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**MEDEAS**  
MODELING THE RENEWABLE ENERGY TRANSITION IN EUROPE

Project Nr: 691287

**Guiding European Policy toward a low-carbon economy. Modelling sustainable Energy system Development under Environmental And Socioeconomic constraints**

**Annex 3: Task 2.2.c.1. Production curves of non-renewable energy resources considering Renewable Energy Transition reports**

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## Document info sheet

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## List of abbreviations and acronyms

EROEI Energy Return On Energy Invested

IEA International Energy Agency

LCA Life-Cycle Analysis

LNG Liquefied Natural gas

NRE Non-Renewable Energy

RE Renewable Energy



# 1. Introduction

The transition towards a sustainable energy future necessitates a profound transformation of the current energy system. This transformation includes not only the use of other, more sustainable energy sources but also the build-up of the respective generation and transformation capacities. As the construction and operation of renewable energy technologies require direct and indirect energy inputs, and a certain share of this energy is currently (and might also be in the future) fossil fuel based, paradoxically the build-up of a sustainable energy system depends to some extent on the supply of fossil energy sources.

As a working hypothesis for this study, it has been assumed that three mechanisms impact future energy scenarios through the limitation of non-renewable energy sources. These mechanisms are:

1. Resource depletion: This mechanism accounts for the effect that the production of non-renewable fuels is limited; this limitation applies to the overall amount of energy that can be (technically and economically) produced as well as the annual production that can be achieved.
2. Extraction effort: In the future, the production of non-renewable fuels is very likely to become more energy intensive (and more expensive as well), given that the “low-hanging fruits” (highly economic reserves) have already been tapped and new reserves are harder to exploit (e.g. offshore oil fields, shale gas and tight oil production, oil sands and arctic resources).
3. Renewable technologies: The production of energy technologies requires energy, starting from the manufacturing of the components, the transportation of the components to and the assembly at the site, until the future decommissioning of the site and the disposal of the waste. All the required construction materials for components of energy technologies require a certain amount of energy for their production, from the extraction of the needed resources (e.g. iron ore), the transport of these resources and the processing and conversion (e.g. the production of steel, copper, concrete or plastics). These energy requirements are currently to some extent linked to the use of fossil fuels and often clearly higher than those related to fossil-based energy plants (like gas-or coal-fired power plants). Hence, the transformation towards a low-carbon energy system requires an upstream “fossil fuel investment”, which needs to be taken into consideration.

## 1.1 Scope of this report

An important goal of the project is to explicitly take into account the constraints imposed to the energy systems by the above mentioned mechanisms. The analysis of these constraints shall be done by answering two main research questions:

1. What are the historic and future production curves (including their energetic costs) of non-renewable energy (NRE) sources?
2. What is the content of fossil fuels embedded in the technologies producing electricity from renewable energy sources?

The results of this analysis shall help to

- understand the underlying mechanisms that link the development of renewable energy technologies with fossil fuels;
- implementing the relevant linkages in the MEDEAS model;
- implement a concept for the endogenous calculation of the EROEI in the MEDEAS model; and to
- provide a guideline for the development of the necessary data;
- understand the limits and possible shortcomings of the implemented approach.

## 1.2 Methodology

The first intention was to carry out the work as a comprehensive literature review. Whereas this approach was possible for the first research question, it could not be applied to the second one.

The analysis showed that data regarding the second research question (i.e. the fossil energy embedded in renewable electricity technologies) are not readily available from literature. Therefore, the literature-based approach was enhanced by the design of a concept that allows an implementation of the available data in the MEDEAS model.

## 1.3 Content of the report

Chapter 2 gives a compact analysis on the non-renewable energy production curves. In chapter 3, findings from the literature review on the fossil fuel content of renewable energy technologies are discussed. This discussion provides methodological and data aspects for the implementation of the

relevant linkages and the calculation of the EROEI in the MEDEAS model (chapter 4). Chapter 5 summarises this report.

In Annex 1:EROEI, selected data for the EROEI of renewable energy technologies and fossil energy carriers is shown.

## 1.4 Limits of the study

This report does not aim at providing a comprehensive literature review on EROEI and LCA data for renewable energy technologies. It focuses on discussing the implementation of the EROEI concept in the context of limited non-renewable technologies, the resource efficient implementation of the main mechanisms in the MEDEAS model and important considerations for data collection and preparation.

The non-renewable primary energy sources that have been analysed in this report are grouped according to the classifications and definitions used in IEA energy balances according (IEA, 2005):

- Coal;
- Crude oil;
- Natural gas, and
- Nuclear.

Nuclear energy is currently a synonym for Uranium<sup>1</sup> and (almost exclusively) used as a fuel for the generation of electricity. As nuclear generated electricity can be directly substituted by electricity from renewable energy sources, uranium will only play a minor role in the following analysis and is only treated with for the sake of completeness.

Non-renewable energy sources are by definition only available in limited quantities, as they have been either formed in the nascent state of the planet (mineral nuclear fuels), or in the geological past from organisms (fossil fuels). Beside the absolute quantity of each energy source, additional factors limit the amount of each fuel that can be made available for human consumption. These factors are specific for each type of non-renewable energy carrier, and dependent on various technological aspects, like the concentration of the resource and the capabilities of the required production technology.

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<sup>1</sup> Although some countries are doing research on Thorium-based reactors (WNA, 2015), currently no commercial plants are available.



The scope of renewable electricity technologies includes the following renewable electricity producing technologies (“RE technologies” for renewable energy technologies):

- Hydropower
- Geothermal power
- Solar PV
- Solarthermal power
- Ocean and tidal power
- Wind power
- Biomass CHP
- Biogas CHP

## 2. NON-RENEWABLE ENERGY PRODUCTION CURVES

The following sections give an overview of the non-renewable energy reserves and resources in the EU and worldwide. Furthermore, based on energy scenarios recently published by the European Commission and the IEA, depletion curves for oil, coal, natural gas and uranium are derived.

It is important to note that data on available resources are subject to considerable uncertainties and long-term projections for energy consumption are based on numerous uncertain parameters and assumptions. Our objective is to put *possible* future developments in non-renewable energy consumption into perspective with the reserves and resources available in the EU and worldwide. It must be stressed that our aim is *not* to make forecasts regarding the range of reserves or whatsoever.

## 2.1 Explanation of terms

The distinction between reserves and resources is based on extraction costs and techniques. “Reserves” comprise volumes that are expected to be produced economically using today’s technology. “Resources” also include volumes which have not yet been fully characterized and which are technically difficult or costly to extract (OECD/IEA, 2013).

The different types of deposits are often categorized as “conventional” or “unconventional”, depending on which extraction techniques have to be applied.

Further options to differentiate resource deposits and fuel types (e.g. between hard coal and lignite) shall be disregarded here.

## 2.2 Situation in the EU

The following data are used to characterize the situation in the EU: the Reference Scenario according to (Capros, De Vita, Tasios, & Siskos, 2016) and data on reserves/resources according to (BGR, 2015).

The Reference Scenario is described as “a projection of where our current set of policies coupled with market trends are likely to lead.” (EC, 2016). Moreover, it is stated that “the Reference Scenario is not designed as a forecast of what is likely to happen in the future. Rather, it provides a benchmark against which new policy proposals can be assessed.”

Hence, the Reference Scenario can be considered a conservative scenario with regard to fossil fuel consumption, i.e. a scenario with a relatively high consumption of fossil fuel. Regarding nuclear energy, stronger ambitions towards a low-carbon energy system are likely to result in higher demand for uranium than in this Reference scenario.

## 2.2.1 Oil

Oil reserves and resources in the EU are very limited in relation to current and projected future consumption, as Figure 1 illustrates. Reserves according to (BGR, 2015) are 46 EJ. Additional conventional resources are estimated 109 EJ and unconventional resources 68 EJ. For comparison, the EU's oil consumption in recent years was around 25 EJ. The cumulative consumption in the Reference Scenario (starting with 2015) exceeds the total reserves and resources within about 10 years (despite a decline of oil consumption to about 20 EJ in 2050).

However, oil demand in the EU is mainly covered with imports rather than indigenous resources. Figure 1 shows the projected resource depletion assuming future developments according to the Reference Scenario. It can be concluded that current reserves (according to (BGR, 2015)) will not suffice to cover the projected supply from EU countries. There are, however, sufficient conventional resources to justify the developments in resource extraction according to the Reference Scenario.

