Report SUSTAINABLE INNOVATION

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Energy indicators for electricity production

Comparing technologies and the nature of the indicators Energy Payback Ratio (EPR), Net Energy Ratio (NER) and Cumulative Energy Demand (CED)

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Comparing technologies and the nature of the indicators Energy Payback Ratio (EPR), Net Energy Ratio (NER) and Cumulative Energy demand (CED)

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Summary

Introduction

CEDREN (Centre for Environmental Design of Renewable Energy) is founded by The Research Council of Norway and energy companies and is one of eight centres that were part of the scheme Centre for Environment-friendly Energy Research (FME) when the scheme was launched in 2009. The main objective of CEDREN is to develop and communicate design solutions for transforming renewable energy sources to the desired energy products, and at the same time address the environmental and societal challenges at local, regional, national and global levels.

CEDREN's board initiated in 2011 a pilot project on the topics 'Energy Pay-back Ratio (EPR)', 'Ecosystem services' and 'multi-criteria analysis (MCA)' in order to investigate the possible use of these concepts/indices in the management of regulated river basins and as tools to benchmark strategies for the development of energy projects/resources. The energy indicator part (documented in this report) has aimed at reviewing the applicability of different energy efficiency indicators, as such, in the strategic management and development of energy resources, and to compare and benchmark technologies for production of electricity. The main findings from this pilot study is also reported in a policy memo (in Norwegian), that is available at www.cedren.no.

The work carried out in this project will be continued in the succeeding research project EcoManage, which was granted by the Research Council of Norway's RENERGI programme in December 2011.

Energy indicators

Several energy indicators for extraction and delivery of an energy product (e.g. transport fuel, heat, electricity etc.) exist today. The main objective of such indicators is to give information about the energy efficiency of the needed extraction and transforming processes throughout the value chain related to the delivered energy product. Figure A shows the value chain of an energy product.

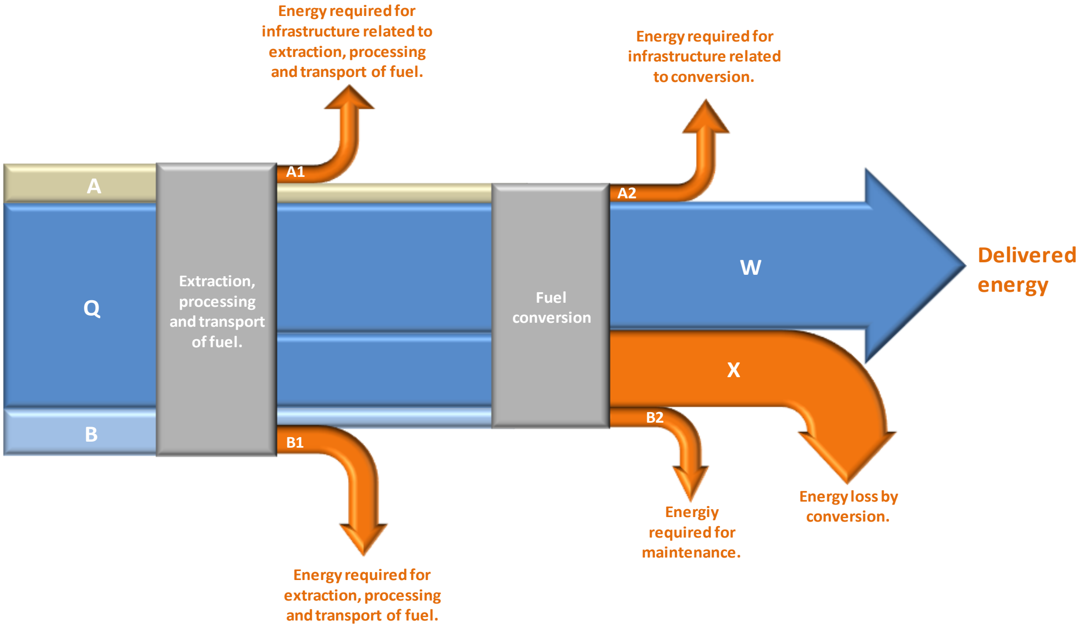

Figure A The value chain of an energy product. The whole lifetime of the fuel conversion plant is used as a basis for all the parameters.

The letters in Figure A denote different energy parameters as listed in Table A.

Table A Description of the different parameters used in Figure A. The whole lifetime of the fuel conversion plant is used as a basis for all the parameters.

Parameter	Description
A	Energy required for building the necessary infrastructure (buildings etc) related to extraction, processing and transport of the fuel/energy source (A1) and energy required for building the necessary infrastructure (buildings etc) related to the conversion of the energy (A2).
B	Energy required for extraction, processing and transport of the fuel/energy source (B1) and energy required for maintenance of the conversion plant (B2).
Q	Total amount of primary energy (related to the energy product) necessary for the generation of a specific amount (e.g. 1 kWh) of the delivered energy. The part of Q which ends up as W is in this report characterized as embedded energy.
X	Energy loss throughout the conversion process (from energy source to delivered energy).
W	Delivered energy (specified energy product) from the energy plant.

In this project the indicators Energy Payback Ratio (EPR), Net Energy Ration (NER) and Cumulative Energy Demand (CED) were chosen to be reviewed and to benchmark technologies for production of electricity. These indicators are presented in table B.

Table B Indicators for energy efficiency used for electricity production, including mathematical expression and a short description.

Indicator	**Expression**	**Comment**
Energy Payback Ratio (EPR)	$EPR = W / (A+B)$	EPR expresses the amount of delivered energy per energy unit invested in infrastructure and extraction/transport processes. Conversion losses through the electricity generation plant are <u>not</u> included. A high EPR value means high energy efficiency.
Net Energy Ratio (NER)	$NER = W / (A+B+Q)$	NER expresses, in the same way as EPR, the amount of delivered energy per energy unit invested. NER includes the conversion losses through the electricity generation plant. A high NER value means high energy efficiency.
Cumulative Energy Demand (CED)	$CED = (A+B+Q) / W$	CED is expressed as the inverse of NER. CED thus presents the amount of energy invested per energy unit delivered. CED has the ability to express important added information regarding different energy sources and life cycle stages. A low CED value means high energy efficiency.

In this report, generic definitions of the different energy indicators are used, making them applicable to different energy products (fuels, heat and electricity). The discussion and conclusions are also made as general as possible when the indicators are compared. In the benchmarking exercise the energy product under study is electricity.

Results

Three investigated energy indicators are compared across technologies. The figures B, C and D present the results for all the investigated cases, showing the range and average values.

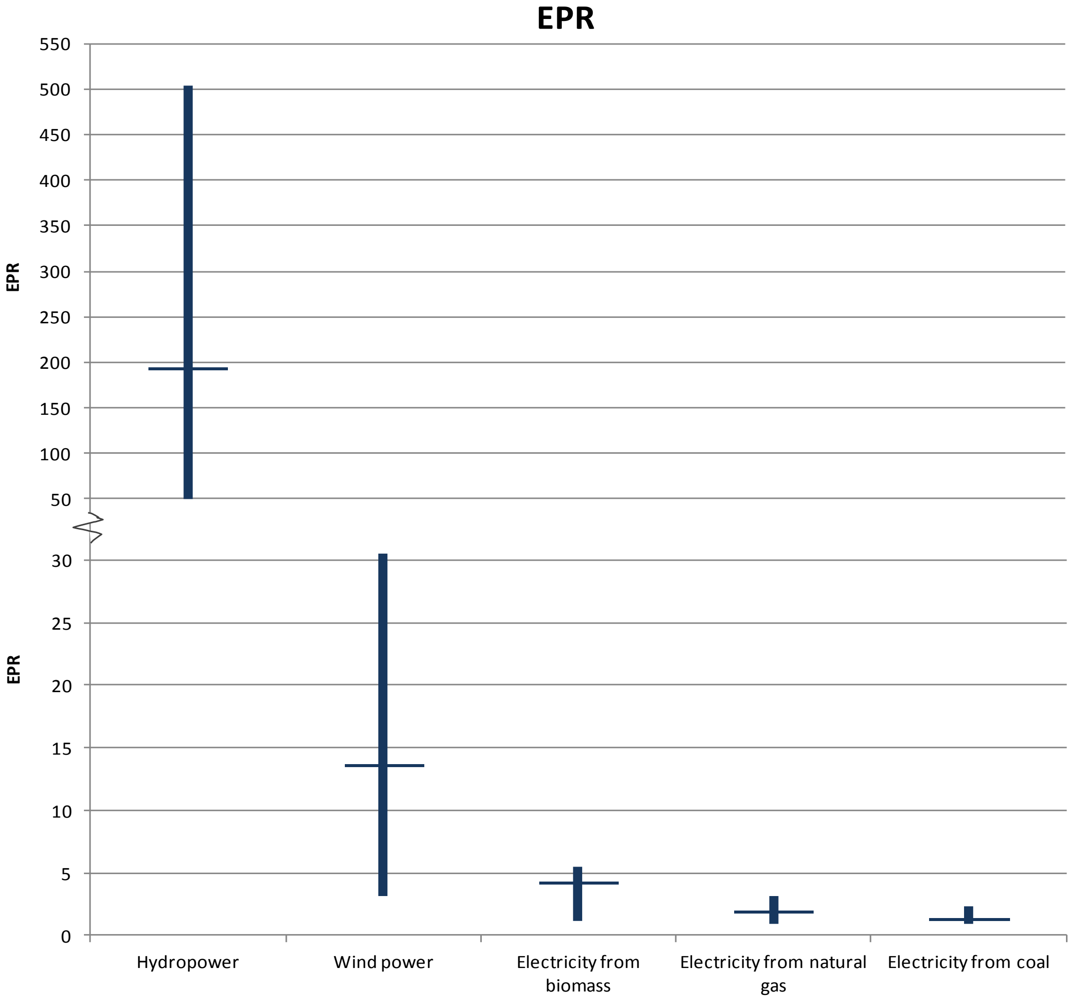

Figure B Comparison of EPR data for different electricity technologies, showing the range and average values.

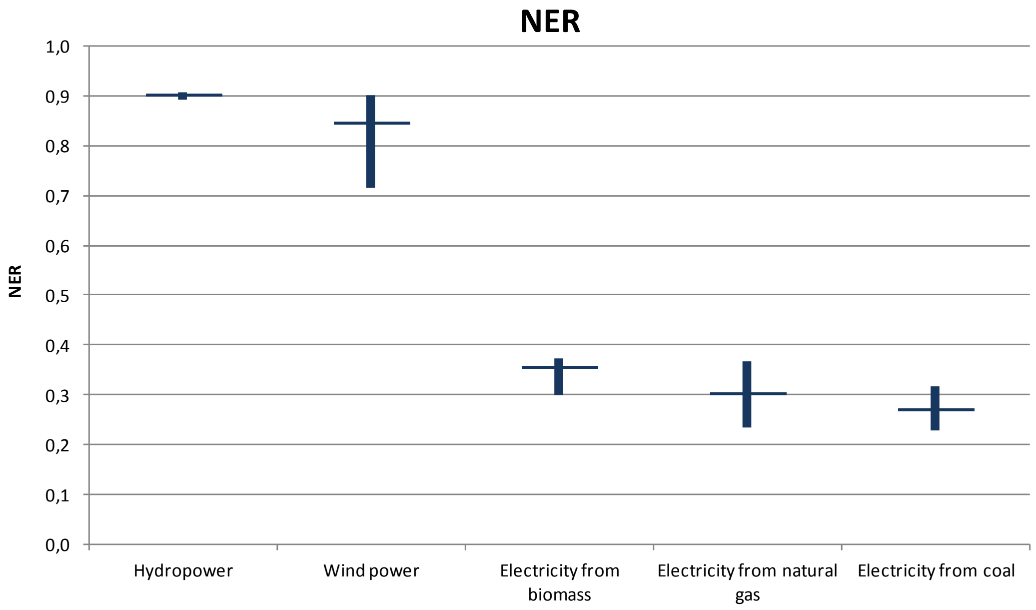

Figure C Comparison of NER data for different electricity technologies, showing the range and average values.

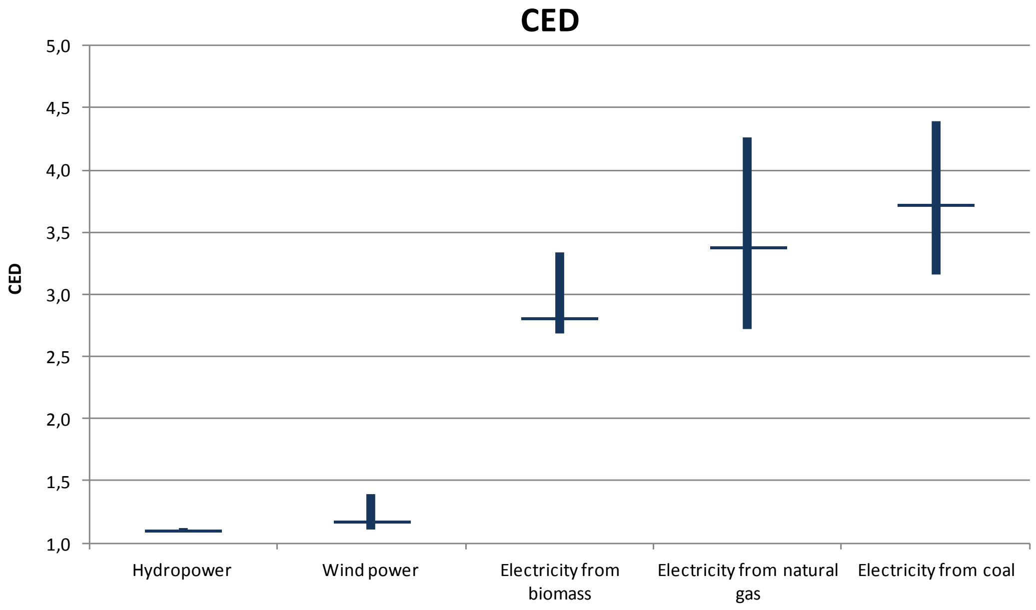

Figure D Comparison of CED data for different electricity technologies, showing the range and average values.

A seen from the figures, hydropower clearly achieves the best energy performance according to all three energy indicators. Wind power achieves the second best performance and the thermal power generation technologies based on biomass and fossil fuels give the lowest energy performance.

It should also be noted that the internal ranking between the coal cases has changed for NER and CED compared to the EPR indicator (not visible in the presented figures).

When comparing energy performance, it may not only be of interest to know the total amount of energy invested in relation to the generated electricity. Important added information can be given by separating the total amount of invested energy into different energy sources and/or life cycle stages. CED split into primary energy sources is shown in figure E. Because of limited resources, this report does not show CED split into the different life cycle stages.

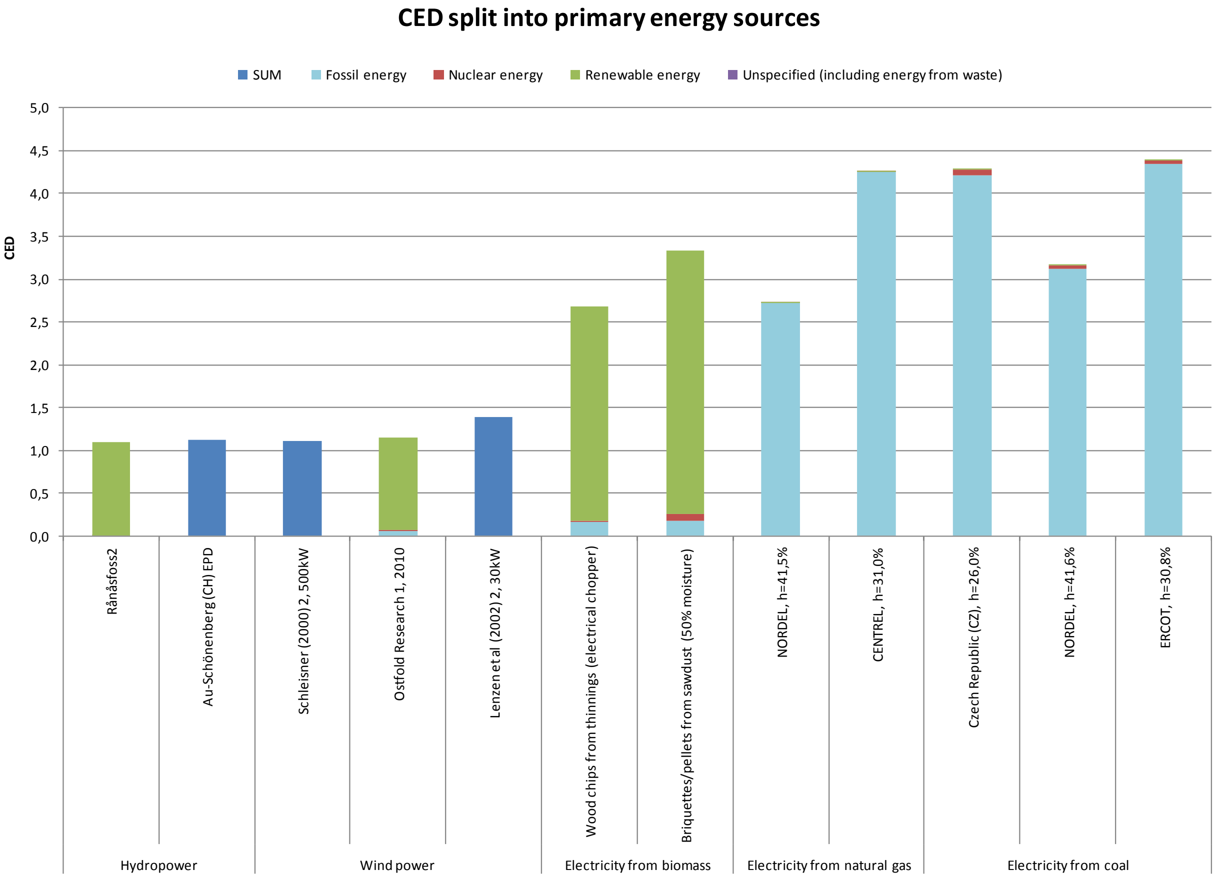

Figure E **Comparison of CED data for different electricity technologies. CED is shown split into different primary energy sources.**

The figure shows that there are large differences between the analysed technologies regarding two major points:

- The amount of primary energy needed to produce 1 kWh of electricity varies from 1.1 kWh (hydro power) to 4.4 kWh (electricity from coal). Thus, the worst case needs an energy input of 400% compared to the best case.
- The sources of primary energy used for producing the electricity vary from >99% renewable (hydro power) to >98% fossil (electricity from natural gas and coal).

It should be noted that the technologies using most primary energy (having the highest CED values) use non-renewable resources for this production, while the least consuming technologies use renewables as primary energy sources.

Conclusions - Comparing technologies

- Hydropower clearly achieves the best energy performance according to the indicators EPR, NER and CED. Wind power achieves the second best performance while thermal power generation technologies based on biomass and fossil fuels give the lowest energy performance.
- There are large variations between the analysed technologies regarding the amount of primary energy needed to produce 1 kWh of electricity.
- The sources of primary energy used for producing electricity vary between the technologies. Electricity from hydropower, in particular, has a very high share of renewable energy as the primary source, while also wind power and bio-energy have high shares of renewables. The main energy sources required for producing electricity from coal and natural gas are fossil based.
- The study shows that 2nd life cycle hydropower plants (which means upgrading and extension of old, existing plants) can have extremely high energy efficiency, measured by EPR. (Such plants are not shown in the figures in the summary, but are part of the results).
- For hydropower, the losses in waterways, turbines, generators and transformers are crucial for the ranking of cases when considering the whole life cycle (NER and CED).
- In general, this study gives no indication whether “large” hydropower installations are more energy efficient than smaller installations, or whether reservoir hydropower plants are more energy efficient than run-of-river plants.

Conclusions - Comparing indicators

- The main reason for the relatively small variations within NER and CED data compared to the large variations within EPR data is the different system boundaries, and the most important factor is the exclusion of the conversion loss in the EPR calculations in contrast to NER and CED.
- The NER and CED indicators show the energy efficiency throughout the total value chain. The EPR indicator ranks technologies based on “supporting energy”, thus excluding the electricity conversion loss. This fundamental difference in system boundaries can lead to the result that a number-one thermal plant according to EPR could be ranked as average, or even the worst case, according to NER and CED, and vice versa.
- However, EPR is a suitable indicator when the goal is to compare the use of supporting energy. This is especially interesting when electricity from some renewable sources is compared.
- The internal ranking between the specific cases of one technology is also dependent on the indicator used.
- When using CED as indicator it is possible to split the results into different energy sources and life cycle stages contributing to the CED. Hence, CED can give added information compared to EPR and NER.

- EPR and NER is defined as energy output divided by energy input. This makes these indicators in line with economical terminology. CED is the inverse of NER (energy input divided by energy output).
- The system boundaries for calculating primary energy input for renewable sources needs further investigation and research.

In table B the different properties of each indicator are summarised.

Table B Summary of energy indicator properties.

Indicator	Life cycle approach	Includes all primary energy sources	Can be split into primary energy sources and life cycle stages	In line with economical terminology
EPR		X		X
NER	X	(X)		X
CED	X	X	X	

1 Introduction

CEDREN – Centre for Environmental Design of Renewable Energy is an interdisciplinary research centre for technical and environmental development of hydro power, wind power, power transmission lines and implementation of environment and energy policy. SINTEF Energy Research, the Norwegian Institute for Nature Research (NINA) and the Norwegian University of Science and Technology (NTNU) are the main research partners. A number of energy companies, Norwegian and international R&D institutes and universities are partners in the project. The centre is founded by The Research Council of Norway and energy companies and is one of eight centres that were part of the scheme Centre for Environment-friendly Energy Research (FME) when the scheme was launched in 2009. The FME scheme consists of time-limited research centres which conduct concentrated, focused and long-term research of high international quality in order to solve specific challenges in the field of renewable energy and the environment. CEDREN's vision is to be an internationally recognized research centre for environmental design of renewable energy - integrating technology, nature and society with the slogan 'renewable energy respecting nature'. The main objective of CEDREN is to develop and communicate design solutions for transforming renewable energy sources to the desired energy products, and at the same time address the environmental and societal challenges at local, regional, national and global levels.

CEDREN's board initiated in 2011 a pilot project on the topics 'Energy Payback Ratio (EPR)', 'Ecosystem services' and 'multi-criteria analysis (MCA)' in order to investigate the possible use of these concepts/indices in the management of regulated river basins and as tools to benchmark strategies for the development of energy projects/resources. EPR came to attention due to the IPCC-report (Edenhofer et al. 2011), where interesting numbers on EPR-values for different transforming technologies for renewable energy sources were published. The EPR-values were much in favour of hydropower, however, without including any studies from Norwegian hydropower production facilities.

The aim of the EPR part of this pilot project has been:

1. To include EPR data for Norwegian hydropower and to compare and benchmark them with international data.
2. Review the applicability of different energy efficiency indicators, as such, in the strategic management and development of energy resources, and to compare and benchmark technologies for production of electricity. This means that this study has examined the energy indicators Net Energy Ratio (NER) and Cumulative Energy Demand (CED) in addition to EPR.

Generic definitions of the different energy indicators (chapter 2) are used, making them applicable to different energy products (fuels, heat and electricity). The discussion and conclusions are also made as general as possible when the indicators are compared. In the benchmarking chapters (chapter 3 and 4) the energy product under study was chosen to be electricity.

The pilot study, from which this report is one of the deliverables, is to a large extent funded by CEDREN, with valuable additional financial support from the Directorate for Nature Management (DN). Furthermore, the pilot-project is coordinated and integrated with parallel project activities by Ostfold Research on calculation of energy indicator values in the bio energy sector, funded by the Norwegian Water Resources and Energy Directorate (NVE).

The work presented here will be continued in the succeeding research project EcoManage[1], which in December 2011 was granted by the Research Council of Norway's RENERGI programme.

