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KEROGREEN

"Production of Sustainable aircraft grade Kerosene from water and air powered by Renewable Electricity, through the splitting of CO_2, syngas formation and Fischer-Tropsch synthesis"

Project No: 763909

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Final report "Sustainability Assessment"

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Table of Contents

Abbreviations

CAPEX: Capital Expenditures
CEPCI: Chemical Engineering Plant Cost Index
DAC: Direct Air Capture
GWP: Greenhouse Warming Potential
LCA: Life Cycle Assessment
LCC: Life Cycle Costing
LCI: Life Cycle Inventory
LCOE: Levelized Cost of Energy
LCIA: Life Cycle Impact Assessment
LCSA: Life Cycle Sustainability Assessment
OPEX: Operational Expenditures
PSA: Pressure Swing Absorption
PtX: Power to X
S-LCA: social Life Cycle Assessment
SE-WGS: Sorption-enhanced Water Gas Shift
SOC: Solid Oxide Cell
VP: Vacuum pump

1 Purpose

The purpose of this report is to present potential sustainability opportunities, issues and risks that could come up with the implementation of KEROGREEN. Environmental, economic and social sustainability aspects are addressed. Its purpose is not to present technical characteristics in detail.

2 Methodology

2.1 Goal & Scope

Goal & Scope and the methods of Life Cycle Assessment (LCA), Life Cycle Costing (LCC) and Social Life Cycle Assessment (S-LCA) that are used for this sustainability assessment were described in deliverable D6.6 Conceptual Paper on acceptability of KEROGREEN and deliverable D6.1 Methods, goal and scope.

The goal is to identify ecological, economic and social hot spots and risks that could arise with the implementation of KEROGREEN in comparison to existing and innovative competing technologies. Similarly, opportunities and chances that could come up with the implementation are addressed.

Despite the high level of uncertainty, the results can be used to address risks at an early stage and implement counter measures. Furthermore, the holistic assessment of environmental, economic and social aspects is supposed to support the methodological development in the field of sustainability assessment. As a step beyond the quantitative results of the sustainability assessment, an approach for the assessment of acceptability is part of this report.

Unlike deliverables 6.1 – 6.5, this deliverable is intended for the public audience. The scope includes the entire process chain of fuel production with energy, water and CO_2 provision up until the point of provided fuel. The use-phase is not part as no further insights on the related impacts were gained.

The geographical scope for the operation of a theoretical KEROGREEN plant includes the following countries that were chosen on the basis of Frontier Economics (2018) [1]: Norway, Chile, Morocco, China, Australia and Saudi Arabia. Additionally, Germany is assessed to represent sub-optimal conditions for wind power and PV which is interesting with respect to the important role of PTF for the German Energiewende. Further, as Brazil and South Africa, Germany is modelled as potential biofuel production location for the competing technologies, which have been the focus of KEROGREEN deliverable D6.4. Fossil kerosene is modelled with the international supply chains that are included in the ecoinvent dataset market for kerosene – Europe without Switzerland and global statistics of oil producing countries [2].

2.2 Life Cycle Inventory

The models are based on material, energy and cost flows that were developed during the course of the KEROGREEN project, complemented with additional data from literature sources or related projects, intensively discussed and agreed by all partners. Four different concepts of potential KEROGREEN plants are compared within the sustainability assessment.

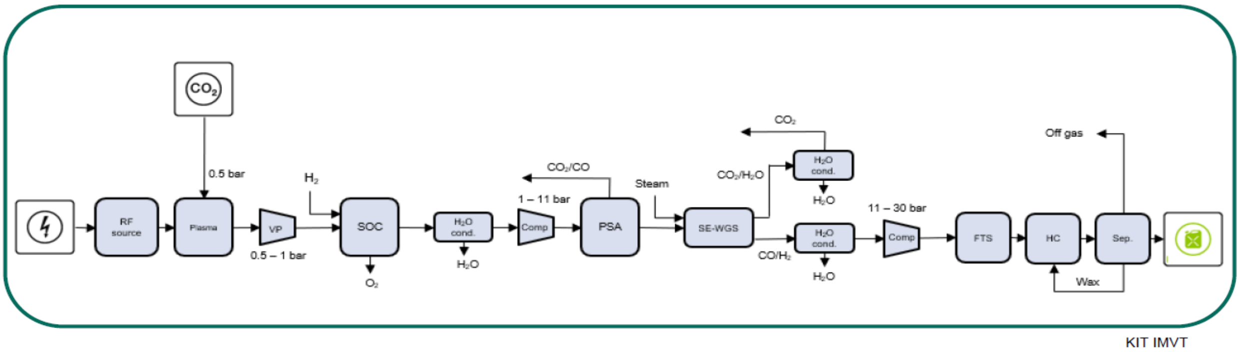

Figure 1: KEROGREEN pilot concept (H2 addition in experimental operation mode)

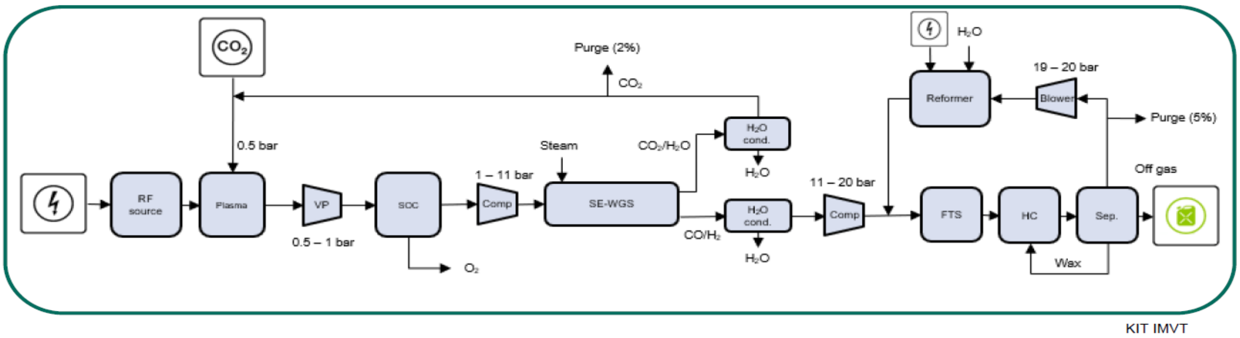

Figure 2: KEROGREEN industrial concept 1

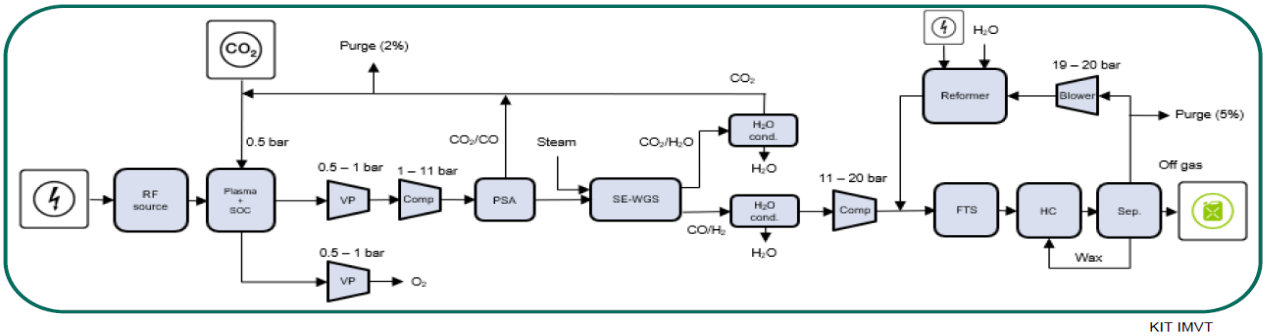

Figure 3: KEROGREEN industrial concept 2

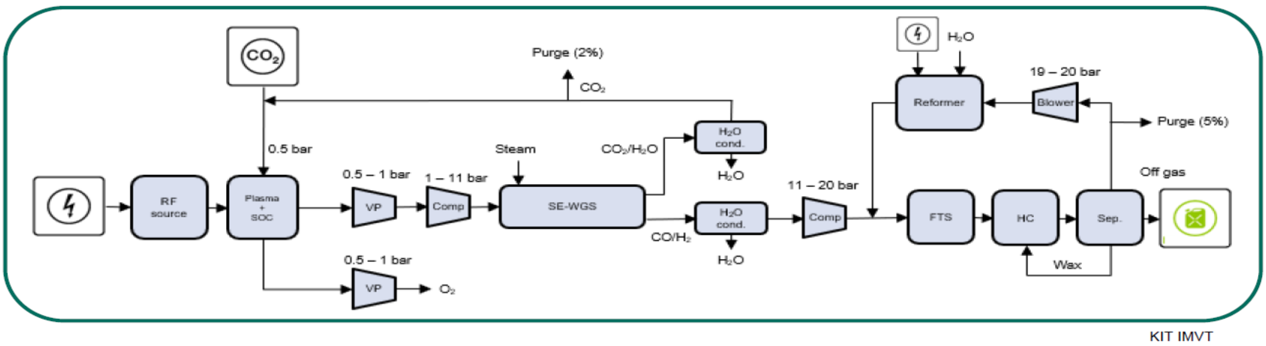

Figure 4: KEROGREEN industrial concept 3

All four concepts are modelled with an equal product output of around 74 kg/h hydrocarbons. The differences between the concepts are:

- The solid oxide cell (SOC) oxygen separator is integrated in the plasmolysis part within concept 2 and 3. This influences the required surface area of SOC.
- The pressure swing adsorption (PSA) CO purifier is only part of the pilot concept and concept 2. The other two concepts rely solely on the sorption-enhanced water-gas-shift (SE-WGS) to remove the CO_2 and form syngas.

The modelled process steps of this section are all based on simulations and assumptions and therefore don´t reflect the actual environmental impacts, costs or social risks of a real plant at this point in time. The level of uncertainty is high. Data which has not been available at the time of preparing this report, has been substituted with related factors, surrogate processes from databases and literature sources. More technical details can be found in the respective deliverables of the technical project partners.

Energy provision

The electricity generation / provision is not within the technological scope of the project, but plays a major role in the sustainability assessment of any Power-to-X technology and is modelled on the basis of literature. Photovoltaics (PV), onshore wind and offshore wind are assessed as potential electricity generating technologies for the entire process. Additionally, the European grid mix electricity as energy source is part of the model. It is not planned to power the process with grid mix electricity, however it is technically possible and the associated potential environmental impacts are assessed and discussed shortly within this work. The levelized cost of electricity (LCOE) for each renewable energy technology is modelled on the basis of Kost et al. (2021) and Vartiainen et al. (2019), the LCI is modelled with the according datasets from the ecoinvent 3.71 database [3], [4]. The social LCI is modelled with respective processes for electricity provision from the PSILCA v.3 database in connection to the levelized cost of electricity (LCOE).

The modelled photovoltaic (PV) plant as electricity providing technology is based on the ecoinvent dataset *electricity production, photovoltaic, 570kWp open ground installation, multi-Si.*

The modelled onshore wind power plant as alternative electricity providing technology is based on the ecoinvent dataset *electricity production, wind,>3MW turbine, onshore.* The modelled offshore wind power plant as alternative electricity providing technology is based on the ecoinvent dataset *electricity production, wind, 1-3MW turbine, offshore.* (Real plants show performances up to the three time value. For a homogeneous database and efficient work the ecoinvent data has been preferred.)

The grid mix electricity scenario is based on the ecoinvent dataset *market group for electricity, medium voltage – Europe without Switzerland.* Costs are neglected in this case.

The capacity factors for renewable energy providing technologies are location-dependent and modelled with the online tool of Pfenninger and Staffell (2016) and Staffell and Pfenninger (2016) [5], [6].

Direct Air Capture (DAC)

All four modelled concepts rely on a direct air capture (DAC) as carbon source. As no technology provider of DAC is directly involved in the project, this part of the model is also exclusively built with data from literature sources. The construction of the plant is modelled with the data from Deutz and Bardow (2021) with a base capacity of 4 ktCO_2 per year and 7.5 g anionic resin as adsorbent per kg CO_2 captured [7]. The cost and energy data is modelled with the data from Fasihi et al. (2019) [8]. Two different data sources were chosen due to different data requirements that could not be covered by the same source.