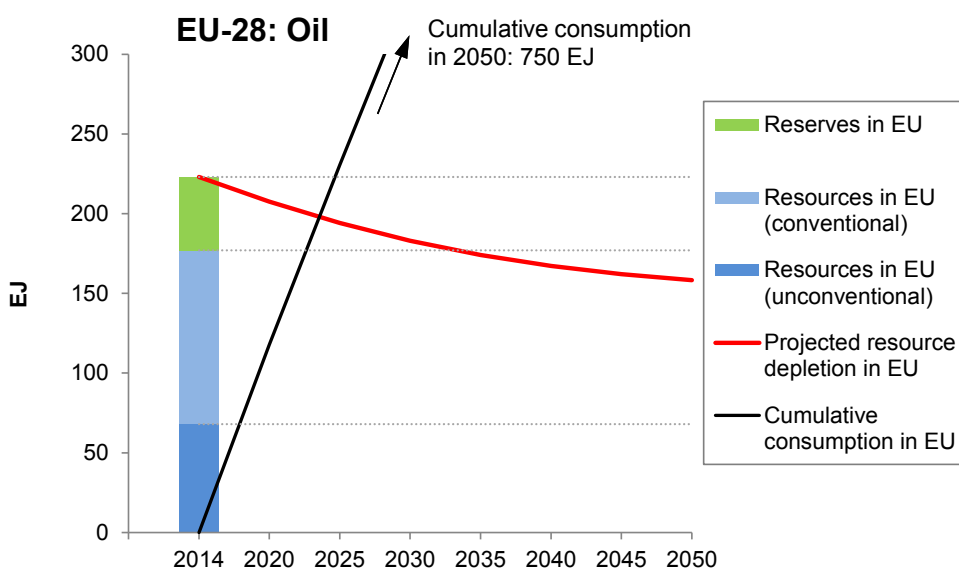


Figure 1: Oil reserves and resources in the EU (BGR, 2015), projected resource depletion and cumulative consumption in the Reference Scenario according to (Capros, De Vita, Tasios, & Siskos, 2016)

## 2.2.2 Natural Gas

The same type of data is shown for natural gas in Figure 2. Natural gas reserves in the EU are equivalent to about 64 EJ; a similar magnitude as oil reserves. This is also true for conventional resources, but unconventional resources are significantly higher than for the case of oil. Total reserves and resources even surpass the projected cumulative consumption until 2050; it is, however, questionable whether substantial quantities of unconventional gas resources can be turned into (economically extractable) reserves anytime soon.

Assuming the developments in natural gas supply and consumption according to the Reference Scenario, current reserves in the EU will be depleted around 2030.

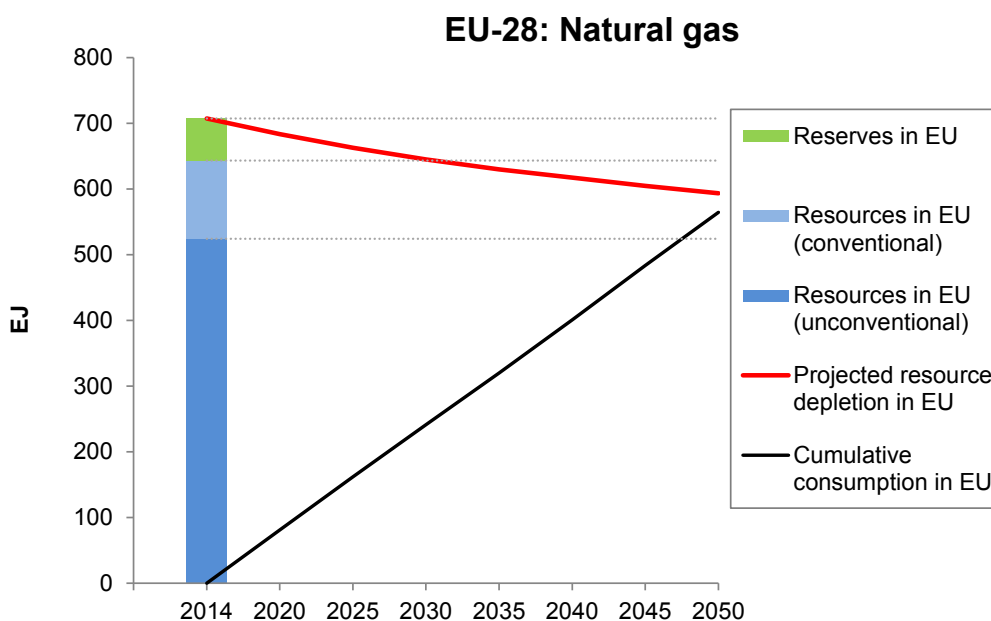


Figure 2: Natural gas reserves and resources in the EU (BGR, 2015), projected resource depletion and cumulative consumption in the Reference Scenario according to (Capros, De Vita, Tasios, & Siskos, 2016)

## 2.2.3 Coal

The situation for coal in the EU is very different from oil and gas. As Figure 3 shows, coal is abundant and reserves according to (BGR, 2015) are far from being depleted in the Reference Scenario. It can be concluded that limited availability is not an issue to be considered in connection with coal.

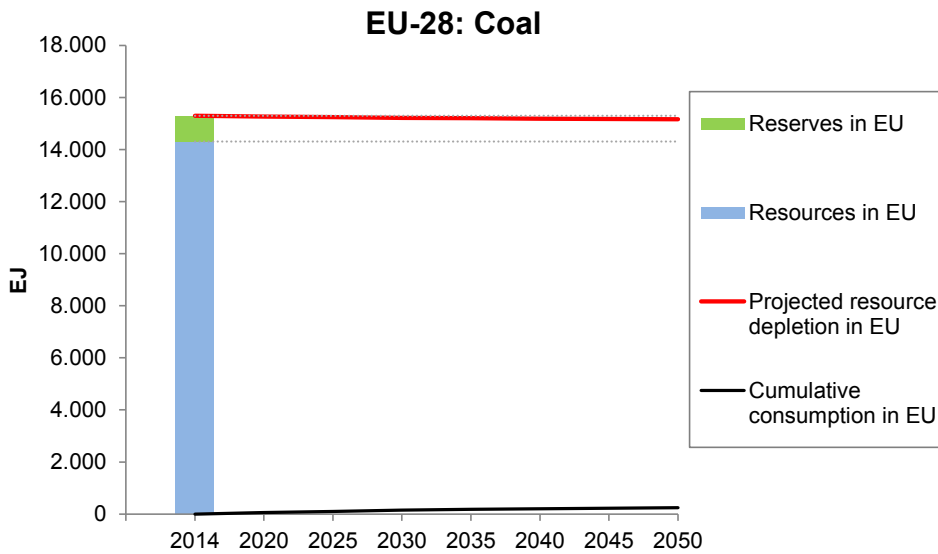


Figure 3: Coal reserves and resources in the EU (BGR, 2015), projected resource depletion and cumulative consumption in the Reference Scenario according to (Capros, De Vita, Tasios, & Siskos, 2016)

## 2.2.4 Uranium

Uranium, on the other hand, is comparatively scarce in the EU. Reserves with estimated extraction costs up to 130 USD/kg are equivalent to about 26 EJ<sup>2</sup> (thereof 10 EJ are estimated to be extractable at less than 80 USD/kg). Data on uranium resources in (BGR, 2015) are differentiated as stated in Figure 4.

Since the Reference Scenario does not include projections for the import share of nuclear fuels, it is not possible to derive a depletion curve. However, considering the projected consumption, it can be concluded that indigenous reserves can only play a minor role.

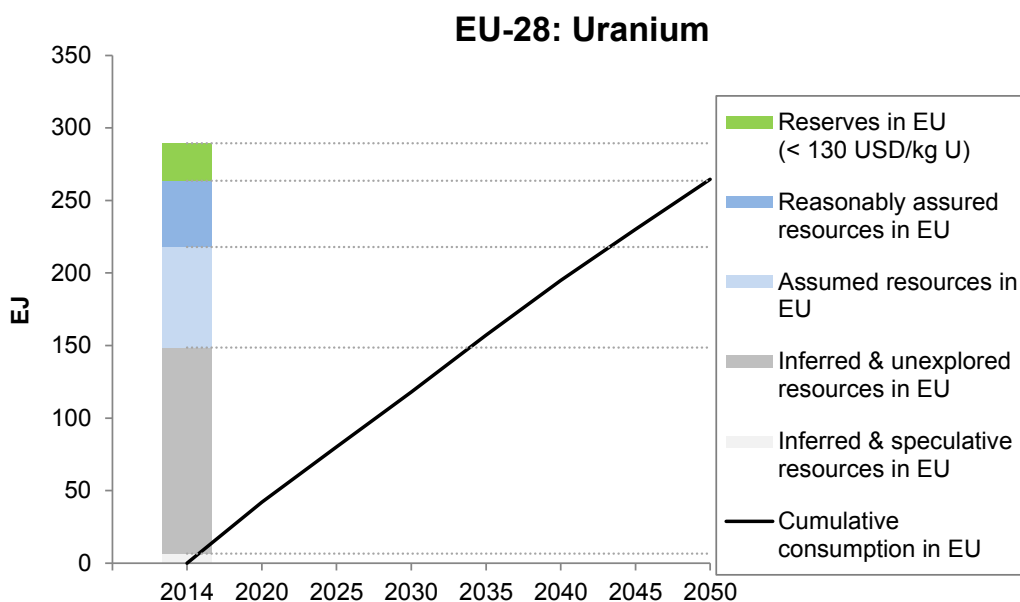


Figure 4: Uranium reserves and resources in the EU (BGR, 2015) and cumulative consumption in the Reference Scenario according to (Capros, De Vita, Tasios, & Siskos, 2016)

<sup>2</sup> Assuming an average net efficiency of 35 % for nuclear power plants (cf. (Capros, et al., 2016)).this corresponds to about 2,500 TWh of electrical energy.

## 2.3 Global situation

The following data are used to illustrate the global situation: Scenarios according to (OECD/IEA, World Energy Outlook 2016, 2016), titled “New Policies Scenario”, “Current Policies Scenario” and “450 Scenario” (see Del.2.2 for a characterization of these scenarios) and reserves/resources data according to (BGR, 2015). Further data on reserves/resources published in other studies as well as a scenario by (BP, 2016) are mentioned in the text.

