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Executive Summary
This document formally describes the key performance indicators, which are supposed to be quantified for the evaluation of H_2-CCS chains using the modelling tool-kit to be developed as part of work package 4 (WP4) of the ERA-Net ACT ELEGANCY project. Further metrics can be quantified in addition as part of national case studies. The purpose of this key performance indicator (KPI) specification is to provide a brief overview about the evaluation metrics, the methodologies used for their quantification and the required input parameters for quantifying the KPI. Potential users of the tool-kit will get an understanding of what the tool-kit will deliver in terms of evaluation metrics. The document also contains a discussion of potential additional performance metrics, which might be relevant for H_2-CCS chains in a national context, but will not be quantified with the tool-kit itself. While the KPI, which are part of the tool-kit, are all characterized in terms of quantitative units, some of the additional indicators are not, but rely on a qualitative evaluation. This issue 1 of the deliverable D4.2.1 serves as a basis for discussion and further development in which the feedback from national case study teams will be taken into account.

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1 INTRODUCTION

1.1 ELEGANCY

The main aim of the ELEGANCY project is to accelerate the deployment of Carbon Capture and Sequestration (CCS) technologies in Europe through H_2-CCS chain networks. ELEGANCY will conduct research and provide solutions to the commercial, technical, legal and social challenges associated with rapid deployment of H_2-CCS chain networks. Furthermore, ELEGANCY will develop an innovative, open-source modelling tool-kit containing multi-scale models, that can design the optimal time-phased evolution of H_2 systems with CCS. Subsequently, the research findings, tools and technologies will be applied to five national case studies, to inform the members of the ELEGANCY consortium on the optimal approach to decarbonise a wide variety of sectors.

1.2 Modelling tool-kit

The ELEGANCY modelling tool-kit to be developed as core output of Work Package (WP) 4 will enable the evaluation of an integrated H_2-CCS chain network with respect to technical and economic efficiency, operability and environmental burdens as well as social and policy related concerns. The tool-kit will incorporate results from WP1 and WP2 to provide an integrated modelling approach and will be used by the national case studies in WP5 for evaluation of their specific H_2-CCS chains.

1.3 Multi-criteria evaluation – key performance indicators

The evaluation of H_2-CCS chains will be based on a portfolio of quantifiable key performance indicators (KPI). These KPI will cover the three traditional pillars of sustainability: economy, environment, and society (UN 1987). Furthermore, KPI related to security of energy supply, technology performance and (energy) policy will be quantified as integral elements of the tool-kit. In addition, each of the national case studies might specify and use their own, supplementary KPI, which will not be generated by the tool-kit and might be of qualitative nature.

There is a vast amount of literature regarding multi-criteria assessment of energy technologies and scenarios, some of them addressing CCS specifically, each with specific sets of KPI – see the related discussion in e.g. (Hirschberg et al. 2008, Roth et al. 2009, Eckle et al. 2009, Bachmann et al. 2013, Volkart et al. 2016, Volkart et al. 2017).

The selection of KPI within the ELEGANCY project is based on their relevance in the context of this project, i.e. in relation to H_2-CCS chains in general and the five national case studies in particular. Depending on the indicator, KPI can either be quantified for specific processes, for certain process chains (e.g., from natural gas extraction to hydrogen supply), or for complete H_2-CCS chains including end-use technologies (e.g., from natural gas extraction to use in mobility for fuel cell vehicles). Indicators, which are quantified for process chains or the complete H_2-CCS chain, respectively, are based on Life Cycle Assessment methodology (ISO 2006a, ISO 2006b, Hauschild et al. 2018), if not explicitly stated otherwise. LCA will be carried out using ecoinvent v3.4 as background database (ecoinvent 2018, Wernet et al. 2016).

The KPI are supposed to be used for comparison of alternative options for supply of energy and mobility services. Quality of hydrogen (i.e. purity) will only be addressed in detail in case it is relevant for KPI quantification. Aggregation of indicators is not intended.