Plasmolysis & Oxygen Separation

The cost data for the plasmolysis is obtained from van Rooij et al. (2018) [9]. Due to a slightly different process concept, the integrated PSA unit and the related process steps were excluded from the adopted CAPEX data. A plasma efficiency of 80 % is assumed, the energy demand for the current of the Solid Oxide Cell is modelled with the voltage and amperage. The cost data for the Solid Oxide Cell (SOC) oxygen separator is based on internal project data. The composition of the cells for the LCA is also based on internal project data which substitutes the respective cell data within the adjusted ecoinvent dataset for a Solid Oxide Electrolyte Fuel Cell and its maintenance: *fuel cell production, solid oxide, 125kW electrical, future; maintenance, solid oxide fuel cell 125kW electrical, future.* These datasets represent surrogates for the materials besides the cell due to the low level of existing data for this process step. The modelled maintenance includes the stack exchange, which is integrated for both LCA and cost with an assumed lifetime per stack of 20,000 hours. After 20,000 hours the entire stack has to be replaced, the housing remains. The separated oxygen is modelled as co-product which results in credits for replacing the original process of air separation, cryogenic.

CO Purification – Pressure Swing Adsorption (PSA)

The cost and energy data for the CO purification with pressure swing adsorption (PSA) is based on internal project data. The construction of the plant is modelled with the ecoinvent dataset *chemical factory, organics.* The scaling of the process step is based on the material output within the KEROGREEN model.

Sorption-enhanced Water Gas Shift (SE-WGS)

The cost and energy data for the SE-WGS is based on Manzolini et al. (2020) [10]. The energy demand for the SE-WGS is modelled in relation to the CO2 sorption, which is why it differs within the different concepts of KEROGREEN. The required materials for the construction and operation of the SE-WGS are modelled with internal project data. This includes a Cu-Zn catalyst and sorption material.

Synthesis & Upgrading & Reforming

The cost of the fuel synthesis, the upgrading and separation of products is based on internal project data. It is assumed that the entire output of the upgrading – except for the purge gas and recycled gas streams - can be used as fuel. The cost data for the reforming part is based on NREL (2006) [11]. The construction data for this part is modelled with the ecoinvent datasets *chemical factory construction* and *intermodal shipping container production, 40-foot.* Material and energy flows are modelled with internal project data, complemented by the data of NREL (2006).

Cost Factors

Installation factors of the equipment were adopted from the respective literature sources. A working capital of 10 % of the fixed capital is assumed. The Chemical Engineering Plant Cost Index (CEPCI) is integrated to account for plant equipment price changes between the referenced price from literature sources and current prices. Due to a limited data availability, the CEPCI for 2020 is implemented as most current price index.

Operating expenses (OPEX) are calculated on the basis of the cost factors from Peters (2004). Costs for operating supplies were complemented with additional data that was available from internal project data. Labor costs were calculated with the formula of Albrecht et al. (2017) and Peters et al (2004) in combination with average salaries in the assessed countries. [12], [13] The average salaries were integrated from eurostat (2020), payscale and salary explorer [14], [15], [16].

Reference Technologies

The LCI of the fossil-based kerosene production is modelled with the ecoinvent dataset *market for kerosene – Europe without Switzerland*. The cost data is sourced from IEA (2020) [17].

The bio-based jet fuel production pathways were already modelled for KEROGREEN deliverable 6.4 Report on modelling and data generation of competing technologies. The models are based on Diederichs et al. (2016), Neuling and Kaltschmitt (2017), and Klein et al. (2017). [14] – [16].

3 Life Cycle Impact Assessment (LCIA)

3.1 Environmental Sustainability

The method ReCiPe 2016 Midpoint (H) was used for the Life Cycle Impact Assessment (LCIA). For each impact category, the different process constellations of KEROGREEN are modelled with their location in Germany. For the assessment of potential other locations, the KEROGREEN pilot concept is modelled as the standard case.

Global Warming Potential

As the processes include negative emissions (CO_2-uptake), credits for substituting the production at another point and emissions from combusting the fuel, it is important to consider the sum in the diagrams as indicator value.

The potential of KEROGREEN to contribute to less GHG emissions in the aviation sector highly depends on the electricity source and the utilization of the co-product oxygen. With a high amount of full load hours, exclusively renewable energy and the utilization of all products, high benefits can be achieved. However, if the energy source is not renewable or the amount of full load hours is low, no benefits are achieved. For example, with the European grid mix as electricity source, the Global Warming of the process could reach values 4 to 5 times as high as the fossil kerosene. It is thereby important that any PtX technology is powered by renewable energy. And the choice of the electricity generating technology should be evaluated according to the local conditions, as high variations between the different countries can be seen.

Fine Particulate Matter Formation

Similarly to the GWP, the impact category of Fine Particulate Matter Formation is substantially influenced by the energy source and the utilization of all products. It is important to consider here that only the fuel production is assessed, not the combustion of the fuel.

Marine Eutrophication

Within the impact category marine eutrophication, benefits against fossil and biogenic fuel production can be achieved. But in most cases the potential impact would also be in between both references.

Land Use

While the impact category of land use is also influenced by the energy source, it becomes clear that the KEROGREEN process would have a potential impact in a range between the production of fossil kerosene and the production of biogenic fuels.

Global Warming Potential

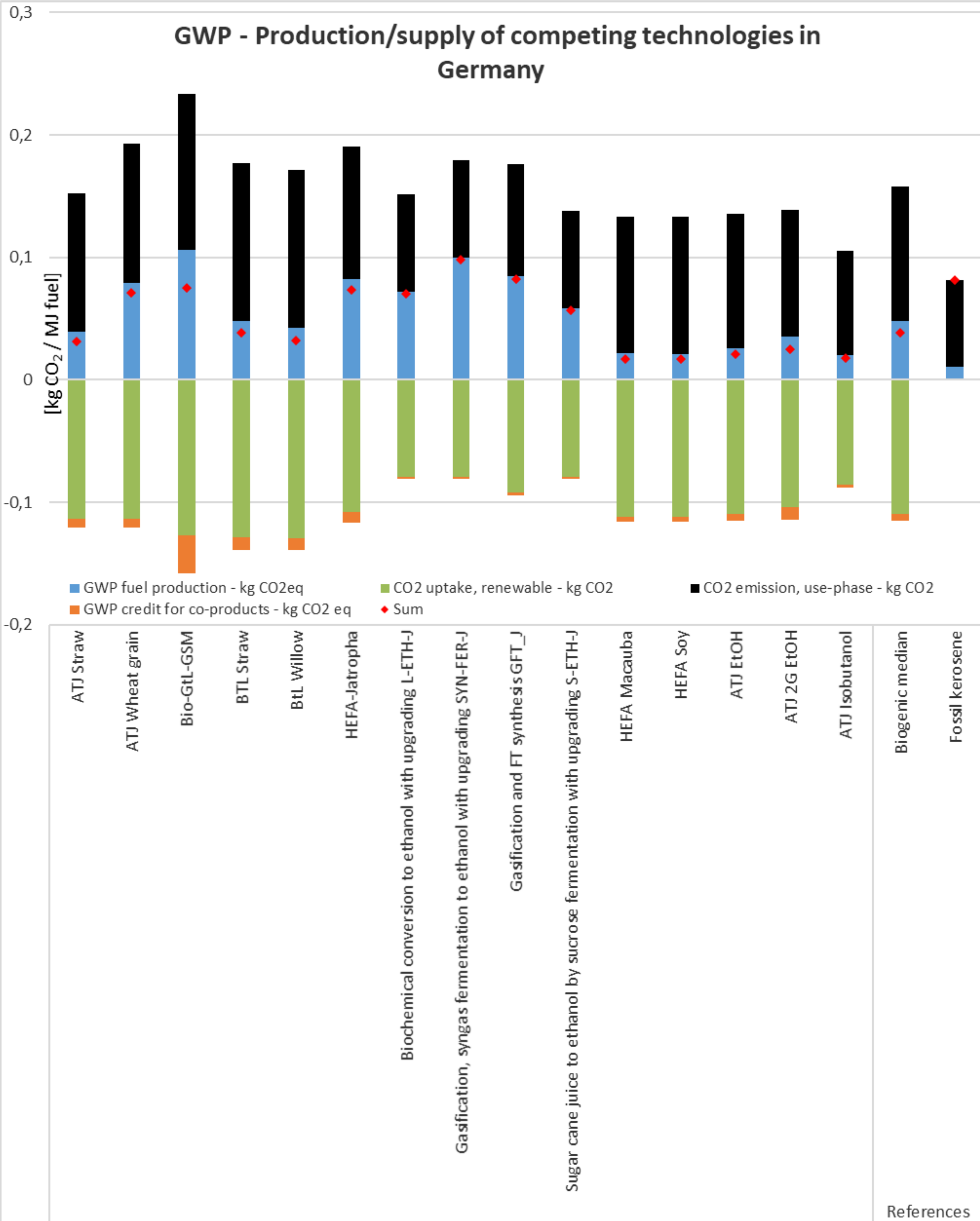

Diagram 1 GWP - Production/supply of competing technologies in Germany - Unit: kg CO2 eq / MJ fuel

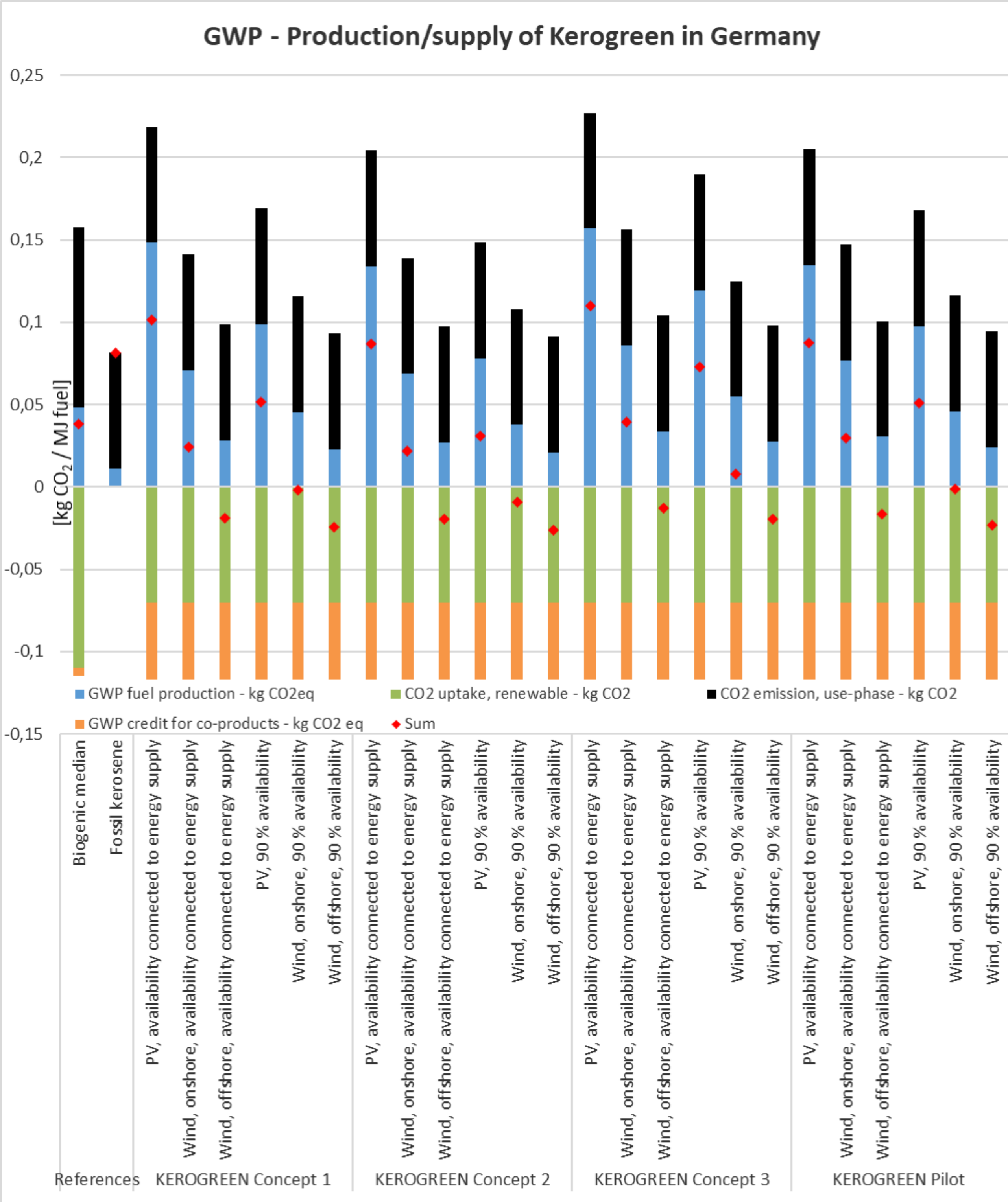

Diagram 2 GWP - Production/supply of Kerogreen in Germany - Variants of plant design and power supply - Unit: kg CO2 eq / MJ fuel