The main findings from the pilot study is also reported in a policy memo (in Norwegian), that is available at www.cedren.no.

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[1] The main objective of EcoManage is to test, evaluate and adapt new concepts and indicators for the improved development and management of energy and water resources. EcoManage is a 4-year project with a total budget of 14 mill. NOK.

2 Different energy indicators

Several energy indicators for extraction and delivery of an energy product (e.g. transport fuel, heat, electricity etc.) exist today. The main objective of such indicators is to give information about the energy efficiency of the needed extraction and transforming processes throughout the value chain related to the delivering an energy product. Figure 1 shows the value chain of an energy product.

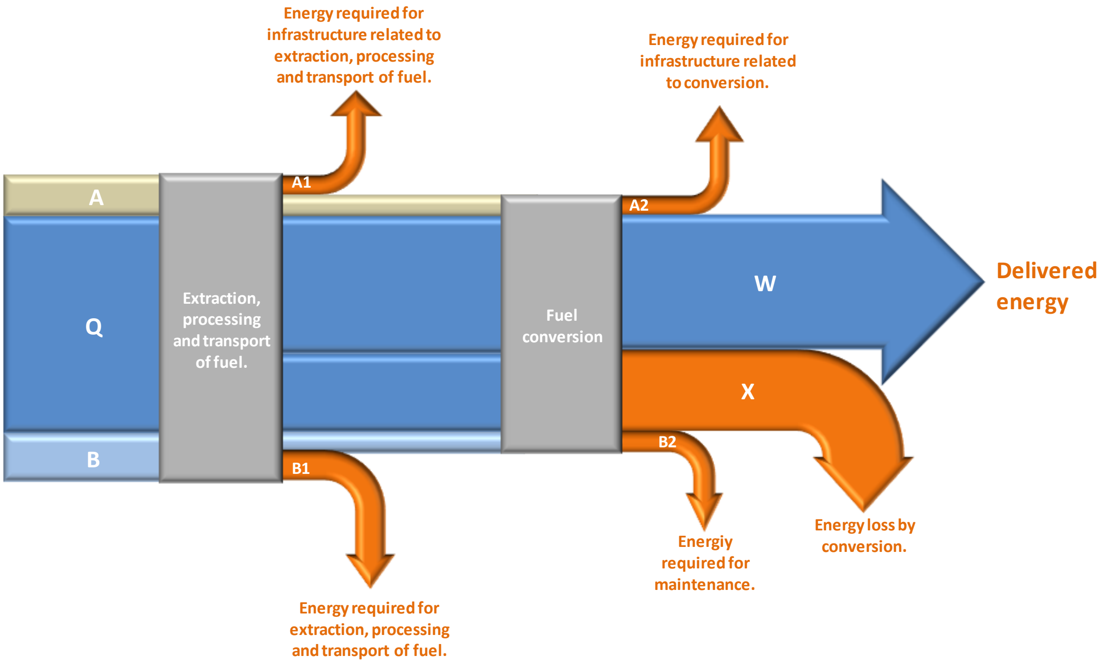


Figure 1: The value chain of an energy product. The whole lifetime of the fuel conversion plant is used as a basis for all the parameters.

Table 1 gives a description of the different parameters denoted by letters in the figure.

Table 1: Description of the different parameters used in Figure 1. The whole lifetime of the fuel conversion plant is used as a basis for all the parameters.

Parameter	Description
A	Energy required for building the necessary infrastructure (buildings etc) related to extraction, processing and transport of the fuel/energy source (A1) and energy required for building the necessary infrastructure (buildings etc) related to the conversion of the energy (A2).
B	Energy required for extraction, processing and transport of the fuel/energy source (B1) and energy required for maintenance of the conversion plant (B2).
Q	Total amount of primary energy (related to the energy product) necessary for the generation of a specific amount (e.g. 1 kWh) of the delivered energy. The part of Q which ends up as W is in this report characterized as embedded energy.
X	Energy loss throughout the conversion process (from energy source to delivered energy).
W	Delivered energy (specified energy product) from the energy plant.

The following sections give a deeper description of the different energy indicators which are examined in this study, based on Figure 1 and Table 1.

2.1 Energy Payback Ratio (EPR)

EPR expresses the amount of delivered energy (over the life time of a plant) per energy unit invested in infrastructure and extraction/transport processes (Gagnon 2008). In accordance with Figure 1, EPR is expressed as follows:

$$EPR = W / (A+B) \tag{1}$$

When rating EPR results, the higher EPR figure an energy product achieves, the better is the energy performance. The reason for this is that a high EPR indicates that more energy is delivered per invested amount of energy, compared to a lower EPR.

According to Equation (1), the EPR calculation excludes the primary energy of the fuel itself as invested energy includes only “supporting energy” (required for infrastructure, extraction processes and transport). This means that most often the total invested energy amount (A + B) in the denominator represents a small value compared to the delivered energy amount (W). This implies that a change or uncertainty in the denominator, which most often will be very small compared to the total delivered energy amount, still will create a large change in the EPR value.

It should be noted that the literature uses different expressions for the EPR indicator. Example of this are *energy ratio*, *external energy ratio*, *energy return on investment (EROI)* and *energy payback ratio*, which all refer to the same basic calculation as EPR (Gagnon 2008). In accordance with Hall (2011), the EROI indicator refers to “how much energy is returned from one unit of energy invested in an energy-producing activity”. Further, he states that it is a critical parameter for understanding and rating different fuels. The EPR indicator (thus expressed in many terms) is based on a life-cycle approach, which means that the nominator represents the amount of energy generated throughout the life time of the studied system, while the denominator shall include all primary energy input throughout the value chain of the energy system. However, these indicators seem to have originally been introduced for the extraction of fuels, thus showing how much fuel energy is produced per energy unit invested (Gupta & Hall 2011) for producing the fuel. Hence, when EPR is used for production of electricity, the electricity conversion loss is not included, which means that this indicator no longer have a full life cycle approach. However, EPR is a suitable indicator when the goal is to compare the use of “supporting energy” only. This is especially interesting when comparing electricity from renewable sources (excluding thermal technologies). The main reasons for this are that the conversion losses for these technologies are marginal compared to thermal technologies and that the lost energy (through the conversion step) represents renewables “being available” (e.g. solar and wind), thus not harvested and transported. An exception from this may be water which has been stored in hydropower reservoirs in order to be transported through pipes/tunnels for electricity generation.

When using the EPR indicator for extraction of fuels, an important point is that as the EPR ratio approaches 1 the extraction processes require the same amount of energy as the energy being available in the fuel.

2.2 Net Energy Ratio (NER)

NER expresses, in the same way as EPR, the amount of delivered energy (over the life time of a plant) per energy unit invested. However, there is a large difference between EPR and NER as NER includes the primary energy input related to the fuel/energy sources itself, while EPR includes only required supported energy (related to infrastructure and supporting processes) as invested energy (Spath & Mann 2000). In accordance with Figure 1, NER is expressed as follows:

$$NER = W / (A+B+Q) \qquad (2)$$

It should be noted that NER, by definition, never equals or exceeds the value of 1 as it is physical impossible to produce and deliver more energy than the amount of invested energy. When it comes to ranking of NER results, this is similar to EPR: the higher number, the better result is achieved (within a scale between zero and 1).

According to Equation (2), the NER calculation includes the primary energy of the fuel itself, as invested energy includes all energy required for the electricity generation (A + B + Q). This means that the total invested energy amount (A + B + Q) in the denominator represents a greater value than the delivered energy amount (W), as losses through the conversion step are also included. When the invested “supporting energy” (A+B) is added to the primary energy of the fuel itself (Q), changes impacted by this “supporting energy” (A+B) becomes small in relation to the primary energy in the fuel itself (Q), and the denominator is still not affected much. This is the reason why the values of A and B are of less importance for the calculated indicator NER, compared to their impact on the EPR calculation.

It should be emphasised that some references (e.g. Spath & Mann, 2000) only includes fossil energy as invested energy. However in this study, all necessary energy investment (whether fossil or renewable) is included in the analyses.

2.3 Cumulative Energy Demand (CED)

CED is expressed as the inverse of NER. CED thus presents the amount of energy invested per energy unit delivered (Frischknecht et al. 2007). CED was chosen as energy indicator in this study due to the indicator’s ability to express important added information regarding different energy sources (see chapter 4.3.2).

CED expresses the required amount of energy invested (in infrastructure and extraction/transport processes in addition to the primary energy related to the energy product itself) in relation to the amount of delivered energy (over the life time of the plant). With regard to Figure 1, CED is expressed as:

$$CED = (A+B+Q) / W \qquad (3)$$

When comparing CED results, the lower CED figure an energy product achieves, the better the energy performance. The reason for this is that a low CED indicates that less energy is invested per energy unit delivered compared to a higher CED. Based on the same physical arguments as for NER, CED will always become greater than 1.

Since CED is based on the same parameters as NER, the “supporting energy” is of less importance for the CED results than they are for the EPR results. The reason for this is explained above (see section 2.2).

3 Energy indicators for different electricity technologies

In this section, different electricity generation technology cases are presented for the three investigated energy indicators EPR, NER and CED.

3.1 Hydropower

The hydropower cases are based on specified LCA studies representing Norway (Vold et al. 1998 and Askham 2007), Sweden (Vattenfall 2010a) and Switzerland (Bureau Veritas Certification Sweden 2009 and Bureau Veritas Certification Sweden 2010), as well as literature data based on the Ecoinvent database (Swiss Centre for Life cycle inventories 2011). In total, 20 cases are presented.

3.1.1 Energy Payback Ratio (EPR) for hydropower

Figure 2 shows EPR data for the 20 investigated hydropower cases. The cases are split into reservoir and run-of-river cases, and further categorised according to countries.

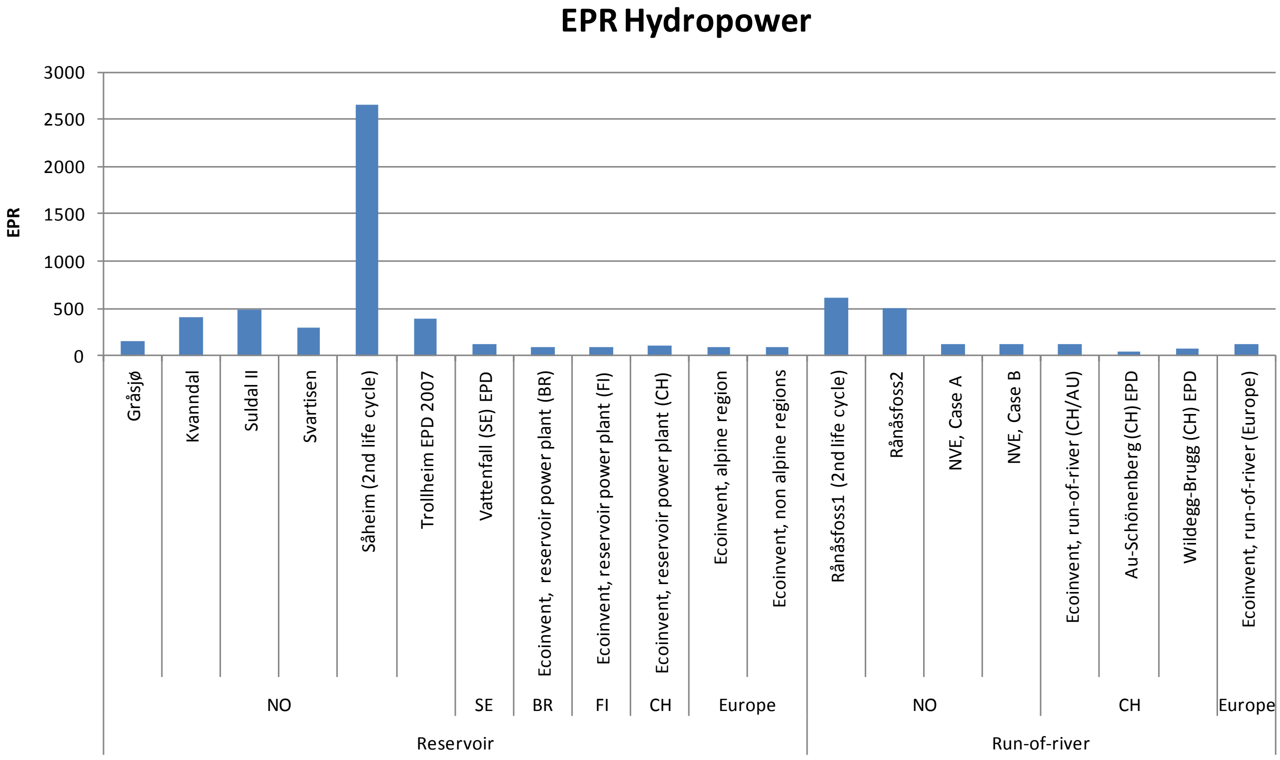


Figure 2: EPR data for hydropower, classified according to reservoir and run-of-river plants, as well as to countries.

As described in section 2.1, the higher EPR value achieved, the better the energy performance.

As seen from the figure, the presented EPR indicators represent large variations, varying from 50 to 2650. The largest EPR (2650) represents the Norwegian Såheim (2nd life cycle) reservoir plant. Because of the age of this plant (started 1915, rebuilt 1959/61/73), it has been investigated as a 2nd life cycle power plant. This means that the life cycle has been "expired", thus the next 100 years of the plant is included in the analysis. The construction phase is therefore excluded from the analysis; instead a major upgrading process is included. The Norwegian run-of-river plant Rånåsfoss1 has also been investigated as a 2nd life cycle plant. However, the EPR result for this plant (about 600) does not represent such a large value as the Såheim case. To make a fair comparison, the 2nd life cycle cases (Såheim and Rånåsfoss1) are excluded from the rest of the presentations in this report, see Figure 3.

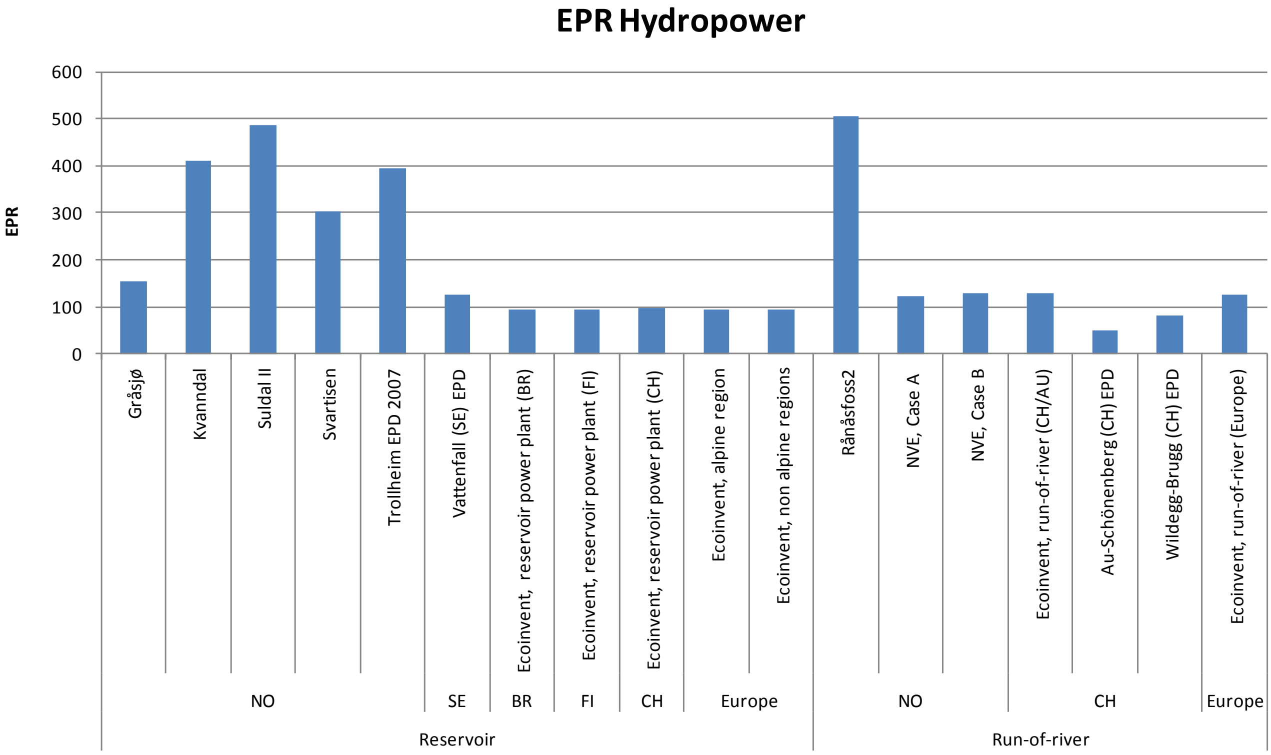


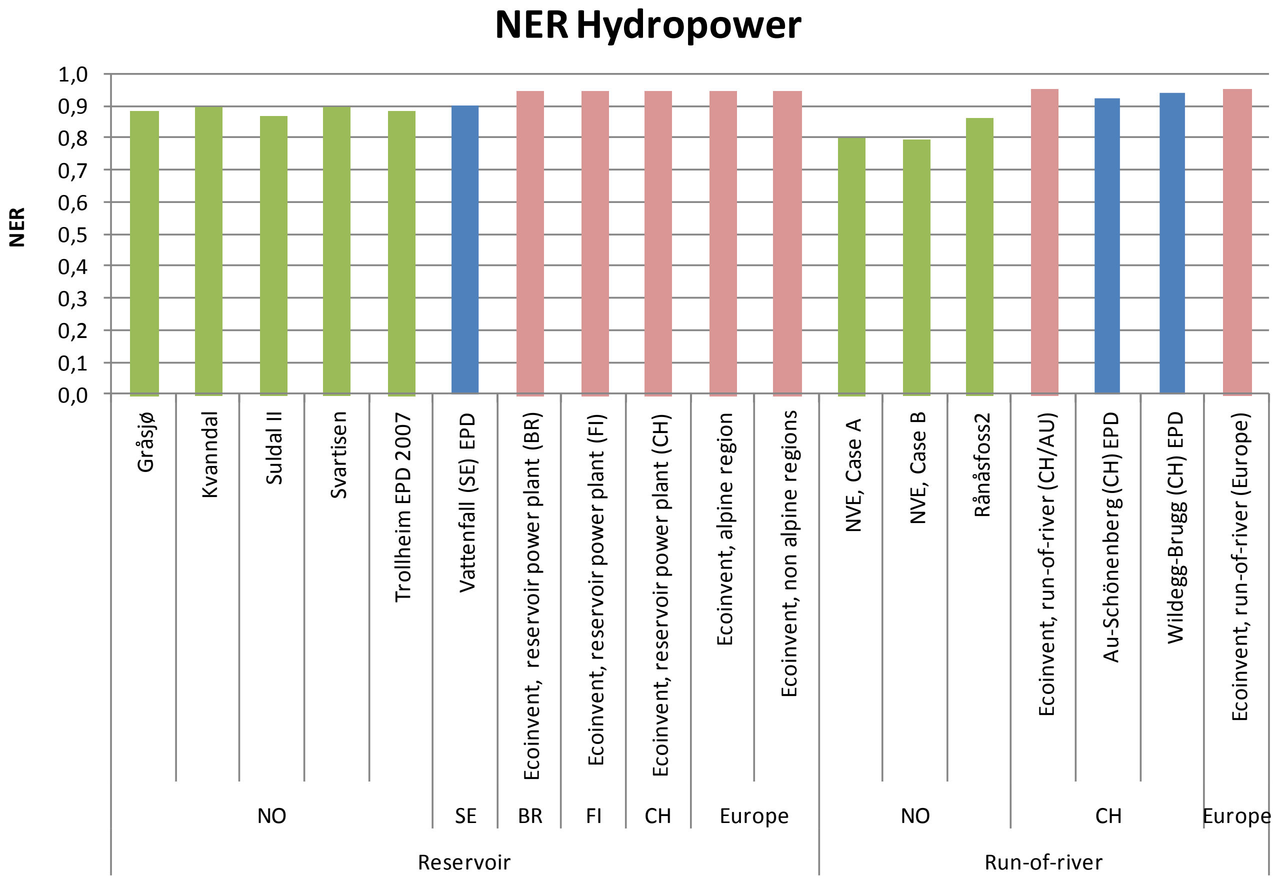
Figure 3: EPR data for hydropower, excluding the 2nd generation reservoir cases (Såheim and Rånåsfoss I).

Despite the exclusion of the 2nd life cycle cases, Figure 3 shows that there are still large EPR variations within the hydropower cases, varying from about 50 (worst case = Au-Schönenberg) to 500 (best case = Rånåsfoss 2). It should be noted that 5 of the Norwegian plants (Vold et al., 1998) achieve EPR values equal to or greater than 300. The other plants achieve EPR values between 50 and 150. As a comparison, Gagnon (2008) presents EPR data for hydropower varying from 205 – 280 and 170 – 267 for reservoir power plants and run-of-river plants, respectively. The EPR results give no indications whether the scale or type of the hydropower installation is important for the energy efficiency or not.

As described in section 2.1, the plant efficiency only affects the nominator in the calculation of EPR (see Figure 1 and Equation (1)) as losses through the plant (e.g. losses in turbine, generator, transformer and losses in waterways) are not included in the calculation of EPR. Thus, the invested energy includes only required energy related to infrastructure and extraction/transport processes. This implies that a relatively small change or uncertainty in the invested energy (compared to the total delivered energy amount) will create a large change in the EPR value, which may be the main reason for the large variations within the EPR indicators.

3.1.2 Net Energy ratio (NER) for hydropower

In Figure 4 the Net Energy Ratio (NER) data for 18 of the investigated hydropower cases are shown (the two 2nd life cycle cases are excluded). The bars are coloured according to the types of losses through the power plants which are included in the analyses.



Green bars	Losses through the power plant include losses in waterways (e.g. tunnels), turbines, generators and transformers.
Light pink bars	Losses through the power plant include losses in generators and transformers.
Blue bars	Losses through the power plant are included, but not specified (only given as potential energy).

Figure 4: NER data for hydropower, classified according to reservoir and run-of-river plants. The two 2nd generation cases are excluded.

As described in section 2.2, the interpretation of the ranking of NER results is similar to EPR: the higher number, the better result is achieved (within a scale between zero and 1).

The NER data in Figure 4 varies between 0.79 and 0.95, a difference in 17% compared to the best case. The figure clearly shows that the cases only including losses in generators and transformers (light pink bars) achieve the best NER performance while the cases also including turbine and waterways losses (green bars) achieve lower NER. This is obvious, as the calculation of NER (see Figure 1 and Equation (2): NER = W / (A+B+Q)) includes all the losses through the plant. Thus, the more losses included, the lower NER, which means lower energy performance of the analysed system.

For hydropower, the total amount of primary energy related to the energy product (Q in figure 1) is defined as the potential energy of the water in relation to the level of the turbine. Water loss due to evaporation and overflow is not included, nor are losses in waterways downstream the turbine (The International EPD system, 2011).

In order to exclude the differences occurring due to different system boundaries regarding losses through the power plant, the losses for the 18 plants are standardised according to a total loss of 0.1 kWh/kWh hydropower generated (Vattenfall 2010a), which equals a total plant efficiency of 91%. The standardised NER data are presented in Figure 5.

