energy storage, i.e. adiabatic compressed air or compressed carbon dioxide, as well as to identify environmental impacts and hot-spots of two hybrid energy storage systems developed within project HESS.

1.2 Functional unit

The functional (FU) unit chosen was "**1 kWh of annual electricity fed to the grid**". 1 kWh of electrical energy is a common FU in life cycle studies regarding storage technologies and electrical power generation.

1.3 System boundaries

The scope of this study is defined as a "cradle-to-gate" boundary, encompassing the construction phase of both proposed HESS plants based on hard coal post-mining shafts located in Upper Silesia, Poland, as well as their operation over a one-year period. According to the literature[1,2,3], the "cradle-to-gate" approach is commonly applied in life cycle assessment studies of hydropower systems. In the present LCA of the HESS configurations, the end-of-life stage was excluded due to the absence of long-term operational experience with comparable energy storage systems, particularly those based on repurposed post-mining infrastructure. Consequently, reliable information regarding the service life of individual components and decommissioning strategies is currently unavailable.
System maintenance and repair activities were also excluded from the analysis, as sufficient and reliable data to quantify the associated material and energy inputs for the proposed HESS system were not available.
The LCA model was developed using openLCA software, which was used to construct and link the unit processes. Where primary data were unavailable, datasets from ecoinvent v3.12 were applied and adapted to reflect the specific conditions of the project. Environmental impacts were assessed using the ReCiPe 2016 v1.03 methodology, with results reported at the midpoint level using the hierarchist (H) perspective.

1.4 Life cycle inventory of individual HESS components

Due to the high degree of complexity of the designed system, as well as very general assumptions regarding its individual components, the inventory of material and energy inputs related to the construction of the entire system, as well as the construction of individual devices, is a very big challenge. Therefore, following assumptions were made for the inventory purposes:

- for the purposes of the inventory, only the main components indicated by the project partners were included;

[1] T.R. Simon, D. Inman, R. Hanes, G. Avery, D. Hettinger, G. Heath, Life Cycle Assessment of Closed-Loop Pumped Storage Hydropower in the United States, Environ. Sci. Technol. 57 (2023), 12251–12258.
[2] L. Grétudóttir, Life Cycle Assessment of a Small Hydropower Plant in Iceland, University of Iceland, 2024.
[3] F. de M. Ribeiro, G.A. da Silva, Life-cycle inventory for hydroelectric generation: a Brazilian case study, Journal of Cleaner Production 18 (2010), 44–54.

- the material inventory of individual electrical devices/turbomachinery of storage systems was based on available literature data;
- for the purposes of calculations, the electricity consumption, calculated taking into account the efficiency of individual systems, was used. Annual electrcity production of PSH-ACAES is 38522 MWh (7865.3 MWh from PSH and 30656.7 from ACAES), while annual consumption 60271 MWh (13106.6 MWh by PSH and 47164.2 by ACAES). Annual electrcity production of PSH-CCES equals 17095 MWh (7865.3 MWh from PSH and 9229.2 MWh from CCES), while annual electricity consumption 27360 MWh (13106.6 MWh by PSH and 14253.6 MWh by CCES);
- based on information provided by the Partner, the production of turbomachinery for the ACAES and CCES systems will take place in Poland, 572 km from the Budryk coal mine, whilst the raw materials for production will be sourced globally.
- it was assumed that the hydropower system for PSH would be manufactured in Austria, approximately 381 km from KWK Budryk.
- due to the general nature of the concept and the lack of information regarding the production of individual components designed/assumed for the system's construction, the LCA does not include energy inputs related to the production of individual devices due to their high complexity and lack of reliable data. Nevertheless, in order to take into account the energy consumption involved in the manufacture of the equipment, *metal working* datasets for different types of steel were applied, with electricity input tailored to the intended country of manufacture (see *Transportation* sheet in attached Excel spreadsheet).
- given that there are several basalt quarries operating in Poland, basalt aggregates production for TES tanks will takes place in Poland, 120 km from HESS location. For modeling, the data set *basalt quarry operation* | *basalt* | *Cutoff, U – RER* from Ecoinvent 3.12 were used and adopted to polish conditions in terms of electricity production. Transport directly from the production plant was assumed and modelled using dataset *market for transport, freight, lorry, >32 metric ton, diesel, EURO 4* | *transport, freight, lorry, >32 metric ton, diesel, EURO 4* | *Cutoff, U – RER*.
- the dolomite required for the construction of the upper reservoir will be sourced from one of the Polish quarries located 262 km from HESS. For modeling, the data set *dolomite production* | *dolomite* | *Cutoff, U – RER* from Ecoinvent 3.12 and were adopted to polish conditions in terms of electricity production. Transport directly from the production plant was assumed and modelled using dataset *market for transport, freight, lorry, >32 metric ton, diesel, EURO 4* | *transport, freight, lorry, >32 metric ton, diesel, EURO 4* | *Cutoff, U – RER*.
- composition of heat transfer fluid Therminol VP-1 was based on SDS provided by manufacturer and was partially approximated using data for production of organic chemicals (*market for chemical, organic, unspecified* | *chemical, organic, unspecified* | *Cutoff, U – GLO, detailed assumption in Excel file, sheet Summary_LCI)* due to the lack of data.
- production of Sikagard WallCoat T and Sikagard P770 protective 2-component seals components indicated in SDS was, to a large extent, approximated using data for production of organic chemicals (*market for chemical, organic, unspecified* | *chemical, organic, unspecified* | *Cutoff, U – GLO, detailed assumption in Excel file, sheet Sika seals).*

- production of assumed Sika® Injection-201 CE 2-component PU resin, which will be used to seal concrete water and pressure dams during the shaft adaptation stage, was modeled based on available SDS and was partially approximated using data for production of organic chemicals (*market for chemical, organic, unspecified* | *chemical, organic, unspecified* | *Cutoff, U – GLO, detailed assumption in Excel file, sheet Sika seals).*
- it was assumed that all types of steel used for HESS component manufacture will be sourced globally and transported to companies responsible for its fabrication– for modelling purpose, market activity for different types of steel– GLO was used for the purpose of modeling the production and delivery of steel to the manufacturing plant;
- production of different types of concrete required to build the systems in both variants will take place at a plant located 16 km from the Budryk coal mine. Cement, gravel and sand for use in the production of concrete will be supplied from plants located 37 and 67 km from the concrete plant.
- clinker and cement will be produced at a single plant, which operates its own raw material quarries (clay, marl, limestone) situated in the immediate vicinity of the cement factory. Consequently, the transport of these raw materials has been deemed insignificant.
- in accordance with the data of Polish Cement Association[4,5] clinker production in Poland is based 75% on alternative fuels, primarily RDF. These data were used to model clinker production and to modify the dataset *clinker production* | *clinker* | *Cutoff, U – RER without CH* available in the Ecoinvent 3.12 database. RDF production was modelled based on data from the literature[6]. Detailed information on the production of concrete, cement and clinker can be found in the *Concrete_production* sheet in the attached Excel spreadsheet.
- Sand and gravel will be produced at polish quarry located 37 km from concrete production site; for modelling purpose, existing Ecoinvent 3.12 *gravel and sand quarry operation – Cuttoff, U - CH* datasets were modified in terms of electricity inputs;
- blast furnance slag will be source form polish steel factory lokacted 124 km from cement factory, while gypsum will be sourced from polish quarry located 219 km away from cement factory;
- for transportion purposes, it has been assumed that all components will be transported using vehicles that comply with the EURO 4 standard. Detailed information regarding the transport of individual components was set out in an Excel spreadsheet, in the *Transportation* sheet.

1.4.1 Pumped Storage Power Plant

According to the technical specifications, the pumped storage hydropower module utilizes post-mining infrastructure, in particular Shaft II of Budryk coal mine, with a depth of approximately 1157 m and a diameter of 9 m.

The project envisages energy storage capacity of approximately 23 MWh, assuming a lower reservoir capacity of approximately 12000–16000 m³. The system can operate in daily cycles, supporting power grid stabilization and integration with renewable energy sources.

[4] https://www.polskicement.pl/broszury/raport-wplywu-2024/;
[5] https://www.polskicement.pl/informatory/informator-2026-spc/;
[6] Helia Salaripoor, Hossein Yousefi, Mahmood Abdoos. Life cycle environmental assessment of Refuse-Derived Fuel (RDF) as an alternative to fossil fuels in cement production: A sustainable approach for mitigating carbon emissions. Fuel Communications 22 (2025), 100135.

The key component of the designed pumped-storage power system inludes a hydropower generating unit consisting of a high-head Pelton turbine coupled with a medium voltage synchronous generator. The unit operates with a head of approximately 900 m, a flow rate of about 0.71 m³/s, and a rotational speed of 1500 rpm, corresponding to a rated power of around 5.3 MW. The three-nozzle turbine is supplied through a DN 400 pipeline, while the generator, directly coupled to the turbine, delivers power to a 6.3 kV grid, operating in parallel and meeting standard synchronization criteria (frequency, voltage, and phase angle).
The upper reservoir of PSH system is designed as partially excavated into the ground, to a maximum depth of 1.1 m. The material excavated during upper reservoir construction will be used to build embankments around the reservoir. In the sections of the reservoir situated above ground level, the reservoir is surrounded by an embankment, with the crest located at an elevation of 2.9 m. The reservoir bottom and side slopes will be lined with a barrier system in order to minimize the losses due to seepage, to protect the reservoir embankments against piping and to protect the groundwater. As planned, the embankments and the bottom of the reservoir will be lined with three layers, comprising of:

- geotextile protective layer – laid directly on the excavation surface and separates the native soil from the compacted stone layer, it is assumed that geotextile fabric used for this project will be made of synthetic, nonwoven PP fibres; total area of geotextile was estimated at 6500 m², which, assuming a density of 0.5 kg/m², equates to a mass of 3.25 kg;
- compacted stone material – approx. 30 cm thick, assumed dolomite aggregates with bulk density of 1500 kg/m3; the total required mass of dolomite aggregates is 3060000 kg;
- concret topping layer – approx. 30 cm thick, assumed C35/45 with CEM II/B, total volume required – 1800 m^3.

Another key component of the PSH system is the pipeline connecting the upper and lower reservoirs. According to information provided by the Partner, the pipeline will be made of steel, and its total weight has been estimated at 603570 kg. Based on the Polish KNR[7] catalogue, it has been estimated that the amount of diesel fuel burned by building machnines during construction of the upper reservoir and the pipeline connecting the upper and lower PSH reservoirs is 38652.8 L, which equates to 1391501.03 MJ. The detailed assumptions used for the calculations were set out in the attached Excel spreadsheet in the *Upper_res_con* sheet.
The lower reservoir of the planned pumped storage plant will be formed within an inactive mining shaft II of Budryk coal mine and will constitute the primary water reservoir of the pumped-storage system operating cyclically in generation and pumping modes. According to information provided by the project partner, the adaptation of Shaft II for use as a lower reservoir will require the construction of three water dams. A total of 260 m³ of C30/37 concrete with CEM III/A base will be used for the construction of the dams. Furthermore, the adaptation of the shaft II for use as a water reservoir will involve the application of a two-component polyurethane resin (2K PUR) injection system (Sika® Injection-201 CE is to be used). The total consumption of 2K PUR for water dams' construction for PSH, as estimated by Partner, is 2.39 m³, which equates to 2477.79 kg (detailed calculation in attached Excel file, *Sika_seals* sheet). The electricity consumption for the construction of three dams and the 2K PUR injection, as estimated by the project Partner, amounts to 4165.56 kWh. In addition, the construction of the dams will involve the excavation of 28 m³ of rock, which will constitute non-hazardous waste.

[7] KNR 2-01. Budowle i roboty ziemne

The adaptation of the shaft for PSH purposes will also require the walls to be protected using Sikagard P770 two-component epoxy resin, which acts as a primer, and Sikagard Wallcoat T two-component liquid membrane. The total application area for each coat has been estimated at 32 741 m², which translates to a total consumption of the Sikagard P770 and the Sikagard Wallcoat T of 11295.65 kg and 10542.60 kg respectively (detailed consumption of both coats can be found in attached Excel file, *Sika_seals* sheet). Before applying the Sikagard P770, it will be necessary to carry out a hydraulic cleaning of the shaft walls, which will require 261928.00 L of water and will result in the need to manage 261928.00 L of generated wastewater. The amount of electricity required to apply the Sikagard P770 and Sikagard Wallcoat T coatings, including the electricity used for shaft cleaning, was estimated at 23958.00 kWh.
The as constructed lower reservoir will be integrated within the same shaft with the Pelton turbine–synchronous generator set and with the DN400 penstock.

According to information provided by project Partner, the penstock supplying water to the Pelton turbine consists of five types of supporting pipes, each equipped with mounting bracket made of steel plates welded to the pipe surface. Three of them correspond to the nominal pressure zones - PN 40 bar between 0 - 326.5 m wall thickness 12.5 mm, PN 63 bar between 326.5 - 570.0 m wall thickness 16 mm, PN 100 bar between 570.0 - 900.0 m wall thickness 20 mm - while two are transitional types:, i.e. PN63/40 and PN100/63. Segments of the penstock are fabricated as welded structures connected by flanges in accordance with the PN-EN 1092-1 standard. Nominal diameter of the designed penstock is DN400 and the length - approx. 900 m. Penstock is made of steel pipes with the outer diameter of Ø406.4 mm. Total weight of the pipeline is 245655 kg. The penstock will be secured to the shaft walls using specially designed mounting brackets, which will be anchored into the shaft wall. The anchoring will require 220 holes to be drilled in the shaft wall, each with a diameter of Ø 36 mm and a depth of 250 mm – based on the data provided by the Partner, the amount of electricity required to power the drill has been estimated at 27 kWh.

Key component PSH, hydropower unit, consist of synchronous generator (5800 kW, 6300 V, 1500 rpm) coupled to vertical Pelton turbine type PV3i-790-160 with bucket made of stainless steel with nickel-plated working surface, spherical shut-off valve with the nominal diameter of DN400 and design pressure of PN100 (equipped with a hydraulic actuator and a mechanical counterweight for closing, with pressure body made of high-pressure carbon steel with connection flanges compliant with PN-EN 1092-1, designed for integration with the DN400 PN100 pipeline), steel annular supply manifold protected with the external surface protected with epoxy resin, regulating nozzles responsible for precise control of the amount of hydraulic energy delivered to the runner and the water jet deflectors ensuring rapid and safe power reduction without the need for immediate closure of the needle nozzles. According to the documentation provided by the project partner, the total mass of the hydropower unit described above is 14500 kg. Due to the lack of data on the mass of individual components, the design and materials used in the construction of the hydropower unit were based on data from the literature concerning the design of Voight Hydro turbine and generator installed at a Scandinavian hydroelectric power station[8]. The proportion of each material was calculated taking into account the total mass of the hydropower unit as specified in the HESS project. For the purposes of the LCA, it was assumed that the nickel-coated surface area is 5 m² and that

[8] Life Cycle Data for Hydroelectric Generation at Embretsfoss 4 (E4) Power Station Background Data for Life Cycle Assessment (LCA) and Environmental Product Declaration (EPD); https://norsus.no/en/publikasjon/life-cycle-data-for-hydroelectric-generation-at-embretsfoss-4-e4-power-station/

the amount of resin used to coat the surface of the annular supply manifold is 0.0145 kg. Detailed information regarding the assumptions made and the material approximations required due to the limited availability of data in the Ecoinvent database were summarised in the *PSH_literature_calculation* and *Summary_LCI* sheets of the attached Excel spreadsheet.

Hydraulic power unit construction was modelled based on the provided total weight of 950 kg and materials data based on a review of data found on the internet. Details on assumed inputs and processes used for hydraulic power unit manufacture can be found in *Summary_LCI* sheet. The upper technical platform, with a total mass of 9608 kg, was modelled as a hot-rolled structure made of non-alloy steel. (see *Summary_LCI* sheet). The control cabinet, which is located on the upper platform, has been modelled based on the total mass specified in the HESS project documentation (90 kg) and Ecoinvent 3.12 dataset *control cabinet production, heat and power co-generation unit, 160kW electrical | control cabinet, heat and power co-generation unit, 160kW electrical | Cutoff, U – RER*.
According to project Partner, the lower platform was designed to be a reinforced concrete slab – the total volume of C35/45 concrete with CEM II/B required for the construction of the lower platform was estimated at 78 m³, and the required amount of reinforcing steel at 11700 kg. Based on data provided by the project Partner, the amount of electricity required to operate the concrete pump was estimated at 132.73 kWh.
The amount of electricity required to transport all PSH components down the shaft using a mining hoist, based on the specified number of 1000 trips, was estimated at 27000 kWh.

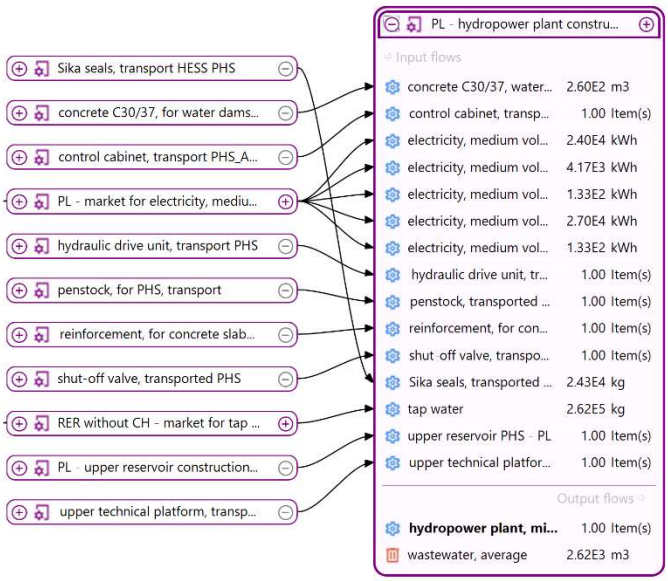

Fig. 1. Pumped storage hydropower plant model

Fig. 1 illustrates the main PSH construction process modelled in the openLCA software. Detailed information on the processes used to model the production of individual components and the construction of the upper reservoir and pipework are set out in the attached Excel spreadsheet in the *Summary_LCI* sheet.

1.4.2 Adiabatic compressed air energy storage (ACAES)

The analysed ACAES energy storage system is an adiabatic compressed air energy storage system, designed to make use of the infrastructure of a decommissioned Budryk hard coal mine: mining shaft no. III with a diameter of 9 meters and a depth of 1089 meters.

Based on the technical description of designed ACEAS, the main machinery side of the adiabatic compressed air energy storage system includes a two-section compressor with a total mean electric power of 33 MW and a single-section expander with a mean electric power of 36 MW. In view of the general assumption of the turbomachinery for ACAES, data for the modelling purpose were based on the available literature[9,10,11]. Based on the reported material bills, it was assumed that the data cited in the literature covered both the compressor/expander, as well as the motor/generator. Consequently, those devices were not considered separately. Furthermore, based on data from one of the manufacturers available on their website[12] and an expert assessment, it was assumed that the masses of the individual devices, estimated by linearly scaling data from the literature, were too low. Consequently, the masses of the compressor/motor and the expander/generator were adjusted by applying scaling factors of 35 and 20 respectively. The masses of the motor/compressor and the expander/generator for ACAES system, adopted for the purposes of the LCA, are 872530.86 kg and 539952.00 kg, respectively (see *A-CAES (Shaft III)* in attached Excel).

The thermal energy storage unit for ACAES system is designed as a segmented, column-type tank. Each segment is a vertical cylindrical steel vessel with an internal diameter of 5 metres and a height of 10 metres. In the recommended variant, the total length of the segments amounts to 40 metres. The segments are stacked one on top of another and connected by DN5000 axial bellows expansion joints. Each segment rests on a support ring fitted with mounting lugs and is suspended by tubular tie rods (with upper and lower pins providing articulation, which eliminates the introduction of secondary loads into the support structure) from the main steel structure anchored to the shaft footings. A double wall filled with mineral wool is provided in the area of the support ring. According to data obtained by project Partner, the total mass of TES tank, with the required allowance for the internal structural stabilising elements and the tank bottom, is 26000 kg. TES tank designed for ACAES is made of P355GH steel (approximated with unalloyed steel due to the lack of data on P355GH steel production). The tank is filled with basalt aggregate, which acts as a heat storage medium, with a total estimated mass of 1347000 kg. The TES tank will be mounted to the shaft casing using mounting components made of HEM 450, with a total estimated weight of 120000 kg. The thermal insulation for the TES tank will consist of stone wool PAROC Pro Wired Mat WR 680, with a total estimated weight of 20000 kg.

According to information provided by the project partner, as in the case of PSH, the adaptation of Shaft III for the use as a high-pressure air storage will require the construction of six pressure dams - 1364 m³ of C30/37 concrete with CEM III/A base will be required for the construction of designed stuctures. Furthermore, in the case of ACAES the application of a two-component polyurethane resin (2K PUR) injection system (Sika® Injection-201 CE is to be used) was also envisaged. The total consumption of 2K PUR for pressure dams' construction in ACAES, as estimated by Partner, is 9.12 m³, which equates to 9439.20 kg (detailed calculation in attached Excel file, *Sika_seals* sheet). The estimated electricity consumption for the construction of all six concrete pressure dams and the 2K PUR injection amounts to 22427.31 kWh. In addition,

[9] S. Kapila, A.O. Oni, E.D. Gemechu, A. Kumar, Development of net energy ratios and life cycle greenhouse gas emissions of large-scale mechanical energy storage systems. Energy 170 (2019), 592-603.
[10] M. Lucas, H. Bewi Komesse, S. Duval-Dachary, D. Teixeir. Comparative Environmental Impact Assessment of a DailyElectricity Restitution Operated by Advanced AdiabaticCompressed Air Energy Storage Systems (A-CAES). Energy Storage 7 (2025), e70194.
[11] Evert A. Bouman, Martha M. Øberg, Edgar G. Hertwich. Environmental impacts of balancing offshore wind power with compressed air energy storage (CAES). Energy 95 (2016), 91-98.
[12] https://www.atlascopco.com/content/dam/atlas-copco/compressor-technique/gas-and-process/documents/driving-centrifugal-compressor-technology-new.pdf

the construction of six dams will result in the generation of non-hazardous waste, i.e. 208.93 m³ of rock, due to the necessary excavation work.
The adaptation of the shaft for ACAES purposes will also require the walls to be protected using the Sikagard P770 two-component epoxy resin and the Sikagard Wallcoat T two-component liquid membrane. The total application area for each coat has been estimated at 30819 m², which translates to a total consumption of Sikagard P770 and Sikagard Wallcoat T of 10632.56 kg and 9923.72 kg, respectively (detailed consumption of both coats can be found in attached Excel file, *Sika_seals* sheet). Also, hydraulic cleaning of the shaft walls with water will be required – according to calculation, 246552 L of water will be required, and 261928.00 L wastewater will be generated. The total amount of electricity required to apply both Sikagard coats in the case of ACAES, including the electricity used for shaft hydraulic cleaning, was estimated at 22701.00 kWh.
A key element in adapting Shaft III for the construction of the ACAES system is a shaft plug designed for as reinforced concrete structure 100 m high and 9 m in diameter. To anchor the plug in the shaft, provision has been made for 8 thrust footings distributed around the circumference of the plug, executed as reinforced-concrete rings of 2.0 m thickness and 1.0 m height and 220 steel anchors in the lower 20-metre section of the plug (made of S355 steel, of 12 m length and 100 mm diameter) which will be fully fixed in the host rock. Based on the dimensions of the plug, it has been estimated that the construction will require 6607 m³ of C30/37 concrete and 518871 kg of reinforcing steel. Based on the data provided for the anchoring of the penstock, the total electricity requirement for drilling 220 boreholes is estimated at 6217 kWh. Furthermore, given the dimensions of the plug, it is envisaged that it will be made in situ – the amount of electricity required for pumping concrete is estimated at 10809 kWh, based on the data used by the project Partner when estimating the costs of constructing pressure dams.
The final component of the ACAES system is a temporary service ventilation system, which will be used during shaft adaptation and when repairs or inspections of Shaft III will be required. Key components of the service ventilation system include the fan, the ventilation duct (diameter of 1000 mm and 1200 mb long) made form antistatic technical fabric coated with plastics, control cabinet and gas sensors, as well as support ropes, anchors and assembly accessories. For the purposes of the LCA, the fan was modelled as a structure with a total mass of 1,355 kg, manufactured from steel and cast iron. The material composition of the fan was based on publicly available literature data (detaile information provided in *Summary_LCI* sheet of attached Excel file). Data on the production of PVC-coated technical polyester fabric was used to model the ventilation duct[13]. Also, for duct production modelling, Ecoinvent 3.12 dataset *market for textile production, nonwoven polyester, needle-punched* | *textile, nonwoven polyester* | *Cutoff, U* - GLO It has been modified in terms of the input and output data relating to textile production. The transport data has been left unchanged, assuming similar global transportation/distribution patterns. Details regarding the production of the ventilation ducting are set out in the '*PVC-coated polyester*' sheet of the attached Excel spreadsheet. Furthermore, it has been assumed that the control cabinet for the service ventilation system will be the same as the control cabinet included in the PSH system.

[13] EPD International AB S-P-13272.

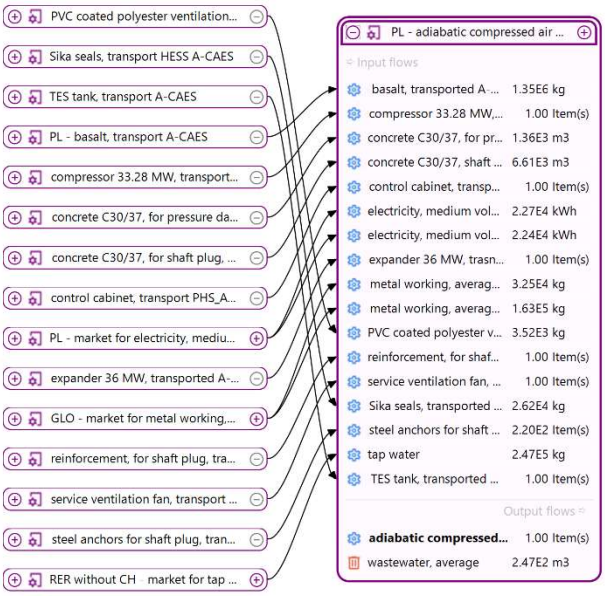

Fig. 2. Adiabatic compressed air energy storage plant model

Fig. 2 illustrates the main ACAES construction process modelled in the openLCA software. Detailed information on the processes used to model the production of individual components are set out in the attached Excel spreadsheet in the *Summary_LCI* sheet.

1.4.3 Compressed Carbon Dioxide Energy Storage (CCES)

The CCES energy storage system is a compressed carbon dioxide energy storage system with isobaric low-pressure and high-pressure tanks, designed to make use of the infrastructure of a decommissioned hard-coal mine Budryk, i.e. Shaf III with a diameter of 9 meters and a depth of 1089 meters.The core idea of the solution is to employ the post-mining shaft as an underground isobaric low-pressure tank (LPT) for carbon dioxide, while an isobaric high-pressure tank (HPT) and a high-temperature thermal energy storage (TES) will be installed on the surface. Total amount of CO_2 required for the operation of CCES system was estimated at 717840 kg.

The main turbomnachnirey of CCES system includes the compressor with the mean electric power at the motor terminals of 10.06 MW and the expander with the mean electric power at the generator terminals of 10.84 MW. As with the turbomachinery for the ACAES system, the equipment for the CCES was modelled on the basis of available literature data[14,15,16]. In this case, too, it was concluded that the masses of the devices resulting from a linear scaling of the available data were too low. Consequently, the masses of the compressor/motor and the expander/generator were adjusted by applying scaling factors of 35 and 20, respectively. The masses of the motor/compressor and the expander/generator for CCES system, adopted for the purposes of the LCA, are 263751.82kg and 162585.55 kg, respectively (see *A-CAES (Shaft III)* in attached Excel).

The TES for CCES system is designed as a two-tank system comprising a hot tank maintained at approximately 300°C and a cold tank maintained at approximately 70°C. The heat transfer fluid circulating between the tanks and the CO_2 heat exchanger is Therminol VP-1 with an

[14] S. Kapila, A.O. Oni, E.D. Gemechu, A. Kumar, Development of net energy ratios and life cycle greenhouse gas emissions of large-scale mechanical energy storage systems. Energy 170 (2019), 592-603.
[15] M. Lucas, H. Bewi Komesse, S. Duval-Dachary, D. Teixeir. Comparative Environmental Impact Assessment of a DailyElectricity Restitution Operated by Advanced AdiabaticCompressed Air Energy Storage Systems (A-CAES). Energy Storage 7 (2025), e70194.
[16] Evert A. Bouman, Martha M. Øberg, Edgar G. Hertwich. Environmental impacts of balancing offshore wind power with compressed air energy storage (CAES). Energy 95 (2016), 91-98.

optimum operating range of 12-400°C. The accumulation material filling each tank is a basalt packed bed. Total basalt mass amounts to approximately 2426000 kg (1213000 kg per tank) and the total Therminol VP-1 mass is approximately 490000 kg, filling the pore space of both packed beds together with the associated pipework and heat exchangers. The TES tanks have been designed as structures made of P355GH steel (approximately 54500 kg). The tanks are fitted with mineral wool-based thermal insulation – 22000 kg for the "hot" tank and 11000 kg for the "cold" tank. In addition, a sheet metal casing with a total weight of 1800 kg has been provided.

To ensure heat exchange between the CO_2 circuit and Therminol-VP1, dedicated shell-and-tube heat exchangers of counter-flow design were provided. Two separate heat exchangers were provided - one on the charging side (total mass of 19200 kg), located between the compressor outlet and the HPT inlet before it is directed to the end cooler (total mass of 7100 kg) and the HPT and one on the discharging side (total mass of 42100 kg), located between the HPT outlet and the expander inlet. All designed heat exchangers are equipped with a carbon steel shell (P355GH steel, or P265GH steel in the case of the end cooler) and tubes manufactured from 316L stainless steel. In addition, all heat exchangers include structural components made of 304 stainless steel.

The high-pressure storage tanks (HPs), a total of 60, have been designed as steel structures made from P460NL2 steel – the mass of a single tank, as assumed for the purposes of the LCA, is 16000 kg (the total mass of the tanks is 960000 kg). According to information provided by the Partner, the tanks will be manufactured in India.

The low-pressure storage tanks (LPT) will be realised by adapting Shaft III at KWK Budryk, with an internal diameter of 9.0 m. The required net storage volume is ≈ 63 300 m^3, corresponding to a shaft depth of approximately 940-950 m. According to the project documentation, the adaptartion of Shaft III for use as a low-pressure CO_2 storage tank will require:

- construction of six pressure dams - 201.93 m³ of C30/37 concrete with CEM III/A will be required for the construction of designed structures. Furthermore, in the case of ACAES the application of a
- injection of Sika® Injection-201 CE two-component polyurethane resin (2K PUR) - the total consumption of 2K PUR for pressure dams' construction in CCES, as estimated by Partner, is 1.99 m³, which equates to 2058.62 kg (detailed calculation in attached Excel file, *Sika_seals* sheet). The estimated electricity consumption for the construction of all six concrete pressure dams and the 2K PUR injection amounts to 2812.06 kWh. In addition, the construction of six dams will result in the generation of non-hazardous waste, i.e. 18.35 m³ of rock, due to the nessesery excavation work.
- Protection of the shaft walls will be achieved by applying two protective coatings: Sikagard P770 two-component epoxy resin followed by the Sikagard Wallcoat T two-component liquid membrane. The total application area for each coating is estimated at 30819 m², resulting in material requirements of approximately 10632.56 kg of Sikagard P770 and 9923.72 kg of Sikagard Wallcoat T. Detailed calculations of coating consumption are provided in the attached Excel file (sheet *Sika_seals*). Prior to the application of protective coatings, the shaft walls will undergo hydraulic cleaning using water. The cleaning process is estimated to consume 246552 L of water and generate approximately 261928 L of wastewater. The total electricity demand associated with hydraulic cleaning and the application of both Sikagard coating systems for the CCES installation has been estimated at 22701 kWh.

- construction of the CCES shaft plug as a reinforced concrete structure with a height of 20 m and a diameter of 9 m. The plug is designed to be secured within the shaft by two reinforced-concrete thrust footings, each measuring 2.0 m in thickness and 1.0 m in height, arranged circumferentially around the plug. In addition, the design includes 44 steel anchors (S355 steel, 12 m long and 100 mm in diameter) installed within the lower 20 m section of the plug and fully embedded in the surrounding rock mass. Based on the proposed dimensions, the construction is expected to require approximately 1334 m³ of C30/37 concrete and 99828 kg of reinforcing steel. According to the data used for the penstock anchoring design, drilling the 44 anchor boreholes is estimated to consume 1243 kWh of electricity. As with the ACAES system, the plug is assumed to be made in situ, with the electricity demand for concrete pumping estimated at 2162 kWh, based on data provided by the project partner during the cost assessment of pressure dam construction.

The CCES system includes also a cryogenic CO_2 post-treatment/purification system designed for a processing capacity of 1000 kg/h. Each unit of the developed syststem is equipped with an automatic control system, including frequency converters for electric motors and heaters, enabling continuous operation within a load range of 30–100% of the nominal capacity. The CO_2 feed stream will be extracted from the mine-shaft energy storage system. A fraction of the main process gas will be diverted to the purification line at a mass flow rate of 1,000 kg/h, corresponding to approximately 550 Nm³/h under normal conditions. The incoming CO_2 stream, cooled to approximately 40°C, will first pass through a filtration unit designed to remove suspended solids, aerosols, and other mechanical impurities originating from the storage system or the underground environment. The filtration stage will effectively separate both fine liquid droplets and solid particles. The dehydration process will be carried out in two successive stages. In the first stage, the gas stream will be pre-cooled to approximately 5°C, causing water vapour to condense. The condensate will be collected in an integrated separator and discharged to the wastewater system. This initial drying stage also protects the downstream CO_2 compressor from handling wet gas. The second stage will provide deep drying using a temperature-regenerated adsorption dryer. To achieve the required low residual moisture content, the adsorption unit will be intentionally oversized. Its nominal capacity exceeds the design flow rate to ensure a sufficient quantity of active adsorbent, allowing the specified drying performance to be maintained. As an alternative, a pressure swing adsorption (PSA) system with purge regeneration could be applied. However, such a solution would result in CO_2 losses of approximately 3–5% of the processed gas due to the regeneration cycle. Following dehydration, the CO_2 stream will be compressed to 20 bars using a two-stage compressor designed for operation in explosive atmospheres. The compressor package will include inlet gas filters, intercoolers, cyclone condensate separators, and an inverter for capacity control. Condensate generated during compression will be discharged to the wastewater system. Purification of the compressed CO_2 will be performed in two stages. The first stage will remove trace organic contaminants by adsorption on activated carbon. The selected adsorption system is designed for inlet hydrocarbon concentrations of up to 10 ppm. The second purification stage consists of cryogenic distillation, where liquid CO_2 is separated from dissolved non-condensable gases. High-purity liquid CO_2 will be withdrawn from the bottom of the distillation column and will satisfy the required raw gas quality specifications. The overhead gas stream, enriched in contaminants, will be discharged through the emission system. The purified CO_2 stream will be liquefied in a dedicated liquefaction unit integrated into the process line. The system comprises a compressor, a regenerative heat exchanger, a water-cooled condenser,

a cooler, and a buffer vessel. Heat removal is achieved using cooling water, while the total electrical power demand of the liquefaction unit is estimated at 70 kW. The liquefied CO_2 product will be stored in stationary vertical cylindrical tanks, each with a storage capacity of approximately 50 tonnes of CO_2. Each vessel has an external diameter of 3 m and an overall height of approximately 11.6 m. To minimize heat ingress, the tanks will be equipped with powder-vacuum insulation.

