Impact on the environment and the economy of technological innovations for the Innovation Fund

Impact on the Environment and the Economy of Technological Innovations for the Innovation Fund (IF)

in the Fields of :

Energy-intensive Industries,
Renewables,
Carbon Capture and Storage / Use (CCS/CCU),
Energy Storage

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Directorate-General for Climate Action
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EXECUTIVE SUMMARY

The aim of this report is to provide insights into:

- Which impacts an exemplary set of technological low-carbon innovations promoted by the Innovation Fund (IF) in the fields of energy-intensive industries, renewables, Carbon Capture and Storage CCS/ Carbon Capture and Use CCU and energy storage could have on the environment;
- The order of magnitude of investments in innovative demonstration projects that would fall within the scope of the Innovation Fund and how this relates to the available funding.

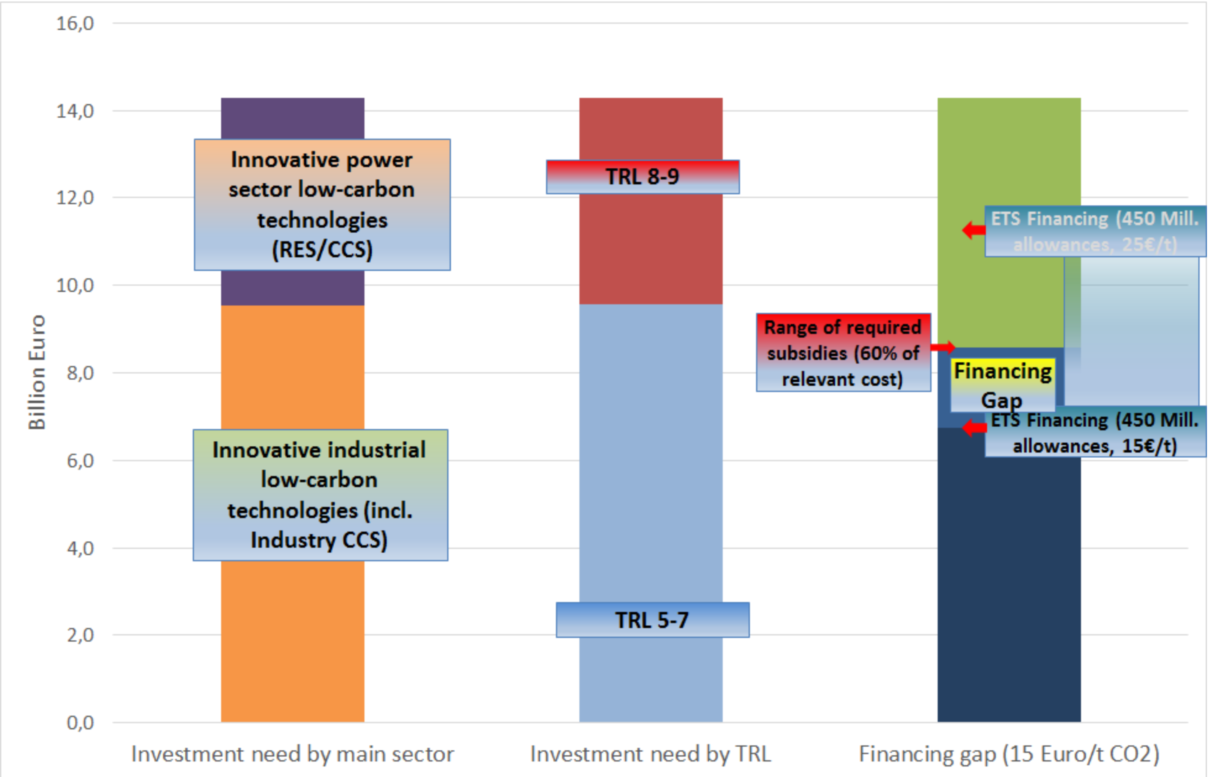
Summed over subsectors and sectors, the total CAPEX range to be financed amounts to EUR 55-68 bn: Energy Intensive Industries EEI (incl. industrial CCS and Carbon Capture and Use CCU) around EUR 31-42 bn, Carbon Capture and Storage CCS (under the assumption of 1 to 2 projects to demonstrate the technology) EUR 0.5-2.8 bn, RES Generation for Wind, bio (including transport), solar PV, hydro and other renewables around EUR 15 bn, RES Transmission/Distribution/Storage around EUR 8 bn.

