Life Cycle Assessment of Conversion Processes for the Large-scale Underground Storage of Electricity from Renewables

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Abstract: The continuously increase of wind and solar power capacities in Europe could cause in future severe grid instabilities without the availability of sufficient backup power due to the highly fluctuating nature of those renewable power sources. One option for balancing the grid is energy storage. Germany has a high incidence of natural geological storages in the form of large-scale underground salt domes, which are located in the north of the country close to the North Sea. Therefore this thesis performs a life cycle assessment on the time horizon of the year 2030 for three different pathways that use offshore wind electricity for converting electricity into gases, namely "compressed air", "hydrogen" and "methane", which are conditioned, stored in salt caverns, transported and afterwards re-electrified in times when backup power is needed to stabilise the grid. The author concludes that compressed air is only suitable for balancing hourly fluctuations, for a longer time scale, the energy carriers with higher volumetric energy densities (hydrogen and "power to gas" methane) seem to be appropriate solutions.

1 Introduction

The main problem for renewable energies is how to include high shares of this fluctuating production in a system that changes instantly with the consumption. One of the alternatives is energy storage, but which technology is appropriate in the scale of a nation electrical system?

When large storage capacities are needed, only the alternatives with high energy densities are suitable. Considering that Germany has a big potential of natural storage in the salt domes located on the north region of the country, this study aimed to compare the use of the suitable technologies for the storage of electricity produced using the planned offshore wind future capacity from the North Sea.

The main question this study tried to answer was: What is the best alternative for Europe for the underground storage in salt caverns of offshore wind renewable energy from the North Sea for 2030 and how much of the needed storage capacity can be covered with the selected technology?

One of the first tasks in the study was to stablish the future perspective for wind power in the North Sea for the time horizon of the analysis. Table 1 shows the offshore and total wind capacity for 2010 and the expected 2030 capacity.

Table 1: Actual and future's capacity of offshore wind energy in the North Sea region and the cumulative installed electricity production capacity.

Installed Power Capacity[MW]				
Year	2010		2030	
Country	Offshore Wind	Cumulative	Offshore Wind	Cumulative
Belgium	195	18 322	3 794	24 782
Denmark	854	13 707	3 800	14 203
Germany	92	153 224	20 000	206 739
Netherlands	247	26 615	12 122	35 623
UK	1 341	93 452	38 250	120 614
Total	**2 729**	**305 320**	**77 966**	**401 961**
Reference	(EWEA 2011a)	(EIA 2013)	(Heinemann 2012)	(Capros, et al. 2010)

The second task of the study was to define the storage capacity that was going to be considered for the calculations. Heide et al. (2010) estimated the required storage energy capacity for a simplified European scenario based on 100% wind and solar power generation. The required maximum stored energy is considered to be 1.5 times the monthly load without storage losses (1.8 for hydrogen storage considering an efficiency of 60% for storing the hydrogen and again 60% for its re-electrification) and amounts to 400 TWh (or 480 TWh in the case of hydrogen).

But how much of this requirement can be fulfilled by European caverns? To answer this question it was necessary to search about these underground formations. As stated by the LBEG (2012) there was an operating total work-gas volume in Germany of 9993 million (Nm^3) i.e. at 101,325 Pa (1,013 bar) and 0°C, at the end of 2011 in 207 individual caverns.

The planned and, at that time, in construction sites had a total work-gas volume of 10854 million normal m^3 for a total of 160 individual caverns. The work-gas volume is the actual useful storage volume that is introduced or taken from the cavern in normal m^3.

A data base of the gas storage capacity produced by the working committee 2: Storage, part of the International Gas Union, is used to derive the data for Europe, cf. IGU (2009). In total there was an operating total work-gas volume in Europe of approximately 10 309 million m³ in 2009 in 240 individual caverns (Germany with a total of 7 886 million normal m³, approximately 77%, in 173 caverns). The planned sites had a total work-gas volume of 19 621 million (Nm³) for a total of 235 individual caverns in 2009 as well (Germany with a total of 11 964 million normal m³, approximately 61%, in 125 caverns).

In the year 2030 Germany could reach a work-gas volume of around 16 600 million (Nm³), which is a personal estimation fitting the LBEG data with a second grade polynomial equation. If all the planned sites mentioned in the IGU (2009) database are developed for 2030, there will be a total work-gas volume capacity in Germany of approximately 20 000 million normal m³ (in Europe around 30 000 million of normal m³).