CO_2 purification unit components included in the LCA study include (for detailed description of components modelled see *Summary_LCI* sheet in attached Excel spreadsheet):

- Filter separators - two filter separators are made mainly of stainless and structural steel. Total mass of stainless steel is 592.2 kg and structural steel 25.2 kg. Additionally, the devices consist of elastomers and sealing weighing (6.3 kg). Measuring equipment and others (manometers, pressure, humidity sensors) weights 6.3 kg;
- Pre-cooler - the pre-cooler is made mainly of stainless and galvanized steel with a high proportion of glycol in the entire mass of the device. Mass of stainless steel is 400 kg, galvanized steel 200 kg and glycol 190 kg. Additionally, the device consist of structural steel (100 kg), copper (100 kg), aluminum (80 kg), thermal insulation (50 kg), plastics and elastomers (30 kg) and coolant R410A (10). Electronics and automation (manometers, pressure, humidity sensors) weighs 40 kg;
- Adsorption dryer - the adsorption dryer consists mainly of stainless steel and adsorbent (molecular sieves or Al_2O_3). Mass of stainless steel is 855 kg and the adsorbent weighs the same. Additionally, the device consists of structural steel (95 kg), elastomers and sealing (19 kg), copper (38 kg), and mineral wool insulation (38 kg);
- CO_2 compressor - consists mainly of cast iron, structural steel and stainless steel. Mass of cast iron is 1890 kg, structural steel is 840 kg and stainless steel 630 kg. Additionally, the devices consist of electrical steel (336 kg), copper (210 kg), elastomers and sealing (42 kg), aluminum (84 kg) and electronics (84 kg);
- Carbon filter - two carbon filters are made mainly of stainless steel and activated carbon. Total mass of stainless steel is 589 kg and activated carbon 214 kg. Additionally, the devices consist of structural steel (46.3 kg) and elastomers/sealing (13.2 kg);
- Cryogenic distillation column - the cryogenic distillation columns are made mainly of stainless steel, unalloyed steel and perlite. Mass of stainless steel is 6.6 t, unalloyed steel is 2.915 t and perlite 1.1 t. Additionally, the device consist of sealing (220 kg) and fittings and automation (165 kg);
- CO_2 condenser - the CO_2 condenser is made mainly of stainless, carbon and unalloyed steel. Mass of stainless steel is 525 kg, carbon and unalloyed steel 225 kg each. Additionally, the device consist cast iron (150 kg), copper (120 kg), insulation (60 kg), aluminum (60 kg), plastics and elastomers (30 kg),coolant R134A (15 kg). Automation and electronics weighs (manometers, pressure, humidity sensors) weighs 60 kg;
- Liquid CO_2 pump - the liquid CO_2 pump is made mainly of stainless steel, unalloyed steel and cast iron. Mass of stainless steel is 40 kg, unalloyed steel is 46 kg and cast iron is 46 kg too. Additionally, the device consist copper (13 kg), aluminum (5 kg), sealing (3 kg), ceramic (5 kg) and electronics (3 kg);
- CO_2 tanks - two CO_2 tanks are made mainly of unalloyed steel, stainless steel and perlite. Total mass of unalloyed steel is 19.978 t, stainless steel 16.612 t and perlite

2,374 t. Additionally, the devices consists sealing (396 kg) and fittings/automation (198 kg).

Fig. 1 illustrates the main CCES construction process modelled in the openLCA software. Detailed information on the processes used to model the production of individual components are set out in the attached Excel spreadsheet in the *Summary_LCI* sheet.

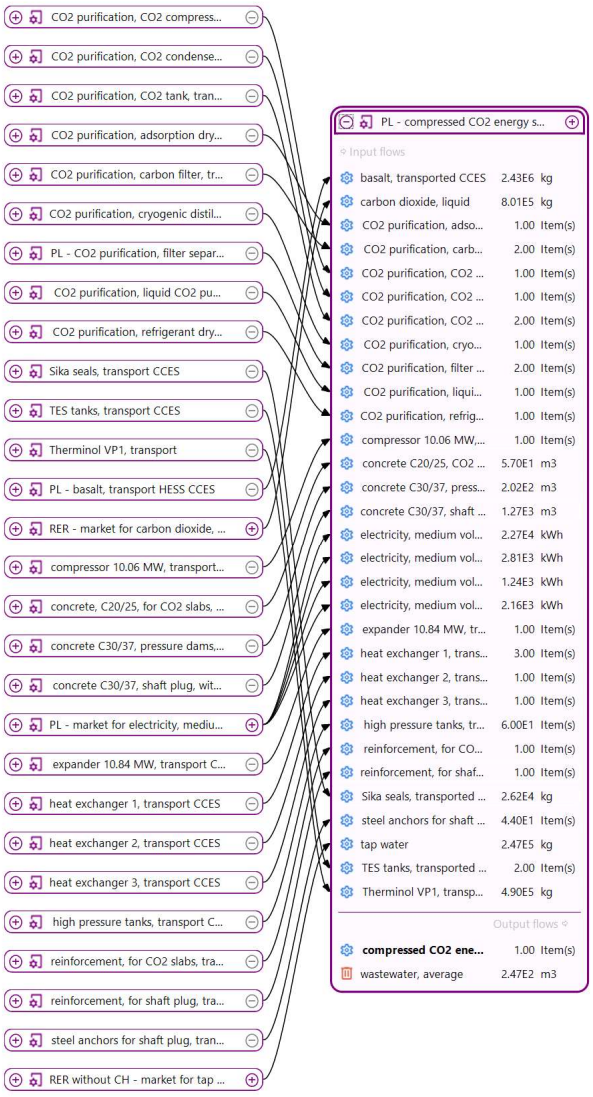

Fig. 3. Compressed CO_2 energy storage plant model

1.4.4 Energy router

The intelligent energy router, developed specifically for the proposed HESS system, constitutes a key component acting as the central unit for integration, control, and optimisation. It is responsible for managing the flow of electrical, thermal, and mechanical energy between the HESS subsystems, the external power grid, and individual storage technologies.

The router determines the optimal operating mode based on multiple operational parameters, including electricity demand, surplus energy availability, state of charge of individual subsystems, pressure and temperature conditions, water levels, technical constraints, safety requirements, and overall system efficiency. During the charging phase, it distributes electrical energy to the PSH pumps and/or the CAES/CCES compressors while simultaneously coordinating heat transfer to the thermal energy storage (TES) unit. During discharging, the router regulates electricity generation from the PSH turbine and the compressed gas expander,

while also managing the delivery of thermal energy from TES to support the expansion process. In addition, it enables hybrid operation, allowing simultaneous operation of multiple subsystems when required by system conditions.
Beyond energy management, the router performs monitoring, diagnostic, and protective functions. It continuously collects data on power flows, pressures, temperatures, water levels, gas storage conditions, thermal storage status, and equipment availability. When predefined operational limits are exceeded, the system can reduce load, switch operating modes, isolate individual subsystems, or initiate controlled shutdown procedures to ensure safe operation.
For life cycle assessment (LCA) purposes, the construction model of the energy router was developed based on material data provided by the project partner responsible for its design. The main materials include various grades of steel, cast iron, plastics, copper, silicon, SF_6, epoxy resins and rubber. Additionally, several background datasets from the Ecoinvent database were applied to model key components. In particular, the dataset *market for transformer, high voltage use* | *Cutoff, U – GLO* was used to represent a high-voltage transformer with a mass of 38500 kg, while available data on printed wiring board (PWB) production were used to approximate PCB electronic components.
Furthermore, the dataset *market for battery, lead acid, rechargeable, stationary* | *Cutoff, U – GLO* was used to model the lead-acid batteries required for system operation. The supporting infrastructure also includes a reinforced concrete slab made of C20/25 concrete with CEM II/A. Based on partner-provided design data, the total concrete volume was estimated at 57 m³.

2 Results

2.1 Operation stage of HESS variants

The conducted life cycle impact assessment (LCIA) results indicate that for both HESS variants the environmental burden associated with system infrastructure is largely overshadowed by impacts related to electricity generation and consumption, which constitute the dominant contributor to the overall environmental profile of the systems under study. In particular, the environmental performance of 1 kWh of electricity annually supplied to the grid is driven primarily by the electricity required for system operation, which is sourced from the Polish national grid, rather than by the impacts associated with equipment manufacturing and the construction phase.
When connected to the same high-voltage Polish grid, the PSH–CAES and PSH–CCES configurations exhibit very similar environmental impacts across all 18 midpoint impact categories (Fig. 4). The LCIA results for both HESS configurations (PSH–ACAES and PSH–CCES) demonstrate a consistently similar environmental performance across all assessed midpoint impact categories, with only marginal differences between the two variants. The most pronounced impact category is climate change, where the results reach 1.52 kg CO_2-eq/kWh for PSH–A-CAES and 1.56 kg CO_2-eq/kWh for PSH–CCES. This confirms previous observations that greenhouse gas emissions are primarily driven by operational electricity demand rather than infrastructure construction or material inputs. A similar trend is observed for fossil resource depletion, with values of 0.36 kg oil-eq/kWh and 0.37 kg oil-eq/kWh, respectively.Human toxicity (non-carcinogenic) also represents one of the most significant impact categories, reaching 2.21 kg 1,4-DCB-eq/kWh for PSH–A-CAES and 2.26 kg 1,4-DCB-eq/kWh for PSH–CCES, followed by terrestrial ecotoxicity (1.02 and 1.05 kg 1,4-DCB-eq/kWh, respectively). These results indicate that toxicity-related impacts are among the dominant contributors to the overall environmental burden of both systems.
Categories related to eutrophication, ozone depletion, particulate matter formation, photochemical oxidant formation, ionising radiation, land use, and water consumption show

comparatively low absolute values and minimal variation between the two configurations. For instance, freshwater eutrophication is 0.00171 vs. 0.00175 kg P-eq/kWh, while ozone depletion remains negligible at the order of 10^{-7} kg CFC-11-eq/kWh for both systems.
The small differences observed consistently favour the PSH–ACAES configuration, although they are not significant enough to indicate a clear environmental advantage of either system.

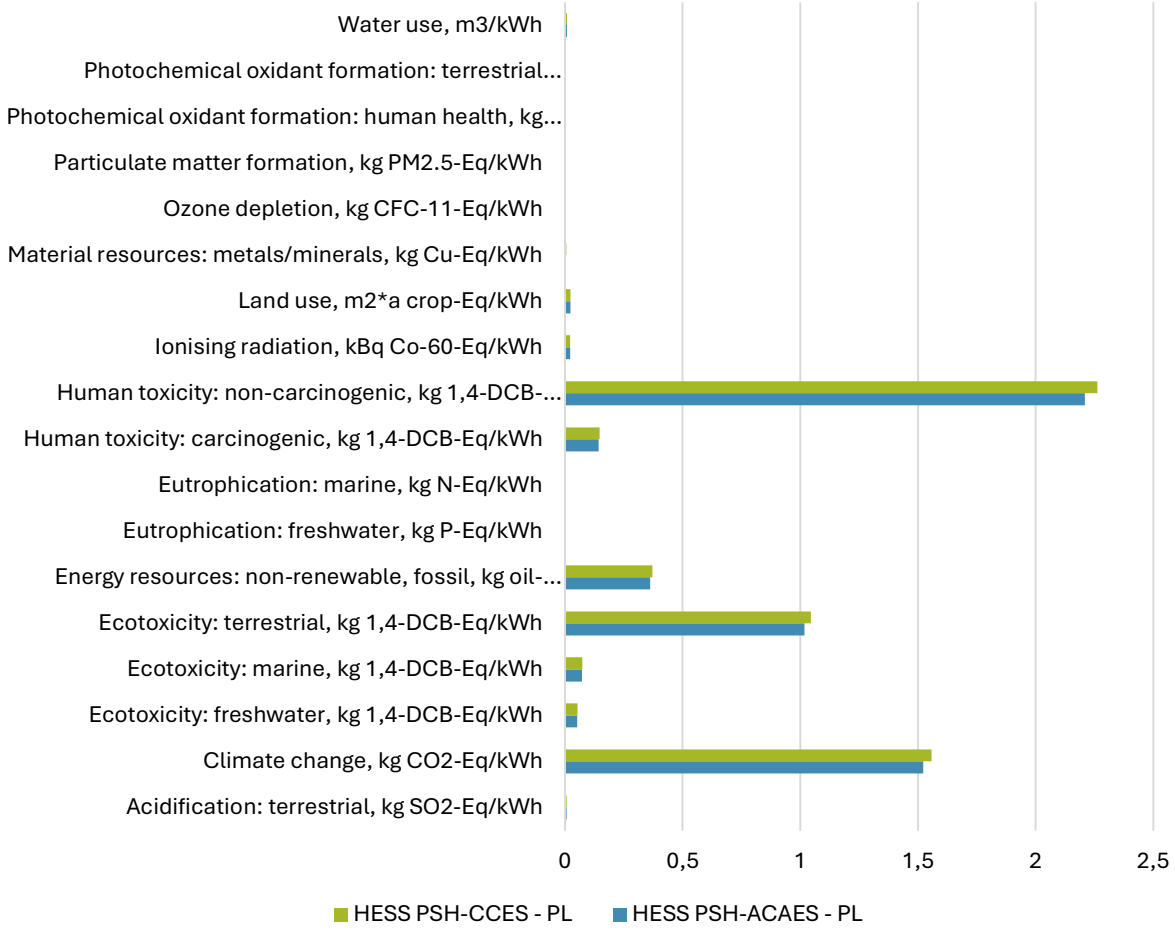

Fig. 4. Impact assesment results - comparisson of 1 kWh electricty fed annually to the grid by PSH-ACAES and PSH-CCES

Based on the contribution analysis shown in the Fig. 5, the environmental profiles of the HESS PSH-ACAES and HESS PSH-CCES scenarios are very similar, with only marginal differences in their climate change impacts. In both cases, the largest contributor to climat change impact category is electricity generated from hard coal power plants in Poland, accounting for 0.68 kg CO_2-eq for PSH-ACAES and 0.70 kg CO_2-eq for PSH-CCES. The second most significant contributor is lignite-based CHP electricity, contributing 0.49 and 0.50 kg CO_2-eq, respectively. Together, these two processes dominate the overall greenhouse gas emissions, highlighting the strong influence of Poland's fossil fuel-dependent electricity mix. Smaller contributions originate from upstream fuel extraction and electricity generation processes, including hard coal mining (0.10–0.11 kg CO_2-eq), hard coal electricity production outside Poland, lignite-fired electricity generation, blast furnace gas power generation, and lignite mining, each contributing less than 0.03 kg CO_2-eq. Electricity from natural gas combined-cycle and conventional CHP plants contributes even less, remaining below 0.02 kg CO_2-eq.

The results indicate that both HESS configurations are dominated by emissions associated with the Polish electricity mix, particularly electricity generated from hard coal and lignite combined heat and power plants. These two processes account for the majority of the climate change impact in both scenarios.

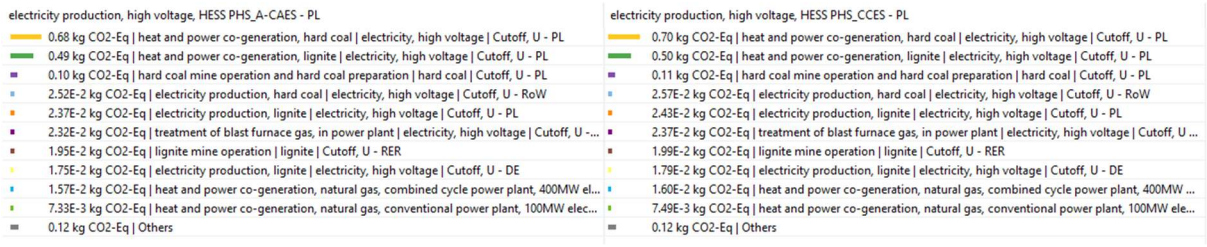

Fig. 5. Top 10 contributions to climat change category for both HESS variants

2.2 PSH-CCES construction stage hot-spots

The contribution tree analysis (Fig. 6 - Fig. 41) regarding the impact of the construction phase of the HESS PSH-CCES system revealed that the environmental profile of the HESS PSH-CCES system varies considerably among the impact categories, reflecting differences in the dominant life-cycle processes and resource requirements. While climate-related categories are primarily driven by electricity generation from fossil fuels, categories associated with resource use and toxicity are mainly influenced by material production and manufacturing processes.

The Climate Change category exhibits a total impact of approximately 1.56 kg CO_2-eq. The dominant contributors are electricity generated from hard coal-fired combined heat and power (CHP) plants (0.70 kg CO_2-eq) and lignite-fired CHP plants (0.50 kg CO_2-eq), followed by hard coal mining (0.11 kg CO_2-eq). Together, these three processes account for approximately 84% of the total climate change impact, demonstrating the overwhelming influence of the fossil-fuel-based Polish electricity mix on the environmental performance of the HESS system.

In contrast, the Water Use category presents a distinctly different contribution pattern. The total water consumption amounts to approximately 1.15 x 10^{-5} m^3 deprived, with the largest contributions originating from the production of Therminol VP-1 (3.19 x 10^{-6} m^3), high-pressure storage tanks (2.56 x 10^{-6} m^3), diphenyl ether production (3.04 x 10^{-6} m^3), low-alloy steel manufacturing (1.42 x 10^{-6} m^3), and metal processing (1.14 x 10^{-6} m^3). Unlike the climate change category, water consumption is governed primarily by the manufacture of construction materials and specialty chemicals rather than electricity generation.

The Acidification: terestial impact category category exhibits a total impact of approximately 7.11 x 10^{-6} kg SO_2-eq per functional unit. Unlike the Climate Change category, where fossil-based electricity generation dominates, Acidification: terestial impact category is primarily associated with the production of the heat transfer fluid and the manufacture of major system components. The largest contribution originates from the Therminol VP-1 production, which contributes 3.27 x 10^{-6} kg SO_2-eq, representing approximately 46.0% of the total acidification potential. Within this subsystem, diphenyl ether production alone contributes 3.19 x 10^{-6} kg SO_2-eq, accounting for approximately 44.9% of the total impact, indicating that the production of aromatic organic compounds is the principal hotspot for this impact category. The second most important contributor is the high-pressure storage tank production, with a cumulative impact of 1.51 x 10^{-6} kg SO_2-eq (21.2%). Transportation contributes only a small fraction of the overall impact. Heavy-duty road transport associated with Therminol VP-1 contributes 1.19 x 10^{-8} kg SO_2-eq, whereas maritime transport of the storage tanks contributes 7.32 x 10^{-8} kg SO_2-eq. Combined, transport-related activities account for less than 2% of the total terrestrial

acidification potential, indicating that logistics have only a minor influence compared with material production.

The Photochemical Oxidant Formation: Human Health category exhibits a total impact of 6.12 x 10^{-6} kg NO_x-eq per 1 kWh. The contribution tree indicates that the formation of photochemical oxidants affecting human health is dominated by the production of the heat-transfer fluid rather than by electricity generation. The largest contributor is the Therminol VP-1 subsystem, with a cumulative impact of 3.77 x 10^{-6} kg NO_x-eq, representing approximately 61.6% of the total impact. Within this subsystem, the production of Therminol VP-1 contributes 3.75 x 10^{-6} kg NO_x-eq (61.3%), while the upstream production of diphenyl ether compounds accounts for 3.69 x 10^{-6} kg NO_x-eq (60.4%). Production of aromatic organic chemicals adds 5.52 x 10^{-8} kg NO_x-eq (0.9%), indicating that emissions associated with petrochemical manufacturing dominate this category. The second-largest hotspot is the high-pressure storage tank subsystem, contributing 8.95 x 10^{-7} kg NO_x-eq, corresponding to approximately 14.6% of the total impact. The manufacture of the storage tanks contributes 7.36 x 10^{-7} kg NO_x-eq (12.0%), while metal working contributes 4.39 x 10^{-7} kg NO_x-eq (7.2%) and low-alloy hot-rolled steel production contributes 2.96 x 10^{-7} kg NO_x-eq (4.8%). Transportation activities play only a minor role. Maritime transport contributes 1.45 x 10^{-7} kg NO_x-eq (2.4%), whereas heavy-duty road transport associated with Therminol VP-1 contributes 2.27 x 10^{-8} kg NO_x-eq (0.4%). Rail transport contributes less than 0.02% of the total impact.

The Photochemical Oxidant Formation: Terrestrial Ecosystems category shows a slightly higher total impact of 6.25 x 10^{-6} kg NO_x-eq, approximately 2.1% greater than the human health indicator. Despite this difference, the contribution pattern remains almost identical. The Therminol VP-1 subsystem remains the dominant contributor, with 3.83 x 10^{-6} kg NO_x-eq, corresponding to approximately 61.2% of the total impact. The production of Therminol VP-1 contributes 3.80 x 10^{-6} kg NO_x-eq (60.8%), while diphenyl ether production contributes 3.74 x 10^{-6} kg NO_x-eq (59.8%). Production of aromatic organic chemicals contributes 6.28 x 10^{-8} kg NO_x-eq (1.0%). The high-pressure storage tank subsystem contributes 9.22 x 10^{-7} kg NO_x-eq (14.8%). Within this subsystem, tank manufacturing contributes 7.60 x 10^{-7} kg NO_x-eq (12.2%), metal working contributes 4.53 x 10^{-7} kg NO_x-eq (7.2%), and low-alloy steel production contributes 3.07 x 10^{-7} kg NO_x-eq (4.9%). Transportation again represents only a minor source of impact. Maritime transport contributes 1.47 x 10^{-7} kg NO_x-eq (2.3%), while heavy-duty road transport contributes 2.40 x 10^{-8} kg NO_x-eq (0.4%). Rail transport remains negligible.

A different pattern is observed for the Human Toxicity (carcinogenic and non-carcinogenic) and Ecotoxicity categories. These impacts are dominated by upstream material production, particularly low-alloy steel, chromium steel, metallurgical processes, and mining activities. Heavy metal emissions and chemical releases occurring during metal extraction and refining contribute more significantly to toxicity-related categories than electricity generation. The Ecotoxicity: freshwater category exhibits a total impact of 2.62 x 10^{-4} kg 1,4-DCB-eq per functional unit. The contribution tree shows that ecotoxicity is primarily associated with the manufacture of structural components rather than operational energy use. The Ecotoxicity: marine category shows a total impact of 3.35 x 10^{-4} kg 1,4-DCB-eq, approximately 28% higher than freshwater ecotoxicity. The Ecotoxicity: terestial category exhibits the largest impact among the three ecotoxicity indicators, reaching 8.55 x 10^{-3} kg 1,4-DCB-eq, which is approximately 33 times higher than freshwater ecotoxicity and 25 times higher than marine ecotoxicity.

The Human Toxicity: carcinogenic category exhibits a total impact of 4.78 x 10^{-4} kg 1,4-DCB-eq per functional unit. The contribution tree indicates that carcinogenic toxicity is dominated by

the manufacture of structural components rather than by operational energy use. The compressed CO_2 energy storage plant contributes 3.00 x 10^{-4} kg 1,4-DCB-eq, corresponding to 62.8% of the total impact. Within this subsystem, the high-pressure storage tanks represent the principal hotspot, with a cumulative impact of 1.67 x 10^{-4} kg 1,4-DCB-eq (34.9%). The 10.06 MW compressor subsystem contributes 2.98 x 10^{-5} kg 1,4-DCB-eq, representing 6.2% of the total carcinogenic toxicity. The main contributors within this subsystem are chromium steel production (1.00 x 10^{-5} kg 1,4-DCB-eq; 2.1%), unalloyed steel (9.18 x 10^{-6} kg 1,4-DCB-eq; 1.9%), steel product manufacturing (3.84 x 10^{-6} kg 1,4-DCB-eq; 0.8%), and chromium steel processing (3.44 x 10^{-6} kg 1,4-DCB-eq; 0.7%). The Human Toxicity: non-carcinogenic category shows a substantially higher total impact of 5.90 x 10^{-3} kg 1,4-DCB-eq, which is approximately 12.3 times greater than the carcinogenic toxicity indicator. As in the carcinogenic category, the compressed CO_2 energy storage plant is the dominant subsystem, contributing 4.74 x 10^{-3} kg 1,4-DCB-eq, or 80.3% of the total impact. The high-pressure storage tanks contribute 2.02 x 10^{-3} kg 1,4-DCB-eq, corresponding to 34.2% of the total impact. The contribution tree clearly indicates that both human toxicity categories are dominated by construction-stage activities, particularly the manufacture of high-pressure storage tanks, low-alloy steel, and metal processing operations. However, the non-carcinogenic toxicity potential (5.90 x 10^{-3} kg 1,4-DCB-eq) is more than an order of magnitude greater than the carcinogenic toxicity potential (4.78 x 10^{-4} kg 1,4-DCB-eq).

The largest contributor in Material resources: metals/minerals is basalt used during the construction of the HESS facility, with a cumulative impact of 1.12 x 10^{-4} kg Cu-eq, representing approximately 33.0% of the total impact. The direct production of basalt accounts for 1.121 x 10^{-4} kg Cu-eq, whereas diesel consumption, electricity use, blasting operations, and road transport associated with basalt extraction contribute only negligible amounts (each <0.01% of the total impact). The second-largest hotspot is the high-pressure storage tank subsystem, contributing 7.26 x 10^{-5} kg Cu-eq, corresponding to 21.4% of the total impact. Within this subsystem, the production of the storage tanks themselves contributes 7.23 x 10^{-5} kg Cu-eq (21.3%). The largest upstream process is the production of low-alloy hot-rolled steel, which contributes 5.74 x 10^{-5} kg Cu-eq, accounting for approximately 16.9% of the total impact. Metal working operations add another 1.49 x 10^{-5} kg Cu-eq (4.4%), while maritime and road transportation together contribute less than 0.1%. The 10.06 MW compressor subsystem contributes 1.68 x 10^{-5} kg Cu-eq, corresponding to approximately 4.9% of the total material resource depletion. Similar to the storage tanks, its impact is primarily associated with steel production and metal processing rather than transportation. Overall, the three largest foreground subsystems - basalt extraction (33.0%), high-pressure storage tanks (21.4%), and the compressed CO_2 energy storage plant (total cumulative contribution 2.55 x 10^{-4} kg Cu-eq, approximately 75.1% of the total) - dominate the depletion of mineral resources.

The Energy Resources: non-renewable, fossil category exhibits a total impact of 3.11 x 10^{-4} kg oil-eq per functional unit. The contribution tree indicates that fossil resource depletion is dominated by the production of construction materials and specialty chemicals rather than by operational electricity generation. The largest contributor is the production of Therminol VP-1, with a cumulative impact of 8.61 x 10^{-5} kg oil-eq, representing approximately 27.6% of the total impact. The production of Therminol VP-1 itself contributes 8.43 x 10^{-5} kg oil-eq (27.1%), while the upstream production of diphenyl ether compounds accounts for 7.07 x 10^{-5} kg oil-eq (22.7%). An additional 1.36 x 10^{-5} kg oil-eq (4.4%) originates from the manufacture of aromatic organic chemicals, indicating that fossil feedstocks used in specialty chemical production constitute a major hotspot in this category.

2.3 PSH-ACAES construction stage hot-spots

The contribution tree analysis (Fig. 42 - Fig. 59) regarding the impact of the construction phase of the HESS PSH-ACAES system are dominated by ACAES turbomachinery production.

In the case of PSH-ACAES variant, the total acidification: terestial potential is 1.68 x 10^{-6} kg SO_2-eq/kWh. The largest contributor is the adiabatic compressed air energy storage (ACAES) plant construction, which contributes 1.09 x 10^{-6} kg SO_2-eq, corresponding to approximately 64.8% of the total impact. Within this subsystem, the main hotspot is the 33.28 MW compressor, contributing 4.37 x 10^{-7} kg SO_2-eq (26.0%), followed by the 36 MW expander, contributing 2.57 x 10^{-7} kg SO_2-eq (15.3%). Unlike the PSH-CCES configuration, where acidification: terestial was strongly influenced by Therminol VP-1 and the high-pressure storage tanks, the ACAES system is dominated by large turbomachinery. Together, these two components account for approximately 41% of the total acidification potential, while the entire ACAES plant contributes nearly 65%.

The total Climate Change impact of the PSH-ACAES system is 4.45 x 10^{-4} kg CO_2-eq/kWh, with the adiabatic compressed air energy storage (ACAES) plant contributing 2.86 x 10^{-4} kg CO_2-eq, corresponding to 64.3% of the total climate change potential. Within the ACAES plant, the 33.28 MW compressor is the largest individual contributor, accounting for 1.05 x 10^{-4} kg CO_2-eq (23.6%). Excluding transport, compressor manufacturing alone contributes 1.04 x 10^{-4} kg CO_2-eq (23.3%). The second-largest hotspot is the 36 MW expander, contributing 6.12 x 10^{-5} kg CO_2-eq, or 13.8% of the total impact. The expander manufacturing itself contributes 6.03 x 10^{-5} kg CO_2-eq (13.6%), with chromium steel, metal working, and unalloyed steel again representing the principal upstream contributors.

The Ecotoxicity: freshwater impact category of the PSH-ACAES system amounts to 1.11 x 10^{-4} kg 1,4-DCB-eq per applied functional unit. The contribution tree indicates that the adiabatic compressed air energy storage plant is the dominant subsystem, contributing 8.03 x 10^{-5} kg 1,4-DCB-eq, which corresponds to 72.6% of the total freshwater ecotoxicity. Within the ACAES plant, the 33.28 MW compressor is the largest individual hotspot, contributing 4.03 x 10^{-5} kg 1,4-DCB-eq (36.4%). The compressor manufacturing process itself contributes 4.02 x 10^{-5} kg 1,4-DCB-eq (36.4%), indicating that transportation contributes negligibly.

The contribution tree demonstrates that marine ecotoxicity is governed almost entirely by the manufacture of turbomachinery and associated materials. The compressor (36.3%) and expander (21.8%) together account for approximately 58% of the total impact, while the entire ACAES plant contributes 72.6%. Ecotoxicity: marine impact of the HESS PHS A-CAES system is 1.42 x 10^{-4} kg 1,4-DCB-eq per 1 kWh. According to the contribution tree, the largest individual contributor (hot-spot) is the 33.28 MW compressor, with a cumulative impact of 5.16 x 10^{-5} kg 1,4-DCB-eq/kWh. The Ecotoxicity: terestial impact (1.70 x 10^{-3} kg 1,4-DCB-eq) is substantially higher than the freshwater (1.11 x 10^{-4} kg 1,4-DCB-eq) and marine (1.42 x 10^{-4} kg 1,4-DCB-eq) ecotoxicity indicators for ACAES system. However, all three ecotoxicity categories share the same hotspot structure, i.e. ACAES plant dominates the impact (c.a. 73%), with compressor and expander being is the largest individual contributors. The total Energy Resources: Non-renewable, Fossil calculated impact for ACAES system is 9.96 x 10^{-5} kg oil-eq per 1 kWh. The ACAES plant construction is the dominant contributor, accounting for 6.40 x 10^{-5} kg oil-eq, which corresponds to 64.3% of the total fossil resource depletion. The manufacturing of the compressor itself contributes 2.50 x 10^{-5} kg oil-eq, while transport contributes only 4.51 x 10^{-7} kg oil-eq (0.45%), indicating that nearly all fossil resource use is associated with manufacturing.

Obtained results demonstrate that Eutrophication: freshwater (2.81 x 10^{-7} kg P-eq) is approximately 9.5 times greater than Eutrophication: marine (2.97 x 10^{-8} kg N-eq). Despite this difference in magnitude, both impact categories are governed by the same upstream manufacturing processes, indicating that material selection and manufacturing efficiency are the key parameters for reducing eutrophication impacts in the HESS PHS ACAES system. The 33.28 MW compressor is again the dominant hotspot in both categories.
The Human toxicity: carcinogenic impact amounts to 2.04 x 10^{-4} kg 1,4-DCB-eq per functional unit, whereas the Human toxicity: non-carcinogenic impact reaches 2.68 x 10^{-3} kg 1,4-DCB-eq, approximately 13.1 times higher. In both categories, the ACAES plant is the dominant life-cycle stage. It contributes 1.26 x 10^{-4} kg 1,4-DCB-eq (61.4%) to carcinogenic toxicity and 2.16 x 10^{-3} kg 1,4-DCB-eq (80.7%) to non-carcinogenic toxicity. This indicates that the environmental burden is primarily associated with equipment manufacturing rather than transport or auxiliary processes.
The ACAES plant contributes 2.59 x 10^{-6} m³, corresponding to 63.9% of the total water use. The 33.28 MW compressor is the largest hotspot, contributing 7.84 x 10^{-7} m³ (19.3%), while the manufacturing stage alone contributes 7.81 x 10^{-7} m³, confirming that transport is negligible (<1% of the compressor contribution).
The total impact is 1.01 × 10^{-6} kg NO_x-eq/kWh. The ACAES plant contributes 6.50 x 10^{-7} kg NO_x-eq, equivalent to 64.4% of the total impact. Again, the compressor is the main hot-spot and contributes 2.45 x 10^{-7} kg NO_x-eq (24.2%), with manufacturing accounting for nearly the entire contribution.

