Application of the CCQI methodology for assessing the quality of carbon credits

This document presents results from the application of version 3.0 of a methodology, developed by Oeko-Institut, World Wildlife Fund (WWF-US) and Environmental Defense Fund (EDF), for assessing the quality of carbon credits. The methodology is applied by Oeko-Institut with support by Carbon Limits, Greenhouse Gas Management Institute (GHGMI), INFRAS, Stockholm Environment Institute, and individual carbon market experts. This document evaluates one specific criterion or sub-criterion with respect to a specific carbon crediting program, project type, quantification methodology and/or host country, as specified in the below table. Please note that the CCQI website Site terms and Privacy Policy apply with respect to any use of the information provided in this document. Further information on the project and the methodology can be found here: www.carboncreditquality.org

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Sub-criterion:	**1.3.2 Robustness of the quantification methodologies applied to determine emission reductions or removals**
Project types:	**Solar photovoltaic power** **Wind power (onshore)** **Hydropower (dams and run-of-river)**
Quantification methodology:	**Clean Development Mechanism (CDM) ACM0002, Version 20.0, and relevant tools**
Assessment based on carbon crediting program documents valid as of:	**15 May 2022**
Date of final assessment:	**12 September 2023**
Score:	**2**

Assessment

Relevant scoring methodology provisions

"The methodology assesses the robustness of the quantification methodologies applied by the carbon crediting program to determine emission reductions or removals. The assessment of the quantification methodologies considers the degree of conservativeness in the light of the uncertainty of the emission reductions or removals. The assessment is based on the likelihood that the emission reductions or removals are under-estimated, estimated accurately, or over-estimated, as follows (see further details in the methodology):"

Assessment outcome	Score
It is very likely (i.e., a probability of more than 90%) that the emission reductions or removals are underestimated, taking into account the uncertainty in quantifying the emission reductions or removals	5
It is likely (i.e., a probability of more than 66%) that the emission reductions or removals are underestimated, taking into account the uncertainty in quantifying the emission reductions or removals OR The emission reductions or removals are likely to be estimated accurately (i.e., there is about the same probability that they are underestimated or overestimated) and uncertainty in the estimates of the emission reductions or removals is low (i.e., up to ±10%)	4
The emission reductions or removals are likely to be estimated accurately (i.e., there is about the same probability that they are underestimated or overestimated) but there is medium to high uncertainty (i.e., ±10-50%) in the estimates of the emission reductions or removals OR It is likely (i.e., a probability of more than 66%) or very likely (i.e., a probability of more than 90%) that the emission reductions or removals are overestimated, taking into account the uncertainty in quantifying the emission reductions or removals, but the degree of overestimation is likely to be low (i.e., up to ±10%)	3
The emission reductions or removals are likely to be estimated accurately (i.e., there is about the same probability that they are underestimated or overestimated) but there is very high uncertainty (i.e., larger than ±50%) in the estimates of the emission reductions or removals OR It is likely (i.e., a probability of more than 66%) or very likely (i.e., a probability of more than 90%) that the emission reductions or removals are overestimated, taking into account the uncertainty in quantifying the emission reductions or removals, and the degree of overestimation is likely to be medium (±10-30%)	2
It is likely (i.e., a probability of more than 66%) or very likely (i.e., a probability of more than 90%) that the emission reductions or removals are overestimated, taking into account the uncertainty in quantifying the emission reductions or removals, and the degree of overestimation is likely to be large (i.e., larger than ±30%)	1

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Assessment outcome

The quantification methodology in combination with version 3 of TOOL03, version 3.0 of TOOL05 version 7.0 of TOOL07 and version 3.0 of TOOL09, is assigned a score of 2.

Justification of assessment

Project type

This assessment refers to the following four project types:

- **Solar photovoltaic power:** Installation of a new solar photovoltaic power plant. The electricity is fed into a national or regional electricity grid, replacing more greenhouse gas intensive electricity generation.
- **Wind power (onshore):** Installation of a new onshore wind power plant. The electricity is fed into a national or regional electricity grid, replacing more greenhouse gas intensive electricity generation.
- **Hydropower (dams):** Installation of a new hydro power plant by building a new dam or the installation of additional power generation capacity at an existing reservoir. The electricity is fed into a national or regional electricity grid. This project type does not include pumped-storage hydropower. The project type reduces emissions by displacing more greenhouse gas intensive electricity generation.
- **Hydropower (run-of-river):** Installation of a new hydro power plant with no or minimal storage. The plant harvests energy from flowing water, such as rivers or streams. The electricity is fed into a national or regional electricity grid. The project type reduces emissions by displacing more greenhouse gas intensive electricity generation.

Applicability conditions

The methodology is applicable to grid-connected renewable energy power generation project activities, including projects using the following technologies: hydro power plant/unit with or without reservoir, wind power plant/unit, geothermal power plant/unit, solar power plant/unit[1], wave power plant/unit or tidal power plant/unit. The methodology is thus applicable to the four project types described above.

Selection of emission sources for calculating emission reductions or removals

The methodology specifies that the following emission source shall be considered:

- For wind, solar PV and all hydropower projects: CO_2 emissions from electricity generation in fossil fuel fired power plants that are displaced due to the project activity
- For hydropower (dams): CH_4 emissions from the reservoir

Furthermore, the emission sources for calculating emission reductions for the assessed project types are also specified in "TOOL07: Tool to calculate the emission factor for an electricity system" and include:

- All existing power plants/units that are physically connected through transmission and distribution lines to the project activity (the project electricity system).
- All existing power plants/units that are physically connected to any connected electricity system. A "connected electricity system" is an electricity system that is connected by transmission lines to the project electricity system, but where transmission constraints exist between the two systems.
- Off-grid power plants in the project electricity system (optional).

The above sources are considered to be a more detailed list/subsets of the emission sources specified in the methodology.

No leakage emissions are considered in the methodology[2]. The emissions potentially arising due to activities such as power plant construction and upstream emissions from fossil fuel use (e.g., extraction, processing, transport etc.) are neglected.

Determination of baseline emissions

The baseline scenario in the case of a greenfield wind, solar PV or hydropower plant is that electricity delivered to the grid by the project activity would have otherwise been generated by the operation of existing grid-connected power plants and by the addition of new generation sources, as reflected in the combined margin (CM) calculations described in "TOOL07: Tool to calculate the emission factor for an electricity system". Baseline emissions are therefore calculated by multiplying the net electricity generation that is generated and fed into the grid because of the implementation of the CDM project activity (in MWh/yr) by the combined margin CO_2 emission factor for grid connected power generation (in t CO_2/MWh) calculated using the latest version of "TOOL07". This generic approach is generally appropriate. Key assumptions in the calculation of baseline emissions are discussed below.

