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ENVIRONMENTAL ASSESSMENT OF A 25 MWE FOSSIL-FIRED SUPERCRITICAL CO₂ CYCLE

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ENVIRONMENTAL ASSESSMENT OF A 25 MWE FOSSIL-FIRED SUPERCRITICAL CO₂ CYCLE

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ABSTRACT

In a global effort to decrease human-sourced Greenhouse-Gas (GHG) emissions, the operation of GHG-emitting plants is only justified if they offer a sufficient ability to smoothen the variability of the net electric demand. The EU-funded project sCO₂-Flex aims at designing a highly flexible 25-MWe supercritical CO₂ cycle suitable for such a cohabitation with renewable energies, and testing its main components. However the performance of such a cycle should not be reached at the expense of its environmental impact. Therefore the present paper focuses on the analysis of the environmental impact of such a plant, following most of the guidelines of the Life Cycle Assessment (LCA) method, as described in the ISO 14040-14044 standards.

The assessment described in this paper was conducted on the open source software OpenLCA using the database Ecoinvent, both acknowledged by the life cycle assessment community. It encompasses four major steps: goal and scope definition of the project, inventory analysis of the data, impact analysis and interpretation. Data was picked directly from the Ecoinvent database, gathered from the project's contributors, or extrapolated from hypotheses if data was to be missing in the inventory analysis. To compensate the uncertainties due to lack of data on equipment scaling and operation practices, an extensive sensibility analysis has been carried out to bring additional robustness to the study.

Overall, this paper shows that the majority of impacts appear to be driven by coal consumption. Hence, thanks to its higher efficiency, the sCO₂-flex power plant outperforms the reference water/steam plant in all the most robust environmental

impact categories: global warming potential at 100 years scope, human and resource use. Among the considered impacts categories, the most significant uncertainties arise from the use of nickel-based-alloys in the boiler.

INTRODUCTION

Supercritical CO₂ Brayton cycles attract wide interest due to their increased compactness as compared to steam Rankine cycles. This compactness is expected to translate into gains in flexibility (startup time and consumption, part-load efficiency, transient speed...) and costs, and is likely to come together with an increased nominal cycle efficiency. Those two major advantages are to be checked in the project sCO₂-Flex [1,2], by achieving the detailed design of a 25 MWe coal-fired supercritical CO₂ cycle.

While flexibility is key to a good complementarity with variable renewable energies, improvements in efficiency and compactness should make a plant more environmentally virtuous than the current state of the art, that is, steam Rankine cycles. However, the overall environmental impact of a plant depends on a variety of parameters (fuel consumption, quantity and quality of materials used, dispatch strategy...) at different stages of the plant's life (construction, operation, decommissioning). That is why the present study follows, whenever possible, the guidelines of Life Cycle Assessment as described in standards ISO 14040 and 14044 [3,4]. It should be mentioned that this study cannot, strictly speaking, be considered a valid Life Cycle Assessment, as no critical review has been carried on to date.

METHOD

Scope of the study

As usual in Life Cycle Assessment, all inputs and outputs are normalized by a reference unit, which is usually the main product delivered by the process analyzed. In the case of a sCO₂-Flex plant, it is the average kWh delivered to the Czech grid, as the boiler was designed for a Czech coal, whose properties are mentioned in [3]. Due to that choice, the results for the sCO₂-Flex plant are compared to an average coal-based Czech kWh. The analysis is restricted to the construction of equipment, landscaping, fuel treatment and supply as well as maintenance and power plant operation.

Because of the multiple uncertainties about the project development and its end of life policy, the adopted hypothesis was to consider that neither the ashes nor the buildings were recycled. This is a conservative hypothesis, and its consequences are discussed further at the end of this paper.

Reference plant's description

In coherence with the chosen reference unit, the reference to which the environmental impact of the sCO₂-Flex plant is to be compared is an average existing Czech coal plant, taken from the database Ecoinvent v3.6 [5]. That plant involves a steam cycle, and its performances result from the average of Czech Republic's installed coal power plants. Its main features are presented in Table 1.

Table 1: Reference plant's main features [6]

Assumption	Value	Unit
Dispatch strategy	5800	h/year
Plant life time	26	years
Plant average yearly efficiency	33.3	%
Plant raw output at full load	> 250	MWe

It should be highlighted that the benchmark plant is significantly bigger (> 250 MW vs. 25 MW) and older (26 years old in 2007 vs. state-of-the-art) than the sCO₂-Flex plant. While being bigger is a considerable advantage in terms of efficiency, being older involves a penalty in performance. The meaning of these differences is discussed in the interpretation section.

sCO₂-Flex plant performance assumptions

In order to determine the number of kWh produced over all the plant's life (with a direct impact on the construction phase's importance) and the amount of coal needed (which is of importance for the exploitation phase), it is necessary to make major assumptions on the way the plant will be used. They are summarized in Table 2.