The exemplary set of innovative low-carbon technologies identified, described and analysed in detail, based on sectoral workshops carried out in the first half of 2017, completed with further literature research and results drawn on two energy system models (FORECAST Industry (energy intensive industries) and ENERTILE (RES and CCS) allows to draw the following conclusions. The exemplary set of technologies is intended as a minimum coverage for the IF.

- The overall GHG reduction potential for the exemplary set of innovative industrial technologies covered by the IF is of the order of 8.3 Mt CO_2eq. (with 2015 emission factors for electricity) and about twice, 19.4 Mt CO_2eq. (with 2050 emission factors for electricity). The latter presents about 2-2.5% of the overall industrial emissions under the ETS of today.
- For innovative power sector low-carbon technologies, the overall GHG reduction is of the order of 3.8 Mt CO_2eq. (with 2015 emission factors for fossil fuel based electricity generation) and 1.7 Mt CO_2eq. (with 2050 emission factors for fossil fuel based electricity generation which still is supposed to be present in the power mix by then, mostly as natural gas).
- The total investments to be triggered by the exemplary set of technologies covered by the IF is about 9.5 billion Euro for innovative industrial low carbon technologies in terms of full investments, and roughly half or 4.5 billion Euro in terms of differential investments, i.e. compared to the reference technology.
- Total investments related to innovative power sector low carbon technologies are about 4.7 billion Euro.
- In total, around 14.2 billion Euro full investments are to be covered by the exemplary IF in order to demonstrate the set of innovative low carbon technologies.

The Innovation Fund volume shall be based on 400 million allowances reserved from 2021 onwards for the purpose of the technology support. In addition, a further 50 million of unallocated allowances from 2013-2020 will be added, together with, as early as 2019; any possible un-used or remaining funds from the NER 300 Programme. Further 50 million allowances could be added to the fund post 2025, if these are not used for free allocation to industry.

The figure below presents the financing needs and the financing gap for the exemplary IF discussed here, if it would provide grants financing only.



Financing needs and financing gap for the exemplary IF

The gap is to be covered by other financing instruments. The main observations are the following:

- Total investment needs for the exemplary set of innovative technologies amount to around 14 billion Euro (initial full cost investment for a first-of-a-kind plant). The approach in the present report leads to a minimum investment volume compared to the maximum range of 55-68 billion Euro estimated, where a certain diversity or redundancy is admitted for individual process routes, i.e. for individual technology routes several innovative technological variants are included (e.g. different variants of carbon capture and storage for steel making).
- The financing needs of the exemplary set of technologies are composed to about two thirds by lower TRL (5-7) and one third by higher TRL (8-9).
- Assuming that the exemplary IF would provide only grant financing at the rate of 60% of relevant costs, the required range of subsidies is in the order of 5.7 - 8.6 billion Euro. Total pre-financing required could be 3.4 billion Euro (based on 40% pre-financing allowed under the revised ETS Directive). The lower subsidy level is valid if the subsidies are mainly required for the lower TRL projects, while the upper limit would apply if all TRL projects are to be supported. The upper limit is therefore a theoretical limit, as a number of projects may not be in need of subsidies but rather risk sharing instruments.
- On the other hand, based on an amount of 450 million allowances and the present carbon price of 15 €/t (average over the last year), the gap to be covered for the exemplary IF by grants, compared to the available 6.75 billion Euro, is not

existing (lower TRLs subsidised only) or up to 1.8 billion Euro (all TRL subsidised). It should be noted that financing instruments may, in principle, also be relevant for the investments in low-carbon technologies with higher TRLs while lower subsidies might be granted for high TRLs.