Now, with all these input the most relevant topic was: How much wind energy can finally be stored in the caverns? In order to find this amount of energy it was necessary to go through the complete process of energy conversion since it is generated in the wind power plants until it is finally used, after been stored for a while. There are three energy vectors or paths in which energy could be stored: compressed air, hydrogen or methane. In the following images the processes are briefly described. The analysed scenarios were derived from these main paths.

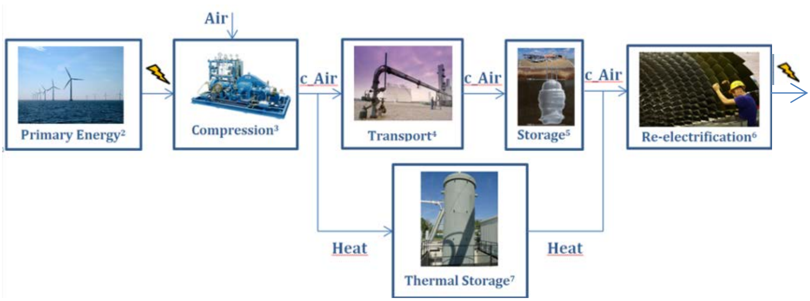

Figure 1: Simplified diagram of a CAES process.

Sources of pictures: [2]buildaroo.com, [3]andreas-hofer.de, [4]personal.psu.edu, [5]trianel.com, [6]boston.com and [7]alsolen-alcen.com.

The path based on compressed air starts with the primary energy in form of electricity produced by the wind turbines of the North Sea. This energy is used to compress the air using air compressors. Then, the compressed air is transported, stored on caverns, heated again with the stored heat from the TES (thermal energy storage) and used in an air turbine or expander when needed. The process scheme for this option is presented in figure 1.

The hydrogen process (see figure 2) is very similar to the CAES; now an inverter is needed to transform AC current to DC current, which is required by the electrolysis process that separates water into hydrogen and oxygen. A solid oxide fuel cell (SOFC) or a gas turbine combined cycle (GTCC) is used for the re-electrification.

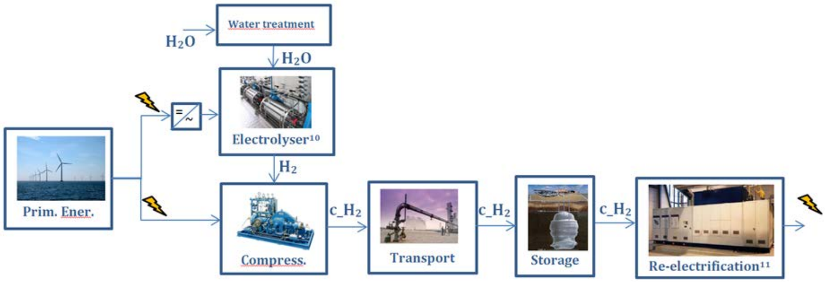

Figure 2: Simplified Diagram of a HES Process

Sources of pictures: [10]itm-power.com and [11]fuelcell.no. For sources of repeated pictures see previous diagrams.

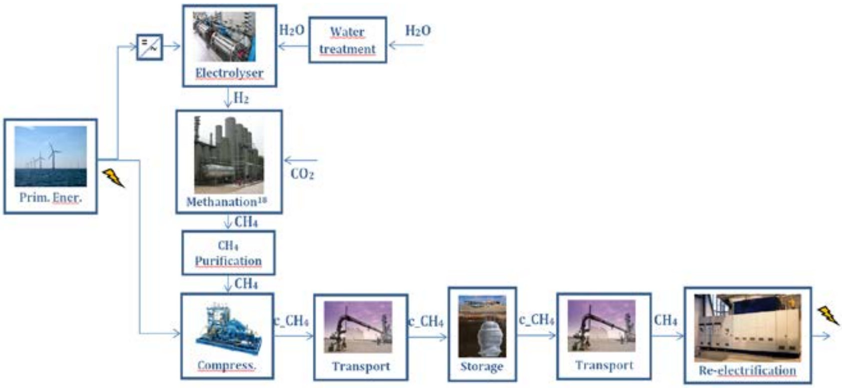

Figure 3: Simplified Diagram of a MES Process.

Sources of pictures: [18]chemchina.com. For sources of repeated pictures see previous diagrams.

Finally, the methane based alternative shown in figure 3, includes a methanation process, to combine hydrogen and CO_2 into methane, the rest of the operation is similar to the HES one, with SOFC or a GTCC for the re-electrification. As no pure methane can be obtained an additional step of methane purification is also needed.