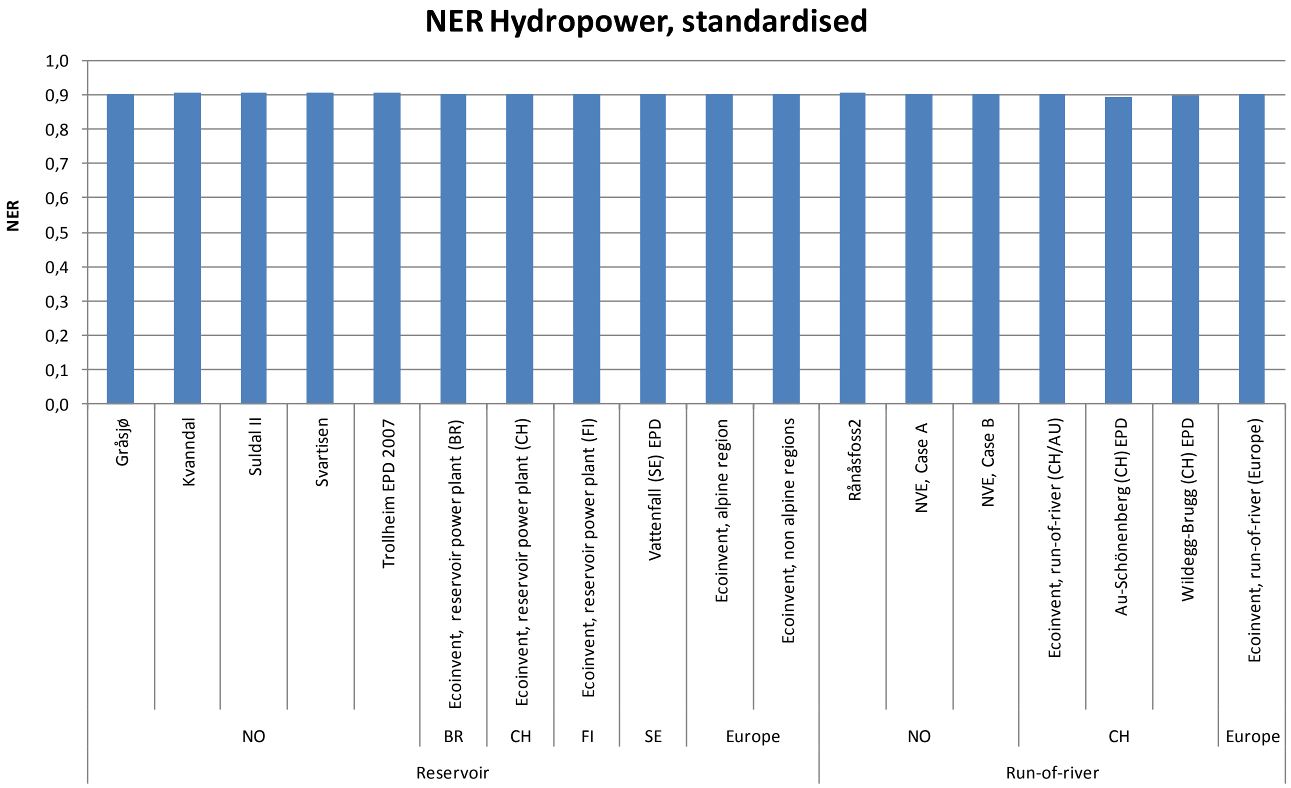


Figure 5: **Standardised NER data for hydropower, classified according to reservoir and run-of-river plants (the sum of losses in waterways, turbines, generators and transformers is standardised to 0.1 kWh / kWh for all cases). The two 2nd generation cases are excluded.**

As seen from the figure, the variation between the hydropower cases, when standardising the losses, has decreased to a large extent. The values now vary between 0.89 (worst case = Au-Schönenberg) and 0.91 (best case = Rånåsfoss 2), a difference in 2% compared to the best case. The results show that the hydropower cases have a close to equal performance with respect to NER after standardising the losses. This means that the losses in waterways, turbines, generators and transformers are crucial for the ranking of hydropower cases when considering the whole life cycle of the electricity generation. Thus, it is important to be aware of if, and how, the different losses through a hydropower plant are included in the analyses when comparing NER, as these data strongly affect the results.

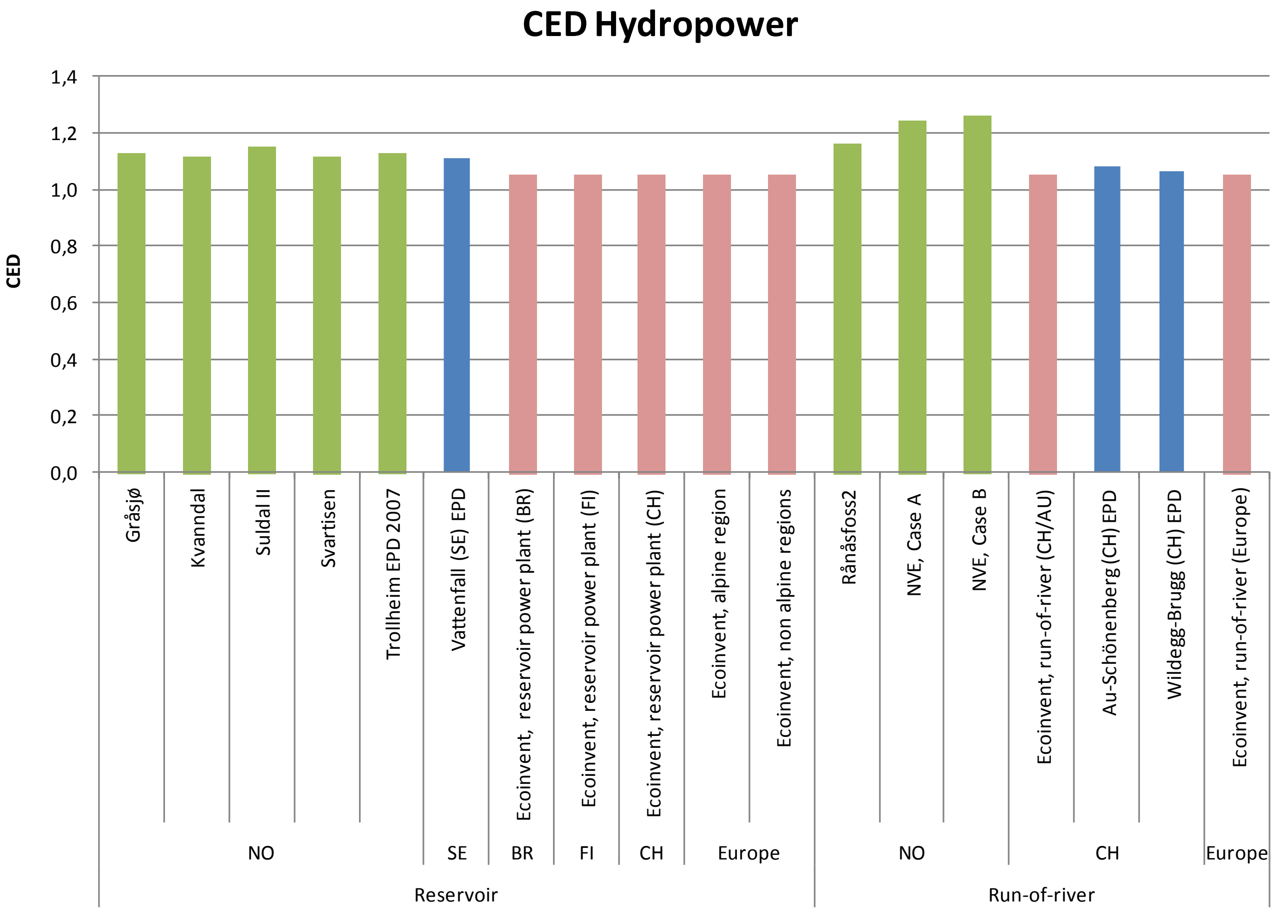
It is also important to bear in mind that data representing losses through hydropower plants may include losses in waterways occurring downstream the turbine. This may be relevant for the data included in this study. Such potentials misunderstandings represent important issues and should be a target for further discussions and research.

The main reason for the relatively small variations within NER data compared to the large variations within EPR data is the different system boundaries regarding losses for the calculation of these two indicators. As EPR excludes the primary energy of the fuel itself as invested energy (includes only “supporting energy” as invested energy, EPR = W / (A+B)), small differences in supporting energy (compared to the total delivered energy amount, W) creates large differences in EPR. This occurs because the invested energy values (A+ B) represent relatively small values compared to the delivered energy amount (W). Thus, a small change in the denominator creates a large change in the EPR value. When the invested energy is added to the primary energy of the fuel itself (as is the case for NER = W / (A+B+ Q), see Equation (2) and Figure 1), these variations in “supporting energy” (A+B) is much smaller than the primary energy in the fuel itself (Q) and the delivered energy amount (W), and is thus of less importance for the calculated indicator NER. This is further described in section 2.1 and 2.2.

As for EPR, the NER results give no indications whether the scale or type of the hydropower installation is important for the energy efficiency or not.

3.1.3 Cumulative Energy Demand (CED) for hydropower

Figure 6 shows CED data for 18 of the investigated hydropower cases (the two 2nd life cycle cases are excluded). The bars are, at the same way as for NER, coloured according to the types of loss through the power plants which are included in the studies.



Green bars	Losses through the power plant include losses in waterways (e.g. tunnels), turbines, generators and transformers.
Light pink bars	Losses through the power plant include losses in generators and transformers.
Blue bars	Losses through the power plant are included, but not specified (only given as potential energy).

Figure 6: CED data for hydropower, classified according to reservoir and run-of-river plants. The two 2nd generation cases are excluded.

As described in section 2.3 the ranking of CER results in general is the opposite of NER and EPR results: the lower CED number, the better result is achieved (thus always greater than 1).

The CED data in Figure 6 vary between 1.26 (worst case = NVE, Case B) and 1.05 (best case = Ecoinvent Run-of-river), a difference in 20 % compared to the best case.

Figure 6 clearly shows that the cases which only include losses in generators and transformers (light pink bars) achieve better CED performance than the cases also including turbines and waterways losses (green bars). Based on the same reason as described for NER, this is obvious as the calculation of CED (see Figure 1 and Equation (3): CED = (A+B+Q)/ W) includes all the losses through the plant. Thus, the more losses included, the higher CED, which also means lower energy performance of the analysed system.

As explained for NER, the total amount of primary energy related to the energy product (Q in figure 1) is defined as the potential energy of the water in relation to the level of the turbine. Water loss due to evaporation and overflow is not included, nor is loss in waterways downstream the turbine (The International EPDsystem, 2011).

In order to exclude the differences occurring because of different system boundaries regarding losses through the power plant, the losses for all the plants are standardised according to a total loss of 0.1 kWh/kWh hydropower generated (Vattenfall 2010a), which equals a total plant efficiency of 91%. The standardised CED data are presented in Figure 7.

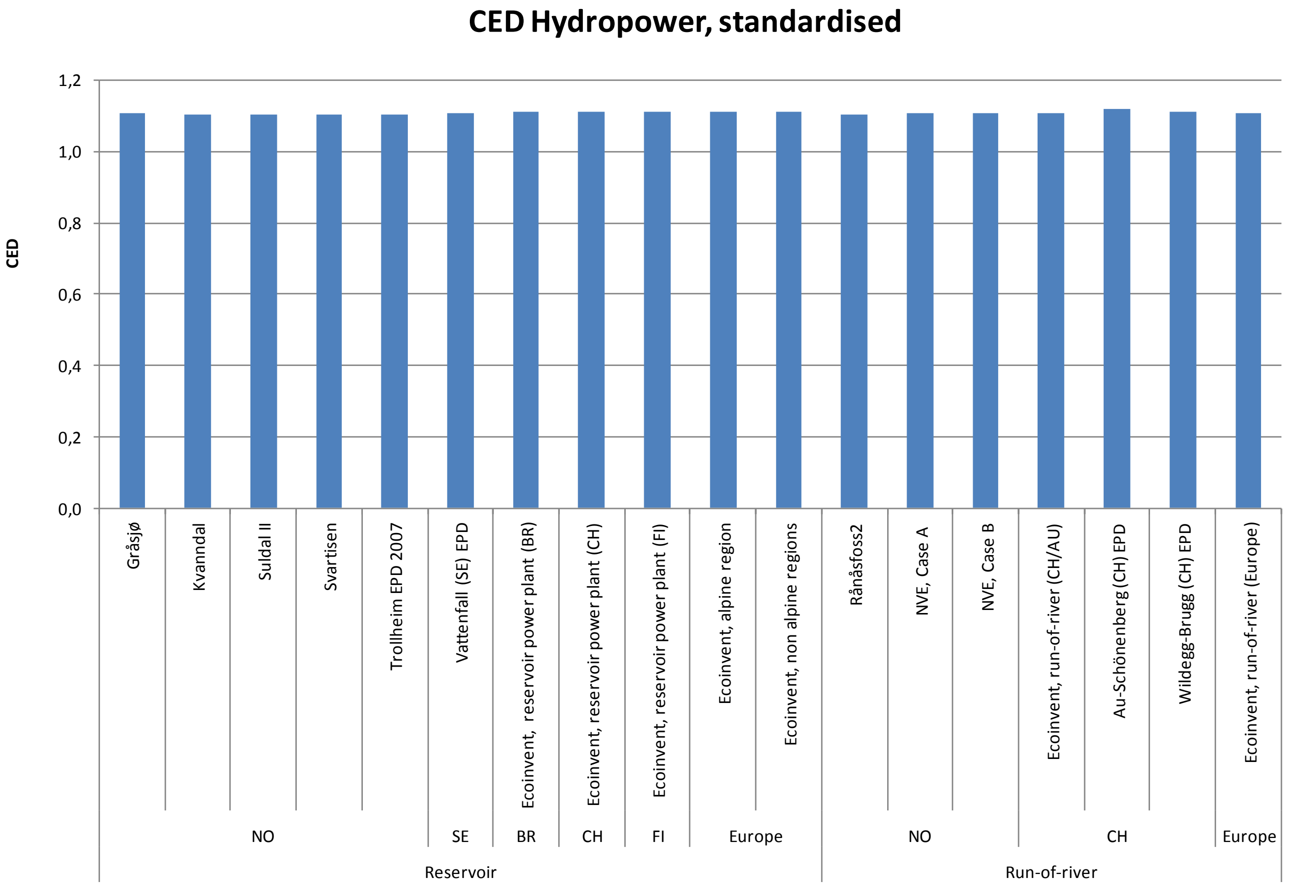


Figure 7: Standardised CED data for hydropower, classified according to reservoir and run-of-river plants (the sum of losses in waterways, turbines, generators and transformers is set to 0.1 kWh / kWh for all cases). The two 2^{nd} generation cases are excluded.

Figure 7 shows that a standardisation of the losses through the power plants decreases the variations between the hydropower cases to a large extend. The values now vary between 1.12 and 1.10, a difference in 2% compared to the best case. This means, in the same way as for NER, that the losses in waterways, turbines, generators and transformers are crucial for the internal ranking of hydropower cases when considering the whole life cycle of the electricity generation. Thus, it is important to be aware of if, and how, the different losses through a hydropower plant are included in the analyses when comparing CED, as these data strongly affect the results.

However, if one is interested in a deeper investigation of the differences between the hydropower cases, the figure above can be shown with a y-scale starting from 1, as 1 kWh primary, embedded energy per kWh generated electricity is equal for all cases. CED values exceeding 1 express necessary invested energy (required for e.g. infrastructure, extraction/transport processes and relevant losses throughout the value chain) for the generation of 1 kWh hydropower. The CED results are presented this way in Figure 8.

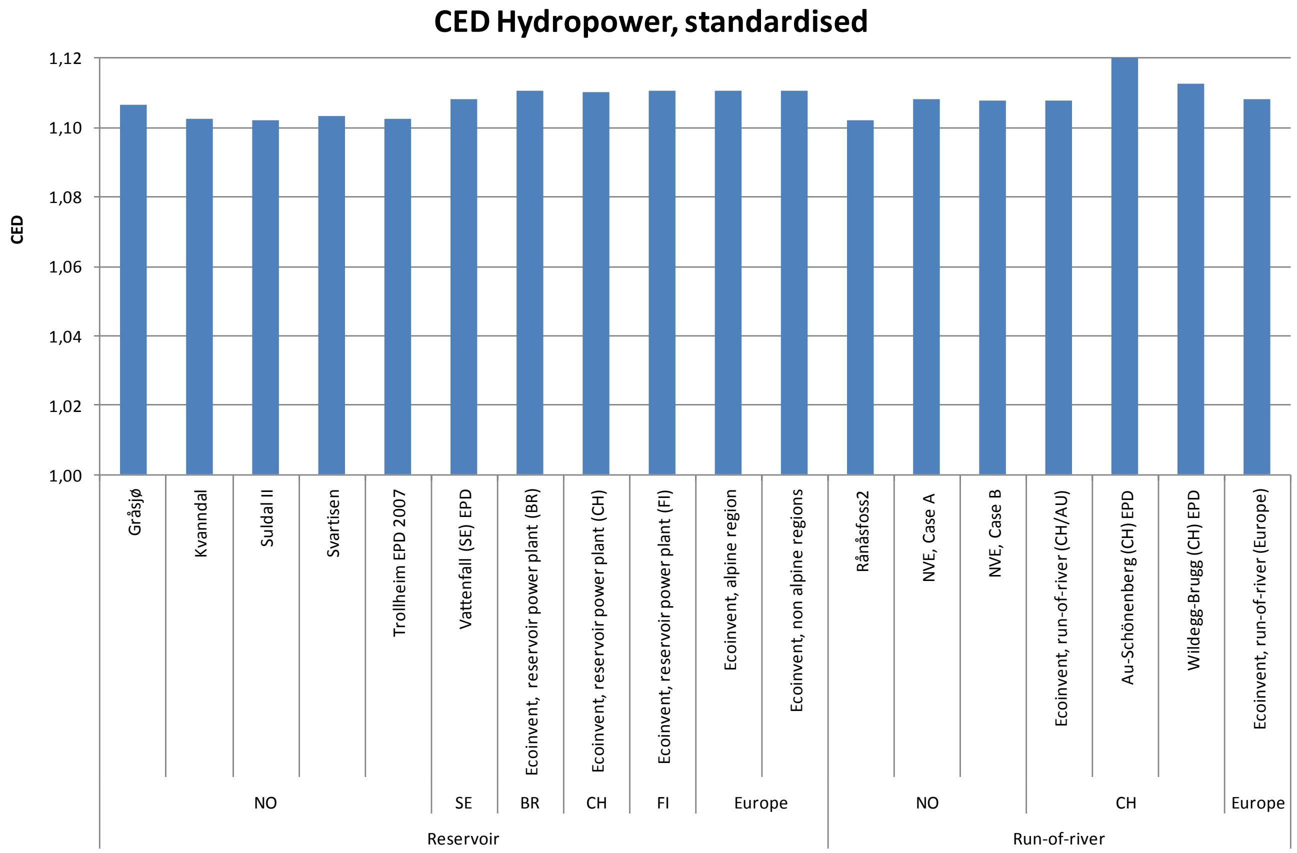


Figure 8: Standardised CED data for hydropower (y-scale starts at 1), classified according to reservoir and run-of-river plants (the sum of losses in waterways, turbines, generators and transformers is standardised to 0.1 kWh / kWh for all cases). The two 2nd generation cases are excluded.

As seen in the figure, it is now easier to rank the cases according to CED data.

It should be noted that the CED ranking of the investigated hydropower cases remain the same as the NER ranking for all the analysed cases when using standardised data for losses through the power plant. This is logic as the total plant efficiency is assumed to be the same (91%) for all the investigated cases when calculating NER and CED. When including the embedded energy and energy losses through the conversion step (W+X=Q), the differences between the cases are much smaller than when using EPR as an indicator, which does not include the primary energy related to the energy product (Q).

As for EPR and NER, the CED results give no indications whether the scale or type of the hydropower installation is important for the energy efficiency or not.

3.2 Wind power

The wind power cases are based on two Norwegian cases (Ostfold Research 2010), as well as other literature studies (Vattenfall 2010b, Lenzen & Munksgaard 2002, Burger & Bauer 2007, Schleisner 2000, Voorspools et al. 2000, Jungbluth et al. 2005, Crawford 2009, Bauer et al. 2008 and Tremeac & Meunier 2009). In total, 37 cases are presented. All data have been standardised according to a lifetime of 20 years.

3.2.1 Energy Payback Ratio (EPR) for wind power

Since the total number of investigated wind power cases is as large as 37, the cases are separated into the following three groups: Small, onshore turbines (< 300 kW), Onshore turbines (> 300 kW) and Offshore turbines. The onshore turbines are split into two groups in order to reduce the amount of cases in each figure.

Figure 9 shows EPR data for the investigated small, onshore wind turbine (< 300 kW) cases, in total 10 cases.

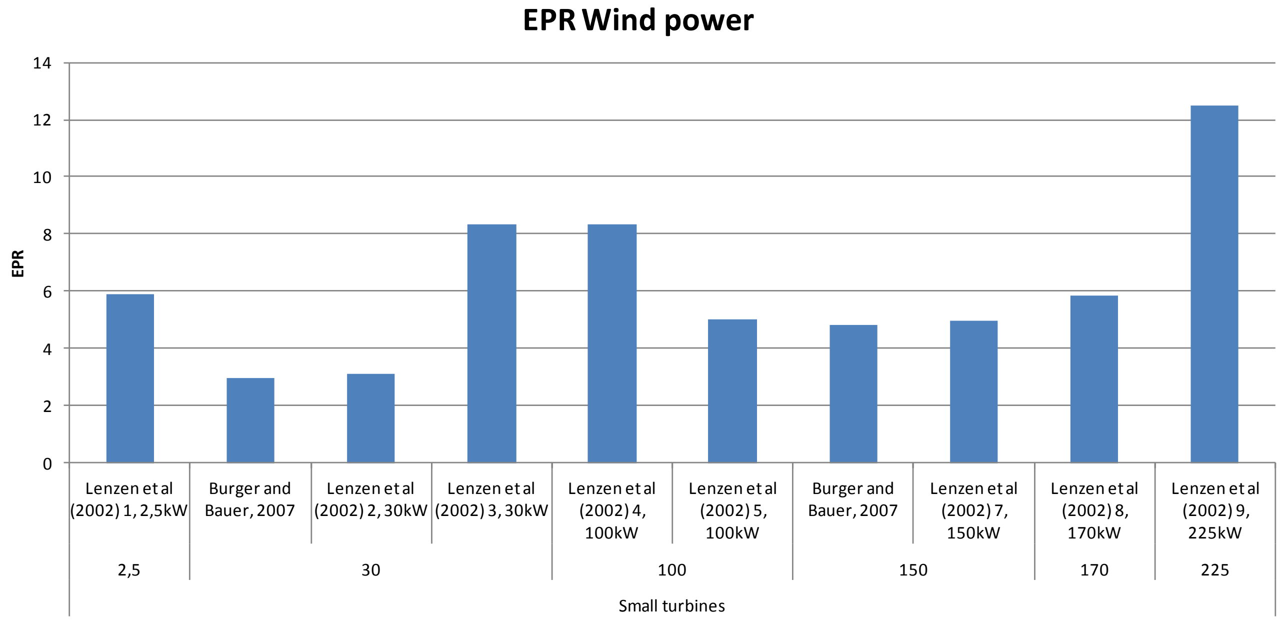


Figure 9: EPR data for small, onshore wind turbines (<300 kW), classified according to turbine size.

As described in section 2.1 and 3.1.1, the higher EPR value, the better result is achieved. The figure shows EPR values varying between about 3 and 13, with an average of 6. Although the largest turbine achieve the highest EPR, there is no correlation between turbine size and EPR.

Figure 10 shows EPR data for the investigated onshore wind turbine (> 300 kW) cases, in total 22 cases.