- From this comparison it appears that given current carbon prices, the investments into exemplary technologies could be largely or totally covered by grants. However, as stated previously, the exemplary IF modelled here with investments in the range of 14 billion Euro should be compared to the 55-68 billion Euro estimated in Chapter 2, where a certain technology diversity is admitted for individual process routes (i.e. for individual technology routes multiple innovative technologies are included). This implies a considerable gap compared to the supposed available subsidies in 2020, and raises the issue of additional financing instruments beyond grants, even of only part of the enlarged technology pool is to be covered.
- In recent times the carbon price has been increasing and is at present reaching levels of over 20 €/t, with an average of 15 €/t. The expectation is that the carbon price will rise over the next decade[1]. We carry out a sensitivity calculation with a carbon price of 25 €/t which may be relevant for the start of the next decade while, at the end of the decade, the price could be well beyond 25 €/t (some project more than 50 €/t[2]). If the carbon price reaches 25 €/t (resulting in 11.3 billion Euro available for grants), the subsidy requirements of the exemplary technology set is by far exceeded, and a larger number of innovative technologies could be supported (with investments in the range of 19 billion Euro)). However, even then, in order to cover the enlarged technology pool, additional financing resources would be, complementing the IF.

Under the assumption of market uptake by 2030 (replication of at least 1-2 times of the technologies promoted under the IF), additional impacts can be achieved for GHG reduction, reaching a range of 177-380 million t CO_2 equivalents from the combined effects of the IF and market uptake by 2030 covering industry and the power sector (10-22% of the EU ETS emissions), depending on blending of grants with further Financial Instruments such as loans or guarantees.

[1] EU Reference Scenario 2016 Energy, transport and GHG emissions. Trends to 2050 https://ec.europa.eu/energy/sites/ener/files/documents/20160713%20draft_publication_REF2016_v13.pdf

[2] https://www.carbontracker.org/eu-carbon-prices-could-double-by-2021-and-quadruple-by-2030/

1 INTRODUCTION

The aim of this report is to provide insights into:

- Which impacts an illustrative set of technological innovations promoted by the Innovation Fund (IF) in the fields of energy-intensive industries, renewables, Carbon Capture and Storage CCS/ Carbon Capture and Use CCU and energy storage could have on the environment and
- The order of magnitude of investments in innovative demonstration projects that would fall within the scope of the Innovation Fund.

The exemplary selection of technologies is based on presentations during several expert round table discussions, as well as the answers to an expert survey ran by the consortium, to which further information was added from detailed energy system models (FORECAST Industry and ENERTILE for RES and CCS (see Appendices) and published sector technology roadmaps and literature.

The assessment of illustrative innovative technologies presented here serves the impact assessment for the IF, notably the quantitative assessment of impacts on the environment and the economy. The following impact categories are assessed quantitatively in detail in this report:

Environmental Impacts:

- Avoidance of CO_2/GHG emissions
- Increased use of renewables
- Improved energy efficiency

Economic Impacts:

- Required Investments
- Employment

The following qualitative aspects are not included in this report:

- Complementarity to other EU instruments
- Compliance with the proportionality principle
- Leverage

Chapter 2 presents the general methodology for establishing and assessing the quantitative impacts of the exemplary set of innovative technologies.

Chapter 3 analyses, by subsector, a minimum set of illustrative innovative technologies for the energy-intensive industries. Chapters 4 and 5 focus on illustrative innovative technologies for the sectors renewables/energy storage and management, CCS/CCU. Note that in this report CCS/CCU for industry is grouped under the energy-intensive industries while the section CCS/CCU is focusing on power sector CCS. This does not necessarily imply the same view under the grouping of technologies for the Innovation Fund.

Chapters 6 discusses the results for the main sectors Industry, Renewables and CCS/CCU, focusing on the minimum set of innovative technologies. Under the assumption of market uptake considerably larger impacts than the minimum set of innovative low-carbon technologies would be achieved.