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2 KEY PERFORMANCE INDICATORS (KPI)

This section contains the core of this deliverable: the description and specification of key performance indicators. Each indicator is briefly described in terms of content and methodology used for quantification, and whether it is of quantitative or qualitative nature. It is also indicated whether the KPI will be a direct output of the modelling tool-kit, or not.

2.1 Tool-kit KPI at a glance

Table 1 shows a summary of the KPI to be quantified with the WP4 tool-kit. Potentially additional indicators are listed as well in sections 2.2 to 2.7.

Table 1: Overview of current, preliminary KPI as part of the modelling tool-kit.

Economics	Environmental
• Levelised cost of hydrogen (LCOH) at a desired purity level • CAPEX and OPEX for design and operation, inclusive of network costs	• Greenhouse gas emissions • Energy efficiency • Key pollutant emissions • Ecosystem damages
Security of Energy supply	**Social**
• Non-renewable primary energy demand • Resource autonomy of energy supply chain • Utilization of "critical" metal resources	• Conflict potential • Human health damages • Social costs of carbon pollution (LCA)
Geography related	**Technical**
• Demand for CO_2 storage capacities • Demand for H_2 storage capacities • Extent of utilization of domestic natural gas reserves • Demand for upgraded or extended pipeline network	• Hydrogen recovery • CO_2 recovery • (V)PSA specific power use per tonne of H_2 or CO_2 • CO_2 capture unit specific heat duty and power consumption • Specific CO_2 avoided • Specific primary energy consumption per tonne of CO_2 avoided • System efficiency – first law • System efficiency – second law • (Load) flexibility • Technology readiness level

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2.2 Economics

2.2.1 Production costs per unit of hydrogen as a parameter of purity level

The Levelized Cost of Hydrogen (LCOH) is the net present value of the unit-cost of hydrogen over the lifetime for the plant. It is equivalent to the minimum required selling price to break even over the life of the plant. This is defined as the price of hydrogen which enables the present value from all sales of hydrogen (including the additional revenue from the sale of electricity) over the economic lifetime of the plant to equal the present value of all costs of building, maintaining and operating the plant over its lifetime. This can be calculated as the net present value of all costs over the lifetime of the plant divided by the total hydrogen or hydrogen energy output of the plant. The unit of LCOH is €/Nm^3 H_2 or €/MWth H_2.

LCOH) is given by

$$LCOH = \frac{sum\ of\ costs\ over\ lifetime}{sum\ of\ hydrogen\ (energy)\ produced\ over\ lifetime}$$

2.2.2 CAPEX

The CAPEX consists of the following elements:

- *Equipment Costs* – The Equipment Cost for each main basic equipment of the different processes can be estimated based on a step-count exponential costing method, using the dominant or a combination of parameters derived from mass and energy balance computations, combined with cost data obtained from equipment suppliers and/or other available data. The *Total Equipment Cost (TEC)* is the sum of all equipment costs.
- *Installation costs* – The installation costs are estimated as additional expenses to integrate the individual equipment, such as costs for piping/valves, civil works, instrumentation, electrical installations, insulation, painting, steel structures, erections and OSBL (outside battery limits).
- *Total Direct Cost (TDC)* – The Direct Cost is the sum of the Equipment Costs and the Installation Costs and includes the appropriate process contingency factor
- *Indirect Costs* – The indirect expenditures is evaluated as a fixed percentage of the TDC and includes the costs for the yard improvement, service facilities and engineering costs as well as the building and sundries.
- *Engineering, Procurement and Construction Costs (EPC)* – The EPC is the sum of Total Direct Cost and Indirect Costs.
- *Owner's Costs and Contingencies* – The owner's costs for planning, designing and commissioning the unit and for working capital, together with project contingencies, is evaluated as a fixed percentage of the total EPC cost.

CAPEX is the total capital investments is the sum of EPC, owner's costs and contingencies.

2.2.3 OPEX

The OPEX is the sum of variable and fixed OPEX.

The variable OPEX consists of:

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- *Utilities and consumables cost:* The variable operating costs include material utilities consumption such as electricity, natural gas, process water, chemicals, sorbent, etc. The costs of the main utilities and consumables are evaluated based on the process energy and mass balance and the costs.
- *Other variable OPEX*: Additional OPEX over and above the specific variable OPEX mentioned above is taken as a constant value per specific product.

