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

Victor MAQUART
Armines
Sophia Antipolis, France

Benoît VALENTIN*
EDF R&D
Chatou, France
Email: benoit.valentin@edf.fr

Albannie CAGNAC
EDF R&D
Chatou, France

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 flexibility to satisfy a highly variable net electric demand in electric grids with a significant share of intermittent renewable power plants. The EU-funded project sCO2-Flex aims at designing a highly flexible 25-MWe supercritical CO_2 cycle suitable for such a complementarity 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 LCA 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 sensitivity analysis has been carried out to bring additional robustness to the study.

Considering the two impact categories selected in this paper (global warming potential at 100 years scope and abiotic resource depletion), the sCO2-Flex plant outperforms the reference water/steam plant for global warming potential thanks to its higher efficiency. This is however at the expense of a considerably higher abiotic resource depletion. Regarding the latter impact category, the most significant uncertainties arise from the amount of nickel-based-alloys used in the boiler.

INTRODUCTION

Supercritical CO_2 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 (start-up 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 CO_2 cycle.

While flexibility is key to a good complementarity with variable renewable energies, improvements in efficiency and compactness should make a plant more environmentally benign 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.

* corresponding author(s)

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The literature is quite abundant regarding the Life Cycle Assessment of coal power plants, however a vast majority of studies focus on greenhouse gas emissions only and are difficult to compare due to very different assumptions. The World Energy Council [5] and Turconi et al. [6] compiled data about the emissions to air of all power production technologies. Whitaker et al. [7] screened publications about greenhouse gas emissions of coal-fired power plants and harmonized their results for a better comparison in spite of different assumptions. Weisser [8] provided guidelines for the Life Cycle Analysis of power production technologies. In particular, this publication identified the main parameters affecting the results: contrary to other types of power plants, the lifetime emissions of coal plants are significantly dependent on the type of fuel burnt and the extraction practices. Finally, Mills [9] investigated the suitability of life cycle assessment methods for the comparison of different coal power plant technologies and focused on the emissions during both combustion and non-combustion stages of the plant's life.

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 the sCO2-Flex plant, it is the average kWh delivered to the Czech grid, as the boiler was designed for a Czech coal. 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, it was assumed that neither the ashes nor the buildings were recycled. This is a conservative assumption, and its consequences are discussed further at the end of this paper.

Reference plant's description

In coherence with the reference unit chosen, the reference to which the environmental impact of the sCO2-Flex plant is to be compared is an average existing Czech coal power plant, taken from the database Ecoinvent v3.6 [10]. 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.

The reference plant does not physically exist: it is a model built by Ecoinvent, using data from several Czech plants, in order to reflect the average environmental impact of the Czech coal power plants.

Table 1: Reference plant's main features [11]

Assumption	Value	Unit
Dispatch strategy	5800	h/year
Plant life time	26	years
Plant average yearly efficiency	33.3	%
Plant gross 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 lifetime (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. Both plants do not have the exact same dispatch strategy: the lifetime of the sCO2-Flex plant was set to 30 years and its annual number of hours equivalent full-load was adjusted so as to match the total number of running hours over the reference plant's lifetime. As a result, both plants are assumed to produce power for 150000 hours equivalent full-load, which allows a fair comparison.

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 gross 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 using the assumptions of Table 3.

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

Assumption	Value	Unit
Cycle gross efficiency	42.3	%
Boiler LHV efficiency	92.5	%
Yearly number of start-ups	30	-
Energy penalty for a start-up	20	MWhth
Overall auxiliary consumption & losses	1.720	MWe

The plant burns Bilina-HP1 coal [2], whose ash-free chemical composition on a molar basis is C: 37.85%, H: 34.81%, O: 9.16%, N: 0.40%, S: 0.25%, H_2O: 17.53% with a LHV equal to 16.9 MJ/kg.

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 or out of the process) into environmental impacts are regularly updated. Though not the most recent one, ILCD 2016 [12] 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:

- GHG emissions are widely considered 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 [13]. GWP is expressed in kg CO_2 equivalent (kg CO_2-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 Resource Depletion (ARD) [14]. In this indicator, the contribution of each material corresponds to the ratio between its mass consumption by the process and the square of its global reserve, normalized by the same ratio for antimony (Sb), which is taken as the reference material. This results in an indicator measured in kg Sb equivalent (kg Sb-eq).