Table 2: Main assumptions on the plant's dispatch and performance.

Assumption	Value	Unit
Dispatch strategy	5000	h/year
Plant life time	30	years
Plant yearly efficiency	36.4	%
Plant raw output at full load	25	MWe
Plant net output at full load	23.3	MWe

The first annual simulations of the plant, which correspond to a work still in progress, indicate that on the Czech market, a higher capacity factor can be reached. That aspect is treated in a dedicated sensitivity study at the end of this paper. The yearly efficiency was estimated based on the assumptions of Table 3.

Table 3: Main assumptions for the calculation of sCO₂-Flex plant's yearly efficiency

Assumption	Value	Unit
Cycle raw efficiency	42.3	%
Boiler LHV efficiency	92.5	%
Yearly number of startups	30	-
Energy penalty for a startup	20	MWhth
Overall auxiliary consumption & losses	1720	kWe

Selection of the impact categories and impact assessment methods

In the life cycle assessment method, the role of the impact categories is to identify the different damages on environment and human health that result from the product's use during its whole life cycle. The impact assessment methods that convert inventory results (that is, flows of mass or energy in out of the process) into environmental impacts are regularly updated. Though not the most recent one, ILCD 2016 [7] is still the most widely used in the Life Cycle Assessment community. All the selected impact categories used in the study were estimated using that method.

As the present study aims at having results that are as general as possible, the effects on human health and ecosystem quality are not in the scope of this assessment. They are considered too sensitive either to the type of coal burnt in the

plant or to the precise location of the plant. That leaves two indicators on which sCO₂-Flex power plant is compared to average Czech power plants:

- Greenhouse gases emissions are the main issue concerning coal plants. Their impact is assessed using the Global Warming Potential (GWP) on 100 years of each greenhouse gas documented in the IPCC climate change synthesis report [8]. GWP is expressed in kg CO₂ equivalent (kg CO₂-eq).
- To be sustainable, one must avoid using too much rare materials for the construction of the plant. The depletion of resources is evaluated by the Abiotic Depletion Potential (ADP) [9], which is the ratio between the annual consumption of an element or material and the square of its global reserve. This ratio is normalized by the ADP of Antimony (Sb), resulting in an indicator measured in kg Sb equivalent (kg Sb-eq).

Description of the model

This study was carried out using OpenLCA v1.10 [10] with the database Ecoinvent v3.6 [5].

As mentioned above, the major steps considered in the environmental assessment are the following:

1. The sCO₂-Flex power plant construction, divided in the present study into two sub steps:
 - The elements of the thermodynamic cycle: the boiler, the turbine, the two compressors, the high temperature recuperator, the low temperature recuperator, the pipework, the cold source;
 - The generic elements of the mechanical structure, of the coal supply chain at the plant, the instrumentation, the inventory management and the flue gas treatment;

For each element of the thermodynamic cycle, a dedicated process was created to model its production taking as inputs the resources (most of the time, specific alloys not available in the Ecoinvent database, whose production was modelled by creating a specific sub process), and energy use. The transport of the assembled equipment to the plant was then modelled using generic goods transport process data.

Concerning the generic elements of the plant's structure, due to a lack of data at this stage of the project the choice was set on extrapolating them linearly on installed capacity for a batch of hard coal-fueled power plants available in the Ecoinvent database (100MW and 500MW).

Because of the limited data on different installed capacities for hard coal power plants available in Ecoinvent to carry out the linear regression, this aspect is subject to a sensitivity analysis at the end of this article.

2. The fuel supply chain, which encompasses the extraction of hard coal, its transport and preparation. The coal is supposed to come from the European market (well-documented in Ecoinvent) and is either extracted from underground or surface mines then prepared to be used as a

fuel for the plant. It is finally transported by truck, boat or train. Once delivered to the plant, the coal is stored.

3. The operation of the plant for electricity production. This phase encompasses several sub steps:
 - The combustion of the coal in the boiler
 - The electricity production by expansion of the CO₂ in the turbine
 - The flue gas treatment
 - The collection and treatment of ashes from the combustion.

The diagrams summing up the different processes and their arrangement in the OpenLCA process tree are shown in Annexes A to D. All the processes whose name begins with "Market", concerning hard coal supply or electricity supply are directly taken from the Ecoinvent database; the others concerning the manufacturing of sCO₂-flex's specific equipment were created manually.