[1] Both solar photovoltaic (PV) and solar thermal

[2] The term "leakage" is also used in this methodology to describe project emissions from the operation of binary geothermal power plants (physical leakage of working fluid contained in heat exchangers), which is not relevant in this assessment.

Quantity of net electricity generation that is produced and fed into the grid

The methodology specifies that electricity meters are used to quantify the net electricity generation that is produced and fed into the grid because of the implementation of the CDM project activity. Meters used for this purpose are usually fiscal meters with a low level of uncertainty, and usually two sets of meters (one owned by the project developer, one by the purchasing grid) are available. Estimation of this parameter is therefore not considered to lead to any significant over- or underestimation of emission reductions or to introduce significant levels of uncertainty.

Combined margin emission factor

With respect to the combined margin emission factor, as calculated by using "TOOL07: Tool to calculate the emission factor for an electricity system". The tool determines the emission factor as a combination of the "build margin (BM)" and the "operating margin (OM)". The build margin aims to reflect that the construction of new renewable power plants may lead to fewer other power plants being constructed. The BM emission factor intends to reflect which mix of power plants would not be constructed due to the registered CDM project. The operating margin aims to reflect that a new renewable power plant may displace electricity generation in existing power plants, in particular those plants that operate at the margin of the dispatch order. The tool uses different weightings for the BM and OM emission factors are used to arrive at a "combined margin (CM)" emission factors.

The following issues are identified to potentially lead to over- or underestimation of emission reductions or to introduce uncertainty:

OE1: Exclusion of registered CDM projects in the calculation of the BM

The tool requires that power plants registered as CDM project activities be excluded when determining the sample group for calculation of the build margin (BM). CDM projects are only included in the BM calculation if other power plants make up a small proportion of electricity generation. By excluding renewable energy projects registered under the CDM, the cohort of power plants used in the BM calculation will probably be biased towards fossil fuel fired power plants. An example of this would be Zambia, where the 120 MW capacity Itezhi-Tezhi power station, which is the only grid connected CDM project in the country, would have to be excluded in the BM calculation. The resulting BM would therefore be biased towards recently built coal fired power plants. In conclusion, the exclusion of CDM plants may lead to an overestimation of emission reductions where the project electricity system relies on CDM projects for a significant proportion of most recently installed generation capacity. This may, however, only apply to a small fraction of projects (Source 21). Moreover, CDM projects are included in the sample group if there are too few non-CDM plants that were constructed in the past 10 years. For these reasons, the risk of over-estimation is relatively small.

U1 / OE2: Weighting of OM and BM in determining the CM

The tool specifies the following default values for weighting of the operating margin (OM) and BM (w_{OM} and w_{BM}):

- Wind and solar power generation project activities: w_{OM} = 0.75 and w_{BM} = 0.25 (owing to their intermittent and non-dispatchable nature) for the first crediting period and for subsequent crediting periods;

- All other projects: w_{OM} = 0.5 and w_{BM} = 0.5 for the first crediting period, and w_{OM} = 0.25 and w_{BM} = 0.75 for the second and third crediting period, unless otherwise specified in the approved methodology which refers to this tool.

The above default values aim to specifically reflect the intermittent and non-dispatchable nature of wind and solar power generation project activities, and that this will result in these projects primarily replacing existing power generation plants. This is a simplified approach to addressing this issue. The tool also invites project developers to propose alternative values for approval by the CDM Executive Board. We are not aware of cases where such alternative values have been approved. Furthermore, the tool allows to calculate a simplified CM. This approach has not been frequently applied though and is not evaluated here.

Ideally, the weighting of the BM should reflect what is termed the capacity value (also called capacity credit) of the specific generation technology. Capacity value gives an indication of the probability that a particular type of generation will reliably contribute to meeting demand, which generally means that it will be available to generate electricity during the peak hours (Source 2). This is an important metric in the planning of future electricity systems, and thus also determines the extent to which the installation of wind or solar power plants only displaces power generation in existing plants (reflected by the OM) or reduces the need to build or maintain other (back-up) power capacity (the BM). In addition to the capacity value, other factors such as the grid stability may play a certain role.

The extent to what new solar and wind power plants need for back-up capacity to address peak demand in times of low solar or wind power supply depends on the location of the project activity. In addition, the capacity factor/intermittency of solar projects may differ significantly to that of wind projects. The capacity value of wind power projects is considered to range from 5 to 40 % whereas that of solar PV is considered to range from <25 to 75% (Sources 2, 11 and 24). This would suggest that a weighting of 0.25 for the w_{BM} might be more or less adequate for wind power as it represents a value reasonably within the range of given capacity values; however, this is associated with considerable uncertainty, given that the actual factor in an electricity grid could be lower or higher (U1). For solar PV, the weighting of 0.25 for the w_{BM} is at the lower end of the indicated range for capacity values. If the weighting should reflect the typical capacity value, then a higher figure would be more appropriate. Given that the BM is lower than the OM in the majority of electricity systems (Source 12), the weighting of 0.25 for the BM is likely to lead to an overestimation of emission reductions (OE2). Noting the values indicated for the BM and OM for different electricity systems in Source 12 and assuming that 0.5 represents a value reasonably within the range of given capacity values, the grid emission factor would be overestimated in the range of 10-15% on average, although it could be overestimated more significantly in some countries, as well as underestimated in a limited number of countries.

For hydropower, the capacity value is typically above 90% (Source 2). The weighing of the w_{BM} is significantly lower: 0.5 in the first crediting period and 0.75 in the second crediting period. Given that the BM is lower than the OM in the majority of electricity systems (Source 12), this weighing is likely to lead to an overestimation of emission reductions (OE2). The degree of overestimation is likely to be more significant than for solar PV, as the discrepancy between the likely capacity value of hydro power and the value used for w_{BM} is even larger for hydro power.

Noting the values indicated for the BM and OM for different electricity systems in Source 12 and assuming that 0.95 represents a reasonable value for the capacity value of hydropower, the grid emission factor would be overestimated in the order of about 30% on average for the first crediting period and about 10-15% in second and third crediting periods on average, although it could be overestimated more significantly in some countries, as well as underestimated in a limited number of countries.

UE1: Inclusion of plants with a relatively low capacity value in the calculation of the BM

The tool includes all type of recently built plants in the calculation of the BM. This includes plants with a relatively low capacity value, such as solar and wind power plants. In practice, these plants can only partially substitute other capacity in the grid. In this regard, their capacity contribution is overweighted in the calculation of the BM. As solar and wind power plants have much lower emissions than fossil fuel power plants, this leads to an underestimation of emission reductions. The degree of underestimation is difficult to estimate, as this strongly depends on the share of solar and wind power plants in recent capacity additions and the capacity value of these technologies in the respective electricity grid.