Description of the model

This study was carried out using OpenLCA v1.10 [15] with the database Ecoinvent v3.6 [10].

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 cooling equipment;
    - 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 with regards to installed capacity from 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:
    - Coal combustion in the boiler
    - Electricity production by expansion of the CO_2 in the turbine
    - Flue gas treatment
    - 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 on nameplate power (ranging from 100 to 500 MWe), from power plants documented in Ecoinvent.

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 ARD) 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

	sCO2-Flex	Average Czech coal plant	Unit
CO_2	1,03	1,09	kg/kWh
N_2O	1,62E-05	1,45E-05	kg/kWh
SF6	4,25E-09	3,40E-09	kg/kWh
SOx	1,47E-03	1,21E-03	kg/kWh
NOx	2,77E-03	2,68E-03	kg/kWh
Particles	2,78E-03	2,32E-03	kg/kWh
VOC	1,58E-04	1,27E-04	kg/kWh
Arsenic	3,07E-08	2,14E-08	kg/kWh
Cadmium	8,80E-09	6,05E-09	kg/kWh
Chromium	3,20E-07	1,79E-07	kg/kWh
Copper	1,78E-07	9,89E-08	kg/kWh
Lead	1,47E-07	1,18E-07	kg/kWh
Mercury	2,07E-08	2,11E-08	kg/kWh
Nickel	3,26E-07	2,22E-07	kg/kWh
Zinc	1,75E-07	1,35E-07	kg/kWh

Table 5 - Summary of the emissions to water

	sCO2-Flex	Average Czech coal plant	Unit
Arsenic	8,03	7,03	mg/kWh
Cadmium	0,67	0,48	mg/kWh
Chrome	9,10	6,93	mg/kWh
Copper	40,9	18,6	mg/kWh
Lead	6,27	2,40	mg/kWh
Mercury	0,203	0,163	mg/kWh
Nickel	74,3	55,4	mg/kWh
Zinc	89,4	70,3	mg/kWh

Table 6 - Summary of the fossil fuel consumption

	sCO2-Flex	Average Czech coal plant	Unit
Oil	10,8	15,2	g/kWh
Lignite	4,78	6,80	g/kWh
Coal	457	672	g/kWh
Gas	3,94E-03	1,18E-02	Nm^3/kWh
Uranium	1,70E-04	2,43E-04	g/kWh

Table 7 - Summary of the metal consumption

	sCO2-Flex	Average Czech coal plant	Unit
Aluminium	69,6	86,3	mg/kWh
Chromium	44,0	35,2	mg/kWh
Copper	117	30,7	mg/kWh
Iron	2930	3300	mg/kWh
Nickel	130	26,4	mg/kWh
Water	0,266	0,370	m^3/kWh

Table 8: Impact results for the two selected categories

Impact category - indicator	Value sCO2-Flex (unit)	Value average Czech plant (unit)
Climate change – GWP 100a	1.123 (kg CO_2-Eq per kWh)	1,168 (kg CO_2-Eq per kWh)
Resources - mineral, fossils and renewables	2.202E-06 (kg Sb-Eq per kWh)	9,71E-07 (kg Sb-Eq per kWh)

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 considered negligible in GWP, while the operation phase produces the major part of the GHG emissions.

The total impacts results for the ARD 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.