### 2.3.1 Oil

World oil reserves, including conventional and unconventional deposits, are equivalent to more than 9,000 EJ according to (BGR, 2015). Estimates according to OECD/IEA (2016) and (BP, 2016) are slightly higher (10,800 and 10,400 EJ, respectively). Further 6,800 EJ of conventional and 11,800 EJ of unconventional oil are categorized as resources in BGR (2016). The estimates for the additional resources in OECD/IEA (2016) (referring to the year 2015 rather than 2014 as BGR, 2016) are 27,000 EJ.<sup>3</sup>

Scenarios according to (OECD/IEA, World Energy Outlook 2016, 2016) indicate that world oil reserves will not be depleted until 2040. Differences in oil consumption between the New Policies and the Current Policies Scenario are moderate. In contrast to these scenarios, the 450 Scenario shows a decrease in oil consumption, resulting in a less steep depletion curve. The scenario according to (BP, 2016) shows a development in oil consumption which is very similar to the Current Policies Scenario until 2030.

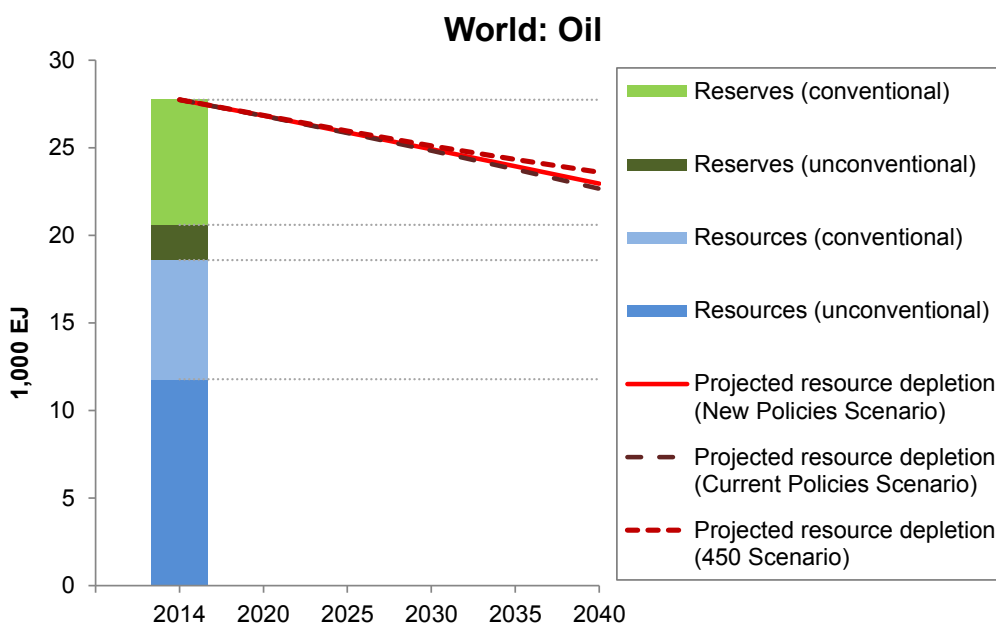


Figure 5: Global oil reserves and resources (BGR, 2015) and projected resource depletion in the New Policies and Current Policies Scenario according to (OECD/IEA, World Energy Outlook 2016, 2016)

<sup>3</sup> Comprising conventional and unconventional resources, excluding the reserves stated above.

## 2.3.2 Natural Gas

Data on gas reserves in the considered studies (BGR, 2015), (BP, 2016) and (OECD/IEA, World Energy Outlook 2016, 2016) show only minor differences and range from about 7,500 EJ to 7,870 EJ. Unconventional gas reserves are relatively small (about 260 EJ) but with regard to the resources, unconventional deposits contribute the largest share.

Global natural gas consumption is assumed to increase in all considered scenarios. Again, the scenario according to (BP, 2016) shows a similar development as the Current Policies Scenario. The projected cumulative consumption from 2014 to 2040 is less than the global conventional reserves.

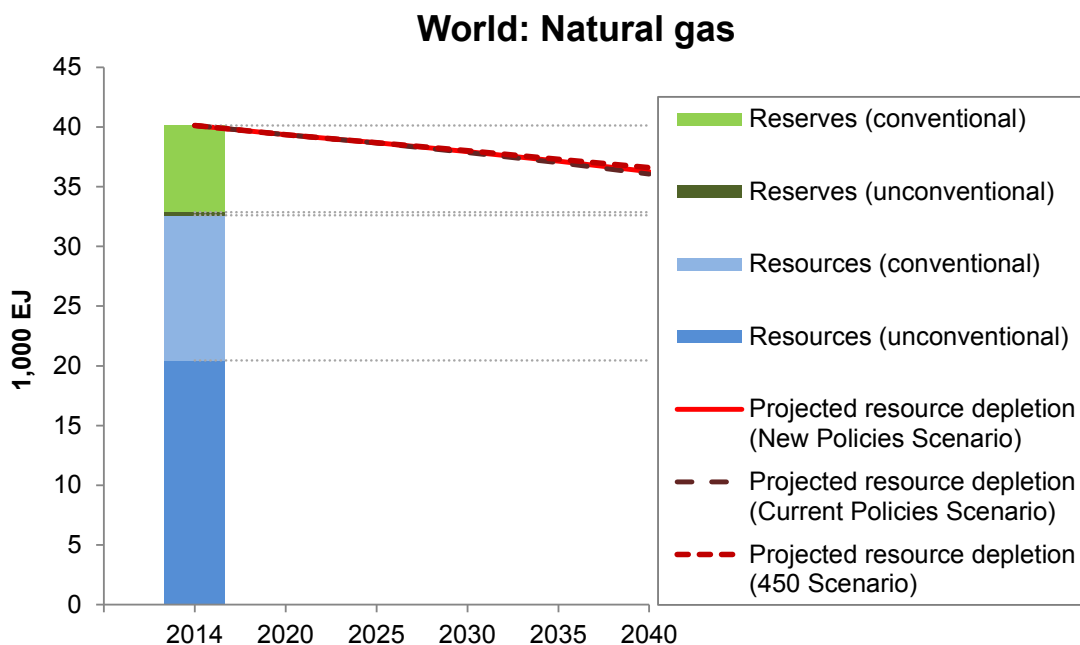


Figure 6: Global natural gas reserves and resources (BGR, 2015) and projected resource depletion in the New Policies and Current Policies Scenario according to (OECD/IEA, World Energy Outlook 2016, 2016)

### 2.3.3 Coal

Global coal resources surpass those of oil and gas (including reserves) by a factor of 13 and 18, respectively. Even in the scenario with the highest coal consumption, the IEA Current Policies Scenario, cumulative consumption until 2040 amounts to only 25 % of current reserves. The differences between the four scenarios are relatively large in the case of coal.

Projections for the consumption in 2040 are in a range from 84 EJ in the 450 Scenario to 223 EJ in the Current Policies Scenario. Regardless, it is clear that coal is abundant and even in coal-rich scenarios, reserves would last far beyond the end of the 21<sup>st</sup> century.

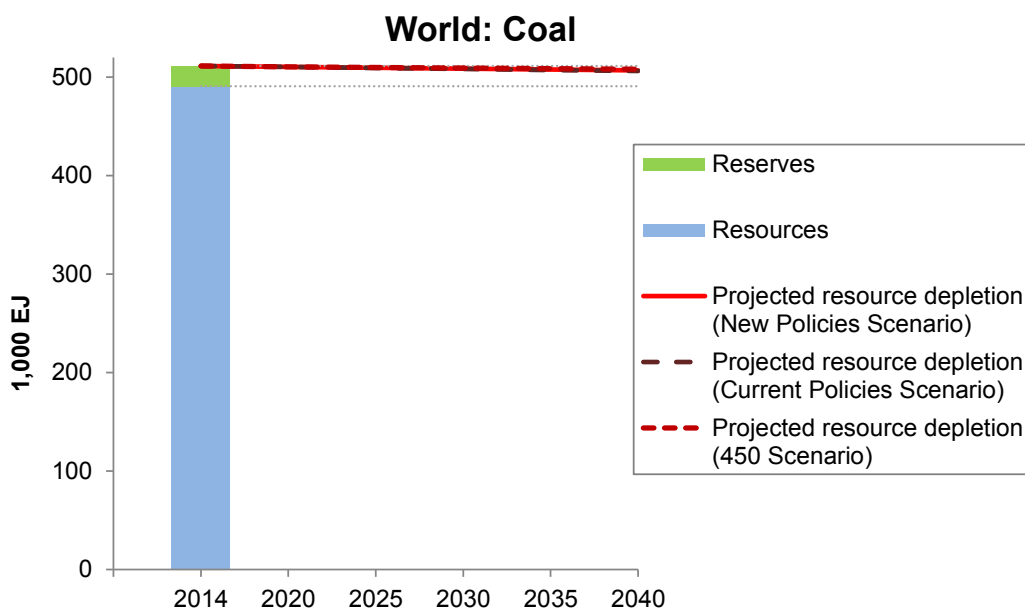


Figure 7: Global coal reserves and resources (BGR, 2015) and projected resource depletion in the New Policies and Current Policies Scenario according to (OECD/IEA, World Energy Outlook 2016, 2016)

## 2.3.4 Uranium

Although nuclear energy increases in all scenarios according to (OECD/IEA, World Energy Outlook 2016, 2016), the projections are quite different. The steepest increase occurs in the 450 Scenario.