Origin of the input data

The generic data concerning the coal supply network was taken from the database Ecoinvent v3.6, in particular the fluxes that involve:

- The processes of the coal supply chain (extraction, preparation and road haul);
- The transport of equipment from their factory to the location of the plant. For this item, typical values of road haul in Europe were taken, as well as the latest criteria of environmental regulation concerning heavy goods vehicles;
- The construction of structural works and generic equipment relative to fossil-fueled plants (chimney, dedusting filters and desulfuration tower). Because of the lack of data concerning these generic equipments at this stage of the project, the data was estimated by linear extrapolation from dimensions of existing power plants relatively to their installed capacity (which in Ecoinvent ranges from 100MWe to 500MWe).

RESULTS

The inventory results are summarized in Table 4 to Table 7 (emissions to air, emissions to water, consumption of fossil fuels, consumption of metals). From those impacts, the two selected impact categories (GWP and ADP) are defined by gathering and pondering the input and output fluxes depending on their potential effect on environment. The overall impact results are shown in Table 8. They are systematically normalized to the reference unit, that is 1 kWh delivered to the Czech grid.

Table 4 - Summary of the emissions to air

	sCO ₂ -Flex	Average Czech coal plant	Unit
CO ₂	1,03E+00	1,09E+00	kg
N ₂ O	1,62E-05	1,45E-05	kg
SF ₆	4,25E-09	3,40E-09	kg
SO _x	1,47E-03	1,21E-03	kg
NO _x	2,77E-03	2,68E-03	kg
Particles	2,78E-03	2,32E-03	kg
VOC	1,58E-04	1,27E-04	kg
Arsenic	3,07E-08	2,14E-08	kg
Cadmium	8,80E-09	6,05E-09	kg
Chromium	3,20E-07	1,79E-07	kg
Copper	1,78E-07	9,89E-08	kg
Lead	1,47E-07	1,18E-07	kg
Mercury	2,07E-08	2,11E-08	kg
Nickel	3,26E-07	2,22E-07	kg
Zinc	1,75E-07	1,35E-07	kg

Table 5 - Summary of the emissions to water

	sCO ₂ -Flex	Average Czech coal plant	Unit
Arsenic	8,03E-06	7,03E-06	kg
Cadmium	6,71E-07	4,81E-07	kg
Chrome	9,10E-06	6,93E-06	kg
Copper	4,09E-05	1,86E-05	kg
Lead	6,27E-06	2,40E-06	kg
Mercury	2,03E-07	1,63E-07	kg
Nickel	7,43E-05	5,54E-05	kg
Zinc	8,94E-05	7,03E-05	kg

Table 6 - Summary of the fossil fuel consumption

	sCO ₂ -Flex	Average Czech coal plant	Unit
Oil	1,08E-02	1,52E-02	kg
Lignite	4,78E-03	6,80E-03	kg
Coal	4,57E-01	6,72E-01	kg
Gas	3,94E-03	1,18E-02	Nm ³
Uranium	1,70E-07	2,43E-07	kg

Table 7 - Summary of the metal consumption

	sCO ₂ -Flex	Average Czech coal plant	Unit
Aluminium	6,96E-05	8,63E-05	kg
Chromium	4,40E-05	3,52E-05	kg
Copper	1,17E-04	3,07E-05	kg
Iron	2,93E-03	3,30E-03	kg
Nickel	1,30E-04	2,64E-05	kg
Water	2,66E-01	3,70E-01	m ³

Table 8: Impact results for the two selected categories

Impact category - indicator	Value sCO ₂ -flex (unit)	Value average Czech plant (unit)
Climate change – GWP 100a	1.123 (kg CO ₂ -Eq)	1,168 (kg CO ₂ -Eq)
Resources - mineral, fossils and renewables	2.202E-06 (kg Sb-Eq)	9,71E-07 (kg Sb-Eq)

A more detailed comparison, over all three phases of the plants' life cycles, is shown on Figure 1 for GWP. On that criterion, the sCO₂-Flex plant has a lesser impact. The construction phase can be considered negligible in GWP, while the operation phase produces the major part of the GHG emissions.