OE3: Use of historical data to determine the grid emission factor

The tool allows project participants to either fix the grid emission factor (GEF) at the start of the crediting period or to update the GEF annually. Fixing the GEF at the start of the crediting period means that the GEF is highly backward looking. Whether this leads to over- or underestimation of emission reductions depends on the energy strategy and trends of the country. Given that most country's energy policies are aimed at increasing the share of renewables and reducing a country's grid emission factor, a backward looking GEF is **likely to lead to an overestimation of emission reductions**.

This issue also arises if the GEF is updated on an annual basis (i.e., due to the need to collect BM data from the previous X years), though to a lesser extent than if the GEF is fixed for the crediting period. Most projects use the option of fixing the GEF for the crediting period. The degree of overestimation depends on how strongly the GEF of the grid decreases over time.

Moreover, the tool does not include any provisions to consider the country's NDC and relevant climate or energy policies. If a country's NDC has a renewable electricity generation target, for example, this will not be reflected in the BM which is calculated based on historical data. In this case, the "real" BM and therefore the combined margin may be lower than what it would be estimated to be based on historical data. This would therefore also lead to an overestimation of emission reductions.

U2: Treatment of electricity transfers

Electricity transfers from a connected electricity systems (CES) to the project electricity system (PES) are defined as electricity imports while electricity transfers from the project electricity system to connected electricity systems are defined as electricity exports. For electricity imports, one of the following options to determine the CO_2 emission factor(s):

(a) 0 t CO_2/MWh; or

(b) The simple operating margin emission rate of the exporting grid, determined as described in Step 4 section 6.4.1, if the conditions for this method, as described in Step 3 below, apply to the exporting grid; or

(c) The simple adjusted operating margin emission rate of the exporting grid, determined as described in Step 4 section 6.4.2 below; or

(d) The weighted average operating margin (OM) emission rate of the exporting grid, determined as described in Step 4 section 6.4.4 below.

Choosing option (a) above leads to underestimation of emission reductions and is therefore considered conservative. Only using the OM as the emission factor for the exporting grid (options (b) to (d)), and no BM component, could instead lead to overestimation of emission reductions, because (1) the implementation of the project could also impact the construction of power plants in a connected electricity and (2) the BM emission factor is typically lower than the OM emission factor. The impact of this issue will depend on the volume of imports of electricity from the CES, which in the majority of cases are not expected to be large. Moreover, the overall effect will depend on how frequently option (a) is chosen and how frequently options (b) to (d) are chosen. Overall, this issue is therefore assessed to contribute to uncertainty, though the overall effect may be limited due to the relatively small size of imports and exports of electricity globally.

Electricity exports from the project electricity system (electricity transfers from the project electricity system to connected electricity systems) are not subtracted from electricity generation data used for calculating and monitoring the electricity emission factors. This is not considered to lead to either over- or underestimation of emission reductions.

OE4: Consideration of off-grid power plants

Project participants may choose to (i) only include grid power plants to calculate the operating margin and build margin emission factor, or (ii) to include both grid power plants and off-grid power plants in the calculation. Option (ii) can only be used when the total capacity or the total electricity generation by off-grid sources amounts to at least 10% in each case. The rationale for choosing (ii) is to reflect that in some countries off-grid power generation is linked to an unreliable and unstable electricity grid (e.g., back-up diesel generation), and that these off-grid sources can partially be displaced by grid-connected CDM project activities, where these project activities improve the reliability of the grid and therefore lead to a reduction in the use of off-grid sources. Given that off-grid power generation is usually supplied by diesel generators, using this option will usually lead to an increase in the calculated grid emission factor. This could lead to **an overestimation of emission reductions** if the project activity does not in fact lead to an improvement in the reliability of the grid and therefore a reduction in the use of off-grid sources. The significance of this issue will depend on a number of factors, including the total installed capacity of off-grid power plants and the extent to which solar and wind power actually improves the reliability of the grid (i.e., for how many hours of the year black-outs are actually reduced). Given limited capacity value of solar and wind power, as identified above, it may not be reasonable to assume that off-grid power plants are displaced to the same extent as grid-connected power plants.

A report from the International Finance Corporation published in 2019 estimates the global back-up generator fleet at 450 gigawatts, with about 25 percent in sub-Saharan Africa (Source 13). In Africa the regional back-up generator fleet is about twice the installed grid capacity excluding South Africa. Countries outside Africa where use of backup generators is high (based on fuel consumption) include India, Pakistan and Iran. This report would therefore indicate that the fraction of projects affected by this element could be significant, at least in Africa and parts of South Asia.

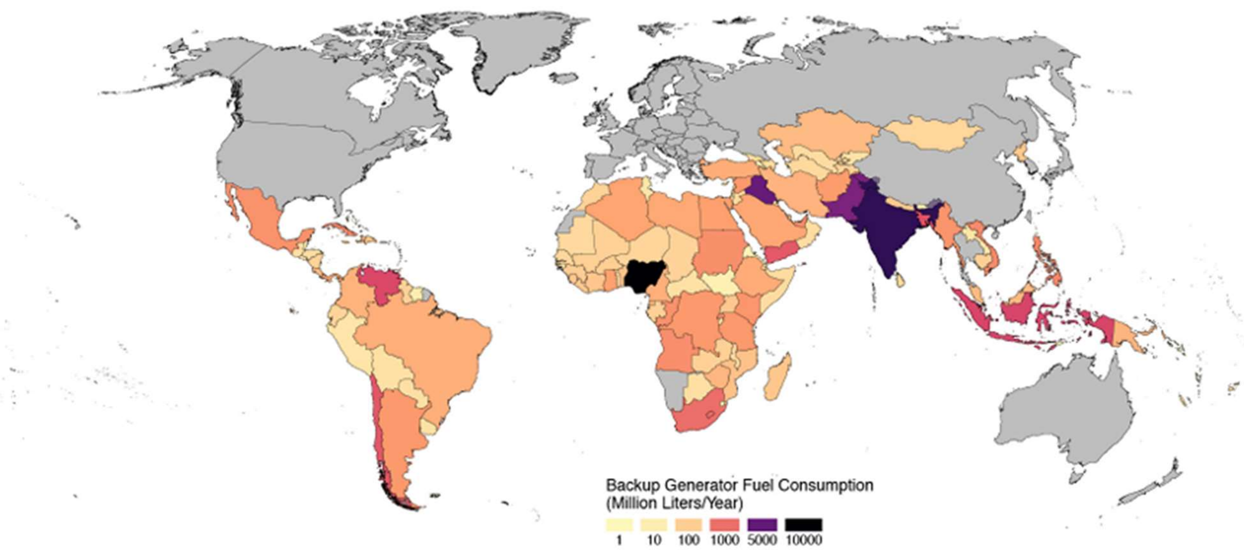


Figure 1: Total diesel and gasoline consumed in 2016 across all modelled countries (Source: IFC)

The average degree of overestimation could also be significant as the EF for diesel generation could be double of the GEF. Although it would be reasonable to assume that providing some additional power supply could reduce the number of power cuts, the impact of this issue is still considered potentially significant.