The fixed operating costs includes maintenance, insurance and labour costs:

- *Insurance and local property taxes:* The total annual cost of insurance, local property taxes and miscellaneous regulatory and overhead fees is set as a percentage of TPC.
- *Maintenance cost:* Maintenance costs include cost of preventive maintenance, corrective maintenance (repair and replacement of failed components) and periodic replacement of materials. A maintenance cost is also set as a percentage of the TPC excluding periodic replacement of materials which are defined based on the process . This cost includes the maintenance labour cost, set as a percentage of the total maintenance cost.
- *Labour costs:* Labour costs include operating labour, administrative and support labour.

2.3 Environmental

2.3.1 Greenhouse gas emissions

Greenhouse gas (GHG) emissions represent the impact on climate change and all its potential global consequences. GHG emissions are quantified for H_2-CCS chains including end-use technologies using LCA methodology. Global warming potentials (GWP) of individual greenhouse gases with a time horizon of 100 years are used according to IPCC (Stocker et al. 2013) and as implemented in SimaPro (SimaPro 2018). GHG emissions will be calculated in terms of CO_2 equivalents, either per unit of hydrogen delivered, or per unit of service provided by the use of hydrogen (e.g., per vehicle kilometre).

2.3.2 Energy efficiency

The Cumulative Energy Demand (CED) is used as measure of overall energy efficiency of H_2-CCS chains. The CED is quantified using the characterization factors for primary energy carriers (fossil, nuclear and renewables) as implemented in SimaPro (SimaPro 2018). The CED will be calculated in terms of MJ (primary energy), either per unit of hydrogen delivered, or per unit of service provided by the use of hydrogen (e.g., per vehicle kilometre).

2.3.3 Key pollutant emissions

Both direct emissions of hydrogen production processes and end use technologies as well as life-cycle emissions (covering H_2-CCS chains) of key pollutants will be quantified. Nitrogen oxides (NO_x), particulate matter (PM), sulphur dioxide (SO_2), and non-methane volatile organic compounds (NMVOC) are considered as key air pollutants, contributing to low air quality on local and regional levels. However, this quantification does not include an estimation of actual impacts of those emissions.

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2.3.4 Ecosystem damages

Negative impacts on ecosystems will be measured based on cumulative life cycle inventories and applying characterization factors according to the ReCiPe methodology (Hierarchist perspective) (Huijbregts et al. 2016) as implemented in SimaPro (SimaPro 2018). Damages to ecosystem quality will be measured in terms of time-integrated species loss due to terrestrial ecotoxicity and acidification, freshwater ecotoxicity and eutrophication, marine ecotoxicity and land use. GHG related impacts due to global warming are excluded in order to avoid overlaps with the GHG emissions indicator. Ecosystem damages will be quantified either per unit of hydrogen delivered, or per unit of service provided by the use of hydrogen (e.g., per vehicle kilometre).

2.4 Social

2.4.1 Conflict potential

The conflict potential is the potential of energy system induced conflicts based on historic evidence such as willingness of NGOs and other citizen movements to act against realisation, mobilisation potential, conflicts on local/regional/national/international level and necessity of participative decision-making processes (Volkart et al. 2016). This indicator is quantified based on expert judgement in a qualitative way and needs to be addressed in each case study individually, since social acceptance of specific technologies can be very different depending on regional/national boundary conditions.

2.4.2 Human health damages

Negative impacts on human health (HH) will be measured based on cumulative life cycle inventories and applying characterization factors according to the ReCiPe methodology (Hierarchist perspective) (Huijbregts et al. 2016) as implemented in SimaPro (SimaPro 2018). Damages to human health will be measured in terms of Disability Adjusted loss of Life Years (DALY) due to human toxicity, photochemical oxidant formation, particulate matter formation and ionising radiation. GHG related impacts due to global warming are excluded in order to avoid overlaps with the GHG emissions indicator. Human health damages will be quantified either per unit of hydrogen delivered, or per unit of service provided by the use of hydrogen (e.g., per vehicle kilometre).