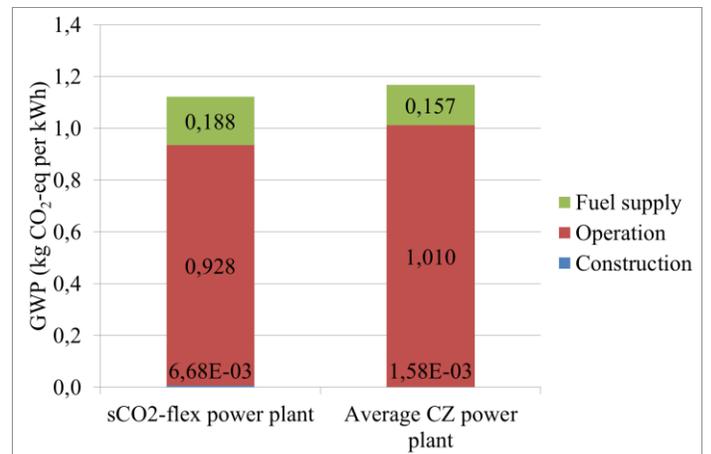


Figure 1: Detailed impact results for the GWP category

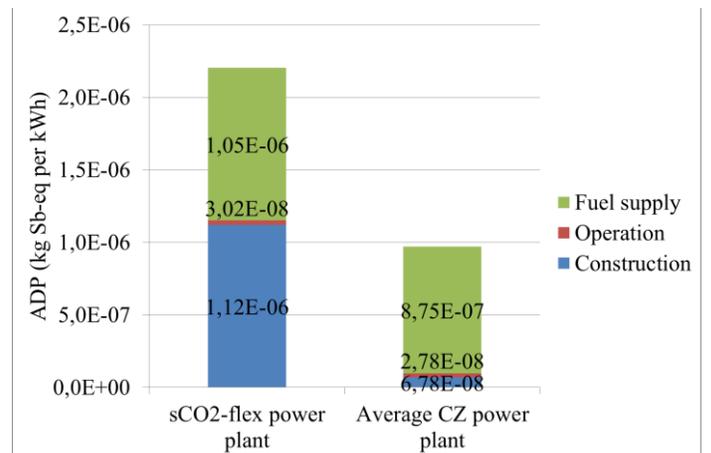


Figure 2: Detailed impact results for the ADP category

The total impacts results for the ADP impact category are displayed in Figure 2. On this criterion, the phase of plant operation has a very marginal impact. This impact category is dominated by the fuel supply phase, and in the case of the sCO₂-Flex plant, the construction phase. Here the sCO₂-Flex

plant appears to have a significantly higher impact than the average Czech plant used as a reference.

INTERPRETATION AND SENSITIVITY ANALYSIS

The main results presented above show that the sCO₂-Flex plant can be expected to outperform most Czech plants in GHG emissions sobriety but will need for more mineral resources in its construction. While the result on GWP could be challenged by a sensitivity study, there is no such debate on ADP.

It must however be noticed that ADP is usually a bigger issue for renewable energies than for fossil-fueled plants, as renewable energies, in spite of their very low GWP, exhibit a considerable consumption of non-renewable materials. A comparison of the sCO₂-Flex plant with world average PV and wind plants is provided on Figure 3. While the plant designed in sCO₂-Flex has a higher ADP than average wind power, it still performs significantly better than PV on that account.

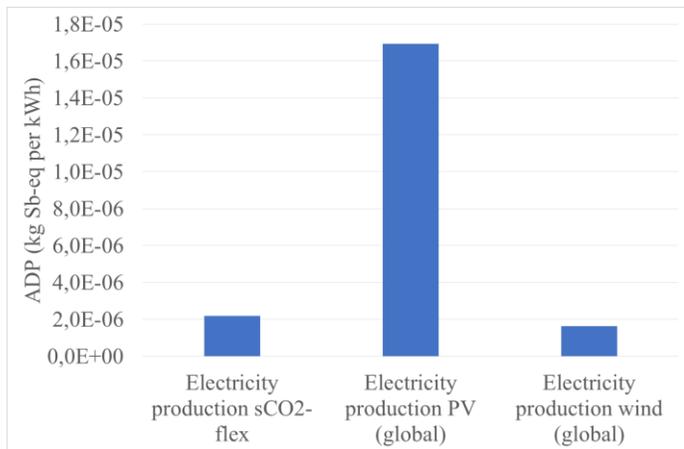


Figure 3: Comparison of sCO₂-Flex plant's ADP with common renewable energies

The fraction of nickel-based alloys in the boiler (which is the major element of the plant responsible for the ADP, see Figure 4) is a major stake both for environmental impact and for costs, and may still decrease, thus improving the plant's environmental impact. Conversely, the share of nickel-based alloys may still increase further if higher temperatures and efficiencies are sought. A sensitivity study is therefore dedicated to the share of nickel-based alloys in the boiler.

As can be seen on Figure 4, the share of nickel-based alloys in the boiler has a major impact on the overall ADP impact of the plant. When changing from 51% (which corresponds to the current knowledge of sCO₂-Flex plant's design) to 100%, the impact on ADP due to nickel-based alloys nearly doubles, while the impact due to iron-based alloys decreases by a similar factor. The overall impact increases significantly.