2 Methodology

2.1 Life cycle assessment (LCA)

LCA is a methodology used to compile and evaluate inputs, outputs and potential environmental impacts of a product system based on a defined functional unit (FU). This methodology is standardised according to EN ISO 14040 (Technische Unterkomitee ISO/TC 207/SC 3 "Life Cycle Assessment" 2009) and EN ISO 14044 (Technische Unterkomitee ISO/TC 207/SC 3 "Life Cycle Assessment" 2006). The original thesis describes in detail the main phases and elements of this methodology, for more detail please refer to the EN ISO standards.

This paper will only mention the main structure of an LCA, which comprises four main phases:

- Goal and scope definition
- Inventory Analysis (LCI)
- Impact Assessment (LCIA) and
- Interpretation

The goal of a LCA shall state unambiguously its intended application, the reasons for making the study, the intended audience and whether the results are intended to be used in comparative assertions open to the public.

The scope definition shall consider and describe the following elements:

- Product system to be studied
- Functions of the product system
- Functional unit
- System boundaries
- Allocation procedures
- LCIA methodology and the types of impacts
- Used interpretation
- Data requirements
- Assumptions
- Value choices and optional elements
- Limitations
- Data quality requirements

- Type of critical review
- Type and format of the report required for the study.

To describe the functions of the product system, a so-called functional unit is used to provide a reference to which the input and output data are normalised, therefore it should be clearly defined and measurable. In comparative studies, different systems shall be compared using the same functional unit and equivalent methodological considerations.

The LCI is the phase of the LCA involving the compilation and quantification of inputs and outputs for a product throughout its life cycle. The LCI starts with the collection of data for each unit process included within the system boundary. The data is used to quantify the inputs and outputs of a unit process.

The LCIA phase is aimed at understanding and evaluating the magnitude and significance of the potential environmental impacts for a product system throughout the life cycle of the product and for doing so, it includes a collection of indicator results for different impact categories which represent the LCIA profile for the product system.

Impact categories are classes that represent environmental issues of concern to which LCI results may be assigned. The category indicators are quantifiable representations of these categories. Characterisation models are applied to convert an assigned LCI result to the common unit of the category indicator; therefore the characterisation is the calculation of category indicator results and involves the conversion of the LCI results to common units using characterisation factors and the aggregation of the converted results within the same impact category.

The resulting data after characterisation is represented by an LCIA profile. An LCIA profile is a discrete compilation of the LCIA category indicator results, for the different impact categories. The data can also be represented by a set of inventory results that are elementary flows but not assigned to impact categories or sets of data not representing elementary flows.

Interpretation is the phase in which the findings from the LCI and LCIA are considered together and it shall include an assessment and a sensitivity check of the significant inputs, outputs and methodological choices in order to understand the uncertainty of the results.

In the following paragraphs several relevant definitions of the LCA performed thorough all the thesis are defined for a better understanding of the results presented in this paper. Further aspects of this methodology, as basic assumptions, quality aspects and more extensive phases as the LCI and LCIA should be checked in the original thesis.

2.1.1 Goal

The goal of the LCA analysis was to provide and compare the energy efficiency and the greenhouse gas direct emissions of different scenarios for large-scale underground gas storage of renewable energy in salt caverns including the re-electrification phase.

The conversion processes from electricity to stored gas analysed are:

- Air compression
- Water electrolysis
- Methanation

The re-electrification technologies which define the 4 scenarios include:

- Air expanders for compressed air
- Fuel Cells for hydrogen and methane storage
- Gas turbines for hydrogen and methane storage

The energy stored is produced intermittently with wind energy converters in offshore power plants. Costs were not considered in this analysis but they are expected to be included in a later work.

2.1.2 Summary of the scope definition

The study is a comparison of three different energy conversion paths analysing their efficiencies and their direct carbon dioxide equivalent emissions. The considered efficiencies for the sub-processes are the ones found in literature available at the time in which this study was done; in most of the cases the highest efficiency is considered assuming that for 2030 those efficiencies will be state-of-the-art.

Since all pathways make use of the electricity provided by offshore wind energy plants, the analysis of this initial energy conversion process i.e. wind to electricity, is not included in the workbooks.

2.1.3 Functional unit

The functional unit is 1 MWh of electricity provided to the grid as balancing power after re-electrification.

2.1.4 Selection of impact categories

In order to simplify the analysis only cumulative energy demand (CED) for providing one Megawatt hour (1 MWh) of backup power after re-electrification and the related greenhouse gas potential expressed in kilograms of CO_2 equivalent emissions (kg of CO_2 eq.), including the CO_2 and CH_4 direct emissions, were selected as impact categories.