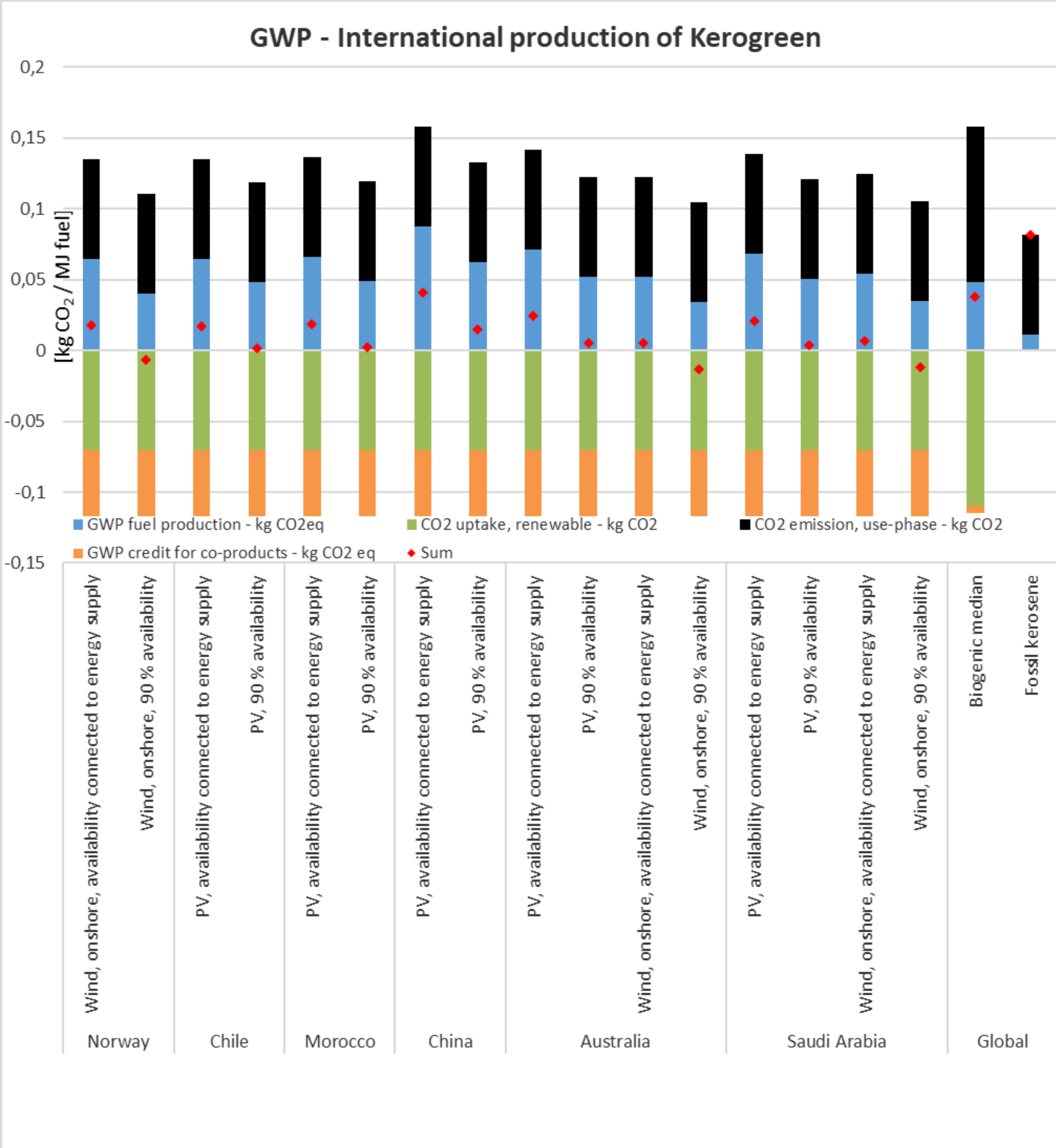

Diagram 3 GWP - International production of Kerogreen - Variants of power supply - Unit: kg CO2 eq / MJ fuel

Fine Particulate Matter Formation

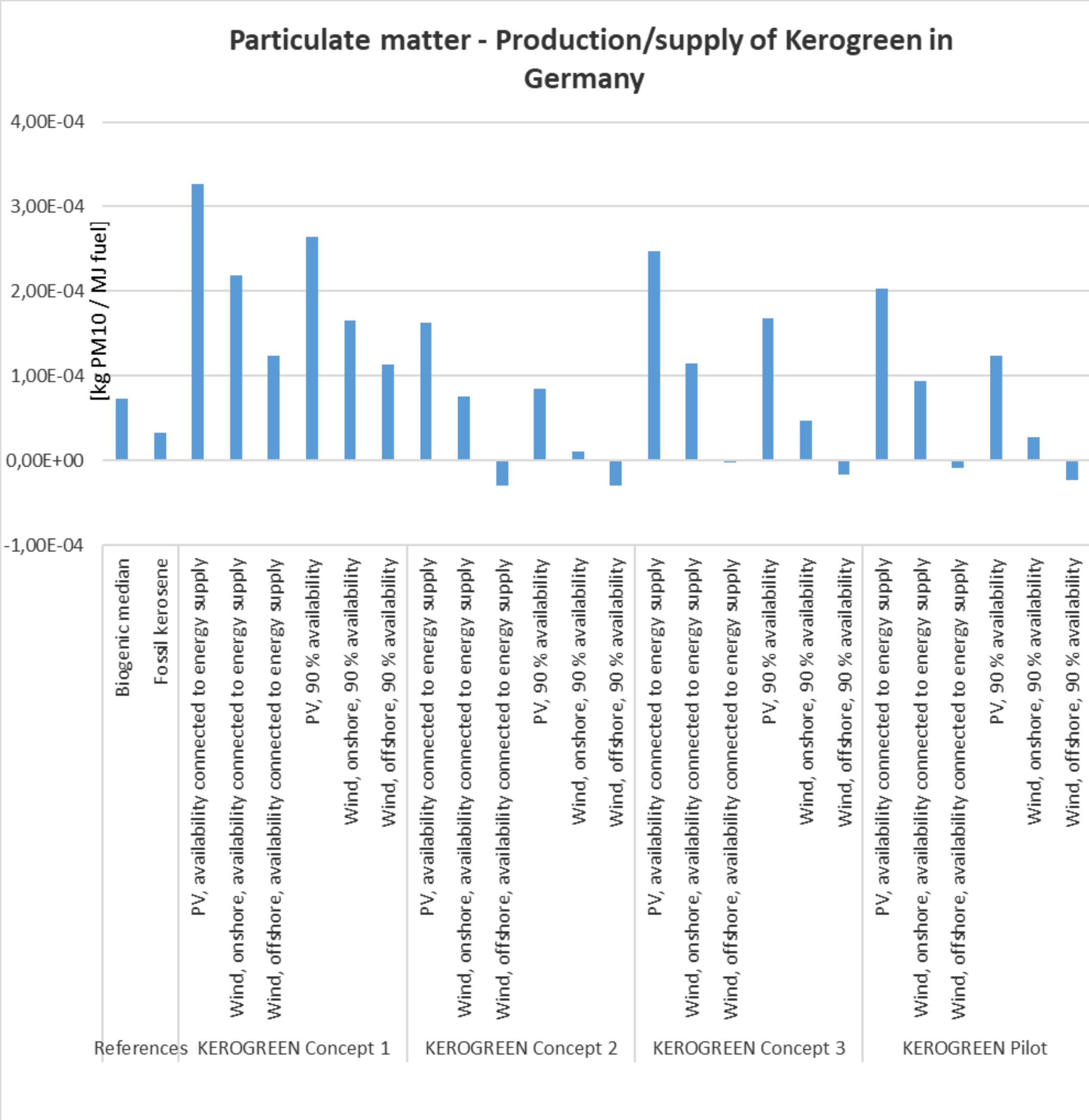

Diagram 4 Particulate matter - Production/supply of Kerogreen in Germany- Variants of plant design and power supply - Unit: kg PM10 / MJ fuel

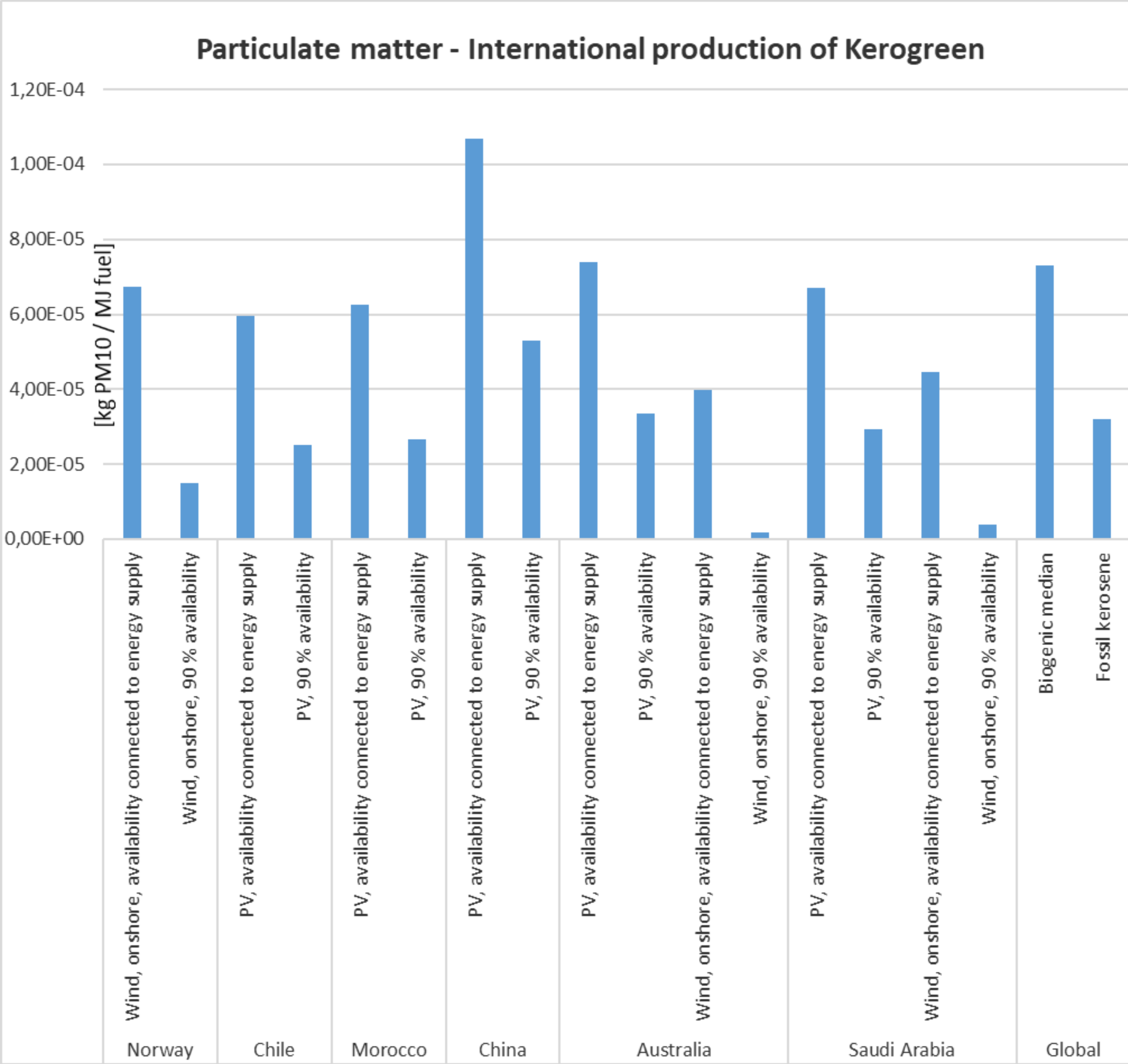

Diagram 5 Particulate matter - International production/supply of Kerogreen - Variants of power supply - Unit: kg PM10 / MJ fuel

