EUROPEAN COMMISSION
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Institute for Energy
SET-Plan Information System (SETIS)

Key Performance Indicators for the CCS - EII

Background

In March 2010, Member States adopted conclusions[1] on the *Strategic Energy Technology Plan (SET-Plan*) on the basis of the Commission Communication *"Investing in the Development of Low Carbon Technologies"* [COM(2009) 519 final]. These included the launch of the six EIIs[2] of the SET-Plan by 2011 and called for the establishment of a common set of principles and practices for their implementation, which include the development and systematic use of key performance indicators (KPIs). In the same meeting the Council requested the Commission "to develop to its full capacity the SET-Plan Information System (SETIS) in order to provide a robust technology-neutral planning tool". SETIS was engaged in all EII Teams to contribute to the identification and quantification of KPIs, which were subsequently incorporated in the Implementation Plans for 2010-2012. **KPIs represent an essential toolkit for monitoring and reviewing the overall progress of the CCS-EII**, and of the individual research, development and demonstration (RDD) activities performed in frame of its implementation. KPIs will become instrumental for planning RDD activities, funded under the current and the upcoming R&D framework programmes and other possible funding schemes (such as NER 300), aiming to support the CCS-EII. More specifically, projects supporting the implementation of the CCS-EII, will need to demonstrate the link between their objectives and the KPIs of the CCS-EII they will be contributing to. As such, these projects will be integrated into the *Monitoring and Review Framework* of the SET-Plan. The practicalities of this exercise and the modus operandi, and particularly with reference to the later stage of analysis of the data and their feeding into the technology-neutral planning tool of SETIS, are still to be defined.

The CCS-EII Team, under the guidance of SETIS[3], developed a set of KPIs, which was incorporated in the Implementation Plan 2010-2012. Taking into consideration the fact that KPIs may need to be modified in the future to adapt to the continuous industrial and technological progress of the sector, the KPIs of the Implementation Plan 2010-2012 have been further refined in order to focus on ongoing and future RDD activities related to prioritized actions of the Implementation Plan of the EII. These KPIs form the ***first***

[1] 3001st Transport, Telecommunications and Energy Council meeting of 12th March 2010.

[2] The European wind initiative, the solar Europe initiative, the European electricity grid initiative, the sustainable bio-energy Europe initiative, the European CO2 capture, transport and storage initiative, the sustainable nuclear fission initiative and the initiative on fuel cells and hydrogen.

[3] The Council has requested the Information System of the SET-Plan (SETIS) *to assess performance and cost-effectiveness and to monitor the progress of the SET Plan activities towards their objectives in a transparent and objective way*.

***generation* of the CCS-EII KPIs**[4]and pave the way to the constitution of the first *Monitoring and Review Framework* for the CCS-EII.

To this end, it is noted that the implementation of planning, monitoring and progress review based on KPIs also requires, first of all access to relevant and reliable data, the setup of data collection/monitoring, review and feedback procedures and the establishment of a knowledge sharing process. These procedures will be elaborated and described in detail by the CCS-EII Team in the course of 2011. In this process, the CCS EII Team will take stock specifically of the work that has already been performed so far in the context of the European CCS Demonstration Project Network (PN)[5], funded by the EU. It is noted that the PN is composed of European demonstration projects that are at a sufficient scale and level of maturity that will generate valuable output and knowledge about the industrial-scale CCS demonstration. Its already developed knowledge sharing protocol listing the information to be shared regularly within and beyond the Network membership, and describing the implementation logic of such a sharing process, will be a solid base for the CCS EII data gathering and monitoring process.