3 Conclusion

In LCA pratice, the most reliable assessments are typically ex post, meaning they evaluate technologies that already exist and operate at commercial scale. In contrast, assessing novel technologies, like hybrid energy storage system using mine infastucture developed within project, requires an ex ante approach, which estimates environmental impacts before large-scale deployment. This creates significant methodological challenges because reliable industrial-scale data are usually unavailable. Instead, inventory data and system specifications are derived from theoretical models, laboratory experiments, prototypes, or pilot-scale facilities. Furthermore, because emerging technologies are still under development, their design parameters, operating conditions, and performance can change rapidly as new knowledge and technological improvements become available. As a result, ex ante LCAs, such as that carried out for the HESS system developed, are subject to greater uncertainty than conventional LCAs and require transparent assumptions.
Steel is the primary construction material used in major components of the developed HESS system, including the thermal energy storage (TES), compressor, turbine, and associated equipment. As a part of the study, linear scaling was employed together with expert's judgement to estimate the total mass and materials share of the turbomachinery. Such approach represents a conservative assumption by approximating the larger installation as multiple smaller units operating in parallel to achieve the desired output power. Consequently, the estimated material requirements - and the associated environmental impacts - are likely to be overestimated rather than underestimated[17].
The dominance of electricity generation indicates that the environmental performance of the developed HESS system is highly sensitive to the composition of the electricity grid. The Polish

[17] M. Lucas, H. Bewi Komesse, S. Duval-Dachary, D. Teixeir. Comparative Environmental Impact Assessment of a DailyElectricity Restitution Operated by Advanced AdiabaticCompressed Air Energy Storage Systems (A-CAES). Energy Storage 7 (2025), e70194.

electricity system remains heavily dependent on hard coal and lignite generation, which explains why fossil-based processes dominate the life-cycle inventory. Since electricity production contributes the overwhelming majority of climate impacts, improvements in storage efficiency alone would produce relatively modest environmental benefits compared with electricity sector decarbonization.

The contribution tree therefore suggests that replacing fossil electricity with renewable sources would reduce not only direct electricity-related emissions, but also upstream impacts associated with coal mining, fuel preparation, and combustion by-products. In both systems, the environmental profile is overwhelmingly governed by the carbon intensity of the Polish electricity system, especially electricity generated from hard coal and lignite plants.

Although both HESS configurations exhibit similar total life-cycle environmental impacts, the construction-stage hotspots differ substantially. In the PSH-CCES system, environmental burdens are primarily associated with the production of Therminol VP-1, high-pressure CO_2 storage tanks and low-alloy steel components. In contrast, the PSH-ACAES configuration is dominated by the manufacture of the compressor and expander, reflecting the larger mass of turbomachinery required by the adiabatic compressed-air storage technology. Consequently, future environmental improvements should focus on reducing the material intensity of these key components rather than transportation processes, which contribute only marginally to the overall impacts.

4 Supplementary materials

Impact category: Acidification: terrestrial

Contribution	Process	Required amount	Total result [kg SO2-Eq]	Direct contribution [kg SO2-Eq]
100.00%	electricity production, high voltage, HESS PHS_CCES - PL	3.60000 MJ	0.00749	
99.91%	market for electricity, high voltage | electricity, high voltage | Cutoff, U - PL	5.76190 MJ	0.00749	
00.09%	HESS PHS CCES facility construction, in mine shafts - PL	5.84980E-11 Item(s)	7.11061E-6	
00.08%	compressed CO2 energy storage plant construction, in mine shaft HESS - PL	5.84980E-11 Item(s)	5.78053E-6	
00.04%	Therminol VP1, transport	2.86640E-5 kg	3.27920E-6	
00.02%	high pressure tanks, transport CCES	3.50988E-9 Item(s)	1.51013E-6	
00.00%	compressor 10.06 MW, transport CCES	5.84980E-11 Item(s)	2.99874E-7	
00.00%	expander 10.84 MW, transport CCES	5.84980E-11 Item(s)	1.75863E-7	
00.00%	TES tanks, transport CCES	1.16996E-10 Item(s)	7.94802E-8	
00.00%	heat exchanger 1, transport CCES	1.75494E-10 Item(s)	7.08516E-8	
00.00%	market for carbon dioxide, liquid | carbon dioxide, liquid | Cutoff, U - RER	4.19922E-5 kg	5.60206E-8	
00.00%	heat exchanger 2, transport CCES	5.84980E-11 Item(s)	5.14917E-8	
00.00%	CO2 purification, CO2 tank, transport CCES	1.16996E-10 Item(s)	4.98375E-8	
00.00%	concrete C30/37, shaft plug, with CEM III/A, transported CCES	7.44095E-8 m3	4.34627E-8	
00.00%	reinforcement, for shaft plug, transported CCES	5.84980E-11 Item(s)	3.20496E-8	
00.00%	steel anchors for shaft plug, transport CCES	2.57391E-9 Item(s)	2.36712E-8	
00.00%	Sika seals, transport CCES	1.53005E-6 kg	1.94537E-8	
00.00%	basalt, transport HESS CCES - PL	0.00014 kg	1.81213E-8	
00.00%	CO2 purification, cryogenic distillation column, transport CCES	5.84980E-11 Item(s)	1.40843E-8	
00.00%	CO2 purification, refrigerant dryer, transport CCES	5.84980E-11 Item(s)	1.03808E-8	
00.00%	heat exchanger 3, transport CCES	5.84980E-11 Item(s)	9.04652E-9	
00.00%	CO2 purification, CO2 compressor, transport CCES	5.84980E-11 Item(s)	8.34522E-9	
00.00%	market for electricity, medium voltage | electricity, medium voltage | Cutoff, U - PL	6.09000E-6 MJ	8.00631E-9	
00.00%	concrete C30/37, pressure dams, with CEM III/A, transport CCES	1.18107E-8 m3	6.83226E-9	
00.00%	CO2 purification, CO2 condenser, transport CCES	5.84980E-11 Item(s)	5.37593E-9	
00.00%	CO2 purification, adsorption dryer, transport CCES	5.84980E-11 Item(s)	3.30611E-9	
00.00%	concrete, C20/25, for CO2 slabs, with cement II/A, transport CCES	3.33439E-9 m3	1.90614E-9	
00.00%	CO2 purification, carbon filter, transport CCES	1.16996E-10 Item(s)	1.28854E-9	
00.00%	CO2 purification, filter separator, transport CCES - PL	1.16996E-10 Item(s)	1.14362E-9	
00.00%	CO2 purification, liquid CO2 pump, transport CCES	5.84980E-11 Item(s)	9.71762E-10	
00.00%	reinforcement, for CO2 slabs, transport HESS	5.84980E-11 Item(s)	2.81457E-10	
00.00%	market for tap water | tap water | Cutoff, U - RER without CH	1.44228E-5 kg	3.87334E-11	
00.00%	treatment of wastewater, average, wastewater treatment | wastewater, average | Cutoff, U...	1.44228E-8 m3	1.61737E-11	1.07216E-12
00.01%	hydropower plant construction, in mine-shaft HESS - PL	5.84980E-11 Item(s)	9.14327E-7	
00.01%	energy router construction HESS	5.84980E-11 Item(s)	4.15758E-7	

Fig. 6. Contribution of HESS PSH-CCES facility construction stage to Acidification: terrestrial impact category – CCES construction stage

Impact category: Acidification: terrestrial

Contribution	Process	Required amount	Total result [kg SO2-Eq]	Direct contribution [kg SO2-Eq]
100.00%	electricity production, high voltage, HESS PHS_CCES - PL	3.60000 MJ	0.00749	
99.91%	market for electricity, high voltage | electricity, high voltage | Cutoff, U - PL	5.76190 MJ	0.00749	
00.09%	HESS PHS CCES facility construction, in mine shafts - PL	5.84980E-11 Item(s)	7.11061E-6	
00.08%	compressed CO2 energy storage plant construction, in mine shaft HESS - PL	5.84980E-11 Item(s)	5.78053E-6	
00.01%	hydropower plant construction, in mine-shaft HESS - PL	5.84980E-11 Item(s)	9.14327E-7	
00.01%	upper reservoir construction PHS - PL	5.84980E-11 Item(s)	6.80000E-7	
00.00%	penstock, for PHS, transport	5.84980E-11 Item(s)	1.80539E-7	
00.00%	Sika seals, transport HESS PHS	1.42244E-6 kg	1.57401E-8	
00.00%	market for electricity, medium voltage | electricity, medium voltage | Cutoff, U - PL	1.16645E-5 MJ	1.53349E-8	
00.00%	concrete C30/37, for water dams, with CEM III/A, transport PHS	1.52095E-8 m3	8.88390E-9	
00.00%	upper technical platform, transport PHS	5.84980E-11 Item(s)	7.09353E-9	
00.00%	reinforcement, for concrete slab/platform, transport HESS - PL	5.84980E-11 Item(s)	3.57940E-9	
00.00%	shut-off valve, transported PHS	5.84980E-11 Item(s)	1.25088E-9	
00.00%	hydraulic drive unit, transport PHS	5.84980E-11 Item(s)	9.50219E-10	
00.00%	control cabinet, transport PHS_A-CAES	5.84980E-11 Item(s)	7.30862E-10	
00.00%	market for wastewater, average | wastewater, average | Cutoff, U - RER without CH	1.53223E-7 m3	1.82913E-10	
00.00%	market for tap water | tap water | Cutoff, U - RER without CH	1.53223E-5 kg	4.11490E-11	
00.01%	energy router construction HESS	5.84980E-11 Item(s)	4.15758E-7	
00.01%	energy router components, transported HESS	5.84980E-11 Item(s)	4.15705E-7	
00.00%	concrete, C20/25, for router slab, with cement II/A, transport CCES	9.18419E-11 m3	5.25148E-11	

Fig. 7. Contribution of HESS PSH-CCES facility construction stage to Acidification: terrestrial impact category – PSH and router construction stage

Impact category: Climate change

Contribution	Process	Required amount	Total result [kg CO2-Eq]	Direct contribution [kg CO2-Eq]
100.00%	electricity production, high voltage, HESS PHS_CCES - PL	3.60000 MJ	1.55797	
99.92%	market for electricity, high voltage | electricity, high voltage | Cutoff, U - PL	5.76190 MJ	1.55677	0.00245
00.08%	HESS PHS CCES facility construction, in mine shafts - PL	5.84980E-11 Item(s)	0.00120	
00.05%	compressed CO2 energy storage plant construction, in mine shaft HESS - PL	5.84980E-11 Item(s)	0.00084	
00.02%	high pressure tanks, transport CCES	3.50988E-9 Item(s)	0.00032	
00.01%	Therminol VP1, transport	2.86640E-5 kg	0.00023	
00.00%	compressor 10.06 MW, transport CCES	5.84980E-11 Item(s)	7.16371E-5	
00.00%	expander 10.84 MW, transport CCES	5.84980E-11 Item(s)	4.15039E-5	
00.00%	market for carbon dioxide, liquid | carbon dioxide, liquid | Cutoff, U - RER	4.19922E-5 kg	3.39556E-5	
00.00%	TES tanks, transport CCES	1.16996E-10 Item(s)	3.02250E-5	
00.00%	heat exchanger 1, transport CCES	1.75494E-10 Item(s)	1.98472E-5	
00.00%	concrete C30/37, shaft plug, with CEM III/A, transported CCES	7.44095E-8 m3	1.70373E-5	
00.00%	CO2 purification, CO2 tank, transport CCES	1.16996E-10 Item(s)	1.49336E-5	
00.00%	heat exchanger 2, transport CCES	5.84980E-11 Item(s)	1.43766E-5	
00.00%	reinforcement, for shaft plug, transported CCES	5.84980E-11 Item(s)	1.36812E-5	
00.00%	steel anchors for shaft plug, transport CCES	2.57391E-9 Item(s)	8.52203E-6	
00.00%	Sika seals, transport CCES	1.53005E-6 kg	6.12295E-6	
00.00%	CO2 purification, cryogenic distillation column, transport CCES	5.84980E-11 Item(s)	4.07578E-6	
00.00%	basalt, transport HESS CCES - PL	0.00014 kg	3.45301E-6	
00.00%	concrete C30/37, pressure dams, with CEM III/A, transport CCES	1.18107E-8 m3	2.68221E-6	
00.00%	heat exchanger 3, transport CCES	5.84980E-11 Item(s)	2.52843E-6	
00.00%	CO2 purification, refrigerant dryer, transport CCES	5.84980E-11 Item(s)	1.93068E-6	
00.00%	market for electricity, medium voltage | electricity, medium voltage | Cutoff, U - PL	6.09000E-6 MJ	1.66310E-6	5.00644E-9
00.00%	concrete, C20/25, for CO2 slabs, with cement II/A, transport CCES	3.33439E-9 m3	9.77292E-7	
00.00%	CO2 purification, CO2 compressor, transport CCES	5.84980E-11 Item(s)	9.43301E-7	
00.00%	CO2 purification, adsorption dryer, transport CCES	5.84980E-11 Item(s)	6.87555E-7	
00.00%	CO2 purification, CO2 condenser, transport CCES	5.84980E-11 Item(s)	6.39961E-7	
00.00%	CO2 purification, carbon filter, transport CCES	1.16996E-10 Item(s)	3.43168E-7	
00.00%	CO2 purification, filter separator, transport CCES - PL	1.16996E-10 Item(s)	2.98292E-7	
00.00%	CO2 purification, liquid CO2 pump, transport CCES	5.84980E-11 Item(s)	1.62577E-7	
00.00%	reinforcement, for CO2 slabs, transport HESS	5.84980E-11 Item(s)	1.20147E-7	
00.00%	market for tap water | tap water | Cutoff, U - RER without CH	1.44228E-5 kg	8.61164E-9	
00.00%	treatment of wastewater, average, wastewater treatment | wastewater, average | Cutoff, U...	1.44228E-8 m3	5.28328E-9	3.98103E-10
00.02%	hydropower plant construction, in mine-shaft HESS - PL	5.84980E-11 Item(s)	0.00032	
00.00%	energy router construction HESS	5.84980E-11 Item(s)	3.40064E-5	

Fig. 8. Contribution of HESS PSH-CCES facility construction stage to Climate change impact category – CCES construction stage

Impact category: Climate change

Contribution	Process	Required amount	Total result [kg CO2-Eq]	Direct contribution [kg CO2-Eq]
100.00%	electricity production, high voltage, HESS PHS_CCES - PL	3.60000 MJ	1.55797	
99.92%	market for electricity, high voltage | electricity, high voltage | Cutoff, U - PL	5.76190 MJ	1.55677	0.00245
00.08%	HESS PHS CCES facility construction, in mine shafts - PL	5.84980E-11 Item(s)	0.00120	
00.05%	compressed CO2 energy storage plant construction, in mine shaft HESS - PL	5.84980E-11 Item(s)	0.00084	
00.02%	hydropower plant construction, in mine-shaft HESS - PL	5.84980E-11 Item(s)	0.00032	
00.02%	upper reservoir construction PHS - PL	5.84980E-11 Item(s)	0.00024	
00.00%	penstock, for PHS, transport	5.84980E-11 Item(s)	6.49511E-5	
00.00%	Sika seals, transport HESS PHS	1.42244E-6 kg	4.81651E-6	
00.00%	concrete C30/37, for water dams, with CEM III/A, transport PHS	1.52095E-8 m3	3.48247E-6	
00.00%	market for electricity, medium voltage | electricity, medium voltage | Cutoff, U - PL	1.16645E-5 MJ	3.18544E-6	9.58911E-9
00.00%	upper technical platform, transport PHS	5.84980E-11 Item(s)	2.55499E-6	
00.00%	reinforcement, for concrete slab/platform, transport HESS - PL	5.84980E-11 Item(s)	1.52796E-6	
00.00%	shut-off valve, transported PHS	5.84980E-11 Item(s)	5.49398E-7	
00.00%	control cabinet, transport PHS_A-CAES	5.84980E-11 Item(s)	1.80370E-7	
00.00%	hydraulic drive unit, transport PHS	5.84980E-11 Item(s)	1.37482E-7	
00.00%	market for wastewater, average | wastewater, average | Cutoff, U - RER without CH	1.53223E-7 m3	6.28351E-8	
00.00%	market for tap water | tap water | Cutoff, U - RER without CH	1.53223E-5 kg	9.14870E-9	
00.00%	energy router construction HESS	5.84980E-11 Item(s)	3.40064E-5	
00.00%	energy router components, transported HESS	5.84980E-11 Item(s)	3.39795E-5	
00.00%	concrete, C20/25, for router slab, with cement II/A, transport CCES	9.18419E-11 m3	2.69234E-8	

Fig. 9. Contribution of HESS PSH-CCES facility construction stage to Climate change impact category – PSH and router construction stage

Impact category: Ecotoxicity: freshwater

Contribution	Process	Required amount	Total result [kg 1,4-DCB-Eq]	Direct contribution [kg 1,4-DCB...
100.00%	electricity production, high voltage, HESS PHS_CCES - PL	3.60000 MJ	0.05339	
99.51%	market for electricity, high voltage | electricity, high voltage | Cutoff, U - PL	5.76190 MJ	0.05313	
00.49%	HESS PHS CCES facility construction, in mine shafts - PL	5.84980E-11 Item(s)	0.00026	
00.36%	compressed CO2 energy storage plant construction, in mine shaft HESS - PL	5.84980E-11 Item(s)	0.00019	
00.18%	high pressure tanks, transport CCES	3.50988E-9 Item(s)	9.69017E-5	
00.05%	compressor 10.06 MW, transport CCES	5.84980E-11 Item(s)	2.74205E-5	
00.03%	Therminol VP1, transport	2.86640E-5 kg	1.66417E-5	
00.03%	expander 10.84 MW, transport CCES	5.84980E-11 Item(s)	1.63881E-5	
00.02%	heat exchanger 1, transport CCES	1.75494E-10 Item(s)	9.54659E-6	
00.01%	heat exchanger 2, transport CCES	5.84980E-11 Item(s)	7.06724E-6	
00.01%	CO2 purification, CO2 tank, transport CCES	1.16996E-10 Item(s)	4.27172E-6	
00.01%	TES tanks, transport CCES	1.16996E-10 Item(s)	3.15973E-6	
00.00%	market for carbon dioxide, liquid | carbon dioxide, liquid | Cutoff, U - RER	4.19922E-5 kg	2.00550E-6	
00.00%	CO2 purification, cryogenic distillation column, transport CCES	5.84980E-11 Item(s)	1.83400E-6	
00.00%	reinforcement, for shaft plug, transported CCES	5.84980E-11 Item(s)	1.75442E-6	
00.00%	CO2 purification, refrigerant dryer, transport CCES	5.84980E-11 Item(s)	1.21643E-6	
00.00%	heat exchanger 3, transport CCES	5.84980E-11 Item(s)	1.20012E-6	
00.00%	steel anchors for shaft plug, transport CCES	2.57391E-9 Item(s)	1.16886E-6	
00.00%	CO2 purification, CO2 compressor, transport CCES	5.84980E-11 Item(s)	7.58954E-7	
00.00%	CO2 purification, CO2 condenser, transport CCES	5.84980E-11 Item(s)	4.98996E-7	
00.00%	concrete C30/37, shaft plug, with CEM III/A, transported CCES	7.44095E-8 m3	4.45857E-7	
00.00%	CO2 purification, adsorption dryer, transport CCES	5.84980E-11 Item(s)	3.10864E-7	
00.00%	Sika seals, transport CCES	1.53005E-6 kg	2.94721E-7	
00.00%	CO2 purification, carbon filter, transport CCES	1.16996E-10 Item(s)	1.54734E-7	
00.00%	CO2 purification, filter separator, transport CCES - PL	1.16996E-10 Item(s)	1.45010E-7	
00.00%	basalt, transport HESS CCES - PL	0.00014 kg	1.08608E-7	
00.00%	CO2 purification, liquid CO2 pump, transport CCES	5.84980E-11 Item(s)	1.07193E-7	
00.00%	concrete C30/37, pressure dams, with CEM III/A, transport CCES	1.18107E-8 m3	7.01438E-8	
00.00%	market for electricity, medium voltage | electricity, medium voltage | Cutoff, U - PL	6.09000E-6 MJ	6.30048E-8	
00.00%	concrete, C20/25, for CO2 slabs, with cement II/A, transport CCES	3.33439E-9 m3	1.70898E-8	
00.00%	reinforcement, for CO2 slabs, transport HESS	5.84980E-11 Item(s)	1.54071E-8	
00.00%	treatment of wastewater, average, wastewater treatment | wastewater, average | Cutoff, U...	1.44228E-8 m3	4.59400E-10	5.17128E-11
00.00%	market for tap water | tap water | Cutoff, U - RER without CH	1.44228E-5 kg	3.79307E-10	
00.06%	hydropower plant construction, in mine-shaft HESS - PL	5.84980E-11 Item(s)	3.46201E-5	
00.06%	energy router construction HESS	5.84980E-11 Item(s)	3.36619E-5	

Fig. 10. Contribution of HESS PSH-CCES facility construction stage to Ecotoxicity: freshwater impact category – CCES construction stage

Impact category: Ecotoxicity: freshwater

Contribution	Process	Required amount	Total result [kg 1,4-DCB-Eq]	Direct contribution [kg 1,4-DCB...
100.00%	electricity production, high voltage, HESS PHS_CCES - PL	3.60000 MJ	0.05339	
99.51%	market for electricity, high voltage | electricity, high voltage | Cutoff, U - PL	5.76190 MJ	0.05313	
00.49%	HESS PHS CCES facility construction, in mine shafts - PL	5.84980E-11 Item(s)	0.00026	
00.36%	compressed CO2 energy storage plant construction, in mine shaft HESS - PL	5.84980E-11 Item(s)	0.00019	
00.06%	hydropower plant construction, in mine-shaft HESS - PL	5.84980E-11 Item(s)	3.46201E-5	
00.05%	upper reservoir construction PHS - PL	5.84980E-11 Item(s)	2.45786E-5	
00.02%	penstock, for PHS, transport	5.84980E-11 Item(s)	8.84114E-6	
00.00%	upper technical platform, transport PHS	5.84980E-11 Item(s)	3.46160E-7	
00.00%	Sika seals, transport HESS PHS	1.42244E-6 kg	2.35568E-7	
00.00%	reinforcement, for concrete slab/platform, transport HESS - PL	5.84980E-11 Item(s)	1.95938E-7	
00.00%	shut-off valve, transported PHS	5.84980E-11 Item(s)	1.28031E-7	
00.00%	market for electricity, medium voltage | electricity, medium voltage | Cutoff, U - PL	1.16645E-5 MJ	1.20677E-7	
00.00%	concrete C30/37, for water dams, with CEM III/A, transport PHS	1.52095E-8 m3	9.11345E-8	
00.00%	hydraulic drive unit, transport PHS	5.84980E-11 Item(s)	6.54551E-8	
00.00%	control cabinet, transport PHS_A-CAES	5.84980E-11 Item(s)	1.03393E-8	
00.00%	market for wastewater, average | wastewater, average | Cutoff, U - RER without CH	1.53223E-7 m3	6.61246E-9	7.79377E-10
00.00%	market for tap water | tap water | Cutoff, U - RER without CH	1.53223E-5 kg	4.02962E-10	
00.06%	energy router construction HESS	5.84980E-11 Item(s)	3.36619E-5	
00.06%	energy router components, transported HESS	5.84980E-11 Item(s)	3.36614E-5	
00.00%	concrete, C20/25, for router slab, with cement II/A, transport CCES	9.18419E-11 m3	4.70851E-10	

Fig. 11. Contribution of HESS PSH-CCES facility construction stage to Ecotoxicity: freshwater impact category – PSH and router construction stage

Impact category: Ecotoxicity: marine

Contribution	Process	Required amount	Total result [kg 1,4-DCB-Eq]	Direct contribution [kg 1,4-DCB...
100.00%	electricity production, high voltage, HESS PHS_CCES - PL	3.60000 MJ	0.07349	
99.54%	market for electricity, high voltage | electricity, high voltage | Cutoff, U - PL	5.76190 MJ	0.07315	
00.46%	HESS PHS CCES facility construction, in mine shafts - PL	5.84980E-11 Item(s)	0.00034	
00.34%	compressed CO2 energy storage plant construction, in mine shaft HESS - PL	5.84980E-11 Item(s)	0.00025	
00.17%	high pressure tanks, transport CCES	3.50988E-9 Item(s)	0.00012	
00.05%	compressor 10.06 MW, transport CCES	5.84980E-11 Item(s)	3.51519E-5	
00.03%	expander 10.84 MW, transport CCES	5.84980E-11 Item(s)	2.10111E-5	
00.03%	Therminol VP1, transport	2.86640E-5 kg	2.05196E-5	
00.02%	heat exchanger 1, transport CCES	1.75494E-10 Item(s)	1.22859E-5	
00.01%	heat exchanger 2, transport CCES	5.84980E-11 Item(s)	9.09511E-6	
00.01%	CO2 purification, CO2 tank, transport CCES	1.16996E-10 Item(s)	5.53628E-6	
00.01%	TES tanks, transport CCES	1.16996E-10 Item(s)	4.21624E-6	
00.00%	market for carbon dioxide, liquid | carbon dioxide, liquid | Cutoff, U - RER	4.19922E-5 kg	2.54286E-6	
00.00%	reinforcement, for shaft plug, transported CCES	5.84980E-11 Item(s)	2.36740E-6	
00.00%	CO2 purification, cryogenic distillation column, transport CCES	5.84980E-11 Item(s)	2.36356E-6	
00.00%	CO2 purification, refrigerant dryer, transport CCES	5.84980E-11 Item(s)	1.58752E-6	
00.00%	heat exchanger 3, transport CCES	5.84980E-11 Item(s)	1.54416E-6	
00.00%	steel anchors for shaft plug, transport CCES	2.57391E-9 Item(s)	1.53457E-6	
00.00%	CO2 purification, CO2 compressor, transport CCES	5.84980E-11 Item(s)	9.64716E-7	
00.00%	CO2 purification, CO2 condenser, transport CCES	5.84980E-11 Item(s)	6.34610E-7	
00.00%	concrete C30/37, shaft plug, with CEM III/A, transported CCES	7.44095E-8 m3	5.99292E-7	
00.00%	CO2 purification, adsorption dryer, transport CCES	5.84980E-11 Item(s)	3.98195E-7	
00.00%	Sika seals, transport CCES	1.53005E-6 kg	3.86243E-7	
00.00%	CO2 purification, carbon filter, transport CCES	1.16996E-10 Item(s)	1.99275E-7	
00.00%	CO2 purification, filter separator, transport CCES - PL	1.16996E-10 Item(s)	1.86470E-7	
00.00%	basalt, transport HESS CCES - PL	0.00014 kg	1.59190E-7	
00.00%	CO2 purification, liquid CO2 pump, transport CCES	5.84980E-11 Item(s)	1.39113E-7	
00.00%	concrete C30/37, pressure dams, with CEM III/A, transport CCES	1.18107E-8 m3	9.41939E-8	
00.00%	market for electricity, medium voltage | electricity, medium voltage | Cutoff, U - PL	6.09000E-6 MJ	8.57731E-8	
00.00%	concrete, C20/25, for CO2 slabs, with cement II/A, transport CCES	3.33439E-9 m3	2.30517E-8	
00.00%	reinforcement, for CO2 slabs, transport HESS	5.84980E-11 Item(s)	2.07903E-8	
00.00%	treatment of wastewater, average, wastewater treatment | wastewater, average | Cutoff, U...	1.44228E-8 m3	6.11260E-10	7.09910E-11
00.00%	market for tap water | tap water | Cutoff, U - RER without CH	1.44228E-5 kg	5.15713E-10	
00.06%	hydropower plant construction, in mine-shaft HESS - PL	5.84980E-11 Item(s)	4.55426E-5	
00.06%	energy router construction HESS	5.84980E-11 Item(s)	4.23239E-5	

Fig. 12. Contribution of HESS PSH-CCES facility construction stage to Ecotoxicity: marine impact category – CCES construction stage

Impact category: Ecotoxicity: marine

Contribution	Process	Required amount	Total result [kg 1,4-DCB-Eq]	Direct contribution [kg 1,4-DCB...
100.00%	electricity production, high voltage, HESS PHS_CCES - PL	3.60000 MJ	0.07349	
99.54%	market for electricity, high voltage | electricity, high voltage | Cutoff, U - PL	5.76190 MJ	0.07315	
00.46%	HESS PHS CCES facility construction, in mine shafts - PL	5.84980E-11 Item(s)	0.00034	
00.34%	compressed CO2 energy storage plant construction, in mine shaft HESS - PL	5.84980E-11 Item(s)	0.00025	
00.06%	hydropower plant construction, in mine-shaft HESS - PL	5.84980E-11 Item(s)	4.55426E-5	
00.04%	upper reservoir construction PHS - PL	5.84980E-11 Item(s)	3.23500E-5	
00.02%	penstock, for PHS, transport	5.84980E-11 Item(s)	1.16055E-5	
00.00%	upper technical platform, transport PHS	5.84980E-11 Item(s)	4.54521E-7	
00.00%	Sika seals, transport HESS PHS	1.42244E-6 kg	3.09144E-7	
00.00%	reinforcement, for concrete slab/platform, transport HESS - PL	5.84980E-11 Item(s)	2.64399E-7	
00.00%	shut-off valve, transported PHS	5.84980E-11 Item(s)	1.66305E-7	
00.00%	market for electricity, medium voltage | electricity, medium voltage | Cutoff, U - PL	1.16645E-5 MJ	1.64286E-7	
00.00%	concrete C30/37, for water dams, with CEM III/A, transport PHS	1.52095E-8 m3	1.22497E-7	
00.00%	hydraulic drive unit, transport PHS	5.84980E-11 Item(s)	8.31042E-8	
00.00%	control cabinet, transport PHS_A-CAES	5.84980E-11 Item(s)	1.34704E-8	
00.00%	market for wastewater, average | wastewater, average | Cutoff, U - RER without CH	1.53223E-7 m3	8.81074E-9	1.05957E-9
00.00%	market for tap water | tap water | Cutoff, U - RER without CH	1.53223E-5 kg	5.47875E-10	
00.06%	energy router construction HESS	5.84980E-11 Item(s)	4.23239E-5	
00.06%	energy router components, transported HESS	5.84980E-11 Item(s)	4.23233E-5	
00.00%	concrete, C20/25, for router slab, with cement II/A, transport CCES	9.18419E-11 m3	6.35142E-10	

Fig. 13. Contribution of HESS PSH-CCES facility construction stage to Ecotoxicity: marine impact category – PSH and router construction stage

Impact category: Ecotoxicity: terrestrial

Contribution	Process	Required amount	Total result [kg 1,4-DCB-Eq]	Direct contribution [kg 1,4-DCB...
100.00%	electricity production, high voltage, HESS PHS_CCES - PL	3.60000 MJ	1.04543	
99.18%	market for electricity, high voltage | electricity, high voltage | Cutoff, U - PL	5.76190 MJ	1.03688	
00.82%	HESS PHS CCES facility construction, in mine shafts - PL	5.84980E-11 Item(s)	0.00855	
00.66%	compressed CO2 energy storage plant construction, in mine shaft HESS - PL	5.84980E-11 Item(s)	0.00693	
00.26%	high pressure tanks, transport CCES	3.50988E-9 Item(s)	0.00268	
00.11%	compressor 10.06 MW, transport CCES	5.84980E-11 Item(s)	0.00113	
00.07%	expander 10.84 MW, transport CCES	5.84980E-11 Item(s)	0.00069	
00.07%	Therminol VP1, transport	2.86640E-5 kg	0.00068	
00.05%	heat exchanger 1, transport CCES	1.75494E-10 Item(s)	0.00049	
00.03%	heat exchanger 2, transport CCES	5.84980E-11 Item(s)	0.00037	
00.02%	market for carbon dioxide, liquid | carbon dioxide, liquid | Cutoff, U - RER	4.19922E-5 kg	0.00022	
00.02%	CO2 purification, CO2 tank, transport CCES	1.16996E-10 Item(s)	0.00021	
00.01%	CO2 purification, cryogenic distillation column, transport CCES	5.84980E-11 Item(s)	8.25438E-5	
00.01%	TES tanks, transport CCES	1.16996E-10 Item(s)	7.79718E-5	
00.01%	heat exchanger 3, transport CCES	5.84980E-11 Item(s)	6.11137E-5	
00.00%	reinforcement, for shaft plug, transported CCES	5.84980E-11 Item(s)	4.14005E-5	
00.00%	concrete C30/37, shaft plug, with CEM III/A, transported CCES	7.44095E-8 m3	4.00354E-5	
00.00%	basalt, transport HESS CCES - PL	0.00014 kg	3.29478E-5	
00.00%	CO2 purification, CO2 compressor, transport CCES	5.84980E-11 Item(s)	2.26776E-5	
00.00%	steel anchors for shaft plug, transport CCES	2.57391E-9 Item(s)	2.01158E-5	
00.00%	Sika seals, transport CCES	1.53005E-6 kg	1.71522E-5	
00.00%	CO2 purification, CO2 condenser, transport CCES	5.84980E-11 Item(s)	1.47730E-5	
00.00%	CO2 purification, refrigerant dryer, transport CCES	5.84980E-11 Item(s)	1.41109E-5	
00.00%	CO2 purification, adsorption dryer, transport CCES	5.84980E-11 Item(s)	1.33313E-5	
00.00%	CO2 purification, carbon filter, transport CCES	1.16996E-10 Item(s)	7.22567E-6	
00.00%	CO2 purification, filter separator, transport CCES - PL	1.16996E-10 Item(s)	6.98130E-6	
00.00%	concrete C30/37, pressure dams, with CEM III/A, transport CCES	1.18107E-8 m3	6.16127E-6	
00.00%	concrete, C20/25, for CO2 slabs, with cement II/A, transport CCES	3.33439E-9 m3	1.58100E-6	
00.00%	CO2 purification, liquid CO2 pump, transport CCES	5.84980E-11 Item(s)	1.49735E-6	
00.00%	market for electricity, medium voltage | electricity, medium voltage | Cutoff, U - PL	6.09000E-6 MJ	1.19398E-6	
00.00%	reinforcement, for CO2 slabs, transport HESS	5.84980E-11 Item(s)	3.63575E-7	
00.00%	treatment of wastewater, average, wastewater treatment | wastewater, average | Cutoff, U...	1.44228E-8 m3	1.56771E-8	5.75707E-13
00.00%	market for tap water | tap water | Cutoff, U - RER without CH	1.44228E-5 kg	1.46042E-8	
00.09%	energy router construction HESS	5.84980E-11 Item(s)	0.00089	
00.07%	hydropower plant construction, in mine-shaft HESS - PL	5.84980E-11 Item(s)	0.00073	

Fig. 14. Contribution of HESS PSH-CCES facility construction stage to Ecotoxicity: terrestrial impact category – CCES construction stage