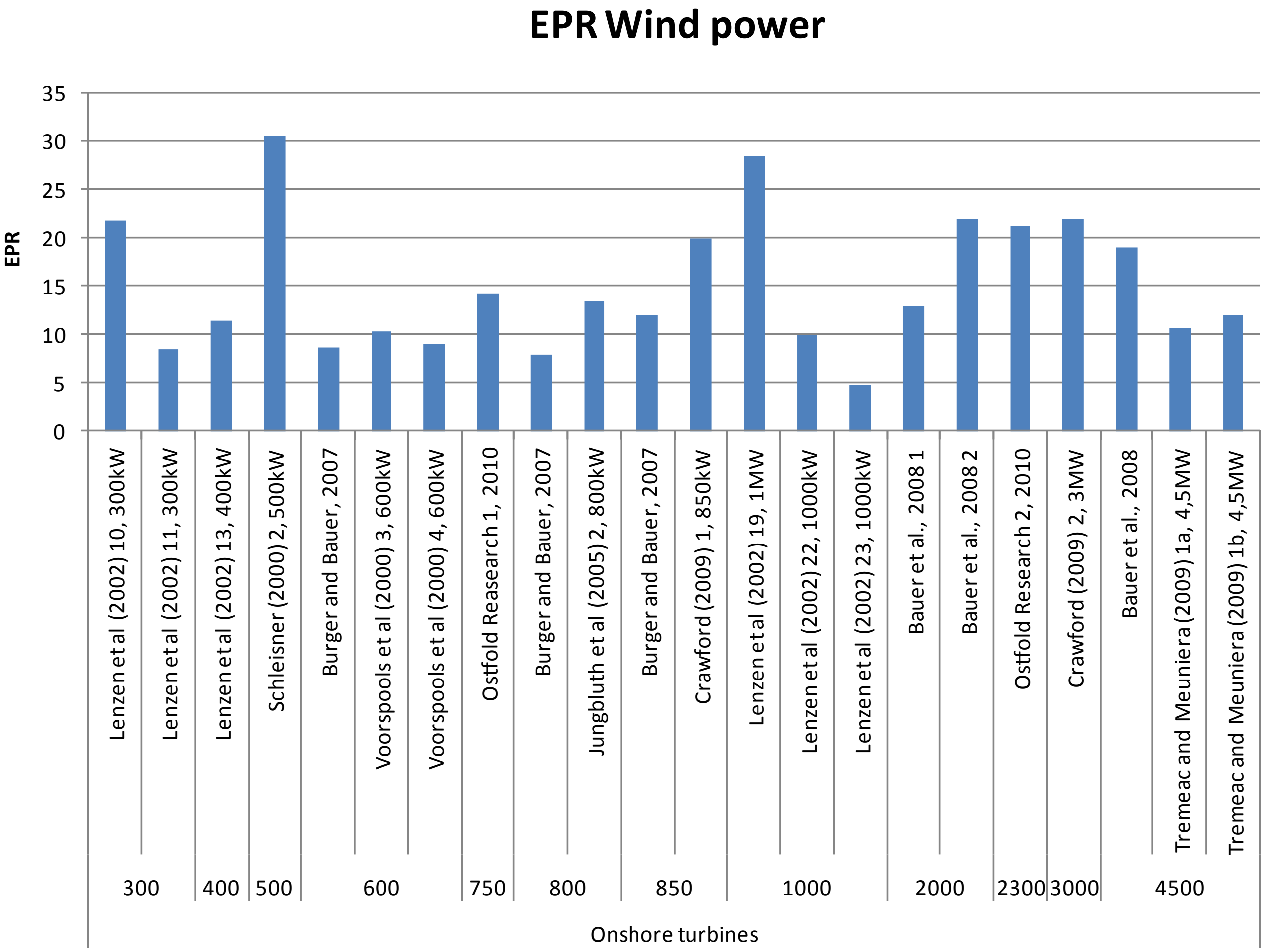


Figure 10: EPR data for onshore wind turbines (> 300 kW), classified according to turbine size.

As seen in the figure, the EPR values vary between about 5 and 30, with an average of 15. Also for this turbine category, there is no correlation between turbine size and EPR. However, these onshore turbines (equal and greater than 300 kW) achieve, in general, higher EPR values than the small, onshore turbines (shown in Figure 9) with average values being 15 and 6, respectively.

Figure 11 shows EPR data for the investigated offshore wind turbine cases, in total 5 cases.

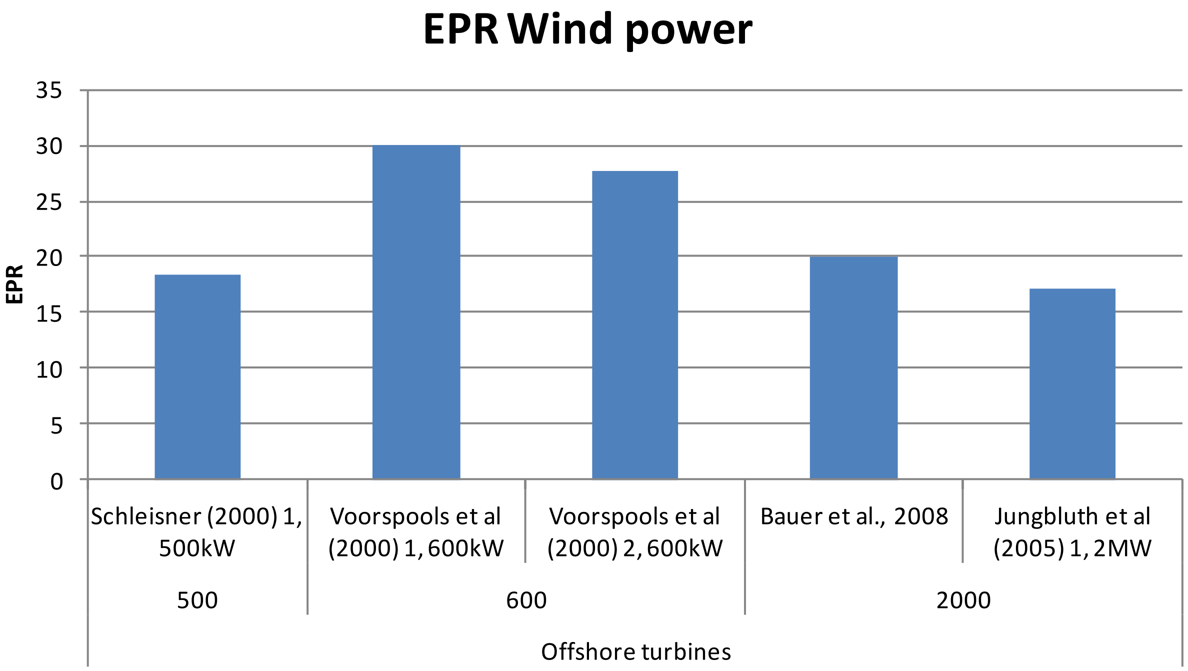


Figure 11: EPR data for offshore wind turbines, classified according to turbine size.

As seen in the figure, the EPR values vary between about 17 and 30, with an average of 23. Based on the investigated cases, there seems to be a tendency that offshore turbines achieve higher EPR values than onshore turbines, which may indicate that the extra energy invested in offshore plants can be beneficial. However, the number of investigated offshore cases (5) is much smaller than the comparable onshore amount of onshore turbines (22) which means that one should be careful to conclude based on these data.

When looking at all the analysed wind power cases (37 in total) the EPR data vary between 3 (worst case = 30 kW turbine, Burger and Bauer, 2007) and 30 (best case = 500 kW turbine, Schleisner, 2002, 2), a difference in 90% compared to the best case.

3.2.2 Net Energy Ratio (NER) for wind power

As described in section 2.1, 2.2 and 3.1.2, the main reason for the relatively small variations within NER data compared to the larger variations within EPR data, is the different system boundaries regarding losses for the calculation of these two indicators. The NER indicator is affected by the total losses through the power plant (see Figure 1 and Equation (2)). Thus, the more losses included, the lower NER value, which also means lower energy performance of the analysed system. The investigated wind power cases show that there seems to be no common practice with regard to whether turbine losses should be included or not for wind power. However, the Ecoinvent database includes turbine/generator losses, based on an average value of 0.075 kWh/kWh wind power generated (equals a turbine efficiency of 93%). Thus, to make the NER data comparable to each other and to the hydropower data, all the wind power data are standardised according to this turbine/generator efficiency. It should be noted that the wind power calculations do not include any other losses, except turbine/generator losses. Thus, the wind energy “not being caught” by the turbines is not accounted for as an energy loss. This is in line with the Product Category Rules for performing Environmental Product Declaration (EPD) for electricity (The International EPDsystem 2011). This is also in line with the hydropower calculations where primary energy in water loss due to evaporation and spill is not included, nor are losses in waterways downstream the turbine.

The standardised NER data for the three different wind power categories are presented in Figure 12, Figure 13 and Figure 14.

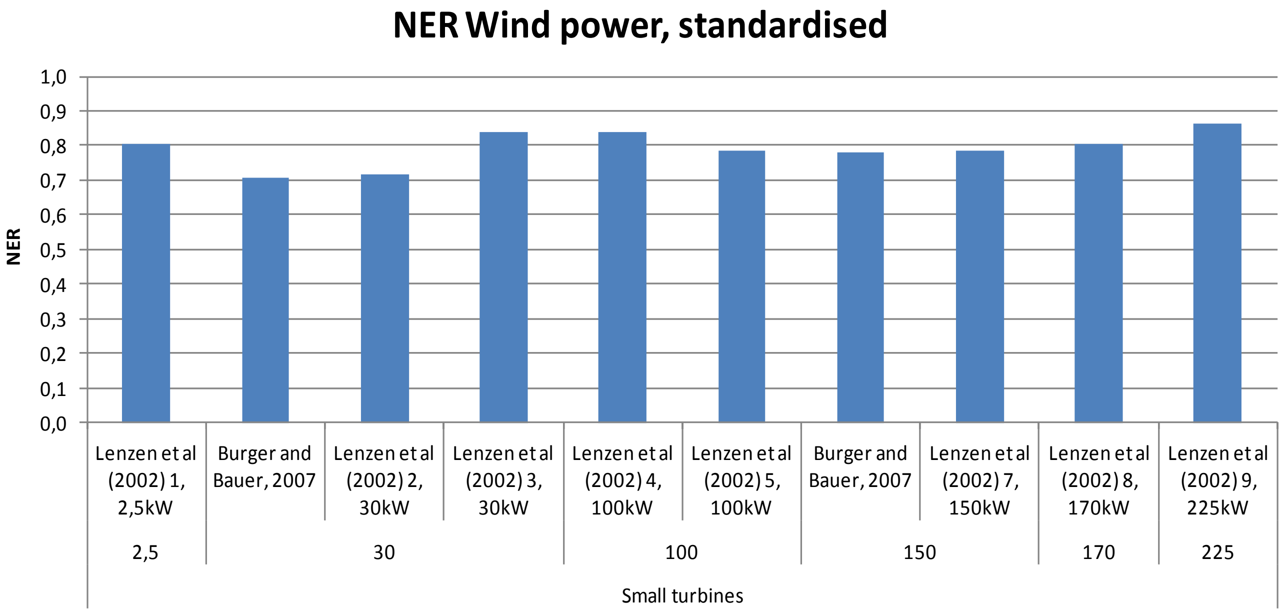


Figure 12: Standardised NER data for small, onshore wind turbines (<300 kW), classified according to turbine size (the losses in turbine/generator are set to 0.075 kWh / kWh for all cases).

As described in section 2.2 and 3.1.2, the ranking interpretation of NER results is similar to EPR: the higher number, the better result is achieved, within a scale between zero and 1.

The NER data in Figure 12 vary between 0.71 (worst case = 30 kW turbine, Burger and Bauer, 2007) and 0.87 (best case = 225 kW turbine, Lenzen et al., 2002, 9), a difference representing 18% compared to the best case. The average NER value for these small, onshore wind turbines is 0.79.

Figure 13 shows the standardised NER data for the investigated onshore wind turbines (> 300 kW).

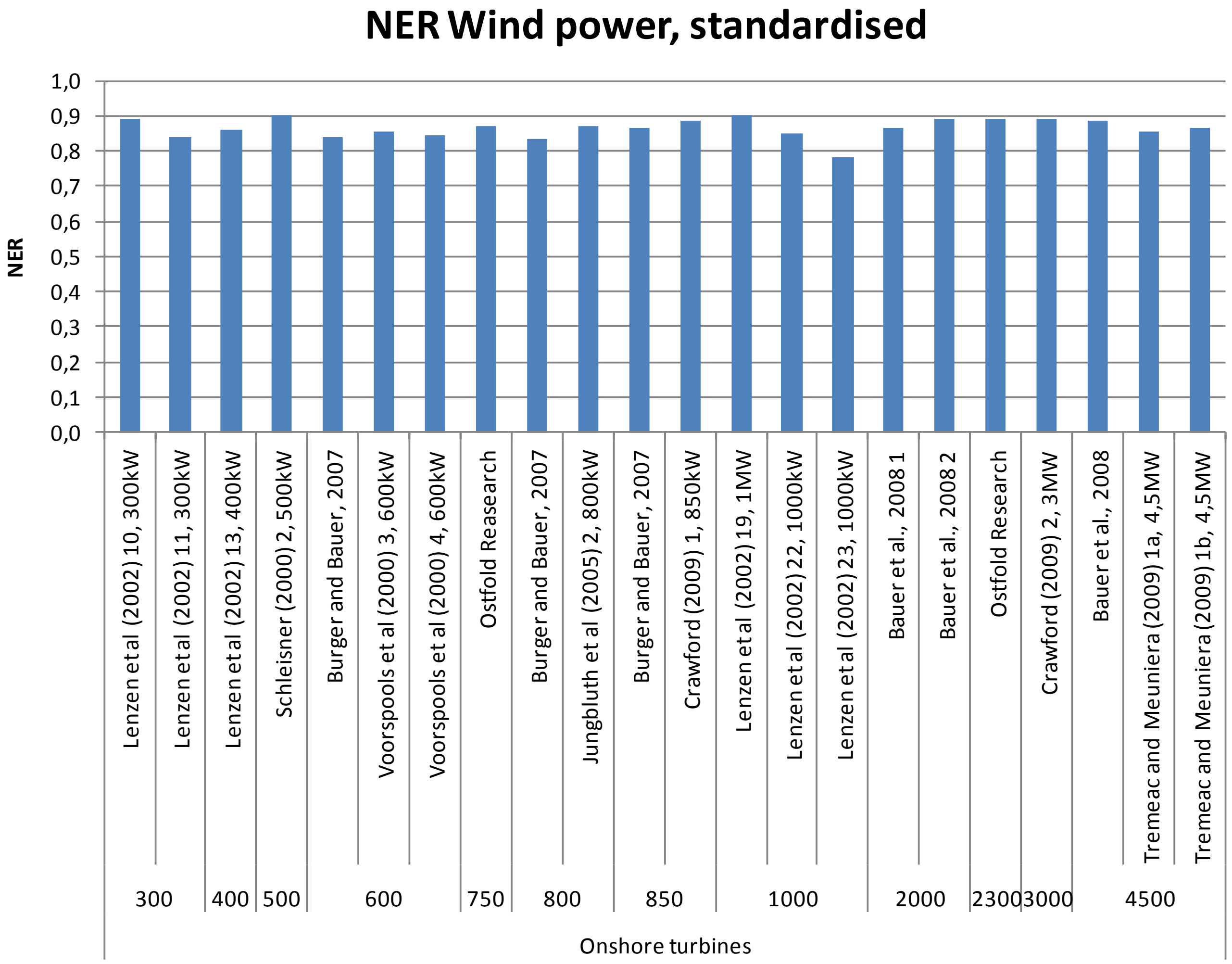


Figure 13: Standardised NER data for onshore wind turbines (>300 kW), classified according to turbine size (the losses in turbine/generator are standardised to 0.075 kWh / kWh for all cases).

The NER data in Figure 13 vary between 0.78 (worst case = 1 MW turbine, Lenzen et al. (2002) 23) and 0.90 (best case = 500 kW turbine, Schleisner, 2000, 2), a difference representing 14% compared to the best case. Average NER value for these onshore wind turbines is 0.87

Figure 14 shows the standardised NER data for the investigated offshore wind turbines.

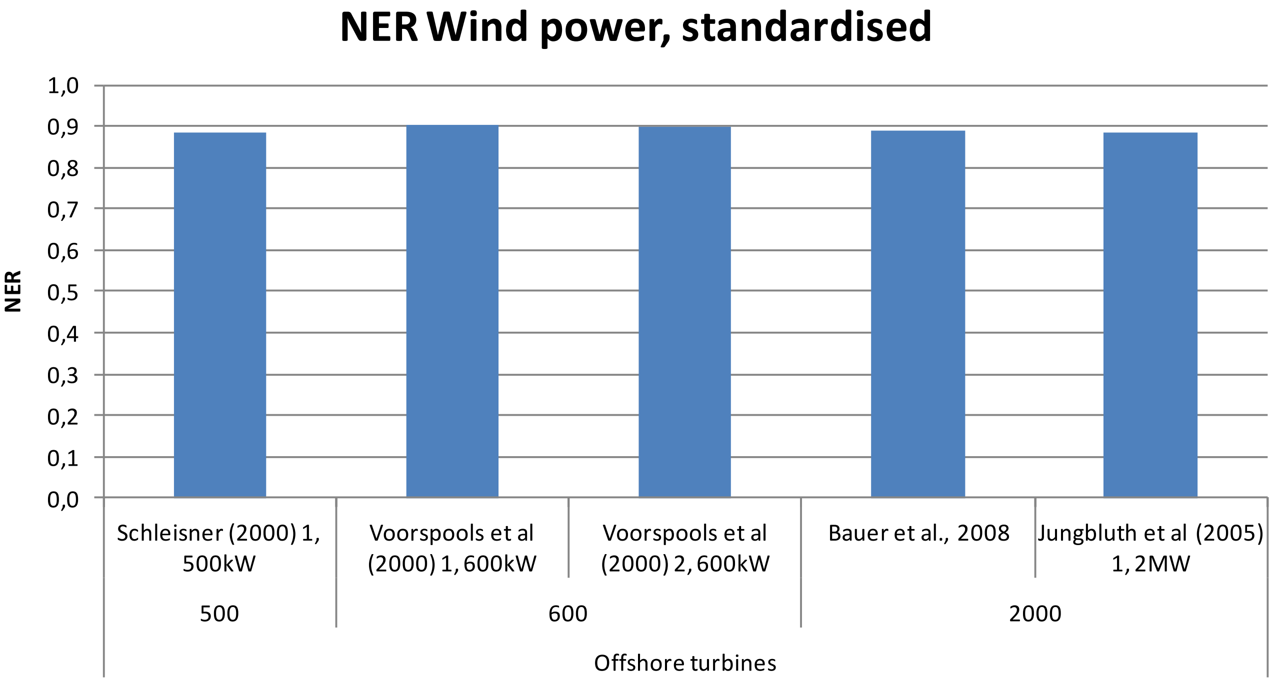


Figure 14: NER data for offshore wind turbines, classified according to turbine size (the loss in turbine/generator is standardised to 0.075 kWh / kWh for all cases).

The NER data in Figure 14 vary between 0.88 (worst case = 1, 2 MW turbine, Jungbluth et al., 2005) and 0.90 (best case = 600 kW turbine, Voorspools et al., 2000, 1), a difference representing 2% compared to the best case. Average NER value for these onshore wind turbines is 0.89.

When looking at all the analysed wind power cases (37 in total), the NER data vary between 0.71 (worst case = 30 kW turbine, Burger and Bauer, 2007) and 0.9 (best case = 500 kW turbine, Schleisner, 2002, 2), a difference representing 21% compared to the best case.

3.2.3 Cumulative Energy demand (CED) for wind power

As described in section 2.3 and 3.1.3, the ranking interpretation of CED results is the opposite of NER and EPR: the lower number, the better result is achieved (always greater than 1).

CED is, in the same way as NER, affected by the total losses throughout the power plant (see Figure 1 and Equation (3)). Thus, the more losses included, the higher CED is achieved, which means lower energy performance of the analysed system.

Based on the same assumptions as for NER (see description in section 3.2.2 above), the CED data are standardised according to a general loss though the wind turbine/generator of 0.075 kWh/kWh wind power generated (equals a turbine efficiency of 93%). This is done to make the CED data comparable to each other and to the hydropower data. The standardised CED data for the three different wind power categories are presented in Figure 15, Figure 16 and Figure 17.

Figure 15 shows standardised CED data for the investigated small, onshore wind turbines (< 300 kW).

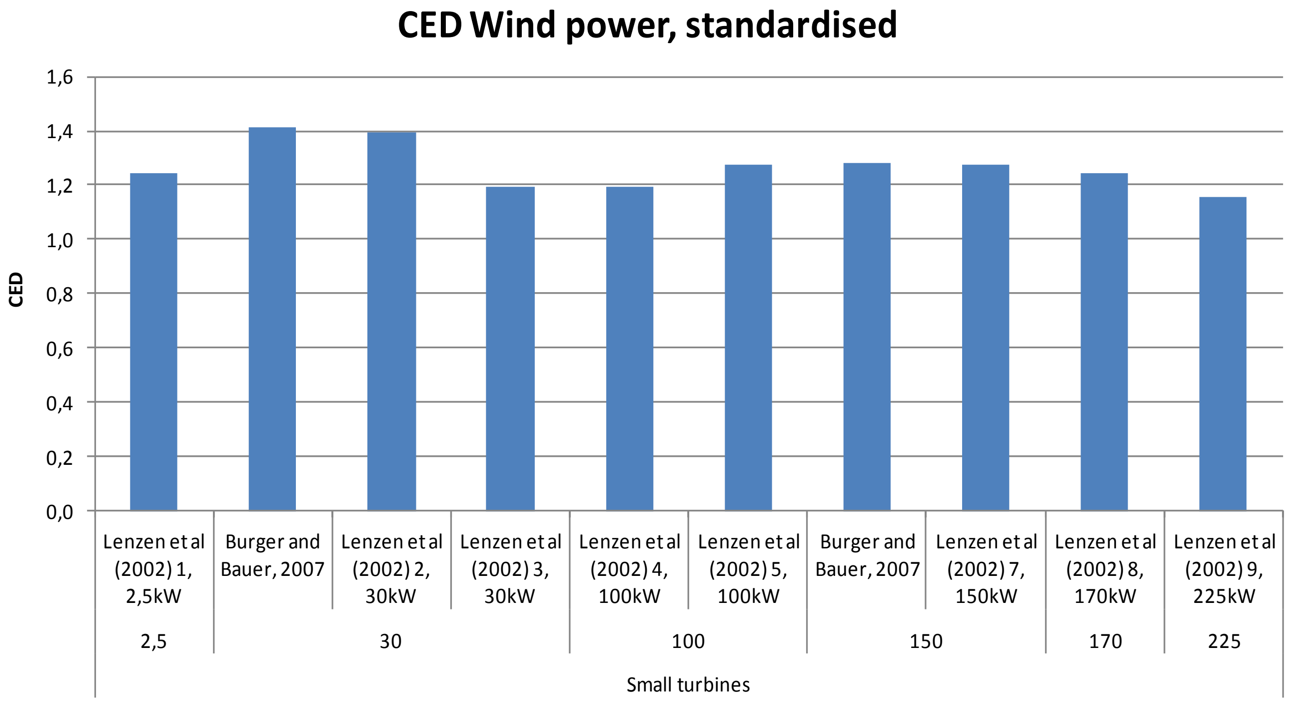


Figure 15: Standardised CED data for small, onshore wind turbines (< 300 kW), classified according to turbine size (the loss in turbine/generator is standardidised to 0.075 kWh / kWh for all cases).

The CED data in Figure 15 vary between 1.42 (worst case = 30 kW turbine, Burger and Bauer, 2007) and 1.16 (best case = 225 kW turbine, Lenzen et al., 2002, 9), a difference representing 23% compared to the best case. Average CED value for these small, onshore wind turbines is 1.27.

Figure 16 shows standardised CED data for the investigated onshore wind turbines (> 300 kW).