General Principles

The KPIs for the CCS-EII have been developed based on the following principles:

- KPIs are defined in a straightforward format (formulas and basic assumptions are provided) so that they can be easily understood (and hence accurately and unambiguously measured and subsequently interpreted) by the EII-Team, programme/project managers and policy makers.
- **Overarching KPIs** are **used to measure the progress of the CCS-EII** towards meeting its strategic objectives, namely the improvement of the **cost competitiveness of the technology and its further development** to allow its application in all carbon intensive industrial sectors.
- **2nd tier KPIs** are used **to measure progress at the project level**. They will be utilized to gauge progress towards the overarching KPIs of the CCS demonstration programme and where feasible of other RDD projects, funded by FP7 and any other funding instrument. To this end, continuity between the overarching KPIs and 2nd tier KPIs is ensured where there is an apparent link.
- KPIs targets are set for critical EII milestones for 2020 and 2015. However the overarching KPIs will only be calculated for large commercial power plants with start of operation in early 2020s. The 2nd tier KPIs at demo project level will be scaled up to large commercial size correspondingly. The current understanding of KPI values is used to define a baseline and reference point for assessing technological improvements achieved by the contributing projects.
- Significant work on the definition and quantification of the KPIs has already been done, in particular, by the CCS Demonstration Project Network and ZEP (Zero Emissions Platform) ETP (European Technology Platform). Thus, this document draws heavily from the newly published reports by ZEP ETP on the costs of CO2 capture[6], transport[7] and storage[8] and the information and experience gathering form of the Project Network[9].

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[4] KPIs for the remaining actions will be addressed at a later stage.

[5] http://www.ccsnetwork.eu/

[6] Add reference

[7] Add reference

- Transport and storage costs are excluded from the calculations of the overarching KPIs. Reason for this is that this cost is not primarily depending on technology development. In the dedicated ZEP cost report, cost of storage has been recognized to be very case dependent (e.g. onshore versus offshore, size, characteristics and complexity of the geology, unknown aquifer or well described mature hydrocarbon reservoir...), and characterized by a large variability (from a few euros per tonne of CO2 to 20€/tCO2). In the absence so far of cost data acquired under representative operating conditions, this cost has been excluded from the Levelised Cost of Electricity calculations. Also the transport costs are very much depending on location, on availability of existing structures, of utilization and if pipelines and terminals are designed for a system or for a single plant. Thus the transport and storage costs but will be considered as soon as demo projects have delivered more precise cost estimates and have identified strategies to reduce these costs. All costs thus represent the cost at the fence of the plant. The development of Transport and Storage of CO_2 has to be monitored by other means than described in this memo, which has to be defined at a later stage.

Overarching KPIs

The two overarching KPIs of the CCS-EII, which will be used for the monitoring and review of progress of the whole EII are:

- Levelised cost of electricity (LCoE), measured in €/MWh
- Cost per tonne of CO_2 avoided, measured in €/t_{CO2}

It is noted however, that LCoE is a KPI tailored to the needs of projects linked with the application of CCS in the power sector. A variant of this overarching KPI will be used for projects focused on CCS in industrial applications, such as in the cement, iron and steel or pulp and paper industries:

- Levelised cost of industrial product (LCoP), measured in €/product unit[10] (to be defined after the successful selection of relevant RDD projects).

The overarching KPIs is calculated for the following cases:

- Large commercial hard coal plant without CCS (Reference coal plant)
- Large commercial hard coal plant with CCS
- Large commercial natural gas (NG) plant without CCS (Reference NG plant)
- Large commercial NG plant with CCS
- Large commercial industrial plant without CCS (Reference industrial plant – to be defined as soon as relevant RDD projects emerge)
- Large commercial industrial plant with CCS (to be defined as soon as relevant RDD projects emerge)

The Overarching KPIs for large commercial plants with CCS will represent average values reflecting the different capture technologies (post- and pre-combustion and oxyfuel). To create an average, the following principle will be used. First the average

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[8] Add reference

[9] http://www.ccsnetwork.eu/uploads/publications/european_ccs_project_network_knowledge_sharing_template_20110120.pdf

[10] E.g., tonne of clinker or cement, tonne of hot-rolled steel, tonne of paper, etc.

from all plants of the same kind are summarized and averaged. If all technologies are represented, three figures will be at hand.

$$\overline{X_a} = \frac{\sum_{i}^{Na} X_{ia}}{N_a}; \overline{X} = \frac{\sum_{a}^{1\to3} N_a * \overline{X_a}}{\sum_{a}^{1\to3} N_a}$$

X is the value in question, index a represents a technology and index i is the individual number of plants in each category a.