Impact category: Ecotoxicity: terrestrial

Contribution	Process	Required amount	Total result [kg 1,4-DCB-Eq]	Direct contribution [kg 1,4-DCB...
100.00%	electricity production, high voltage, HESS PHS_CCES - PL	3.60000 MJ	1.04543	
99.18%	market for electricity, high voltage | electricity, high voltage | Cutoff, U - PL	5.76190 MJ	1.03688	
00.82%	HESS PHS CCES facility construction, in mine shafts - PL	5.84980E-11 Item(s)	0.00855	
00.66%	compressed CO2 energy storage plant construction, in mine shaft HESS - PL	5.84980E-11 Item(s)	0.00693	
00.09%	energy router construction HESS	5.84980E-11 Item(s)	0.00089	
00.09%	energy router components, transported HESS	5.84980E-11 Item(s)	0.00089	
00.00%	concrete, C20/25, for router slab, with cement II/A, transport CCES	9.18419E-11 m3	4.36199E-8	
00.07%	hydropower plant construction, in mine-shaft HESS - PL	5.84980E-11 Item(s)	0.00073	
00.05%	upper reservoir construction PHS - PL	5.84980E-11 Item(s)	0.00054	
00.01%	penstock, for PHS, transport	5.84980E-11 Item(s)	0.00015	
00.00%	Sika seals, transport HESS PHS	1.42244E-6 kg	1.39864E-5	
00.00%	concrete C30/37, for water dams, with CEM III/A, transport PHS	1.52095E-8 m3	8.18341E-6	
00.00%	upper technical platform, transport PHS	5.84980E-11 Item(s)	5.95805E-6	
00.00%	reinforcement, for concrete slab/platform, transport HESS - PL	5.84980E-11 Item(s)	4.62373E-6	
00.00%	shut-off valve, transported PHS	5.84980E-11 Item(s)	2.35575E-6	
00.00%	market for electricity, medium voltage | electricity, medium voltage | Cutoff, U - PL	1.16645E-5 MJ	2.28690E-6	
00.00%	hydraulic drive unit, transport PHS	5.84980E-11 Item(s)	1.73774E-6	
00.00%	control cabinet, transport PHS_A-CAES	5.84980E-11 Item(s)	3.53104E-7	
00.00%	market for wastewater, average | wastewater, average | Cutoff, U - RER without CH	1.53223E-7 m3	2.28438E-7	4.76545E-26
00.00%	market for tap water | tap water | Cutoff, U - RER without CH	1.53223E-5 kg	1.55150E-8	

Fig. 15. Contribution of HESS PSH-CCES facility construction stage to Ecotoxicity: terrestrial impact category – PSH and router construction stage

Impact category: Energy resources: non-renewable, fossil

Contribution	Process	Required amount	Total result [kg oil-Eq]	Direct contribution [kg oil-Eq]
100.00%	electricity production, high voltage, HESS PHS_CCES - PL	3.60000 MJ	0.37092	
99.92%	market for electricity, high voltage | electricity, high voltage | Cutoff, U - PL	5.76190 MJ	0.37061	
00.08%	HESS PHS CCES facility construction, in mine shafts - PL	5.84980E-11 Item(s)	0.00031	
00.06%	compressed CO2 energy storage plant construction, in mine shaft HESS - PL	5.84980E-11 Item(s)	0.00023	
00.02%	Therminol VP1, transport	2.86640E-5 kg	8.60912E-5	
00.02%	high pressure tanks, transport CCES	3.50988E-9 Item(s)	7.85516E-5	
00.00%	compressor 10.06 MW, transport CCES	5.84980E-11 Item(s)	1.73150E-5	
00.00%	expander 10.84 MW, transport CCES	5.84980E-11 Item(s)	1.00216E-5	
00.00%	TES tanks, transport CCES	1.16996E-10 Item(s)	7.26516E-6	
00.00%	market for carbon dioxide, liquid | carbon dioxide, liquid | Cutoff, U - RER	4.19922E-5 kg	5.85542E-6	
00.00%	heat exchanger 1, transport CCES	1.75494E-10 Item(s)	4.66822E-6	
00.00%	CO2 purification, CO2 tank, transport CCES	1.16996E-10 Item(s)	3.70578E-6	
00.00%	heat exchanger 2, transport CCES	5.84980E-11 Item(s)	3.37365E-6	
00.00%	reinforcement, for shaft plug, transported CCES	5.84980E-11 Item(s)	3.20072E-6	
00.00%	concrete C30/37, shaft plug, with CEM III/A, transported CCES	7.44095E-8 m3	2.23702E-6	
00.00%	Sika seals, transport CCES	1.53005E-6 kg	2.15501E-6	
00.00%	steel anchors for shaft plug, transport CCES	2.57391E-9 Item(s)	2.02972E-6	
00.00%	basalt, transport HESS CCES - PL	0.00014 kg	1.01152E-6	
00.00%	CO2 purification, cryogenic distillation column, transport CCES	5.84980E-11 Item(s)	1.01118E-6	
00.00%	heat exchanger 3, transport CCES	5.84980E-11 Item(s)	5.97251E-7	
00.00%	CO2 purification, refrigerant dryer, transport CCES	5.84980E-11 Item(s)	4.97971E-7	
00.00%	market for electricity, medium voltage | electricity, medium voltage | Cutoff, U - PL	6.09000E-6 MJ	3.94726E-7	
00.00%	concrete C30/37, pressure dams, with CEM III/A, transport CCES	1.18107E-8 m3	3.48400E-7	
00.00%	CO2 purification, CO2 compressor, transport CCES	5.84980E-11 Item(s)	2.36891E-7	
00.00%	CO2 purification, adsorption dryer, transport CCES	5.84980E-11 Item(s)	1.75476E-7	
00.00%	CO2 purification, CO2 condenser, transport CCES	5.84980E-11 Item(s)	1.60121E-7	
00.00%	concrete, C20/25, for CO2 slabs, with cement II/A, transport CCES	3.33439E-9 m3	8.91676E-8	
00.00%	CO2 purification, carbon filter, transport CCES	1.16996E-10 Item(s)	8.57693E-8	
00.00%	CO2 purification, filter separator, transport CCES - PL	1.16996E-10 Item(s)	7.28519E-8	
00.00%	CO2 purification, liquid CO2 pump, transport CCES	5.84980E-11 Item(s)	4.12959E-8	
00.00%	reinforcement, for CO2 slabs, transport HESS	5.84980E-11 Item(s)	2.81085E-8	
00.00%	market for tap water | tap water | Cutoff, U - RER without CH	1.44228E-5 kg	2.08287E-9	
00.00%	treatment of wastewater, average, wastewater treatment | wastewater, average | Cutoff, U...	1.44228E-8 m3	8.95551E-10	
00.02%	hydropower plant construction, in mine-shaft HESS - PL	5.84980E-11 Item(s)	7.03930E-5	
00.00%	energy router construction HESS	5.84980E-11 Item(s)	9.80687E-6	

Fig. 16. Contribution of HESS PSH-CCES facility construction stage to Energy resources: non-renewable, fossil impact category – CCES construction stage

Impact category: Energy resources: non-renewable, fossil

Contribution	Process	Required amount	Total result [kg oil-Eq]	Direct contribution [kg oil-Eq]
100.00%	electricity production, high voltage, HESS PHS_CCES - PL	3.60000 MJ	0.37092	
99.92%	market for electricity, high voltage | electricity, high voltage | Cutoff, U - PL	5.76190 MJ	0.37061	
00.08%	HESS PHS CCES facility construction, in mine shafts - PL	5.84980E-11 Item(s)	0.00031	
00.06%	compressed CO2 energy storage plant construction, in mine shaft HESS - PL	5.84980E-11 Item(s)	0.00023	
00.02%	hydropower plant construction, in mine-shaft HESS - PL	5.84980E-11 Item(s)	7.03930E-5	
00.01%	upper reservoir construction PHS - PL	5.84980E-11 Item(s)	5.08141E-5	
00.00%	penstock, for PHS, transport	5.84980E-11 Item(s)	1.54904E-5	
00.00%	Sika seals, transport HESS PHS	1.42244E-6 kg	1.66749E-6	
00.00%	market for electricity, medium voltage | electricity, medium voltage | Cutoff, U - PL	1.16645E-5 MJ	7.56041E-7	
00.00%	upper technical platform, transport PHS	5.84980E-11 Item(s)	6.10609E-7	
00.00%	concrete C30/37, for water dams, with CEM III/A, transport PHS	1.52095E-8 m3	4.57254E-7	
00.00%	reinforcement, for concrete slab/platform, transport HESS - PL	5.84980E-11 Item(s)	3.57466E-7	
00.00%	shut-off valve, transported PHS	5.84980E-11 Item(s)	1.34019E-7	
00.00%	control cabinet, transport PHS_A-CAES	5.84980E-11 Item(s)	5.04400E-8	
00.00%	hydraulic drive unit, transport PHS	5.84980E-11 Item(s)	4.08673E-8	
00.00%	market for wastewater, average | wastewater, average | Cutoff, U - RER without CH	1.53223E-7 m3	1.20254E-8	
00.00%	market for tap water | tap water | Cutoff, U - RER without CH	1.53223E-5 kg	2.21277E-9	
00.00%	energy router construction HESS	5.84980E-11 Item(s)	9.80687E-6	
00.00%	energy router components, transported HESS	5.84980E-11 Item(s)	9.80441E-6	
00.00%	concrete, C20/25, for router slab, with cement II/A, transport CCES	9.18419E-11 m3	2.45761E-9	

Fig. 17. Contribution of HESS PSH-CCES facility construction stage to Energy resources: non-renewable, fossil impact category – PSH and router construction stage

Impact category: Eutrophication: freshwater

Contribution	Process	Required amount	Total result [kg P-Eq]	Direct contribution [kg P-Eq]
100.00%	electricity production, high voltage, HESS PHS_CCES - PL	3.60000 MJ	0.00175	
99.96%	market for electricity, high voltage | electricity, high voltage | Cutoff, U - PL	5.76190 MJ	0.00175	
00.04%	HESS PHS CCES facility construction, in mine shafts - PL	5.84980E-11 Item(s)	7.39780E-7	
00.03%	compressed CO2 energy storage plant construction, in mine shaft HESS - PL	5.84980E-11 Item(s)	5.29669E-7	
00.01%	high pressure tanks, transport CCES	3.50988E-9 Item(s)	2.53782E-7	
00.01%	Therminol VP1, transport	2.86640E-5 kg	8.95796E-8	
00.00%	compressor 10.06 MW, transport CCES	5.84980E-11 Item(s)	5.72373E-8	
00.00%	expander 10.84 MW, transport CCES	5.84980E-11 Item(s)	3.34087E-8	
00.00%	heat exchanger 1, transport CCES	1.75494E-10 Item(s)	1.77815E-8	
00.00%	heat exchanger 2, transport CCES	5.84980E-11 Item(s)	1.29995E-8	
00.00%	CO2 purification, CO2 tank, transport CCES	1.16996E-10 Item(s)	1.12489E-8	
00.00%	TES tanks, transport CCES	1.16996E-10 Item(s)	1.09108E-8	
00.00%	market for carbon dioxide, liquid | carbon dioxide, liquid | Cutoff, U - RER	4.19922E-5 kg	9.56497E-9	
00.00%	reinforcement, for shaft plug, transported CCES	5.84980E-11 Item(s)	5.88809E-9	
00.00%	concrete C30/37, shaft plug, with CEM III/A, transported CCES	7.44095E-8 m3	5.39053E-9	
00.00%	steel anchors for shaft plug, transport CCES	2.57391E-9 Item(s)	4.59957E-9	
00.00%	CO2 purification, cryogenic distillation column, transport CCES	5.84980E-11 Item(s)	3.53688E-9	
00.00%	CO2 purification, refrigerant dryer, transport CCES	5.84980E-11 Item(s)	2.48531E-9	
00.00%	heat exchanger 3, transport CCES	5.84980E-11 Item(s)	2.26084E-9	
00.00%	market for electricity, medium voltage | electricity, medium voltage | Cutoff, U - PL	6.09000E-6 MJ	1.86079E-9	
00.00%	Sika seals, transport CCES	1.53005E-6 kg	1.44331E-9	
00.00%	CO2 purification, CO2 compressor, transport CCES	5.84980E-11 Item(s)	1.19804E-9	
00.00%	basalt, transport HESS CCES - PL	0.00014 kg	1.15129E-9	
00.00%	concrete C30/37, pressure dams, with CEM III/A, transport CCES	1.18107E-8 m3	8.54059E-10	
00.00%	CO2 purification, CO2 condenser, transport CCES	5.84980E-11 Item(s)	8.19839E-10	
00.00%	CO2 purification, adsorption dryer, transport CCES	5.84980E-11 Item(s)	5.68332E-10	
00.00%	CO2 purification, carbon filter, transport CCES	1.16996E-10 Item(s)	3.01235E-10	
00.00%	CO2 purification, filter separator, transport CCES - PL	1.16996E-10 Item(s)	2.80775E-10	
00.00%	concrete, C20/25, for CO2 slabs, with cement II/A, transport CCES	3.33439E-9 m3	2.25424E-10	
00.00%	CO2 purification, liquid CO2 pump, transport CCES	5.84980E-11 Item(s)	2.13149E-10	
00.00%	reinforcement, for CO2 slabs, transport HESS	5.84980E-11 Item(s)	5.17087E-11	
00.00%	treatment of wastewater, average, wastewater treatment | wastewater, average | Cutoff, U...	1.44228E-8 m3	1.89508E-11	1.25020E-11
00.00%	market for tap water | tap water | Cutoff, U - RER without CH	1.44228E-5 kg	7.98568E-12	
00.01%	hydropower plant construction, in mine-shaft HESS - PL	5.84980E-11 Item(s)	1.62121E-7	
00.00%	energy router construction HESS	5.84980E-11 Item(s)	4.79903E-8	

Fig. 18. Contribution of HESS PSH-CCES facility construction stage to Eutrophication: freshwater impact category – CCES construction stage

Impact category: Eutrophication: freshwater

Contribution	Process	Required amount	Total result [kg P-Eq]	Direct contribution [kg P-Eq]
100.00%	electricity production, high voltage, HESS PHS_CCES - PL	3.60000 MJ	0.00175	
99.96%	market for electricity, high voltage | electricity, high voltage | Cutoff, U - PL	5.76190 MJ	0.00175	
00.04%	HESS PHS CCES facility construction, in mine shafts - PL	5.84980E-11 Item(s)	7.39780E-7	
00.03%	compressed CO2 energy storage plant construction, in mine shaft HESS - PL	5.84980E-11 Item(s)	5.29669E-7	
00.01%	hydropower plant construction, in mine-shaft HESS - PL	5.84980E-11 Item(s)	1.62121E-7	
00.01%	upper reservoir construction PHS - PL	5.84980E-11 Item(s)	1.18858E-7	
00.00%	penstock, for PHS, transport	5.84980E-11 Item(s)	3.47083E-8	
00.00%	market for electricity, medium voltage | electricity, medium voltage | Cutoff, U - PL	1.16645E-5 MJ	3.56407E-9	
00.00%	upper technical platform, transport PHS	5.84980E-11 Item(s)	1.35853E-9	
00.00%	Sika seals, transport HESS PHS	1.42244E-6 kg	1.14833E-9	
00.00%	concrete C30/37, for water dams, with CEM III/A, transport PHS	1.52095E-8 m3	1.10184E-9	
00.00%	reinforcement, for concrete slab/platform, transport HESS - PL	5.84980E-11 Item(s)	6.57599E-10	
00.00%	shut-off valve, transported PHS	5.84980E-11 Item(s)	2.69215E-10	
00.00%	market for wastewater, average | wastewater, average | Cutoff, U - RER without CH	1.53223E-7 m3	2.67290E-10	8.72664E-11
00.00%	hydraulic drive unit, transport PHS	5.84980E-11 Item(s)	1.07316E-10	
00.00%	control cabinet, transport PHS_A-CAES	5.84980E-11 Item(s)	7.18913E-11	
00.00%	market for tap water | tap water | Cutoff, U - RER without CH	1.53223E-5 kg	8.48370E-12	
00.00%	energy router construction HESS	5.84980E-11 Item(s)	4.79903E-8	
00.00%	energy router components, transported HESS	5.84980E-11 Item(s)	4.79841E-8	
00.00%	concrete, C20/25, for router slab, with cement II/A, transport CCES	9.18419E-11 m3	6.20941E-12	

Fig. 19. Contribution of HESS PSH-CCES facility construction stage to Eutrophication: freshwater impact category – PSH and router construction stage

Impact category: Eutrophication: marine

Contribution	Process	Required amount	Total result [kg N-Eq]	Direct contribution [kg N-Eq]
100.00%	electricity production, high voltage, HESS PHS_CCES - PL	3.60000 MJ	0.00011	
99.86%	market for electricity, high voltage | electricity, high voltage | Cutoff, U - PL	5.76190 MJ	0.00011	
00.14%	HESS PHS CCES facility construction, in mine shafts - PL	5.84980E-11 Item(s)	1.51067E-7	
00.11%	compressed CO2 energy storage plant construction, in mine shaft HESS - PL	5.84980E-11 Item(s)	1.24922E-7	
00.07%	Therminol VP1, transport	2.86640E-5 kg	8.18079E-8	
00.02%	high pressure tanks, transport CCES	3.50988E-9 Item(s)	2.38620E-8	
00.00%	compressor 10.06 MW, transport CCES	5.84980E-11 Item(s)	5.08711E-9	
00.00%	expander 10.84 MW, transport CCES	5.84980E-11 Item(s)	2.77912E-9	
00.00%	market for carbon dioxide, liquid | carbon dioxide, liquid | Cutoff, U - RER	4.19922E-5 kg	2.31220E-9	
00.00%	TES tanks, transport CCES	1.16996E-10 Item(s)	2.19993E-9	
00.00%	Sika seals, transport CCES	1.53005E-6 kg	1.26312E-9	
00.00%	heat exchanger 1, transport CCES	1.75494E-10 Item(s)	1.12632E-9	
00.00%	CO2 purification, CO2 tank, transport CCES	1.16996E-10 Item(s)	8.42741E-10	
00.00%	heat exchanger 2, transport CCES	5.84980E-11 Item(s)	7.87944E-10	
00.00%	steel anchors for shaft plug, transport CCES	2.57391E-9 Item(s)	7.20257E-10	
00.00%	reinforcement, for shaft plug, transported CCES	5.84980E-11 Item(s)	5.90250E-10	
00.00%	concrete C30/37, shaft plug, with CEM III/A, transported CCES	7.44095E-8 m3	3.89160E-10	
00.00%	CO2 purification, cryogenic distillation column, transport CCES	5.84980E-11 Item(s)	2.91575E-10	
00.00%	heat exchanger 3, transport CCES	5.84980E-11 Item(s)	1.49673E-10	
00.00%	CO2 purification, refrigerant dryer, transport CCES	5.84980E-11 Item(s)	1.18572E-10	
00.00%	basalt, transport HESS CCES - PL	0.00014 kg	1.18024E-10	
00.00%	market for electricity, medium voltage | electricity, medium voltage | Cutoff, U - PL	6.09000E-6 MJ	1.17489E-10	
00.00%	treatment of wastewater, average, wastewater treatment | wastewater, average | Cutoff, U...	1.44228E-8 m3	7.65468E-11	7.36625E-11
00.00%	concrete C30/37, pressure dams, with CEM III/A, transport CCES	1.18107E-8 m3	6.13778E-11	
00.00%	CO2 purification, CO2 compressor, transport CCES	5.84980E-11 Item(s)	5.30466E-11	
00.00%	CO2 purification, CO2 condenser, transport CCES	5.84980E-11 Item(s)	4.73649E-11	
00.00%	CO2 purification, adsorption dryer, transport CCES	5.84980E-11 Item(s)	4.54822E-11	
00.00%	CO2 purification, carbon filter, transport CCES	1.16996E-10 Item(s)	2.22828E-11	
00.00%	CO2 purification, filter separator, transport CCES - PL	1.16996E-10 Item(s)	2.06216E-11	
00.00%	concrete, C20/25, for CO2 slabs, with cement II/A, transport CCES	3.33439E-9 m3	1.55977E-11	
00.00%	CO2 purification, liquid CO2 pump, transport CCES	5.84980E-11 Item(s)	1.02819E-11	
00.00%	reinforcement, for CO2 slabs, transport HESS	5.84980E-11 Item(s)	5.18352E-12	
00.00%	market for tap water | tap water | Cutoff, U - RER without CH	1.44228E-5 kg	5.99384E-13	
00.02%	hydropower plant construction, in mine-shaft HESS - PL	5.84980E-11 Item(s)	2.42335E-8	
00.00%	energy router construction HESS	5.84980E-11 Item(s)	1.91131E-9	

Fig. 20. Contribution of HESS PSH-CCES facility construction stage to Eutrophication: marine impact category – CCES construction stage

Impact category: Eutrophication: marine

Contribution	Process	Required amount	Total result [kg N-Eq]	Direct contribution [kg N-Eq]
100.00%	electricity production, high voltage, HESS PHS_CCES - PL	3.60000 MJ	0.00011	
99.86%	market for electricity, high voltage | electricity, high voltage | Cutoff, U - PL	5.76190 MJ	0.00011	
00.14%	HESS PHS CCES facility construction, in mine shafts - PL	5.84980E-11 Item(s)	1.51067E-7	
00.11%	compressed CO2 energy storage plant construction, in mine shaft HESS - PL	5.84980E-11 Item(s)	1.24922E-7	
00.02%	hydropower plant construction, in mine-shaft HESS - PL	5.84980E-11 Item(s)	2.42335E-8	
00.01%	upper reservoir construction PHS - PL	5.84980E-11 Item(s)	1.62732E-8	
00.00%	penstock, for PHS, transport	5.84980E-11 Item(s)	5.43467E-9	
00.00%	Sika seals, transport HESS PHS	1.42244E-6 kg	9.69507E-10	
00.00%	market for wastewater, average | wastewater, average | Cutoff, U - RER without CH	1.53223E-7 m3	8.89732E-10	1.79300E-10
00.00%	market for electricity, medium voltage | electricity, medium voltage | Cutoff, U - PL	1.16645E-5 MJ	2.25033E-10	
00.00%	upper technical platform, transport PHS	5.84980E-11 Item(s)	2.12823E-10	
00.00%	concrete C30/37, for water dams, with CEM III/A, transport PHS	1.52095E-8 m3	7.95455E-11	
00.00%	shut-off valve, transported PHS	5.84980E-11 Item(s)	7.08800E-11	
00.00%	reinforcement, for concrete slab/platform, transport HESS - PL	5.84980E-11 Item(s)	6.59209E-11	
00.00%	control cabinet, transport PHS_A-CAES	5.84980E-11 Item(s)	6.53151E-12	
00.00%	hydraulic drive unit, transport PHS	5.84980E-11 Item(s)	5.00813E-12	
00.00%	market for tap water | tap water | Cutoff, U - RER without CH	1.53223E-5 kg	6.36764E-13	
00.00%	energy router construction HESS	5.84980E-11 Item(s)	1.91131E-9	
00.00%	energy router components, transported HESS	5.84980E-11 Item(s)	1.91088E-9	
00.00%	concrete, C20/25, for router slab, with cement II/A, transport CCES	9.18419E-11 m3	4.29710E-13	

Fig. 21. Contribution of HESS PSH-CCES facility construction stage to Eutrophication: marine impact category – PSH and router construction stage

Impact category: Human toxicity: carcinogenic

Contribution	Process	Required amount	Total result [kg 1,4-DCB-Eq]	Direct contribution [kg 1,4-DCB...
100.00%	electricity production, high voltage, HESS PHS_CCES - PL	3.60000 MJ	0.14664	
99.67%	market for electricity, high voltage | electricity, high voltage | Cutoff, U - PL	5.76190 MJ	0.14617	
00.33%	HESS PHS CCES facility construction, in mine shafts - PL	5.84980E-11 Item(s)	0.00048	
00.20%	compressed CO2 energy storage plant construction, in mine shaft HESS - PL	5.84980E-11 Item(s)	0.00030	
00.11%	high pressure tanks, transport CCES	3.50988E-9 Item(s)	0.00017	
00.02%	compressor 10.06 MW, transport CCES	5.84980E-11 Item(s)	2.98373E-5	
00.01%	Therminol VP1, transport	2.86640E-5 kg	1.80760E-5	
00.01%	expander 10.84 MW, transport CCES	5.84980E-11 Item(s)	1.76747E-5	
00.01%	TES tanks, transport CCES	1.16996E-10 Item(s)	1.76551E-5	
00.01%	reinforcement, for shaft plug, transported CCES	5.84980E-11 Item(s)	1.26552E-5	
00.01%	heat exchanger 1, transport CCES	1.75494E-10 Item(s)	1.06760E-5	
00.01%	heat exchanger 2, transport CCES	5.84980E-11 Item(s)	7.91819E-6	
00.00%	CO2 purification, CO2 tank, transport CCES	1.16996E-10 Item(s)	5.89687E-6	
00.00%	steel anchors for shaft plug, transport CCES	2.57391E-9 Item(s)	5.06223E-6	
00.00%	market for carbon dioxide, liquid | carbon dioxide, liquid | Cutoff, U - RER	4.19922E-5 kg	1.66557E-6	
00.00%	CO2 purification, cryogenic distillation column, transport CCES	5.84980E-11 Item(s)	1.63021E-6	
00.00%	heat exchanger 3, transport CCES	5.84980E-11 Item(s)	1.30130E-6	
00.00%	concrete C30/37, shaft plug, with CEM III/A, transported CCES	7.44095E-8 m3	7.54107E-7	
00.00%	CO2 purification, CO2 compressor, transport CCES	5.84980E-11 Item(s)	4.90267E-7	
00.00%	CO2 purification, adsorption dryer, transport CCES	5.84980E-11 Item(s)	4.49332E-7	
00.00%	Sika seals, transport CCES	1.53005E-6 kg	4.39861E-7	
00.00%	CO2 purification, refrigerant dryer, transport CCES	5.84980E-11 Item(s)	4.13936E-7	
00.00%	CO2 purification, CO2 condenser, transport CCES	5.84980E-11 Item(s)	2.72127E-7	
00.00%	basalt, transport HESS CCES - PL	0.00014 kg	2.27065E-7	
00.00%	market for electricity, medium voltage | electricity, medium voltage | Cutoff, U - PL	6.09000E-6 MJ	1.57052E-7	
00.00%	CO2 purification, carbon filter, transport CCES	1.16996E-10 Item(s)	1.21994E-7	
00.00%	concrete C30/37, pressure dams, with CEM III/A, transport CCES	1.18107E-8 m3	1.18632E-7	
00.00%	CO2 purification, filter separator, transport CCES - PL	1.16996E-10 Item(s)	1.14960E-7	
00.00%	reinforcement, for CO2 slabs, transport HESS	5.84980E-11 Item(s)	1.11137E-7	
00.00%	CO2 purification, liquid CO2 pump, transport CCES	5.84980E-11 Item(s)	3.63860E-8	
00.00%	concrete, C20/25, for CO2 slabs, with cement II/A, transport CCES	3.33439E-9 m3	3.04778E-8	
00.00%	market for tap water | tap water | Cutoff, U - RER without CH	1.44228E-5 kg	1.31416E-9	
00.00%	treatment of wastewater, average, wastewater treatment | wastewater, average | Cutoff, U...	1.44228E-8 m3	4.63387E-10	2.30945E-11
00.11%	hydropower plant construction, in mine-shaft HESS - PL	5.84980E-11 Item(s)	0.00016	
00.01%	energy router construction HESS	5.84980E-11 Item(s)	1.48276E-5	

Fig. 22. Contribution of HESS PSH-CCES facility construction stage to Human toxicity: carcinogenic impact category – CCES construction stage

Impact category: Human toxicity: carcinogenic

Contribution	Process	Required amount	Total result [kg 1,4-DCB-Eq]	Direct contribution [kg 1,4-DCB...
100.00%	electricity production, high voltage, HESS PHS_CCES - PL	3.60000 MJ	0.14664	
99.67%	market for electricity, high voltage | electricity, high voltage | Cutoff, U - PL	5.76190 MJ	0.14617	
00.33%	HESS PHS CCES facility construction, in mine shafts - PL	5.84980E-11 Item(s)	0.00048	
00.20%	compressed CO2 energy storage plant construction, in mine shaft HESS - PL	5.84980E-11 Item(s)	0.00030	
00.11%	hydropower plant construction, in mine-shaft HESS - PL	5.84980E-11 Item(s)	0.00016	
00.08%	upper reservoir construction PHS - PL	5.84980E-11 Item(s)	0.00012	
00.03%	penstock, for PHS, transport	5.84980E-11 Item(s)	3.87839E-5	
00.00%	upper technical platform, transport PHS	5.84980E-11 Item(s)	1.51766E-6	
00.00%	reinforcement, for concrete slab/platform, transport HESS - PL	5.84980E-11 Item(s)	1.41337E-6	
00.00%	shut-off valve, transported PHS	5.84980E-11 Item(s)	6.32926E-7	
00.00%	Sika seals, transport HESS PHS	1.42244E-6 kg	3.49286E-7	
00.00%	market for electricity, medium voltage | electricity, medium voltage | Cutoff, U - PL	1.16645E-5 MJ	3.00811E-7	
00.00%	concrete C30/37, for water dams, with CEM III/A, transport PHS	1.52095E-8 m3	1.54142E-7	
00.00%	hydraulic drive unit, transport PHS	5.84980E-11 Item(s)	9.41673E-8	
00.00%	control cabinet, transport PHS_A-CAES	5.84980E-11 Item(s)	1.65857E-8	
00.00%	market for wastewater, average | wastewater, average | Cutoff, U - RER without CH	1.53223E-7 m3	7.67715E-9	6.84473E-12
00.00%	market for tap water | tap water | Cutoff, U - RER without CH	1.53223E-5 kg	1.39612E-9	
00.01%	energy router construction HESS	5.84980E-11 Item(s)	1.48276E-5	
00.01%	energy router components, transported HESS	5.84980E-11 Item(s)	1.48267E-5	
00.00%	concrete, C20/25, for router slab, with cement II/A, transport CCES	9.18419E-11 m3	8.39727E-10	

Fig. 23. Contribution of HESS PSH-CCES facility construction stage to Human toxicity: carcinogenic impact category – PSH and router construction stage

Impact category: Human toxicity: non-carcinogenic

Contribution	Process	Required amount	Total result [kg 1,4-DCB-Eq]	Direct contribution [kg 1,4-DCB...
100.00%	electricity production, high voltage, HESS PHS_CCES - PL	3.60000 MJ	2.26220	
99.74%	market for electricity, high voltage | electricity, high voltage | Cutoff, U - PL	5.76190 MJ	2.25630	
00.26%	HESS PHS CCES facility construction, in mine shafts - PL	5.84980E-11 Item(s)	0.00590	
00.21%	compressed CO2 energy storage plant construction, in mine shaft HESS - PL	5.84980E-11 Item(s)	0.00474	
00.09%	high pressure tanks, transport CCES	3.50988E-9 Item(s)	0.00202	
00.03%	compressor 10.06 MW, transport CCES	5.84980E-11 Item(s)	0.00078	
00.02%	expander 10.84 MW, transport CCES	5.84980E-11 Item(s)	0.00047	
00.02%	heat exchanger 1, transport CCES	1.75494E-10 Item(s)	0.00035	
00.02%	Therminol VP1, transport	2.86640E-5 kg	0.00035	
00.01%	heat exchanger 2, transport CCES	5.84980E-11 Item(s)	0.00026	
00.01%	CO2 purification, CO2 tank, transport CCES	1.16996E-10 Item(s)	0.00015	
00.00%	CO2 purification, cryogenic distillation column, transport CCES	5.84980E-11 Item(s)	5.95704E-5	
00.00%	TES tanks, transport CCES	1.16996E-10 Item(s)	5.90459E-5	
00.00%	heat exchanger 3, transport CCES	5.84980E-11 Item(s)	4.36109E-5	
00.00%	market for carbon dioxide, liquid | carbon dioxide, liquid | Cutoff, U - RER	4.19922E-5 kg	4.08830E-5	
00.00%	reinforcement, for shaft plug, transported CCES	5.84980E-11 Item(s)	4.08817E-5	
00.00%	CO2 purification, refrigerant dryer, transport CCES	5.84980E-11 Item(s)	2.15761E-5	
00.00%	steel anchors for shaft plug, transport CCES	2.57391E-9 Item(s)	1.95656E-5	
00.00%	CO2 purification, CO2 compressor, transport CCES	5.84980E-11 Item(s)	1.49012E-5	
00.00%	concrete C30/37, shaft plug, with CEM III/A, transported CCES	7.44095E-8 m3	1.29037E-5	
00.00%	CO2 purification, CO2 condenser, transport CCES	5.84980E-11 Item(s)	1.03719E-5	
00.00%	CO2 purification, adsorption dryer, transport CCES	5.84980E-11 Item(s)	8.97349E-6	
00.00%	Sika seals, transport CCES	1.53005E-6 kg	7.37816E-6	
00.00%	CO2 purification, carbon filter, transport CCES	1.16996E-10 Item(s)	5.19146E-6	
00.00%	CO2 purification, filter separator, transport CCES - PL	1.16996E-10 Item(s)	5.04049E-6	
00.00%	basalt, transport HESS CCES - PL	0.00014 kg	3.24383E-6	
00.00%	market for electricity, medium voltage | electricity, medium voltage | Cutoff, U - PL	6.09000E-6 MJ	2.45622E-6	
00.00%	concrete C30/37, pressure dams, with CEM III/A, transport CCES	1.18107E-8 m3	2.02837E-6	
00.00%	CO2 purification, liquid CO2 pump, transport CCES	5.84980E-11 Item(s)	1.90036E-6	
00.00%	concrete, C20/25, for CO2 slabs, with cement II/A, transport CCES	3.33439E-9 m3	4.93004E-7	
00.00%	reinforcement, for CO2 slabs, transport HESS	5.84980E-11 Item(s)	3.59019E-7	
00.00%	treatment of wastewater, average, wastewater treatment | wastewater, average | Cutoff, U...	1.44228E-8 m3	5.25587E-8	1.79388E-9
00.00%	market for tap water | tap water | Cutoff, U - RER without CH	1.44228E-5 kg	1.31916E-8	
00.03%	hydropower plant construction, in mine-shaft HESS - PL	5.84980E-11 Item(s)	0.00061	
00.02%	energy router construction HESS	5.84980E-11 Item(s)	0.00055	

Fig. 24. Contribution of HESS PSH-CCES facility construction stage to Human toxicity: non-carcinogenic impact category – CCES construction stage