The CED represents the direct and indirect energy throughout a product's life cycle, including the primary energy and the energy consumed along the whole process chain. Therefore it represents the amount of energy invested in the storage process in MWh per MWh of electricity delivered. The primary energy demand (PED) is also used in the figures presented in the thesis and it is an indicator that considers only the primary energy invested during the processes. The PED and the CED are therefore related through the following equation:

$$\mathrm{CED} = \mathrm{PED} + 1\ \mathrm{MWh}$$

The PED and the total process efficiency are related as well, through the equation:

$$h = 1/\ \mathrm{PED}$$

The results related to the CED are presented in this paper as efficiencies in order to help the reader to reach a better understanding of the graphics comparing the different scenarios.

Climate change is the impact of human emissions on the radiative forcing of the atmosphere, causing an increase on Earth’s surface temperature i.e. greenhouse gas effect as mentioned in Hake, et al. (2004). The global warming effect is used as indicator cf. IPCC (2005) using kilograms of CO_2 equivalent emissions (kg of CO_2-eq) as unit.

2.2 Software tools and data sources

The tools used for calculations are based on the results spread sheet used in the NATURALHY project (University of Loughborough 2004). The standard results format for recording, calculating, presenting and comparing results of the LCA study is based on MS Excel workbooks. Each technology is represented by a single standard workbook composed of a series of linked worksheets. Each spreadsheet incorporates key parameters which has the most significant influence on the results derived for the technology. By careful selection of these parameters and preparation of appropriate relationships within the worksheets, it is possible to produce results which represent expected circumstances. The basic outputs are specific results, or point values, which reflect specific circumstances for each technology at a given point in time. For further detail please refer to the original thesis.

2.3 Limits and sensitivity of LCA results

The derived scenarios are constructed from the sub-processes needed to convert wind energy into a storable gas and then back to backup electricity to offer the grid balancing services.

These sub-processes have limitations due to data availability, limited time for data acquisition, limited resources for the development of the study and data quality among others. These limitations have an effect on the total process and therefore on the LCA results. Sensitivity analysis was performed to investigate the effect of changing specific parameters in different stages of the processes. All limitations and data quality are clearly stated on the thesis. Among others, some important limitations, defined in the scope of LCA, are:

- Only CO2 and CH4 direct emissions are considered
- Only cradle-to-usage analysis, no decommissioning of plants
- The calculations have been performed by considering all technologies state-of-the-art for the according time horizon, i.e. 2030.

2.4 Definition of scenarios

Three main scenarios were derived from the 3 energy conversion paths (see figure 4), Scenarios AA-CAES for the compressed air path (group 1), HES for the hydrogen path (group 2) and MES for the renewable methane (or "power to gas") case (group 3).

Process segments were used to classify the different sub-processes in common stages. The first process segment, characterized in the figures through the entire document with the colour blue is "electricity transmission". This segment includes the transport of the renewable electricity from the offshore wind power plants to the process plant, were the storage equipment and the process plant is installed.

A second process segment called "electricity conversion" and represented with pink colour, comprises the means used to transform the renewable electricity into compressed air, hydrogen or methane and even into heat.

"Gas conditioning and storage" encloses a third segment mirrored through green colour. In this stage, the energy vector is conditioned and stored in the underground storages.

The fifth segment, "transport of energy carrier" (yellow), includes the pressure and fluid losses in the piping systems; and finally the "re-electrification" process segment in red, which takes into account the equipment and technologies applied for the re-conversion of the energy vectors into back-up electricity for grid balancing services.

The creation of two more scenarios was needed to include two different technologies for the production of electricity from hydrogen in case of group 2 (HES), and from methane in case of group 3 (MES scenarios): I) solid oxide fuel cells (SOFC) and II) gas turbine combined cycles (GTCC); giving birth to 5 scenarios in total: AA-CAES (scenario 1), HES-SOFC (scenario 2-I), HES-GTCC (scenario 2-II), MES-SOFC (scenario 3-I) and MES-GTCC (scenario 3-II). All these scenarios were analysed in the thesis in order to assess the cumulative energy demand (CED in MWh) and direct greenhouse gas emissions (CO2-eq. in kg) to provide the functional unit (FU).