Reserves with extraction costs up to 130 USD/kg are estimated at about 2,500 EJ. Additionally, reasonably assured resources with extraction costs up to 260 USD/kg are equivalent to about 1,700 EJ, and further (assumed or inferred) resources are estimated about 5,000 EJ. A comparison of the depletion curves in Figure 8 with these data indicates that cheap reserves are quite limited and total reserves are likely to be depleted before the middle of the present century.

These depletion curves are based on the use of uranium in conventional nuclear power systems, i.e. mainly boiling and pressurised water reactors. The large scale deployment of fast breeder reactors would increase the range of the uranium resources significantly, but is still subject of controversial discussions and remains therefore very uncertain. On the other hand, the use of uranium and plutonium from dismantled nuclear weapons in the last decades is likely cease in the near future, and will accelerate the depletion of the reserves.

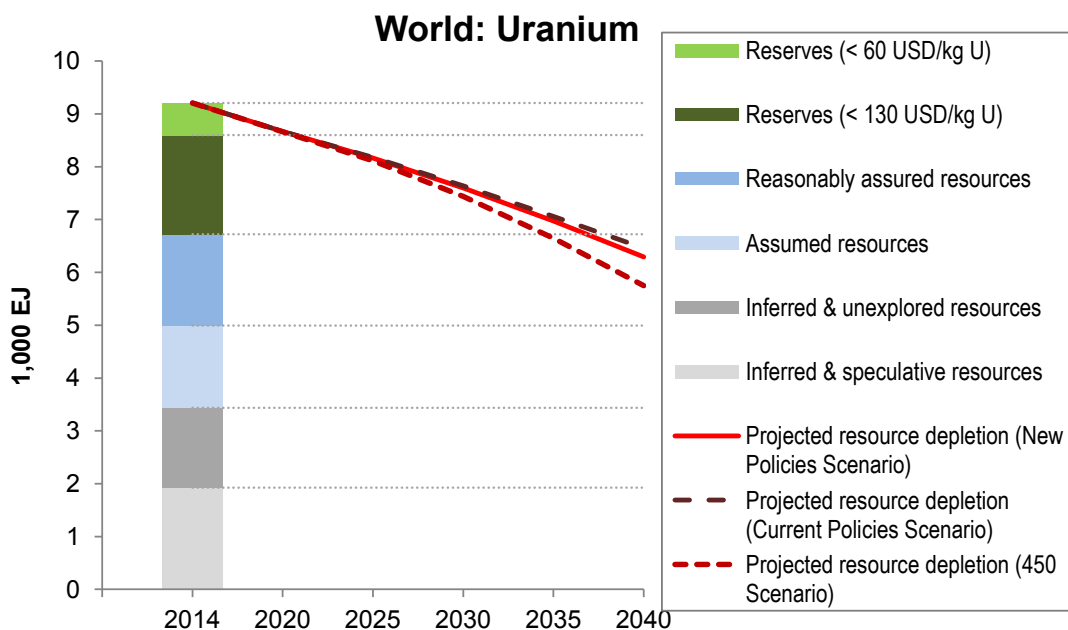


Figure 8: Global uranium reserves and resources (BGR, 2015) and projected resource depletion in the New Policies and Current Policies Scenario according to (OECD/IEA, World Energy Outlook 2016, 2016)

### 3. Fossil energy embedded in renewable electricity technologies

A literature review was carried out to analyse the amount of fossil fuels that are embedded in renewable electricity technologies. It showed that although many studies address the issue of the overall (sustainability) performance of renewable energy technologies, detailed information which directly answers the research question is not available.

The studies can be roughly divided into two groups, based on the issues they address. The first group addresses the environmental impact, and the second focusses on the overall energetic performance of RE technologies. Combining data from these two groups gives a sound idea of the data basis for implementing fossil energy demand of RE technologies in the MEDEAS model.

## 3.1. Available data/Literature review

### 3.1.1 Life cycle Assessment/Analysis (LCA)

A Life Cycle Assessment of energy technologies is carried out to allow the comparison of renewable energy technologies with other technologies with respect to their environmental impact. It relates these impacts to the energy production<sup>4</sup> of the technology, to allow the comparison of the costs and benefits of a technology. Quite often, the focus of these studies lies on GHG and other emissions, which are considered the main environmental “costs”.

While the total energy output over its lifetime can quite easily be estimated with sufficient accuracy, the side of the costs is more complicated. For a systematic assessment, bottom-up approaches are usually applied. An exemplary concept with 3 different phases of the technology life cycle can be seen in Figure 9. In each phase, the (environmental) costs are again disaggregated according to their nature (e.g. transportation or manufacturing). In phase 2, the contributions to the energy consumption from the operation of the technology and from its fuel production are treated separately.

Examples for typical LCA results are shown in Figure 10 to Figure 12.

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<sup>4</sup> The term „production” refers to all processes in which energy carriers or fuels are generated, although the term “transformation” would be more accurate.



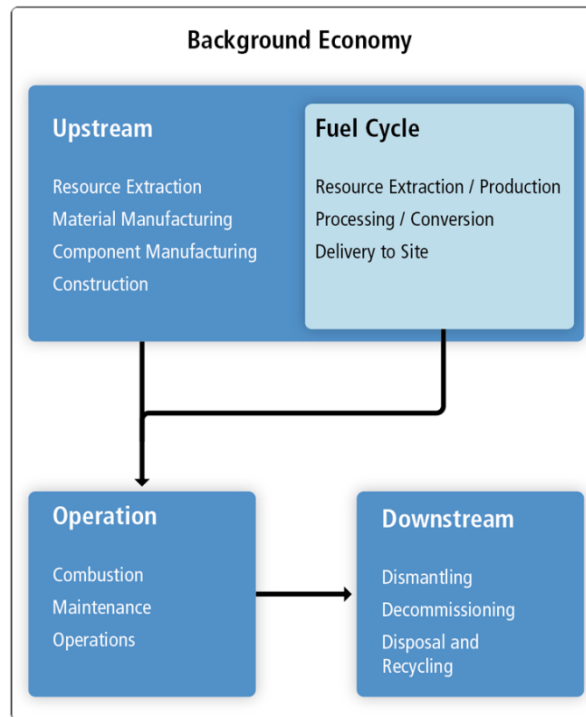


Figure 9: Illustration of generalized lifecycle stages for an energy technology. Fuel cycle applies to fossil and nuclear chains and bioenergy. (Sathaye, et al., 2011)

	g-CO <sub>2</sub> /kW h	Share (%)
Construction	9.3	82.8
Machinery	0.9	8.0
Dam	0.5	4.5
Penstock	4.5	39.8
Other foundations	2.4	21.0
Site construction	1.1	9.6
Operation	1.9	17.2
Total	11.3	100.0

Figure 10: Example: Breakdown of CO<sub>2</sub>-Emissions of hydro-power plants; from: (Hondo, 2005), Table 7

	Base case		Future case	
	g-CO <sub>2</sub> /kW h	Share (%)	g-CO <sub>2</sub> /kW h	Share (%)
Construction	21.2	71.9	14.2	69.8
Foundations	7.4	25.1	4.0	19.4
Blades	1.4	4.8	1.3	6.3
Nacelle	5.9	20.0	3.3	16.3
Tower	3.4	11.7	3.7	18.1
Turbine, etc.	3.0	10.3	2.0	9.7
Operation	8.3	28.1	6.1	30.2
Total	29.5	100.0	20.3	100.0

Figure 11: Example: Breakdown of CO<sub>2</sub>-Emissions of wind-power plants; from: (Hondo, 2005), Table 9

	Base case		Future case 1		Future case 2	
	g-CO <sub>2</sub> /kW h	Share (%)	g-CO <sub>2</sub> /kW h	Share (%)	g-CO <sub>2</sub> /kW h	Share (%)
Construction	41.1	76.9	33.7	76.9	20.0	76.9
PV panel	28.3	53.0	21.0	47.8	6.8	26.2
Support	9.8	18.3	9.8	22.3	10.2	39.3
Others	3.0	5.6	3.0	6.8	3.0	11.4
Operation	12.3	23.1	10.1	23.1	6.0	23.1
Total	53.4	100.0	43.9	100.0	26.0	100.0

Figure 12: Example: Breakdown of CO<sub>2</sub>-Emissions of PV cells; from: (Hondo, 2005), Table 10

Based on the examples shown above, the following shortcomings of a typical LCA (with respect to our research question) can be identified:

- Although the LCA approach would allow assessing both environmental impact and energy consumption of a technology at the same time, published LCA results often do not include the energy consumption but only the associated environmental impacts and emissions.
- The different types of contributions to the emissions, i.e. the fuel consumption due to activities, the emissions from material production, and other effects like land-use-change are reported as one aggregated number.

- Although the impact of major contributions is listed in a reasonable level of detail, other factors are often missing (e.g. in this example, the downstream of the technology is not taken into account).
- The aggregation of the results does not allow assessing the consumption of the main materials.
- Published data are often difficult to interpret. E.g., it is not clear which contributions lead to the operational emissions of PV cells of 12.3 g CO<sub>2</sub>/kWh (Figure 12).