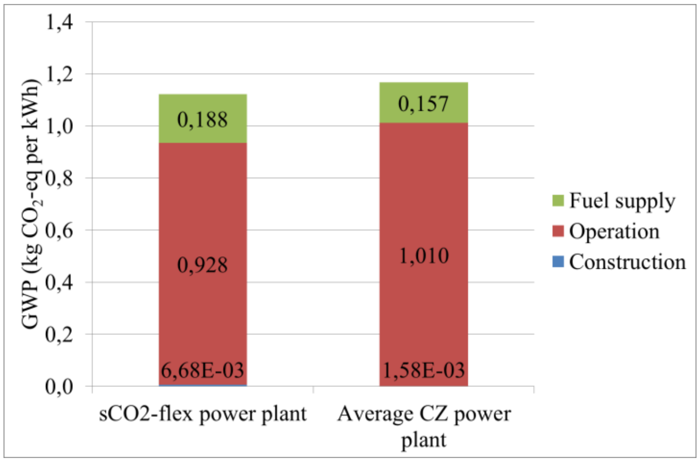

Figure 1: Detailed impact results for the GWP category

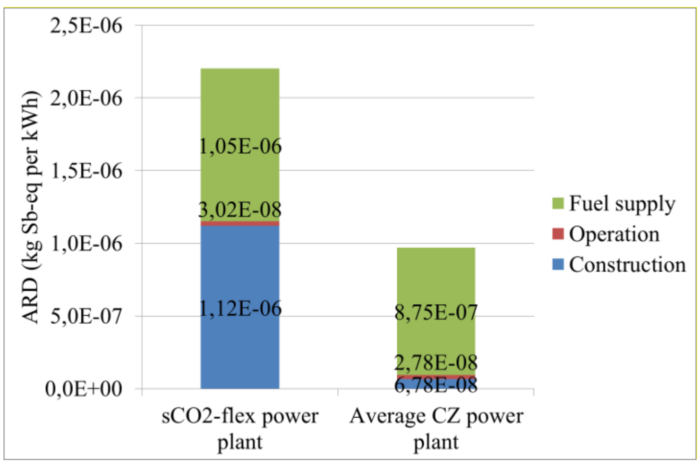

Figure 2: Detailed impact results for the ARD category

INTERPRETATION AND SENTIVITY ANALYSIS

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

It must however be noticed that ARD 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 ARD than average wind power, it still performs significantly better than PV on that account.

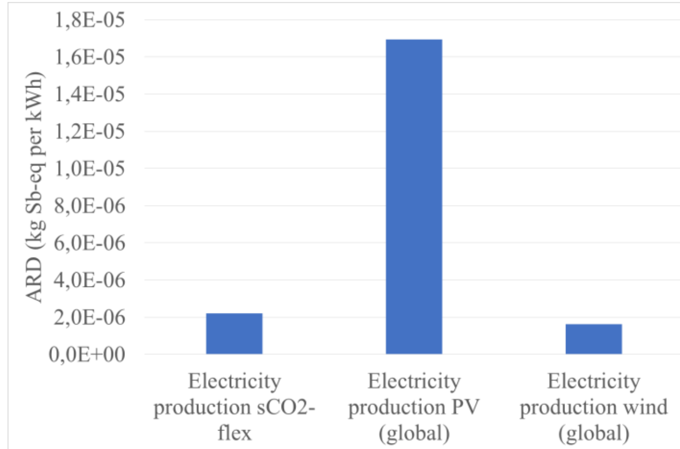

Figure 3: Comparison of sCO2-Flex plant's ARD with common renewable energies

The fraction of nickel-based alloys in the boiler (which is the major element of the plant responsible for the ARD, 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 influence on the overall ARD 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 ARD 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.

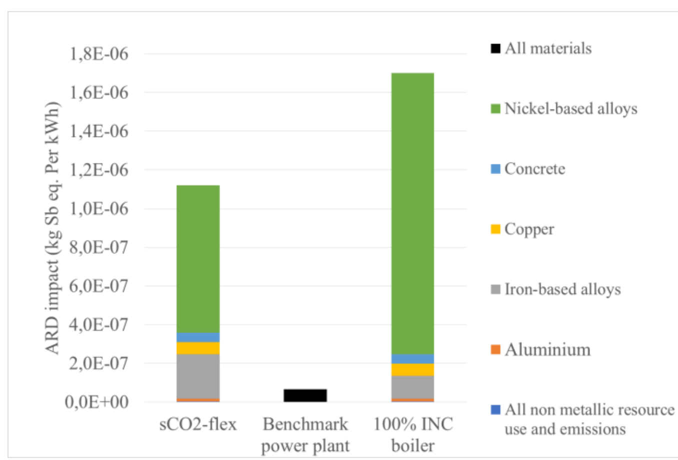

Figure 4: ARD impact on the construction phase split by material, with a sensitivity study on the share of Nickel-based alloys in the boiler

It must also be observed that even without including the effect of nickel-based alloys, the sCO2-Flex plant has a significantly higher ARD 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 ARD (though not so strong as nickel-based alloys).