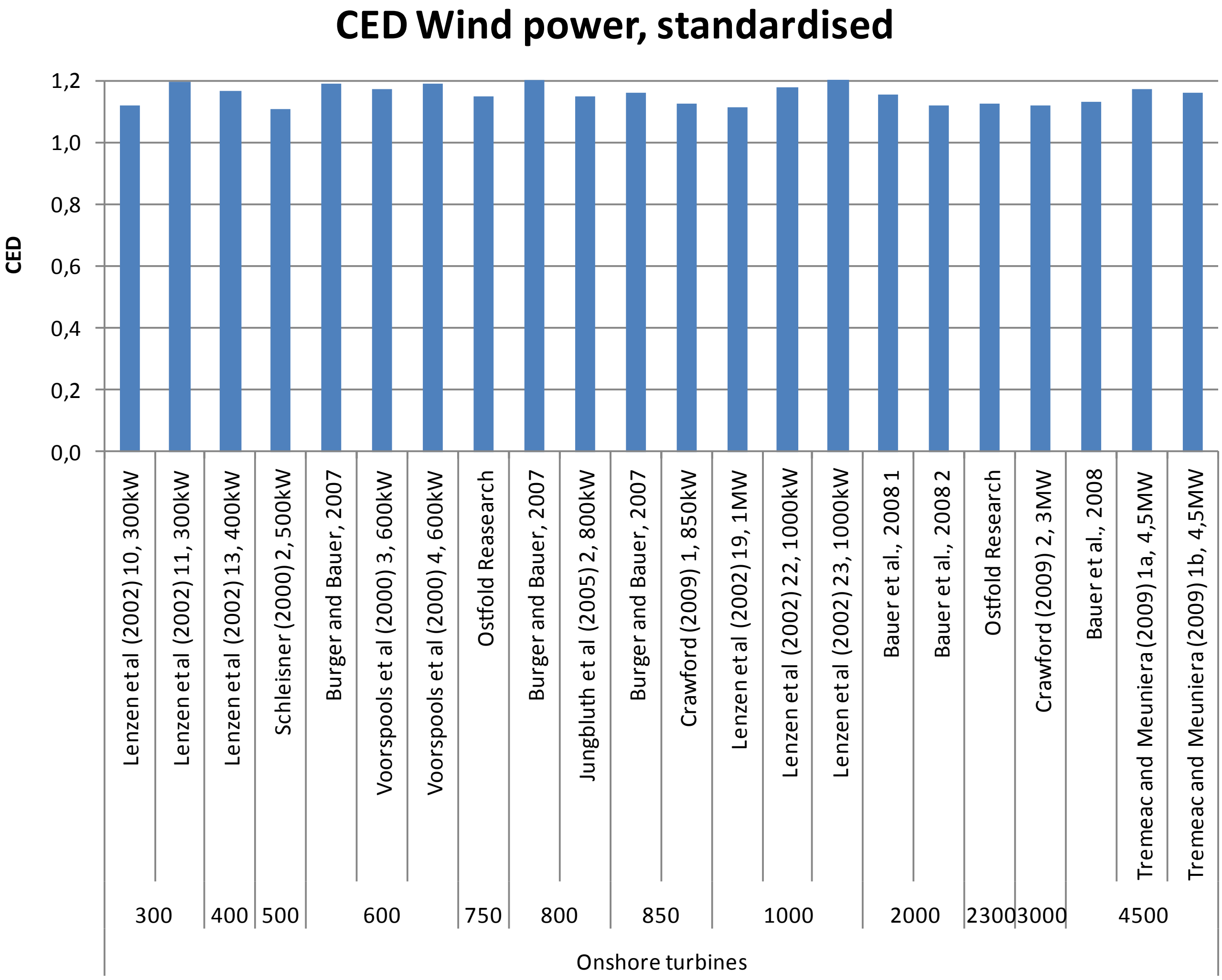


Figure 16: Standardised CED data for onshore wind turbines (>300 kW), classified according to turbine size (the loss in turbine/generator is standardised to 0.075 kWh / kWh for all cases).

The CED data in Figure 16 vary between 1.28 (worst case = 1 MW turbine, Lenzen et al., 2002, 23) and 1.11 (best case = 500 kW turbine, Schleisner, 2000, 2), a difference representing 16% compared to the best case. Average CED value for these onshore wind turbines is 1.16.

Figure 17 shows standardised CED data for the investigated offshore wind turbines.

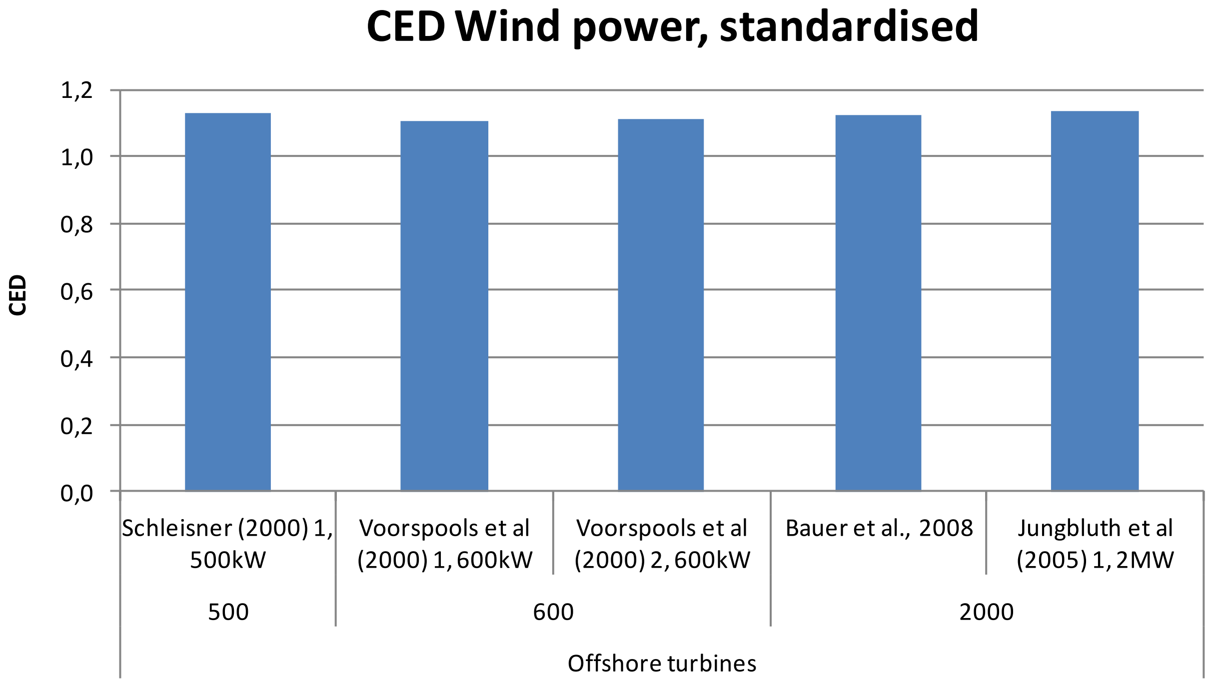


Figure 17: Standardised CED data for onshore wind turbines, classified according to turbine size (the loss in turbine/generator is standardised to 0.075 kWh / kWh for all cases).

The CED data in Figure 17 vary between 1.13 (worst case = 1.2 MW turbine, Jungbluth et al. 2005) and 1.11 (best case = 600 kW turbine, Voorspools et al., 2000, 1), a difference representing 2% compared to the best case. Average CED value for these small wind turbines is 1.12.

When looking at all the analysed wind power cases (37 in total), the CED data vary between 1.42 (worst case = 30 kW turbine, Burger and Bauer, 2007) and 1.11 (best case = 500 kW turbine, Schleisner, 2002, 2), a difference representing 28% compared to the best case.

As seen from Figure 15, Figure 16 and Figure 17, the CED ranking of the investigated wind power cases remain the same as the NER ranking for all the analysed energy indicators. This is logic as the turbine efficiency is assumed to be the same (93%) for all the investigated cases when calculating NER and CED. When including the embedded energy and losses through the conversion step (W+X=Q), the differences between the cases decrease compared to using EPR as indicator, as the difference between best and worst case decreases from 90% to 21% for EPR and NER[2], respectively.

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[2] The corresponding difference between the worst and best case when using CED as indicator is 28%. The reason why the difference between the worst and best case is 21% when using the NER indicator and 28% when using the CED indicator respectively, is purely mathematical. The deviation occurs due to the shift from high to low value as a basis for the calculation (the difference is always calculated in relation to the best value, which is “high” for NER and “low” for CED).

3.3 Electricity from biomass

The electricity from biomass cases are based on the literature study by Vold et al. (2011) which analyses different value chains for biomass fuels, mainly for Nordic conditions. The results presented in this study are extended by including a conversion step (production of electricity) based on infrastructure and operation data from the Ecoinvent database ("Electricity, at cogen ORC 1400kWth, wood, allocation exergy/CH U") and a conversion efficiency of 40% (Brekke et al. 2008).

3.3.1 Energy Payback Ratio (EPR) for electricity from biomass

Figure 18 shows EPR data for the 6 investigated biomass cases.

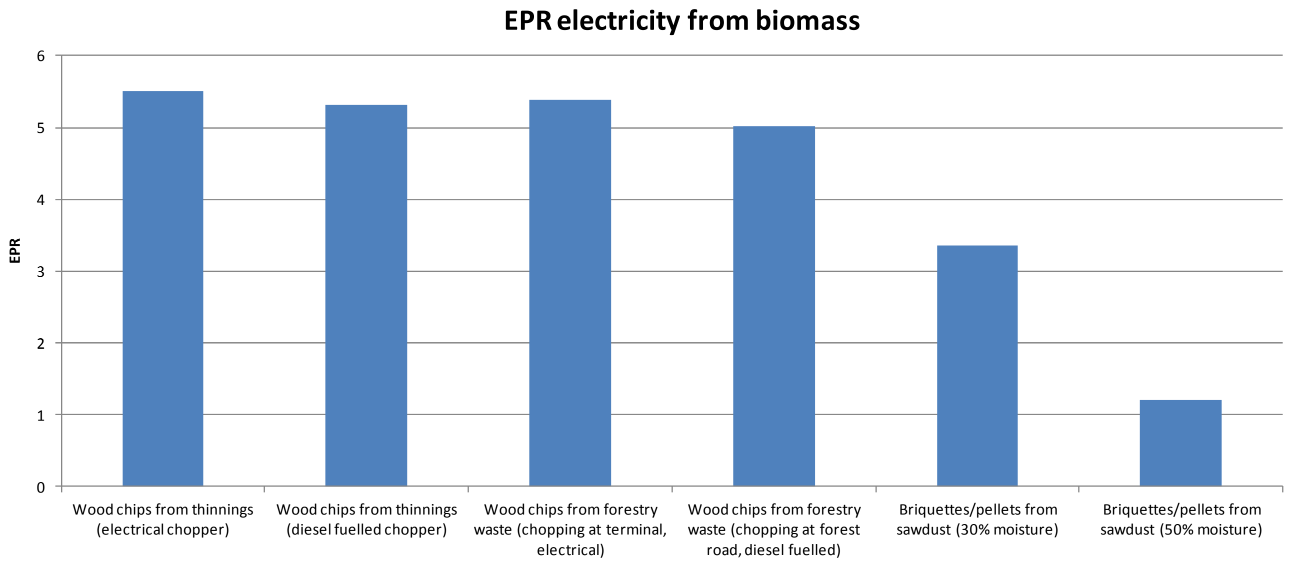

Figure 18: EPR data for electricity from different biomass fuels.

As described in section 2.1, the higher EPR value, the better result is achieved. The figure shows that the EPR values vary between 1.2 (worst case = Briquettes/pellets from sawdust (50% moisture)) and 5.5 (best case = Wood chips from thinning (electrical chopper), a difference representing 78% compared to the best case. The average CED value is 4.3.

The main reason for the difference between briquettes/pellets and wood chips is the energy required for drying during the compression process for briquettes/pellets.

3.3.2 Net Energy Ratio (NER) for electricity from biomass

Figure 19 shows NER data for the 6 investigated biomass cases. The plant efficiency for the conversion of fuel to electricity is assumed to be 40% for all the investigated cases.

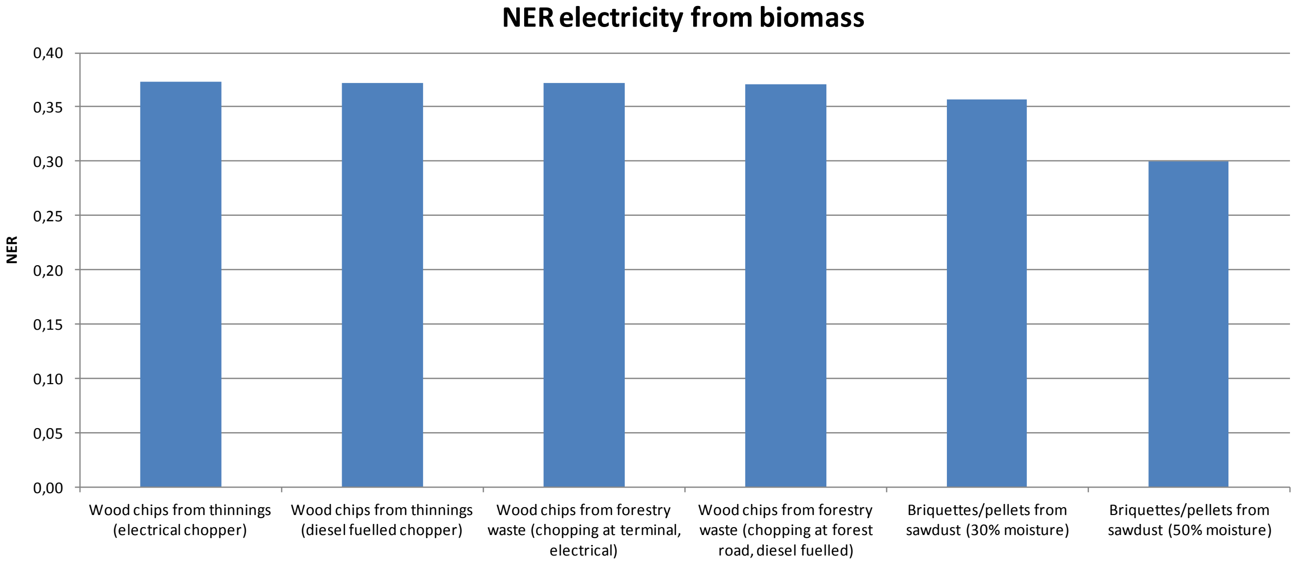

Figure 19: NER data for electricity from different biomass fuels.

As described in section 2.2, the higher NER value, the better result is achieved. Figure 19 shows NER values varying between 0.30 (worst case = Briquettes/pellets from sawdust (50% moisture)) to 0.37 (best case = Wood chips from thinning (electrical chopper), a difference representing 20% compared to the best case. The average CED value is 0.36.

3.3.3 Cumulative Energy Demand (CED) for electricity from biomass

Figure 20 shows CED data for the 6 investigated biomass cases. The plant efficiency for the conversion of fuel to electricity is assumed to be 40% for all the investigated cases.

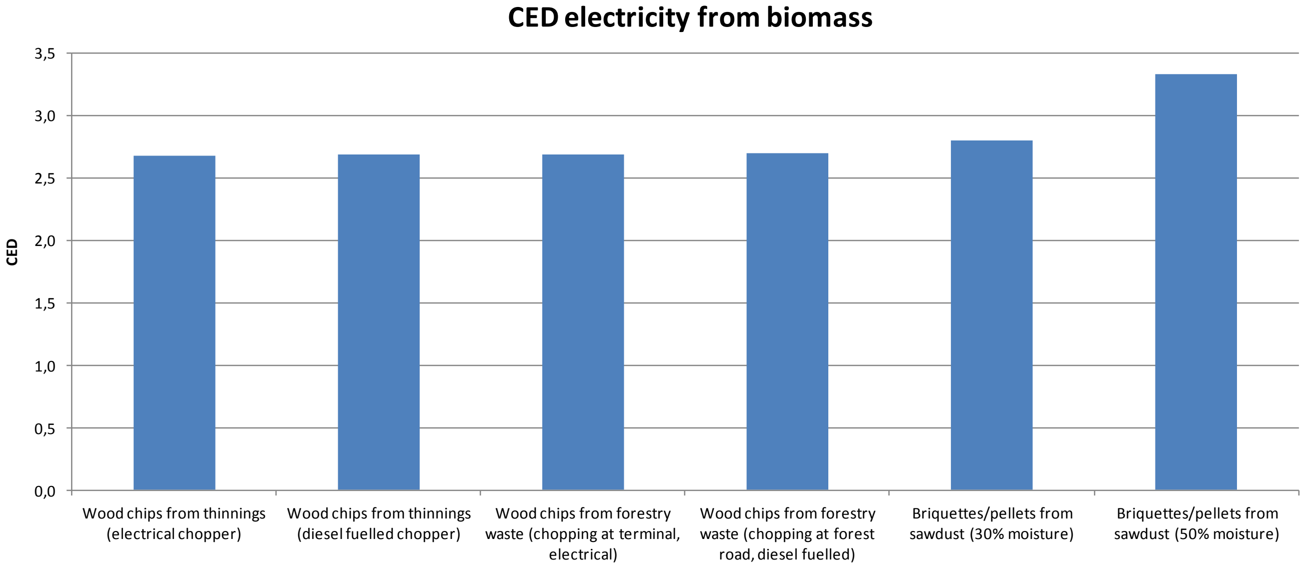

Figure 20: CED data for electricity from different biomass fuels.

As described in section 2.3, the lower CED value, the better result is achieved. Figure 20 shows CED values varying between 3.3 (worst case = Briquettes/pellets from sawdust (50% moisture)) and 2.7 (best case = Wood chips from thinning (electrical chopper)), a difference representing 24% compared to the best case. The average CED value is 2.8.

As seen from the Figure 18, Figure 19 and Figure 20, the CED ranking of the 6 investigated biomass cases remain the same as the NER ranking for all the analysed energy indicators. This is logic as the conversion efficiency is assumed to be the same (40%) for all the investigated cases when calculating NER and CED. When including the embedded energy and losses through the conversion step (W+X=Q), the differences between the cases decrease compared to using EPR as indicator, as the difference between worst and best case decreases from 78% to 20% for EPR and NER[3], respectively.

3.4 Electricity from fossil fuels

The electricity from fossil fuel cases are based on the Ecoinvent database (Swiss Centre for Life cycle inventories 2011) for coal and natural gas. The database includes data for a number of countries and grids. When choosing the cases for this study, the following criteria were used: coverage of the whole range of electricity production efficiencies, mostly European data, completeness of data, no outliers (China was excluded) and the same countries and grids for both coal and natural gas.

3.4.1 Energy Payback Ratio (EPR) for electricity from fossil fuels

Figure 21 shows EPR data for the investigated fossil fuel cases. The plant efficiency for the different cases are based on the actual data from Ecoinvent data base and presented in the figure.

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[3] The corresponding difference between the worst and best case when using CED as indicator is 24%. For an explanation of the deviation between the NER and CED differences between worst and best case, see footnote no. 2.

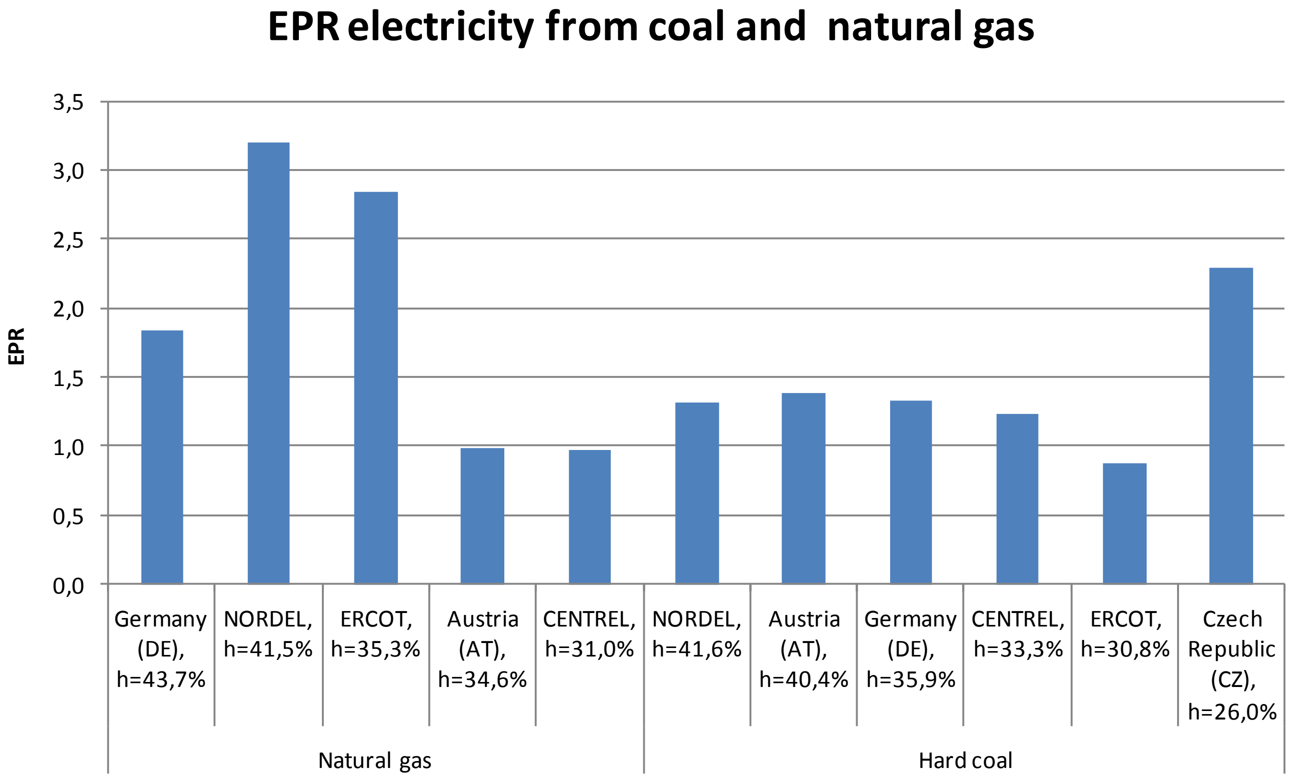

Figure 21: EPR data for electricity from different fossil fuels. The results are sorted based on plant efficiencies (h), which are shown specifically for each case.

As described in section 2.1, the higher EPR value, the better result is achieved. The figure shows that for natural gas, the EPR values vary between 0.97 (CENTREL, h=31%) and 3.2 (best case = NORDEL, h=41.5%) and a difference representing 70% compared to the best case. The average EPR value for natural gas is 2.0.

For hard coal the EPR values vary between 0.88 (ERCOT, h=30.8%) and 2.3 (best case = Czech Republic (CZ), h=26%), a difference representing 62% compared to the best case. The average EPR value for hard coal is 1.4.

It should, however, be emphasised that the plant efficiency (conversion efficiency) does not impact the amount of invested energy in the EPR calculation as this indicator excludes the primary energy of the fuel itself as invested energy. Only “supporting energy” (required for infrastructure, extraction processes and transport) is included as invested energy in EPR calculations (see section 2.1).

3.4.2 Net Energy Ratio (NER) for electricity from fossil fuels

Figure 22 shows NER data for the investigated fossil fuel cases. The plant efficiency for the different cases are based on the actual data from Ecoinvent data base and presented in the figure.