Marine Eutrophication

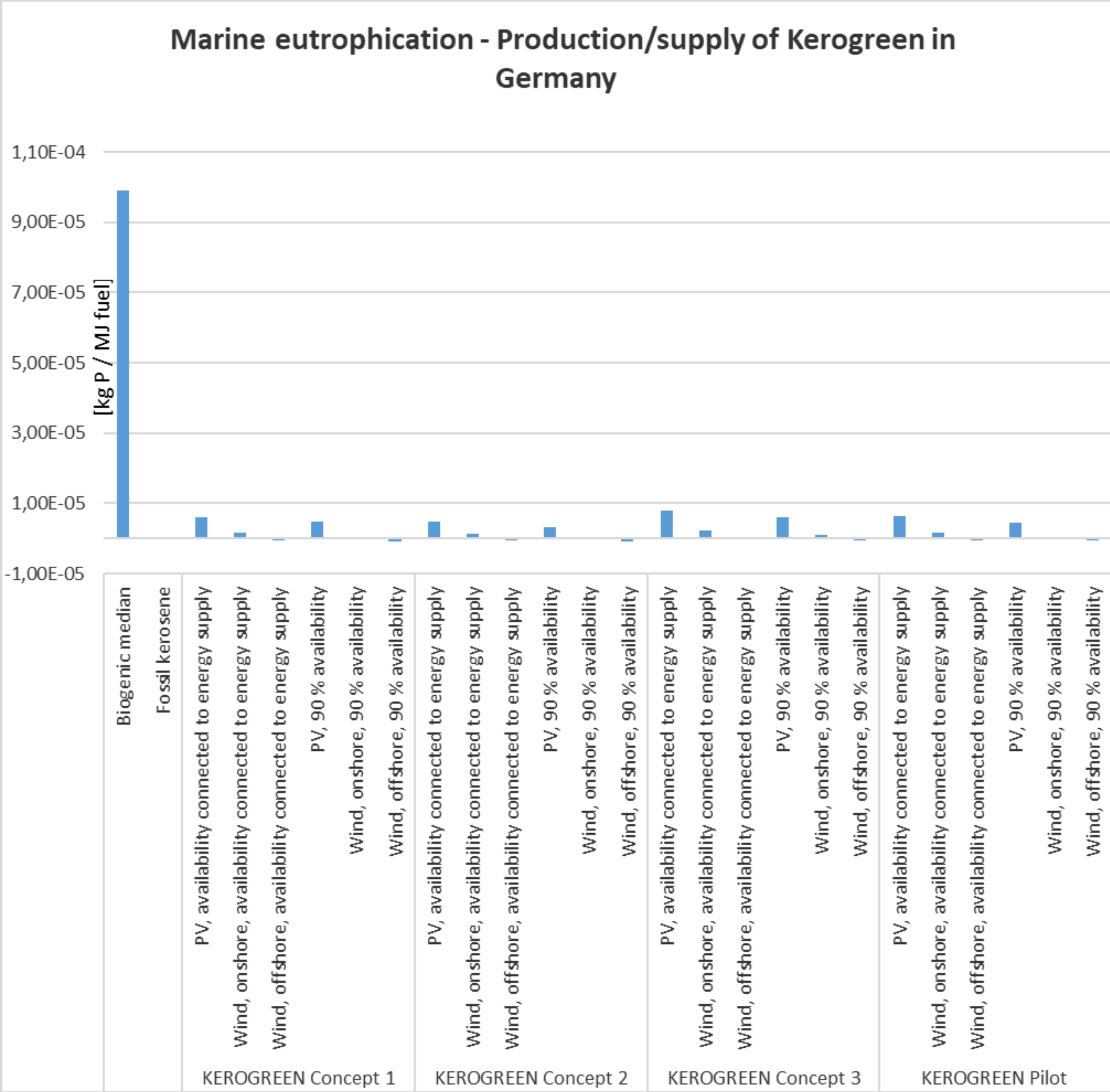

Diagram 6 Marine eutrophication - Production/supply of Kerogreen in Germany - Variants of plant design and power supply - Unit: kg P / MJ fuel

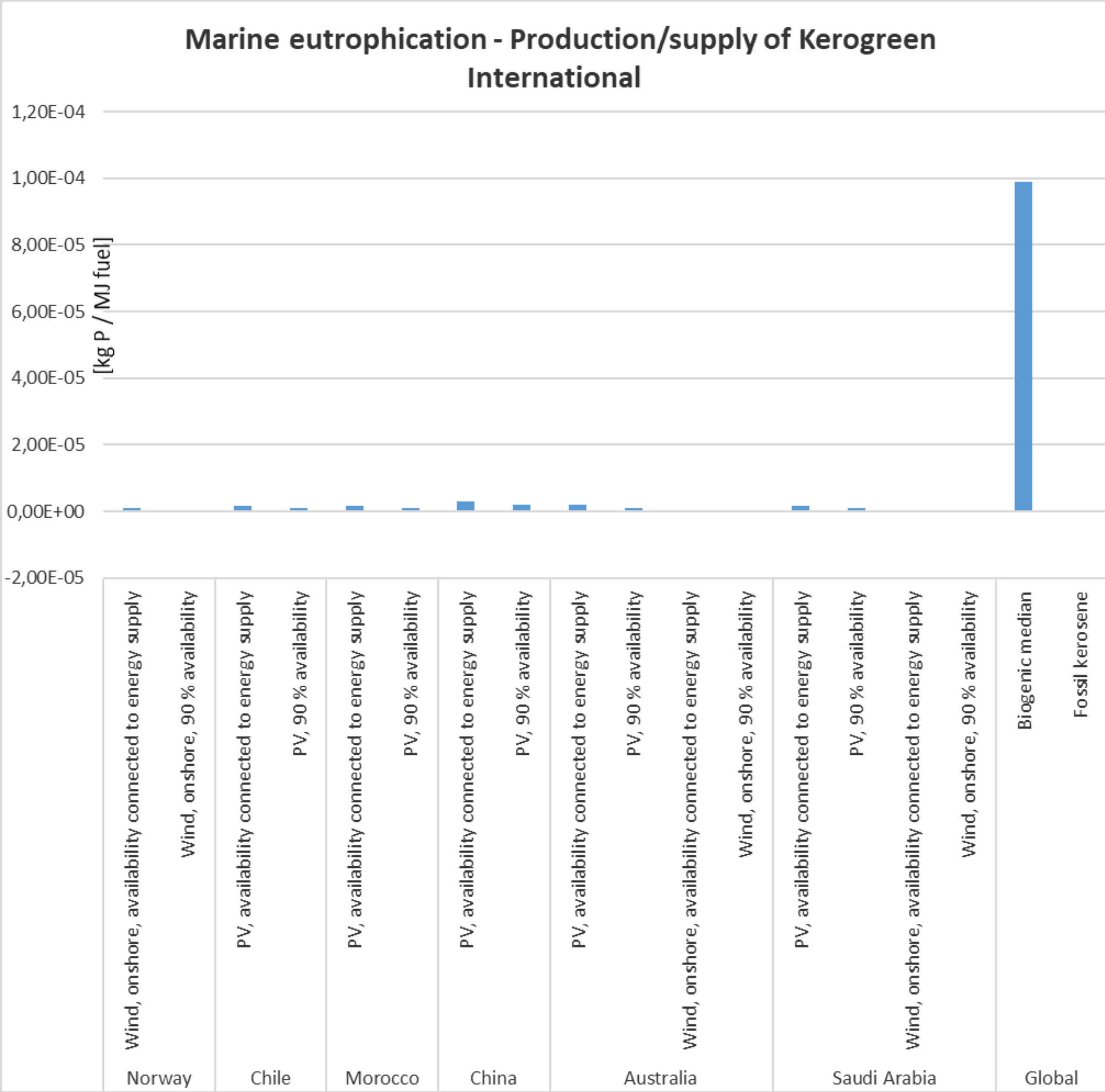

Diagram 7 Marine eutrophication - International production of Kerogreen - Variants of power supply - Unit: kg P / MJ fuel

Land Use

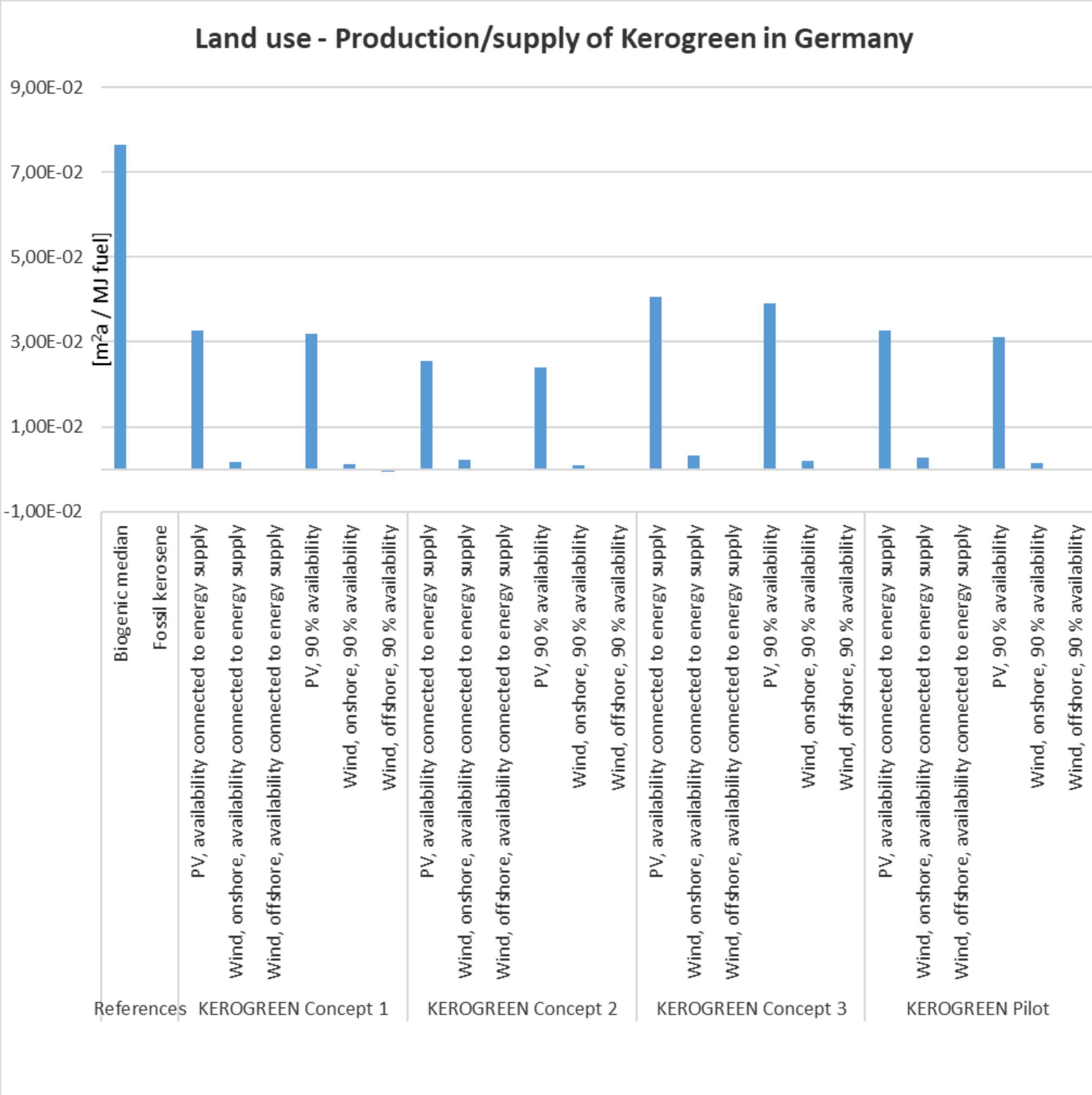

Diagram 8 Land use - Production/supply of Kerogreen in Germany - Variants of plant design and power supply - Unit: m2a / MJ fuel