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 ARD 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.

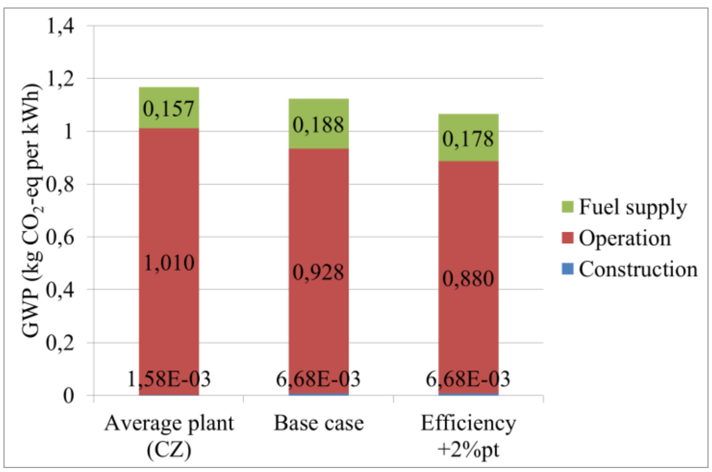

Figure 5: Impact of a +2%pt increment in plant efficiency (LHV-based) on GWP

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.

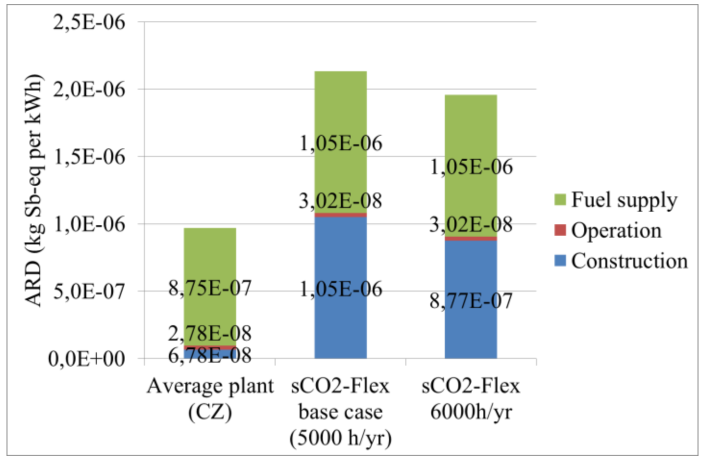

Figure 6: Impact on ARD of a +1000 h/yr full-load equivalent dispatch

Finally, one of the unexpected results is that the sCO2-Flex plant has a higher impact during its fuel supply phase (see Figure 1 and Figure 2). 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 lower moisture contents, resulting in 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 coal consumption for the same power output, thus in a lower environmental impact during the phase of fuel supply.

Figure 7 and Figure 8 show that, for both GWP and ARD, 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 its low relevance when trying to perform a general comparison between supercritical CO_2 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 ARD (-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 ARD and GWP, as ARD 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 start-ups only, that is only a few hours per year.