OE5: Determination of the OM emission factor

The calculation of the operating margin (OM) emission factor is based on one of the following four methods: (a) Simple OM, (b) Simple adjusted OM, (c) Dispatch data analysis OM, or (d) Average OM. The choice of method is up to the project participants, though the applicability of some methods depends on data availability and the share of and production from low-cost/must-run resources. The method with highest accuracy is method (c) – the dispatch data analysis OM. All other methods are expected to have a lower accuracy than dispatch data analysis OM (Source 20).

Methods (b) and (d) may potentially lead to an **underestimation of emission reductions**. This is because in most electricity grids fossil fuels will be at the margin at most times, but these methods consider a significant share of renewable sources in determining the OM. An increasing share of wind or solar PV in the system may indeed lead to a situation in which renewable power generation is at the margin in some hours. In many instances, however, the power plants at the margin during these times are hydropower dams or storage systems which have the ability to store energy and dispatch electricity based on the demand in the grid. In this case, the total renewable power generation from the grid would hardly be affected, as the non-dispatch hydro power electricity generation due to a high supply from wind or solar PV systems could be dispatched at a later point in time, when fossil fuels are at the margin of the grid. Only in few electricity systems and during a limited set of hours, other non-dispatchable renewable power generation plants are shut down due to oversupply in the grid. During these hours, it is reasonable to assume that any wind or solar PV generation would not displace any fossil fuels emissions.

Method (a) allows to exclude low-cost/must-run power plants from the calculation of the OM. However, 'low-cost' power plants are not clearly defined. The methodology identifies that low-cost/must-run plants include “hydro, geothermal, wind, low-cost biomass, nuclear and solar generation”. The methodology further specifies that “if a fossil fuel plant is dispatched independently of the daily or seasonal load of the grid and if this can be demonstrated based on the publicly available data, it should be considered as a low-cost/must-run”. It is indeed important to consider fossil fuel power plants that run steadily as low-cost/must-run plants, given that in many countries coal power plants are operated as base load power plants. The methodology, however, specifies that such plants should only be included as low-cost/must-run if “this can be demonstrated based on publicly available data”. This opens the door for project developers to not include such plants, as the detailed data may not always be publicly available. Not including such plants could lead to an overestimation of emission reductions, as it would include plants with a particularly high emission factor (coal power plants) in the simple OM, while in reality their operation may not be affected by solar or wind power generation. In addition, the methodology identifies low-cost biomass as a plant type that should be considered as low-cost/must-run; in practice, however, some of these plants may be dispatchable and do not operate in the base load. Overall, the provision of excluding low-cost/must-run power plants may thus lead to an overestimation of baseline emissions and therefore **an overestimation of emission reductions**.

It should be noted that method (a) is by far the most adopted method, being used many more times than all other methods combined (Source 12). Overall, we therefore assess that the OM emission factor is more likely to be overestimated than underestimated, through the degree of overestimation is uncertain.

UE2: Use of default values

The tool allows using several default values for parameters such as the electric efficiency of power plants, and refers to Table 2, Appendix of “TOOL09: Determining the baseline efficiency of thermal or electric energy generation systems". The values provided can be considered to be conservative, i.e., they assume rather high electric efficiencies. Where these default values are used, this may lead to an underestimation of baseline emissions and therefore an **underestimation of emission reductions**.

Determination of project emissions

The methodology specifies that for most renewable energy power generation project activities, project emissions are equal to zero, but that some project activities may involve project emissions that can be significant. In these instances, the methodology requires estimating project emissions from three possible sources:

- Project emissions from fossil fuel consumption in year *y* (specifically for geothermal and solar thermal projects)
- Project emissions from the operation of dry, flash steam or binary geothermal power plants in year *y*
- Project emissions from water reservoirs of hydro power plants in year *y*

Given that wind power and solar PV projects do not cause any major on-site emissions during their operation, not considering any project emissions is appropriate. For hydropower the methodology requires accounting for project emissions from reservoirs as discussed below. This only applies to hydropower plants with dams.

U3 / OE6: Emissions from water reservoirs of hydropower plants (dam)

Reservoirs created by dams are a source of greenhouse gas emissions. Building reservoirs often involves the flooding of large stocks of terrestrial organic matter. This matter decomposes below the water surface, a process which can result in methane (CH_4), carbonon dioxide (CO_2) and Nitric oxide (N_2O) emissions.

The methodology prescribes a two-step approach to account for emissions from reservoirs:

1) Project developers must determine the power density of the hydroelectric plant. It is measured in Watt per square meter (W/m^2) and an expression of the amount of reservoir surface area required to generate a unit of energy. Higher power densities mean that less surface area is required to generate a unit of energy. They are achieved by, inter alia, bigger drop heights between reservoir and power station.

2) Depending on the power density, project developers must follow one of the following options:

    a. Hydroelectric power plants that have a power density of less than $4W/m^2$ are not eligible under the methodology

    b. For hydroelectric power plants that have a power density between 4 and 10 W/m^2, project developers must calculate reservoir emissions applying a default emission factor of 90 $kgCO_2e/MWh$

    c. For hydroelectric power plants that have a power density of more than $10W/m^2$, project developers can neglect emissions from reservoirs

The assumptions behind this approach are that for plants with a power density of less than 4 W/m^2 there is a high risk that reservoir emissions exceed emission reductions from displacing other forms of power generation. For plants with power densities above 10 W/m^2, emission reductions from displacing fossil fuels are assumed to significantly exceed reservoir emissions.

The assessment of the robustness of the approach focusses on the following two elements:

1) The robustness of the default factor for calculating reservoir emissions for plants with a power density between 4 and 10 W/m^2

2) The robustness of the power density threshold of $10W/m^2$ to filter out reservoirs with negligible GHG emissions

Each of the two elements are discussed in the following.

<u>Robustness of the default emission factor for emissions from reservoirs</u>

The current default factor of 90 $kgCO_2e/MWh$ for emissions from reservoirs was adopted by the CDM Executive Board in 2006 (Source 28) and has not been updated since. It was derived from an analysis of seven hydroelectric power plants in Brazil (Source 29).