Impact category: Human toxicity: non-carcinogenic

Contribution	Process	Required amount	Total result [kg 1,4-DCB-Eq]	Direct contribution [kg 1,4-DCB...
100.00%	electricity production, high voltage, HESS PHS_CCES - PL	3.60000 MJ	2.26220	
99.74%	market for electricity, high voltage | electricity, high voltage | Cutoff, U - PL	5.76190 MJ	2.25630	
00.26%	HESS PHS CCES facility construction, in mine shafts - PL	5.84980E-11 Item(s)	0.00590	
00.21%	compressed CO2 energy storage plant construction, in mine shaft HESS - PL	5.84980E-11 Item(s)	0.00474	
00.03%	hydropower plant construction, in mine-shaft HESS - PL	5.84980E-11 Item(s)	0.00061	
00.02%	upper reservoir construction PHS - PL	5.84980E-11 Item(s)	0.00043	
00.01%	penstock, for PHS, transport	5.84980E-11 Item(s)	0.00015	
00.00%	Sika seals, transport HESS PHS	1.42244E-6 kg	5.86455E-6	
00.00%	upper technical platform, transport PHS	5.84980E-11 Item(s)	5.80796E-6	
00.00%	market for electricity, medium voltage | electricity, medium voltage | Cutoff, U - PL	1.16645E-5 MJ	4.70454E-6	
00.00%	reinforcement, for concrete slab/platform, transport HESS - PL	5.84980E-11 Item(s)	4.56579E-6	
00.00%	concrete C30/37, for water dams, with CEM III/A, transport PHS	1.52095E-8 m3	2.63756E-6	
00.00%	shut-off valve, transported PHS	5.84980E-11 Item(s)	2.10969E-6	
00.00%	hydraulic drive unit, transport PHS	5.84980E-11 Item(s)	1.01311E-6	
00.00%	market for wastewater, average | wastewater, average | Cutoff, U - RER without CH	1.53223E-7 m3	5.61668E-7	2.34413E-8
00.00%	control cabinet, transport PHS_A-CAES	5.84980E-11 Item(s)	2.56521E-7	
00.00%	market for tap water | tap water | Cutoff, U - RER without CH	1.53223E-5 kg	1.40143E-8	
00.02%	energy router construction HESS	5.84980E-11 Item(s)	0.00055	
00.02%	energy router components, transported HESS	5.84980E-11 Item(s)	0.00055	
00.00%	concrete, C20/25, for router slab, with cement II/A, transport CCES	9.18419E-11 m3	1.35834E-8	

Fig. 25. Contribution of HESS PSH-CCES facility construction stage to Human toxicity: non-carcinogenic impact category – PSH and router construction stage

Impact category: Ionising radiation

Contribution	Process	Required amount	Total result [kBq Co-60-Eq]	Direct contribution [kBq Co-60...
100.00%	electricity production, high voltage, HESS PHS_CCES - PL	3.60000 MJ	0.02184	
99.76%	market for electricity, high voltage | electricity, high voltage | Cutoff, U - PL	5.76190 MJ	0.02179	
00.24%	HESS PHS CCES facility construction, in mine shafts - PL	5.84980E-11 Item(s)	5.20126E-5	
00.20%	compressed CO2 energy storage plant construction, in mine shaft HESS - PL	5.84980E-11 Item(s)	4.43426E-5	
00.11%	Therminol VP1, transport	2.86640E-5 kg	2.39645E-5	
00.04%	high pressure tanks, transport CCES	3.50988E-9 Item(s)	8.26945E-6	
00.02%	market for carbon dioxide, liquid | carbon dioxide, liquid | Cutoff, U - RER	4.19922E-5 kg	3.51554E-6	
00.01%	compressor 10.06 MW, transport CCES	5.84980E-11 Item(s)	2.37014E-6	
00.01%	expander 10.84 MW, transport CCES	5.84980E-11 Item(s)	1.39864E-6	
00.01%	TES tanks, transport CCES	1.16996E-10 Item(s)	1.21101E-6	
00.00%	heat exchanger 1, transport CCES	1.75494E-10 Item(s)	8.98658E-7	
00.00%	heat exchanger 2, transport CCES	5.84980E-11 Item(s)	6.64257E-7	
00.00%	CO2 purification, CO2 tank, transport CCES	1.16996E-10 Item(s)	5.02873E-7	
00.00%	reinforcement, for shaft plug, transported CCES	5.84980E-11 Item(s)	3.21293E-7	
00.00%	CO2 purification, cryogenic distillation column, transport CCES	5.84980E-11 Item(s)	2.06761E-7	
00.00%	steel anchors for shaft plug, transport CCES	2.57391E-9 Item(s)	2.06019E-7	
00.00%	CO2 purification, refrigerant dryer, transport CCES	5.84980E-11 Item(s)	1.65919E-7	
00.00%	Sika seals, transport CCES	1.53005E-6 kg	1.56312E-7	
00.00%	concrete C30/37, shaft plug, with CEM III/A, transported CCES	7.44095E-8 m3	1.21895E-7	
00.00%	heat exchanger 3, transport CCES	5.84980E-11 Item(s)	1.12778E-7	
00.00%	CO2 purification, CO2 compressor, transport CCES	5.84980E-11 Item(s)	5.19794E-8	
00.00%	basalt, transport HESS CCES - PL	0.00014 kg	4.14282E-8	
00.00%	CO2 purification, adsorption dryer, transport CCES	5.84980E-11 Item(s)	3.64098E-8	
00.00%	CO2 purification, CO2 condenser, transport CCES	5.84980E-11 Item(s)	3.17125E-8	
00.00%	market for electricity, medium voltage | electricity, medium voltage | Cutoff, U - PL	6.09000E-6 MJ	2.32528E-8	
00.00%	concrete C30/37, pressure dams, with CEM III/A, transport CCES	1.18107E-8 m3	1.89747E-8	
00.00%	CO2 purification, carbon filter, transport CCES	1.16996E-10 Item(s)	1.81068E-8	
00.00%	CO2 purification, filter separator, transport CCES - PL	1.16996E-10 Item(s)	1.38661E-8	
00.00%	CO2 purification, liquid CO2 pump, transport CCES	5.84980E-11 Item(s)	1.26791E-8	
00.00%	concrete, C20/25, for CO2 slabs, with cement II/A, transport CCES	3.33439E-9 m3	4.20806E-9	
00.00%	reinforcement, for CO2 slabs, transport HESS	5.84980E-11 Item(s)	2.82157E-9	
00.00%	treatment of wastewater, average, wastewater treatment | wastewater, average | Cutoff, U...	1.44228E-8 m3	8.62753E-10	
00.00%	market for tap water | tap water | Cutoff, U - RER without CH	1.44228E-5 kg	2.39623E-10	
00.03%	hydropower plant construction, in mine-shaft HESS - PL	5.84980E-11 Item(s)	5.76673E-6	
00.01%	energy router construction HESS	5.84980E-11 Item(s)	1.90324E-6	

Fig. 26. Contribution of HESS PSH-CCES facility construction stage to Ionising radiation impact category – CCES construction stage

Impact category: Ionising radiation

Contribution	Process	Required amount	Total result [kBq Co-60-Eq]	Direct contribution [kBq Co-60...
100.00%	electricity production, high voltage, HESS PHS_CCES - PL	3.60000 MJ	0.02184	
99.76%	market for electricity, high voltage | electricity, high voltage | Cutoff, U - PL	5.76190 MJ	0.02179	
00.24%	HESS PHS CCES facility construction, in mine shafts - PL	5.84980E-11 Item(s)	5.20126E-5	
00.20%	compressed CO2 energy storage plant construction, in mine shaft HESS - PL	5.84980E-11 Item(s)	4.43426E-5	
00.03%	hydropower plant construction, in mine-shaft HESS - PL	5.84980E-11 Item(s)	5.76673E-6	
00.02%	upper reservoir construction PHS - PL	5.84980E-11 Item(s)	4.12520E-6	
00.01%	penstock, for PHS, transport	5.84980E-11 Item(s)	1.29766E-6	
00.00%	Sika seals, transport HESS PHS	1.42244E-6 kg	1.22460E-7	
00.00%	shut-off valve, transported PHS	5.84980E-11 Item(s)	5.13618E-8	
00.00%	upper technical platform, transport PHS	5.84980E-11 Item(s)	5.09466E-8	
00.00%	market for electricity, medium voltage | electricity, medium voltage | Cutoff, U - PL	1.16645E-5 MJ	4.45374E-8	
00.00%	reinforcement, for concrete slab/platform, transport HESS - PL	5.84980E-11 Item(s)	3.58830E-8	
00.00%	concrete C30/37, for water dams, with CEM III/A, transport PHS	1.52095E-8 m3	2.49157E-8	
00.00%	market for wastewater, average | wastewater, average | Cutoff, U - RER without CH	1.53223E-7 m3	8.37276E-9	
00.00%	hydraulic drive unit, transport PHS	5.84980E-11 Item(s)	3.19711E-9	
00.00%	control cabinet, transport PHS_A-CAES	5.84980E-11 Item(s)	1.94314E-9	
00.00%	market for tap water | tap water | Cutoff, U - RER without CH	1.53223E-5 kg	2.54567E-10	
00.01%	energy router construction HESS	5.84980E-11 Item(s)	1.90324E-6	
00.01%	energy router components, transported HESS	5.84980E-11 Item(s)	1.90313E-6	
00.00%	concrete, C20/25, for router slab, with cement II/A, transport CCES	9.18419E-11 m3	1.15978E-10	

Fig. 27. Contribution of HESS PSH-CCES facility construction stage to Ionising radiation impact category – PSH and router construction stage

Impact category: Land use

Contribution	Process	Required amount	Total result [m2*a crop-Eq]	Direct contribution [m2*a crop...
100.00%	electricity production, high voltage, HESS PHS_CCES - PL	3.60000 MJ	0.02395	
99.88%	market for electricity, high voltage | electricity, high voltage | Cutoff, U - PL	5.76190 MJ	0.02392	
00.12%	HESS PHS CCES facility construction, in mine shafts - PL	5.84980E-11 Item(s)	2.93001E-5	
00.09%	compressed CO2 energy storage plant construction, in mine shaft HESS - PL	5.84980E-11 Item(s)	2.15597E-5	
00.03%	high pressure tanks, transport CCES	3.50988E-9 Item(s)	8.04832E-6	
00.02%	Therminol VP1, transport	2.86640E-5 kg	5.07223E-6	
00.01%	compressor 10.06 MW, transport CCES	5.84980E-11 Item(s)	2.09848E-6	
00.01%	expander 10.84 MW, transport CCES	5.84980E-11 Item(s)	1.23047E-6	
00.00%	basalt, transport HESS CCES - PL	0.00014 kg	9.65944E-7	
00.00%	TES tanks, transport CCES	1.16996E-10 Item(s)	6.99267E-7	
00.00%	heat exchanger 1, transport CCES	1.75494E-10 Item(s)	6.48931E-7	
00.00%	market for carbon dioxide, liquid | carbon dioxide, liquid | Cutoff, U - RER	4.19922E-5 kg	5.27229E-7	
00.00%	heat exchanger 2, transport CCES	5.84980E-11 Item(s)	4.75855E-7	
00.00%	CO2 purification, CO2 tank, transport CCES	1.16996E-10 Item(s)	4.02258E-7	
00.00%	concrete C30/37, shaft plug, with CEM III/A, transported CCES	7.44095E-8 m3	3.08014E-7	
00.00%	reinforcement, for shaft plug, transported CCES	5.84980E-11 Item(s)	2.47105E-7	
00.00%	Sika seals, transport CCES	1.53005E-6 kg	1.78489E-7	
00.00%	steel anchors for shaft plug, transport CCES	2.57391E-9 Item(s)	1.71911E-7	
00.00%	CO2 purification, cryogenic distillation column, transport CCES	5.84980E-11 Item(s)	1.37039E-7	
00.00%	heat exchanger 3, transport CCES	5.84980E-11 Item(s)	8.20201E-8	
00.00%	CO2 purification, refrigerant dryer, transport CCES	5.84980E-11 Item(s)	6.16261E-8	
00.00%	concrete C30/37, pressure dams, with CEM III/A, transport CCES	1.18107E-8 m3	4.87354E-8	
00.00%	CO2 purification, CO2 compressor, transport CCES	5.84980E-11 Item(s)	3.93157E-8	
00.00%	CO2 purification, CO2 condenser, transport CCES	5.84980E-11 Item(s)	2.59907E-8	
00.00%	market for electricity, medium voltage | electricity, medium voltage | Cutoff, U - PL	6.09000E-6 MJ	2.56283E-8	
00.00%	CO2 purification, adsorption dryer, transport CCES	5.84980E-11 Item(s)	2.43315E-8	
00.00%	concrete, C20/25, for CO2 slabs, with cement II/A, transport CCES	3.33439E-9 m3	1.18093E-8	
00.00%	CO2 purification, carbon filter, transport CCES	1.16996E-10 Item(s)	1.11495E-8	
00.00%	CO2 purification, filter separator, transport CCES - PL	1.16996E-10 Item(s)	9.84096E-9	
00.00%	CO2 purification, liquid CO2 pump, transport CCES	5.84980E-11 Item(s)	5.32791E-9	
00.00%	reinforcement, for CO2 slabs, transport HESS	5.84980E-11 Item(s)	2.17005E-9	
00.00%	market for tap water | tap water | Cutoff, U - RER without CH	1.44228E-5 kg	1.52651E-10	
00.00%	treatment of wastewater, average, wastewater treatment | wastewater, average | Cutoff, U...	1.44228E-8 m3	1.21326E-10	2.01521E-11
00.03%	hydropower plant construction, in mine-shaft HESS - PL	5.84980E-11 Item(s)	6.25981E-6	
00.01%	energy router construction HESS	5.84980E-11 Item(s)	1.48058E-6	

Fig. 28. Contribution of HESS PSH-CCES facility construction stage to Land use impact category – CCES construction stage

Impact category: Land use

Contribution	Process	Required amount	Total result [m2*a crop-Eq]	Direct contribution [m2*a crop...
100.00%	electricity production, high voltage, HESS PHS_CCES - PL	3.60000 MJ	0.02395	
99.88%	market for electricity, high voltage | electricity, high voltage | Cutoff, U - PL	5.76190 MJ	0.02392	
00.12%	HESS PHS CCES facility construction, in mine shafts - PL	5.84980E-11 Item(s)	2.93001E-5	
00.09%	compressed CO2 energy storage plant construction, in mine shaft HESS - PL	5.84980E-11 Item(s)	2.15597E-5	
00.03%	hydropower plant construction, in mine-shaft HESS - PL	5.84980E-11 Item(s)	6.25981E-6	
00.02%	upper reservoir construction PHS - PL	5.84980E-11 Item(s)	4.62071E-6	
00.01%	penstock, for PHS, transport	5.84980E-11 Item(s)	1.27421E-6	
00.00%	Sika seals, transport HESS PHS	1.42244E-6 kg	1.46778E-7	
00.00%	concrete C30/37, for water dams, with CEM III/A, transport PHS	1.52095E-8 m3	6.29590E-8	
00.00%	upper technical platform, transport PHS	5.84980E-11 Item(s)	5.07933E-8	
00.00%	market for electricity, medium voltage | electricity, medium voltage | Cutoff, U - PL	1.16645E-5 MJ	4.90872E-8	
00.00%	reinforcement, for concrete slab/platform, transport HESS - PL	5.84980E-11 Item(s)	2.75974E-8	
00.00%	shut-off valve, transported PHS	5.84980E-11 Item(s)	1.70331E-8	
00.00%	control cabinet, transport PHS_A-CAES	5.84980E-11 Item(s)	5.32609E-9	
00.00%	hydraulic drive unit, transport PHS	5.84980E-11 Item(s)	3.72612E-9	
00.00%	market for wastewater, average | wastewater, average | Cutoff, U - RER without CH	1.53223E-7 m3	1.42775E-9	
00.00%	market for tap water | tap water | Cutoff, U - RER without CH	1.53223E-5 kg	1.62171E-10	
00.01%	energy router construction HESS	5.84980E-11 Item(s)	1.48058E-6	
00.01%	energy router components, transported HESS	5.84980E-11 Item(s)	1.48026E-6	
00.00%	concrete, C20/25, for router slab, with cement II/A, transport CCES	9.18419E-11 m3	3.25513E-10	

Fig. 29. Contribution of HESS PSH-CCES facility construction stage to Land use impact category – PSH and router construction stage

Impact category: Material resources: metals/minerals

Contribution	Process	Required amount	Total result [kg Cu-Eq]	Direct contribution [kg Cu-Eq]
100.00%	electricity production, high voltage, HESS PHS_CCES - PL	3.60000 MJ	0.00525	
93.52%	market for electricity, high voltage | electricity, high voltage | Cutoff, U - PL	5.76190 MJ	0.00491	
06.48%	HESS PHS CCES facility construction, in mine shafts - PL	5.84980E-11 Item(s)	0.00034	
04.87%	compressed CO2 energy storage plant construction, in mine shaft HESS - PL	5.84980E-11 Item(s)	0.00026	
02.14%	basalt, transport HESS CCES - PL	0.00014 kg	0.00011	
01.38%	high pressure tanks, transport CCES	3.50988E-9 Item(s)	7.25993E-5	
00.32%	compressor 10.06 MW, transport CCES	5.84980E-11 Item(s)	1.68151E-5	
00.26%	Therminol VP1, transport	2.86640E-5 kg	1.34069E-5	
00.21%	TES tanks, transport CCES	1.16996E-10 Item(s)	1.10261E-5	
00.19%	expander 10.84 MW, transport CCES	5.84980E-11 Item(s)	1.00900E-5	
00.14%	reinforcement, for shaft plug, transported CCES	5.84980E-11 Item(s)	7.14407E-6	
00.05%	steel anchors for shaft plug, transport CCES	2.57391E-9 Item(s)	2.87328E-6	
00.05%	heat exchanger 1, transport CCES	1.75494E-10 Item(s)	2.54222E-6	
00.05%	CO2 purification, CO2 tank, transport CCES	1.16996E-10 Item(s)	2.41928E-6	
00.03%	heat exchanger 2, transport CCES	5.84980E-11 Item(s)	1.78906E-6	
00.01%	CO2 purification, cryogenic distillation column, transport CCES	5.84980E-11 Item(s)	5.46773E-7	
00.01%	market for carbon dioxide, liquid | carbon dioxide, liquid | Cutoff, U - RER	4.19922E-5 kg	4.14415E-7	
00.01%	concrete C30/37, shaft plug, with CEM III/A, transported CCES	7.44095E-8 m3	3.47875E-7	
00.01%	heat exchanger 3, transport CCES	5.84980E-11 Item(s)	3.19794E-7	
00.01%	Sika seals, transport CCES	1.53005E-6 kg	2.89537E-7	
00.00%	CO2 purification, CO2 compressor, transport CCES	5.84980E-11 Item(s)	2.04071E-7	
00.00%	CO2 purification, refrigerant dryer, transport CCES	5.84980E-11 Item(s)	1.13175E-7	
00.00%	CO2 purification, CO2 condenser, transport CCES	5.84980E-11 Item(s)	8.11988E-8	
00.00%	reinforcement, for CO2 slabs, transport HESS	5.84980E-11 Item(s)	6.27387E-8	
00.00%	CO2 purification, adsorption dryer, transport CCES	5.84980E-11 Item(s)	6.08855E-8	
00.00%	concrete C30/37, pressure dams, with CEM III/A, transport CCES	1.18107E-8 m3	5.45082E-8	
00.00%	CO2 purification, carbon filter, transport CCES	1.16996E-10 Item(s)	2.73421E-8	
00.00%	CO2 purification, filter separator, transport CCES - PL	1.16996E-10 Item(s)	2.57965E-8	
00.00%	concrete, C20/25, for CO2 slabs, with cement II/A, transport CCES	3.33439E-9 m3	2.09218E-8	
00.00%	CO2 purification, liquid CO2 pump, transport CCES	5.84980E-11 Item(s)	1.43528E-8	
00.00%	market for electricity, medium voltage | electricity, medium voltage | Cutoff, U - PL	6.09000E-6 MJ	5.45471E-9	
00.00%	market for tap water | tap water | Cutoff, U - RER without CH	1.44228E-5 kg	8.11167E-10	
00.00%	treatment of wastewater, average, wastewater treatment | wastewater, average | Cutoff, U...	1.44228E-8 m3	1.48760E-10	
01.49%	hydropower plant construction, in mine-shaft HESS - PL	5.84980E-11 Item(s)	7.84709E-5	
00.12%	energy router construction HESS	5.84980E-11 Item(s)	6.07930E-6	

Fig. 30. Contribution of HESS PSH-CCES facility construction stage to Material resources: metals/minerals impact category – CCES construction stage

Impact category: Material resources: metals/minerals

Contribution	Process	Required amount	Total result [kg Cu-Eq]	Direct contribution [kg Cu-Eq]
100.00%	electricity production, high voltage, HESS PHS_CCES - PL	3.60000 MJ	0.00525	
93.52%	market for electricity, high voltage | electricity, high voltage | Cutoff, U - PL	5.76190 MJ	0.00491	
06.48%	HESS PHS CCES facility construction, in mine shafts - PL	5.84980E-11 Item(s)	0.00034	
04.87%	compressed CO2 energy storage plant construction, in mine shaft HESS - PL	5.84980E-11 Item(s)	0.00026	
01.49%	hydropower plant construction, in mine-shaft HESS - PL	5.84980E-11 Item(s)	7.84709E-5	
01.04%	upper reservoir construction PHS - PL	5.84980E-11 Item(s)	5.46621E-5	
00.41%	penstock, for PHS, transport	5.84980E-11 Item(s)	2.16982E-5	
00.02%	upper technical platform, transport PHS	5.84980E-11 Item(s)	8.49066E-7	
00.02%	reinforcement, for concrete slab/platform, transport HESS - PL	5.84980E-11 Item(s)	7.97872E-7	
00.00%	Sika seals, transport HESS PHS	1.42244E-6 kg	2.45999E-7	
00.00%	concrete C30/37, for water dams, with CEM III/A, transport PHS	1.52095E-8 m3	7.11066E-8	
00.00%	shut-off valve, transported PHS	5.84980E-11 Item(s)	6.88645E-8	
00.00%	hydraulic drive unit, transport PHS	5.84980E-11 Item(s)	5.72764E-8	
00.00%	market for electricity, medium voltage | electricity, medium voltage | Cutoff, U - PL	1.16645E-5 MJ	1.04477E-8	
00.00%	control cabinet, transport PHS_A-CAES	5.84980E-11 Item(s)	6.14237E-9	
00.00%	market for wastewater, average | wastewater, average | Cutoff, U - RER without CH	1.53223E-7 m3	2.94762E-9	
00.00%	market for tap water | tap water | Cutoff, U - RER without CH	1.53223E-5 kg	8.61755E-10	
00.12%	energy router construction HESS	5.84980E-11 Item(s)	6.07930E-6	
00.12%	energy router components, transported HESS	5.84980E-11 Item(s)	6.07872E-6	
00.00%	concrete, C20/25, for router slab, with cement II/A, transport CCES	9.18419E-11 m3	5.76415E-10	

Fig. 31. Contribution of HESS PSH-CCES facility construction stage to Material resources: metals/minerals impact category – PSH and router construction stage

Impact category: Ozone depletion

Contribution	Process	Required amount	Total result [kg CFC-11-Eq]	Direct contribution [kg CFC-11...
100.00%	electricity production, high voltage, HESS PHS_CCES - PL	3.60000 MJ	2.50599E-7	
99.81%	market for electricity, high voltage | electricity, high voltage | Cutoff, U - PL	5.76190 MJ	2.50118E-7	9.03354E-8
00.19%	HESS PHS CCES facility construction, in mine shafts - PL	5.84980E-11 Item(s)	4.80712E-10	
00.15%	compressed CO2 energy storage plant construction, in mine shaft HESS - PL	5.84980E-11 Item(s)	3.80009E-10	
00.09%	Therminol VP1, transport	2.86640E-5 kg	2.24578E-10	
00.03%	high pressure tanks, transport CCES	3.50988E-9 Item(s)	7.34145E-11	
00.01%	Sika seals, transport CCES	1.53005E-6 kg	2.05838E-11	
00.01%	compressor 10.06 MW, transport CCES	5.84980E-11 Item(s)	1.60033E-11	
00.00%	expander 10.84 MW, transport CCES	5.84980E-11 Item(s)	9.30154E-12	
00.00%	TES tanks, transport CCES	1.16996E-10 Item(s)	5.47310E-12	
00.00%	market for carbon dioxide, liquid | carbon dioxide, liquid | Cutoff, U - RER	4.19922E-5 kg	5.21911E-12	
00.00%	heat exchanger 1, transport CCES	1.75494E-10 Item(s)	4.89500E-12	
00.00%	CO2 purification, CO2 tank, transport CCES	1.16996E-10 Item(s)	4.12625E-12	
00.00%	heat exchanger 2, transport CCES	5.84980E-11 Item(s)	3.57632E-12	
00.00%	basalt, transport HESS CCES - PL	0.00014 kg	2.01103E-12	
00.00%	reinforcement, for shaft plug, transported CCES	5.84980E-11 Item(s)	2.00454E-12	
00.00%	concrete C30/37, shaft plug, with CEM III/A, transported CCES	7.44095E-8 m3	1.69914E-12	
00.00%	steel anchors for shaft plug, transport CCES	2.57391E-9 Item(s)	1.49119E-12	
00.00%	CO2 purification, cryogenic distillation column, transport CCES	5.84980E-11 Item(s)	1.46917E-12	
00.00%	CO2 purification, refrigerant dryer, transport CCES	5.84980E-11 Item(s)	1.26715E-12	
00.00%	CO2 purification, CO2 condenser, transport CCES	5.84980E-11 Item(s)	8.37594E-13	
00.00%	heat exchanger 3, transport CCES	5.84980E-11 Item(s)	6.21548E-13	
00.00%	CO2 purification, CO2 compressor, transport CCES	5.84980E-11 Item(s)	3.33316E-13	
00.00%	market for electricity, medium voltage | electricity, medium voltage | Cutoff, U - PL	6.09000E-6 MJ	2.67964E-13	
00.00%	concrete C30/37, pressure dams, with CEM III/A, transport CCES	1.18107E-8 m3	2.64809E-13	
00.00%	CO2 purification, adsorption dryer, transport CCES	5.84980E-11 Item(s)	2.14663E-13	
00.00%	CO2 purification, carbon filter, transport CCES	1.16996E-10 Item(s)	9.81177E-14	
00.00%	CO2 purification, filter separator, transport CCES - PL	1.16996E-10 Item(s)	7.82515E-14	
00.00%	CO2 purification, liquid CO2 pump, transport CCES	5.84980E-11 Item(s)	6.91493E-14	
00.00%	concrete, C20/25, for CO2 slabs, with cement II/A, transport CCES	3.33439E-9 m3	6.46239E-14	
00.00%	treatment of wastewater, average, wastewater treatment | wastewater, average | Cutoff, U...	1.44228E-8 m3	2.64110E-14	1.10126E-14
00.00%	reinforcement, for CO2 slabs, transport HESS	5.84980E-11 Item(s)	1.76037E-14	
00.00%	market for tap water | tap water | Cutoff, U - RER without CH	1.44228E-5 kg	1.64890E-15	
00.03%	hydropower plant construction, in mine-shaft HESS - PL	5.84980E-11 Item(s)	6.83172E-11	
00.01%	energy router construction HESS	5.84980E-11 Item(s)	3.23858E-11	

Fig. 32. Contribution of HESS PSH-CCES facility construction stage to Ozone depletion impact category – CCES construction

Impact category: Ozone depletion

Contribution	Process	Required amount	Total result [kg CFC-11-Eq]	Direct contribution [kg CFC-11...
100.00%	electricity production, high voltage, HESS PHS_CCES - PL	3.60000 MJ	2.50599E-7	
99.81%	market for electricity, high voltage | electricity, high voltage | Cutoff, U - PL	5.76190 MJ	2.50118E-7	9.03354E-8
00.19%	HESS PHS CCES facility construction, in mine shafts - PL	5.84980E-11 Item(s)	4.80712E-10	
00.15%	compressed CO2 energy storage plant construction, in mine shaft HESS - PL	5.84980E-11 Item(s)	3.80009E-10	
00.03%	hydropower plant construction, in mine-shaft HESS - PL	5.84980E-11 Item(s)	6.83172E-11	
00.02%	upper reservoir construction PHS - PL	5.84980E-11 Item(s)	3.94844E-11	
00.01%	Sika seals, transport HESS PHS	1.42244E-6 kg	1.57724E-11	
00.00%	penstock, for PHS, transport	5.84980E-11 Item(s)	1.10607E-11	
00.00%	market for electricity, medium voltage | electricity, medium voltage | Cutoff, U - PL	1.16645E-5 MJ	5.13246E-13	
00.00%	upper technical platform, transport PHS	5.84980E-11 Item(s)	4.36073E-13	
00.00%	concrete C30/37, for water dams, with CEM III/A, transport PHS	1.52095E-8 m3	3.47310E-13	
00.00%	market for wastewater, average | wastewater, average | Cutoff, U - RER without CH	1.53223E-7 m3	2.47585E-13	
00.00%	reinforcement, for concrete slab/platform, transport HESS - PL	5.84980E-11 Item(s)	2.23873E-13	
00.00%	shut-off valve, transported PHS	5.84980E-11 Item(s)	1.60679E-13	
00.00%	control cabinet, transport PHS_A-CAES	5.84980E-11 Item(s)	3.63373E-14	
00.00%	hydraulic drive unit, transport PHS	5.84980E-11 Item(s)	3.29461E-14	
00.00%	market for tap water | tap water | Cutoff, U - RER without CH	1.53223E-5 kg	1.75173E-15	
00.01%	energy router construction HESS	5.84980E-11 Item(s)	3.23858E-11	
00.01%	energy router components, transported HESS	5.84980E-11 Item(s)	3.23841E-11	
00.00%	concrete, C20/25, for router slab, with cement II/A, transport CCES	9.18419E-11 m3	1.78116E-15	

Fig. 33. Contribution of HESS PSH-CCES facility construction stage to Ozone depletion impact category – PSH and router construction

Impact category: Particulate matter formation

Contribution	Process	Required amount	Total result [kg PM2.5-Eq]	Direct contribution [kg PM2.5-...
100.00%	electricity production, high voltage, HESS PHS_CCES - PL	3.60000 MJ	0.00257	
99.89%	market for electricity, high voltage | electricity, high voltage | Cutoff, U - PL	5.76190 MJ	0.00257	
00.11%	HESS PHS CCES facility construction, in mine shafts - PL	5.84980E-11 Item(s)	2.95375E-6	
00.09%	compressed CO2 energy storage plant construction, in mine shaft HESS - PL	5.84980E-11 Item(s)	2.38665E-6	
00.04%	Therminol VP1, transport	2.86640E-5 kg	1.02312E-6	
00.03%	high pressure tanks, transport CCES	3.50988E-9 Item(s)	7.67635E-7	
00.01%	compressor 10.06 MW, transport CCES	5.84980E-11 Item(s)	1.77519E-7	
00.00%	expander 10.84 MW, transport CCES	5.84980E-11 Item(s)	1.05813E-7	
00.00%	heat exchanger 1, transport CCES	1.75494E-10 Item(s)	6.03322E-8	
00.00%	heat exchanger 2, transport CCES	5.84980E-11 Item(s)	4.45102E-8	
00.00%	TES tanks, transport CCES	1.16996E-10 Item(s)	4.40157E-8	
00.00%	CO2 purification, CO2 tank, transport CCES	1.16996E-10 Item(s)	3.83544E-8	
00.00%	market for carbon dioxide, liquid | carbon dioxide, liquid | Cutoff, U - RER	4.19922E-5 kg	2.23186E-8	
00.00%	reinforcement, for shaft plug, transported CCES	5.84980E-11 Item(s)	1.98454E-8	
00.00%	concrete C30/37, shaft plug, with CEM III/A, transported CCES	7.44095E-8 m3	1.60667E-8	
00.00%	steel anchors for shaft plug, transport CCES	2.57391E-9 Item(s)	1.12715E-8	
00.00%	CO2 purification, cryogenic distillation column, transport CCES	5.84980E-11 Item(s)	1.08244E-8	
00.00%	Sika seals, transport CCES	1.53005E-6 kg	8.12706E-9	
00.00%	basalt, transport HESS CCES - PL	0.00014 kg	7.72187E-9	
00.00%	heat exchanger 3, transport CCES	5.84980E-11 Item(s)	7.59037E-9	
00.00%	CO2 purification, refrigerant dryer, transport CCES	5.84980E-11 Item(s)	5.13060E-9	
00.00%	CO2 purification, CO2 compressor, transport CCES	5.84980E-11 Item(s)	3.66098E-9	
00.00%	market for electricity, medium voltage | electricity, medium voltage | Cutoff, U - PL	6.09000E-6 MJ	2.74716E-9	
00.00%	concrete C30/37, pressure dams, with CEM III/A, transport CCES	1.18107E-8 m3	2.52232E-9	
00.00%	CO2 purification, CO2 condenser, transport CCES	5.84980E-11 Item(s)	2.38186E-9	
00.00%	CO2 purification, adsorption dryer, transport CCES	5.84980E-11 Item(s)	1.93199E-9	
00.00%	CO2 purification, carbon filter, transport CCES	1.16996E-10 Item(s)	9.59111E-10	
00.00%	CO2 purification, filter separator, transport CCES - PL	1.16996E-10 Item(s)	8.90234E-10	
00.00%	concrete, C20/25, for CO2 slabs, with cement II/A, transport CCES	3.33439E-9 m3	7.06732E-10	
00.00%	CO2 purification, liquid CO2 pump, transport CCES	5.84980E-11 Item(s)	4.60085E-10	
00.00%	reinforcement, for CO2 slabs, transport HESS	5.84980E-11 Item(s)	1.74281E-10	
00.00%	market for tap water | tap water | Cutoff, U - RER without CH	1.44228E-5 kg	1.44479E-11	
00.00%	treatment of wastewater, average, wastewater treatment | wastewater, average | Cutoff, U...	1.44228E-8 m3	5.48400E-12	3.51595E-13
00.02%	hydropower plant construction, in mine-shaft HESS - PL	5.84980E-11 Item(s)	4.13552E-7	
00.01%	energy router construction HESS	5.84980E-11 Item(s)	1.53548E-7	

Fig. 34. Contribution of HESS PSH-CCES facility construction stage to Particulate matter formation impact category – CCES construction