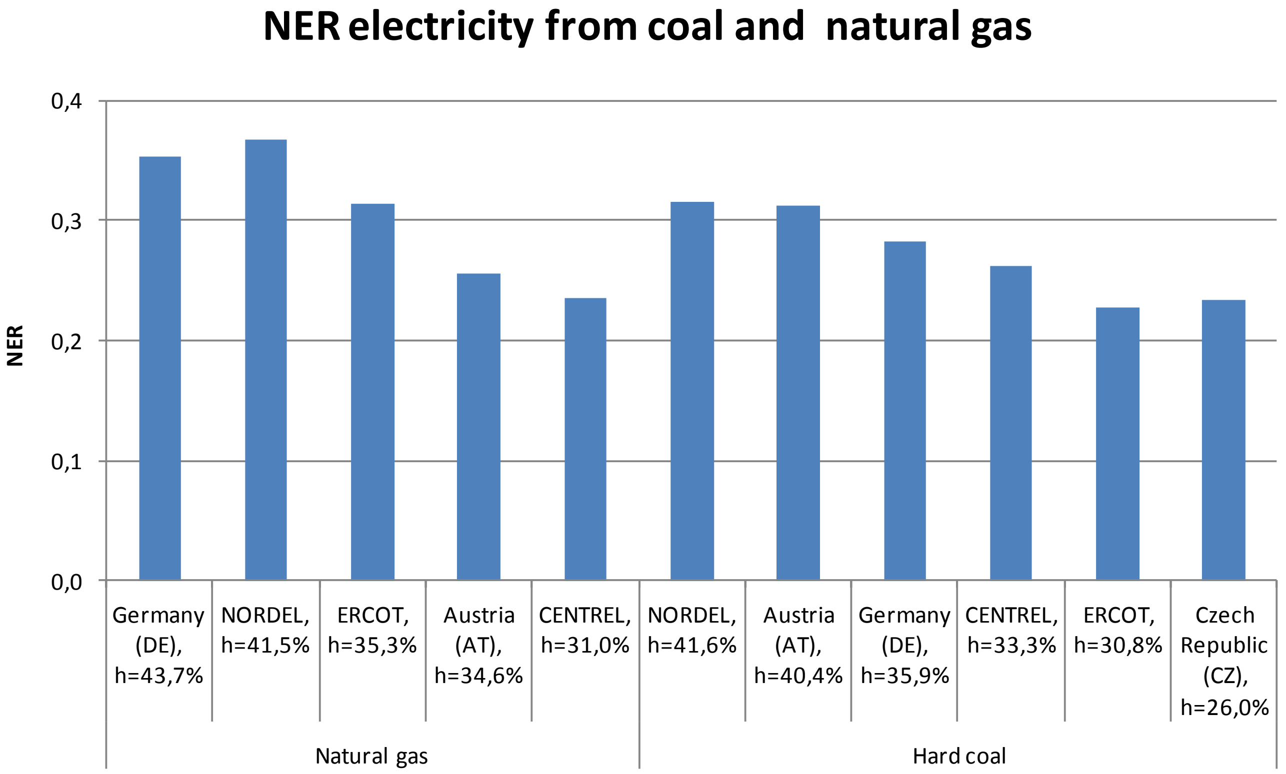

Figure 22: NER data for electricity from different fossil fuels. The results are sorted based on plant efficiencies (h), which are shown specifically for each case.

As described in section 2.2, the higher NER value, the better result is achieved. The figure shows that for natural gas the NER values vary between 0.23 (CENTREL, h=31%) and 0.37 (best case = NORDEL, h=41.5%), a difference in 36% compared to the best case. The average NER value for natural gas is 0.31.

For hard coal the NER values vary between 0.23 (ERCOT, h=30.8%) and 0.32 (best case = NORDEL, h=41.6%), a difference in 28% compared to the best case. The average NER value for hard coal is 0.27.

It should be noted that the internal ranking within the coal cases has changed compared to the EPR data: As the case “Czech Republic (CZ), h=26%” represented the best EPR case (EPR = 2.3), it has ended as the second worst NER case (NER = 0.23). In the same way, the fourth best EPR case (NORDEL, h=41.6%) has ended as the best NER case. The reason for this is that the actual plant efficiency is taken into account when calculating the NER indicators, which means that these results show the energy efficiency throughout the whole value chain ending in electricity generation.

Also the internal ranking within the natural gas cases has changed when comparing EPR and NER results, as the second (ERCOT, h=35.3%) and the third (Germany, h=43.7%) best cases according to the EPR results change order according to the NER results. This happens because of higher plant efficiency in the German case (43.7%) which results in an overall better energy performance compared to the ERCOT case (with a plant efficiency of 35.3%).

It is also worthwhile paying attention to the fact that the overall ranking within the coal and natural gas cases changes when comparing EPR and NER results. According to the EPR results, the best coal case (Czech Republic, h=26%) is also the third best fossil case, but when looking at the NER ranking, this case ends up as the second worst fossil case.

To summarise, the ranking of fossil fuel electricity generation technologies according to NER is, to a large extent, dependent of the plant efficiency as losses occurring at this conversion step increase the value of the denominator (Q is included, together with A and B) when calculating NER (see Equation (2) and Figure 1).

3.4.3 Cumulative Energy Demand (CED) for electricity from fossil fuels

Figure 23 shows CED data for the investigated fossil fuel cases. The plant efficiency for the different cases are based on data from Ecoinvent data base and presented in the figure.

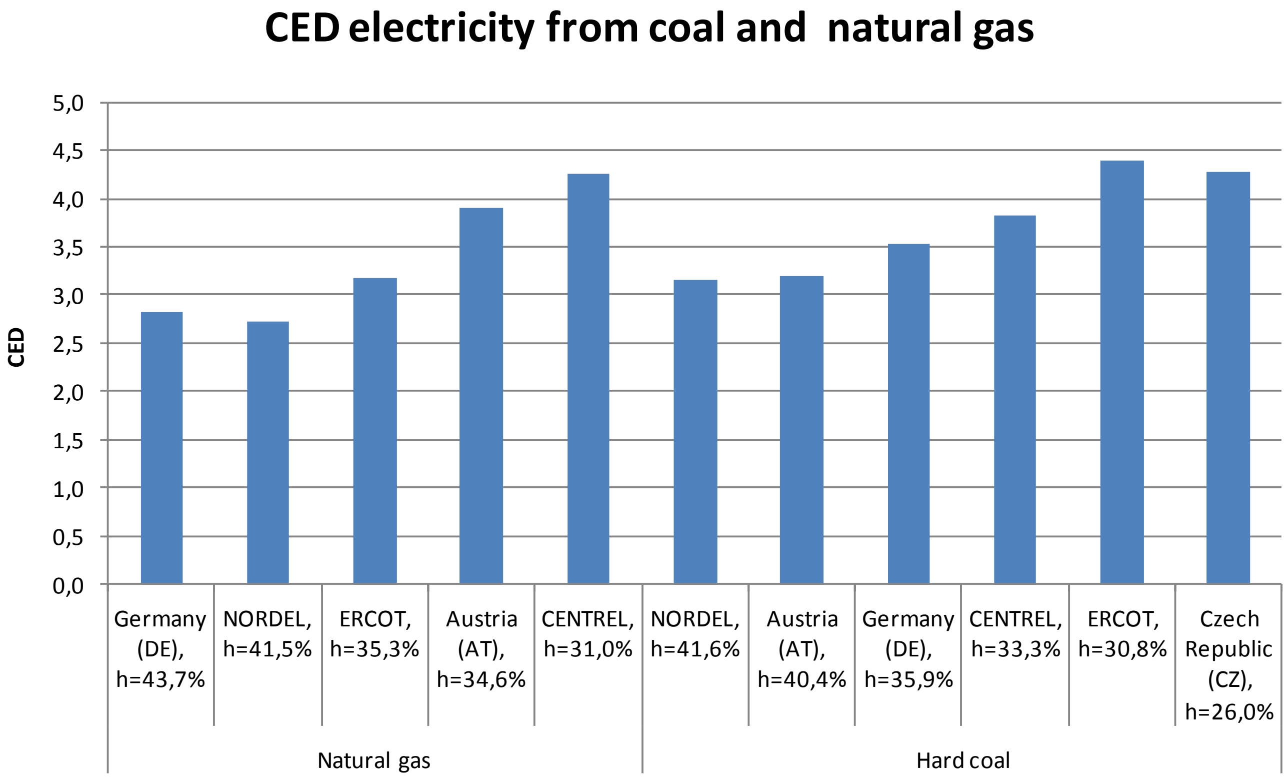

Figure 23: CED data for electricity from different fossil fuels. The results are sorted based on plant efficiencies (h), which are shown specifically for each case.

As described in section 2.3, the lower CED value, the better result is achieved.

The figure shows that the CED values for natural gas vary between 4.3 (worst case = CENTREL, h=31%) and 2.7 (best case = NORDEL, h=41.5%), a difference representing 56% compared to the best case. The average NER value for natural gas is 3.4.

For hard coal the CED values vary between 4.4 (worst case = ERCOT, h=30.8) and 3.2 (best case = NORDEL, h=41.6%), a difference representing 39% compared to the best case. The average NER value for hard coal is 3.7.

When including the embedded energy and losses through the conversion step (W+X=Q), the differences between the cases decrease compared to using EPR as indicator, as the difference between worst and best case decreases from 70% (natural gas) and 62% (coal) for EPR to 36% (natural gas) and 28% (coal) for NER[4].

The ranking of the different coal and natural gas cases according to CED is identical to the ranking according to NER, as CED is the inverse of NER. Thus, also the CED ranking is strongly dependent on the plant efficiencies.

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[4] The corresponding difference between the worst and best case when using CED as indicator is 56% (natural gas) and 39% (coal). For an explanation of the deviation between the NER and CED differences between worst and best case, see footnote no. 2.

4 Comparisons of the energy indicators and electricity technologies

In this section a comparison of the three investigated energy indicators across technologies is presented. Two (or three) cases, representing the best and worst value within each technology according to each of the three energy indicators, are presented simultaneously. For wind power the additional selected case was needed in order to present more detailed information regarding CED (detailed information for the best and worst wind case was not available). The third wind case was thus chosen to represent median values for wind. For electricity from coal the ranking of the best case differs depending on which indicator used. Hence, for electricity from coal both the best case according to EPR and the best case according to NER/CED are shown.

The data used for hydro power and wind power in this chapter is based on standardised data for losses through the power plant (turbine and generator). Further, no 2nd life cycle cases are included in this section.

4.1 EPR data for different electricity technologies

Figure 24 shows EPR data for the chosen electricity cases.

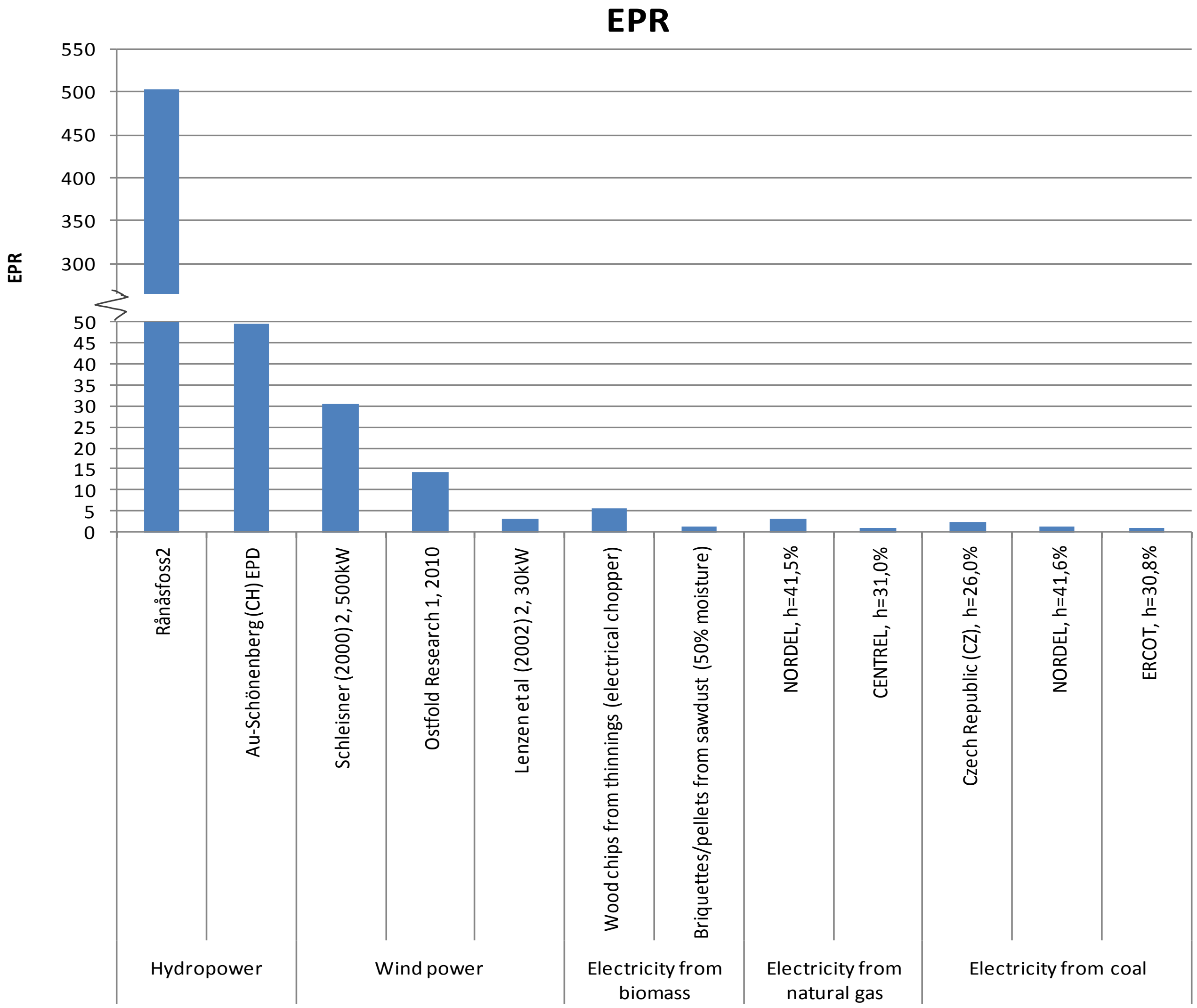

Figure 24: Comparison of EPR data for different electricity technologies.

A seen from the figure, hydropower clearly achieves the best energy performance according to the EPR indicator, representing values between 50 and 500. Wind power achieves the second best performance, with EPR values between 3 and 30. The thermal power generation technologies based on biomass and fossil fuels give the lowest energy performance according to EPR with values varying between 1 and 6.

Figure 25 presents the results for all the investigated cases, showing the range and average values only.

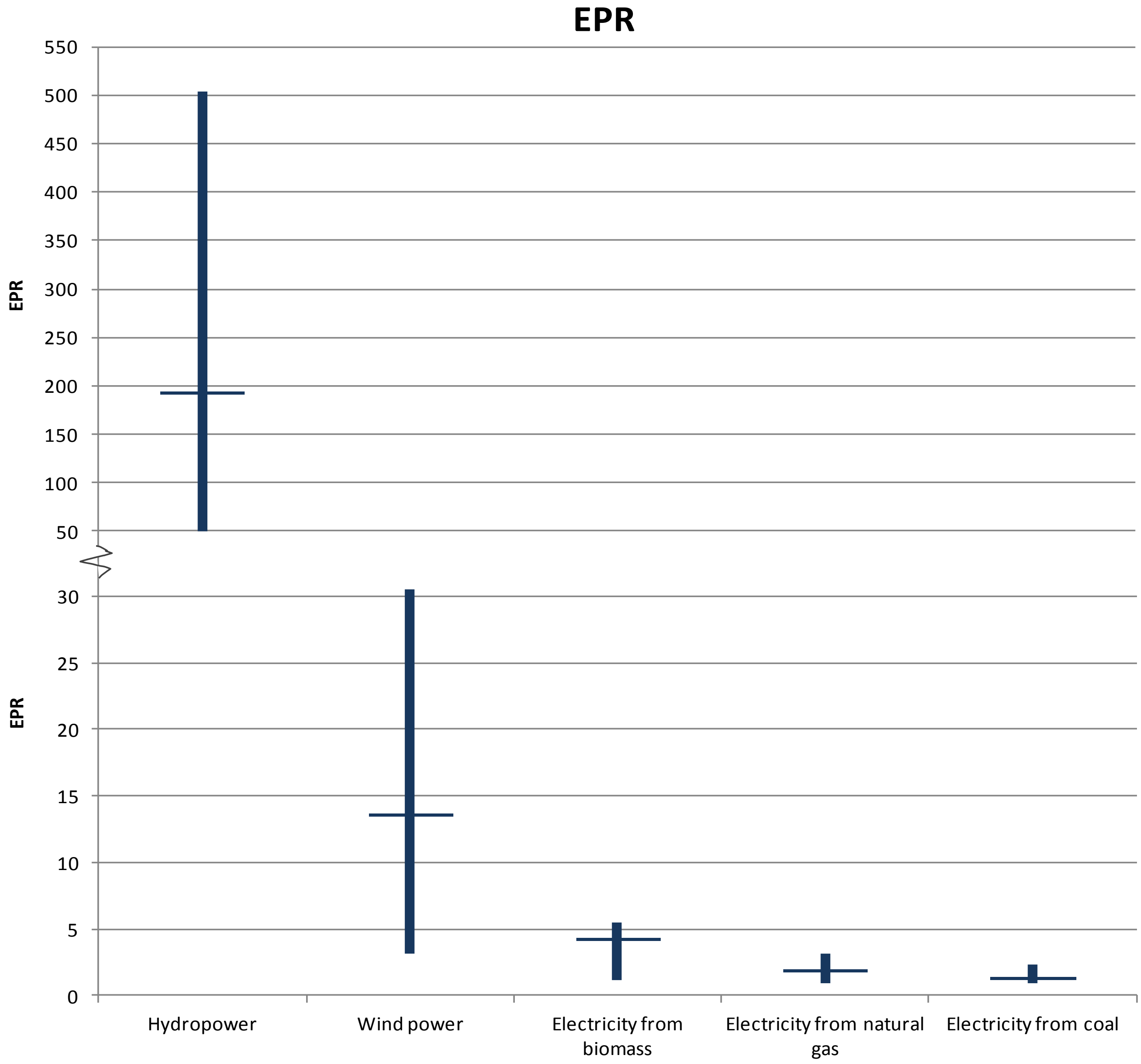

Figure 25: Comparison of EPR data for different electricity technologies, showing the range and average values only.

As shown in the figure, hydropower and wind power clearly represent the best energy performance according to the EPR indicator. However, the variations within the technologies are large.

4.2 NER data for different electricity technologies

Figure 26 shows NER data for the chosen electricity cases.

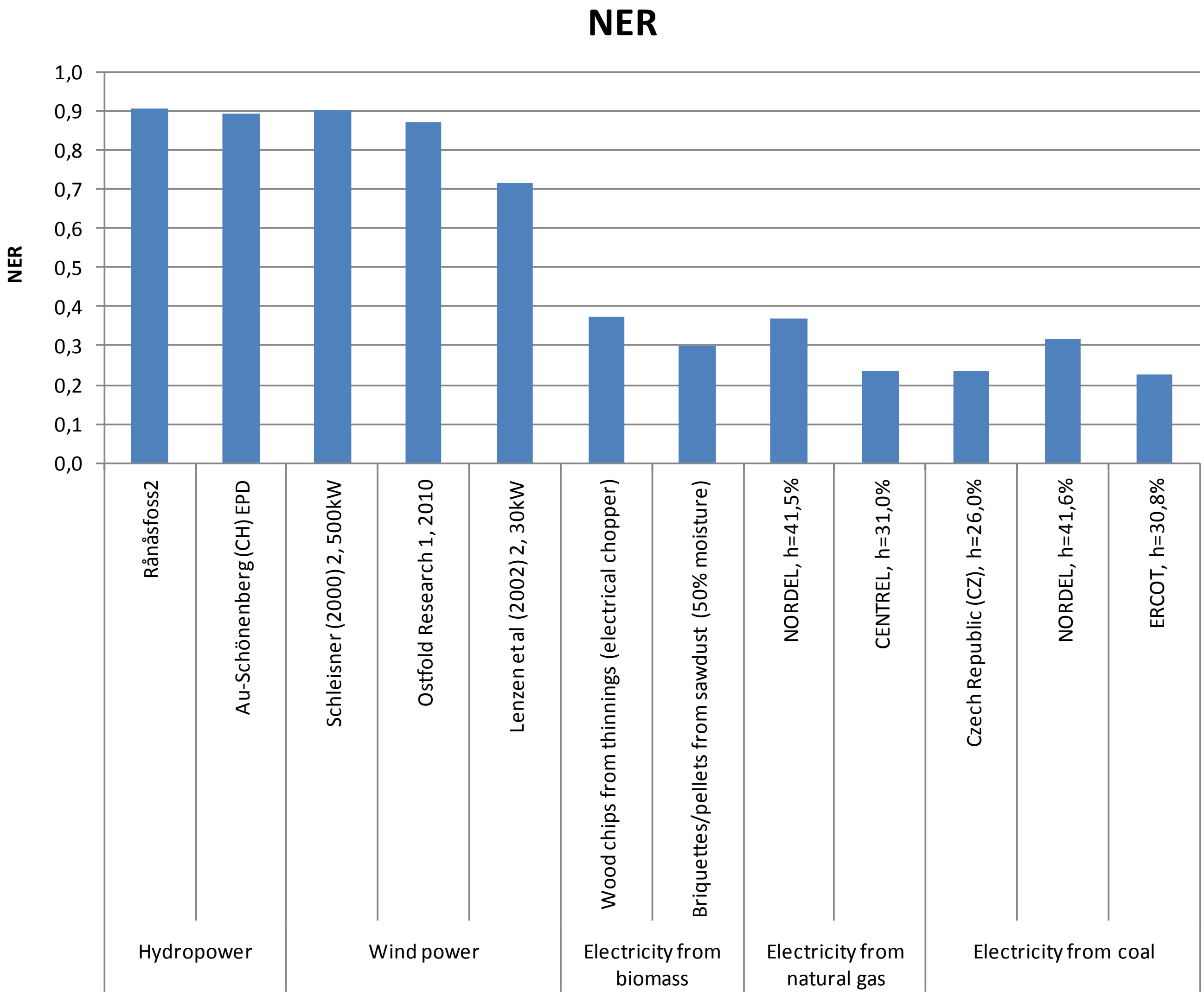

Figure 26: Comparison of NER data for different electricity technologies.

Also for the NER indicator, hydropower achieves the best energy performance (values between 0.89-0.91), followed by wind power (values between 0.71-0.90). The thermal power generation technologies based on biomass and fossil fuels give the lowest energy performance according to NER with values varying between 0.23 and 0.34. It should be noted that the internal ranking between the coal cases has changed compared to the EPR indicator (according to EPR, the Czech Republic was the best case, while the Nordel case represents the best case for NER).

Figure 27 presents the results for all the investigated cases, showing the range and average values only.