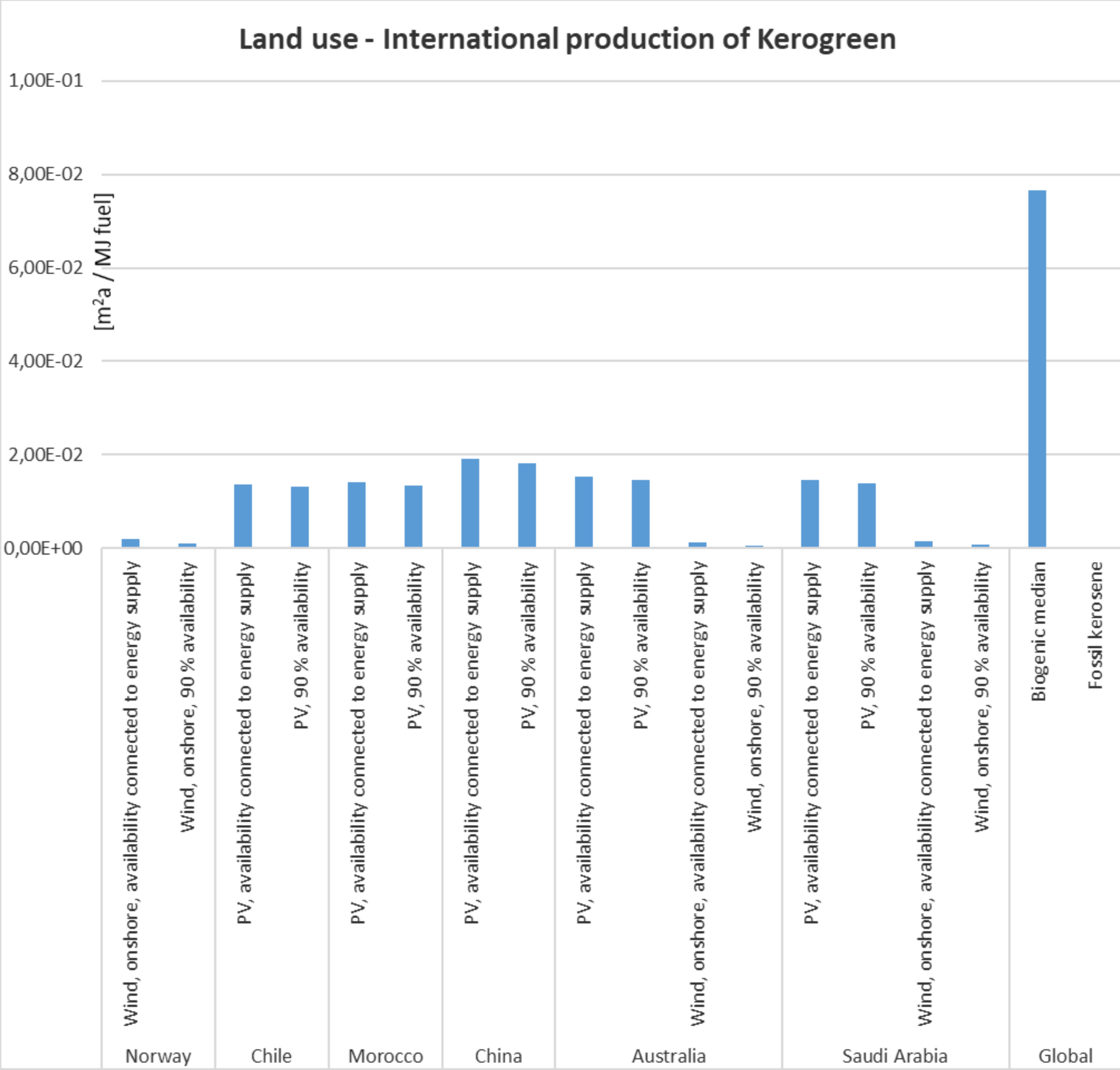

Diagram 9 Land use - International production of Kerogreen - Variants of power supply - Unit: m2a / MJ fuel

3.2 Economic Sustainability

The levelized cost of fuel production is expressed in € / kg produced fuel. It is assumed that all jet fuels have a similar calorific value [21]. Very similar calorific values are also required by the American Society for Testing and Materials [22]. The different process constellations of KEROGREEN are modelled with their location in Germany. For the assessment of potential other locations, the KEROGREEN pilot concept is modelled as the default case.

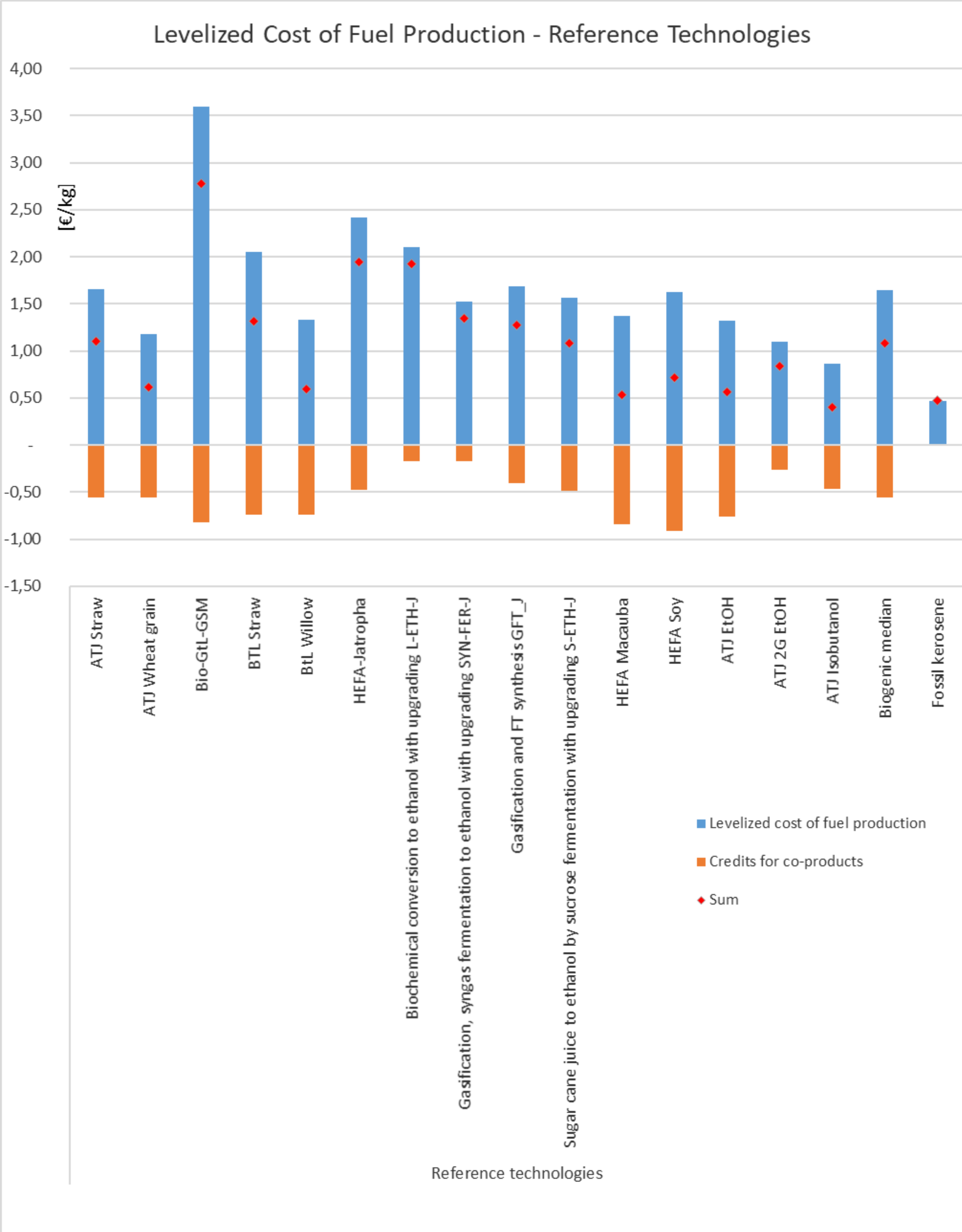

Diagram 10: Levelized cost of fuel production for reference technologies Unit: €/kg.

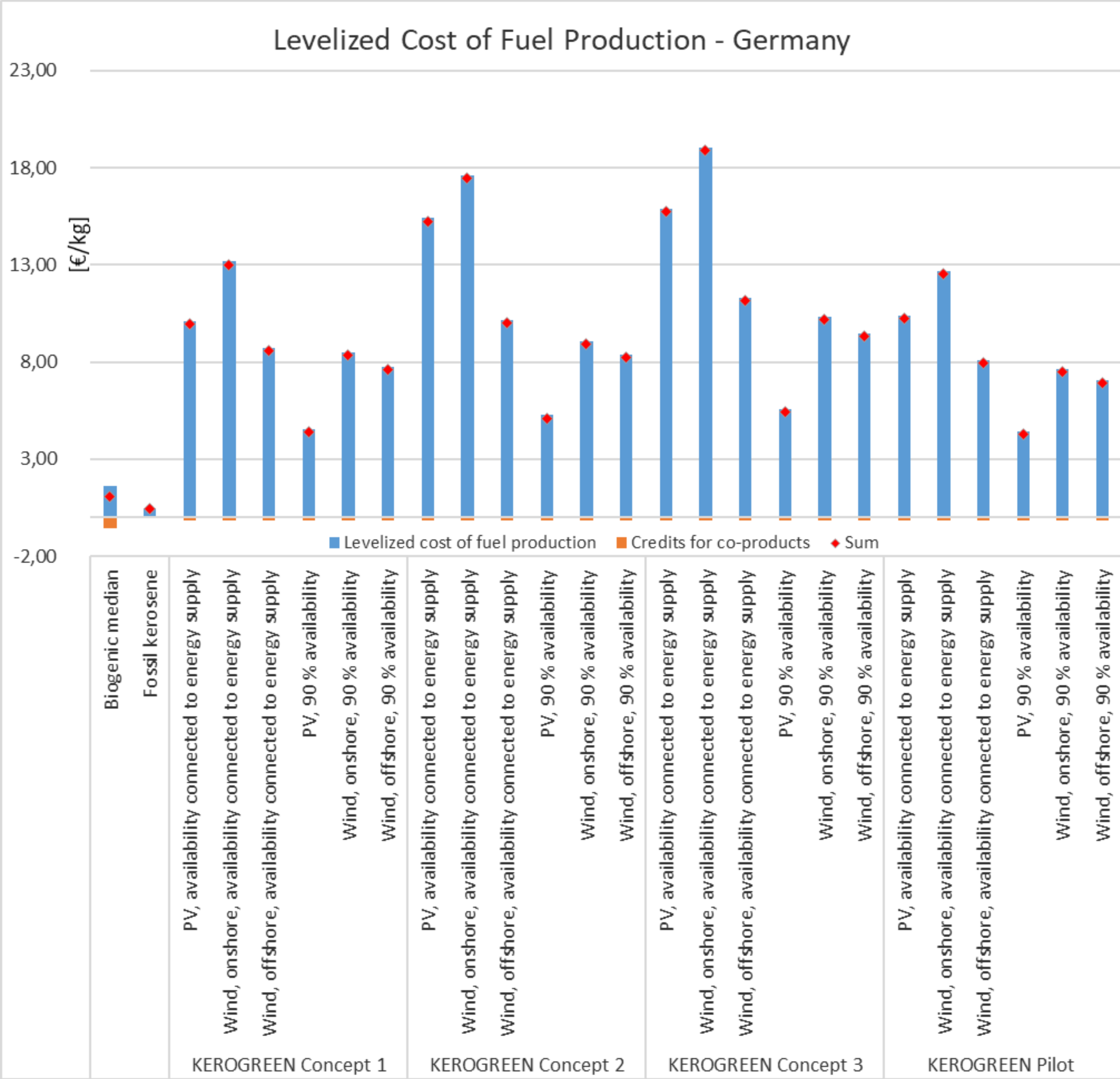

Diagram 11: Levelized cost of fuel production for Kerogreen in Germany Unit: €/kg

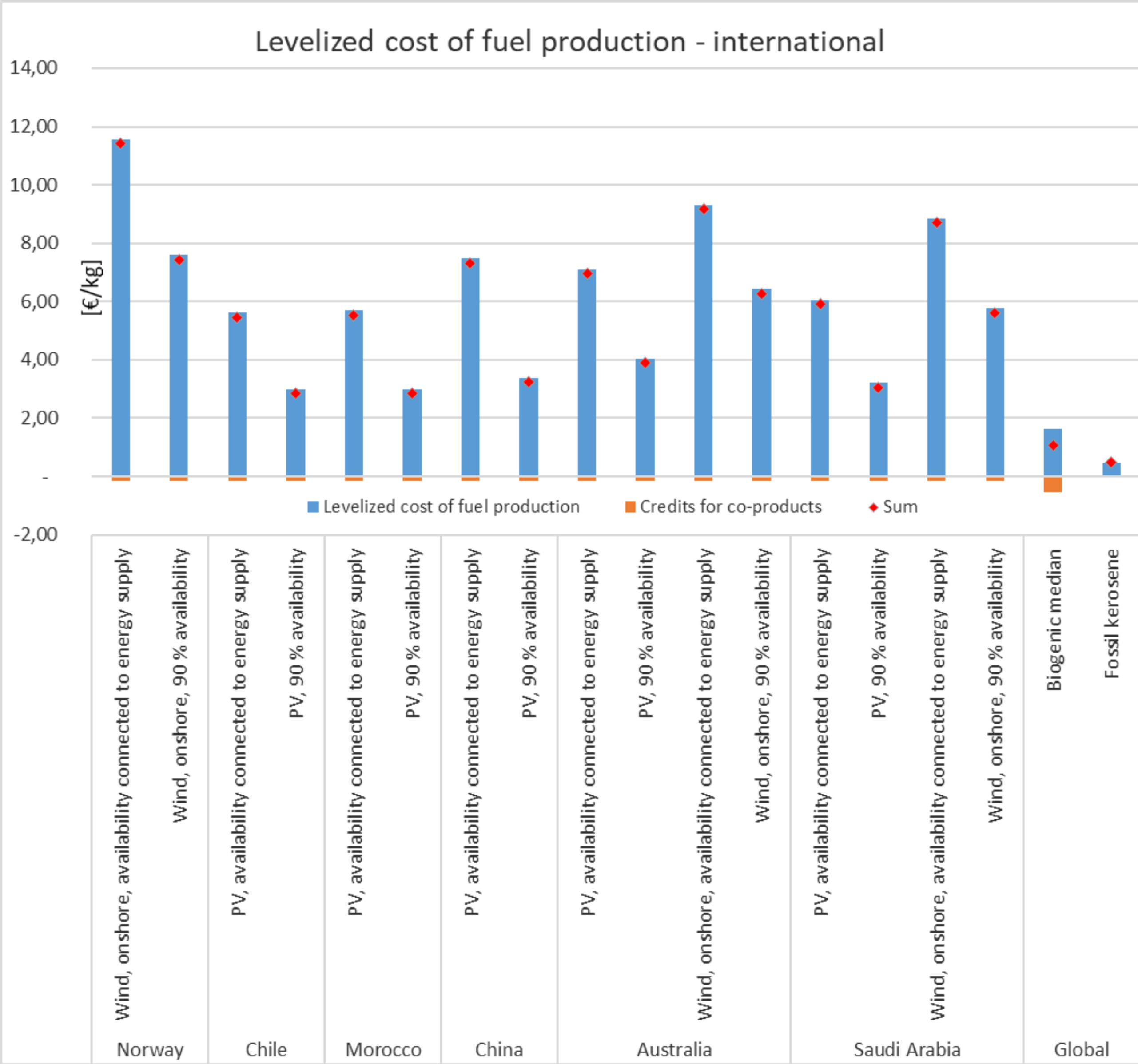

Diagram 12: Levelized cost of fuel production for Kerogreen international Unit: €/kg

The cost of fuel production is higher for KEROGREEN than for fossil or biogenic fuel production. The lower costs of the pilot concept compared to the industrial concept could be due to the uncertainty in the data in the pilot scale. Even with a high amount of full load hours and cheap labour costs, the fuel production would not be cheaper with the current circumstances. However, if learning curves for these new technologies, lower prices for renewable energy and higher prices for fossil fuels are expected for the future, it might become more competitive.