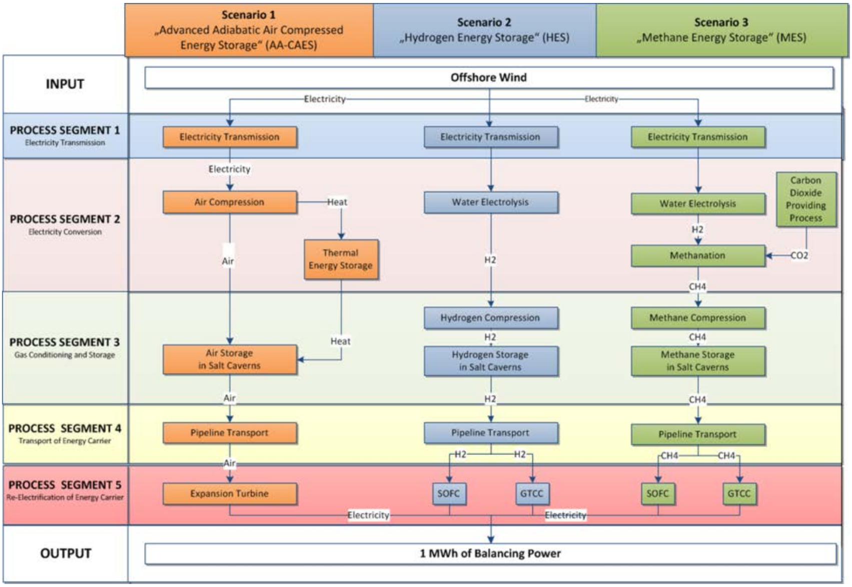

Figure 4: Different routes to convert electricity produced from wind energy offshore farms into stored gas i.e. methane, hydrogen and compressed air. After the compression process, the three compressed gases of the three possible paths are being sent to the storage caverns and are being re-electrified by the grid, when needed. The result is 1 MWh of balancing power (Functional Unit).

Additionally, 3 more sensitivity scenarios analysed the impact of the carbon dioxide source in group 3-I. Carbon capture and sequestration (CCS) of CO_2 from thermal power plants was assumed to be one of the sources for the needed carbon dioxide for the 2030 time horizon of the study. The impacts of the CCS processes on the reference power plant efficiency according to IPCC (2005) were used to calculate the required energy in kWh/Nm³ of CO_2. The resulting range is included in the efficiency process chain to analyse the sensitivity of the CO_2 source. The other source considered was CO_2 production from atmospheric air.

The three derived scenarios are MES-SOFC-CCS_GTCC (scenario 3-Ia) which considers a CCS process applied to a GTCC power plant as CO_2 source, MES-SOFC-CCS_PC (scenario 3-Ib), using a CCS process applied to a pulverized coal (PC) power plant and finally, MES-SOFC-CCS_Air (scenario

3-Ic) which considers CO_2 production from atmospheric air, a highly energy intensive process. More scenarios are included in the thesis but are not mentioned in this paper; please refer to the original thesis in order to read about the impact of the possibility of CO_2 recycling or about the dependence of MES and HES energy conversion pathways on electrolysis.

The most important assumptions and references considered in the study are shown in table 1.

Table 2: Main assumptions and references

Paramater	Value	Unit	Reference
Compression efficiency	84,5	%	(Freund, Schainker and Moreau 2012)
Air transport losses	4	%	(Crotogino 2012-2013)
Expansion efficiency	89,5	%	(Freund, Schainker and Moreau 2012)
Shaft mechanical efficiency	99,5	%	(Freund, Schainker and Moreau 2012)
Generator/motor efficiency	98,5	%	(Freund, Schainker and Moreau 2012)
TES efficiency	90	%	(Hänchen, Brücker and Steinfeld 2011)
Cavern wellhead pressure, max., charging for air	60	bar	(Crotogino 2012-2013)
Cavern wellhead pressure, min., discharging for air	40	bar	(Crotogino 2012-2013)
Electrolyser efficiency (LHV)	73	%	(Smolinka, Günther and Garche 2010)
Hydrogen compression efficiency	98	%	(Gardiner 2009)
Hydrogen transport losses	2,4	%	(Bossel, Eliasson and Taylor 2003) and (Feck 2009)
Cavern wellhead pressure, max., charging for H_2 & CH_4	180	bar	(Crotogino 2012-2013)
Cavern wellhead pressure, min., discharging for H_2 & CH_4	60	bar	(Crotogino 2012-2013)
Methanation efficiency (LHV)	83,3	%	(Zuberbühler 2013)
Methane compression efficiency	96,4	%	(Bossel, Eliasson and Taylor 2003)
Transport losses	0,8	%	(Bossel, Eliasson and Taylor 2003) and (Feck 2009)
CCGT efficiency (LHV)	63	%	(Kobayashi, et al. 2011)

Paramater	Value	Unit	Reference
SOFC efficiency (LHV)	70	%	(Steinberger-Wilckens 2012)
Cavern wellhead pressure, max., charging	180	bar	(Crotogino 2012-2013)
Cavern wellhead pressure, min., discharging	60	bar	(Crotogino 2012-2013)

3 Results

3.1 Overall energy efficiencies

Figure 5 presents a comparison of the efficiencies of each scenario and how they develop through the different process stages.