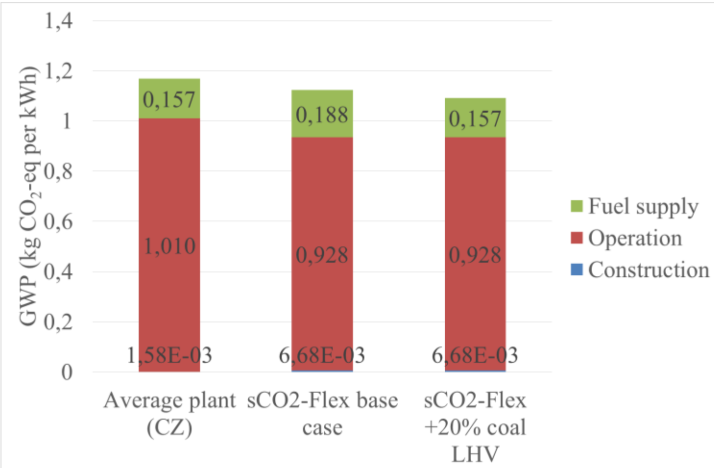

Figure 7: Impact on GWP of using a coal with +20% LHV

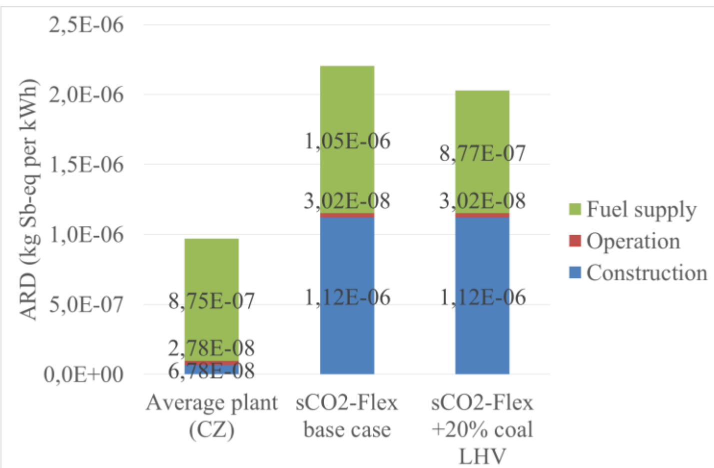

Figure 8: Impact on ARD of using a coal with +20% LHV

CONCLUSION

The partial environmental assessment of the supercritical CO_2 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 ARD. 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 in several ways. 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: while the fuel used in the reference plant reflects the average fuel consumption of Czech coal power plants, a specific fuel had to be selected for the detailed design of the sCO2-Flex boiler. This has an artificial influence 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 CO_2 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

ARD = Abiotic Resource Depletion (kg Sb-eq)
GHG = GreenHouse Gas(es)
GWP = Global Warming Potential (kg CO_2-eq), here considered on 100 years
kg CO_2-eq = kilogram CO_2 equivalent
kg Sb-eq = kilogram antimony equivalent
LHV = Lower Heating Value
PV = PhotoVoltaic power

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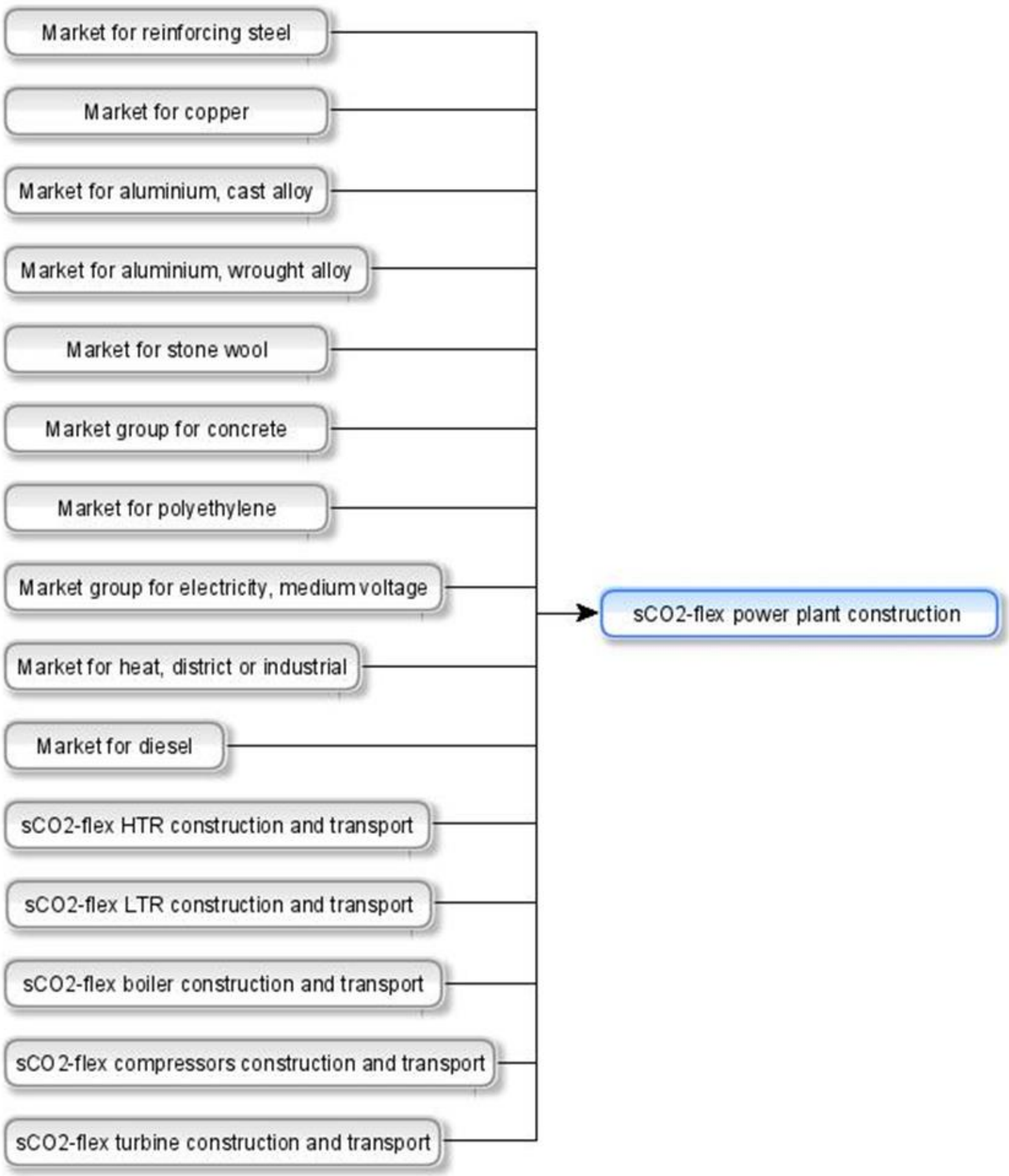
REFERENCES