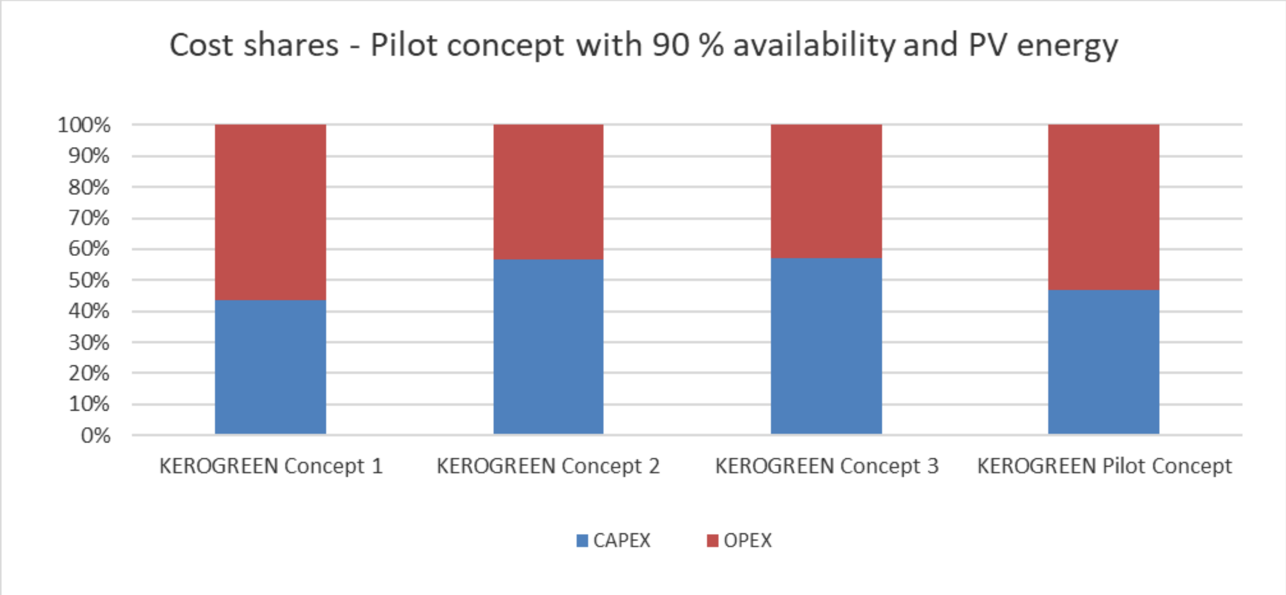

Diagram 13: Ratio of CAPEX and OPEX in total costs.

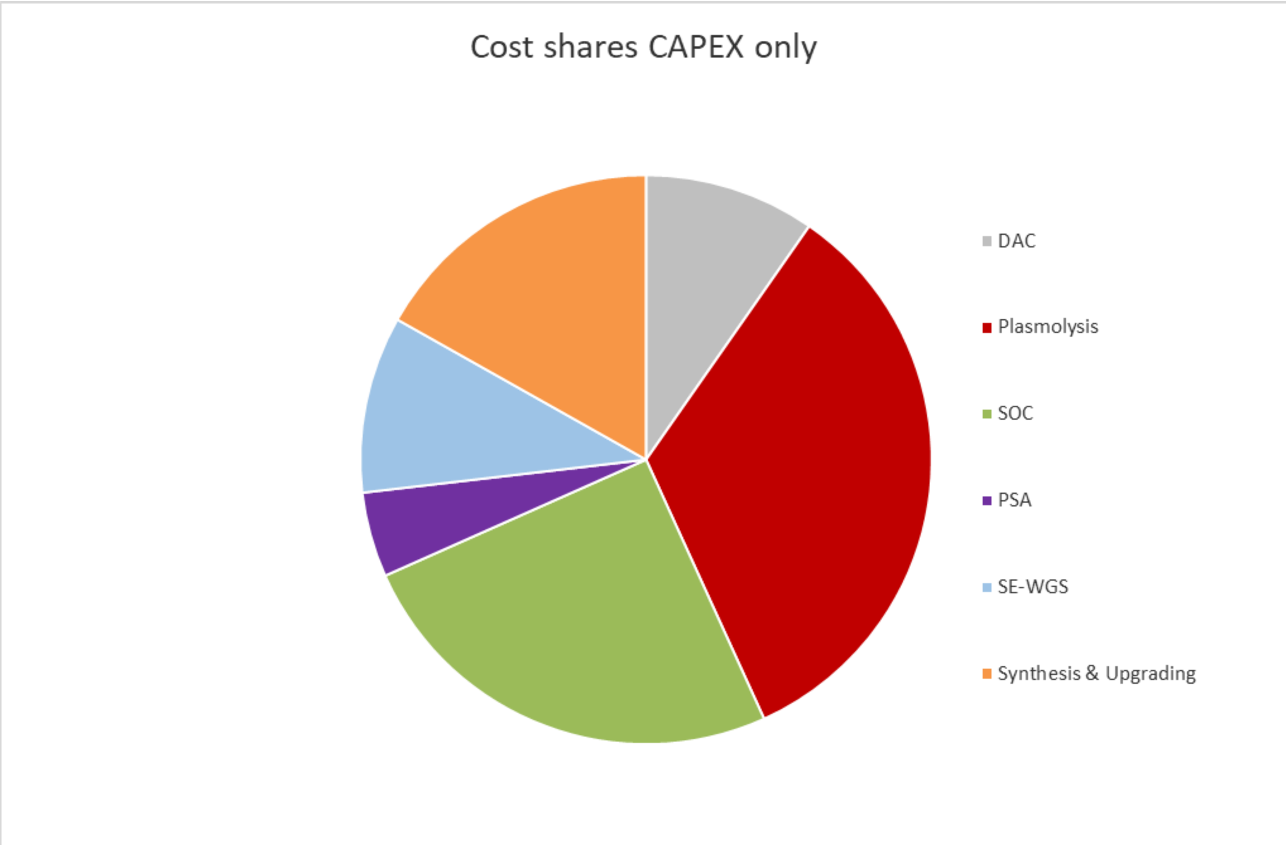

Diagram 14: Cost share of the individual processes in the total costs.

3.3 Social Sustainability

For the assessment of the social sustainability, only the feedstock is assessed here due to a low availability of data. The main feedstock (biomass for biogenic fuel production, crude petroleum for fossil kerosene production and electricity for KEROGREEN) is connected to the feedstock costs of each technology per kg of fuel. Hence, the displayed results show the medium risk hours per kg of fuel produced. In case of electricity, the used datasets could not be divided into renewable and fossil-based electricity generating technologies. This means that the social sustainability assessment of electricity provision is based on the energy sector and not on KEROGREEN specifically.

The assessment of social sustainability is influenced by the value / costs that are involved and the social circumstances in the assessed countries. It is not intended to actually evaluate any country or to identify the “most suitable” country to produce any kind of fuel. The idea is to identify risks that could happen with the implementation and that should be considered when implementing these new technologies on a international level. Therefore, all countries are assessed together and expressed in minimum, maximum and median values.

Corruption and Bribery

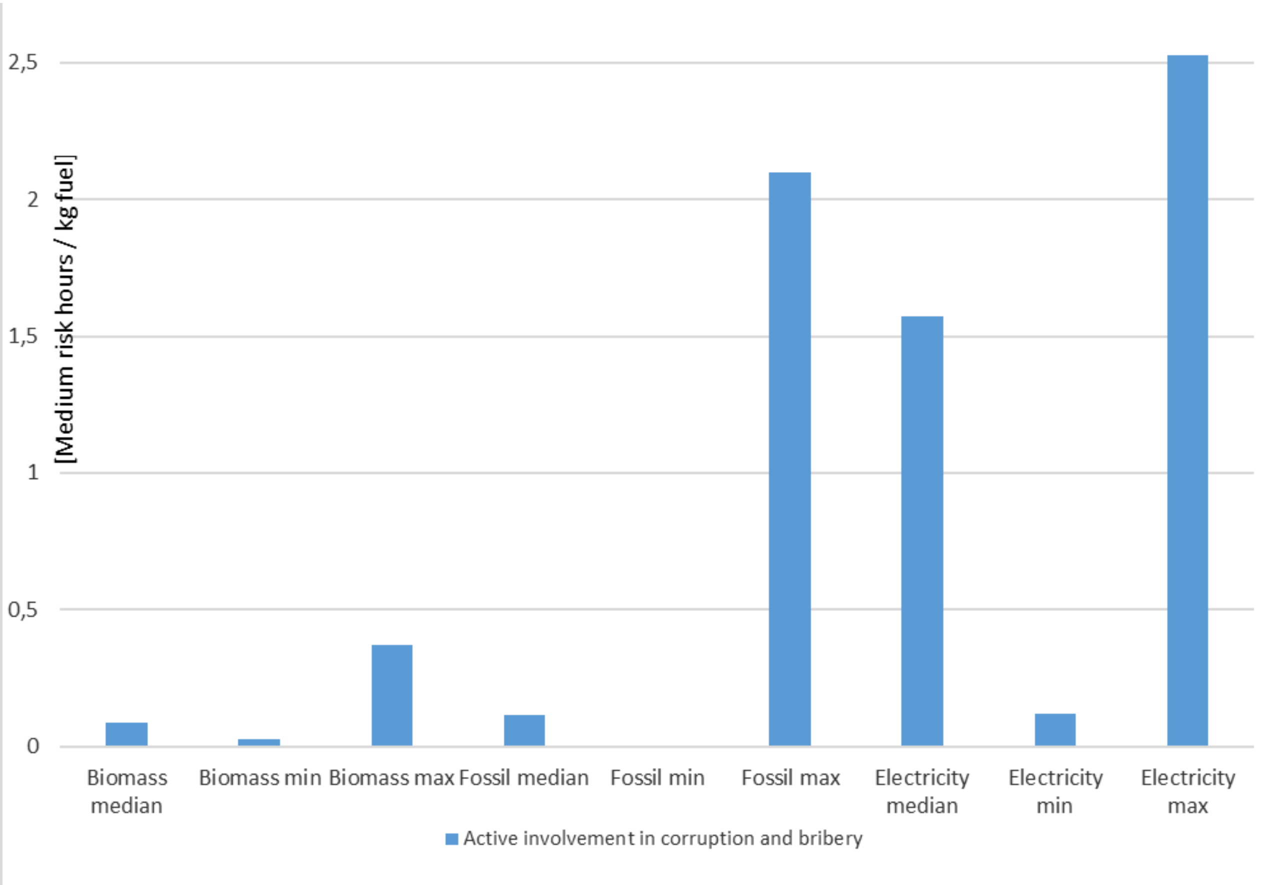

Diagram 15: Active involvement in corruption and bribery in relation to the corresponding feedstock. Unit: Medium risk hours / kg fuel.

The risk for an active involvement in corruption and bribery is high in comparison with biogenic fuel production and also higher than the fossil fuel production. This risk of corruption in the renewable energy sector includes many practices which have to be considered along the value chain. More information can be found at Transparency International and U4 Anti-Corruption (2020) [23].