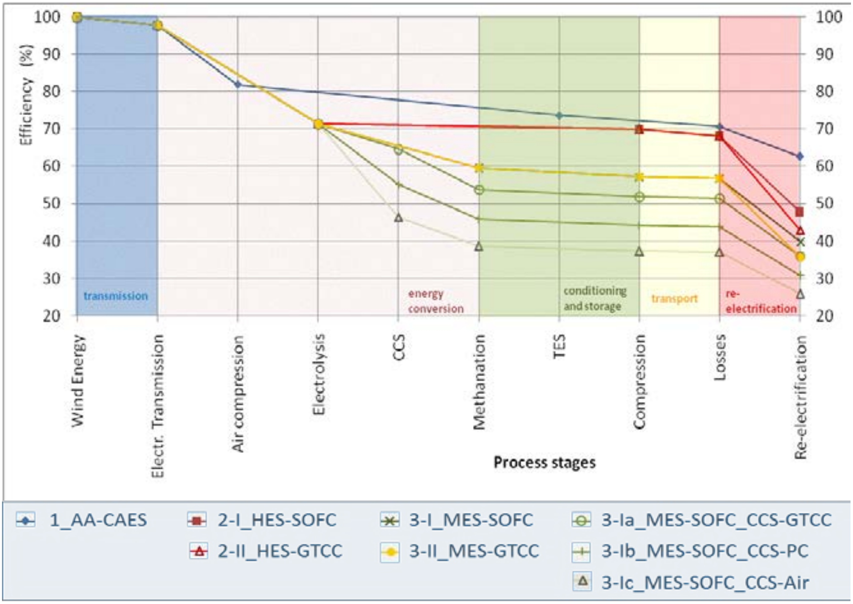

Figure 5: Decrease of efficiency of 8 representative scenarios through the process segments.

The highest efficiency value for a complete process was reached by the AA-CAES scenario i.e. 63%. In second place come the HES scenarios, with 48% efficiency for the scenario using SOFC technology for re-electrification and

43% for the one using GTCC. MES scenarios result in the lowest efficiencies: 40% for the SOFC (scenario 3-I) and 36% for the GTCC (scenario 3-II).

Considering the decrease of efficiencies due to the CO_2 source in the MES SOFC scenarios, the percentages drop to 36% if CO_2 is obtained from a CCS process applied to a GTCC power plant (scenario 3-Ia). When the source is a new supercritical pulverized coal power plant the efficiency decreases to 31% (scenario 3-Ib) and if CO_2 comes from atmospheric air the efficiency yields 26% (scenario 3-Ic).

In Scenario 1, the most important decrease of efficiency is observed in the air compression process (part of the energy conversion segment), but also in the re-electrification through air expanders. For the rest of the scenarios the energy conversion and re-electrification segments are of great significance as well. The only exception to the rule is the MES scenario using CO_2 extracted from atmospheric air; in this scenario the CO_2 production is almost as energy intensive as the electrolysis process, overpassing the re-electrification process in energy requirements.

The production of hydrogen and methane requires big amounts of energy and this is reflected in the graph. Electrolysis seems to be the process that will require further development in order to optimize the methane and hydrogen paths. High temperature electrolysis (HTE) represents a good opportunity for improvement, an absolute increase of more than 11% in the efficiency of the HES processes or more than 8% for the MES processes could be expected if HTE reach 90% LHV efficiencies (the theoretical maximum value).

The greatest difference between scenario 1 (AA-CAES) in one hand and scenarios 2-I and 2-II (HES-SOFC and HES-GTCC) in the other hand, is the decrease in efficiency due to the re-electrification process. GTCC already reached a level of matureness and it will be very difficult for this technology to achieve higher efficiencies, but SOFC is quite new, and it is possible that in a mid-term period higher efficiencies could be accomplished giving HES the chance to get closer to AA-CAES efficiencies.

3.2 Direct emissions

As shown in figure 6, no direct emissions of equivalent carbon dioxide arise in the AA-CAES and HES pathways. MES scenarios do produce important quantities of equivalent carbon dioxide, yielding values as high as 338 kg per MWh of back-up electricity (MWhe) in case of scenario 3-II.

An interesting opportunity was also considered in the thesis in order to reduce these high emissions: capturing and reusing the CO_2 after the re-electrification processes. It was shown in the sensitivity analysis that this possibility could reduce the equivalent CO_2 emissions to 17 kg per MWhe, considering the CO_2 capture rates of 90% and 97% presented in IPCC (2005).