### 3.3.2 Energy Return on Energy Invested (EROEI)

In the second group of studies, the Energy Return on Energy Invested (EROEI) is in the focus. This parameter relates the energy production of a technology or fuel to the energy consumption necessary for its production:

$$EROEI = \frac{\text{Energy produced by technology}}{\text{Energy consumed by technology}}$$

The energy production as well as the energy consumption is calculated by covering the whole lifetime of a technology. The calculation of the energy consumption is often based on a bottom-up-approach following the same structure as in the LCA studies (Figure 9).

Installed capacity	90 MW
Lifetime	100 a
Location	Waitaki River, New Zealand
Full-load hours	3000 (predictable)
Energy demand construction	1800 TJ
Energy demand maintenance	75 TJ (100 TJ for an assumed turbine replacement not included here)
Decommissioning	60 TJ
<b>EROI</b>	<b>50</b>
<b>EROI, buffered</b>	<b>35</b>

Figure 13: Example: Input data and results of the EROEI of a hydro power plant ; from : (Weißbach, Ruprecht, Huke, Czerski, Gottlieb, & Hussein, 2013)

In contrast to the LCA studies, in these studies the energy consumption of a technology is being reported. Unfortunately, results from these studies are also usually reported on a relatively high level of aggregation:

- The material consumption<sup>5</sup> and the type of fuel consumed is often not specified.
- No disaggregation of the energy consumption in the different stages of the life cycle.

<sup>5</sup> E.g., it often remains unclear if the energy consumption for the construction of components includes the production of the raw materials.

## 3.2 General aspects

As demonstrated, both LCA and EROEI studies cover important aspects of renewable energy technologies, but data available in literature have their shortcomings<sup>6</sup> with respect to the amount of fossil fuels embedded in renewable energy technologies. The EROEI studies address the net energetic return of energy technologies, but miss a fuel specific breakdown of the energy consumption, and often mix the energy embedded in the raw materials of the components with the rest of the energy consumption. The LCA studies often provide this differentiation, but report mainly GHG emissions that include both assumptions on the underlying fuel mix and non-energetic emissions (e.g. due to land-use change).

From the results of LCA and EROEI studies, some aspects of the calculation of the EROEI shall be pointed out. These aspects shall give advice for a methodological framework that allows the development of an endogenous implementation of the EROEI parameter and deriving the necessary data from existing studies.

Based on the concept shown in Figure 9, some definitions of terms have been developed to make the following explanations more simple and precise:

- “Phase”: Collection of contribution with respect to the technical lifetime of a RE technology
- “Contribution”: Energy consumption specific for a RE technology (e.g. dam for a hydro plant, turbine for wind or hydro power)
- “Process”: Energy consumption for a process, specific for the contribution but not for the RE technology (e.g. a truck is used for transporting materials or equipment)
- “Fuel”: Fuel (energy carrier) or fuel mix used for a process

Figure 14 gives an overview on the relationship between these terms.

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<sup>6</sup> It has to be stated that more detailed data may have been used for the study, but it is generally not reported in the published version.

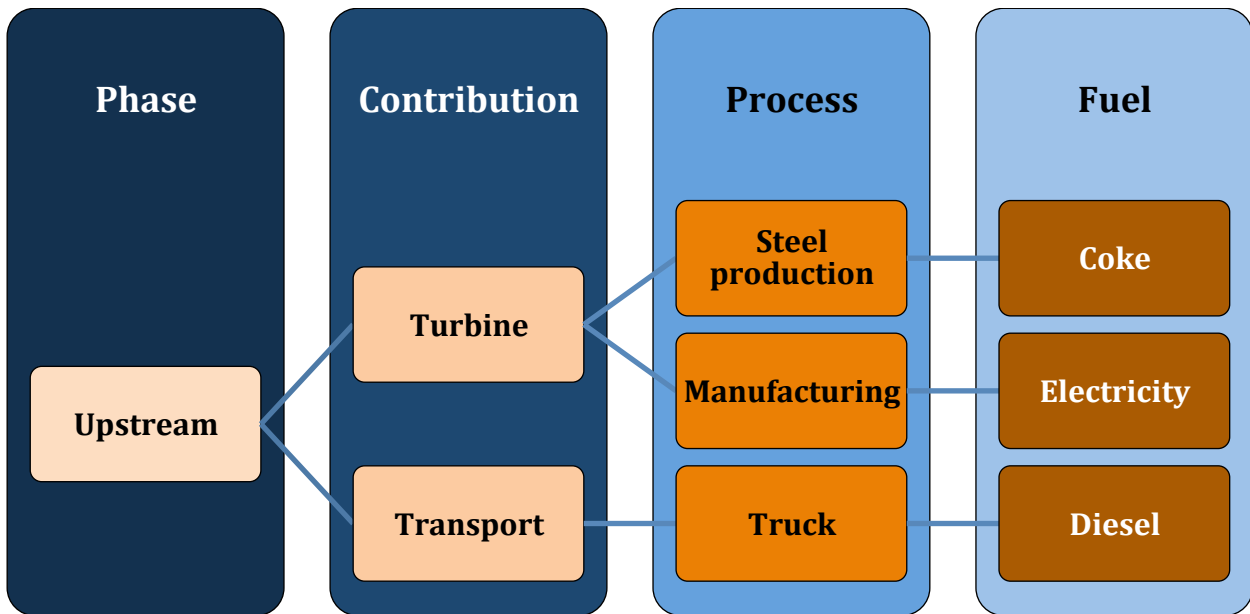


Figure 14: Definition of terms - example

### 3.2.1 Bottom-up approach

The concept shown in Figure 9 allows the disaggregation of the energy consumption in three different life cycle phases and 4 different groups of contributions (Upstream, Operation, Downstream and Fuel Cycle). Both LCA and EROEI studies are usually based on such a bottom-up analysis of the energy consumption and emissions related to a technology. This bottom-up approach allows differentiating between the different kinds of contributions to the calculated energy consumption and emissions, based on the assessed concept and used process technology.

In each group of contributions, the energy consumption is calculated bottom-up, taking into account the different process steps that are necessary for the production, operation and dismantling of a technology.

For example, the energy consumption due to material manufacturing as well as the disposal and recycling efforts scale with the associated masses and materials and therefore with the unit size or capacity, while the efforts for maintenance also scale with the technical lifetime of the system.

### 3.2.2 Fuel types and shares

For each of the process steps, not only the total consumption of energy must be considered but also the type of energy (e.g. electricity, low/high temperature heat, transport fuels) which is again depending on the process technologies used. For example, transport and earthworks are relying heavily on diesel, in contrast to many manufacturing machines which require electricity. This differentiation is also important with regard to raw material supply. For example, the production of steel from iron requires also coke (and therefore coal), whereas for aluminium and PV cell production electricity plays an important role.

The amount and shares of the fuels used can change over time (e.g. chemical function of coke in steel production can be fulfilled by hydrogen produced via electrolysis, i.e. with electricity). Similarly diesel, the currently predominant fuel in earth works and transport equipment, might (partly) be replaced by LNG, hydrogen, biodiesel or electricity in the coming decades.

### 3.2.3 Temporal distribution

In the context of modelling, it is also important to consider the temporal distribution of energy consumption related to RE technology deployment, operation and dismantling. A bottom-up approach like it is being applied in LCA or EROEI studies has the advantage that the temporal distribution of the energy consumption in each phase can be modelled quite easily (**Error! Reference source not found.**).

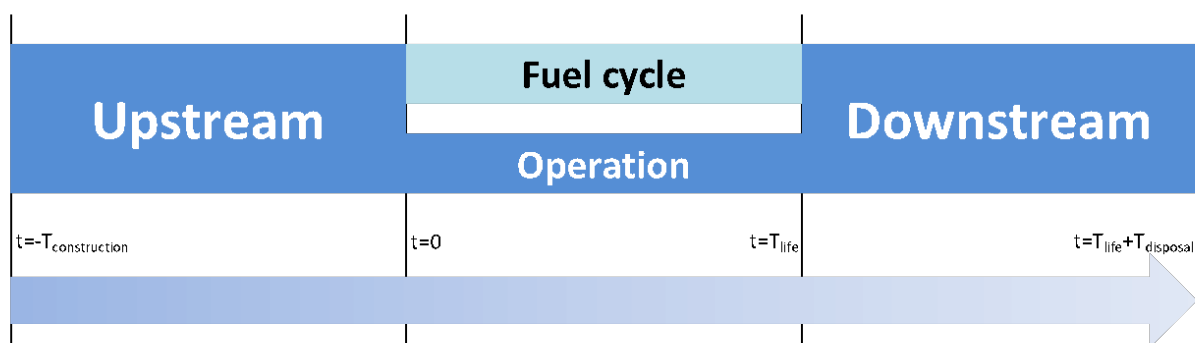


Figure 15: Chronological order of the 3 phases of the energy consumption

### 3.2.4 Impact of site- and plant-specific parameters on energy production

Both LCA and EROEI studies relate the costs of a technology (in terms of either energy or emission) to its lifetime energy output.

However, the output of renewable energy technologies is often strongly influenced by site- and plant-specific parameters (e.g. wind characteristics of a specific location, geographical latitude of PV installations). Some of the technical parameters of the technology can be optimised by the choice of the design to optimise the output of a technology on a specific site, but certain geographical and site-specific factors that limit the maximum output cannot be altered.

For example, the production of a wind turbine can be optimised by choosing optimising the height of the tower or the length of the rotor blades, but the maximum energy output of a given site is limited by the local wind conditions. So even if technological progress allows approaching the exploitation of the maximum wind potential available, it is very likely that future sites for wind turbines will have less optimal conditions than the sites already exploited.