Impact category: Particulate matter formation

Contribution	Process	Required amount	Total result [kg PM2.5-Eq]	Direct contribution [kg PM2.5-...
100.00%	electricity production, high voltage, HESS PHS_CCES - PL	3.60000 MJ	0.00257	
99.89%	market for electricity, high voltage | electricity, high voltage | Cutoff, U - PL	5.76190 MJ	0.00257	
00.11%	HESS PHS CCES facility construction, in mine shafts - PL	5.84980E-11 Item(s)	2.95375E-6	
00.09%	compressed CO2 energy storage plant construction, in mine shaft HESS - PL	5.84980E-11 Item(s)	2.38665E-6	
00.02%	hydropower plant construction, in mine-shaft HESS - PL	5.84980E-11 Item(s)	4.13552E-7	
00.01%	upper reservoir construction PHS - PL	5.84980E-11 Item(s)	3.04454E-7	
00.00%	penstock, for PHS, transport	5.84980E-11 Item(s)	8.70446E-8	
00.00%	Sika seals, transport HESS PHS	1.42244E-6 kg	6.55581E-9	
00.00%	market for electricity, medium voltage | electricity, medium voltage | Cutoff, U - PL	1.16645E-5 MJ	5.26179E-9	
00.00%	upper technical platform, transport PHS	5.84980E-11 Item(s)	3.41997E-9	
00.00%	concrete C30/37, for water dams, with CEM III/A, transport PHS	1.52095E-8 m3	3.28407E-9	
00.00%	reinforcement, for concrete slab/platform, transport HESS - PL	5.84980E-11 Item(s)	2.21640E-9	
00.00%	shut-off valve, transported PHS	5.84980E-11 Item(s)	5.92798E-10	
00.00%	hydraulic drive unit, transport PHS	5.84980E-11 Item(s)	3.85176E-10	
00.00%	control cabinet, transport PHS_A-CAES	5.84980E-11 Item(s)	2.49725E-10	
00.00%	market for wastewater, average | wastewater, average | Cutoff, U - RER without CH	1.53223E-7 m3	7.22914E-11	
00.00%	market for tap water | tap water | Cutoff, U - RER without CH	1.53223E-5 kg	1.53489E-11	
00.01%	energy router construction HESS	5.84980E-11 Item(s)	1.53548E-7	
00.01%	energy router components, transported HESS	5.84980E-11 Item(s)	1.53528E-7	
00.00%	concrete, C20/25, for router slab, with cement II/A, transport CCES	9.18419E-11 m3	1.94717E-11	

Fig. 35. Contribution of HESS PSH-CCES facility construction stage to Particulate matter formation impact category – PSH and router construction

Impact category: Photochemical oxidant formation: human health

Contribution	Process	Required amount	Total result [kg NOx-Eq]	Direct contribution [kg NOx-Eq]
100.00%	electricity production, high voltage, HESS PHS_CCES - PL	3.60000 MJ	0.00270	
99.77%	market for electricity, high voltage | electricity, high voltage | Cutoff, U - PL	5.76190 MJ	0.00269	
00.23%	HESS PHS CCES facility construction, in mine shafts - PL	5.84980E-11 Item(s)	6.11834E-6	
00.20%	compressed CO2 energy storage plant construction, in mine shaft HESS - PL	5.84980E-11 Item(s)	5.30773E-6	
00.14%	Therminol VP1, transport	2.86640E-5 kg	3.77185E-6	
00.03%	high pressure tanks, transport CCES	3.50988E-9 Item(s)	8.95065E-7	
00.01%	compressor 10.06 MW, transport CCES	5.84980E-11 Item(s)	1.66647E-7	
00.00%	expander 10.84 MW, transport CCES	5.84980E-11 Item(s)	9.80177E-8	
00.00%	TES tanks, transport CCES	1.16996E-10 Item(s)	6.24982E-8	
00.00%	heat exchanger 1, transport CCES	1.75494E-10 Item(s)	4.68947E-8	
00.00%	CO2 purification, CO2 tank, transport CCES	1.16996E-10 Item(s)	3.99533E-8	
00.00%	heat exchanger 2, transport CCES	5.84980E-11 Item(s)	3.41999E-8	
00.00%	concrete C30/37, shaft plug, with CEM III/A, transported CCES	7.44095E-8 m3	3.40280E-8	
00.00%	market for carbon dioxide, liquid | carbon dioxide, liquid | Cutoff, U - RER	4.19922E-5 kg	3.13800E-8	
00.00%	reinforcement, for shaft plug, transported CCES	5.84980E-11 Item(s)	3.10917E-8	
00.00%	basalt, transport HESS CCES - PL	0.00014 kg	2.58273E-8	
00.00%	steel anchors for shaft plug, transport CCES	2.57391E-9 Item(s)	1.65476E-8	
00.00%	Sika seals, transport CCES	1.53005E-6 kg	1.27356E-8	
00.00%	CO2 purification, cryogenic distillation column, transport CCES	5.84980E-11 Item(s)	9.75330E-9	
00.00%	CO2 purification, refrigerant dryer, transport CCES	5.84980E-11 Item(s)	6.15256E-9	
00.00%	heat exchanger 3, transport CCES	5.84980E-11 Item(s)	5.94296E-9	
00.00%	concrete C30/37, pressure dams, with CEM III/A, transport CCES	1.18107E-8 m3	5.25922E-9	
00.00%	CO2 purification, CO2 compressor, transport CCES	5.84980E-11 Item(s)	3.07084E-9	
00.00%	market for electricity, medium voltage | electricity, medium voltage | Cutoff, U - PL	6.09000E-6 MJ	2.87423E-9	
00.00%	CO2 purification, CO2 condenser, transport CCES	5.84980E-11 Item(s)	1.94317E-9	
00.00%	CO2 purification, adsorption dryer, transport CCES	5.84980E-11 Item(s)	1.84266E-9	
00.00%	concrete, C20/25, for CO2 slabs, with cement II/A, transport CCES	3.33439E-9 m3	1.79369E-9	
00.00%	CO2 purification, carbon filter, transport CCES	1.16996E-10 Item(s)	8.40358E-10	
00.00%	CO2 purification, filter separator, transport CCES - PL	1.16996E-10 Item(s)	7.10535E-10	
00.00%	CO2 purification, liquid CO2 pump, transport CCES	5.84980E-11 Item(s)	5.14113E-10	
00.00%	reinforcement, for CO2 slabs, transport HESS	5.84980E-11 Item(s)	2.73044E-10	
00.00%	market for tap water | tap water | Cutoff, U - RER without CH	1.44228E-5 kg	1.73077E-11	
00.00%	treatment of wastewater, average, wastewater treatment | wastewater, average | Cutoff, U...	1.44228E-8 m3	1.18640E-11	1.84452E-12
00.03%	hydropower plant construction, in mine-shaft HESS - PL	5.84980E-11 Item(s)	6.95751E-7	
00.00%	energy router construction HESS	5.84980E-11 Item(s)	1.14854E-7	

Fig. 36. Contribution of HESS PSH-CCES facility construction stage to Photochemical oxidant formation: human health impact category – CCES construction

Impact category: Photochemical oxidant formation: human health

Contribution	Process	Required amount	Total result [kg NOx-Eq]	Direct contribution [kg NOx-Eq]
100.00%	electricity production, high voltage, HESS PHS_CCES - PL	3.60000 MJ	0.00270	
99.77%	market for electricity, high voltage | electricity, high voltage | Cutoff, U - PL	5.76190 MJ	0.00269	
00.23%	HESS PHS CCES facility construction, in mine shafts - PL	5.84980E-11 Item(s)	6.11834E-6	
00.20%	compressed CO2 energy storage plant construction, in mine shaft HESS - PL	5.84980E-11 Item(s)	5.30773E-6	
00.03%	hydropower plant construction, in mine-shaft HESS - PL	5.84980E-11 Item(s)	6.95751E-7	
00.02%	upper reservoir construction PHS - PL	5.84980E-11 Item(s)	5.36806E-7	
00.00%	penstock, for PHS, transport	5.84980E-11 Item(s)	1.25858E-7	
00.00%	Sika seals, transport HESS PHS	1.42244E-6 kg	1.01772E-8	
00.00%	concrete C30/37, for water dams, with CEM III/A, transport PHS	1.52095E-8 m3	6.95545E-9	
00.00%	market for electricity, medium voltage | electricity, medium voltage | Cutoff, U - PL	1.16645E-5 MJ	5.50518E-9	
00.00%	upper technical platform, transport PHS	5.84980E-11 Item(s)	4.98404E-9	
00.00%	reinforcement, for concrete slab/platform, transport HESS - PL	5.84980E-11 Item(s)	3.47241E-9	
00.00%	shut-off valve, transported PHS	5.84980E-11 Item(s)	1.09729E-9	
00.00%	hydraulic drive unit, transport PHS	5.84980E-11 Item(s)	3.87130E-10	
00.00%	control cabinet, transport PHS_A-CAES	5.84980E-11 Item(s)	3.44765E-10	
00.00%	market for wastewater, average | wastewater, average | Cutoff, U - RER without CH	1.53223E-7 m3	1.44755E-10	
00.00%	market for tap water | tap water | Cutoff, U - RER without CH	1.53223E-5 kg	1.83870E-11	
00.00%	energy router construction HESS	5.84980E-11 Item(s)	1.14854E-7	
00.00%	energy router components, transported HESS	5.84980E-11 Item(s)	1.14804E-7	
00.00%	concrete, C20/25, for router slab, with cement II/A, transport CCES	9.18419E-11 m3	4.94295E-11	

Fig. 37. Contribution of HESS PSH-CCES facility construction stage to Photochemical oxidant formation: human health impact category – PSH and router construction

Impact category: Photochemical oxidant formation: terrestrial ecosystems

Contribution	Process	Required amount	Total result [kg NOx-Eq]	Direct contribution [kg NOx-Eq]
100.00%	electricity production, high voltage, HESS PHS_CCES - PL	3.60000 MJ	0.00271	
99.77%	market for electricity, high voltage | electricity, high voltage | Cutoff, U - PL	5.76190 MJ	0.00271	
00.23%	HESS PHS CCES facility construction, in mine shafts - PL	5.84980E-11 Item(s)	6.24827E-6	
00.20%	compressed CO2 energy storage plant construction, in mine shaft HESS - PL	5.84980E-11 Item(s)	5.41073E-6	
00.14%	Therminol VP1, transport	2.86640E-5 kg	3.82503E-6	
00.03%	high pressure tanks, transport CCES	3.50988E-9 Item(s)	9.22218E-7	
00.01%	compressor 10.06 MW, transport CCES	5.84980E-11 Item(s)	1.72236E-7	
00.00%	expander 10.84 MW, transport CCES	5.84980E-11 Item(s)	1.01260E-7	
00.00%	TES tanks, transport CCES	1.16996E-10 Item(s)	6.51191E-8	
00.00%	heat exchanger 1, transport CCES	1.75494E-10 Item(s)	4.84816E-8	
00.00%	CO2 purification, CO2 tank, transport CCES	1.16996E-10 Item(s)	4.11659E-8	
00.00%	heat exchanger 2, transport CCES	5.84980E-11 Item(s)	3.53537E-8	
00.00%	concrete C30/37, shaft plug, with CEM III/A, transported CCES	7.44095E-8 m3	3.49151E-8	
00.00%	market for carbon dioxide, liquid | carbon dioxide, liquid | Cutoff, U - RER	4.19922E-5 kg	3.28979E-8	
00.00%	reinforcement, for shaft plug, transported CCES	5.84980E-11 Item(s)	3.21553E-8	
00.00%	basalt, transport HESS CCES - PL	0.00014 kg	2.66873E-8	
00.00%	steel anchors for shaft plug, transport CCES	2.57391E-9 Item(s)	1.71774E-8	
00.00%	Sika seals, transport CCES	1.53005E-6 kg	1.37687E-8	
00.00%	CO2 purification, cryogenic distillation column, transport CCES	5.84980E-11 Item(s)	1.01409E-8	
00.00%	CO2 purification, refrigerant dryer, transport CCES	5.84980E-11 Item(s)	6.32682E-9	
00.00%	heat exchanger 3, transport CCES	5.84980E-11 Item(s)	6.14534E-9	
00.00%	concrete C30/37, pressure dams, with CEM III/A, transport CCES	1.18107E-8 m3	5.39527E-9	
00.00%	CO2 purification, CO2 compressor, transport CCES	5.84980E-11 Item(s)	3.16857E-9	
00.00%	market for electricity, medium voltage | electricity, medium voltage | Cutoff, U - PL	6.09000E-6 MJ	2.89041E-9	
00.00%	CO2 purification, CO2 condenser, transport CCES	5.84980E-11 Item(s)	2.00934E-9	
00.00%	CO2 purification, adsorption dryer, transport CCES	5.84980E-11 Item(s)	1.90970E-9	
00.00%	concrete, C20/25, for CO2 slabs, with cement II/A, transport CCES	3.33439E-9 m3	1.82932E-9	
00.00%	CO2 purification, carbon filter, transport CCES	1.16996E-10 Item(s)	8.71363E-10	
00.00%	CO2 purification, filter separator, transport CCES - PL	1.16996E-10 Item(s)	7.36019E-10	
00.00%	CO2 purification, liquid CO2 pump, transport CCES	5.84980E-11 Item(s)	5.28115E-10	
00.00%	reinforcement, for CO2 slabs, transport HESS	5.84980E-11 Item(s)	2.82385E-10	
00.00%	market for tap water | tap water | Cutoff, U - RER without CH	1.44228E-5 kg	1.75485E-11	
00.00%	treatment of wastewater, average, wastewater treatment | wastewater, average | Cutoff, U...	1.44228E-8 m3	1.22094E-11	1.84452E-12
00.03%	hydropower plant construction, in mine-shaft HESS - PL	5.84980E-11 Item(s)	7.18205E-7	
00.00%	energy router construction HESS	5.84980E-11 Item(s)	1.19329E-7	

Fig. 38. Contribution of HESS PSH-CCES facility construction stage to Photochemical oxidant formation: terrestrial ecosystems impact category – CCES construction

Impact category: Energy resources: non-renewable, fossil

Contribution	Process	Required amount	Total result [kg oil-Eq]	Direct contribution [kg oil-Eq]
ation, liquid CO2 pump, transport CCES				
100.00%	electricity production, high voltage, HESS PHS_CCES - PL	3.60000 MJ	0.37092	
99.92%	market for electricity, high voltage | electricity, high voltage | Cutoff, U - PL	5.76190 MJ	0.37061	
00.08%	HESS PHS CCES facility construction, in mine shafts - PL	5.84980E-11 Item(s)	0.00031	
00.06%	compressed CO2 energy storage plant construction, in mine shaft HESS - PL	5.84980E-11 Item(s)	0.00023	
00.02%	hydropower plant construction, in mine-shaft HESS - PL	5.84980E-11 Item(s)	7.03930E-5	
00.01%	upper reservoir construction PHS - PL	5.84980E-11 Item(s)	5.08141E-5	
00.00%	penstock, for PHS, transport	5.84980E-11 Item(s)	1.54904E-5	
00.00%	Sika seals, transport HESS PHS	1.42244E-6 kg	1.66749E-6	
00.00%	market for electricity, medium voltage | electricity, medium voltage | Cutoff, U - PL	1.16645E-5 MJ	7.56041E-7	
00.00%	upper technical platform, transport PHS	5.84980E-11 Item(s)	6.10609E-7	
00.00%	concrete C30/37, for water dams, with CEM III/A, transport PHS	1.52095E-8 m3	4.57254E-7	
00.00%	reinforcement, for concrete slab/platform, transport HESS - PL	5.84980E-11 Item(s)	3.57466E-7	
00.00%	shut-off valve, transported PHS	5.84980E-11 Item(s)	1.34019E-7	
00.00%	control cabinet, transport PHS_A-CAES	5.84980E-11 Item(s)	5.04400E-8	
00.00%	hydraulic drive unit, transport PHS	5.84980E-11 Item(s)	4.08673E-8	
00.00%	market for wastewater, average | wastewater, average | Cutoff, U - RER without CH	1.53223E-7 m3	1.20254E-8	
00.00%	market for tap water | tap water | Cutoff, U - RER without CH	1.53223E-5 kg	2.21277E-9	
00.00%	energy router construction HESS	5.84980E-11 Item(s)	9.80687E-6	
00.00%	energy router components, transported HESS	5.84980E-11 Item(s)	9.80441E-6	
00.00%	concrete, C20/25, for router slab, with cement II/A, transport CCES	9.18419E-11 m3	2.45761E-9	

Fig. 39. Contribution of HESS PSH-CCES facility construction stage to Photochemical oxidant formation: terrestrial ecosystems impact category – PSH and router construction

Impact category: Water use

Contribution	Process	Required amount	Total result [m3]	Direct contribution [m3]
100.00%	electricity production, high voltage, HESS PHS_CCES - PL	3.60000 MJ	0.00898	
99.87%	market for electricity, high voltage | electricity, high voltage | Cutoff, U - PL	5.76190 MJ	0.00897	
00.13%	HESS PHS CCES facility construction, in mine shafts - PL	5.84980E-11 Item(s)	1.14828E-5	
00.09%	compressed CO2 energy storage plant construction, in mine shaft HESS - PL	5.84980E-11 Item(s)	8.17559E-6	
00.04%	Therminol VP1, transport	2.86640E-5 kg	3.19827E-6	
00.03%	high pressure tanks, transport CCES	3.50988E-9 Item(s)	2.57286E-6	
00.01%	compressor 10.06 MW, transport CCES	5.84980E-11 Item(s)	5.33907E-7	
00.00%	expander 10.84 MW, transport CCES	5.84980E-11 Item(s)	3.10059E-7	
00.00%	concrete C30/37, shaft plug, with CEM III/A, transported CCES	7.44095E-8 m3	2.47973E-7	
00.00%	TES tanks, transport CCES	1.16996E-10 Item(s)	2.44604E-7	
00.00%	heat exchanger 1, transport CCES	1.75494E-10 Item(s)	1.96895E-7	
00.00%	market for carbon dioxide, liquid | carbon dioxide, liquid | Cutoff, U - RER	4.19922E-5 kg	1.93657E-7	
00.00%	heat exchanger 2, transport CCES	5.84980E-11 Item(s)	1.45802E-7	
00.00%	reinforcement, for shaft plug, transported CCES	5.84980E-11 Item(s)	1.35586E-7	
00.00%	CO2 purification, CO2 tank, transport CCES	1.16996E-10 Item(s)	1.05526E-7	
00.00%	steel anchors for shaft plug, transport CCES	2.57391E-9 Item(s)	7.07528E-8	
00.00%	Sika seals, transport CCES	1.53005E-6 kg	4.75653E-8	
00.00%	concrete C30/37, pressure dams, with CEM III/A, transport CCES	1.18107E-8 m3	3.93267E-8	
00.00%	CO2 purification, cryogenic distillation column, transport CCES	5.84980E-11 Item(s)	3.30781E-8	
00.00%	heat exchanger 3, transport CCES	5.84980E-11 Item(s)	2.43481E-8	
00.00%	CO2 purification, refrigerant dryer, transport CCES	5.84980E-11 Item(s)	1.59546E-8	
00.00%	concrete, C20/25, for CO2 slabs, with cement II/A, transport CCES	3.33439E-9 m3	1.13209E-8	
00.00%	basalt, transport HESS CCES - PL	0.00014 kg	1.05490E-8	
00.00%	market for electricity, medium voltage | electricity, medium voltage | Cutoff, U - PL	6.09000E-6 MJ	9.56339E-9	
00.00%	CO2 purification, CO2 compressor, transport CCES	5.84980E-11 Item(s)	8.12769E-9	
00.00%	CO2 purification, adsorption dryer, transport CCES	5.84980E-11 Item(s)	6.48250E-9	
00.00%	CO2 purification, CO2 condenser, transport CCES	5.84980E-11 Item(s)	5.59827E-9	
00.00%	CO2 purification, carbon filter, transport CCES	1.16996E-10 Item(s)	2.65096E-9	
00.00%	CO2 purification, filter separator, transport CCES - PL	1.16996E-10 Item(s)	2.51397E-9	
00.00%	CO2 purification, liquid CO2 pump, transport CCES	5.84980E-11 Item(s)	1.31140E-9	
00.00%	reinforcement, for CO2 slabs, transport HESS	5.84980E-11 Item(s)	1.19071E-9	
00.00%	market for tap water | tap water | Cutoff, U - RER without CH	1.44228E-5 kg	5.69589E-11	
00.00%	treatment of wastewater, average, wastewater treatment | wastewater, average | Cutoff, U...	1.44228E-8 m3	5.54275E-11	3.86473E-12
00.03%	hydropower plant construction, in mine-shaft HESS - PL	5.84980E-11 Item(s)	2.81203E-6	
00.01%	energy router construction HESS	5.84980E-11 Item(s)	4.95147E-7	

Fig. 40. Contribution of HESS PSH-CCES facility construction stage to Water use impact category – CCES construction

Impact category: Water use

Contribution	Process	Required amount	Total result [m3]	Direct contribution [m3]
r energy and auxilliary inputs, metal working machine | energy and auxilliary inputs, metal working machine | Cutoff, U IN - RoW		3.60000 MJ	0.00898	
99.87%	market for electricity, high voltage | electricity, high voltage | Cutoff, U - PL	5.76190 MJ	0.00897	
00.13%	HESS PHS CCES facility construction, in mine shafts - PL	5.84980E-11 Item(s)	1.14828E-5	
00.09%	compressed CO2 energy storage plant construction, in mine shaft HESS - PL	5.84980E-11 Item(s)	8.17559E-6	
00.03%	hydropower plant construction, in mine-shaft HESS - PL	5.84980E-11 Item(s)	2.81203E-6	
00.02%	upper reservoir construction PHS - PL	5.84980E-11 Item(s)	2.12783E-6	
00.01%	penstock, for PHS, transport	5.84980E-11 Item(s)	5.33011E-7	
00.00%	concrete C30/37, for water dams, with CEM III/A, transport PHS	1.52095E-8 m3	5.06862E-8	
00.00%	Sika seals, transport HESS PHS	1.42244E-6 kg	3.81474E-8	
00.00%	upper technical platform, transport PHS	5.84980E-11 Item(s)	2.08753E-8	
00.00%	market for electricity, medium voltage | electricity, medium voltage | Cutoff, U - PL	1.16645E-5 MJ	1.83173E-8	
00.00%	reinforcement, for concrete slab/platform, transport HESS - PL	5.84980E-11 Item(s)	1.51427E-8	
00.00%	shut-off valve, transported PHS	5.84980E-11 Item(s)	5.67186E-9	
00.00%	hydraulic drive unit, transport PHS	5.84980E-11 Item(s)	1.14530E-9	
00.00%	market for wastewater, average | wastewater, average | Cutoff, U - RER without CH	1.53223E-7 m3	6.89177E-10	
00.00%	control cabinet, transport PHS_A-CAES	5.84980E-11 Item(s)	4.45303E-10	
00.00%	market for tap water | tap water | Cutoff, U - RER without CH	1.53223E-5 kg	6.05111E-11	
00.01%	energy router construction HESS	5.84980E-11 Item(s)	4.95147E-7	
00.01%	energy router components, transported HESS	5.84980E-11 Item(s)	4.94835E-7	
00.00%	concrete, C20/25, for router slab, with cement II/A, transport CCES	9.18419E-11 m3	3.11832E-10	

Fig. 41. Contribution of HESS PSH-CCES facility construction stage to Water use impact category – PSH and router construction

Impact category: Acidification: terrestrial

Contribution	Process	Required amount	Total result [kg SO2-Eq]	Direct contribution [kg SO2-Eq]
100.00%	electricity production, high voltage, HESS PHS_A-CAES - PL	3.60000 MJ	0.00732	
99.98%	market for electricity, high voltage | electricity, high voltage | Cutoff, U - PL	5.63400 MJ	0.00732	
00.02%	HESS PHS A-CAES facility construction, in mine shafts - PL	2.59600E-11 Item(s)	1.67844E-6	
00.01%	adiabatic compressed air energy storage plant construction, in mine shaft A-CAES - PL	2.59600E-11 Item(s)	1.08818E-6	
00.01%	compressor 33.28 MW, transported A-CAES	2.59600E-11 Item(s)	4.40238E-7	
00.00%	expander 36 MW, transported A-CAES	2.59600E-11 Item(s)	2.59186E-7	
00.00%	concrete C30/37, for shaft plug, with CEM III/A, transport A-CAES	1.71518E-7 m3	1.00184E-7	
00.00%	market for metal working, average for metal product manufacturing | metal working, av...	5.06791E-6 kg	8.45230E-8	
00.00%	reinforcement, for shaft plug, transported A-CAES	2.59600E-11 Item(s)	7.04446E-8	
00.00%	steel anchors for shaft plug, transport A-CAES	5.71120E-9 Item(s)	5.25235E-8	
00.00%	TES tank, transport A-CAES	2.59600E-11 Item(s)	3.92318E-8	
00.00%	concrete C30/37, for pressure dams, with CEM III/A, transport A-CAES	3.54094E-8 m3	2.06829E-8	
00.00%	Sika seals, transport HESS A-CAES	6.79000E-7 kg	7.27102E-9	
00.00%	market for electricity, medium voltage | electricity, medium voltage | Cutoff, U - PL	4.21751E-6 MJ	5.54461E-9	
00.00%	basalt, transport A-CAES - PL	3.49908E-5 kg	4.46807E-9	
00.00%	PVC coated polyester ventilation duct, transport A-CAES	9.14571E-8 kg	2.26175E-9	
00.00%	service ventilation fan, transport A-CAES	2.59600E-11 Item(s)	1.27553E-9	
00.00%	control cabinet, transport PHS_A-CAES	2.59600E-11 Item(s)	3.24339E-10	
00.00%	market for tap water | tap water | Cutoff, U - RER without CH	6.40049E-6 kg	1.71890E-11	
00.00%	market for wastewater, average | wastewater, average | Cutoff, U - RER without CH	6.40049E-9 m3	7.64074E-12	
00.01%	hydropower plant construction, in mine-shaft HESS - PL	2.59600E-11 Item(s)	4.05756E-7	
00.00%	upper reservoir construction PHS - PL	2.59600E-11 Item(s)	3.01768E-7	
00.00%	penstock, for PHS, transport	2.59600E-11 Item(s)	8.01190E-8	
00.00%	Sika seals, transport HESS PHS	6.31244E-7 kg	6.98509E-9	
00.00%	market for electricity, medium voltage | electricity, medium voltage | Cutoff, U - PL	5.17644E-6 MJ	6.80528E-9	
00.00%	concrete C30/37, for water dams, with CEM III/A, transport PHS	6.74960E-9 m3	3.94246E-9	
00.00%	upper technical platform, transport PHS	2.59600E-11 Item(s)	3.14794E-9	
00.00%	reinforcement, for concrete slab/platform, transport HESS - PL	2.59600E-11 Item(s)	1.58845E-9	
00.00%	shut-off valve, transported PHS	2.59600E-11 Item(s)	5.55108E-10	
00.00%	hydraulic drive unit, transport PHS	2.59600E-11 Item(s)	4.21684E-10	
00.00%	control cabinet, transport PHS_A-CAES	2.59600E-11 Item(s)	3.24339E-10	
00.00%	market for wastewater, average | wastewater, average | Cutoff, U - RER without CH	6.79965E-8 m3	8.11725E-11	
00.00%	market for tap water | tap water | Cutoff, U - RER without CH	6.79965E-6 kg	1.82609E-11	
00.00%	energy router construction HESS	2.59600E-11 Item(s)	1.84503E-7	
00.00%	energy router components, transported HESS	2.59600E-11 Item(s)	1.84480E-7	
00.00%	concrete, C20/25, for router slab, with cement II/A, transport CCES	4.07572E-11 m3	2.33048E-11	

Fig. 42. Contribution of HESS PSH-ACAES facility construction stage to Acidification: terrestrial impact category – ACAES, PSH and router construction

Impact category: Climate change

Contribution	Process	Required amount	Total result [kg CO2-Eq]	Direct contribution [kg CO2-Eq]
100.00%	electricity production, high voltage, HESS PHS_A-CAES - PL	3.60000 MJ	1.52266	
99.97%	market for electricity, high voltage | electricity, high voltage | Cutoff, U - PL	5.63400 MJ	1.52222	0.00239
00.03%	HESS PHS A-CAES facility construction, in mine shafts - PL	2.59600E-11 Item(s)	0.00044	
00.02%	adiabatic compressed air energy storage plant construction, in mine shaft A-CAES - PL	2.59600E-11 Item(s)	0.00029	
00.01%	compressor 33.28 MW, transported A-CAES	2.59600E-11 Item(s)	0.00011	
00.00%	expander 36 MW, transported A-CAES	2.59600E-11 Item(s)	6.11683E-5	
00.00%	concrete C30/37, for shaft plug, with CEM III/A, transport A-CAES	1.71518E-7 m3	3.92720E-5	
00.00%	reinforcement, for shaft plug, transported A-CAES	2.59600E-11 Item(s)	3.00711E-5	
00.00%	steel anchors for shaft plug, transport A-CAES	5.71120E-9 Item(s)	1.89093E-5	
00.00%	market for metal working, average for metal product manufacturing | metal working, av...	5.06791E-6 kg	1.14174E-5	
00.00%	concrete C30/37, for pressure dams, with CEM III/A, transport A-CAES	3.54094E-8 m3	8.10766E-6	
00.00%	TES tank, transport A-CAES	2.59600E-11 Item(s)	7.02332E-6	
00.00%	Sika seals, transport HESS A-CAES	6.79000E-7 kg	2.32681E-6	
00.00%	market for electricity, medium voltage | electricity, medium voltage | Cutoff, U - PL	4.21751E-6 MJ	1.15175E-6	3.46711E-9
00.00%	basalt, transport A-CAES - PL	3.49908E-5 kg	8.51414E-7	
00.00%	PVC coated polyester ventilation duct, transport A-CAES	9.14571E-8 kg	4.80226E-7	
00.00%	service ventilation fan, transport A-CAES	2.59600E-11 Item(s)	1.54726E-7	
00.00%	control cabinet, transport PHS_A-CAES	2.59600E-11 Item(s)	8.00440E-8	
00.00%	market for tap water | tap water | Cutoff, U - RER without CH	6.40049E-6 kg	3.82164E-9	
00.00%	market for wastewater, average | wastewater, average | Cutoff, U - RER without CH	6.40049E-9 m3	2.62478E-9	
00.01%	hydropower plant construction, in mine-shaft HESS - PL	2.59600E-11 Item(s)	0.00014	
00.01%	upper reservoir construction PHS - PL	2.59600E-11 Item(s)	0.00011	
00.00%	penstock, for PHS, transport	2.59600E-11 Item(s)	2.88237E-5	
00.00%	Sika seals, transport HESS PHS	6.31244E-7 kg	2.13745E-6	
00.00%	concrete C30/37, for water dams, with CEM III/A, transport PHS	6.74960E-9 m3	1.54544E-6	
00.00%	market for electricity, medium voltage | electricity, medium voltage | Cutoff, U - PL	5.17644E-6 MJ	1.41362E-6	4.25542E-9
00.00%	upper technical platform, transport PHS	2.59600E-11 Item(s)	1.13384E-6	
00.00%	reinforcement, for concrete slab/platform, transport HESS - PL	2.59600E-11 Item(s)	6.78072E-7	
00.00%	shut-off valve, transported PHS	2.59600E-11 Item(s)	2.43810E-7	
00.00%	control cabinet, transport PHS_A-CAES	2.59600E-11 Item(s)	8.00440E-8	
00.00%	hydraulic drive unit, transport PHS	2.59600E-11 Item(s)	6.10111E-8	
00.00%	market for wastewater, average | wastewater, average | Cutoff, U - RER without CH	6.79965E-8 m3	2.78847E-8	
00.00%	market for tap water | tap water | Cutoff, U - RER without CH	6.79965E-6 kg	4.05997E-9	
00.00%	energy router construction HESS	2.59600E-11 Item(s)	1.50912E-5	
00.00%	energy router components, transported HESS	2.59600E-11 Item(s)	1.50793E-5	
00.00%	concrete, C20/25, for router slab, with cement II/A, transport CCES	4.07572E-11 m3	1.19480E-8	

Fig. 43. Contribution of HESS PSH-ACAES facility construction stage to Climate change impact category – ACAES, PSH and router construction

Impact category: Ecotoxicity: freshwater

Contribution	Process	Required amount	Total result [kg 1,4-DCB-Eq]	Direct contribution [kg 1,4-DCB...
100.00%	electricity production, high voltage, HESS PHS_A-CAES - PL	3.60000 MJ	0.05206	
99.79%	market for electricity, high voltage | electricity, high voltage | Cutoff, U - PL	5.63400 MJ	0.05195	
00.21%	HESS PHS A-CAES facility construction, in mine shafts - PL	2.59600E-11 Item(s)	0.00011	
00.15%	adiabatic compressed air energy storage plant construction, in mine shaft A-CAES - PL	2.59600E-11 Item(s)	8.02640E-5	
00.08%	compressor 33.28 MW, transported A-CAES	2.59600E-11 Item(s)	4.02554E-5	
00.05%	expander 36 MW, transported A-CAES	2.59600E-11 Item(s)	2.41527E-5	
00.01%	market for metal working, average for metal product manufacturing | metal working, av...	5.06791E-6 kg	6.73305E-6	
00.01%	reinforcement, for shaft plug, transported A-CAES	2.59600E-11 Item(s)	3.85618E-6	
00.00%	steel anchors for shaft plug, transport A-CAES	5.71120E-9 Item(s)	2.59355E-6	
00.00%	TES tank, transport A-CAES	2.59600E-11 Item(s)	1.07231E-6	
00.00%	concrete C30/37, for shaft plug, with CEM III/A, transport A-CAES	1.71518E-7 m3	1.02773E-6	
00.00%	concrete C30/37, for pressure dams, with CEM III/A, transport A-CAES	3.54094E-8 m3	2.12173E-7	
00.00%	Sika seals, transport HESS A-CAES	6.79000E-7 kg	1.11959E-7	
00.00%	service ventilation fan, transport A-CAES	2.59600E-11 Item(s)	9.74668E-8	
00.00%	PVC coated polyester ventilation duct, transport A-CAES	9.14571E-8 kg	7.60493E-8	
00.00%	market for electricity, medium voltage | electricity, medium voltage | Cutoff, U - PL	4.21751E-6 MJ	4.36327E-8	
00.00%	basalt, transport A-CAES - PL	3.49908E-5 kg	2.67794E-8	
00.00%	control cabinet, transport PHS_A-CAES	2.59600E-11 Item(s)	4.58835E-9	
00.00%	market for wastewater, average | wastewater, average | Cutoff, U - RER without CH	6.40049E-9 m3	2.76219E-10	3.25565E-11
00.00%	market for tap water | tap water | Cutoff, U - RER without CH	6.40049E-6 kg	1.68327E-10	
00.03%	hydropower plant construction, in mine-shaft HESS - PL	2.59600E-11 Item(s)	1.53636E-5	
00.02%	upper reservoir construction PHS - PL	2.59600E-11 Item(s)	1.09074E-5	
00.01%	penstock, for PHS, transport	2.59600E-11 Item(s)	3.92348E-6	
00.00%	upper technical platform, transport PHS	2.59600E-11 Item(s)	1.53617E-7	
00.00%	Sika seals, transport HESS PHS	6.31244E-7 kg	1.04539E-7	
00.00%	reinforcement, for concrete slab/platform, transport HESS - PL	2.59600E-11 Item(s)	8.69528E-8	
00.00%	shut-off valve, transported PHS	2.59600E-11 Item(s)	5.68168E-8	
00.00%	market for electricity, medium voltage | electricity, medium voltage | Cutoff, U - PL	5.17644E-6 MJ	5.35534E-8	
00.00%	concrete C30/37, for water dams, with CEM III/A, transport PHS	6.74960E-9 m3	4.04433E-8	
00.00%	hydraulic drive unit, transport PHS	2.59600E-11 Item(s)	2.90474E-8	
00.00%	control cabinet, transport PHS_A-CAES	2.59600E-11 Item(s)	4.58835E-9	
00.00%	market for wastewater, average | wastewater, average | Cutoff, U - RER without CH	6.79965E-8 m3	2.93445E-9	3.45869E-10
00.00%	market for tap water | tap water | Cutoff, U - RER without CH	6.79965E-6 kg	1.78825E-10	
00.03%	energy router construction HESS	2.59600E-11 Item(s)	1.49383E-5	
00.03%	energy router components, transported HESS	2.59600E-11 Item(s)	1.49381E-5	
00.00%	concrete, C20/25, for router slab, with cement II/A, transport CCES	4.07572E-11 m3	2.08952E-10	