2 OVERVIEW OF THE METHODOLOGICAL APPROACH FOR QUANTITATIVE ASSESSMENT OF IMPACTS FOR THE INNOVATION FUND

This chapter describes the methodological approach for the quantitative assessment carried out in the frame of the impact assessment under the Innovation Fund (IF). The present report focuses on the steps described in the following.

(1) Setting up the low-carbon technology matrix "Typology of Innovative Technologies versus Technology Readiness Level TRL" for each major product from workshops

The first step consisted in condensing information collected during 2017 from the different sector-workshops and from an expert survey (110 replies) in the form of a matrix which clusters the different low carbon technologies by type of mitigation option and by Technology Readiness Level TRL[3] (for a short description of the clusters and of the TRL see Appendix 1).

Each important sector discussed during the four sector workshops is covered by a set of 4-5 generic technology groups which presents the main technological and economic features discussed during the sector workshops and covered by the expert survey. The matrix does not strive for completeness in the details of covering low carbon technologies but nevertheless allows for a broad coverage in terms of clusters of mitigation options, in terms of TRL and in terms of size of options. This implies that the technology selection does not necessarily focus only on the options which promise the largest carbon reduction but strive for a suitable mixture of larger and smaller reduction options which may be most adequately describing the real submission and selection of projects.

Nevertheless, in a number of sectors discussed in this report, there is a relatively large if not full coverage of innovative technologies. This is for example the case of sectors like steel or cement. The approach taken here simplifies by proposing for different technological variants discussed during the workshops a representative process. This does not imply that the IF will not fund competing designs but important questions are whether:

1) Multiple projects aiming at demonstrating the <u>same</u> technology under the same circumstances (for example two projects demonstrating "catalytic cracking" as innovative technologies to produce the chemical "ethylene") could be funded from the IF (and if not, how the selection process would prevent this);
2) Multiple projects aiming at demonstrating a <u>different</u> technology to reduce the GHG emissions from one process (for example different innovative technologies to produce the chemical ethylene) could be funded from the IF.

[3] The table focuses on TRL 6-9 given the discussion in the report on design elements. In selected cases in may be useful to also consider lower TRL-levels (mostly TRL5), when it can be expected that major progress is possible before 2030 and the technologies may be ready for the IF by 2030. Also, there is some uncertainty in the classification of TRL levels.

Table 1: Example low-carbon technology matrix "Typology of Innovative Technologies versus TRL

Clusters of mitigation options Product X / Sub-Sector X	**Technology Readiness Level TRL**			
	5[4]/6	**7**	**8**	**9**
Integrated process improvement				
- Energy Efficiency (modernization and replacement)				T1 (technology name)
- Reduction in process-related emissions				
Fuel switch				
- Towards renewable energy sources (e.g. based on hydrogen)		T2 (technology name)		
- Towards decarbonized electricity (indirect emissions)				T3 (technology name)
Carbon Capture and Storage CCS/ Carbon Capture and Use CCU (End-of-pipe)	T4 (technology name)			
Recycling and re-use (innovative recycling processes)				
Material efficiency (in production and downstream)			T5 (technology name)	
Material substitution (downstream)				

In the assessment, it has been assumed that the answer to the first question is "no" and the answer to the second question is "yes".

For other sectors, in particular for the chemical sector, the coverage with innovative technologies can only be partial, given the limited amount of time available for this analysis. In the benchmarking studies for the EU ETS[5], it was found that with 8 processes a relatively large share of the emissions of the chemical sector can be covered. It would be preferable to analyse a number of innovative processes similar to this but in the frame of this work, the technologies chosen for this sector have a limited coverage. Overall, it can be stated that the coverage of the industrial sector with around 30 innovative technologies, of the renewables with around 25 technologies and of CCS with 5 technologies, in total around 60 innovative technologies, is rather extended. In 2017,

[4] The IF is aiming at projects demonstrating the technology at TRL 6-9. A technology now at TRL 5 with a project aiming at bringing it at TRL 6 would be eligible.