Researchers continued to study reservoir emissions and they are better understood today. Important new findings since 2006 include the following:

- There are three pathways for hydropower plants to emit greenhouse gases from reservoirs:

Degassing, bubbling and diffusion.[3]

- Traditional measuring approaches that quantify diffusive fluxes of gases across the air-water interfaces do not capture methane emissions accurately. While CO_2 and N_2O are soluble in water, CH_4 is less soluble and predominantly emitted in bubbles. Bubbling events occur in a non-linear fashion and traditional measuring techniques as described above might underestimate or overestimate methane emissions, depending on whether measurements coincide with bubbling events or not (Source 30). Measuring emissions from a one-year pulse of emissions can therefore be misleading as it ignores the temporal variability of reservoir emissions (Source 31).
- In 2014, the IPCC estimated that worldwide median lifecycle emissions of hydropower amounts to 24 gCO_2e/kWh while individual plants can emit as much as 2200 gCO_2e/kWh (Source 32).
- More recent modelling approaches based on data from 1473 reservoirs suggest a global average of reservoir emissions of 404 $kgCO_2e/MWh$ (using GWP100 as metric to account for the relative impact of the different greenhouse gases) (Source 33). The researchers however caution that this value is driven by a few hydroelectric power plants with very high emissions. The median value is 136 $kgCO_2e/MWh$. Considering that reservoirs might serve multiple purposes (e.g., fishing, recreation etc.), of which electricity generation is only one, the researchers further adjusted these values by identifying the shares that can be attributed to hydropower plants. With attribution, the identified average and median are 273 and 84 $kgCO_2e/MWh$, respectively.
- The variety of estimates for individual reservoirs is large with some reservoirs estimated to be a net sink while others emitting significant amounts of greenhouse gases (Source 33).
- Reservoir drawdown, which influences CO_2 emissions, is not accounted for in most emission factors. Dry aquatic sediments can be significant sources of CO_2. Calculations of CO_2 emissions however assume that reservoirs are completely filled. A recent study using satellite observations of 6,794 reservoirs between 1985 and 2015 concludes that 15% of global reservoir area was dry. The researchers estimate that including emissions from drawdown events into calculations could increase global CO_2 emissions from reservoirs by about 53% (Source 34). The effect of drawdown events on CH_4 emissions is still unclear but the reduced hydrostatic pressure might increase ebullition activities of reservoirs resulting in more CH_4 emissions over the short-term.
- Turbines and spillways have been identified as an additional sources of methane emissions that is not considered in traditional approaches to measure the emission intensity of hydropower (Source 35).
- There is a better understanding how different drivers contribute to reservoir emissions which include age, temperature, latitude, ecosystem composition before impoundment, and performance, amongst others. This knowledge allows more accurate calculations based on age and location of reservoirs.
- There are now refined methodological approaches are available to calculate the effect of most of them on individual plant sites.

[3] Degassing refers to the release of methane when the water passes through the turbine. Bubbling refers to the process of methane bubbles rising from the bottom of the reservoir. Diffusion refers to methane, carbon dioxide and nitric oxide emissions from the reservoir water surface and further downstream.

Considering the high variability of reservoir emissions, with emission levels and drivers being highly specific to individual plants, using a default emission factor of 90 kg CO_2e/MWh entails a risk to over- or underestimate emission reductions for specific projects. Scherer and Pfister (2016) identified a median value of 84 kg CO_2e/MWh when modelling reservoir emissions of 1474 hydropower plants. While this value is similar to the default value used in ACM0002, the value in ACM0002 is meant to represent plants with a power density of less than 10 W/m^2, whereas the analysis by Scherer and Pfister (2016) also includes plants with a higher power density and thus likely lower emissions. It is therefore possible that emission reductions are more likely to be overestimated than underestimated. Due to lack of data consistency, it is however not possible to assess with sufficient confidence whether for existing projects overestimation or underestimation are more frequent. The modelling results further show a high variance, suggesting that application of a default value leads to very high uncertainty (i.e., larger than ±50%) when estimating reservoir emissions of individual plants. For these reasons, the use of the emission factor of 90 kg CO_2e/MWh in ACM0002 is assessed to lead to significant uncertainty but not systematic over- or underestimation of emission reductions (U3).

Robustness of the power density threshold

The objective of setting a power density threshold is to identify projects where there is a high likelihood that reservoirs will emit negligible amounts of greenhouse gases. Such an approach is appropriate if the selected threshold is robust in screening out such cases.

Regarding the 10 W/m^2 threshold that was set by the CDM Executive Board in 2006, analysis by the Climate Bonds Initiative concludes that the value indeed identifies reservoirs with low GHG emissions. The analysis uses the G-res modelling database (Source 37) which includes modelling results for 498 reservoirs and shows that most plants with a power density above 10 W/m^2 have emission intensities of less than about 25 g CO_2e/kWh. Except for one case all plants with power densities above 10 W/m^2 have emission intensities of less than 50 g CO_2e/kWh (Source 36). Neglecting reservoir emissions for plants with a power density above 10 W/m2 will thus lead to overestimation of emission reductions but a relatively low degree (OE6).

Determination of leakage emissions

The methodology does not include any leakage emissions.

U4 / UE3: Neglection of leakage emissions

Leakage emissions can arise from the construction and decommissioning of the solar, wind and hydropower plants as well as from emission sources associated with power plants operated in the baseline scenario that are not considered as part of baseline emissions. This includes emissions from (see Figure 2):

- upstream processes such as the construction of the plants;
- operational processes, such as the extraction, processing, and transportation of fossil fuels; and
- downstream processes, such as the decommissioning of the power plants.

Emissions from raw material extraction and fossil fuel use for the manufacturing of components and construction of solar, wind and hydropower plants can be significant. Likewise, upstream emissions from fossil fuel extraction in the baseline scenario can also be significant. To assess whether neglecting these emissions results in any significant under- or overestimation of emission reductions a review was carried out of published research which aims to assess the upstream emissions of GHGs of various renewable technologies compared to the emissions from upstream processes for fossil fuels. This review was not comprehensive, but some findings are presented below:

- The National Renewable Energy Laboratory (NREL) concluded that upstream processes for solar PV may be as high as 30 gCO_2eq/kWh, whereas for coal this figure would be <10 gCO_2eq/kWh (Figure 2) (Source 15). It should be noted, however, that this publication includes emissions from coal mining, preparation and transport in operational processes and not other processes. A direct comparison between emissions from upstream processes for solar PV and coal as reported in this publication would not be valid, however, the reference is useful for the purposes of providing emissions estimates from upstream processes for solar PV.