2.4.3 Social costs of carbon pollution

The social costs of carbon emissions are a measure to monetize the impacts of climate change due to anthropogenic emissions of greenhouse gases (GHG). These are costs which society has to cover and they can be used for quantification of the benefits of reducing GHG emissions.
Social costs of carbon emissions are meant to be a comprehensive estimate of climate change damages and includes changes in net agricultural productivity, human health, property damages from increased flood risk, and changes in energy system costs, such as reduced costs for heating and increased costs for air conditioning. However, given current modelling and data limitations, it does not include all important damages. The IPCC Fifth Assessment report observed that social costs of carbon emissions estimates omit various impacts that would likely increase damages. The models used to develop these estimates, known as integrated assessment models, do not currently include all of the important physical, ecological, and economic impacts of

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climate change recognized in the climate change literature because of a lack of precise information on the nature of damages and because the science incorporated into these models naturally lags behind the most recent research. Nonetheless, the current estimates of the social carbon costs are a useful measure to assess the climate impacts of GHG emission changes (US EPA 2017). The social costs of carbon will be quantified either per unit of hydrogen delivered, or per unit of service provided by the use of hydrogen (e.g., per vehicle kilometre), taking into account the large range of CO_2 damage cost estimates available in state-of-the-art literature (Nordhaus 2017).

2.5 Security of energy supply

2.5.1 Non-renewable primary energy demand

Non-renewable Cumulative Energy Demand (n-re CED) is used as measure for dependency on limited fossil and nuclear primary energy resources. The n-re CED is quantified using the characterization factors for primary energy carriers (fossil, nuclear and renewables) as implemented in SimaPro (SimaPro 2018). The CED will be calculated in terms of MJ (primary energy), either per unit of hydrogen delivered, or per unit of service provided by the use of hydrogen (e.g., per vehicle kilometre).

2.5.2 Resource autonomy of energy supply chain

This indicator measures the resource autonomy of H_2-CCS chains. Use of domestic and/or storable energy resources results in a better performance than dependency on non-domestic resources (Volkart et al. 2016). The indicator is country-specific, i.e. it needs to be addressed in each case study individually, and covers complete H_2-CCS chains; The indicator is estimated in qualitative terms by expert judgement.

2.5.3 Utilization of “critical” metal resources

This “metal criticality” indicator will be calculated by linking specific metal resource flows from the cumulative life cycle inventories (LCA results on the level of individual environmental flows) and the metal criticality method developed by the European Commission (EC 2014, EC 2017). This indicator will be quantified either per unit of hydrogen delivered, or per unit of service provided by the use of hydrogen (e.g., per vehicle kilometre).

2.6 Geography related

2.6.1 Demand for CO_2 storage capacities

The required CO_2 storage capacities can be calculated from the percentage of CO_2 that is produced in the pressure swing adsorption unit and that is subsequently transported and sent for storage. These storage capacities will be quantified for each H_2-CCS chain alternative for each country case study.

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2.6.2 Demand for H_2 storage capacities

The required H_2 storage capacities depend on the hydrogen use case and will be calculated from for each H_2-CCS chain alternative for each country case study. Potentials for using existing storage infrastructure will be taken into account.

2.6.3 Extent of utilization of domestic natural gas reserves

Based on the market potential for clean hydrogen in each country case study, and the use of natural gas for hydrogen production, domestic natural gas reserves will be exploited. This measure quantifies this extent of utilization and will provide insights into the timeline of exploitation and potential needs for imports.

2.6.4 Demand for upgraded or extended pipeline network

Transport of hydrogen and CO_2 – if performed on large-scale – will require pipelines. Either existing ones will have to be upgraded, or new pipeline infrastructure will have to be built. The demand for upgrade of or new infrastructure will be quantified for each country case study, taking into account local boundary conditions, projected demand patterns and H_2/CO_2 use cases.

2.7 Technical

2.7.1 Hydrogen recovery (%)

The hydrogen recovery corresponds to the percentage of H_2 that is recovered in different stages of the process such as pressure swing adsorption unit and transportation pipes.