[5] http://www.ecofys.com/files/files/091102_chemicals.pdf

the European Commission hosted a series of stakeholder consultations with representatives from energy-intensive industries, the energy and finance sectors. The resulting summary report points to over 80 potential technologies, including cross-cutting innovations, such as CCUS, green hydrogen or energy storage. The number of 60 representative technologies is lower than the mentioned >80 for the reason that there is some overlap of innovative technologies, which was eliminated in the exemplary set and also some of the technologies mentioned were lacking quantification.

For renewables this matrix is further split into different types of renewables technologies.

Such a matrix has been set up for the following sectors and sub-sectors:

- Sector energy-intensive Industries:
  - Iron/steel
  - Cement/Lime
  - Glass/Ceramics
  - Pulp/paper
  - Chemicals
  - Non-ferrous metals
  - Refineries
- Sector Renewables (off-shore wind,…) /energy storage and management
- Sector Carbon Capture and Storage (in electricity supply)

Example 1: Cement

	A	B	C	D	E	F	G	H	I	J	K	L
1								red=high priority				
2	Charac	**Technology name**		**Process**		**Sub-Sector**	**Reference Technology**	**Specific saving potential [GJ/t]**		**Specific energy consumption (SEC) [GJ/t]**		
3							Describe what the project replaces	The specific saving potentials compares a process with the mentioned saving option / technology with a process not using that saving option. The difference is the specific saving potential.		Alternative: the SEC per ton of product		Concern only conversion, t
4		Max 100 signs, better shorter										
5		Name_SavingOption_English	avin	Process	ID_process	Sub-Sector		electricity	Fuels	electricity	Fuels	CO2
6	New cli	Aether		Clinker Calcination-Dry		Non-metallic mir	Today's CaCO3 based c	?	0,5			0,104
7	New bi	Solidia		New cement process		Non-metallic mir	Today's portland ceme	-	?			0,55
8	New bi	Celitement		New cement process		Non-metallic minerals			1,8			0,29
9		Geopolymers				Non-metallic minerals						
10		...				Non-metallic minerals						
11		...				Non-metallic minerals						
12		...				Non-metallic minerals						
13		...				Non-metallic minerals						

	A	B	L	M	N	O	P	Q	X	Y	Z	AA	AB	AC	AD
1															
2	Charac	**Technology name**	**Specific (process) GHG mitigation potential [t CO2 equivalent / t of acivity]**						**Technology readiness level (TRL)**	**Market entry**	**Possible share of Production [% of tonne production] in:**			**Maximum market share [% of tonne**	**Lifet**
3			Concern only direct process related emissions! No emissions related to energy conversion, these will be calculated during the modelling process						1 = basic principles observed 9= actual system	Earliest date of market entry at industrial scale.	(assuming successful market entry)			technical limit, not bound to a specific year (often 100%)	The calculatory lif investment calculatio influences the diffu
4		Max 100 signs, better shorter													
5		Name_SavingOption_English	CO2	CH4	N2O	PFC	SF6	HFC			2030	2040	2050		Calculatory
6	New cli	Aether	0,104						6-7?	2020				100	
7	New bi	Solidia	0,55						8	2020				?	
8	New bi	Celitement	0,29						6	2025				100	
9		Geopolymers													
10		...													
11		...													
12		...													
13		...													