Definitions

Levelised Cost of Electricity[11]

The levelised cost of electricity takes into consideration plant capital costs, O&M costs, fuel and CO_2 costs, site location and financial assumptions over the lifetime of the power plant in order to calculate the electricity cost without profit. It is calculated using the following expression:

$$LCoE = \frac{SCI * CRF}{8760 * LF} + OMC + FC + CC, \quad CRF = \frac{d(1+d)^n}{\left((1+d)^n - 1\right)} \qquad (1)$$

The parameters in the above equation are defined as follows:

LCoE… Levelised cost of electricity, in €$_{2010}$/MWh$_{net}$ (Overarching KPI)

SCI… Specific Capital Investment, in €$_{2010}$/MW$_{net}$, defined as the total capital cost of the plant normalised with its net power generation capacity. The total investment cost includes the Engineering, Procurement and Construction costs (EPC) of the power plant, as well as the owner's costs to develop the project. This is a 2nd tier KPI. The SCI is annualized to its net present value.

CRF… Capital recovery factor, defined in Equation 1

d… Real discount rate

n… Economic plant life, in years

LF… Load factor, defined as the equivalent full load operating hours of the plant divided by the total hours of a year. LF can be calculated as the total generated energy in a year, divided with the nominal full capacity energy theoretically possible in a year.

OMC Annualised operational and maintenance costs, in €$_{2010}$/MWh$_{net}$. OMC is a 2nd tier KPI defined as:

[11] The definition and calculation methodology of LCoP is similar to these of LCoE.

$$OMC = \frac{FOM}{8760 * LF} + VOM$$

FOM and VOM refer to the annualised fixed and variable operating costs respectively. FOM includes maintenance and salaries expressed in €/installed MW, while VOM accounts for the cost of consumables, chemicals, auxiliary power, etc expressed as €/ MWh_{net}. OMC are considered through an annualizing process, where the annual *FOM and VOM* values are discounted to the net present value and then multiplied by the *CRF*.

FC Fuel costs, in $€_{2010}/MWh_{net}$, annualised through the procedure described above for OMC. Annual fuel costs (FC) are calculated based on the annual fuel consumption and fuel price as follows:

$$FC = \frac{Q_{net}}{\eta_{net}} * FP$$

Where Q_{net} is the net annual electricity generated, η_{net} is the net thermal efficiency and FP the fuel price in €/MWh. The above formula needs to be further complemented with coefficients that will ensure the compatibility of measuring units used.

CC Annualised CO_2 costs for the quantity of CO_2 emitted by the plant during the plant lifetime, in $€_{2010}/MWh_{net}$. Annual carbon costs (CC) are calculated based on annual fuel consumption, the fuel carbon content, FCC expressed as ton CO_2/MWh, the CO_2 capture rate (CR) and the CO_2 price (CP) in €/tonne. The above formula needs to be further complemented with coefficients that will ensure the compatibility of the measuring units used.

$$CC = \frac{E_{net}}{\eta_{net}} * FCC * (1 - CR) * CP$$

B. Cost of CO_2 avoided (avoidance cost)

The CO_2 avoidance cost (AC) of a CO2 capture technology is calculated for NG-fired and coal-fired plants. It is determined by comparing the ratios of CO2 emissions to the power produced of a power plant concept with CO_2 capture against a reference power plant without CO_2 capture, which uses the same fuel. It is calculated as follows:

$$AC = \frac{LCoE_{CCS} - LCoE_{ref}}{SCE_{ref} - SCE_{CCS}} \qquad (2)$$

The parameters in equation 2 are defined as follows:

AC… Avoidance cost, in $€_{2010}/t_{CO2}$. (Overarching KPI)

$LCOE_{CCS}$… LCoE of the CCS plant, in $€_{2010}/kWh_{net}$ (Overarching KPI)

$LCOE_{ref...}$ LCoE of the reference plant, in $€_{2010}/kWh_{net}$ (Overarching KPI)

$SCE_{ref...}$ Specific CO_2 emissions of the reference plant, in t_{CO2}/MWh.