[1] Mecheri, M., and Bedogni, S., 2018, *Report on the Selected Cycle Architecture*, D1.3.
[2] Alfani, D., Astolfi, M., Binotti, M., Macchi, E., and Silva, P., 2019, "Part-Load Operation of Coal Fired SCO2 Power Plants," *Proceeding of the 3rd European Supercritical CO2 Conference*, Paris, France.
[3] 2006, "ISO 14040 : Environmental Management - Life Cycle Assessment - Principles and Framework."
[4] 2006, "ISO 14044 : Environmental Management - Life Cycle Assessment - Requirements and Guidelines."
[5] World Energy Council, 2004, *Comparison of Energy Systems Using Life Cycle Assessment*, World Energy Council.
[6] Turconi, R., Boldrin, A., and Astrup, T., 2013, "Life Cycle Assessment (LCA) of Electricity Generation Technologies: Overview, Comparability and Limitations," Renewable and Sustainable Energy Reviews, **28**, pp. 555–565.
[7] Whitaker, M., Heath, G. A., O'Donoughue, P., and Vorum, M., 2012, "Life Cycle Greenhouse Gas Emissions of Coal-

Fired Electricity Generation: Systematic Review and Harmonization," Journal of Industrial Ecology, **16**, pp. S53–S72.
[8] Weisser, D., 2007, "A Guide to Life-Cycle Greenhouse Gas (GHG) Emissions from Electric Supply Technologies," Energy, **32**(9), pp. 1543–1559.
[9] Mills, S. J., IEA Coal Research, and Clean Coal Centre, 2005, *Coal Full Life Cycle Analysis*, IEA Coal Research, Clean Coal Centre, London.
[10] Wernet, G., Bauer, C., Steubing, B., Reinhard, J., Moreno-Ruiz, E., and Weidema, B., 2016, "The Ecoinvent Database Version 3 (Part I): Overview and Methodology," Int J Life Cycle Assess, **21**(9), pp. 1218–1230.
[11] Dones, R., Bauer, C., and Rôder, A., 2007, "Kohle," *Sachbilanzen von Energiesyste-Men: Grundlagen Für Den Ökologischen Vergleich von Energiesystemen Und Den Einbezug von Energiesys-Temen in Ökobilanzen Für Die Schweiz*, Paul Scherrer Institut Villigen, Swiss Centre for Life Cycle Inventories, Dübendorf, CH.
[12] Wolf, M.-A., Pant, R., Chomkhamsri, K., Sala, S., Pennington, D., European Commission, and Joint Research F06776Centre, 2012, *The International Reference Life Cycle Data System (ILCD) Handbook: Towards More Sustainable Production and Consumption for a Resource-Efficient Europe.*, Publications Office, Luxembourg.
[13] Intergovernmental Panel on Climate Change, ed., 2014, "Anthropogenic and Natural Radiative Forcing," *Climate Change 2013 - The Physical Science Basis*, Cambridge University Press, Cambridge, pp. 659–740.
[14] van Oers, L., Guinée, J. B., and Heijungs, R., 2020, "Abiotic Resource Depletion Potentials (ADPs) for Elements Revisited—Updating Ultimate Reserve Estimates and Introducing Time Series for Production Data," Int J Life Cycle Assess, **25**(2), pp. 294–308.
[15] Ciroth, A., 2007, "ICT for Environment in Life Cycle Applications OpenLCA — A New Open Source Software for Life Cycle Assessment," Int J Life Cycle Assess, **12**(4), pp. 209–210.