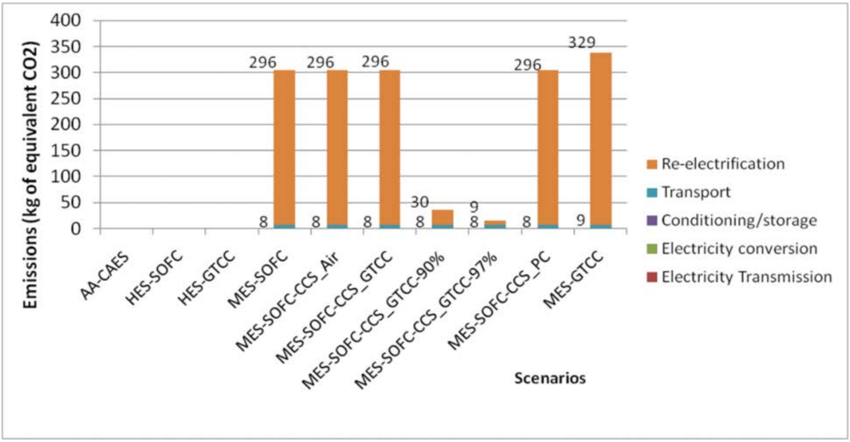

Figure 6: Direct emissions of equivalent carbon dioxide

3.3 Energy stored along the different pathways

The energy that can be stored using the 3 considered gases was computed using the efficiencies presented in figure 5 and the storage salt cavern capacities introduced at the beginning of this document.

Starting from the normal volume (30 000 million m³ of working natural gas) it is possible to know the cavern's volumetric capacity of the underground storage in Europe using the densities of methane as an approximation (natural gas has very high shares of methane i.e. 97%) at normal conditions and at the cavern conditions (180 bar and 50°C). This volumetric capacity is actually 169 million m³.

The 2030 expected gross electricity generation for Europe is 4073 TWh (Capros, et al. 2010). The monthly production multiplied by a factor of 1,5 (Heide, et al. 2010) gives the maximum required stored energy for that year, roughly 500 TWhe.

For AA-CAES with a volumetric energy storage density of 2,1 kWh/m³ at a mean storage density the total energy that could be stored in this volume is 0,35 TWh and after re-electrification 0,3 TWhe would be available. Less than one hour of the 2030 Europe's electricity demand mentioned in the previous section could be continuously supplied by underground storage of compressed air i.e. short term storage. This scenario shows that the AA-CAES technology is not enough for middle-term or long-term storage, but suitable for hourly grid balancing.

Considering an average capacity factor of 42,8% for Europe for 2030 (EWEA 2011a) and the 78 GW offshore wind capacity for 2030 (see Table 1), the maximum energy that could be produced by all the offshore capacity in the North Sea is 292 TWh during a complete year. 0,5 TWh of electricity will have to be produced in the offshore wind energy plants of the North Sea to convert it into compressed air i.e. only 0,2% of the 292 TWh.

In the case of hydrogen 45,6 TWh could be stored if a volumetric energy storage density of 270,4 kWh/m³ is used, after the re-electrification process 31,9 TWhe would be available. With this energy around 3 days could be continuously supplied by underground storage of hydrogen considering the 2030 Europe's electric energy demand. Hence, hydrogen storage is suitable for middle-term storage. This stored energy represents only a 6,4% of the 500 TWh assuming a 100% renewable scenario based on solar and wind energy only.

66,8 TWh of electricity would need to be produced in the wind plants in order to store the 31,9 TWhe. 139,6 TWhe could be stored and re-electrified from the total 292 TWh from the offshore wind power plants but, due to the low energy density of hydrogen only the 31,9 TWhe mentioned can be stored in the salt caverns (only a ~23%). This means that 17,8 GW of offshore capacity would be sufficient to fill the storage capacity with hydrogen.

For methane with an energy density of 1166,1 kWh/m³ a total of 196,8 TWh of energy could be stored, meaning that after re-electrification 137,7 TWhe would be available. Approximately 13 days of the 2030 Europe's electricity demand can be continuously supplied with methane stored in salt caverns i.e. long term storage. This stored energy represents only a 27,5% of 2030`s required 500 TWh assuming a 100% renewable scenario based on solar and wind energy only.

381,5 TWh of electricity will have to be produced in the offshore wind energy plants in order to completely fill the salt caverns with renewable methane, more than the available in 2030. Thus 89 TWh should be provided by other energy source to fill completely the salt caverns.