$SCE_{CCS...}$ Specific CO_2 emissions of the CCS plant, calculated as a function of thermal efficiency of the CCS plant (a 2nd tier KPI), the carbon content of the fuel, FCC[12] and the capture rate CR

$$SCE_{CCS} = \frac{FCC}{\eta_{netCCS}} * (1 - CR)$$

Boundary conditions and calculation assumptions

The boundary conditions used here are referring to the cost study of the ZEP in May 2011. The major conditions are:

- The calculations of the LCoE are for commercial large scale CCS plant that starts operating in mid 2020s after a successful demonstration phase of the CCS technology with optimised technology based on 1st commercial experience but still not for mature technology (OPTI).

- The CCS and the reference plants operate in base-load mode for 7500 h annually at full nominal load (CF=0.856).

- Transport and storage costs are excluded from the calculations of LCoE and avoidance costs. Reason is described above. All costs thus represent the cost at the fence of the plant.

- To illustrate the cost of Transport and Storage, this can be calculated based on a reference transport and storage system. For example, in a transport system which comprises a 10 km onshore feederline, and a 180 km offshore pipeline[13], a storage site which is a Saline aquifer on-shore[14] and for about 10 mio tonne/year (e.g. two large 1000 MW coal plants) the cost for transport is about 2 €/tonne of CO2 and storage is about 5 €/tonne. The same figures are also valid if calculated per MWh for coal plants, together about 7 €/MWh. If transported volumes are reduced to 2.5 million tonnes/year, the cost is about doubled. If calculated for gas combined cycle plants, the cost per tonne is the same, while the cost per MWh is about half.

- Fuel costs are calculated based on the assumption that coal and fuel prices escalate with an average of 1.5 % per year for the project lifetime, and the cost in 2010 was 2.4 €/GJ for coal and 8.0 €/GJ for NG.

- LCOE and CO2 capture or avoidance costs (€/t) are calculated, when so stated, including EUA costs. The calculation in these cases are based on a fixed EUA CO2 price of 35 €/t expressed in today's money. It is stressed that this EUA CO2 price assumption does not represent a future expectation for the evolution of EUA CO2 prices but is included in the analysis to illustrate the complete costs also for

[12] See indicator 1.2.1 in the PN data gathering form

[13] Network 1b of the ZEP report on the cost of CO2 transport

[14] Case 4 of the ZEP report on the cost of CO2 storage

plants without CCS and give an example for the potential competitiveness of CCS.

- The CO_2 avoidance costs for the power plant concepts with capture, are calculated based on the following reference power plants without CO_2 capture[15]:
    - Natural gas-fired single-shaft F Class Combined Cycle Gas Turbine producing 420 MWe net at an efficiency of 60%
    - Hard Coal 736 MWe net pulverised fuel (PF) ultra supercritical (280 bar 600/620ºC steam cycle) power plant at an efficiency of 46%.

The Table below summarises the performance of these reference plants. More details on other technical, ambient site, CO2 quality and compression processing conditions can be found in the ZEP report on the cost of CO2 capture.

Parameters		**PF Hard Coal**	**CCGT NG**
Net Electricity Output	MWe	736	420
HP Turbine Steam Inlet Pressure	Bara	280	113.8/27.7/3.99
HP Turbine Inlet Temperature	ºC	600	549
IP Turbine Inlet Steam Reheat Temperature	ºC	620	549
SCI of reference plant	€/kW	1555	714
Operation & maintenance cost of ref. plant	€/MWh	7.1	5.8
Net Full Load Plant Efficiency	% LHV	46%	58% (BASE) 60% (OPTI)
Plant Load Factor	h/year	7500	7500
Plant Life	Year	40	25
CO_2 Emissions Calculated from Fuel Carbon Content	T/MWh	0.759	0.347

- The reference fuel considered has the following properties :
    - Coal: Average hard coal traded on World market. Energy content: 25 MJ/kg, Carbon intensity: 0,344 tonnes/MWh_{th}
    - NG: Natural gas. Energy content: 50 MJ/kg, Carbon intensity: 0,210 tons/MWh_{th}

- Economic assumptions:
    - Weight Averaged Cost of Capital, WACC: 8%
    - Project life: Coal: 40 years; NG: 25 years.