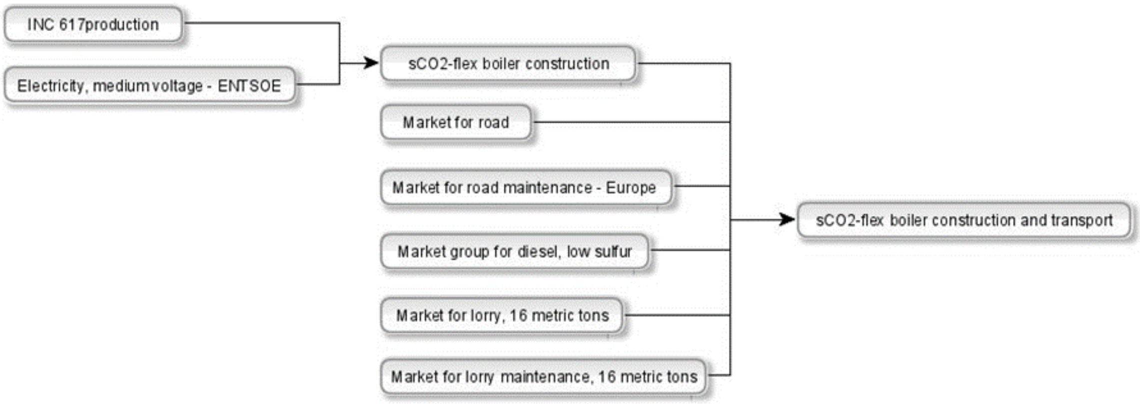
ANNEX A

PROCESS DIAGRAM FOR THE SCO2-FLEX POWER PLANT CONSTRUCTION



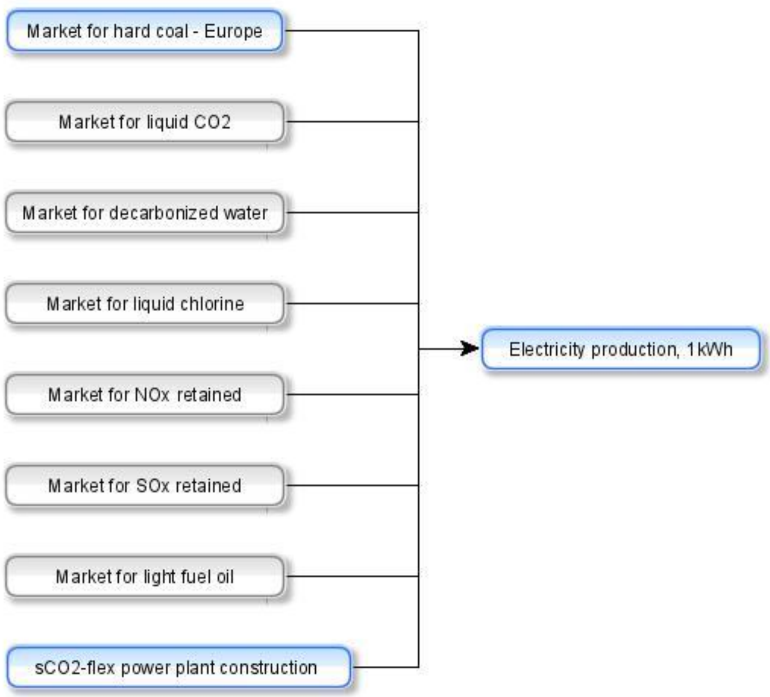
ANNEX B

DETAIL OF THE PROCESS DIAGRAM FOR THE