The performance of conventional energy technologies is partly also influenced by site-specific parameters, but most RE technologies are clearly more influenced by such factors. The choice of favouring and selecting sites with more advantageous production properties over sites less optimal (i.e. the “picking of low-hanging fruits”) will have a negative impact on the EROEI of RE technologies<sup>7</sup>. The extent to which this effect can be balanced by technological progress is uncertain.

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<sup>7</sup> This effect can already be observed for the EROEI of fossil fuels.



### 3.3. Conclusions from the literature review

From the literature review, it became clear that the data necessary for a disaggregated and explicit calculation of the amount of fossil fuel embedded in renewable energy technologies is not directly available. The studies report either emissions or energy consumption, but only in one single number for the technology or selected process steps. No systematic disaggregation of the results on the fuels consumed has been reported. The material consumption of renewable technologies has been analysed in a small number studies. In these studies, no link of the results to (fossil) energy consumption or emissions has been found.

The analysis of a variety of studies would probably allow the calculation of the parameters necessary for the endogenous implementation of the EROEI in the MEDEAS model. A final description of the requirements for the data preparation will depend on the approach that shall be implemented in the MEDEAS model. The selection of the approach has to be decided on within the project consortium.

Especially for scenarios covering a time horizon until 2050 with a huge potential for technological progress and technological change, the possible changes of the energy consumption of various processes (like the transport or manufacturing of components, or the production of materials) and the respective fuel shares has to be considered.

The future development of the parameters that describe the EROEI of technologies is even more complicated. The historical development of the EROEI factors has only been studied for fossil fuels. Especially for renewable energy technologies, the results are strongly dependent on the specific plant, i.e. on the geographical conditions, like solar irradiation, precipitation or wind speed. The dependence on the application of different (carbon-free) processes or technologies in the upstream and downstream of the technology has not been studied.

## 4. Implementation

The goal of this chapter is to develop from the findings in chapter 3 the necessary recommendations for the implementation in the MEDEAS model.

### 4.1 Purpose of the implementation

In the development of the MEDEAS model, one of the goals is to implement an endogenous treatment of the fossil fuels embedded in renewable energy technologies, by:

- Explicitly calculating the energy consumption of the deployment of renewable energy technologies, and
- Endogenous calculating the resulting EROEI of renewable energy technologies.

## 4.2 Current structure of the MEDEAS model

In (de Blas & et.al., 2016), the current structure<sup>8</sup> of the MEDEAS world model is being described. Figure 16 gives an overview on the general structure of the model.

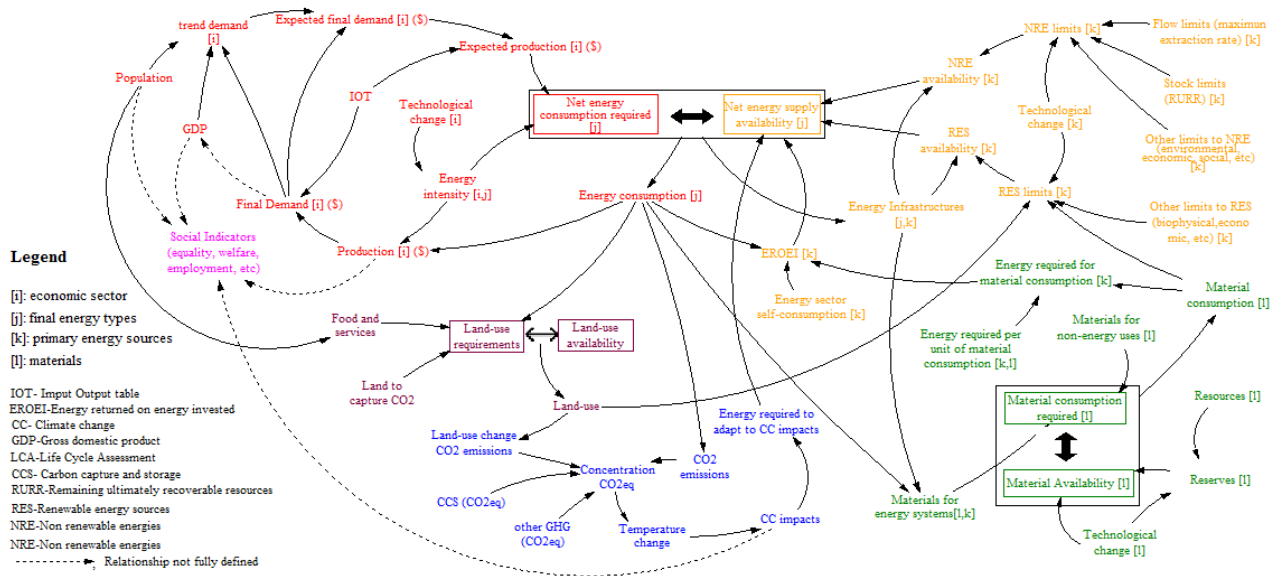


Figure 16: Current structure of the MEDEAS Model; from: (de Blas & et.al., 2016)

From this structure, several mechanisms can be identified that are related to the EROEI of energy technologies. These mechanisms are:

- The link between energy consumption and the materials for the energy system;
- The link between energy between sector self-consumption, EROEI and net energy supply availability;
- The link between material consumption and energy required for material consumption.

In the current approach, the EROEI is calculated from the energy investments, in particular the variables “Energy required for material consumption” and “Energy sector self-consumption”, and the final “Energy consumption” (de Blas & et.al., 2016).

<sup>8</sup> The structure of the MEDEAS model is still under development. Therefore, the concept for the implementation of the endogenous calculation of the EROEI is likely to be adapted.

As the model is still under development and not detailed information is available, it was not possible to develop a concrete concept for the implementation of the mechanisms related to the amount of fossil fuels embedded in renewable energy technologies can be proposed.

As a contribution to the model development, several aspects shall be pointed out that shall help to clarify the development of a methodological approach for the endogenous implementation of the EROEI of renewable technologies.

In 3.2, different aspects of the calculations of EROEI and LCA have been pointed out. In the following sections, these aspects shall be related to the development of the MEDEAS model.

## 4.3 Methodological issues of explicit energy demand calculation

### 4.3.1 Reduction of complexity

It is obvious that an approach for the calculation of the various contributions to the energy consumption that takes into account this complexity become a burden when it shall be implemented in a mathematical model covering the whole energy system and time horizons until 2050.

To simplify data provision and computational complexity while keeping the features relevant for the MEDEAS model (i.e. fuel shares and explicit accounting of materials), it is necessary to focus on the main influencing parameters and work on a manageable level of aggregation.

The first step of such a simplification is illustrated in Figure 17 and Table 1.

*Table 1 : Simplified life cycle concept with 5 contributions*

Phase	Contribution	Description
Upstream	Materials	Production of the materials for the components, including resource extraction and transportation of the materials to the component production facilities
	Construction	Manufacturing of the components from the materials, transportation of the components to the site and assembly of the components at the site
Operation	Operation	Operation and maintenance
Downstream	Decommissioning	Dismantling of the plant, decommissioning of the site, disposal and recycling of the materials and all associated transport
Fuel cycle	Production	Resource extraction, fuel processing and transport to the site

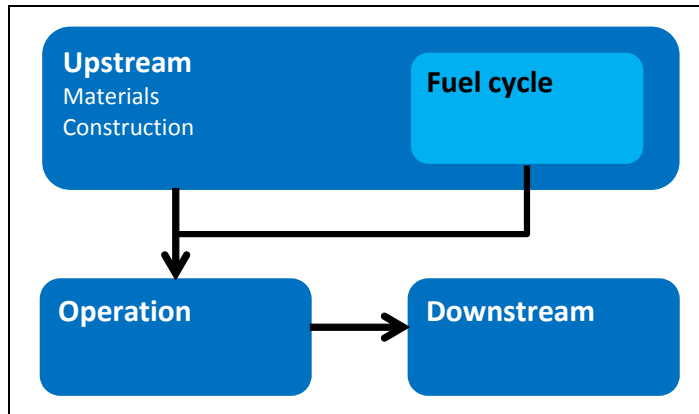


Figure 17: Simplified life cycle concept with 5 contributions

The complexity of the concept in Figure 17 can further be reduced. Neglecting of the temporal distribution of the energy consumption of upstream and downstream, a concept with 4 contributions is the result (Figure 18).

The downside of neglecting the temporal dimension of the energy consumption plays no role for a comprehensive assessment of energy technologies. In such an assessment, the costs and benefits of the whole lifecycle are set into relation. The implementation of such a concept in a model considering the temporal development of the energy system, the temporal distribution of the energy consumption becomes important.

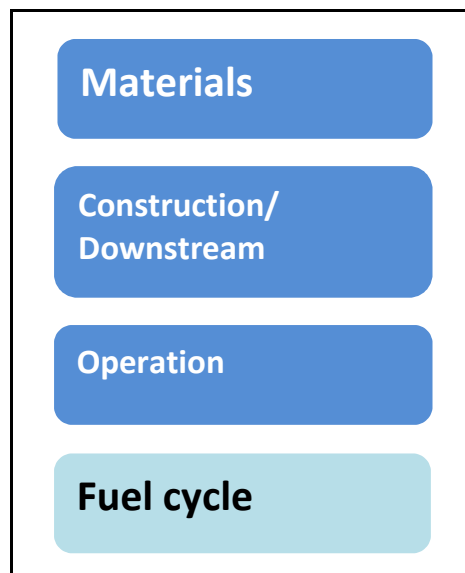


Figure 18: Simplified life cycle concept - 4 contributions neglecting the temporal distribution

### 4.3.2 Fuel Share

The fuel share from the various contributions can be taken into account through a bottom-up or a top-down approach. The bottom-up-approach would assign fuel-specific energy consumption per unit of technology to each type of contribution considered; the resulting total energy consumption would be the sum of each fuel consumed. The top-down approach would need a parameter describing the overall energy consumption per unit of technology, and a share of the fuels needed for this consumption.