Fig. 44. Contribution of HESS PSH-ACAES facility construction stage to Ecotoxicity: freshwater impact category – ACAES, PSH and router construction

Impact category: Ecotoxicity: marine

Contribution	Process	Required amount	Total result [kg 1,4-DCB-Eq]	Direct contribution [kg 1,4-DCB...
100.00%	electricity production, high voltage, HESS PHS_A-CAES - PL	3.60000 MJ	0.07167	
99.80%	market for electricity, high voltage | electricity, high voltage | Cutoff, U - PL	5.63400 MJ	0.07153	
00.20%	HESS PHS A-CAES facility construction, in mine shafts - PL	2.59600E-11 Item(s)	0.00014	
00.14%	adiabatic compressed air energy storage plant construction, in mine shaft A-CAES - PL	2.59600E-11 Item(s)	0.00010	
00.07%	compressor 33.28 MW, transported A-CAES	2.59600E-11 Item(s)	5.16057E-5	
00.04%	expander 36 MW, transported A-CAES	2.59600E-11 Item(s)	3.09660E-5	
00.01%	market for metal working, average for metal product manufacturing | metal working, av...	5.06791E-6 kg	8.49410E-6	
00.01%	reinforcement, for shaft plug, transported A-CAES	2.59600E-11 Item(s)	5.20352E-6	
00.00%	steel anchors for shaft plug, transport A-CAES	5.71120E-9 Item(s)	3.40503E-6	
00.00%	TES tank, transport A-CAES	2.59600E-11 Item(s)	1.45923E-6	
00.00%	concrete C30/37, for shaft plug, with CEM III/A, transport A-CAES	1.71518E-7 m3	1.38140E-6	
00.00%	concrete C30/37, for pressure dams, with CEM III/A, transport A-CAES	3.54094E-8 m3	2.85190E-7	
00.00%	Sika seals, transport HESS A-CAES	6.79000E-7 kg	1.45956E-7	
00.00%	service ventilation fan, transport A-CAES	2.59600E-11 Item(s)	1.23128E-7	
00.00%	PVC coated polyester ventilation duct, transport A-CAES	9.14571E-8 kg	1.01844E-7	
00.00%	market for electricity, medium voltage | electricity, medium voltage | Cutoff, U - PL	4.21751E-6 MJ	5.94005E-8	
00.00%	basalt, transport A-CAES - PL	3.49908E-5 kg	3.92515E-8	
00.00%	control cabinet, transport PHS_A-CAES	2.59600E-11 Item(s)	5.97782E-9	
00.00%	market for wastewater, average | wastewater, average | Cutoff, U - RER without CH	6.40049E-9 m3	3.68047E-10	4.42611E-11
00.00%	market for tap water | tap water | Cutoff, U - RER without CH	6.40049E-6 kg	2.28861E-10	
00.03%	hydropower plant construction, in mine-shaft HESS - PL	2.59600E-11 Item(s)	2.02107E-5	
00.02%	upper reservoir construction PHS - PL	2.59600E-11 Item(s)	1.43561E-5	
00.01%	penstock, for PHS, transport	2.59600E-11 Item(s)	5.15025E-6	
00.00%	upper technical platform, transport PHS	2.59600E-11 Item(s)	2.01705E-7	
00.00%	Sika seals, transport HESS PHS	6.31244E-7 kg	1.37191E-7	
00.00%	reinforcement, for concrete slab/platform, transport HESS - PL	2.59600E-11 Item(s)	1.17334E-7	
00.00%	shut-off valve, transported PHS	2.59600E-11 Item(s)	7.38022E-8	
00.00%	market for electricity, medium voltage | electricity, medium voltage | Cutoff, U - PL	5.17644E-6 MJ	7.29062E-8	
00.00%	concrete C30/37, for water dams, with CEM III/A, transport PHS	6.74960E-9 m3	5.43612E-8	
00.00%	hydraulic drive unit, transport PHS	2.59600E-11 Item(s)	3.68796E-8	
00.00%	control cabinet, transport PHS_A-CAES	2.59600E-11 Item(s)	5.97782E-9	
00.00%	market for wastewater, average | wastewater, average | Cutoff, U - RER without CH	6.79965E-8 m3	3.91000E-9	4.70214E-10
00.00%	market for tap water | tap water | Cutoff, U - RER without CH	6.79965E-6 kg	2.43134E-10	
00.03%	energy router construction HESS	2.59600E-11 Item(s)	1.87823E-5	
00.03%	energy router components, transported HESS	2.59600E-11 Item(s)	1.87820E-5	
00.00%	concrete, C20/25, for router slab, with cement II/A, transport CCES	4.07572E-11 m3	2.81861E-10	

Fig. 45. Contribution of HESS PSH-ACAES facility construction stage to Ecotoxicity: marine impact category – ACAES, PSH and router construction

Impact category: Ecotoxicity: terrestrial

Contribution	Process	Required amount	Total result [kg 1,4-DCB-Eq]	Direct contribution [kg 1,4-DCB...
100.00%	electricity production, high voltage, HESS PHS_A-CAES - PL	3.60000 MJ	1.01773	
99.62%	market for electricity, high voltage | electricity, high voltage | Cutoff, U - PL	5.63400 MJ	1.01387	
00.38%	HESS PHS A-CAES facility construction, in mine shafts - PL	2.59600E-11 Item(s)	0.00386	
00.31%	adiabatic compressed air energy storage plant construction, in mine shaft A-CAES - PL	2.59600E-11 Item(s)	0.00314	
00.16%	compressor 33.28 MW, transported A-CAES	2.59600E-11 Item(s)	0.00166	
00.10%	expander 36 MW, transported A-CAES	2.59600E-11 Item(s)	0.00101	
00.02%	market for metal working, average for metal product manufacturing | metal working, av...	5.06791E-6 kg	0.00018	
00.01%	concrete C30/37, for shaft plug, with CEM III/A, transport A-CAES	1.71518E-7 m3	9.22853E-5	
00.01%	reinforcement, for shaft plug, transported A-CAES	2.59600E-11 Item(s)	9.09976E-5	
00.00%	steel anchors for shaft plug, transport A-CAES	5.71120E-9 Item(s)	4.46343E-5	
00.00%	TES tank, transport A-CAES	2.59600E-11 Item(s)	2.29197E-5	
00.00%	concrete C30/37, for pressure dams, with CEM III/A, transport A-CAES	3.54094E-8 m3	1.90529E-5	
00.00%	basalt, transport A-CAES - PL	3.49908E-5 kg	8.12432E-6	
00.00%	Sika seals, transport HESS A-CAES	6.79000E-7 kg	5.33674E-6	
00.00%	service ventilation fan, transport A-CAES	2.59600E-11 Item(s)	2.36944E-6	
00.00%	PVC coated polyester ventilation duct, transport A-CAES	9.14571E-8 kg	1.61504E-6	
00.00%	market for electricity, medium voltage | electricity, medium voltage | Cutoff, U - PL	4.21751E-6 MJ	8.26867E-7	
00.00%	control cabinet, transport PHS_A-CAES	2.59600E-11 Item(s)	1.56699E-7	
00.00%	market for wastewater, average | wastewater, average | Cutoff, U - RER without CH	6.40049E-9 m3	9.54242E-9	1.99065E-27
00.00%	market for tap water | tap water | Cutoff, U - RER without CH	6.40049E-6 kg	6.48099E-9	
00.04%	energy router construction HESS	2.59600E-11 Item(s)	0.00040	
00.04%	energy router components, transported HESS	2.59600E-11 Item(s)	0.00040	
00.00%	concrete, C20/25, for router slab, with cement II/A, transport CCES	4.07572E-11 m3	1.93575E-8	
00.03%	hydropower plant construction, in mine-shaft HESS - PL	2.59600E-11 Item(s)	0.00032	
00.02%	upper reservoir construction PHS - PL	2.59600E-11 Item(s)	0.00024	
00.01%	penstock, for PHS, transport	2.59600E-11 Item(s)	6.47547E-5	
00.00%	Sika seals, transport HESS PHS	6.31244E-7 kg	6.20683E-6	
00.00%	concrete C30/37, for water dams, with CEM III/A, transport PHS	6.74960E-9 m3	3.63160E-6	
00.00%	upper technical platform, transport PHS	2.59600E-11 Item(s)	2.64404E-6	
00.00%	reinforcement, for concrete slab/platform, transport HESS - PL	2.59600E-11 Item(s)	2.05190E-6	
00.00%	shut-off valve, transported PHS	2.59600E-11 Item(s)	1.04542E-6	
00.00%	market for electricity, medium voltage | electricity, medium voltage | Cutoff, U - PL	5.17644E-6 MJ	1.01487E-6	
00.00%	hydraulic drive unit, transport PHS	2.59600E-11 Item(s)	7.71169E-7	
00.00%	control cabinet, transport PHS_A-CAES	2.59600E-11 Item(s)	1.56699E-7	
00.00%	market for wastewater, average | wastewater, average | Cutoff, U - RER without CH	6.79965E-8 m3	1.01375E-7	2.11479E-26
00.00%	market for tap water | tap water | Cutoff, U - RER without CH	6.79965E-6 kg	6.88517E-9	

Fig. 46. Contribution of HESS PSH-ACAES facility construction stage to Ecotoxicity: terrestrial impact category – ACAES, PSH and router construction

Impact category: Energy resources: non-renewable, fossil

Contribution	Process	Required amount	Total result [kg oil-Eq]	Direct contribution [kg oil-Eq]
100.00%	electricity production, high voltage, HESS PHS_A-CAES - PL	3.60000 MJ	0.36249	
99.97%	market for electricity, high voltage | electricity, high voltage | Cutoff, U - PL	5.63400 MJ	0.36239	
00.03%	HESS PHS A-CAES facility construction, in mine shafts - PL	2.59600E-11 Item(s)	9.95985E-5	
00.02%	adiabatic compressed air energy storage plant construction, in mine shaft A-CAES - PL	2.59600E-11 Item(s)	6.40077E-5	
00.01%	compressor 33.28 MW, transported A-CAES	2.59600E-11 Item(s)	2.54198E-5	
00.00%	expander 36 MW, transported A-CAES	2.59600E-11 Item(s)	1.47698E-5	
00.00%	reinforcement, for shaft plug, transported A-CAES	2.59600E-11 Item(s)	7.03514E-6	
00.00%	concrete C30/37, for shaft plug, with CEM III/A, transport A-CAES	1.71518E-7 m3	5.15648E-6	
00.00%	steel anchors for shaft plug, transport A-CAES	5.71120E-9 Item(s)	4.50371E-6	
00.00%	market for metal working, average for metal product manufacturing | metal working, av...	5.06791E-6 kg	2.81697E-6	
00.00%	TES tank, transport A-CAES	2.59600E-11 Item(s)	1.67304E-6	
00.00%	concrete C30/37, for pressure dams, with CEM III/A, transport A-CAES	3.54094E-8 m3	1.06456E-6	
00.00%	Sika seals, transport HESS A-CAES	6.79000E-7 kg	8.32657E-7	
00.00%	market for electricity, medium voltage | electricity, medium voltage | Cutoff, U - PL	4.21751E-6 MJ	2.73360E-7	
00.00%	basalt, transport A-CAES - PL	3.49908E-5 kg	2.49413E-7	
00.00%	PVC coated polyester ventilation duct, transport A-CAES	9.14571E-8 kg	1.51557E-7	
00.00%	service ventilation fan, transport A-CAES	2.59600E-11 Item(s)	3.74314E-8	
00.00%	control cabinet, transport PHS_A-CAES	2.59600E-11 Item(s)	2.23840E-8	
00.00%	market for tap water | tap water | Cutoff, U - RER without CH	6.40049E-6 kg	9.24329E-10	
00.00%	market for wastewater, average | wastewater, average | Cutoff, U - RER without CH	6.40049E-9 m3	5.02330E-10	
00.01%	hydropower plant construction, in mine-shaft HESS - PL	2.59600E-11 Item(s)	3.12387E-5	
00.01%	upper reservoir construction PHS - PL	2.59600E-11 Item(s)	2.25501E-5	
00.00%	penstock, for PHS, transport	2.59600E-11 Item(s)	6.87428E-6	
00.00%	Sika seals, transport HESS PHS	6.31244E-7 kg	7.39991E-7	
00.00%	market for electricity, medium voltage | electricity, medium voltage | Cutoff, U - PL	5.17644E-6 MJ	3.35513E-7	
00.00%	upper technical platform, transport PHS	2.59600E-11 Item(s)	2.70974E-7	
00.00%	concrete C30/37, for water dams, with CEM III/A, transport PHS	6.74960E-9 m3	2.02918E-7	
00.00%	reinforcement, for concrete slab/platform, transport HESS - PL	2.59600E-11 Item(s)	1.58635E-7	
00.00%	shut-off valve, transported PHS	2.59600E-11 Item(s)	5.94742E-8	
00.00%	control cabinet, transport PHS_A-CAES	2.59600E-11 Item(s)	2.23840E-8	
00.00%	hydraulic drive unit, transport PHS	2.59600E-11 Item(s)	1.81359E-8	
00.00%	market for wastewater, average | wastewater, average | Cutoff, U - RER without CH	6.79965E-8 m3	5.33657E-9	
00.00%	market for tap water | tap water | Cutoff, U - RER without CH	6.79965E-6 kg	9.81974E-10	
00.00%	energy router construction HESS	2.59600E-11 Item(s)	4.35205E-6	
00.00%	energy router components, transported HESS	2.59600E-11 Item(s)	4.35096E-6	
00.00%	concrete, C20/25, for router slab, with cement II/A, transport CCES	4.07572E-11 m3	1.09063E-9	

Fig. 47. Contribution of HESS PSH-ACAES facility construction stage to Energy resources: non-renewable, fossil impact category – ACAES, PSH and router construction

Impact category: Eutrophication: freshwater

Contribution	Process	Required amount	Total result [kg P-Eq]	Direct contribution [kg P-Eq]
100.00%	electricity production, high voltage, HESS PHS_A-CAES - PL	3.60000 MJ	0.00171	
99.98%	market for electricity, high voltage | electricity, high voltage | Cutoff, U - PL	5.63400 MJ	0.00171	
00.02%	HESS PHS A-CAES facility construction, in mine shafts - PL	2.59600E-11 Item(s)	2.80981E-7	
00.01%	adiabatic compressed air energy storage plant construction, in mine shaft A-CAES - PL	2.59600E-11 Item(s)	1.87739E-7	
00.00%	compressor 33.28 MW, transported A-CAES	2.59600E-11 Item(s)	8.40287E-8	
00.00%	expander 36 MW, transported A-CAES	2.59600E-11 Item(s)	4.92376E-8	
00.00%	reinforcement, for shaft plug, transported A-CAES	2.59600E-11 Item(s)	1.29419E-8	
00.00%	concrete C30/37, for shaft plug, with CEM III/A, transport A-CAES	1.71518E-7 m3	1.24255E-8	
00.00%	market for metal working, average for metal product manufacturing | metal working, av...	5.06791E-6 kg	1.03524E-8	
00.00%	steel anchors for shaft plug, transport A-CAES	5.71120E-9 Item(s)	1.02059E-8	
00.00%	TES tank, transport A-CAES	2.59600E-11 Item(s)	3.47110E-9	
00.00%	concrete C30/37, for pressure dams, with CEM III/A, transport A-CAES	3.54094E-8 m3	2.56521E-9	
00.00%	market for electricity, medium voltage | electricity, medium voltage | Cutoff, U - PL	4.21751E-6 MJ	1.28865E-9	
00.00%	Sika seals, transport HESS A-CAES	6.79000E-7 kg	5.54104E-10	
00.00%	basalt, transport A-CAES - PL	3.49908E-5 kg	2.83864E-10	
00.00%	PVC coated polyester ventilation duct, transport A-CAES	9.14571E-8 kg	1.69732E-10	
00.00%	service ventilation fan, transport A-CAES	2.59600E-11 Item(s)	1.67924E-10	
00.00%	control cabinet, transport PHS_A-CAES	2.59600E-11 Item(s)	3.19036E-11	
00.00%	market for wastewater, average | wastewater, average | Cutoff, U - RER without CH	6.40049E-9 m3	1.11654E-11	3.64533E-12
00.00%	market for tap water | tap water | Cutoff, U - RER without CH	6.40049E-6 kg	3.54385E-12	
00.00%	hydropower plant construction, in mine-shaft HESS - PL	2.59600E-11 Item(s)	7.19452E-8	
00.00%	upper reservoir construction PHS - PL	2.59600E-11 Item(s)	5.27462E-8	
00.00%	penstock, for PHS, transport	2.59600E-11 Item(s)	1.54027E-8	
00.00%	market for electricity, medium voltage | electricity, medium voltage | Cutoff, U - PL	5.17644E-6 MJ	1.58165E-9	
00.00%	upper technical platform, transport PHS	2.59600E-11 Item(s)	6.02884E-10	
00.00%	Sika seals, transport HESS PHS	6.31244E-7 kg	5.09602E-10	
00.00%	concrete C30/37, for water dams, with CEM III/A, transport PHS	6.74960E-9 m3	4.88970E-10	
00.00%	reinforcement, for concrete slab/platform, transport HESS - PL	2.59600E-11 Item(s)	2.91827E-10	
00.00%	shut-off valve, transported PHS	2.59600E-11 Item(s)	1.19471E-10	
00.00%	market for wastewater, average | wastewater, average | Cutoff, U - RER without CH	6.79965E-8 m3	1.18617E-10	3.87267E-11
00.00%	hydraulic drive unit, transport PHS	2.59600E-11 Item(s)	4.76243E-11	
00.00%	control cabinet, transport PHS_A-CAES	2.59600E-11 Item(s)	3.19036E-11	
00.00%	market for tap water | tap water | Cutoff, U - RER without CH	6.79965E-6 kg	3.76486E-12	
00.00%	energy router construction HESS	2.59600E-11 Item(s)	2.12969E-8	
00.00%	energy router components, transported HESS	2.59600E-11 Item(s)	2.12942E-8	
00.00%	concrete, C20/25, for router slab, with cement II/A, transport CCES	4.07572E-11 m3	2.75559E-12	

Fig. 48. Contribution of HESS PSH-ACAES facility construction stage to Eutrophication: freshwater impact category – ACAES, PSH and router construction

Impact category: Eutrophication: marine

Contribution	Process	Required amount	Total result [kg N-Eq]	Direct contribution [kg N-Eq]
100.00%	electricity production, high voltage, HESS PHS_A-CAES - PL	3.60000 MJ	0.00011	
99.97%	market for electricity, high voltage | electricity, high voltage | Cutoff, U - PL	5.63400 MJ	0.00011	
00.03%	HESS PHS A-CAES facility construction, in mine shafts - PL	2.59600E-11 Item(s)	2.97202E-8	
00.02%	adiabatic compressed air energy storage plant construction, in mine shaft A-CAES - PL	2.59600E-11 Item(s)	1.81177E-8	
00.01%	compressor 33.28 MW, transported A-CAES	2.59600E-11 Item(s)	7.46828E-9	
00.00%	expander 36 MW, transported A-CAES	2.59600E-11 Item(s)	4.09585E-9	
00.00%	steel anchors for shaft plug, transport A-CAES	5.71120E-9 Item(s)	1.59816E-9	
00.00%	market for metal working, average for metal product manufacturing | metal working, av...	5.06791E-6 kg	1.46088E-9	
00.00%	reinforcement, for shaft plug, transported A-CAES	2.59600E-11 Item(s)	1.29736E-9	
00.00%	concrete C30/37, for shaft plug, with CEM III/A, transport A-CAES	1.71518E-7 m3	8.97037E-10	
00.00%	Sika seals, transport HESS A-CAES	6.79000E-7 kg	5.03053E-10	
00.00%	TES tank, transport A-CAES	2.59600E-11 Item(s)	3.98690E-10	
00.00%	concrete C30/37, for pressure dams, with CEM III/A, transport A-CAES	3.54094E-8 m3	1.85192E-10	
00.00%	market for electricity, medium voltage | electricity, medium voltage | Cutoff, U - PL	4.21751E-6 MJ	8.13644E-11	
00.00%	PVC coated polyester ventilation duct, transport A-CAES	9.14571E-8 kg	4.96375E-11	
00.00%	market for wastewater, average | wastewater, average | Cutoff, U - RER without CH	6.40049E-9 m3	3.71663E-11	7.48979E-12
00.00%	basalt, transport A-CAES - PL	3.49908E-5 kg	2.91006E-11	
00.00%	service ventilation fan, transport A-CAES	2.59600E-11 Item(s)	1.28108E-11	
00.00%	control cabinet, transport PHS_A-CAES	2.59600E-11 Item(s)	2.89852E-12	
00.00%	market for tap water | tap water | Cutoff, U - RER without CH	6.40049E-6 kg	2.65992E-13	
00.01%	hydropower plant construction, in mine-shaft HESS - PL	2.59600E-11 Item(s)	1.07543E-8	
00.01%	upper reservoir construction PHS - PL	2.59600E-11 Item(s)	7.22167E-9	
00.00%	penstock, for PHS, transport	2.59600E-11 Item(s)	2.41177E-9	
00.00%	Sika seals, transport HESS PHS	6.31244E-7 kg	4.30244E-10	
00.00%	market for wastewater, average | wastewater, average | Cutoff, U - RER without CH	6.79965E-8 m3	3.94841E-10	7.95688E-11
00.00%	market for electricity, medium voltage | electricity, medium voltage | Cutoff, U - PL	5.17644E-6 MJ	9.98640E-11	
00.00%	upper technical platform, transport PHS	2.59600E-11 Item(s)	9.44456E-11	
00.00%	concrete C30/37, for water dams, with CEM III/A, transport PHS	6.74960E-9 m3	3.53004E-11	
00.00%	shut-off valve, transported PHS	2.59600E-11 Item(s)	3.14548E-11	
00.00%	reinforcement, for concrete slab/platform, transport HESS - PL	2.59600E-11 Item(s)	2.92541E-11	
00.00%	control cabinet, transport PHS_A-CAES	2.59600E-11 Item(s)	2.89852E-12	
00.00%	hydraulic drive unit, transport PHS	2.59600E-11 Item(s)	2.22249E-12	
00.00%	market for tap water | tap water | Cutoff, U - RER without CH	6.79965E-6 kg	2.82580E-13	
00.00%	energy router construction HESS	2.59600E-11 Item(s)	8.48192E-10	
00.00%	energy router components, transported HESS	2.59600E-11 Item(s)	8.48001E-10	
00.00%	concrete, C20/25, for router slab, with cement II/A, transport CCES	4.07572E-11 m3	1.90695E-13	

Fig. 49. Contribution of HESS PSH-ACAES facility construction stage to Eutrophication: marine impact category – ACAES, PSH and router construction

Impact category: Human toxicity: carcinogenic

Contribution	Process	Required amount	Total result [kg 1,4-DCB-Eq]	Direct contribution [kg 1,4-DCB...
100.00%	electricity production, high voltage, HESS PHS_A-CAES - PL	3.60000 MJ	0.14313	
99.86%	market for electricity, high voltage | electricity, high voltage | Cutoff, U - PL	5.63400 MJ	0.14292	
00.14%	HESS PHS A-CAES facility construction, in mine shafts - PL	2.59600E-11 Item(s)	0.00020	
00.09%	adiabatic compressed air energy storage plant construction, in mine shaft A-CAES - PL	2.59600E-11 Item(s)	0.00013	
00.03%	compressor 33.28 MW, transported A-CAES	2.59600E-11 Item(s)	4.38035E-5	
00.02%	reinforcement, for shaft plug, transported A-CAES	2.59600E-11 Item(s)	2.78160E-5	
00.02%	expander 36 MW, transported A-CAES	2.59600E-11 Item(s)	2.60489E-5	
00.01%	steel anchors for shaft plug, transport A-CAES	5.71120E-9 Item(s)	1.12325E-5	
00.01%	TES tank, transport A-CAES	2.59600E-11 Item(s)	1.02841E-5	
00.00%	market for metal working, average for metal product manufacturing | metal working, av...	5.06791E-6 kg	3.75096E-6	
00.00%	concrete C30/37, for shaft plug, with CEM III/A, transport A-CAES	1.71518E-7 m3	1.73826E-6	
00.00%	concrete C30/37, for pressure dams, with CEM III/A, transport A-CAES	3.54094E-8 m3	3.58863E-7	
00.00%	Sika seals, transport HESS A-CAES	6.79000E-7 kg	1.67148E-7	
00.00%	market for electricity, medium voltage | electricity, medium voltage | Cutoff, U - PL	4.21751E-6 MJ	1.08763E-7	
00.00%	PVC coated polyester ventilation duct, transport A-CAES	9.14571E-8 kg	9.36279E-8	
00.00%	service ventilation fan, transport A-CAES	2.59600E-11 Item(s)	8.14861E-8	
00.00%	basalt, transport A-CAES - PL	3.49908E-5 kg	5.59872E-8	
00.00%	control cabinet, transport PHS_A-CAES	2.59600E-11 Item(s)	7.36035E-9	
00.00%	market for tap water | tap water | Cutoff, U - RER without CH	6.40049E-6 kg	5.83193E-10	
00.00%	market for wastewater, average | wastewater, average | Cutoff, U - RER without CH	6.40049E-9 m3	3.20694E-10	2.85921E-13
00.05%	hydropower plant construction, in mine-shaft HESS - PL	2.59600E-11 Item(s)	7.22338E-5	
00.04%	upper reservoir construction PHS - PL	2.59600E-11 Item(s)	5.30307E-5	
00.01%	penstock, for PHS, transport	2.59600E-11 Item(s)	1.72114E-5	
00.00%	upper technical platform, transport PHS	2.59600E-11 Item(s)	6.73499E-7	
00.00%	reinforcement, for concrete slab/platform, transport HESS - PL	2.59600E-11 Item(s)	6.27221E-7	
00.00%	shut-off valve, transported PHS	2.59600E-11 Item(s)	2.80877E-7	
00.00%	Sika seals, transport HESS PHS	6.31244E-7 kg	1.55005E-7	
00.00%	market for electricity, medium voltage | electricity, medium voltage | Cutoff, U - PL	5.17644E-6 MJ	1.33493E-7	
00.00%	concrete C30/37, for water dams, with CEM III/A, transport PHS	6.74960E-9 m3	6.84043E-8	
00.00%	hydraulic drive unit, transport PHS	2.59600E-11 Item(s)	4.17892E-8	
00.00%	control cabinet, transport PHS_A-CAES	2.59600E-11 Item(s)	7.36035E-9	
00.00%	market for wastewater, average | wastewater, average | Cutoff, U - RER without CH	6.79965E-8 m3	3.40693E-9	3.03752E-12
00.00%	market for tap water | tap water | Cutoff, U - RER without CH	6.79965E-6 kg	6.19563E-10	
00.00%	energy router construction HESS	2.59600E-11 Item(s)	6.58011E-6	
00.00%	energy router components, transported HESS	2.59600E-11 Item(s)	6.57974E-6	
00.00%	concrete, C20/25, for router slab, with cement II/A, transport CCES	4.07572E-11 m3	3.72651E-10	

Fig. 50. Contribution of HESS PSH-ACAES facility construction stage to Human toxicity: carcinogenic impact category – ACAES, PSH and router construction

Impact category: Human toxicity: non-carcinogenic

Contribution	Process	Required amount	Total result [kg 1,4-DCB-Eq]	Direct contribution [kg 1,4-DCB...
100.00%	electricity production, high voltage, HESS PHS_A-CAES - PL	3.60000 MJ	2.20890	
99.88%	market for electricity, high voltage | electricity, high voltage | Cutoff, U - PL	5.63400 MJ	2.20622	
00.12%	HESS PHS A-CAES facility construction, in mine shafts - PL	2.59600E-11 Item(s)	0.00268	
00.10%	adiabatic compressed air energy storage plant construction, in mine shaft A-CAES - PL	2.59600E-11 Item(s)	0.00216	
00.05%	compressor 33.28 MW, transported A-CAES	2.59600E-11 Item(s)	0.00115	
00.03%	expander 36 MW, transported A-CAES	2.59600E-11 Item(s)	0.00070	
00.01%	market for metal working, average for metal product manufacturing | metal working, av...	5.06791E-6 kg	0.00011	
00.00%	reinforcement, for shaft plug, transported A-CAES	2.59600E-11 Item(s)	8.98573E-5	
00.00%	steel anchors for shaft plug, transport A-CAES	5.71120E-9 Item(s)	4.34138E-5	
00.00%	concrete C30/37, for shaft plug, with CEM III/A, transport A-CAES	1.71518E-7 m3	2.97438E-5	
00.00%	TES tank, transport A-CAES	2.59600E-11 Item(s)	2.22899E-5	
00.00%	concrete C30/37, for pressure dams, with CEM III/A, transport A-CAES	3.54094E-8 m3	6.14059E-6	
00.00%	PVC coated polyester ventilation duct, transport A-CAES	9.14571E-8 kg	5.17595E-6	
00.00%	Sika seals, transport HESS A-CAES	6.79000E-7 kg	2.80422E-6	
00.00%	market for electricity, medium voltage | electricity, medium voltage | Cutoff, U - PL	4.21751E-6 MJ	1.70101E-6	
00.00%	service ventilation fan, transport A-CAES	2.59600E-11 Item(s)	1.52539E-6	
00.00%	basalt, transport A-CAES - PL	3.49908E-5 kg	7.99831E-7	
00.00%	control cabinet, transport PHS_A-CAES	2.59600E-11 Item(s)	1.13838E-7	
00.00%	market for wastewater, average | wastewater, average | Cutoff, U - RER without CH	6.40049E-9 m3	2.34623E-8	9.79202E-10
00.00%	market for tap water | tap water | Cutoff, U - RER without CH	6.40049E-6 kg	5.85412E-9	
00.01%	hydropower plant construction, in mine-shaft HESS - PL	2.59600E-11 Item(s)	0.00027	
00.01%	upper reservoir construction PHS - PL	2.59600E-11 Item(s)	0.00019	
00.00%	penstock, for PHS, transport	2.59600E-11 Item(s)	6.57637E-5	
00.00%	Sika seals, transport HESS PHS	6.31244E-7 kg	2.60254E-6	
00.00%	upper technical platform, transport PHS	2.59600E-11 Item(s)	2.57743E-6	
00.00%	market for electricity, medium voltage | electricity, medium voltage | Cutoff, U - PL	5.17644E-6 MJ	2.08776E-6	
00.00%	reinforcement, for concrete slab/platform, transport HESS - PL	2.59600E-11 Item(s)	2.02619E-6	
00.00%	concrete C30/37, for water dams, with CEM III/A, transport PHS	6.74960E-9 m3	1.17048E-6	
00.00%	shut-off valve, transported PHS	2.59600E-11 Item(s)	9.36228E-7	
00.00%	hydraulic drive unit, transport PHS	2.59600E-11 Item(s)	4.49595E-7	
00.00%	market for wastewater, average | wastewater, average | Cutoff, U - RER without CH	6.79965E-8 m3	2.49255E-7	1.04027E-8
00.00%	control cabinet, transport PHS_A-CAES	2.59600E-11 Item(s)	1.13838E-7	
00.00%	market for tap water | tap water | Cutoff, U - RER without CH	6.79965E-6 kg	6.21921E-9	
00.01%	energy router construction HESS	2.59600E-11 Item(s)	0.00025	
00.01%	energy router components, transported HESS	2.59600E-11 Item(s)	0.00025	
00.00%	concrete, C20/25, for router slab, with cement II/A, transport CCES	4.07572E-11 m3	6.02800E-9	

Fig. 51. Contribution of HESS PSH-ACAES facility construction stage to Human toxicity: non-carcinogenic impact category – ACAES, PSH and router construction