It must also be observed that even without including the effect of nickel-based alloys, the sCO₂-Flex plant has a significantly higher ADP than the benchmark plant. That may be

due to the fact that apart from the major equipments of the supercritical plant, the construction materials were extrapolated linearly from data available for much bigger plants (100 and 500 MWe outputs) and the need for construction materials is likely to have been widely overestimated in the process. Another plausible cause is that the iron-based alloys used in the sCO₂-Flex boiler are still high-alloyed steels, with a strong impact on ADP (though not so strong as nickel-based alloys).

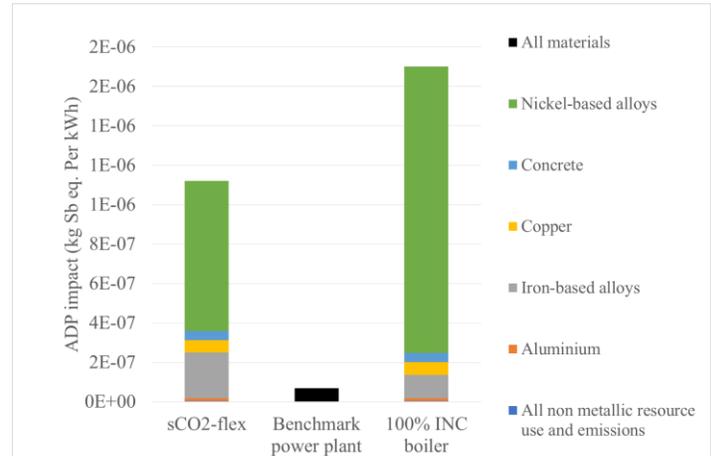


Figure 4: ADP impact on the construction phase split by material, with a sensitivity study on the share of Nickel-based alloys in the boiler

Depending on the future size of the plant, its efficiency may increase, with a double effect on the plant's environmental footprint: its specific GHG emissions would decrease during operation, and the capacity factor, i.e. the number of hours of full-load equivalent production over one year, would increase, thus diminishing the relative importance of the construction phase. The results of the dedicated sensitivity studies are displayed on Figure 5 and Figure 6.

When changing the plant's efficiency, the choice was made not to affect the plant's net output. Only the amount of coal provided and burnt changed, which only had an impact on the fuel supply and operation phases. This lowers the ADP of the plant in those two phases; however, the most significantly lowered impact is GWP, as shown on Figure 5. Construction is not impacted by a change in efficiency, if one assumes that the plant's design is not affected.

As regards dispatch strategy, if one considers that the plant's yearly efficiency is unchanged there is no impact on fuel supply and plant operation phases. Such a change only affects the impact of the construction phase, as the same design allows the production of more kWh. As mentioned above, the dispatch strategy is directly dependent on the plant's efficiency. Nevertheless the extent of that effect is market-dependent, and could not be modeled in the present study.