However, in this case it also has to be considered that the feedstock costs and therefore the activity variable for the fossil fuel production are several times lower than the cost of renewable electricity per kg of fuel.

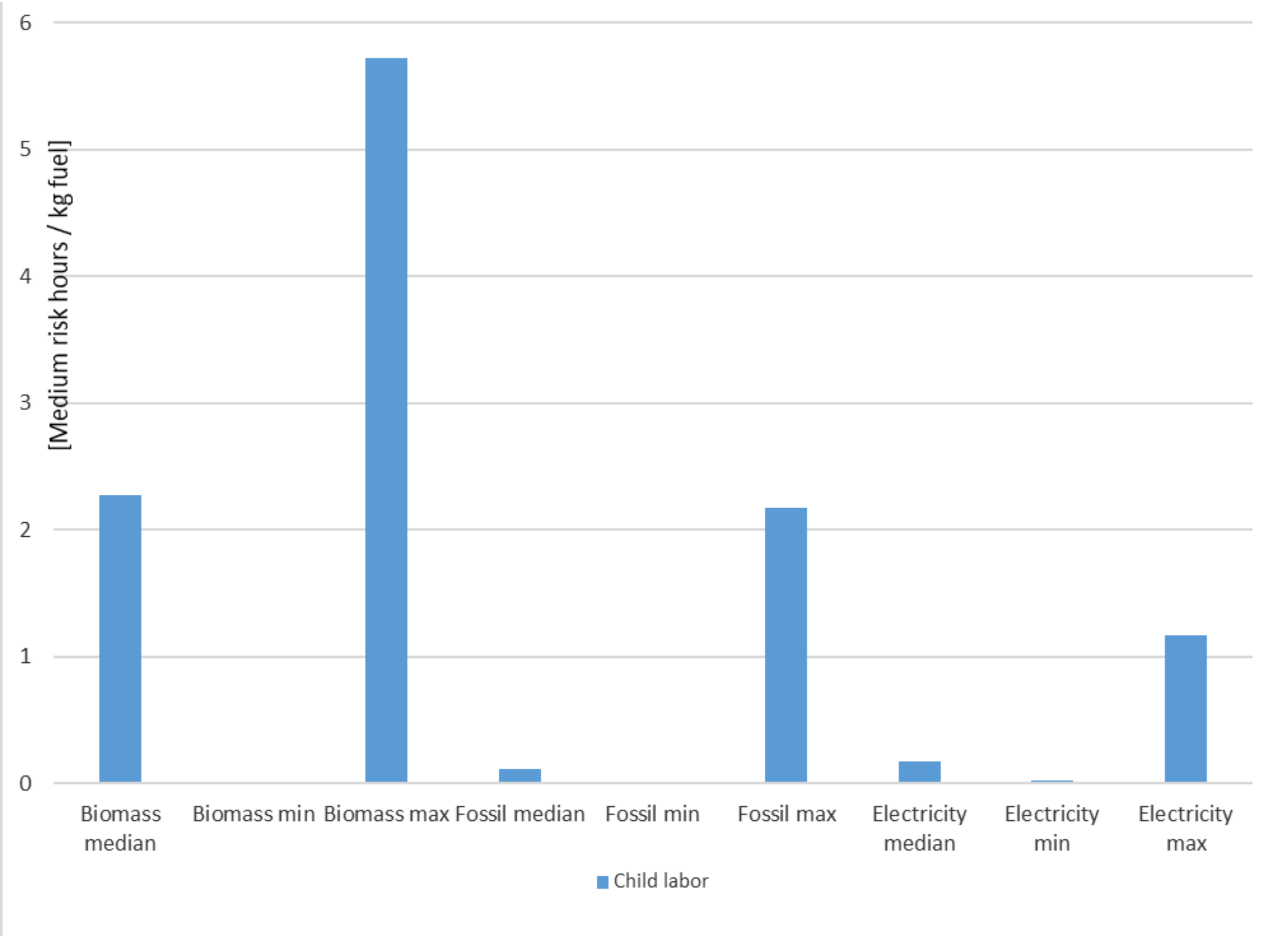

Diagram 16: Child labour indicator in relation to the corresponding feedstock. Unit: medium risk hours / kg fuel.

The risk for child labor along the value chain is low in comparison to biogenic fuel production and comparable to the fossil fuel production. However, there are areas / countries where the risk is still high along the value chain. Considering the mining for the required resources, this risk is evident and should be considered, especially as the demand will increase in the future [24].

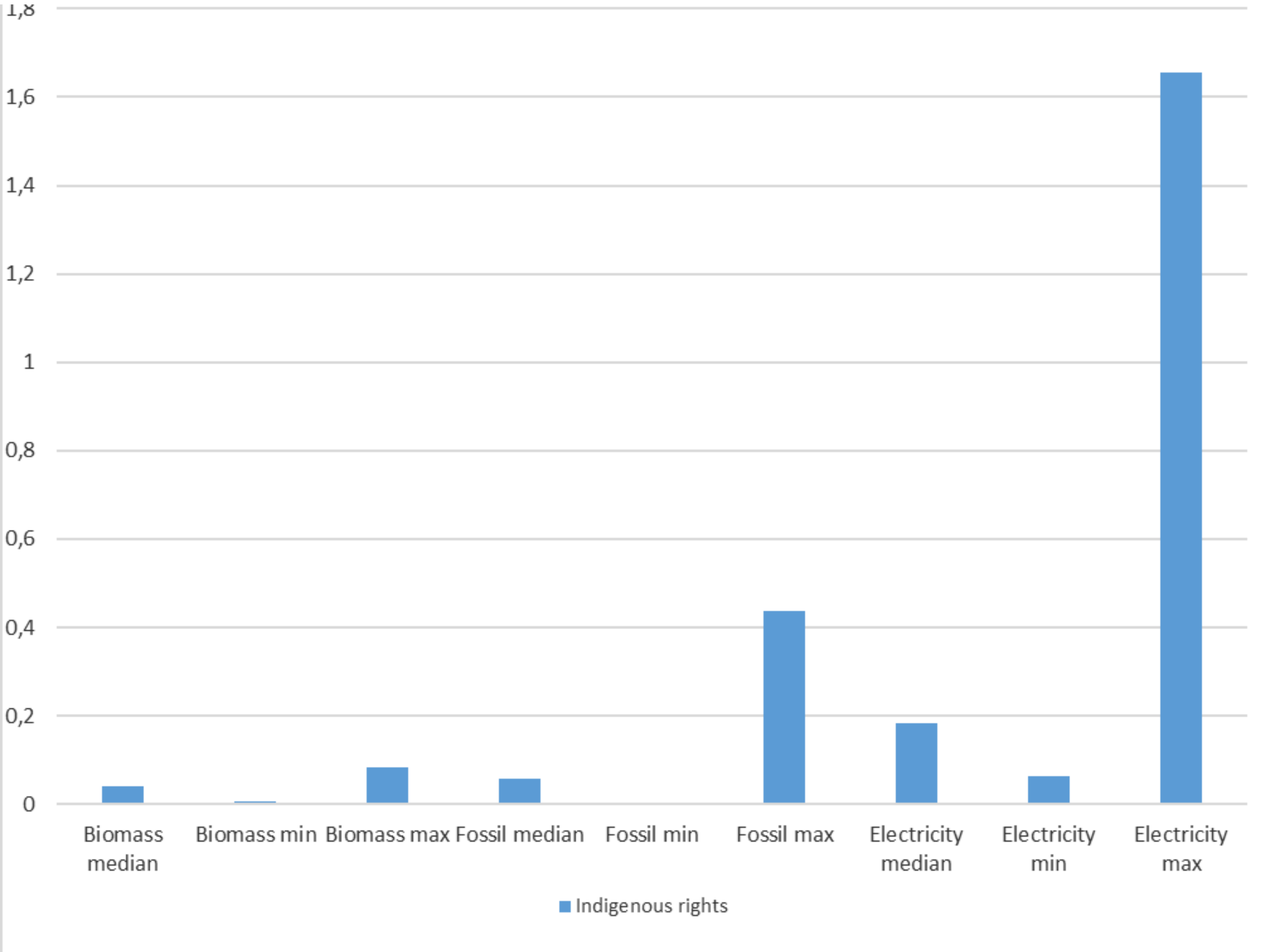

Diagram 17: Indigenous rights in relation to the corresponding feedstock. Unit: medium risk hours / kg fuel.

While the risk of undermining the rights of Indigenous peoples exists for all three types of feedstock provision, the highest values can be seen for the specific amount of electricity provided per kg of fuel in this case. But it has to be noted that several datasets were excluded due to a low level of data availability in the database. Nevertheless, any land use change should not be happening without a dialogue that involves Indigenous peoples in the region. [25]

3.4 Impact Assessment Matrix & Acceptability

Nielsen (1993) divided acceptability into two different dimensions: Practical and social. The practical dimension would include the costs and usefulness as sustainable aviation fuel (as in potential environmental impacts), while the social dimension stands for itself. Innovative technologies are often inconvenient as some of the acceptability aspects might be worse than with conventional technologies – at least at early stages. Whether these aspects lead to a lower acceptance eventually depends on the criticality of these. The criticality might depend on the type of technology (maybe some factors are less relevant for one technology than for another) and personal preferences. [26], [27]

As there is a whole bandwidth of potential environmental impacts, social risks and fuel production costs along the concepts and locations, the median, optimal and all scenarios are included in the matrix. This gives a broader overview of the opportunities and risks.

Impact assessment matrix

Impact / Risk Category	All scenarios achieve lower impact than bio and fossil	Best case scenario achieve lower impact than bio and fossil	All scenarios could achieve lower impact than bio or fossil	Best case scenario could achieve lower impact than bio or fossil	Median with lower impact	No improvement	Weighting
Potential GWP		X					
Potential Fine Particulate Matter Formation		X					
Potential Land Use		X					
Potential Marine Eutrophication		X					
Potential Fuel Production Costs						X	
Risk of Corruption and Bribery				X			
Risk of Child Labor					X		
Risk of Human Rights Issues faced by Indigenous peoples						X	

Whether KEROGREEN can play a sustainable role in defossilizing the aviation sector depends on many aspects and there are always trade-offs. With usability- or acceptability-driven engineering, the potentially critical aspects can be considered and implemented into the further development of innovative technologies. For a sustainable development it is important to consider the alternatives: If synthetic fuel production is only compared with fossil-based fuels, many sustainability aspects might be evaluated in a way that leads to no sustainable development, as the alternatives are neglected.

4 Limitations

Due to an early stage of the involved technologies, the level of uncertainty is rather high in all three sustainability dimensions. Additionally, the assessment of the social sustainability itself is at an early development stage and is based on entire industry sectors, not on the specific technologies. None of the three assessment methods reflects actual impacts, as more aspects come into place during operation of plants. However, they serve as a first assessment to make the readers aware of high risk areas and help to develop counter measures.

On a more technical level, the full load hours of the model are based on average values within the entire countries, not on specific locations with optimal circumstances. Therefore, the capacity factors are part of the sensitivity analysis.