2.7.2 CO_2 recovery (%)

The carbon dioxide recovery corresponds to the percentage of CO_2 that is recovered in different stages of the process such as pressure swing adsorption unit and transportation pipes.

2.7.3 (V)PSA specific power use per tonne of H_2 or CO_2 (GJ/t)

All uses of power in the (V)PSA separation process have to be evaluated and summed up, including mainly vacuum and compression units.

2.7.4 CO_2 capture unit specific heat duty and power consumption (GJ/t CO_2)

Absorption-based CO_2 capture units such as the state-of-the-art amine technologies have various energy needs, mainly including the heat requirement of the regeneration, as well as the power requirements of blowers, pumps and compressors. They can be summed up in terms of GJ per ton CO_2 captured.

2.7.5 Specific CO_2 avoided (kg CO_2/kg H_2)

Depending on the H_2 production process and on the CO_2 capture technology applied, including the capture rate that can be achieved, the amount of CO_2 that is captured per kg of H_2 produced may vary. This metric allows to evaluate the reduction of the CO_2 emissions associated to the production of 1 kg of H_2.

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2.7.6 Specific primary energy consumption per tonne of CO_2 avoided (SPECCA, GJ/t)

This metric is used to compare the energy penalty of different CO_2 capture processes. Due to the fact that CO_2 capture processes require different forms of energy (heat, cooling, electricity), a rigorous assessment requires the conversion of these different energy needs into one common form of energy, i.e. primary energy. The SPECCA can either be defined in terms of process efficiency (η) and specific emissions (ϵ) or in terms of mass flow rates of fuel ($\dot{m}_F$) and CO_2 ($\dot{m}_{CO_2}$) and power (P). Power and efficiency have to be calculated based on the effective output of H_2 from the process.

$$e_{\text{SPECCA}} = \frac{\left(\frac{1}{\eta_{\text{el}}}\right)_{\text{CCS}} - \left(\frac{1}{\eta_{\text{el}}}\right)_{\text{ref}}}{\dot{Q}_{\text{ref}} - \dot{Q}_{\text{CCS}}} = \frac{\left[\left(\frac{\dot{m}_F}{P_{\text{el}}}\right)_{\text{CCS}} - \left(\frac{\dot{m}_F}{P_{\text{el}}}\right)_{\text{ref}}\right]\Delta H^{\text{LHV}}}{\left(\frac{\dot{m}_{\text{CO}_2}}{P_{\text{el}}}\right)_{\text{ref}} - \left(\frac{\dot{m}_{\text{CO}_2}}{P_{\text{el}}}\right)_{\text{CCS}}}$$

2.7.7 System efficiency – first law ($\%_{LHV/HHV}$)

A simple first law efficiency analysis of the process can serve as a first indicator in the optimization and comparison of different processes. The first law efficiency can be defined as the ratio of the calorific value of (i) the H_2 produced and (ii) the CH_4 entering the process.

2.7.8 System efficiency – second law (% exergy)

Similar to the first law efficiency, this indicator considers the ratio of exergy output and exergy input.

2.7.9 (Load) flexibility

The flexibility of the processes in following intermittent demand for H_2 and intermittent supply of CH_4 can be assessed in terms of ramping rate (% per minute) and start-up and shut-down times.

2.7.10 Technology readiness level (TRL)

Technology readiness levels (TRL) are a method of estimating technology maturity. They are determined during a Technology Readiness Assessment (TRA) that examines program concepts, technology requirements, and demonstrated technology capabilities. TRL are based on a scale from 1 to 9 with 9 being the most mature technology. The use of TRLs enables consistent, uniform discussions of technical maturity across different types of technology (Mankins 1995, EARTO 2014). TLR will be measured for all main components of H_2-CCS chains for all national case studies.

3 FUTURE EXTENSIONS AND REVISIONS

This issue 1 of the KPI specification deliverable D4.2.1 will be revised and extended based on the feedback from the complete ELEGANCY consortium, in particular from the national case study teams. The release of issue 2 is scheduled for late 2018.

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