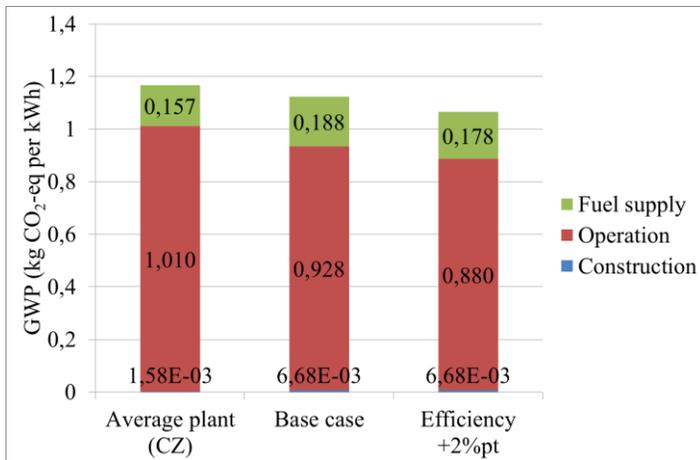


Figure 5: Impact of a +2%pt increment in plant efficiency (LHV-based) on GWP

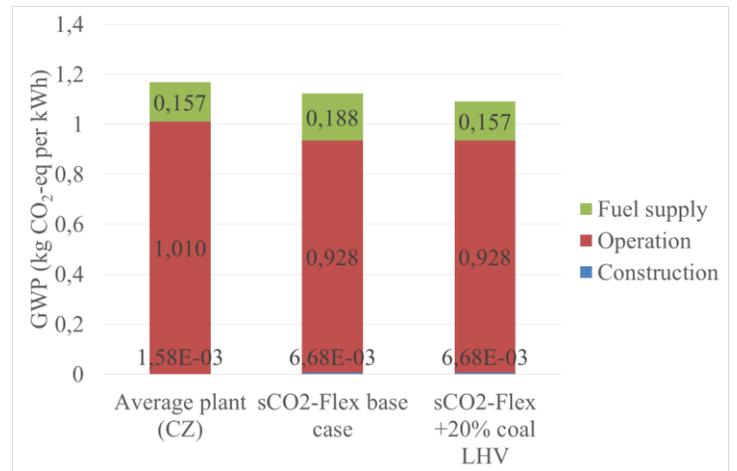


Figure 7: Impact on GWP of using a coal with +20% LHV

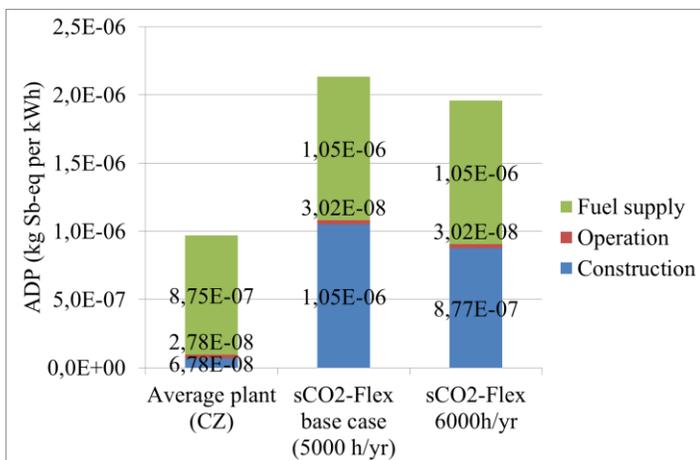


Figure 6: Impact on ADP of a +1000 h/yr full-load equivalent dispatch

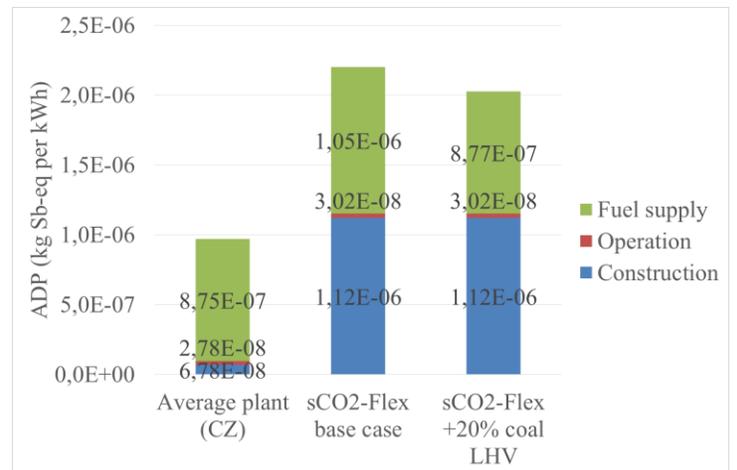


Figure 8: Impact on ADP of using a coal with +20% LHV

Finally, one of the unexpected outcomes of the study is that the sCO₂-Flex plant has a higher impact during its fuel supply phase. As the same module for coal mining and supply was used for the sCO₂-Flex plant and for the average Czech plant used as benchmark, the impact of coal supply depends linearly on the amount of coal used during the plant's life. Thus using a coal with a higher LHV (and assuming, in a first approach, that it does not affect significantly the plant's design and emissions) should result in a lower environmental impact during this part of the plant's life.

Figure 7 and Figure 8 show that, for both GWP and ADP, an increase of coal LHV by 20% nearly equalizes the impact of sCO₂-Flex plant and the benchmark plant on their fuel supply phase. This confirms the significant sensitivity of this phase's impact to the type of coal that is used, and the low relevance of this phase's impact when comparing supercritical CO₂ and steam cycles.

Additionally, a number of other parameters were subject to a sensitivity study:

- the amount of construction materials can be shown to have a limited impact on the overall ADP (-2.7% for a -20% decrease in structural materials consumption).
- the transport distance of equipment and the energy consumption during materials production have little to no impact on the plant's overall ADP and GWP, as ADP is dominated by coal supply and use of materials for construction, and GWP is dominated by the combustion and supply of coal during operation.
- oil and gas consumption during operation also have no impact on the overall result, as a double consumption has no visible effect on the plant's GWP during operation. This is not surprising, as oil and gas are typically used during cold startups only, that is a few hours per year.

CONCLUSION

The partial environmental assessment of the supercritical CO₂ cycle developed in the project sCO₂-Flex shows that this technology can be expected to bring a significant improvement on GWP, to the expense of a considerably higher ADP. The use of nickel-based alloys is the major penalty on such a plant (construction materials probably overestimated, but no significant impact on that conclusion). That is where efforts should be made, from both economic and environmental points of view. Nevertheless, as the present study assumes a total absence of reuse of recycling, the actual impact of such a plant can be expected to be lower.