5 Sensitivity Analysis

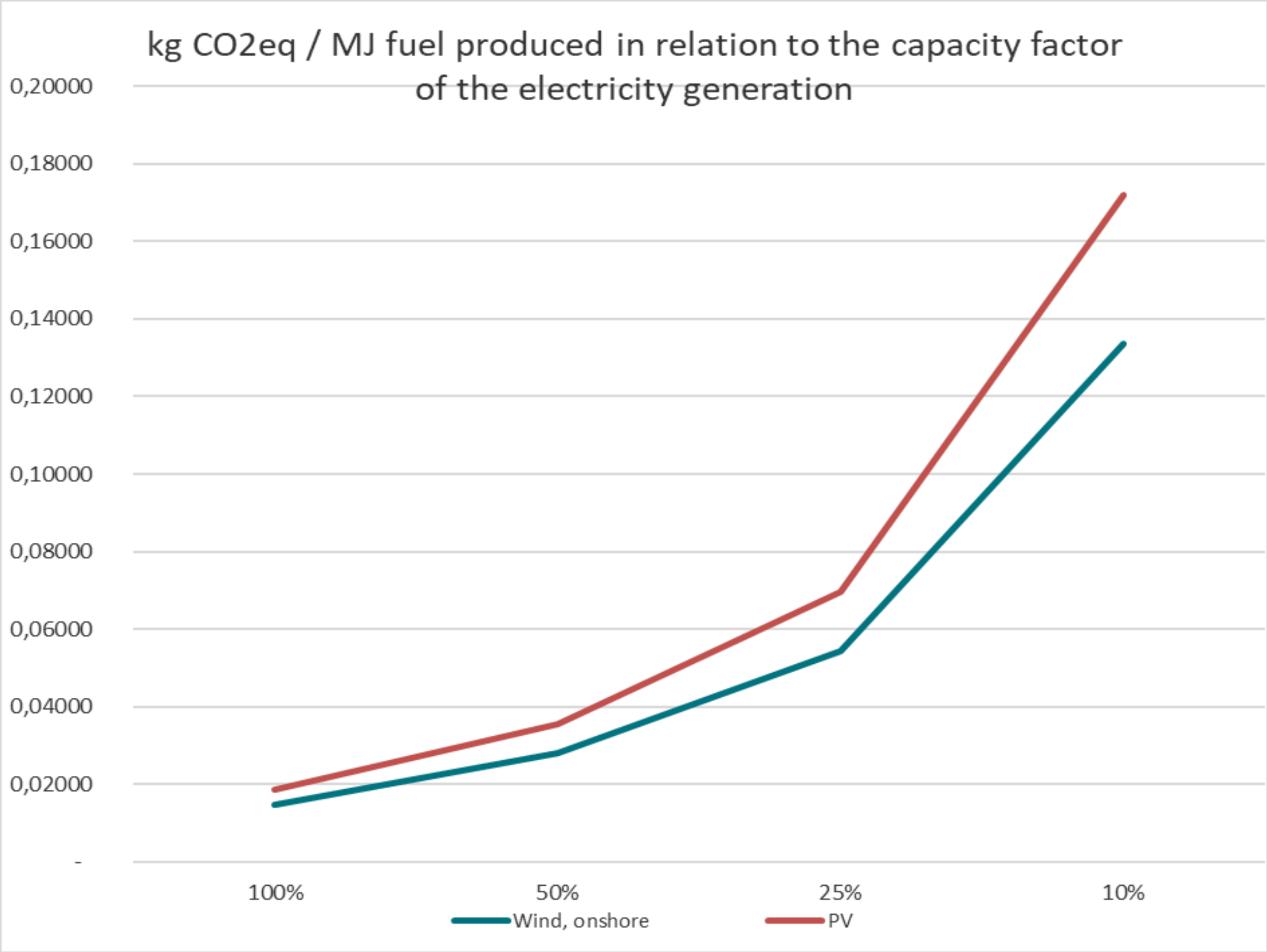

Diagram 18: Sensitivity analysis of the change in emissions per energy content following capacity factor of electricity generation. Unit: kg CO_2 eq. / MJ fuel.

The pilot concept is used as default case here to assess the impact of varying capacity factors. Their influence is very high and should always be considered for any assessment.

A 90 % availability of the plant is assumed for the sensitivity analysis of the LCOE. The fuel production costs of all concepts heavily depend on the cost of electricity.

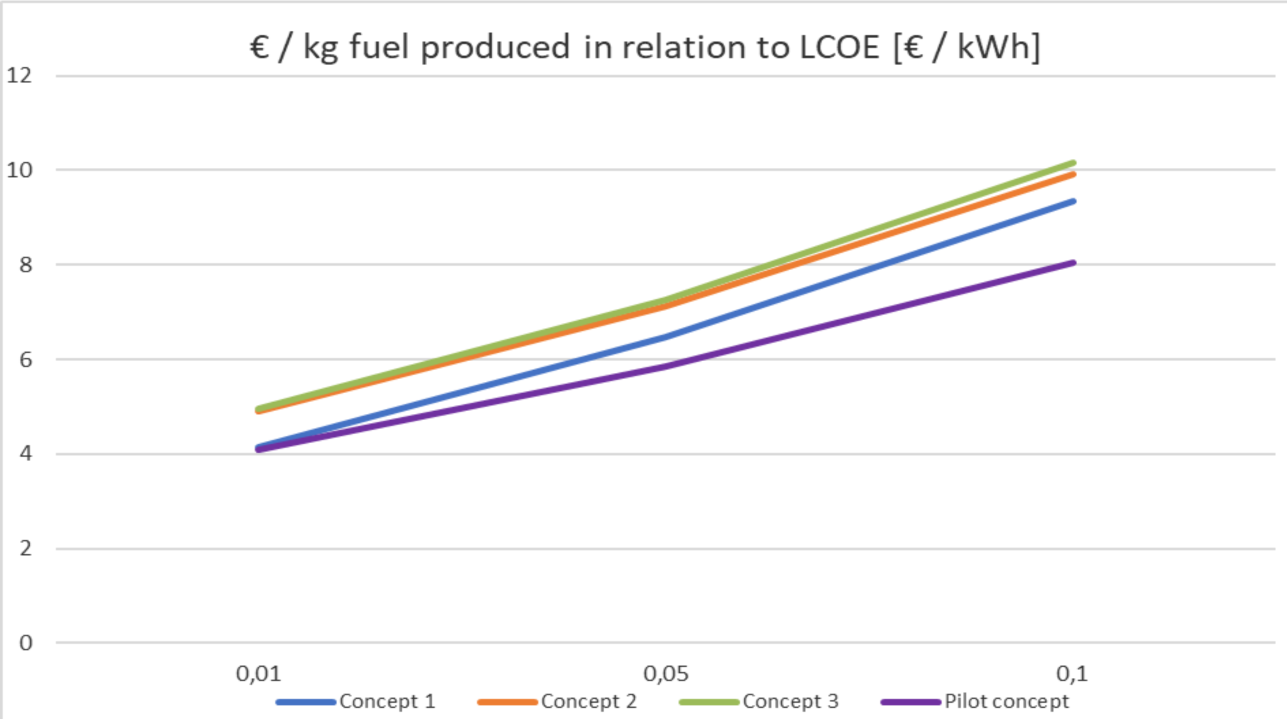

Diagram 19: Relation of LCOE and fuel costs: x: €/kWh, y: €/kg

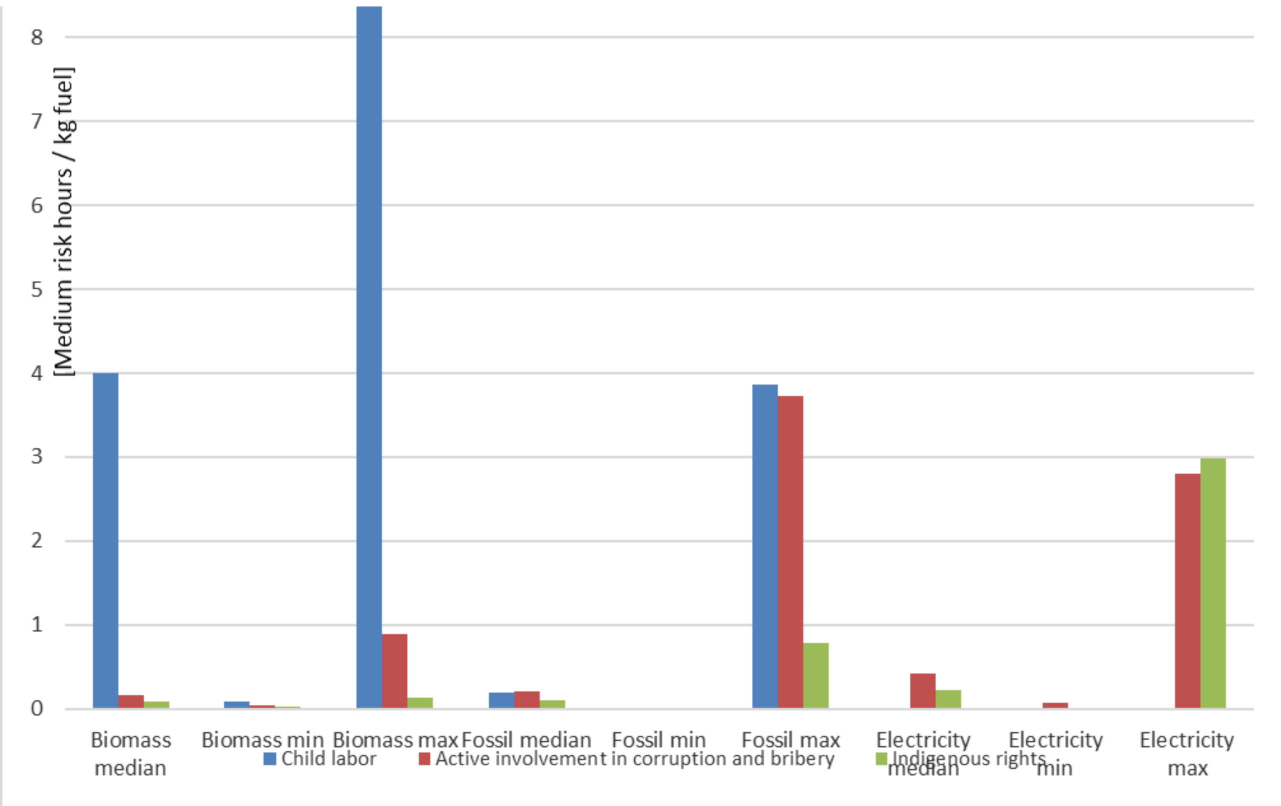

Diagram 20: Summary of all three social indicators regarding the feedstock at equal costs. Unit: risk hours / kg fuel.

As the feedstock costs vary across the different references, this part of the sensitivity analysis shows the effects of equal feedstock prices per kg of fuel for fossil, biogenic and PtX fuels. With this, the risk of child labor is reaching the lowest level for PtX. However, the other categories still remain critical and should be observed.

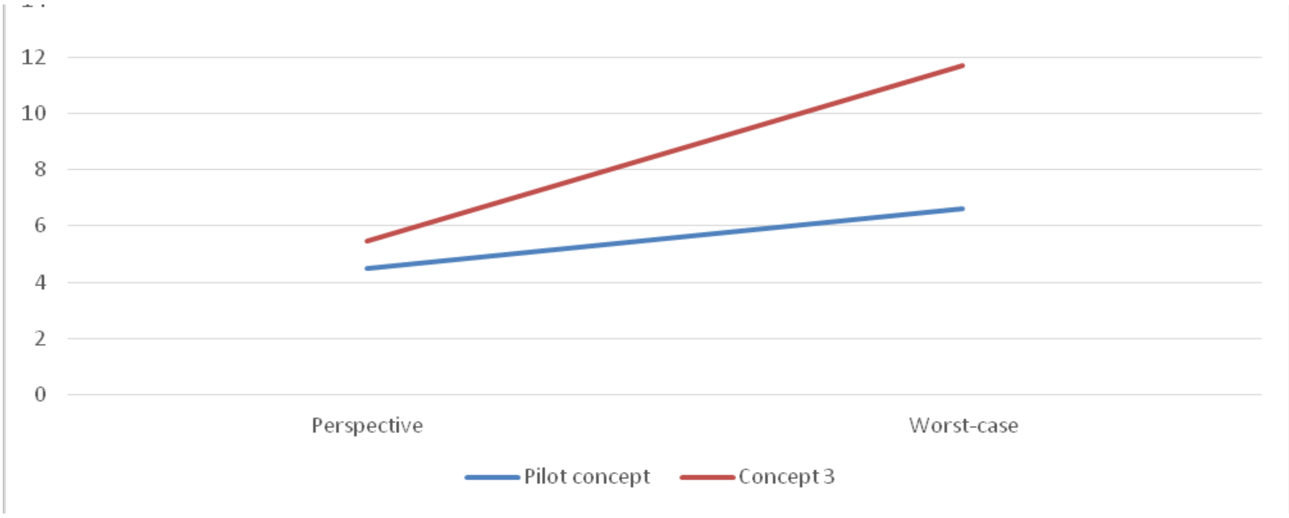

Diagram 21: Relation of SOC and fuel costs

Due to the different process constellations and the integration of SOC into the plasmolysis in concept 2 and 3, two different concepts are assessed for the required SOC surface area. This is another critical parameter, especially for the integrated concept.

The capacity factor, the LCOE and the SOC surface area are all important factors that determine the competitiveness of KEROGREEN in the ecological, social and economic dimensions.

6 Conclusions

KEROGREEN can contribute to a sustainable development in several aspects, if the right conditions are met. With the relatively low energy efficiency, it is vital to choose an energy source with a low CO_2-footprint and a high amount of full load hours. This affects the potential environmental impacts, fuel production costs and social risks. Regarding the social risks, the contributions should be anticipated along the value chain rather than at the actual fuel production process. This certainly makes it more difficult to monitor and – if necessary – improve the conditions. Again, it should be noted that the social LCA results of this report are based on aggregated industry data from many countries that could produce PtX fuels. The risks are only connected with the KEROGREEN process through the energy demand. The fuel production costs are high but could be improved in several aspects – Learning curves for the technologies and subsidies are not implemented in the model. These might be relevant factors that could lead to more competitive costs. However, this can´t be determined exactly at the moment. There could be several benefits regarding the potential environmental impacts when compared to biogenic and fossil-based fuels, but the chosen electricity source is the determining factor here.

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