SCO2-FLEX BOILER CONSTRUCTION AND TRANSPORT



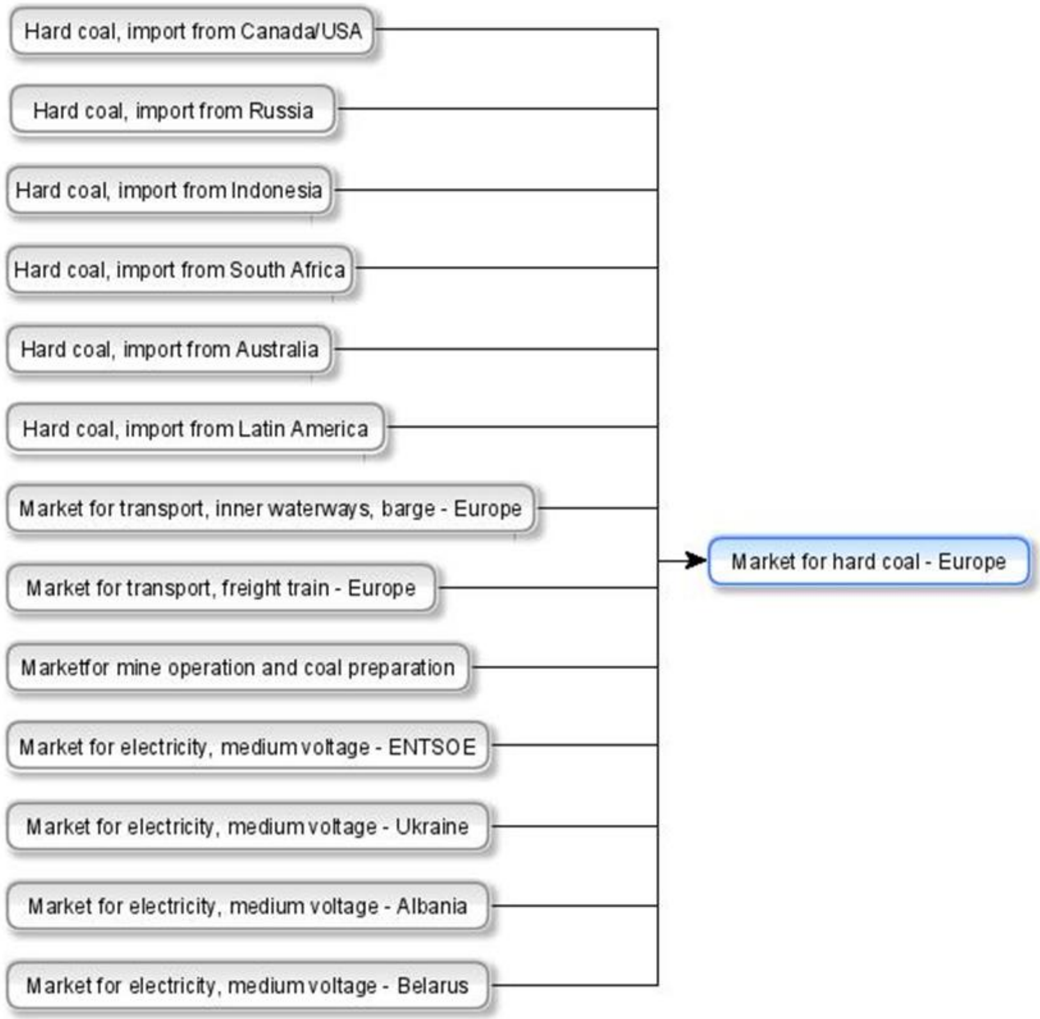
ANNEX C

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



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