The advantage of the bottom-up approach is that a change of the process technology used for a single contribution that leads to a change of both fuel and specific energy consumption of this contribution can be easily calculated without changing the other contributions. On the other hand, the top-down approach requires less data and therefore more easily obtainable data.

## 4.4 Methodological issues of the EROEI calculation

### 4.4.1 Double-Counting of Contributions

The endogenous implementation of the EROEI in a comprehensive model like raises the important issue of double-counting of energy and material consumption.

The deployment of renewable energy requires a variety of contributions, e.g. for the fuel production, the material production, and the manufacturing and transport requirements. In the MEDEAS model, all these different demands are currently accounted for in different sectors. For example, the energy demand for the production of raw material like iron ore is a part of the consumption of the sector (“Mining and Quarrying”, the material and energy consumption for the manufacturing of the components is calculated in the sectors “Manufacture of electrical equipment” and “Manufacture of machinery and equipment”.

Once these contributions to the material and energy consumption are calculated endogenously, it has to be assured that they are not accounted for in other sectors as well.

### 4.4.2 Temporal distribution

The LCA and EROEI studies give as a result a single number for the energetic and environmental performance of a technology. While this approach is reasonable for the comprehensive assessment of a technology, it falls short for energy system modelling.

In the MEDEAS model, the temporal evolution of the energy system is an important aspect for the assessment of pathways towards a low carbon society. Thus, it is relevant for the results to distinguish between past or future energy and material consumption.

The production of energy from RE technologies is also accounted for with respect to this temporal development. But as stated in 0, such an approach could lead to a complexity too high for a model to handle, both in terms of computational time and data provision.

A possible work-around could be to neglect the temporal distribution of the energy and material consumption (Figure 19), and distribute them over the operating lifetime of the RE technology (Figure 20).

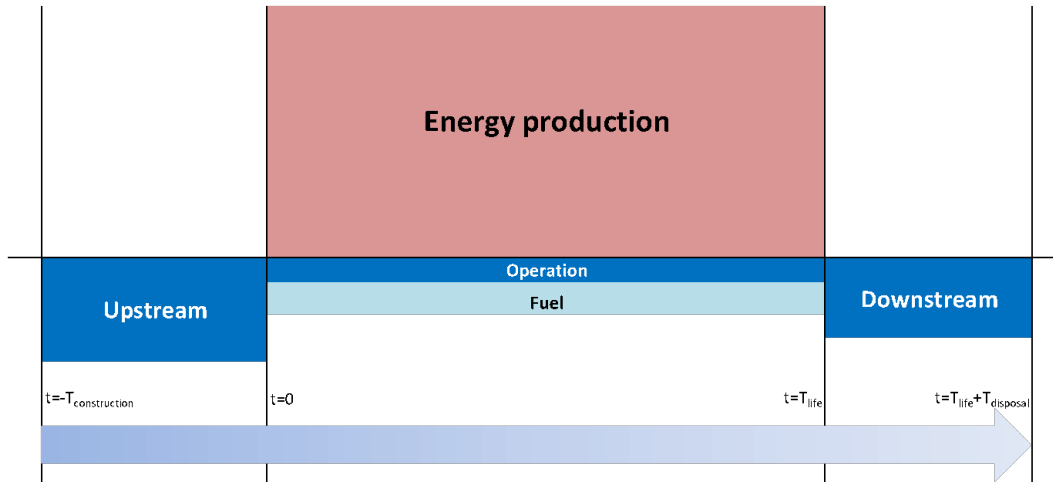


Figure 19: Temporal distribution of energy consumption (blue) and production (red)

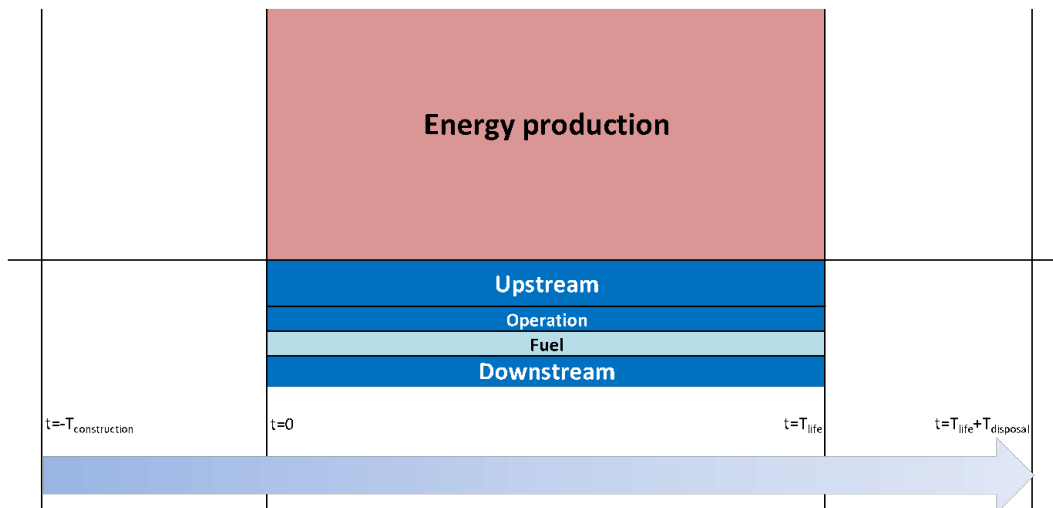


Figure 20: Neglecting the temporal distribution of energy consumption (blue) and production (red)

## 4.5 Possible approaches for the implementation

Based on the reduced concept in Figure 18 in 0, the EROEI of a technology can be calculated from the following contributions:

- Energy consumption for the production of the construction materials;
- Energy for the manufacturing of the components and the dismantling of the technology;
- Energy consumption for the production of the fuels
- Energy production for the operation of the technology; and the
- Lifetime energy production from the technology.

The accounting of the material and energy consumption can be either done in a direct or in an indirect way:

- In a direct approach the consumption is explicitly calculated and triggers a demand for energy and materials, and the respective demand is subtracted from the demand of the industrial sectors.
- In an indirect approach, the construction of infrastructure increases the activity of the commercial sectors necessary for its construction and operation, thus indirectly increasing the material and energy consumption.

## 4.5.1 Approach one: Direct implementation

The direct approach is characterised by the following properties:

- The energy and material demand of renewable electricity technologies are calculated explicitly and contribute to the overall demand for energy and materials.
- The consumption of the final energy demand sectors is the sum of the consumption due to the demand of the RE technologies and the demand from other uses.
- The EROEI is calculated based on these explicitly calculated demands according to the concept in Figure 18.

For each technology  $i$ , the energy consumption  $E_{cons,i}$  and production  $E_{prod,i}$  have to be calculated. The energy consumption is given by:

$$E_{cons,i} = \frac{1}{T_{Life,i}} \cdot (E_{Materials,i} + E_{Upstream/Downstream,i} + E_{Operation,i}) + E_{Fuel,i}$$

With

$E_{Materials,i}$	<i>Energy for the production of the materials for the technology</i>
$E_{Upstream/Downstream,i}$	<i>Energy for constructing and dismantling the technology, excluding the energy for the material production</i>
$E_{Operation,i}$	<i>Energy for operating the technology</i>
$E_{Fuel,i}$	<i>Energy for the production of the fuel</i>
$T_{Life,i}$	<i>(Operational) lifetime of the technology</i>

The energy for the material production has to be calculated in the materials module of the MEDEAS model (see (de Blas & et.al., 2016)). The energy for the production of the fuel has to be calculated in a way analogue to the energy for the materials. The energy for the operation is currently accounted for in the self-consumption of the energy sector.

The resulting energy demand with respect to the final energy fuels  $j$  is calculated by

$$E_{cons,i,j} = \frac{1}{T_{Life,i,j}} \cdot (E_{Materials,i,j} + E_{Upstream/Downstream,i,j} + E_{Operation,i,j}) + E_{Fuel,i,j}$$

and

$$E_{Materials,i,j} = E_{Materials,i} \cdot \gamma_{Materials,i,j}$$

with

$\gamma_{Materials,i,j}$

*Share of final energy fuel  $j$  for production of the materials of technology  $i$*

By summing over the energy production and consumption of all technologies, the *EROEI* of the energy system in a given year is

$$EROEI = \frac{\sum_j E_{prod,j}}{\sum_i E_{cons,i}}$$

Table 2 gives a short overview on the possible advantages and disadvantages of the implementation of the direct approach.