Example 2: Iron/steel

	A	B	C	D	E	F	G	H	I	J	K
1								red=high priority			
2	Characterisati	Technology name		Process		Sub-Sector	Reference Technolog	Specific saving potential [GJ/t]		Specific energy consumption (SEC) [GJ/t]	
3							Describe what the project replaces	The specific saving potentials compares a process with the mentioned saving option / technology with a process not using that saving option. The difference is the specific saving potential.		Alternative: the SEC per ton of product	
4		Max 100 signs, better shorter									
5	Country	Name_SavingOption_English	vi	Process	ID_process	Sub-Sector		electricity	Fuels	electricity	Fuels
6		...									
7		**Top gas recycling**		Blast furnace	2	Iron and steel			-1.226		
8		**HIsarna**		Bath smelting reduction	2	Iron and steel			-1.562		
9		**Natural gas based reduction (ULCORED/SALCOS)**		Natural gas based reduction	2	Iron and steel			-2.464		
10		**(Green) Hydrogen reduction**		(Green) Hydrogen based direct reduction	2	Iron and steel					
11		**CCS - blast furnace**		Blast furnace	2	Iron and steel			+0.749		
12		**CCU (Steelanol/Charbon2Chem)**		Blast furnace	2	Iron and steel					

(2) Collect in the low carbon technology matrix typical performance data

After having selected the set of generic technologies in step 1 for each product a matrix is set up with typical performance data in terms of energy/ CO_2 reduction, fuel used, investment/ maintenance costs, maximum shares for diffusion etc. (see for this the information structure for the expert survey). For each cluster of mitigation options there could be a number of variants (for example different CCS technologies for industrial processes with different carbon reduction rates and different investment costs). If necessary, such variants are considered; however typically the modeling focusses on one major variant. The exemplary selection of technologies is based on presentations during several expert round table discussions, as well as the answers to an expert survey ran by the consortium, to which further information was added from detailed energy system models (FORECAST Industry and ENERTILE for RES and CCS (see Appendices), published sector technology roadmaps and literature provided by stakeholders before and during the meetings, additional discussions with sector experts.

(3) Broad coverage of innovative technologies versus narrow coverage

The principle of a broad coverage of production with several innovative technologies is followed, rather than a narrow coverage with just one or two technologies. This is justified by the fact that in many cases different technological routes are under discussion and followed at present. It is therefore too early to operate a selection in the assessment of impacts.

(4) Assessment of the impacts

In this step quantitative impacts are assessed for the energy-intensive industries, for renewables, CCS and energy storage, according to the different option packages differentiated by sectors/TRLs as set up in the previous steps. The outcome of this step are:

- Possible CO_2/energy reduction achievable with the low carbon technologies
- Comparison of these reduction levels with the benchmarks established under the ETS
- Total investment volumes for each of the product groups analyzed. The latter is based on investment figures collected from the surveys and from considerations made during the roundtables on financial volumes for low carbon technologies.

These figures are specified as bands or categories, as quite often, technologies are in a too early stage to provide for example investment volumes with enough certainty for fixed values.

(5) Investment volumes

Together with the impacts on energy consumption and GHG emissions the necessary investment volumes are established, once the technology is penetrating.

The following is a brief discussion of different approaches undertaken to estimate the necessary investment volumes and how this enters the analysis in this report:

i. The total CAPEX requirements for projects for which respondents from the **expert survey** filled in the CAPEX added up to EUR 4.5 bn; these 33 projects are expected to form just a small part from the total of all potential projects that could ask for IF funding.

ii. A **high-level top-down "order of magnitude" estimation** by Ecofys experts determined the total investment needs for all included IF sectors at EUR 21 bn to EUR 41 bn.

iii. Table 2 shows a **bottom-up estimate** of the CAPEX range to be financed for demonstration of innovative technologies in sectors covered by the IF[6]. Table 2 shows that the CAPEX ranges vary within multiple orders of magnitude across sectors. What the table does not show, however, is what share of the CAPEX qualifies as relevant costs and to what extent the projects are in the position to repay debt, and thus supportable by a loan guarantee instrument.[7] Summed over subsectors and sectors, the total CAPEX range to be financed amounts to EUR 54.6-67.9 bn. A few notes on the different sector:

    - *Energy Intensive Industries EEI (incl. Carbon Capture and Use CCU):* An indicative bottom-up estimation of investment needs, when all identified innovations would be tried once for several sectors in the energy intensive industry, is EUR 24 bn - EUR 33 bn. With an "order of magnitude correction" for non-covered sectors and adding an estimate for cross-sector innovative projects estimation increases to EUR 31 bn to EUR 42 bn[8].
    - *Carbon Capture and Storage CCS:* The CAPEX to be financed for 1-2 innovative first-of-a-kind CCS projects can be estimated to be between EUR 0.5 bn and EUR 2.8 bn (ICF, 2016), or in case 12 projects would be required to demonstrate the technology in the range of EUR 8 bn – EUR 12.5 bn (Global CCS Institute, n.d.). In the following we rely on the first estimate[9].