The comparison between the plant developed in sCO₂-Flex and the average Czech plant taken as benchmark is asymmetric on several aspects. For instance, GWP reduction should be taken with care as it results from the higher efficiency of a small, state-of-the-art plant as compared to a big, old average plant. The net effect of age and size on efficiency is not clear at this point. Similarly, the fuel used in both plants is not the same, which has an artificial impact on the environmental impact of the fuel supply phase. Finally, the impact of an increased efficiency on the dispatch strategy of the plant could not be taken into account in the present study.

Further works on the subject could include the environmental impact assessment of a small state-of-the-art water/steam plant, designed with the same constraints as in sCO₂-Flex. Furthermore, the supercritical CO₂ cycle developed in sCO₂-Flex should also provide additional flexibility and substantial changes in maintenance and operation (much smaller turbine making maintenance easier and availability potentially higher). An estimate of the impact of these improvements on the annual dispatch of the plant would be a precious addition to the present study.

NOMENCLATURE

ADP = Abiotic Depletion Potential (kg Sb-eq)
GHG = GreenHouse Gas(es)
GWP = Global Warming Potential (kg CO₂-eq), here considered on 100 years
kg CO₂-eq = kilogram CO₂ equivalent
kg Sb-eq = kilogram antimony equivalent
LHV = Lower Heating Value
PV = PhotoVoltaic power

ACKNOWLEDGEMENTS

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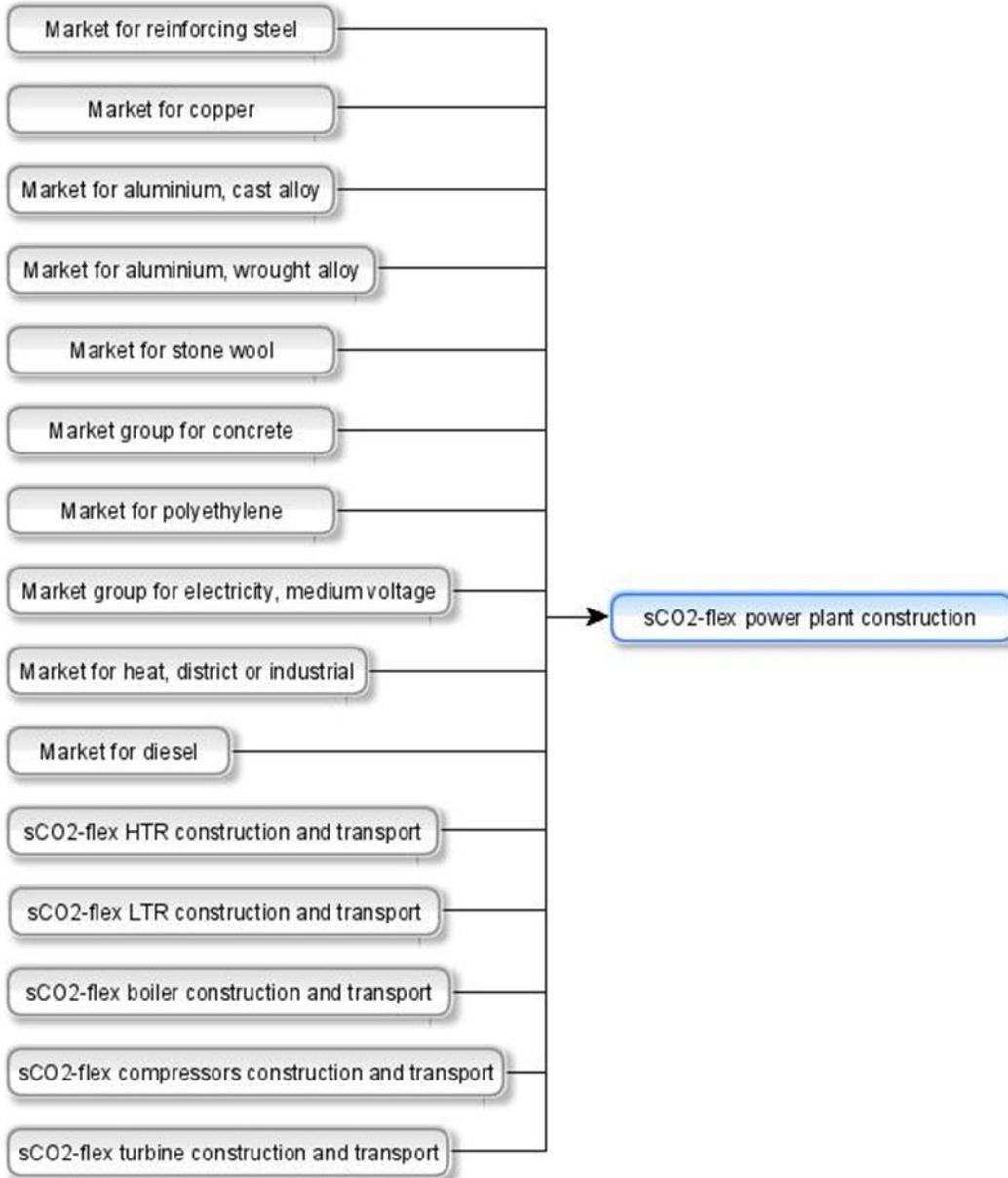
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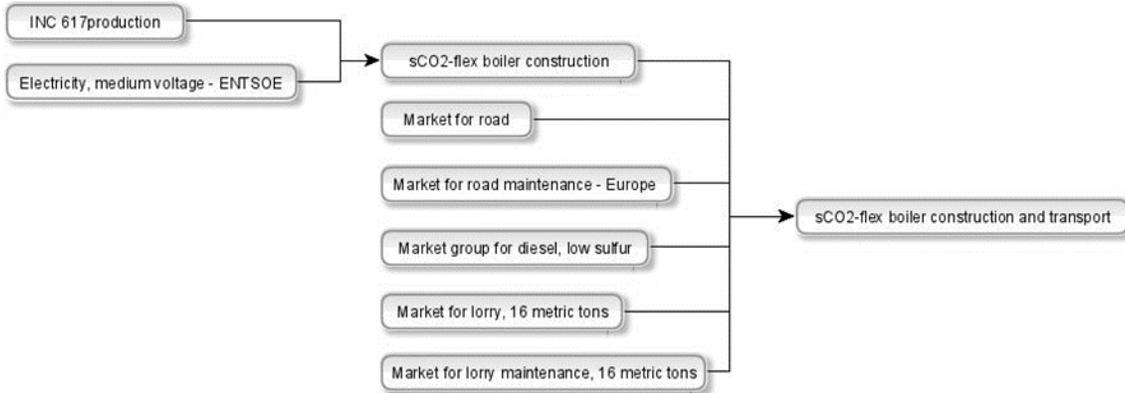
ANNEX A