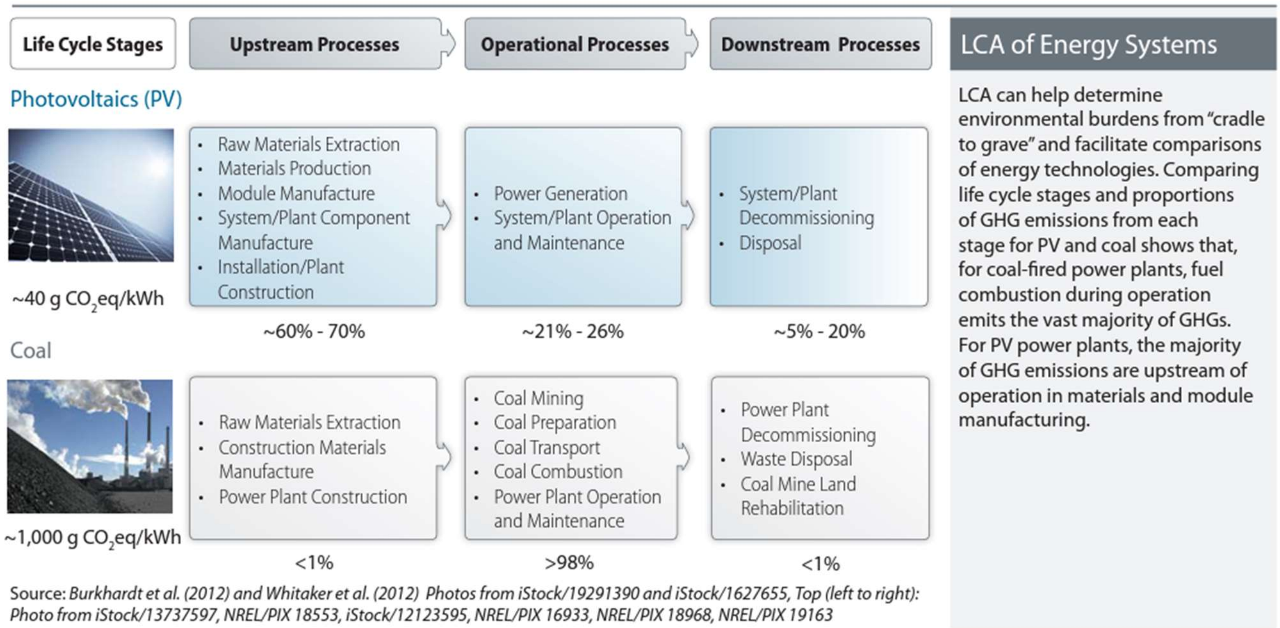
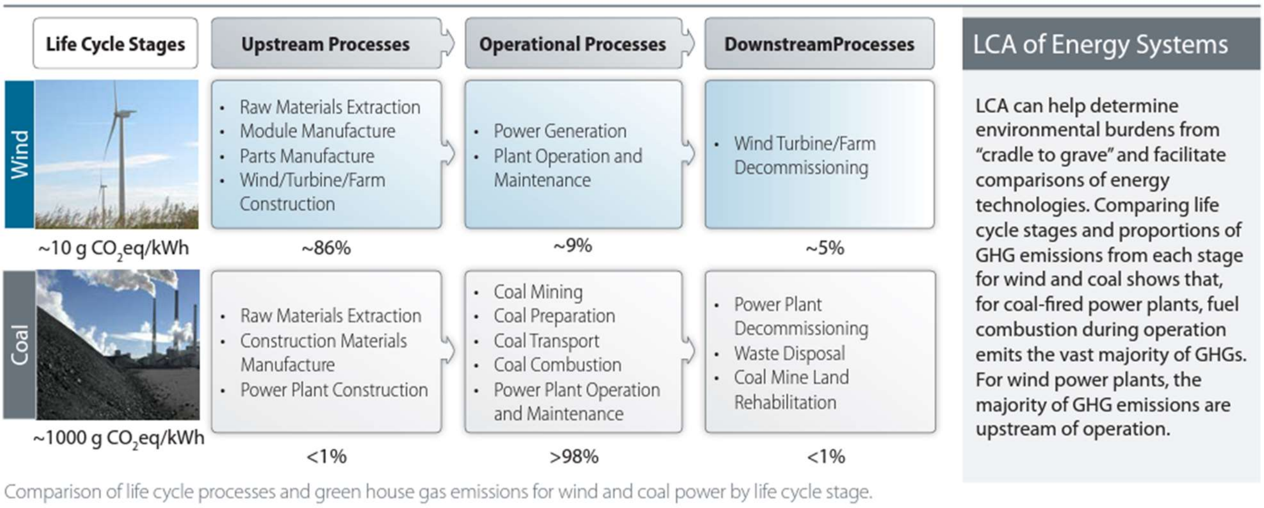


Figure 2: Comparison of life cycle processes and greenhouse gas emissions for solar PV and coal power by life cycle stage.

- NREL also concluded that upstream processes for wind may be as high as 10 gCO_2eq/kWh (Source 18) (Figure 3). As for the previous reference a direct comparison between emissions from upstream processes for wind and coal as reported in this publication would not be valid.



Source: *Dolan and Heath. (2012) and Whitaker et al. (2012), NREL 21205 andiStock/1627655, Top (left to right): Photo from iStock/13737597, NREL 19893, iStock/12123595, NREL 16933, NREL 18381, NREL 19163*

Figure 3: Comparison of life cycle processes and greenhouse gas emissions for wind and coal power by life cycle stage.

- A study funded by the Norwegian Research Council concluded that the LCA GHG emissions for onshore wind power farms are 11.0 and 15.1 gCO_2eq/kWh, and vary between 18.0 and 31.4 g gCO_2eq/kWh for offshore wind power farms (Source 10).
- A paper published in 2020 showed a correlation between capacity of wind power projects and emissions, which varied between 10.0 and 40 gCO_2eq/kWh (Source 1) (Figure 4).

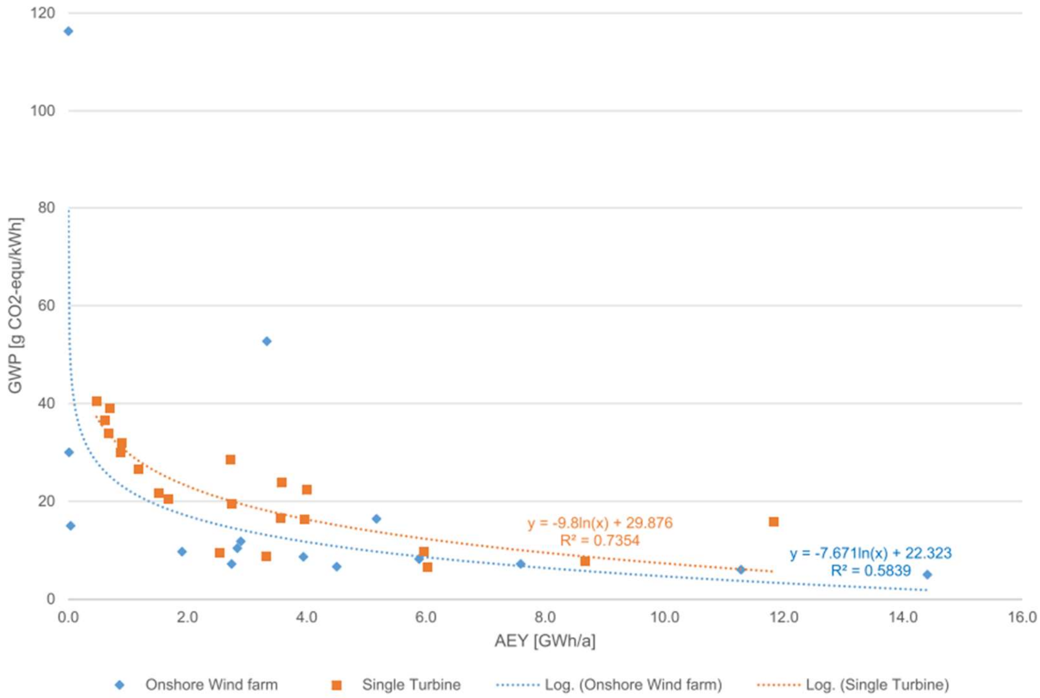


Figure 4: **Relationship between the Annual Energy Yield (AEY) and the GWP for single turbines and onshore wind farms**