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[6] Table 2 is not based on a thorough analysis and is therefore not intended to be used for establishing a distribution of funds over (sub)sectors.

[7] In terms of providing support thought a loan guarantee instrument, EDP InnovFin provides a close benchmark. Because it is a fairly new instrument, it is too early to draw conclusions based on it (currently one project is supported). (based on consultation with the EIB, June, 2017)

[8] This range assumes that relevant innovations identified in the BEIS industrial decarbonization roadmaps (UK's Department for Business, Energy and Industrial Strategy, conducted a series of sector decarbonisation and energy efficiency roadmaps published in 2015 (BEIS, n.d.)), provided in the expert survey and provided by sector associations in the preparation of the expert roundtables are all implemented once at full scale. This implies that multiple innovations are included for some of the major technology routes.

[9] There may well be upward potential, as there are four European Projects of Common Interest on CO_2 transport, and as the 2030 SET plan's targets include at least one commercial scale whole chain CCS project operating in the power sector (Target 1), at least 1 active EU Project of Common Interest (PCI) for CO_2 transport infrastructure (Target 4) and at least 3 pilots on promising new capture technologies (Target 6), and at least one to test the potential of sustainable Bio-CCS at TRL 6-7 study (Target 6) and at least 3 new CO_2 storage pilots in preparation or operating in different settings (Target 7) (European Commission, 2017a and 2017b). This is not quantified further.

Table 2: Estimate of the CAPEX range to be financed for demonstration of innovative technologies in sectors covered by the IF

Sector	Subsector	CAPEX range to be financed in billion EUR	Key technologies	Source
EII	Ceramics	0.06-0.14	Carbon capture, gasification of biomass, new process technology	Aggregation of the set of relevant innovations[10], assuming that each innovation is demonstrated once at commercial scale
EII	Glass	0.180-0.21	Improved furnace design, electric melting, carbon capture	As *Ceramics*
EII	Iron & steel	6.3-8.3	Hydrogen-based, CCU, ULCOS blast furnace, advanced technologies blast furnace and basic oxygen furnace, carbon capture	As *Ceramics*
EII	Pulp & paper	0.02-0.05	Dry sheet forming, impulse drying, gasification of biomass, 100% electricity	As *Ceramics*
EII	Oil refining	0.36-2	(Bio-refineries are included in the bio-based subsector)	As Ceramics, upper boundary is based on the CAPEX of a new refinery is GBP 8.5 billion, of which 1/5 is included
EII	Cement	0.59–1.5	Carbon capture, kiln technology	As *Ceramics*
EII	Lime	0	-	Insufficient information for an informed estimate.
EII	Bio-based	5	-	Extrapolation of the funding for the bio-based consortium, and the CAPEX of a bio-refinery
EII	Non-ferrous Metals	1.8–5.9	Improvements in the aluminium production process	Expert Survey, Expert Roundtables, information provided by sector associations
EII	Chemical	6.5	-	CAPEX of building a new olefins plant, a new ammonia plant, and a new chlorine plant multiplied by a factor of 2 2 to account for the heterogeneous character of the chemical industry.
CCU	-	3	CAPEX required to build a new olefins plant, a new ammonia plant, and a new chlorine plant was added and multiplied with a factor 2 to account for the heterogeneous character of the chemical industry	Assuming of 15 projects with an average CAPEX of EUR 200m. (In the Expert Roundtables the CAPEX of EUR 10m was mentioned, which is believed to be at the very low end)
EII	**Total EEI** incl. CCU/ ind. CCS	**23.81-32.60**	**Sum of the above**	
EII	**Total EEI** incl. CCU/ ind. CCS	**31-42**	**Incl. non-covered sectors and adding an estimate for cross-sector innovative projects**	