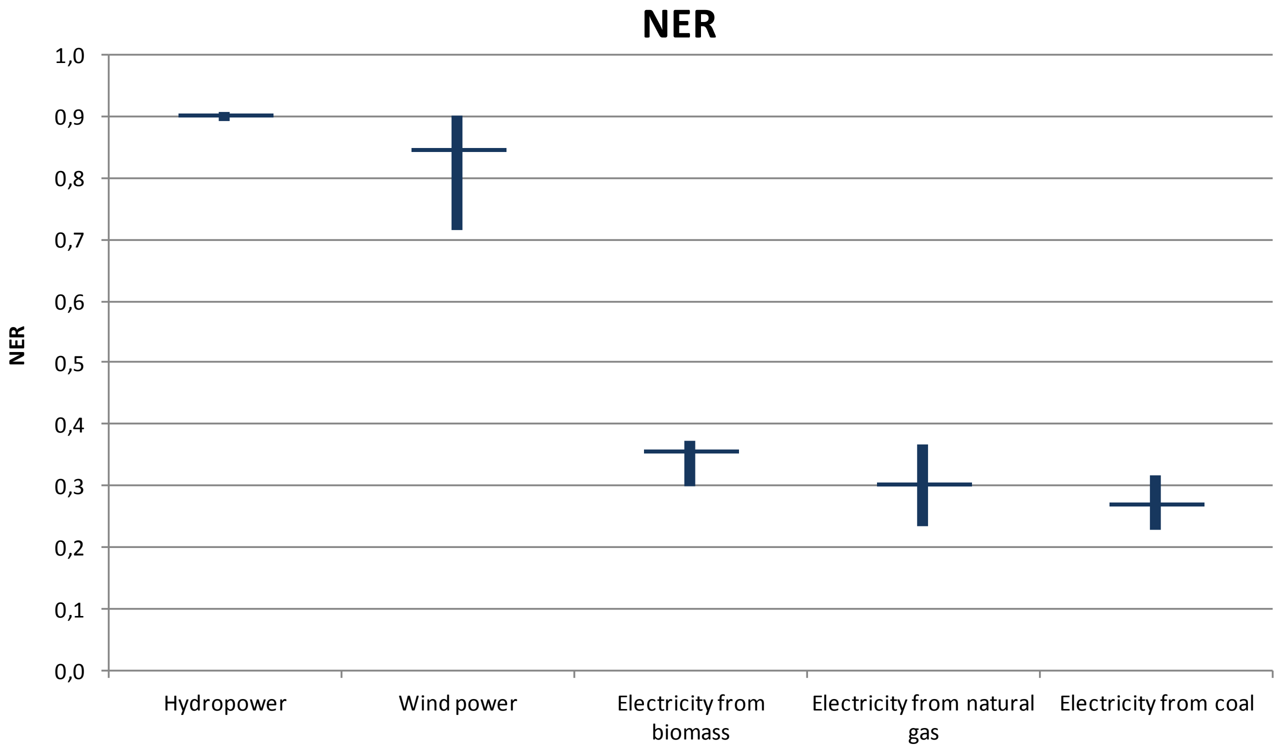

Figure 27: Comparison of NER data for different electricity technologies, showing the range and average values only.

As shown in the figure, hydropower and wind power clearly represent the best energy performance according to the NER indicator.

4.3 CED data for different electricity technologies

For CED the comparisons are presented as total CED results and for total CED the results split into energy sources.

4.3.1 CED (total)

Figure 28 shows CED data for the chosen electricity cases.

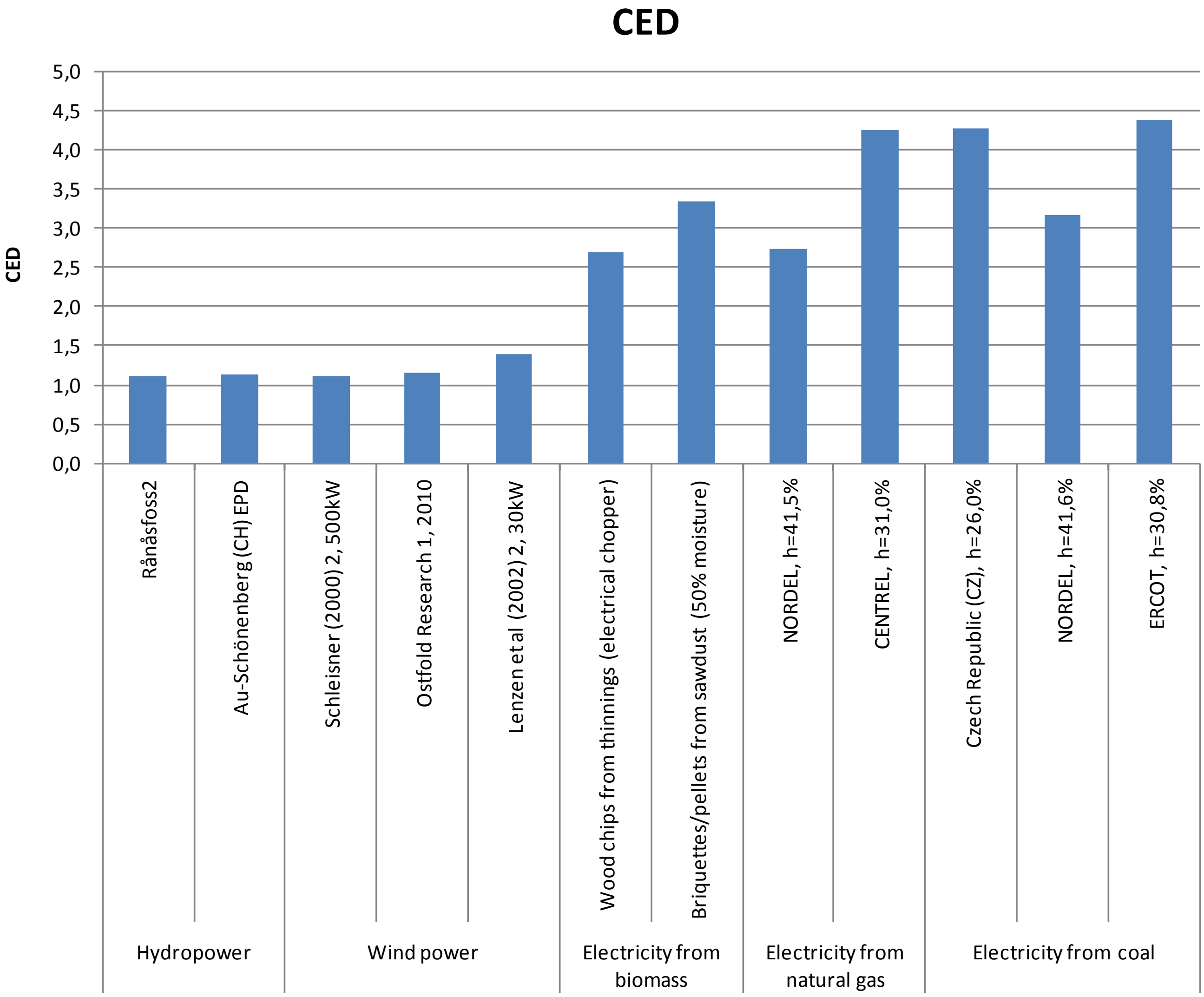

Figure 28: Comparison of CED data for different electricity technologies.

The CED indicator gives, of course, the exact same ranking of the different electricity technologies according to each other, as given by the NER indicator (as the indicators are the inverse of each other). The figure clearly shows that hydropower and wind power achieve the best energy performance representing the lowest CED values.

At the same way as for hydropower (see Figure 8), the CED results are also presented by a figure starting the y-scale at 1 (see Figure 29). This opens up for a deeper investigation of the differences between the technologies as the bars show the necessary invested energy (required for e.g. infrastructure and transport or relevant losses throughout the value chain) for the generation of 1 kWh hydropower (the 1 kWh generated is not shown).

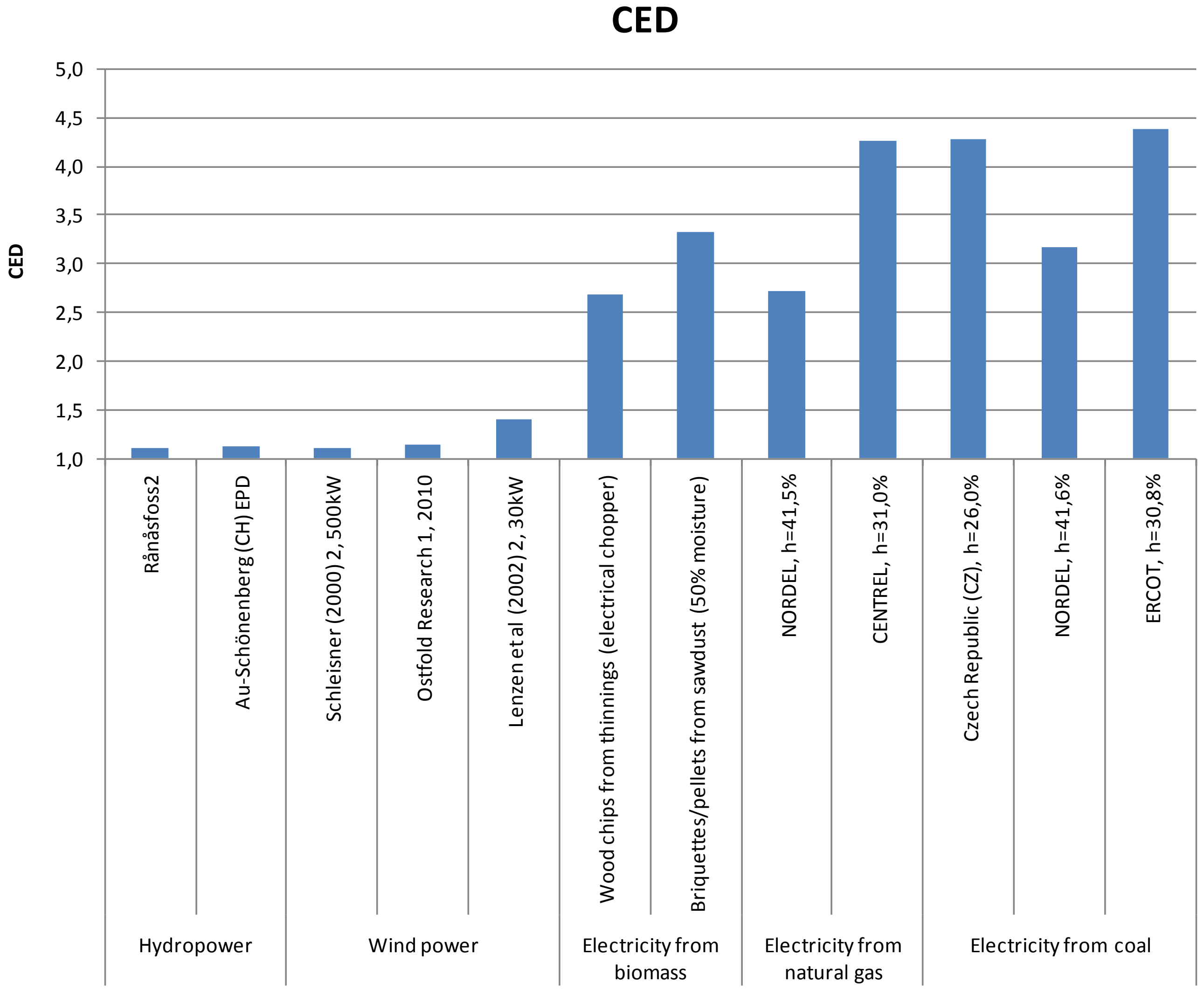

Figure 29: Comparison of CED data for different electricity technologies (note that the X-axis crosses the y-scale at 1).

The ranking and values are, of course, equal to those presented in Figure 28. However, it may be easier to understand that the energy amounts displayed represent the “extra energy invested” for the generation of 1 kWh of electricity.

Figure 30 presents the results for all the investigated cases, showing the range and average values only.

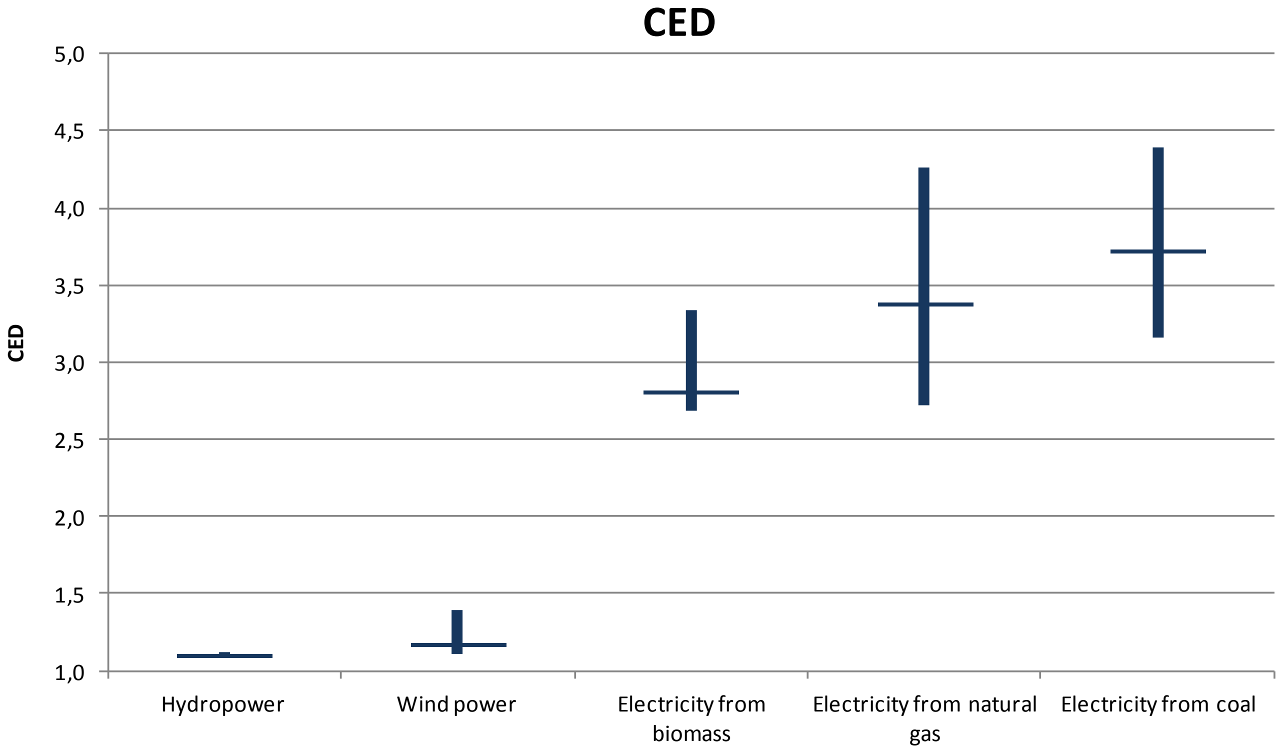

Figure 30: Comparison of CED data for different electricity technologies, showing the range and average values only.

As shown in the figure, hydropower and wind power clearly represent the best energy performance according to the CED indicator.

4.3.2 CED split into energy sources

When comparing energy performance, it may not only be of interest to know the total amount of energy invested in relation to the generated electricity. Important added information can be given by separating the total amount of invested energy into different energy sources and/or life cycle stages. Figure 31 to Figure 34 present CED results for the investigated cases split into primary energy sources. It should be noted that such a presentation of CED requires comprehensive and detailed data for each case, which lacks for some of the investigated cases in this study. Hence, Figure 31 to Figure 34 shows only the cases with sufficiently detailed data. At the end of this section, Figure 35 presents the range of performance across technologies with respect to CED. This report does not show CED split into the different life cycle stages (due to limited resources).

Figure 31 presents the standardised CED data split into energy sources for the relevant hydropower cases.

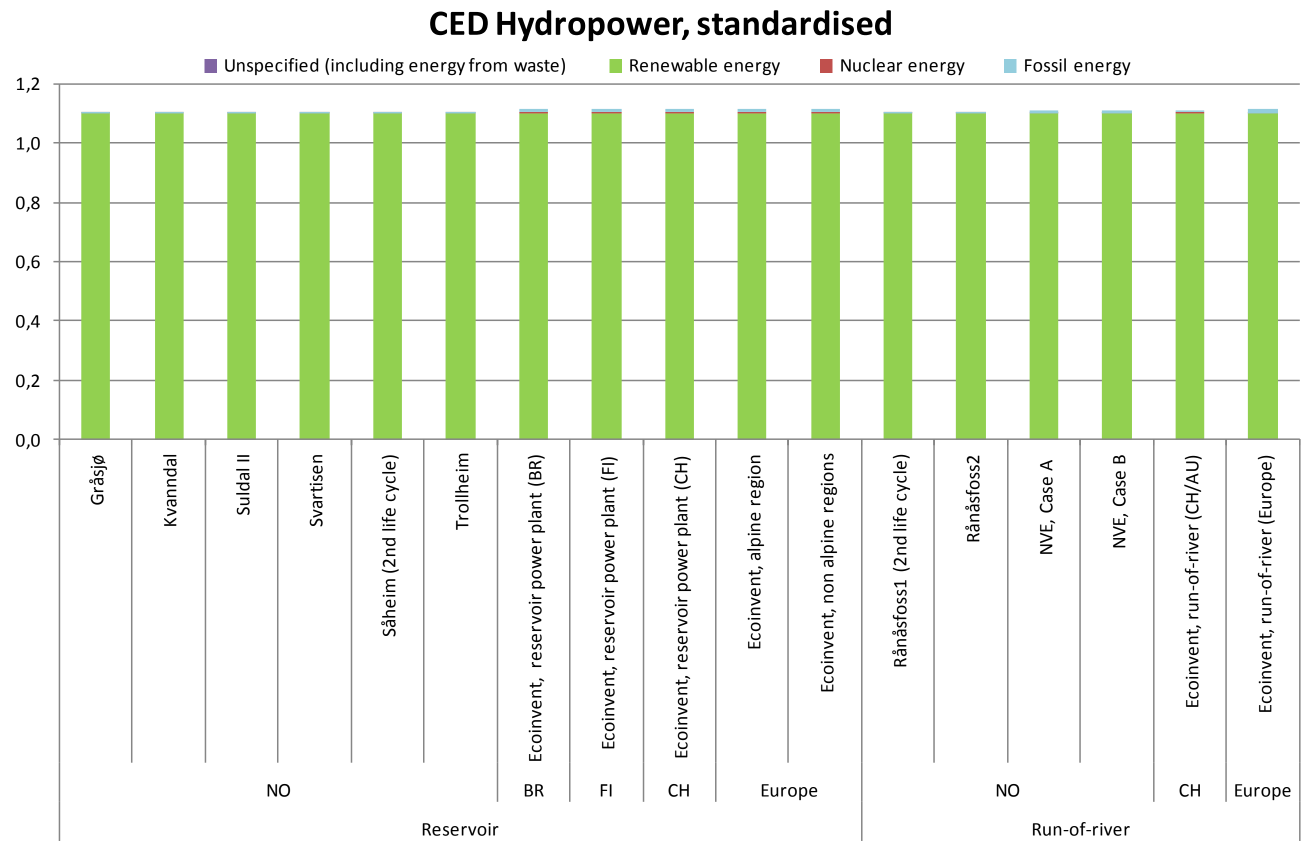

Figure 31: CED split into different energy sources – examples for hydropower (the sum of losses in waterways, turbines, generators and transformers is standardised to 0.1 kWh/kWh for all cases).

The figure shows that renewable energy is the dominant (>99%) primary energy source for producing electricity from hydro power. Some nuclear and fossil energy are used, but in small amounts (<1%), and hence not even visible in the figure.

Figure 32 shows the standardised CED data split into energy sources for the relevant wind power cases.

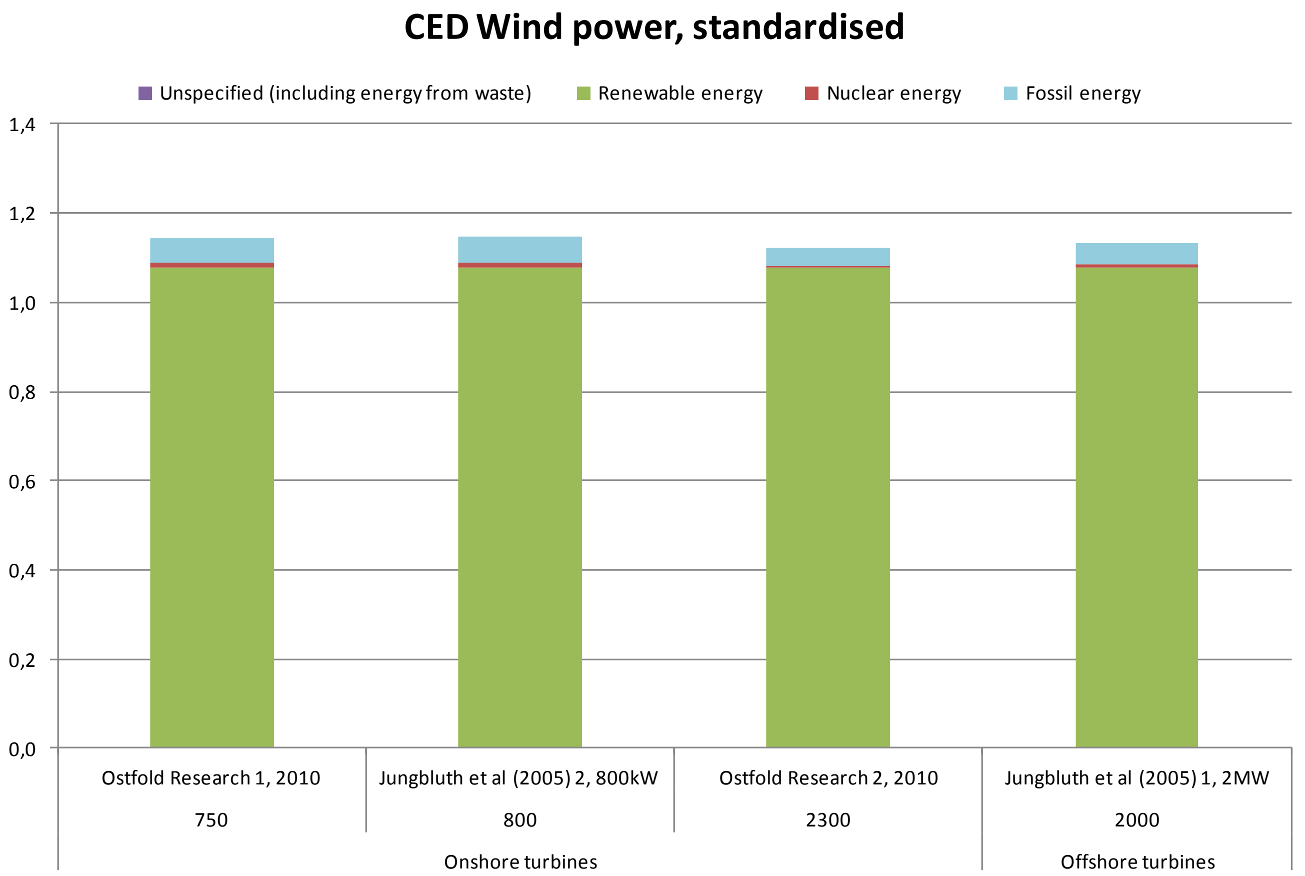

Figure 32: CED split into different energy sources – examples for wind power (the loss in turbine/generator is standardised to 0.075 kWh/kWh for all cases).

The figure shows that also for wind power, renewable energy is the dominant (>94%) primary energy source. Fossil energy contributes with 3-5% of the CED.

Figure 33 shows CED data split into energy sources for the relevant cases representing electricity from biomass.

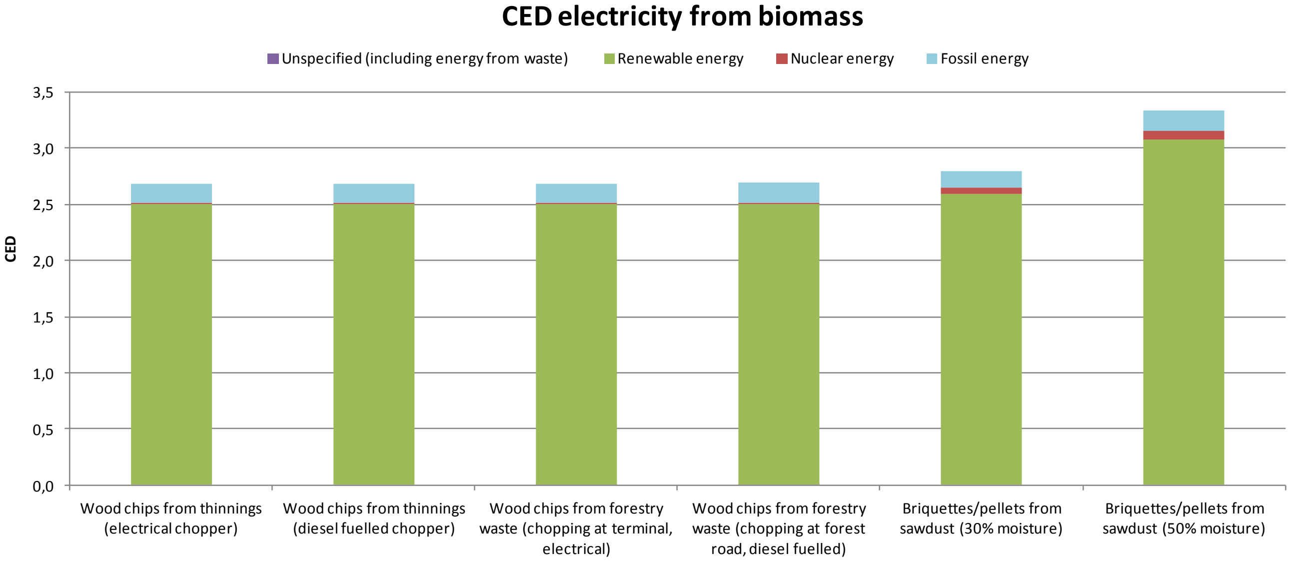

Figure 33: CED split into different energy sources – examples for electricity from biomass.