- A meta-survey assessing the lifecycle greenhouse gas emissions from solar PV and wind energy showed a mean of 43 gCO_2eq/kWh for solar PV and a mean of 57 gCO_2eq/kWh for wind projects (incl. onshore and offshore) (Source 19)

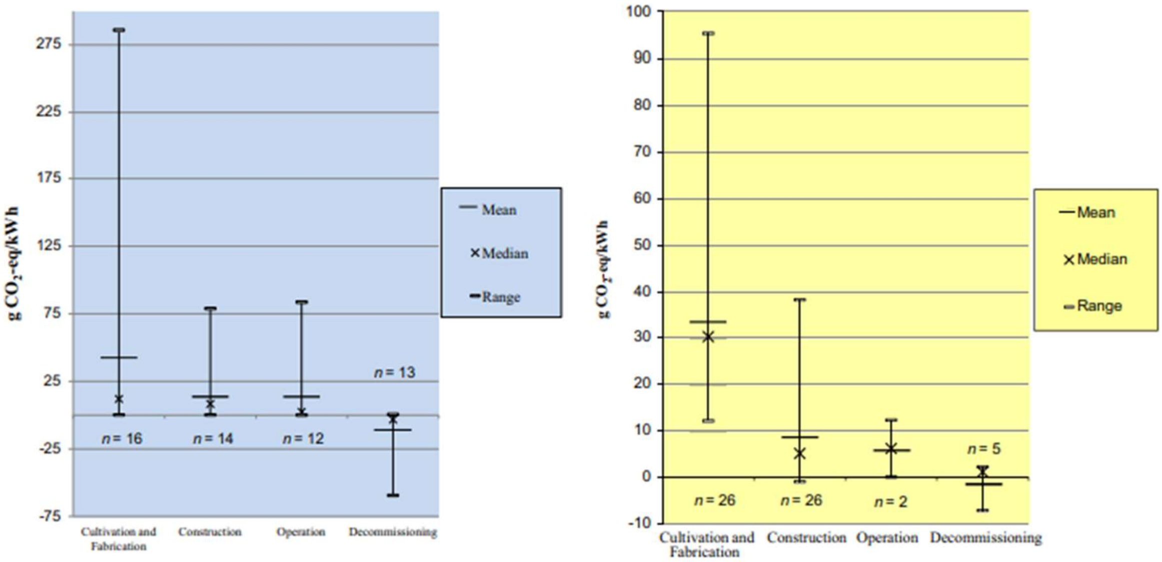


Figure 5: **Lifecycle greenhouse gas emissions for wind (blue) and solar PV (yellow) energy by lifecycle stage**

- A study by the Department of Energy shows a median of 21 gCO_2eq/kWh for hydropower lifecycle emissions (both reservoir and run-of-river) with estimates ranging from 0.57 to 75 gCO_2eq/kWh.
- NREL have also published Median Life Cycle Emissions Factors for Electricity Generation Technologies, by Life Cycle Phase (Source 17). This includes figures for solar PV, wind, hydropower and fossil fuels such as coal and natural gas (Figure 6).

	Generation Technology	One-Time Upstream	Ongoing Combustion	Ongoing Non Combustion	One-Time Downstream	Total Life Cycle	Sources
Renewable	Biomass	NR	—	NR	NR	52	EPRI 2013 Renewable Electricity Futures Study 2012
Renewable	Photovoltaic[a]	~28	—	~10	~5	43	Kim et al. 2012 Hsu et al. 2012 NREL 2012
Renewable	Concentrating Solar Power[b]	20	—	10	0.53	28	Burkhardt et al. 2012
Renewable	Geothermal	15	—	6.9	0.12	37	Eberle et al. 2017
Renewable	Hydropower	6.2	—	1.9	0.004	21	DOE 2016
Renewable	Ocean	NR	—	NR	NR	8	IPCC 2011
Renewable	Wind[c]	12	—	0.74	0.34	13	DOE 2015
Storage	Pumped-storage hydropower	3.0	—	1.8	0.07	7.4	DOE 2016
Storage	Lithium-ion battery	32	—	NR	3.4	33	Nicholson et al. 2021
Storage	Hydrogen fuel cell	27	—	2.5	1.9	38	Khan et al. 2005
Nonrenewable	Nuclear[d]	2.0	—	12	0.7	13	Warner and Heath 2012
Nonrenewable	Natural gas	0.8	389	71	0.02	486	O'Donoughue et al. 2013
Nonrenewable	Oil	NR	NR	NR	NR	840	IPCC 2011
Nonrenewable	Coal	<5	1010	10	<5	1001	Whitaker et al. 2012

Figure 6: Median Published Life Cycle Emissions Factors for Electricity Generation Technologies, by Life Cycle Phase (g CO2e/kWh)

Emissions of GHGs from flaring of associated gas and fugitive emissions of methane during extraction and transport of fossil fuels can be significant. **Error! Reference source not found.**The World Resources Institute presents a more comprehensive review of upstream emissions (production and processing) as a percentage of overall emissions (including combustion). This is a significant issue, as there are inconsistencies in how the emission factors for upstream processes for fossil fuels presented in the above-mentioned studies are estimated and how different sources of emissions are allocated to different life cycle phases. For example, for natural gas the fugitive emissions of methane during extraction and transport of the fuel are included in the phase entitled "on-going non-combustions" in some studies whereas in others emissions of methane from coal mining are included in the "on-going combustion" phase. This makes direct comparison between different generation technologies and different life cycle phases challenging.

With respect to coal, a study undertaken within Germany concluded that coal-based electric power generation resulted in mean methane emissions of 0.6 g CH_4/kWh, (15 g CO_2e/kWh)[4], based on the country-specific methane content of hard coals imported to Germany, the coal mix and power plant efficiencies (Source 15). The same study highlighted, however, that emission factors varied significantly depending on the source country of the coal, as summarized in Table 1. The same study concluded that upstream CO_2 emissions from mining, preparation and transport of coal to power plant sites in Germany were ~ 8 g/kWh for domestic and of ~ 12 g/kWh for imported hard coal. Combining emission factors upstream CO_2 and CH_4 suggests a combined emission factor of ~ 23 g CO_2e/kWh for domestic and of ~ 27 g CO_2e/kWh for imported hard coal for Germany. Table 1 therefore also presents this range of upstream CO_2 emissions from mining, preparation and transport of coal, and total upstream CO_2e/kWh (upstream emissions of CH_4, as CO_2e, and CO_2).