In order to offer the reader a clearer picture of the results, Table 2 presents a summary of the calculations explained above. A reference value (Donadei and Crotogino 2009) for the energy densities is also included in this table to be compared with the ones used.

In this table, the total energy after storage in the salt caverns considers the total Europe's volume capacity, the energy density values and the total efficiencies.

The total time considers the 2030 total generation capacity of the North Sea countries. The needed energy production is the offshore wind energy needed to produce the total energy stored in the salt caverns i.e. not considering the re-electrification efficiencies. The last column is the energy after the storage and re-electrifying processes if the complete 78 GW 2030 offshore capacity is used for the gas production and storage considering the process efficiencies.

Table 2: Comparison of storage capacities

	Energy Density (kWh/m³)	Reference energy density (kWh/m³)	Total energy after storage (TWh_e)	Total days of production of 2030 energy demand	Total Efficiency (%)	Needed energy production (TWh)	Needed offshore capacity (GW)	Energy 78 GW offshore capacity (TWh_e)
AA-CAES	2,1	2,4	0,3	0,03	62,5	0,5	0,1	183,4
HES	270,4	280,0	31,9	3,14	47,6	66,8	17,8	139,8
MES	1166,1	1100,0	137,7	13,5	36,1	381,5	101,8	105,6

4 Conclusions and recommendations

4.1 Efficiencies

The most efficient process for underground storage is compress air storage, namely scenario 1 AA-CAES with an efficiency of 62,5%. This scenario is based on the advance adiabatic compressed air energy storage technology and on air expanders (turbines) for the re-electrification of the stored compressed air and heat.

At the second place regarding efficiency is scenario 2 HES-SOFC, using hydrogen production with electrolysers and compressed hydrogen stored in salt caverns, with 47,6%. The re-electrification in this scenario is performed through solid oxide fuel cells.

In third place, with an efficiency of 36,1% is the 3b_MES-SOFC-CCS_GTCC scenario. This scenario is based on the production of renewable methane from hydrogen generated through electrolysis and CO_2 from a carbon capture and sequestration process integrated to a gas turbine combined cycle power plant.

The re-electrification of the renewable methane stored in the salt caverns is performed through solid oxide fuel cells.

4.2 Storage capacities

With a capacity of only 0,5 TWhe AA-CAES in salt caverns is only suitable for short term storage. If HES is used, from a total 139,6 TWhe of energy that could be produced from the offshore wind capacity in 2030 only 31,9 TWhe can be stored in the salt caverns (only ~23%) due to the low energy density of hydrogen and the limited storage volume. This energy is equivalent to more than 3 days of the required storage capacity of 2030. This capacity makes HES insufficient for Europe's 2030 needs of long term storage for seasonal balancing.

Underground gas storage in salt caverns is capable of supplying 27,5% of the 2030 Europe's required storage capacity i.e. 500 TWhe (for a 100% renewable scenario) using MES from offshore and from an additional energy source. This balancing power can supply electricity to the grid during slightly more than 13 days, considering a monthly 2030 Europe's electricity production of 339 TWh. The efficiency is lower but the volumetric energy density of renewable methane is very high.

If only the offshore wind power plants are used for the renewable methane production only 105,6 TWhe (~77% of the total 2030 salt caverns capacity) can be filled with renewable methane. It will be necessary to use more renewable energies to fill the underground storage capacity, 38 GW in case onshore power plants are used.

4.3 Emissions

In total 304 kg/MWhe of equivalent CO_2 are emitted with MES technology (MES-SOFC scenarios), but if a CCS plant is integrated in the re-electrification stage to recycle the CO_2, only 16,7 kg/MWhe of equivalent CO_2 would be released to the atmosphere, considering CO_2 capture rates of 97%. The MES and HES scenarios release no direct emissions to the atmosphere.

4.4 Recommendations

Research and development should be concentrated in the high temperature electrolysis process in the case of HES and MES. Regarding the AA-CAES the increase of the efficiencies of the compression and expansion stages should be the main research and development objective.

The use of additional storage capacity like the one in aquifers or depleted oil and gas fields should be considered as well.

The AA-CAES technology is not sufficient for the long term balancing of the European grid and HES will require much more storage volume. The only suitable alternative that, according to the present work, can be used as part of the solution is the MES technology and the scientific efforts and research should be concentrated on its improvement.

To provide a complete picture and final recommendations a deeper analyses and a life cycle cost analysis of the scenarios defined in this thesis have to be performed. This will be part of future works of the author the supervising research institutions of the thesis.

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