The figure shows that also the biomass cases are dominated by renewable energy (>92%) as the primary energy source for production of electricity. Fossil energy contributes with 5-6% of the CED and nuclear energy contributes with 2% or less.

Figure 34 shows CED data split into energy sources for the relevant cases representing electricity from fossil fuels.

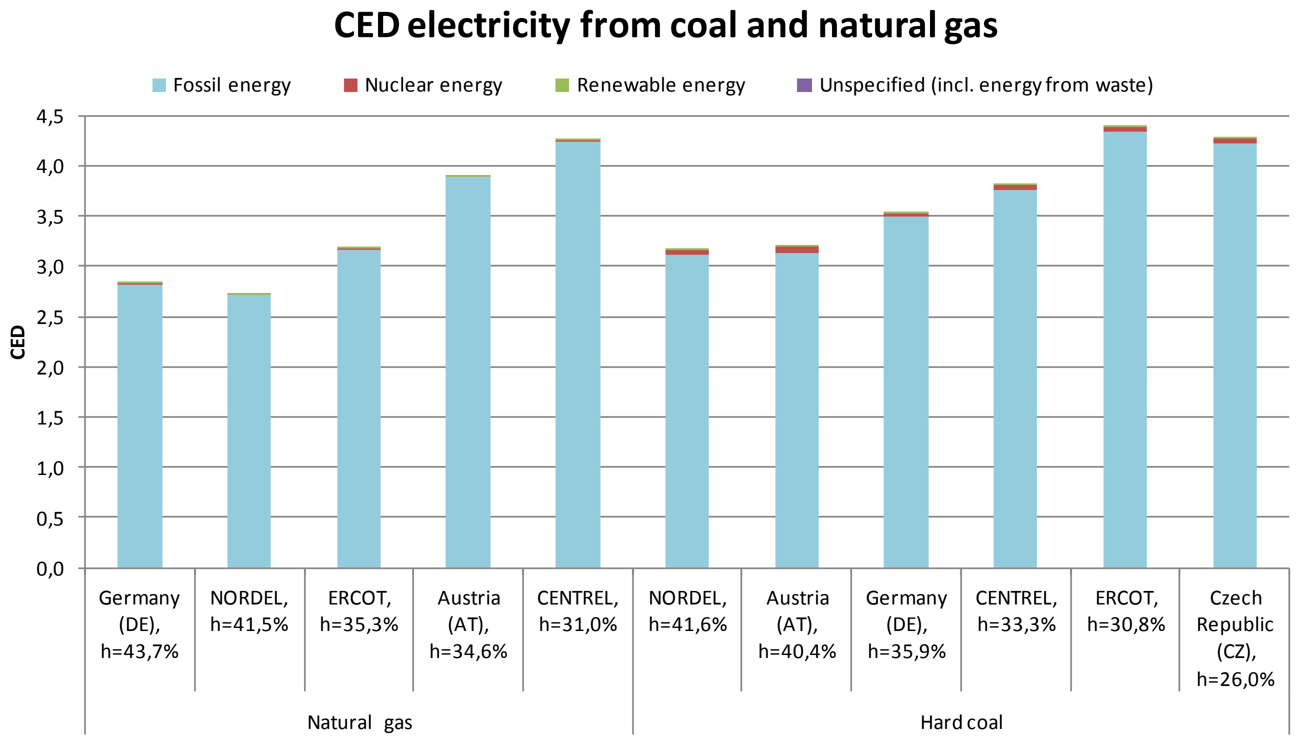

Figure 34: CED split into different energy sources – examples for electricity from fossil fuels. The results are sorted based on plant efficiencies (h), which are shown specifically for each case.

In contrast to the results for hydro power, wind power and electricity from biomass, fossil energy is the dominant (>98%) primary energy source for production of electricity from natural gas and coal. For these technologies nuclear energy contribute to <2% of the CED and renewable energy contribute with 0.3% or less.

Figure 35 shows an overall comparison of CED data representing the best and worst case for each electricity technology.

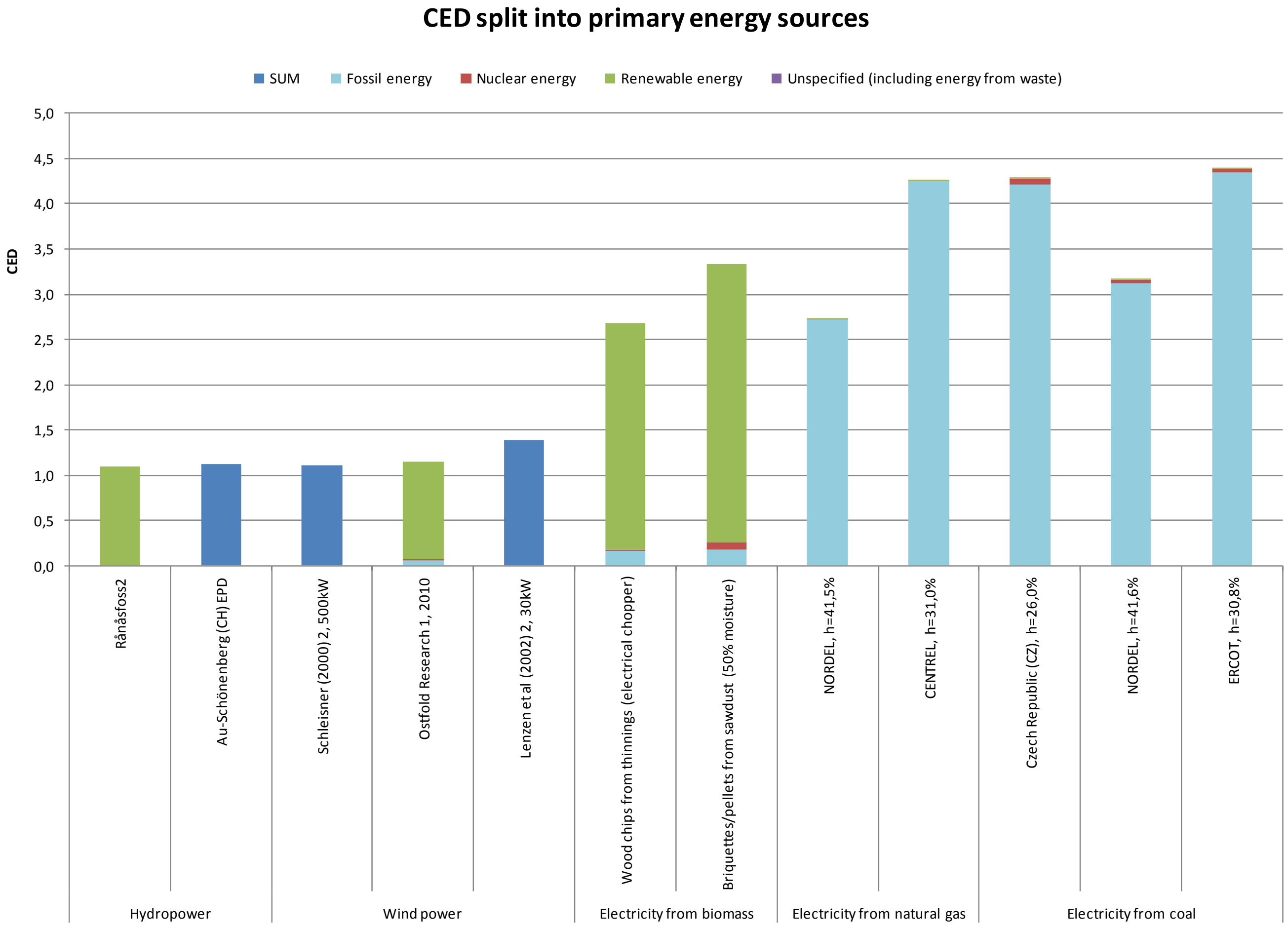

Figure 35: Comparison of CED data for different electricity technologies. CED is shown split into different energy sources.

The figure shows that there are large differences between the analysed technologies regarding two major points:

- The amount of primary energy needed to produce 1 kWh of electricity varies from 1.1 kWh (hydro power) to 4.4 kWh (electricity from coal). Thus, the worst case use an energy input of 400% compared to the best case.
- The sources of primary energy used for producing the electricity vary from >99% renewable (hydro power) to >98% fossil (electricity from natural gas and coal).

It should be noted that the technologies using most primary energy (having the highest CED values) use non-renewable resources for this production, while the least consuming technologies use renewables as primary energy sources.

5 Discussion

5.1 Time boundaries and data used - effect of 2nd life cycle

Some plants (mainly hydro power plants) can be investigated as 2nd life cycle power plants. This means that the life cycle has been "expired", thus the construction phase is excluded from the analysis and replaced by a major upgrading process and presented together with the other relevant life cycle stages (e.g. use and maintenance). Such 2nd life cycle plants get a low primary energy use for the development of infrastructure (as the majority of energy is invested in the 1st life cycle). Hence, the study shows that 2nd life cycle plants can achieve extremely high energy efficiency, measured as EPR. As the results from the 2nd life cycle hydropower plants have a different basis than all the other plants, independent of technology, these plants are not included in the comparison across technologies.

5.2 Comparing technologies

5.2.1 Effect of losses

When investigating literature data regarding hydro power and wind power, it is not always clear if, and how, the different losses through the power plant are included. The results for NER and CED for hydro and wind power show that the variations between the hydropower cases, when standardising the losses, decrease and are almost negligible. This means that the losses in waterways, turbines, generators and transformers are crucial for the ranking of hydropower cases when considering the whole life cycle of electricity generation. This also means that it is important to be aware of if, and how, the different losses through a hydropower plant are included in the analyses when comparing NER and CED, as these data affect the results for internal comparison.

It is also important to bear in mind that data representing losses through hydropower plants may include losses in waterways occurring downstream the turbine, which might be the case for some of the data included in this study. However, losses downstream the electricity generation unit should not be accounted for in LCA. Such potentials misunderstandings represent important issues and should be a target for further discussions and research.

When it comes to thermal power generation, which means considerably lower plant efficiencies compared to wind and hydropower, the relation between plant efficiency and NER/CED is of more importance. The ranking of thermal electricity generation technologies is, to a large extent, dependent on the plant efficiency as losses occurring at this conversion step increase the value of the denominator (for NER and nominator for CED).

5.2.2 Ranking

Hydropower achieves the best energy performance according to the indicators EPR, NER and CED. Wind power achieves the second best performance and the thermal power generation technologies based on biomass and fossil fuels give the lowest energy performance. This means that hydropower and wind power in general have better performance taking into account both the energy investments in infrastructure and processing/transport of ‘fuel’ (dams, tunnels etc.) and in the conversion steps from fuel to electricity (infrastructure related to the conversion plant, loss in turbines, maintenance, etc.) compared to thermal generation technologies. It should, however, be noted that the variations within the technologies can be large.

In general, this study give no indication whether hydropower from large installations is more energy efficient than hydropower from smaller installations, or whether hydropower plants with reservoir storage are more energy efficient than hydropower from run-of-river plants.

It should also be noted that the internal ranking between the specific cases is dependent on the indicator used, due to different system boundaries. NER and CED have the same system boundaries and will always give the same ranking, given that all primary energy sources are included in NER, and not only the fossil ones. The NER and CED ranking can, however, deviate from the EPR ranking.

5.2.3 Primary energy sources

There are large differences between the analysed technologies in the amount of primary energy and the types of primary energy sources needed to produce 1 kWh of electricity. It should be noted that the most primary energy consuming technologies (representing the highest CED values) use mostly non-renewable resources for this production, while the least consuming technologies use mostly renewables as primary energy sources.

5.3 Comparing indicators

The basis for the indicators is shown in Figure 36 where the use of energy throughout a value chain for an energy product is shown.

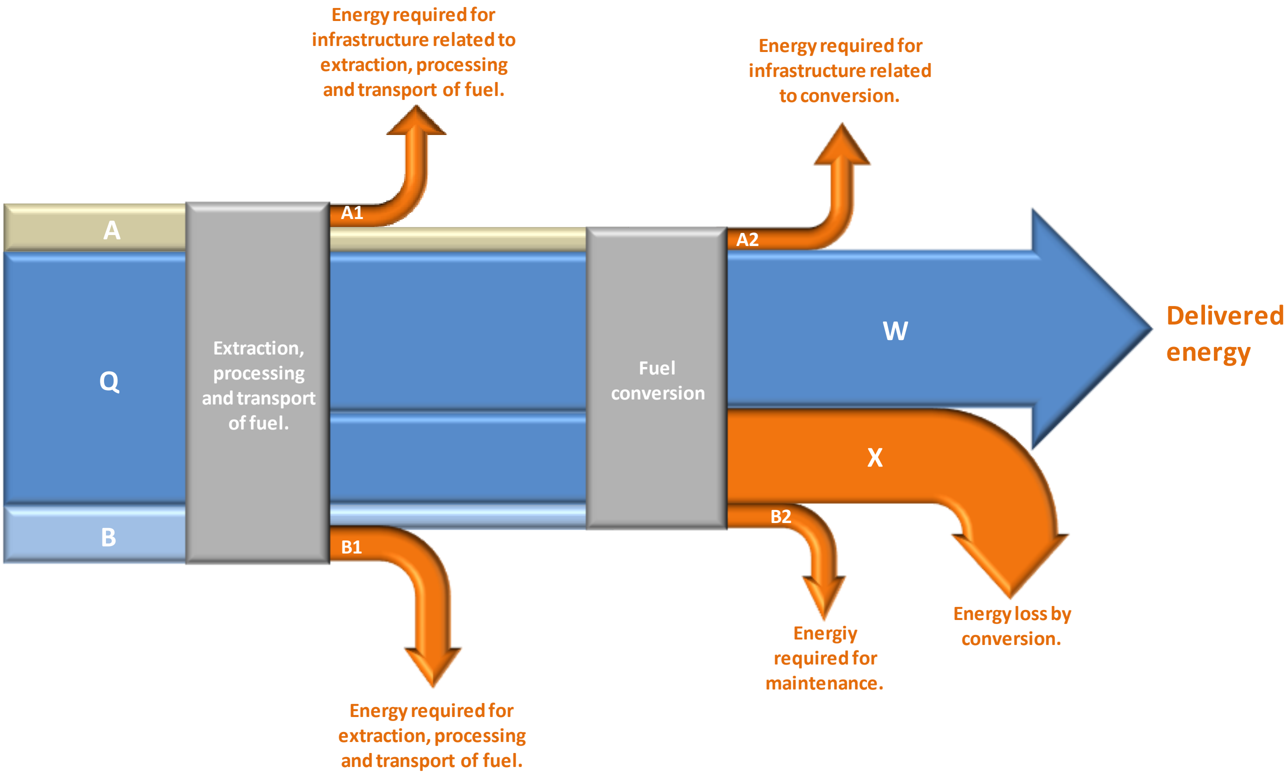

Figure 36: The value chain of an energy product.

5.3.1 Effect of losses

EPR is defined as W/(A+B), NER as W/(A+B+Q) and CED as (A+B+Q)/W. By definition EPR does not include primary energy lost by conversion while in NER and CED this is included. The aim of this work has been twofold; (1) to investigate the nature of different energy indicators, and (2) to compare technologies for production of electricity. To be able to compare the principle differences between the indicators, the hydro power and wind power cases have been standardised regarding losses throughout the power plant.

The conversion losses for the technologies using fossil fuels have not been standardised. The reason for this is that for thermal electricity generation, the ranking according to NER and CED to a large extent depend on the plant efficiency, as losses occurring at this conversion step represent the main losses throughout the life cycle of electricity generation. As the different fossil energy sources and technologies are represented by different plant efficiencies during the conversion stage, these differences play an important role for the value of NER and CED indicators. In order to investigate how the selection of indicator affected the ranking between the plants and technologies, the plant losses have not been standardised (see chapter 5.3.2).

The main reason for the relatively small variations within NER data compared to the large variations within EPR data is the different system boundaries regarding losses for the calculation of these two indicators. As EPR excludes the primary energy of the fuel itself as invested energy (includes only "supporting energy" as invested energy, EPR = W / (A+B)), small differences in supporting energy (compared to the total delivered energy amount, W) creates large differences in EPR. This occurs because the invested energy values (A+ B) represent relatively small values compared to the delivered energy amount (W). Thus, a small change in the denominator creates a large change in the EPR value. When the invested energy is added to the primary energy of the fuel itself (as is the case for NER = W / (A+B+ Q)), these variations in "supporting energy" (A+B) become much smaller in relation to the primary energy in the fuel itself (Q) and the delivered energy amount (W), and is thus of less importance for the calculated indicator NER. The same arguments apply for CED, since this indicator has the same system boundaries as NER, the only difference being that they are each other's inverse.

The system boundaries for calculating primary energy input for renewable sources represent a topic for further research. For hydropower, the total amount of primary energy related to the energy product (Q in figure 1) is defined as the potential energy given by the available volume of water multiplied with the altitude difference between the reservoir and the generation unit (net head). Water loss due to evaporation and overflow is not included, nor is loss in waterways downstream the turbine (The International EPDsystem, 2011). The same principle goes for wind power, where the wind energy "not being caught" by the turbines is not accounted for as a primary energy input (e.g. loss). However, whether the turbine losses should be included or not is not that clear. When it comes to solar power, the same discussion occurs regarding lost potential solar energy. More research is needed with regard to this.

5.3.2 The ranking is not necessarily the same for the different indicators

When calculating the NER and CED indicators, the actual plant efficiencies are taken into account, which means that the NER and CED results show the energy efficiency throughout the total value chain. This is in contrast to the EPR indicator, which ranks technologies based on "supporting energy" throughout the value chain. This fundamental difference in system boundaries can lead to the result that a number-one thermal plant according to EPR could be ranked as average, or even the worst case according to NER and CED, and vice versa.

However, EPR is a suitable indicator when the goal is to compare the use of "supporting energy" only. This is especially interesting when comparing electricity from renewable sources (excluding thermal technologies). The main reasons for this are that the conversion losses for these technologies are marginal compared to thermal technologies and that the lost energy (through the conversion step) represents renewables "being available" (e.g. solar and wind), thus not harvested and transported. An exception from this may be water which has been stored in hydropower reservoirs in order to be transported through pipes/tunnels for electricity generation.

5.3.3 How to be able to show the amounts of different primary energy sources within one indicator

When using CED as indicator it is possible to split the indicator into the different energy sources contributing to the CED (it is also possible to split CED into life cycle phases). A detailed CED figure makes it possible not only to see the total amount of primary energy needed to produce 1 kWh of electricity for different technologies, but also to see which sources of primary energy is used. Two technologies could, in principle, have the same CED value, and still be quite different regarding the amounts of renewables and fossil fuels used. Hence, when using CED it is possible to focus on certain energy sources without losing the bigger picture.

The nature of EPR/NER is quite different compared to CED, using the output as nominator and the input as denominator, thus making it mathematical impossible to split the contributions from the invested energy into e.g. energy sources, life cycle stages etc.

5.3.4 Comparing indicators – a summary

In Table 2 the three analysed energy indicators are listed, together with their mathematical definitions, pros and cons. The symbols used in the mathematical are defined in Figure 36.

Table 2: Overview of the mathematical definitions, pros and cons of the three energy indicators analysed. The symbols used in the mathematical expressions are defined in Figure 36.

Energy indicator	Mathematical definition	Pros	Cons
EPR Energy Payback Ratio	W/(A+B)	• Shows how much electricity is generated in relation to the energy investment in infrastructure and extraction/transport processes of the fuel used. • In line with economical terminology	• Does not tell anything about the energy loss by conversion of the fuel to electricity, or the use of fuel as such. • It is not possible to show the contributions from different primary energy sources separately, nor for the different life cycle steps.
NER Net Energy Ratio	W/(A+B+Q)	• Shows how much electricity is generated in relation to the energy investment in infrastructure, extraction/transport processes and conversion from fuel to electricity (life cycle approach). • In line with economical terminology	• It is not possible to show the contributions from different primary energy sources separately, nor for the different life cycle steps. • Some studies include only fossil energy as invested energy.

CED Cumulative Energy Demand	(A+B+Q)/W	• Shows the total invested energy (in infrastructure, extraction/transport processes and conversion from fuel to electricity) in relation to the electricity generated (life cycle approach). • It is possible to show the contributions from different primary energy sources separately, as well for the different life cycle steps. • The use of fuel as such (Q) and the energy investment in infrastructure and extraction/transport processes (A and B) is always included, regardless of the origin of the primary energy source.	• Is not on the same form as economical indicators (inverse).

6 Conclusions

Comparing technologies

- Hydropower clearly achieves the best energy performance according to the indicators EPR, NER and CED. Wind power achieves the second best performance while thermal power generation technologies based on biomass and fossil fuels give the lowest energy performance.
- There are large variations between the analysed technologies regarding the amount of primary energy needed to produce 1 kWh electricity.
- The sources of primary energy used for producing electricity vary between the technologies. Electricity from hydropower, in particular, has a very high share of renewable energy as the primary source, while also wind power and bio-energy have high shares of renewables. The main energy sources required for producing electricity from coal and natural gas are fossil based.
- The study shows that 2^{nd} life cycle hydropower plants (which means upgrading and extension of old, existing plants) can have extremely high energy efficiency, measured by EPR.
- For hydropower the losses in waterways, turbines, generators and transformers are crucial for the ranking of cases when the whole life cycle is considered.
- In general, this study gives no indication whether “large” hydropower installations are more energy efficient than smaller installations, or whether reservoir hydropower plants are more energy efficient than run-of-river plants.

Comparing indicators

- The main reason for the relatively small variations within NER and CED data compared to the large variations within EPR data is the different system boundaries, and the most important factor is the exclusion of the conversion loss in the EPR calculations in contrast to NER and CED.
- The NER and CED indicators show the energy efficiency throughout the total value chain. The EPR indicator ranks technologies based on “supporting energy”, thus excluding the electricity conversion loss. This fundamental difference in system boundaries can lead to the result that a number-one thermal plant according to EPR could be ranked as average, or even the worst case, according to NER and CED, and vice versa.
- However, EPR is a suitable indicator when the goal is to compare the use of supporting energy. This is especially interesting when electricity from renewable sources is compared.
- The internal ranking between the specific cases of one technology is also dependent on the indicator used.
- When using CED as indicator it is possible to split the results into the different energy sources and life cycle stages contributing to the CED. Hence, CED can give added information compared to EPR and NER.
- EPR and NER is defined as energy output divided by energy input. This makes these indicators in line with economical terminology. CED is the inverse of NER (energy input divided by energy output).
- The system boundaries for calculating primary energy input for renewable sources needs further investigation and research.

Table 3 summarises the different properties of each indicator.

Table 3: Summary of the different properties of the investigated indicators.

Indicator	Life cycle approach	Includes all primary energy sources	Can be split into primary energy sources and life cycle stages	In line with economical terminology
EPR		X		X
NER	X	(X)		X
CED	X	X	X	

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