Table 1: Country specific mean CH4 emissions for power generation

Origin country	gCH_4/kWh	gCO_2e/kWh	gCO_2/kWh	gCO_2e/kWh
Russia Federation	2.0	50	8 - 12	58-62
USA	0.8	20	8 - 12	28-32
South Africa	0.6	15	8 - 12	23-27
Colombia	1.7	42.5	8 - 12	50.5-54.5
Poland	2.5	62.5	8 - 12	70.5-74.5
Germany	1.4	35	8 - 12	43-47
Others	1.5	37.5	8 - 12	45.5-49.5

The above quoted studies show a large degree of variation in the given estimates for upstream emission factors for GHGs of both renewable energy and fossil fuel technologies. Table 2 summarizes the higher and a lower upstream emission factor for solar PV and wind, plus the emission factors for natural gas and coal fired electricity generation, as presented in the referenced studies.

4 Using a 100-year GWP of 25 to align the studies.

Table 2: Lifecycle emissions for renewable energy and thermal projects (not including ongoing combustion)

Technology	Lifecycle EF gCO2eq/kWh
Solar	~ 35 to ~48
Wind	~ 13 to ~ 58
Hydropower	~ 0.57 to ~75
Natural gas	75
Coal	~ 25 to ~ 80

In conclusion, neglecting emissions from power plant construction and decommissioning, and upstream emissions from fossil fuel use, may for renewable power generation projects in some cases lead to underestimation of emission reductions, specifically in the case of wind power generation where the baseline grid has a significant share of natural gas in the fuel mix, and in other cases to overestimation of emission reductions (e.g. a solar PV project where the baseline is a grid with mainly coal with a relatively emissions intensity). On average, wind and hydro power generation is expected to have lower emissions from power plant construction and decommissioning than solar PV power. Therefore, neglecting these leakage emissions is likely to lead to an underestimation of emission reductions (UE3), whereas the impact for solar PV power is uncertain (U4).

Summary and conclusion

Table 3 summarizes the results of the assessment and, where possible, presents the potential impact on the quantification of emission reductions for each of the previously discussed elements.

Table 3 Relevant elements of assessment and qualitative ratings

Element	Fraction of projects affected by this element[5]	Average degree of under- or overestimation where element materializes[6]	Variability among projects where element materializes[7]
Elements likely to contribute to overestimating emission reductions or removals			
OE1: Exclusion of registered CDM projects in the calculation of the BM	Low	Low	Medium
OE2: Weighting of OM and BM in determining the CM (for solar PV and hydropower)	High	Medium	High
OE3: Use of historical data to determine the GEF	High	Medium	Medium
OE4: Including off-grid power plants in the calculation of GEF	Low to Medium	Low to Medium	High
OE5: Choice of method for calculation of the operating margin (specifically for method (a))	High	Low	Low
OE6: Emissions from reservoirs (only for hydropower dams with power density larger than 10 W/m^2)	Unknown	Low	High
Elements likely to contribute to underestimating emission reductions or removals			

5 This parameter refers to the likely fraction of individual projects (applying the same methodology) that are affected by this element, considering the potential portfolio of projects. “Low” indicates that the element is estimated to be relevant for less than one third of the projects, “Medium” for one to two thirds of the projects, “High” for more than two third of the projects, and “All” for all of the projects. “Unknown” indicates that no information on the likely fraction of projects affected is available.

6 This parameter refers to the likely average degree / magnitude to which the element contributes to an over- or underestimation of the total emission reductions or removals for those projects for which this element materializes (i.e., the assessment shall not refer to average over- or underestimation resulting from all projects). “Low” indicates an estimated deviation of the calculated emission reductions or removals by less than 10% from the actual (unknown) emission reductions or removals, “Medium” refers to an estimated deviation of 10 to 30%, and high refers to an estimated deviation larger than 30%. “Unknown” indicates that it is likely that the element contributes to an over- or underestimation (e. g. overestimation of emission reductions in case of an omitted project emission source) but that no information is available on the degree / magnitude of over- or underestimation. Where relevant information is available, the degree of over- or underestimation resulting from the element may be expressed through a percentage range.

7 This refers to the variability with respect to the element among those projects for which the element materializes. “Low” means that the variability of the relevant element among the projects is at most ±10% based on a 95% confidence interval. For example, an emission factor may be estimated to vary between values from 18 and 22 among projects, with 20 being the mean value. “Medium” refers to a variability of at most ±30%, and “High” of more than ±30%.

UE1: Inclusion of plants with lower capacity value in the calculation of the BM	All	Low to Medium	High
UE2: Use of default values provided in Tool 09	Low	Low	Low
UE3: Neglection of leakage emissions (for wind power and hydropower)	High	Low	Low to Medium
Elements with unknown impact			
U1: Weighting of OM and BM in determining the CM (for wind power only)	High	Low	High
U2: Treatment of electricity transfers	Low	Low	Low to Medium
U3: Emissions from reservoirs (only for hydropower dams with a power density of less than 10 W/m2)	Unknown	High	High
U4: Neglection of leakage emissions (for solar PV only)	High	Low	Low to Medium

The table shows that the potential sources of overestimation outweigh the potential sources of underestimation. The use of historical data to determine the grid emission factor (OE3) is the most important factor contributing to overestimation. Other factors could, however, also have significant impact. In aggregate, we estimate that emission reductions are likely to be overestimated within the range of 10-30%. Although wind power performs somewhat better than solar photovoltaic power, we estimate that this degree of overestimation is still applicable to both project types. For hydropower (dams) the default emission factor to calculate reservoir emissions likely introduces very high uncertainty to the estimation of emission reductions. Therefore, a score of 2 is assigned to this methodology for all four project types.

Annex: Summary of changes from previous assessment sheet versions

The following table describes the main substantive changes implemented in comparison to the assessment from 31 January 2023.

Topic	Rationale
Inclusion of analysis for hydropower plants	The analysis was amended to cover hydropower plants. This includes in particular the consideration of the weight of the BM and OM in TOOL07, the consideration of leakage emissions #
Overestimation risk due to the weight of the BM and OM for solar power	The analysis regarding the magnitude of the overestimation risk due to the weighting of the BM and OM was updated based on more detailed calculations.
Inclusion of plants with a relatively low capacity value in the calculation of the BM	A potential underestimation of the BM emission factor due to the inclusion of plants with a relatively low capacity value was identified and included in the analysis.
Minor improvements and corrections	Through the analysis some minor improvements and corrections were implemented.