Impact category: Ionising radiation

Contribution	Process	Required amount	Total result [kBq Co-60-Eq]	Direct contribution [kBq Co-60...
100.00%	electricity production, high voltage, HESS PHS_A-CAES - PL	3.60000 MJ	0.02132	
99.94%	market for electricity, high voltage | electricity, high voltage | Cutoff, U - PL	5.63400 MJ	0.02131	
00.06%	HESS PHS A-CAES facility construction, in mine shafts - PL	2.59600E-11 Item(s)	1.18599E-5	
00.04%	adiabatic compressed air energy storage plant construction, in mine shaft A-CAES - PL	2.59600E-11 Item(s)	8.45613E-6	
00.02%	compressor 33.28 MW, transported A-CAES	2.59600E-11 Item(s)	3.47955E-6	
00.01%	expander 36 MW, transported A-CAES	2.59600E-11 Item(s)	2.06130E-6	
00.00%	market for metal working, average for metal product manufacturing | metal working, av...	5.06791E-6 kg	7.93197E-7	
00.00%	reinforcement, for shaft plug, transported A-CAES	2.59600E-11 Item(s)	7.06198E-7	
00.00%	TES tank, transport A-CAES	2.59600E-11 Item(s)	5.11114E-7	
00.00%	steel anchors for shaft plug, transport A-CAES	5.71120E-9 Item(s)	4.57130E-7	
00.00%	concrete C30/37, for shaft plug, with CEM III/A, transport A-CAES	1.71518E-7 m3	2.80975E-7	
00.00%	Sika seals, transport HESS A-CAES	6.79000E-7 kg	6.04515E-8	
00.00%	concrete C30/37, for pressure dams, with CEM III/A, transport A-CAES	3.54094E-8 m3	5.80075E-8	
00.00%	PVC coated polyester ventilation duct, transport A-CAES	9.14571E-8 kg	1.64164E-8	
00.00%	market for electricity, medium voltage | electricity, medium voltage | Cutoff, U - PL	4.21751E-6 MJ	1.61033E-8	
00.00%	basalt, transport A-CAES - PL	3.49908E-5 kg	1.02151E-8	
00.00%	service ventilation fan, transport A-CAES	2.59600E-11 Item(s)	4.15562E-9	
00.00%	control cabinet, transport PHS_A-CAES	2.59600E-11 Item(s)	8.62319E-10	
00.00%	market for wastewater, average | wastewater, average | Cutoff, U - RER without CH	6.40049E-9 m3	3.49751E-10	
00.00%	market for tap water | tap water | Cutoff, U - RER without CH	6.40049E-6 kg	1.06339E-10	
00.01%	hydropower plant construction, in mine-shaft HESS - PL	2.59600E-11 Item(s)	2.55914E-6	
00.01%	upper reservoir construction PHS - PL	2.59600E-11 Item(s)	1.83066E-6	
00.00%	penstock, for PHS, transport	2.59600E-11 Item(s)	5.75871E-7	
00.00%	Sika seals, transport HESS PHS	6.31244E-7 kg	5.43448E-8	
00.00%	shut-off valve, transported PHS	2.59600E-11 Item(s)	2.27931E-8	
00.00%	upper technical platform, transport PHS	2.59600E-11 Item(s)	2.26089E-8	
00.00%	market for electricity, medium voltage | electricity, medium voltage | Cutoff, U - PL	5.17644E-6 MJ	1.97646E-8	
00.00%	reinforcement, for concrete slab/platform, transport HESS - PL	2.59600E-11 Item(s)	1.59240E-8	
00.00%	concrete C30/37, for water dams, with CEM III/A, transport PHS	6.74960E-9 m3	1.10570E-8	
00.00%	market for wastewater, average | wastewater, average | Cutoff, U - RER without CH	6.79965E-8 m3	3.71563E-9	
00.00%	hydraulic drive unit, transport PHS	2.59600E-11 Item(s)	1.41880E-9	
00.00%	control cabinet, transport PHS_A-CAES	2.59600E-11 Item(s)	8.62319E-10	
00.00%	market for tap water | tap water | Cutoff, U - RER without CH	6.79965E-6 kg	1.12971E-10	
00.00%	energy router construction HESS	2.59600E-11 Item(s)	8.44613E-7	
00.00%	energy router components, transported HESS	2.59600E-11 Item(s)	8.44562E-7	
00.00%	concrete, C20/25, for router slab, with cement II/A, transport CCES	4.07572E-11 m3	5.14682E-11	

Fig. 52. Contribution of HESS PSH-ACAES facility construction stage to Ionising radiation impact category – ACAES, PSH and router construction

Impact category: Land use

Contribution	Process	Required amount	Total result [m2*a crop-Eq]	Direct contribution [m2*a crop...
100.00%	electricity production, high voltage, HESS PHS_A-CAES - PL	3.60000 MJ	0.02340	
99.95%	market for electricity, high voltage | electricity, high voltage | Cutoff, U - PL	5.63400 MJ	0.02339	
00.05%	HESS PHS A-CAES facility construction, in mine shafts - PL	2.59600E-11 Item(s)	1.10523E-5	
00.03%	adiabatic compressed air energy storage plant construction, in mine shaft A-CAES - PL	2.59600E-11 Item(s)	7.61728E-6	
00.01%	compressor 33.28 MW, transported A-CAES	2.59600E-11 Item(s)	3.08073E-6	
00.01%	expander 36 MW, transported A-CAES	2.59600E-11 Item(s)	1.81346E-6	
00.00%	concrete C30/37, for shaft plug, with CEM III/A, transport A-CAES	1.71518E-7 m3	7.09993E-7	
00.00%	reinforcement, for shaft plug, transported A-CAES	2.59600E-11 Item(s)	5.43132E-7	
00.00%	market for metal working, average for metal product manufacturing | metal working, av...	5.06791E-6 kg	4.11172E-7	
00.00%	steel anchors for shaft plug, transport A-CAES	5.71120E-9 Item(s)	3.81448E-7	
00.00%	basalt, transport A-CAES - PL	3.49908E-5 kg	2.38165E-7	
00.00%	TES tank, transport A-CAES	2.59600E-11 Item(s)	1.76695E-7	
00.00%	concrete C30/37, for pressure dams, with CEM III/A, transport A-CAES	3.54094E-8 m3	1.46579E-7	
00.00%	Sika seals, transport HESS A-CAES	6.79000E-7 kg	6.26498E-8	
00.00%	PVC coated polyester ventilation duct, transport A-CAES	9.14571E-8 kg	2.78050E-8	
00.00%	market for electricity, medium voltage | electricity, medium voltage | Cutoff, U - PL	4.21751E-6 MJ	1.77483E-8	
00.00%	service ventilation fan, transport A-CAES	2.59600E-11 Item(s)	5.21141E-9	
00.00%	control cabinet, transport PHS_A-CAES	2.59600E-11 Item(s)	2.36359E-9	
00.00%	market for tap water | tap water | Cutoff, U - RER without CH	6.40049E-6 kg	6.77428E-11	
00.00%	market for wastewater, average | wastewater, average | Cutoff, U - RER without CH	6.40049E-9 m3	5.96409E-11	
00.01%	hydropower plant construction, in mine-shaft HESS - PL	2.59600E-11 Item(s)	2.77795E-6	
00.01%	upper reservoir construction PHS - PL	2.59600E-11 Item(s)	2.05056E-6	
00.00%	penstock, for PHS, transport	2.59600E-11 Item(s)	5.65465E-7	
00.00%	Sika seals, transport HESS PHS	6.31244E-7 kg	6.51367E-8	
00.00%	concrete C30/37, for water dams, with CEM III/A, transport PHS	6.74960E-9 m3	2.79397E-8	
00.00%	upper technical platform, transport PHS	2.59600E-11 Item(s)	2.25408E-8	
00.00%	market for electricity, medium voltage | electricity, medium voltage | Cutoff, U - PL	5.17644E-6 MJ	2.17837E-8	
00.00%	reinforcement, for concrete slab/platform, transport HESS - PL	2.59600E-11 Item(s)	1.22471E-8	
00.00%	shut-off valve, transported PHS	2.59600E-11 Item(s)	7.55888E-9	
00.00%	control cabinet, transport PHS_A-CAES	2.59600E-11 Item(s)	2.36359E-9	
00.00%	hydraulic drive unit, transport PHS	2.59600E-11 Item(s)	1.65356E-9	
00.00%	market for wastewater, average | wastewater, average | Cutoff, U - RER without CH	6.79965E-8 m3	6.33603E-10	
00.00%	market for tap water | tap water | Cutoff, U - RER without CH	6.79965E-6 kg	7.19675E-11	
00.00%	energy router construction HESS	2.59600E-11 Item(s)	6.57048E-7	
00.00%	energy router components, transported HESS	2.59600E-11 Item(s)	6.56903E-7	
00.00%	concrete, C20/25, for router slab, with cement II/A, transport CCES	4.07572E-11 m3	1.44455E-10	

Fig. 53. Contribution of HESS PSH-ACAES facility construction stage to Land use impact category – ACAES, PSH and router construction

Impact category: Material resources: metals/minerals

Contribution	Process	Required amount	Total result [kg Cu-Eq]	Direct contribution [kg Cu-Eq]
100.00%	electricity production, high voltage, HESS PHS_A-CAES - PL	3.60000 MJ	0.00493	
97.34%	market for electricity, high voltage | electricity, high voltage | Cutoff, U - PL	5.63400 MJ	0.00480	
02.66%	HESS PHS A-CAES facility construction, in mine shafts - PL	2.59600E-11 Item(s)	0.00013	
01.90%	adiabatic compressed air energy storage plant construction, in mine shaft A-CAES - PL	2.59600E-11 Item(s)	9.35155E-5	
00.56%	basalt, transport A-CAES - PL	3.49908E-5 kg	2.76598E-5	
00.50%	compressor 33.28 MW, transported A-CAES	2.59600E-11 Item(s)	2.46858E-5	
00.32%	reinforcement, for shaft plug, transported A-CAES	2.59600E-11 Item(s)	1.57026E-5	
00.30%	expander 36 MW, transported A-CAES	2.59600E-11 Item(s)	1.48706E-5	
00.13%	steel anchors for shaft plug, transport A-CAES	5.71120E-9 Item(s)	6.37546E-6	
00.03%	TES tank, transport A-CAES	2.59600E-11 Item(s)	1.72222E-6	
00.03%	market for metal working, average for metal product manufacturing | metal working, av...	5.06791E-6 kg	1.34246E-6	
00.02%	concrete C30/37, for shaft plug, with CEM III/A, transport A-CAES	1.71518E-7 m3	8.01873E-7	
00.00%	concrete C30/37, for pressure dams, with CEM III/A, transport A-CAES	3.54094E-8 m3	1.65546E-7	
00.00%	Sika seals, transport HESS A-CAES	6.79000E-7 kg	1.03511E-7	
00.00%	service ventilation fan, transport A-CAES	2.59600E-11 Item(s)	4.91300E-8	
00.00%	PVC coated polyester ventilation duct, transport A-CAES	9.14571E-8 kg	2.94735E-8	
00.00%	market for electricity, medium voltage | electricity, medium voltage | Cutoff, U - PL	4.21751E-6 MJ	3.77755E-9	
00.00%	control cabinet, transport PHS_A-CAES	2.59600E-11 Item(s)	2.72584E-9	
00.00%	market for tap water | tap water | Cutoff, U - RER without CH	6.40049E-6 kg	3.59976E-10	
00.00%	market for wastewater, average | wastewater, average | Cutoff, U - RER without CH	6.40049E-9 m3	1.23129E-10	
00.71%	hydropower plant construction, in mine-shaft HESS - PL	2.59600E-11 Item(s)	3.48235E-5	
00.49%	upper reservoir construction PHS - PL	2.59600E-11 Item(s)	2.42577E-5	
00.20%	penstock, for PHS, transport	2.59600E-11 Item(s)	9.62913E-6	
00.01%	upper technical platform, transport PHS	2.59600E-11 Item(s)	3.76795E-7	
00.01%	reinforcement, for concrete slab/platform, transport HESS - PL	2.59600E-11 Item(s)	3.54076E-7	
00.00%	Sika seals, transport HESS PHS	6.31244E-7 kg	1.09168E-7	
00.00%	concrete C30/37, for water dams, with CEM III/A, transport PHS	6.74960E-9 m3	3.15554E-8	
00.00%	shut-off valve, transported PHS	2.59600E-11 Item(s)	3.05604E-8	
00.00%	hydraulic drive unit, transport PHS	2.59600E-11 Item(s)	2.54179E-8	
00.00%	market for electricity, medium voltage | electricity, medium voltage | Cutoff, U - PL	5.17644E-6 MJ	4.63644E-9	
00.00%	control cabinet, transport PHS_A-CAES	2.59600E-11 Item(s)	2.72584E-9	
00.00%	market for wastewater, average | wastewater, average | Cutoff, U - RER without CH	6.79965E-8 m3	1.30808E-9	
00.00%	market for tap water | tap water | Cutoff, U - RER without CH	6.79965E-6 kg	3.82426E-10	
00.05%	energy router construction HESS	2.59600E-11 Item(s)	2.69785E-6	
00.05%	energy router components, transported HESS	2.59600E-11 Item(s)	2.69759E-6	
00.00%	concrete, C20/25, for router slab, with cement II/A, transport CCES	4.07572E-11 m3	2.55799E-10	

Fig. 54. Contribution of HESS PSH-ACAES facility construction stage to Material resources: metals/minerals impact category – ACAES, PSH and router construction

Impact category: Ozone depletion

Contribution	Process	Required amount	Total result [kg CFC-11-Eq]	Direct contribution [kg CFC-11...
100.00%	electricity production, high voltage, HESS PHS_A-CAES - PL	3.60000 MJ	2.44675E-7	
99.96%	market for electricity, high voltage | electricity, high voltage | Cutoff, U - PL	5.63400 MJ	2.44566E-7	8.83302E-8
00.04%	HESS PHS A-CAES facility construction, in mine shafts - PL	2.59600E-11 Item(s)	1.09153E-10	
00.03%	adiabatic compressed air energy storage plant construction, in mine shaft A-CAES - PL	2.59600E-11 Item(s)	6.44636E-11	
00.01%	compressor 33.28 MW, transported A-CAES	2.59600E-11 Item(s)	2.34940E-11	
00.01%	expander 36 MW, transported A-CAES	2.59600E-11 Item(s)	1.37086E-11	
00.00%	Sika seals, transport HESS A-CAES	6.79000E-7 kg	8.21305E-12	
00.00%	reinforcement, for shaft plug, transported A-CAES	2.59600E-11 Item(s)	4.40594E-12	
00.00%	concrete C30/37, for shaft plug, with CEM III/A, transport A-CAES	1.71518E-7 m3	3.91663E-12	
00.00%	market for metal working, average for metal product manufacturing | metal working, av...	5.06791E-6 kg	3.77131E-12	
00.00%	steel anchors for shaft plug, transport A-CAES	5.71120E-9 Item(s)	3.30877E-12	
00.00%	TES tank, transport A-CAES	2.59600E-11 Item(s)	1.45475E-12	
00.00%	concrete C30/37, for pressure dams, with CEM III/A, transport A-CAES	3.54094E-8 m3	8.08592E-13	
00.00%	PVC coated polyester ventilation duct, transport A-CAES	9.14571E-8 kg	6.32079E-13	
00.00%	basalt, transport A-CAES - PL	3.49908E-5 kg	4.95849E-13	
00.00%	market for electricity, medium voltage | electricity, medium voltage | Cutoff, U - PL	4.21751E-6 MJ	1.85573E-13	
00.00%	service ventilation fan, transport A-CAES	2.59600E-11 Item(s)	4.12735E-14	
00.00%	control cabinet, transport PHS_A-CAES	2.59600E-11 Item(s)	1.61256E-14	
00.00%	market for wastewater, average | wastewater, average | Cutoff, U - RER without CH	6.40049E-9 m3	1.03423E-14	
00.00%	market for tap water | tap water | Cutoff, U - RER without CH	6.40049E-6 kg	7.31741E-16	
00.01%	hydropower plant construction, in mine-shaft HESS - PL	2.59600E-11 Item(s)	3.03175E-11	
00.01%	upper reservoir construction PHS - PL	2.59600E-11 Item(s)	1.75222E-11	
00.00%	Sika seals, transport HESS PHS	6.31244E-7 kg	6.99939E-12	
00.00%	penstock, for PHS, transport	2.59600E-11 Item(s)	4.90846E-12	
00.00%	market for electricity, medium voltage | electricity, medium voltage | Cutoff, U - PL	5.17644E-6 MJ	2.27766E-13	
00.00%	upper technical platform, transport PHS	2.59600E-11 Item(s)	1.93518E-13	
00.00%	concrete C30/37, for water dams, with CEM III/A, transport PHS	6.74960E-9 m3	1.54128E-13	
00.00%	market for wastewater, average | wastewater, average | Cutoff, U - RER without CH	6.79965E-8 m3	1.09872E-13	
00.00%	reinforcement, for concrete slab/platform, transport HESS - PL	2.59600E-11 Item(s)	9.93494E-14	
00.00%	shut-off valve, transported PHS	2.59600E-11 Item(s)	7.13055E-14	
00.00%	control cabinet, transport PHS_A-CAES	2.59600E-11 Item(s)	1.61256E-14	
00.00%	hydraulic drive unit, transport PHS	2.59600E-11 Item(s)	1.46207E-14	
00.00%	market for tap water | tap water | Cutoff, U - RER without CH	6.79965E-6 kg	7.77375E-16	
00.01%	energy router construction HESS	2.59600E-11 Item(s)	1.43721E-11	
00.01%	energy router components, transported HESS	2.59600E-11 Item(s)	1.43713E-11	
00.00%	concrete, C20/25, for router slab, with cement II/A, transport CCES	4.07572E-11 m3	7.90434E-16	

Fig. 55. Contribution of HESS PSH-ACAES facility construction stage to Ozone depletion impact category – ACAES, PSH and router construction

Impact category: Particulate matter formation

Contribution	Process	Required amount	Total result [kg PM2.5-Eq]	Direct contribution [kg PM2.5-...
100.00%	electricity production, high voltage, HESS PHS_A-CAES - PL	3.60000 MJ	0.00251	
99.97%	market for electricity, high voltage | electricity, high voltage | Cutoff, U - PL	5.63400 MJ	0.00251	
00.03%	HESS PHS A-CAES facility construction, in mine shafts - PL	2.59600E-11 Item(s)	8.36705E-7	
00.02%	adiabatic compressed air energy storage plant construction, in mine shaft A-CAES - PL	2.59600E-11 Item(s)	5.85040E-7	
00.01%	compressor 33.28 MW, transported A-CAES	2.59600E-11 Item(s)	2.60612E-7	
00.01%	expander 36 MW, transported A-CAES	2.59600E-11 Item(s)	1.55946E-7	
00.00%	reinforcement, for shaft plug, transported A-CAES	2.59600E-11 Item(s)	4.36200E-8	
00.00%	concrete C30/37, for shaft plug, with CEM III/A, transport A-CAES	1.71518E-7 m3	3.70347E-8	
00.00%	market for metal working, average for metal product manufacturing | metal working, av...	5.06791E-6 kg	3.38361E-8	
00.00%	steel anchors for shaft plug, transport A-CAES	5.71120E-9 Item(s)	2.50102E-8	
00.00%	TES tank, transport A-CAES	2.59600E-11 Item(s)	1.27593E-8	
00.00%	concrete C30/37, for pressure dams, with CEM III/A, transport A-CAES	3.54094E-8 m3	7.64578E-9	
00.00%	Sika seals, transport HESS A-CAES	6.79000E-7 kg	3.03686E-9	
00.00%	basalt, transport A-CAES - PL	3.49908E-5 kg	1.90394E-9	
00.00%	market for electricity, medium voltage | electricity, medium voltage | Cutoff, U - PL	4.21751E-6 MJ	1.90249E-9	
00.00%	PVC coated polyester ventilation duct, transport A-CAES	9.14571E-8 kg	1.13923E-9	
00.00%	service ventilation fan, transport A-CAES	2.59600E-11 Item(s)	4.73193E-10	
00.00%	control cabinet, transport PHS_A-CAES	2.59600E-11 Item(s)	1.10822E-10	
00.00%	market for tap water | tap water | Cutoff, U - RER without CH	6.40049E-6 kg	6.41163E-12	
00.00%	market for wastewater, average | wastewater, average | Cutoff, U - RER without CH	6.40049E-9 m3	3.01979E-12	
00.01%	hydropower plant construction, in mine-shaft HESS - PL	2.59600E-11 Item(s)	1.83524E-7	
00.01%	upper reservoir construction PHS - PL	2.59600E-11 Item(s)	1.35109E-7	
00.00%	penstock, for PHS, transport	2.59600E-11 Item(s)	3.86283E-8	
00.00%	Sika seals, transport HESS PHS	6.31244E-7 kg	2.90931E-9	
00.00%	market for electricity, medium voltage | electricity, medium voltage | Cutoff, U - PL	5.17644E-6 MJ	2.33506E-9	
00.00%	upper technical platform, transport PHS	2.59600E-11 Item(s)	1.51770E-9	
00.00%	concrete C30/37, for water dams, with CEM III/A, transport PHS	6.74960E-9 m3	1.45739E-9	
00.00%	reinforcement, for concrete slab/platform, transport HESS - PL	2.59600E-11 Item(s)	9.83584E-10	
00.00%	shut-off valve, transported PHS	2.59600E-11 Item(s)	2.63069E-10	
00.00%	hydraulic drive unit, transport PHS	2.59600E-11 Item(s)	1.70932E-10	
00.00%	control cabinet, transport PHS_A-CAES	2.59600E-11 Item(s)	1.10822E-10	
00.00%	market for wastewater, average | wastewater, average | Cutoff, U - RER without CH	6.79965E-8 m3	3.20812E-11	
00.00%	market for tap water | tap water | Cutoff, U - RER without CH	6.79965E-6 kg	6.81149E-12	
00.00%	energy router construction HESS	2.59600E-11 Item(s)	6.81408E-8	
00.00%	energy router components, transported HESS	2.59600E-11 Item(s)	6.81321E-8	
00.00%	concrete, C20/25, for router slab, with cement II/A, transport CCES	4.07572E-11 m3	8.64109E-12	

Fig. 56. Contribution of HESS PSH-ACAES facility construction stage to Particulate matter formation impact category – ACAES, PSH and router construction

Impact category: Photochemical oxidant formation: human health

Contribution	Process	Required amount	Total result [kg NOx-Eq]	Direct contribution [kg NOx-Eq]
100.00%	electricity production, high voltage, HESS PHS_A-CAES - PL	3.60000 MJ	0.00263	
99.96%	market for electricity, high voltage | electricity, high voltage | Cutoff, U - PL	5.63400 MJ	0.00263	
00.04%	HESS PHS A-CAES facility construction, in mine shafts - PL	2.59600E-11 Item(s)	1.01014E-6	
00.02%	adiabatic compressed air energy storage plant construction, in mine shaft A-CAES - PL	2.59600E-11 Item(s)	6.50410E-7	
00.01%	compressor 33.28 MW, transported A-CAES	2.59600E-11 Item(s)	2.44651E-7	
00.01%	expander 36 MW, transported A-CAES	2.59600E-11 Item(s)	1.44458E-7	
00.00%	concrete C30/37, for shaft plug, with CEM III/A, transport A-CAES	1.71518E-7 m3	7.84370E-8	
00.00%	reinforcement, for shaft plug, transported A-CAES	2.59600E-11 Item(s)	6.83390E-8	
00.00%	steel anchors for shaft plug, transport A-CAES	5.71120E-9 Item(s)	3.67170E-8	
00.00%	market for metal working, average for metal product manufacturing | metal working, av...	5.06791E-6 kg	2.99665E-8	
00.00%	TES tank, transport A-CAES	2.59600E-11 Item(s)	1.63823E-8	
00.00%	concrete C30/37, for pressure dams, with CEM III/A, transport A-CAES	3.54094E-8 m3	1.61934E-8	
00.00%	basalt, transport A-CAES - PL	3.49908E-5 kg	6.36814E-9	
00.00%	Sika seals, transport HESS A-CAES	6.79000E-7 kg	4.62825E-9	
00.00%	market for electricity, medium voltage | electricity, medium voltage | Cutoff, U - PL	4.21751E-6 MJ	1.99049E-9	
00.00%	PVC coated polyester ventilation duct, transport A-CAES	9.14571E-8 kg	1.69065E-9	
00.00%	service ventilation fan, transport A-CAES	2.59600E-11 Item(s)	4.21050E-10	
00.00%	control cabinet, transport PHS_A-CAES	2.59600E-11 Item(s)	1.52998E-10	
00.00%	market for tap water | tap water | Cutoff, U - RER without CH	6.40049E-6 kg	7.68072E-12	
00.00%	market for wastewater, average | wastewater, average | Cutoff, U - RER without CH	6.40049E-9 m3	6.04676E-12	
00.01%	hydropower plant construction, in mine-shaft HESS - PL	2.59600E-11 Item(s)	3.08758E-7	
00.01%	upper reservoir construction PHS - PL	2.59600E-11 Item(s)	2.38222E-7	
00.00%	penstock, for PHS, transport	2.59600E-11 Item(s)	5.58529E-8	
00.00%	Sika seals, transport HESS PHS	6.31244E-7 kg	4.51640E-9	
00.00%	concrete C30/37, for water dams, with CEM III/A, transport PHS	6.74960E-9 m3	3.08666E-9	
00.00%	market for electricity, medium voltage | electricity, medium voltage | Cutoff, U - PL	5.17644E-6 MJ	2.44307E-9	
00.00%	upper technical platform, transport PHS	2.59600E-11 Item(s)	2.21180E-9	
00.00%	reinforcement, for concrete slab/platform, transport HESS - PL	2.59600E-11 Item(s)	1.54097E-9	
00.00%	shut-off valve, transported PHS	2.59600E-11 Item(s)	4.86950E-10	
00.00%	hydraulic drive unit, transport PHS	2.59600E-11 Item(s)	1.71799E-10	
00.00%	control cabinet, transport PHS_A-CAES	2.59600E-11 Item(s)	1.52998E-10	
00.00%	market for wastewater, average | wastewater, average | Cutoff, U - RER without CH	6.79965E-8 m3	6.42386E-11	
00.00%	market for tap water | tap water | Cutoff, U - RER without CH	6.79965E-6 kg	8.15972E-12	
00.00%	energy router construction HESS	2.59600E-11 Item(s)	5.09693E-8	
00.00%	energy router components, transported HESS	2.59600E-11 Item(s)	5.09474E-8	
00.00%	concrete, C20/25, for router slab, with cement II/A, transport CCES	4.07572E-11 m3	2.19356E-11	

Fig. 57. Contribution of HESS PSH-ACAES facility construction stage to Photochemical oxidant formation: human health impact category – ACAES, PSH and router construction

Impact category: Photochemical oxidant formation: terrestrial ecosystems

Contribution	Process	Required amount	Total result [kg NOx-Eq]	Direct contribution [kg NOx-Eq]
100.00%	electricity production, high voltage, HESS PHS_A-CAES - PL	3.60000 MJ	0.00265	
99.96%	market for electricity, high voltage | electricity, high voltage | Cutoff, U - PL	5.63400 MJ	0.00265	
00.04%	HESS PHS A-CAES facility construction, in mine shafts - PL	2.59600E-11 Item(s)	1.04392E-6	
00.03%	adiabatic compressed air energy storage plant construction, in mine shaft A-CAES - PL	2.59600E-11 Item(s)	6.72239E-7	
00.01%	compressor 33.28 MW, transported A-CAES	2.59600E-11 Item(s)	2.52855E-7	
00.01%	expander 36 MW, transported A-CAES	2.59600E-11 Item(s)	1.49237E-7	
00.00%	concrete C30/37, for shaft plug, with CEM III/A, transport A-CAES	1.71518E-7 m3	8.04816E-8	
00.00%	reinforcement, for shaft plug, transported A-CAES	2.59600E-11 Item(s)	7.06768E-8	
00.00%	steel anchors for shaft plug, transport A-CAES	5.71120E-9 Item(s)	3.81144E-8	
00.00%	market for metal working, average for metal product manufacturing | metal working, av...	5.06791E-6 kg	3.12023E-8	
00.00%	TES tank, transport A-CAES	2.59600E-11 Item(s)	1.70651E-8	
00.00%	concrete C30/37, for pressure dams, with CEM III/A, transport A-CAES	3.54094E-8 m3	1.66155E-8	
00.00%	basalt, transport A-CAES - PL	3.49908E-5 kg	6.58019E-9	
00.00%	Sika seals, transport HESS A-CAES	6.79000E-7 kg	5.02408E-9	
00.00%	market for electricity, medium voltage | electricity, medium voltage | Cutoff, U - PL	4.21751E-6 MJ	2.00170E-9	
00.00%	PVC coated polyester ventilation duct, transport A-CAES	9.14571E-8 kg	1.77870E-9	
00.00%	service ventilation fan, transport A-CAES	2.59600E-11 Item(s)	4.33938E-10	
00.00%	control cabinet, transport PHS_A-CAES	2.59600E-11 Item(s)	1.58763E-10	
00.00%	market for tap water | tap water | Cutoff, U - RER without CH	6.40049E-6 kg	7.78760E-12	
00.00%	market for wastewater, average | wastewater, average | Cutoff, U - RER without CH	6.40049E-9 m3	6.25117E-12	
00.01%	hydropower plant construction, in mine-shaft HESS - PL	2.59600E-11 Item(s)	3.18722E-7	
00.01%	upper reservoir construction PHS - PL	2.59600E-11 Item(s)	2.45457E-7	
00.00%	penstock, for PHS, transport	2.59600E-11 Item(s)	5.79567E-8	
00.00%	Sika seals, transport HESS PHS	6.31244E-7 kg	4.86814E-9	
00.00%	concrete C30/37, for water dams, with CEM III/A, transport PHS	6.74960E-9 m3	3.16712E-9	
00.00%	market for electricity, medium voltage | electricity, medium voltage | Cutoff, U - PL	5.17644E-6 MJ	2.45682E-9	
00.00%	upper technical platform, transport PHS	2.59600E-11 Item(s)	2.29568E-9	
00.00%	reinforcement, for concrete slab/platform, transport HESS - PL	2.59600E-11 Item(s)	1.59369E-9	
00.00%	shut-off valve, transported PHS	2.59600E-11 Item(s)	5.14257E-10	
00.00%	hydraulic drive unit, transport PHS	2.59600E-11 Item(s)	1.79298E-10	
00.00%	control cabinet, transport PHS_A-CAES	2.59600E-11 Item(s)	1.58763E-10	
00.00%	market for wastewater, average | wastewater, average | Cutoff, U - RER without CH	6.79965E-8 m3	6.64102E-11	
00.00%	market for tap water | tap water | Cutoff, U - RER without CH	6.79965E-6 kg	8.27327E-12	
00.00%	energy router construction HESS	2.59600E-11 Item(s)	5.29555E-8	
00.00%	energy router components, transported HESS	2.59600E-11 Item(s)	5.29332E-8	
00.00%	concrete, C20/25, for router slab, with cement II/A, transport CCES	4.07572E-11 m3	2.23717E-11	

Fig. 58. Contribution of HESS PSH-ACAES facility construction stage to Photochemical oxidant formation: terrestrial ecosystems impact category – ACAES, PSH and router construction

Impact category: Water use

Contribution	Process	Required amount	Total result [m3]	Direct contribution [m3]
100.00%	electricity production, high voltage, HESS PHS_A-CAES - PL	3.60000 MJ	0.00878	
99.95%	market for electricity, high voltage | electricity, high voltage | Cutoff, U - PL	5.63400 MJ	0.00877	
00.05%	HESS PHS A-CAES facility construction, in mine shafts - PL	2.59600E-11 Item(s)	4.06158E-6	
00.03%	adiabatic compressed air energy storage plant construction, in mine shaft A-CAES - PL	2.59600E-11 Item(s)	2.59394E-6	
00.01%	compressor 33.28 MW, transported A-CAES	2.59600E-11 Item(s)	7.83817E-7	
00.01%	concrete C30/37, for shaft plug, with CEM III/A, transport A-CAES	1.71518E-7 m3	5.71590E-7	
00.01%	expander 36 MW, transported A-CAES	2.59600E-11 Item(s)	4.56963E-7	
00.00%	reinforcement, for shaft plug, transported A-CAES	2.59600E-11 Item(s)	2.98017E-7	
00.00%	steel anchors for shaft plug, transport A-CAES	5.71120E-9 Item(s)	1.56992E-7	
00.00%	concrete C30/37, for pressure dams, with CEM III/A, transport A-CAES	3.54094E-8 m3	1.18004E-7	
00.00%	market for metal working, average for metal product manufacturing | metal working, av...	5.06791E-6 kg	9.28515E-8	
00.00%	TES tank, transport A-CAES	2.59600E-11 Item(s)	8.26393E-8	
00.00%	Sika seals, transport HESS A-CAES	6.79000E-7 kg	1.81569E-8	
00.00%	market for electricity, medium voltage | electricity, medium voltage | Cutoff, U - PL	4.21751E-6 MJ	6.62293E-9	
00.00%	PVC coated polyester ventilation duct, transport A-CAES	9.14571E-8 kg	4.21803E-9	
00.00%	basalt, transport A-CAES - PL	3.49908E-5 kg	2.60103E-9	
00.00%	service ventilation fan, transport A-CAES	2.59600E-11 Item(s)	1.21267E-9	
00.00%	control cabinet, transport PHS_A-CAES	2.59600E-11 Item(s)	1.97615E-10	
00.00%	market for wastewater, average | wastewater, average | Cutoff, U - RER without CH	6.40049E-9 m3	2.87886E-11	
00.00%	market for tap water | tap water | Cutoff, U - RER without CH	6.40049E-6 kg	2.52770E-11	
00.01%	hydropower plant construction, in mine-shaft HESS - PL	2.59600E-11 Item(s)	1.24791E-6	
00.01%	upper reservoir construction PHS - PL	2.59600E-11 Item(s)	9.44281E-7	
00.00%	penstock, for PHS, transport	2.59600E-11 Item(s)	2.36537E-7	
00.00%	concrete C30/37, for water dams, with CEM III/A, transport PHS	6.74960E-9 m3	2.24933E-8	
00.00%	Sika seals, transport HESS PHS	6.31244E-7 kg	1.69289E-8	
00.00%	upper technical platform, transport PHS	2.59600E-11 Item(s)	9.26397E-9	
00.00%	market for electricity, medium voltage | electricity, medium voltage | Cutoff, U - PL	5.17644E-6 MJ	8.12877E-9	
00.00%	reinforcement, for concrete slab/platform, transport HESS - PL	2.59600E-11 Item(s)	6.71996E-9	
00.00%	shut-off valve, transported PHS	2.59600E-11 Item(s)	2.51704E-9	
00.00%	hydraulic drive unit, transport PHS	2.59600E-11 Item(s)	5.08255E-10	
00.00%	market for wastewater, average | wastewater, average | Cutoff, U - RER without CH	6.79965E-8 m3	3.05840E-10	
00.00%	control cabinet, transport PHS_A-CAES	2.59600E-11 Item(s)	1.97615E-10	
00.00%	market for tap water | tap water | Cutoff, U - RER without CH	6.79965E-6 kg	2.68534E-11	
00.00%	energy router construction HESS	2.59600E-11 Item(s)	2.19734E-7	
00.00%	energy router components, transported HESS	2.59600E-11 Item(s)	2.19596E-7	
00.00%	concrete, C20/25, for router slab, with cement II/A, transport CCES	4.07572E-11 m3	1.38383E-10	

Fig. 59. Contribution of HESS PSH-ACAES facility construction stage to Water use impact category – ACAES, PSH and router construction