[15] It is understood that these 2 reference systems may be inadequate to capture developments in innovative CO2 capture technologies, such as membranes, or chemical looping. Furthermore, reference systems for industrial CCS applications need to be developed once projects linked to specific industrial sectors are selected. Hence, additional reference systems may need to be developed in the future to cover all projects linked to the Implementation Plan.

2nd tier KPIs

The second tier KPIs are to be used to mainly gauge progress of the demonstration programme towards the overarching KPIs. Most of the data for second tier KPIs will be provided by the Project Network (PN) in accordance with its knowledge sharing protocol as discussed earlier. FP7 projects, and other relevant actions, could be also providing input where feasible, while qualitative entries could also be encouraged where appropriate. Input is expected to be collected at 6 months intervals for the PN projects, in line with their practices. For other projects (including FP7 actions) the collection of data or updating of data will be done in accordance to their contractually obligated reporting practices. The detailed description and definitions of most of these KPIs can be provided directly by the PN document and the ZEP reports.

Thirteen 2nd tier KPIs are used to monitor and assess progress achieved by individual RDD projects, and to feed into the calculation of the overarching KPIs. These KPIs are grouped as follows:

A. Progress in the demonstration programme

- Cumulative number of final investment decisions (FIDs), measured at the EII level
- Gross installed cumulative capacity of CCS projects (MW), measured at the EII level.
- Number of projects in the project network

B. Cost effectiveness

- Additional specific capital investment in capture, aggregated average per technology, in €/kW_{net} (defined above)
- Additional fixed and variable operating costs of capture, aggregated average per technology, in €/MWh_{net} (defined above)
- Annual average time plant availability, linked to indicators 1.4.1 and 1.4.2 of the Project Network
- Annual average plant efficiency, linked to indicator 1.5.3 and 1.5.4 of the Project Network
- Annual average CO2 capture rate, linked to indicators 1.7.1 and 1.7.2 of the Project Network
- Annual average time availability of the complete CCS chain

It is noted that, with the exception of the last KPI above, values for all KPIs in the 'cost effectiveness' group will be provided for coal CCS plants, NG CCS plants and average values for all CCS plants. Targets for these subgroups of 2nd tier KPIs will be set at a later stage.

C. Environmental effectiveness and safety

- Annual average CO_2 avoided, defined as is the difference in the specific emissions, in kg_{CO2}/kWh_{net}, of the reference plant and the power plant with CCS, divided by the specific emissions of the reference plant:

$$\frac{\left(\frac{CE}{QP}\right)_{REF} - \left(\frac{CE}{QP}\right)_{CCS}}{\left(\frac{CE}{QP}\right)_{REF}}$$

  Where CE refers to the total CO2 emissions and QP to the total net electricity energy generation of the CCS and the reference plants. This KPI should be expressed in such a way so as to account also for the case of biomass co-firing and its integration in the system

- Cumulative CO2 stored, in metric tonnes, linked to indicator 1.23.1 the Project Network, measured at the EII level
- Number of instances of CO2 movement out of the designated containment volume.
- Quantity of CO2 movement out of designated containment volume

D. Public awareness of CO2 storage

- Number of permits granted for CO2 storage projects, linked to indicator 3.9.1 of the Project Network
- Rating at a Eurobarometer pole on the level of acceptance of CCS.

Quantification of the Baseline and KPI targets – KPI monitoring

The values for the LCoE for the reference systems are calculated based on the information provided in the boundary conditions above, using an Excel-based assessment tool developed by ZEP ETP.

The 2015 target values for the LCoE and AC of the CCS plant are calculated based on today's knowledge of CCS technology plant concepts (BASE). The assumption is that they represent the first large plants after the experience from the Demonstration plants is available. The figures thus can represent the design targets for 2015 for a plant to be commissioned in the early 2020'ies (allowing 5 – 7 year time for build and commissioning). The basis for the calculations is the following set of assumptions:

- SCI for the coal plant: 2860 €/ installed kW, for the NG plant: 1828 €/kW
- OM: Coal: 14.5 €/MWh NG: 12.6 €/MWh
- Thermal efficiency: Coal: 36 % at MCR NG: 48 % at MCR
- Capture rate: 90%, defined as total amount of CO2 emitted divided with amount of CO2 generated over a time period.