PROCESS DIAGRAM FOR THE sCO₂-FLEX POWER PLANT CONSTRUCTION



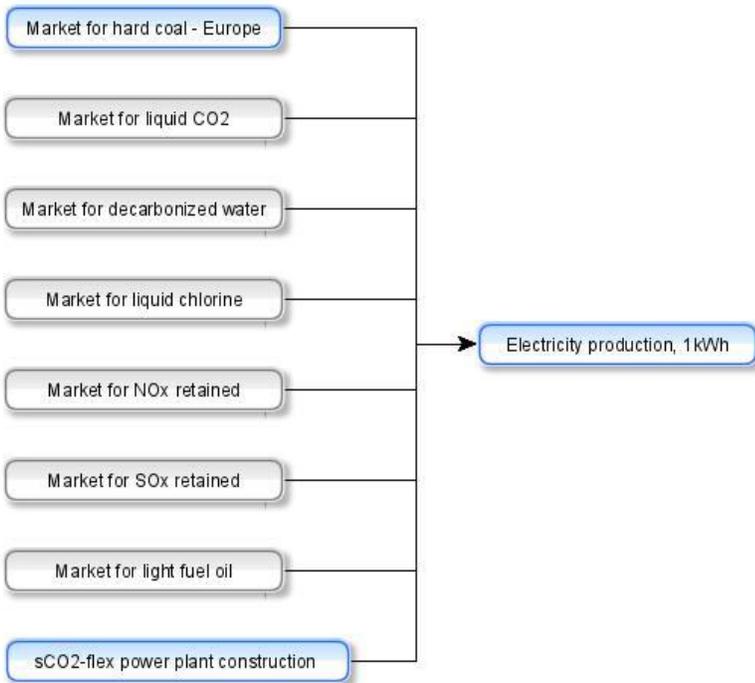
ANNEX B

DETAIL OF THE PROCESS DIAGRAM FOR THE sCO₂-FLEX BOILER CONSTRUCTION AND TRANSPORT



ANNEX C

PROCESS DIAGRAM FOR THE OPERATION PHASE OF THE sCO₂-FLEX PLANT



ANNEX D

PROCESS DIAGRAM FOR THE FUEL SUPPLY PHASE OF THE SCO₂-FLEX PLANT