*Table 2 : Pros and cons of the direct approach*

Pros	Cons
<ul style="list-style-type: none"> <li>• The calculation of the EROEI is simple.</li> <li>• The methodology for the provision of the necessary data is easy.</li> </ul>	<ul style="list-style-type: none"> <li>• The implementation of the concept is complex and requires a separate subsector in the model.</li> <li>• The amount of necessary data is high.</li> <li>• The demand of the final energy sectors has to be re-calibrated to avoid double-counting.</li> </ul>

## 4.5.2 Approach 2: Indirect implementation

In the indirect approach, the deployment of renewable energy technologies increases the energy consumption by increasing the economic activity of the commercial and industrial sectors that provide the materials, components and services necessary. The amount of increase of the activity has to be adjusted so that the resulting increase of material and energy consumption matches the requirements for the RE technologies.

As the structure of the MEDEAS model is still under development, a more detailed concept of the both the calculation of the energy and material demands for RE technologies and the calculation of the EROEI cannot be developed. Currently, it can be expected that an additional link between the variable “Energy infrastructures [j,k]” (see Figure 16) and “Expected final demand [i] (\$)” might become necessary.

The calculation of the EROEI of the energy system has to be done by summation and weighing of the (exogenous given) EROEI factors of the single technologies.

Table 3 gives a short overview on the possible advantages and disadvantages of the implementation of the indirect approach.

*Table 3 : Pros and cons of the indirect approach*

Pros	Cons
<ul style="list-style-type: none"> <li>• The implementation of the concept is simple.</li> <li>• The amount of necessary data is lower.</li> <li>• The final energy sectors do not have to be re-calibrated.</li> </ul>	<ul style="list-style-type: none"> <li>• The calculation of the material and energy consumption is less accurate.</li> <li>• The calculation of the EROEI can only be done indirectly.</li> <li>• The methodology for the provision of the necessary data is complicated and requires separate studies.</li> </ul>

## 4.6 Data requirements

In the literature reviewed, a variety of different data is being reported that can be used for the endogenous implementation of the EROEI of RE in the MEDEAS model.

Both LCA and EROEI studies have the aim to make a comprehensive assessment of the impacts and benefits of a technology. The results of these assessments are usually aggregated into one single indicator, to allow an easy benchmarking of the technology against its competitors.

Depending on the type of study, either the GHG emissions or the energy consumption per electricity are reported. In LCA studies, quite often the results are presented as a breakdown on the life cycle phases (like construction of the technology) or major contributions (like manufacturing of turbines).

In many studies, more detailed data on the production parameters are presented (like annual full load hours, generation capacity, operational lifetime or efficiency). These data are either site-specific (common for RE technologies) or generic (i.e. for a typical installation).

In a few studies, more detailed data of the calculation of the main results have been found, like material masses consumed, or the specific consumption of energy for a contribution. These data is always only presented for selected and important contributions; in no publication all the data used has been found.

So far, no study has been found that contains all the data needed for the approaches described in section 0. However, it seems likely that the necessary data can be extracted from the existing literature with a more comprehensive review, although the required effort is expected to be significant.

*Table 4* gives an overview on the data necessary for the implementation of the direct and indirect approach.

*Table 4: Data required for the implementation of the direct and indirect approach (for each technology)*

Direct approach	Indirect approach
Energy for construction and dismantling	Economic activity of each sector for each unit of capacity



---

Energy for fuel production	EROEI
Energy for operation	Operational lifetime
Material consumption per material	
Share of fuels for the construction and dismantling	
Share of fuels for fuel production	
Share of fuels for operation	
Share of fuels for material production	
Operational lifetime	

---



## 4.7 Findings

In the following, some findings about the implementation of the EROEI in the MEDEAS models are shortly discussed.

### CURRENT EROEI APPROACH IN MEDEAS MODEL

The comparison of the reviewed literature and the description of the EROEI calculation in the MEDEAS model show that the approach planned for implementation is not an EROEI comparable to the definition and use in the literature. The first issue is here that it does not cover all aspects of the EROEI. Additionally, it takes into account the energy consumption to cover the whole material demand, thus including also non-energy related consumption.

### LINKS BETWEEN NRE AND RE FUELS

The use of data from current studies for the calculation of the contributions to the EROEI of RE technologies requires the careful definition of the system boundaries. E.g. the energy consumption from transport requirements usually takes into account the amount of transport fuel (i.e. mainly diesel) used. In general, the energy for the production of the fuel itself (for oil production, transportation and refineries) is not taken into account. But as the EROEI of fossil fuels show a decreasing trend, this real energy consumption for transportation is also increasing.

### TEMPORAL DISTRIBUTION

A general issue is the use of results from comprehensive assessments in models with the aim of developing pathways. Whereas the results of comprehensive assessments are neglecting the temporal perspective, this perspective becomes important in models where not only the amount of energy consumption but also the period of its occurrence is explicitly modelled.

### DOUBLE COUNTING

An important issue is the double-counting of energy demand for material and component production in energy infrastructures and in industry. In the data currently used for modelling (like IO tables), the energy consumption for the deployment of RE technologies is considered in the economic activity of end use sectors (like mining, concrete production, transport or steel production), or in the energy sector in form of the self-consumption. The endogenous and explicit modelling of the contributions to the EROEI requires the re-calibration of these sectors, otherwise the contributions would be counted double.



## REGIONAL BREAKDOWN

In general the studies providing the data do not differentiate the regional distribution of the energy consumption. Whereas this is no problem in a global model, it becomes one in model for the EU or a single country. In such a case, a part of the energy consumption for the build-up of RE technologies is taking place outside the region modelled and only considered via the import of goods.

## ADVANTAGES AND DRAWBACKS OF THE TWO APPROACHES

Both approaches proposed in section 0 have their advantages as well as disadvantages. For a well-funded decision about which one should be implemented, the priorities about the aim of an endogenous implementation of the EROEI have to be set clear. Following such a clarification and the more detailed description of the internal structure of the MEDEAS model, an approach that should be implemented can be proposed.

## 5. Summary

For this report, available literature on NRE extraction curves and fossil fuel embedded in RE has been reviewed. Based on this review, the major points have been discussed.

The review of the existing literature gave two important insights. First, the endogenous implementation of the EROEI in the MEDEAS model is a complex task. Second, the provision of the data necessary for such an implementation requires a significant effort as it seems to be not available in the existing literature.

From the current state of knowledge, the implementation of a direct approach for the endogenous treatment of the EROEI seems recommendable. Although such an approach requires the implementation of some additional model complexity and the elaboration of a significant amount of data, the methodology for such an undertaking is much more straight-forward.

Once more clarity on the structure of the MEDEAS model is achieved a more well-funded decision about the implementation of the EROEI can be made.

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## Annex 1: EROEI

Table 5 gives an overview on the EROEI data found in the literature.

The main findings are:

- The EROEI of fossil fuels is generally decreasing.
- Coal has the highest EROEI among the fossil fuels.
- Data on temporal development of the EROEI is only available for fossil fuels.

*Table 5 : Overview on the EROEI of fuels and technologies*

Resources	Year	EROEI	Country	Comments	Source
<b><i>non-renewable</i></b>					
coal	1950	80	US		1
coal	1995	35	China		3
coal	2000	80	US		1
coal	2007	60	US		1
coal	2010	27	China		3
coal	2014	46			5
oil and gas	1930	100	US		2
oil and gas	1970	30	US		2
oil and gas	1970	65	Canada		3
oil and gas	1999	35	global	<sup>9</sup>	1
oil and gas	2000	18 to 11	US		2
oil and gas	2006	18	global		1
oil and gas	2010	15	Canada		3
oil and gas	2010	10	China		3
oil and gas	2014	20		<sup>9</sup>	5
oil shale	2014	7			5
tar sands	2014	4			5

<sup>9</sup> Oil and gas EROEI values are typically aggregated together.





natural gas	1993	38	Canada	3
natural gas	2000	26	Canada	3
natural gas	2005	10	US	1
natural gas	2009	20	Canada	3
nuclear	-	5 to 15	US	1
nuclear	2014	14		5
<b>renewables</b>				
geothermal electricity	2014	9		5
<b>production</b>				
hydroelectric power	2014	84		5
hydropower	-	>100	-	1
photovoltaik	-	6 to 12	-	1
solar (PV)	2014	10		5
wind power	2014	20		5
Wind power	-	19,8	-	4
<b>biomass</b>				
biodiesel	-	1,3	-	1
biodiesel	2014	2		5
ethanol	-	0,8 to 10	-	1
ethanol	2014	5		5



*Table 6 : Data sources for the overview on the EROEI of fuels and technologies*

No	Source
1	Lambert et al. EROI of Global Energy Resources - Preliminary Status and Trends, State University of New York, College of Environmental Science and Forestry, 17.
2	Murphy, D.J., Hall, A.S. 2010. Year in review - EROI or energy return on (energy) invested. Annals of the New York Academy of Sciences. Issue: Ecological Economics Reviews, 110.
3	Hall, C.A., Lambert, J.G., Balogh, S.B. 2014. EROI of different fuels and the implication for society, Energy Policy, 145.
4	Kubiszewski, I., Cleveland, C.J., Endres, P.K. 2010. Meta-analysis of net return for wind power systems [Online] Available at: <a href="http://www.soest.hawaii.edu/GG/FACULTY/ITO/GG410/Wind/Kubiszewski_EROI_Wind_RenEn10.pdf">http://www.soest.hawaii.edu/GG/FACULTY/ITO/GG410/Wind/Kubiszewski_EROI_Wind_RenEn10.pdf</a> [Zugriff am 1.12.2016]
5	Hall, C.A., Lambert, J.G., Balogh, S.B. 2014. EROI of different fuels and the implication for society, Energy Policy, 143.