The target values for the LCoE and AC of the CCS plant for 2020 are calculated for the presently known CCS power plant technology, but after the experience from the

first large scale commercial plants. (denoted OPTI case in ZEP cost report) This technology can represent the design data for 2020, for a plant to be in full operation after 2025. This is still not a mature technology, but partially down the learning curve, based on 1st commercial experience but still not on mature technology (OPTI). These data are calculated, using the following assumptions:

- SCI: Coal: 2530 €/kW NG: 1511 €/kW
- OM: Coal: 13.1 €/MWh NG: 9.8 €/MWh
- Thermal efficiency: Coal: 38 % NG: 52 %
- Capture rate: 90%

Finally, it is noted that in view of the state of CCS technology, no baseline values can be provided for KPIs referring to the techno-economic performance of CCS technology.

Baseline and target values of the KPIs have been discussed and agreed within the EII Team. The values of the 2nd tier KPIs will be updated on a regular basis. The Project Network will provide updates from the demonstration projects on a biannual basis, while the frequency of updates from the other RDD activities remains to be defined, but it is expected to be on an annual basis. As such, the values of the overarching KPIs can be updated also on a biannual basis.

The baseline values and targets for the KPIs is presented in the Table below:

	Metric	**Baseline**	**Targets 2015** 1st calculation based on ZEP cost reports	**Targets 2020** 1st calc. based on ZEP cost reports	**Update** future calculation based on data of CCS PN and other sources
Overarching KPIs					
LCoE					
Coal ref. power plant w/o EUA costs	€/MWh	48.2			EC/ZEP
Coal ref. power plant incl. EUA costs	€/MWh	74.8			EC/ZEP
NG ref. power plant w/o EUA costs	€/MWh	71.9			EC/ZEP
NG ref. power plant incl. EUA costs	€/MWh	84.0			EC/ZEP
Coal power plant with CCS but w/o EUA costs	€/MWh	Not applicable (n/a)	72.9	67.2	EC/PN/ZEP for different capture technologies
Coal power plant with CCS and incl. EUA costs	€/MWh	n/a	77.9	70.4	
NG power plant with CCS but w/o EUA costs	€/MWh	n/a	103.5	91.5	EC/PN/ZEP for different capture technologies
NG power plant with CCS and incl. EUA costs	€/MWh	n/a	105.6	93.5	

Cost of CO_2 avoided					
Coal power plant with CCS	€/t CO2	n/a	37.2	28.5	EC/PN/ZEP
NG power plant with CCS	€/t CO2	n/a	109.7	79.0	EC/PN/ZEP
Second Tier KPIs for coal plants					
cumulative FIDs		0	8	12	EC
installed capacity	MW-gross	0	1300	2000	EC
number of projects		6	10	12	EC/PN
spec. additional CAPEX capture, aggregated average per technology	€/kW-net	n/a	1500	1200	EC/PN/ZEP
spec. additional OPEX capture, aggregated average per technology	€/MWh,net	n/a	8.0	6.5	EC/PN/ZEP
average plant availability	%, h/a	n/a	74	80	EC/PN/ZEP
average CCS chain availability	%, h/a	n/a	74	80	EC/PN/ZEP
average plant efficiency	%	n/a	36	38	EC/PN/ZEP
average capture rate	%	n/a	85	90	EC/PN/ZEP
CO_2 stored	Mt/a	0	2	8	EC
Number of instances of CO2 movement out of designated containment volume.		0	0	0	ZEP
Quantity of CO2 movement out of designated containment volume	Mt	0	0	0	ZEP
Permits for CO_2 storage		0	2	8	EC
Eurobarometer CO_2 storage		A *Special Eurobarometer survey on CO2 Capture and Storage* published[16].	TBD	TBD	EC

[16] http://ec.europa.eu/public_opinion/archives/eb_special_379_360_en.htm#364. Report_Public Awareness and Acceptance of CO2 capture and storage: http://ec.europa.eu/public_opinion/archives/ebs/ebs_364_en.pdf