[10] Set of relevant innovations consists of 1) innovations relevant in the context of the IF from BEIS 2050 roadmaps (TRL 5-8 only, and only in the case adoption in UK is 0%), 2) findings from the Expert Survey conducted for this project (after elimination of overlaps), 3) innovations delivered by sector associations for the purpose of this project (after elimination of overlaps). For many innovations no CAPEX was reported. The lower bound is the sum over all innovations with zero values for missing CAPEX values. The upper bound is the sum over relevant innovations (with missing values replaced with average values, average over subsector).

Table 2 continued

Sector	Subsector	CAPEX range to be financed in billion EUR	Key technologies	Source
CCS[11]	-	0.5-2.8	Assuming 1 or 2 demonstrators[12]	As *Ceramics*
CCS[11]		8-12.5	12 projects, as aspired to the European Council in 2007	
CCS	**Total CCS**	**0.5-2.8**	**1/2 demonstrators[9]**	
RES	Wind	6.35	Next generation turbines, floating foundations	Top-down estimation based on average annual investments in the EU in the New Policies Scenario 2021-2030, multiplied by observed sector specific R&D intensities
RES	Other RES[13]	3.28	Geothermal energy, ocean energy	As *Wind*
RES	Bio, including transport	2.52	Synthetic fuels produced with renewable electricity, advanced biofuels	As *Wind*
RES	Solar PV	1.68	Concentrated solar power, solar roof-tiles, floating PV installations	As *Wind*
RES	Hydro	0.84	-	As *Wind*
RES	**Total RES generation**	**14.67**		
RES	Transmission	1.86	“Hybrid systems” of renewable electricity generation plus storage	As *Wind*
RES	Distribution	6.57	Innovative management in the distribution grid	As *Wind*
RES	**Total RES Transmission, Distribution, Storage**	**8.43**		
TOTAL	**TOTAL**	**54.6-67.9**	**EEI: Incl. non-covered sectors and adding an estimate for cross-sector innovative projects** **CCS: With 12 demonstrators for CCS**	**-**

Note: Because of the severe limitations of the table, it is inappropriate to use it to establish a distribution of funds over sectors and subsectors. Design elements of the Innovation Fund which rely on sectoral financing needs should be based on a more detailed mapping of the type of demonstrations (size, number, etc.) relevant for each innovative technology and more accurate estimates of their CAPEX.[14] [15] [16]

[11] It is assumed that the 1-2 projects are sufficient, mainly for the power sector, while industrial CCU/CCS is included under EEI in the table (https://setis.ec.europa.eu/system/files/integrated_set-plan/setplan_doi_ccus-final.pdf). If, however it is assumed that 12 projects are required to demonstrate the technology, the cost is in the range of EUR 8-12.5bn, as substantiated in JRC (2010) The cost of carbon capture and storage demonstration projects in Europe, https://hub.globalccsinstitute.com/publications/cost-carbon-capture-and-storage-demonstration-projects-europe/5-cost-european-ccs-demonstration-programme.

[12] ICF (2016). Innovative Financial Instruments for First-of-a-Kind, commercial-scale demonstration projects in the field of Energy, DG RTD

[13] Based on estimates from Ocean Energy Strategic Research Agenda, http://oceanenergy-europe.eu/images/Publications/TPOcean-Strategic_Research_Agenda_Nov2016.pdf, and Renewable Heat Cooling – Platform, http://www.rhc-platform.org/fileadmin/user_upload/members/Downloads/RHC_SRA_epo_final_lowres.pdf, the value for the category *Other RES* may be significantly underestimated.

[14] The table assumes that all innovations mentioned in the BEIS roadmaps are implemented in full scale. In reality some may be implemented at lower TRL and thus at lower cost. On the other hand, the table assumes projects implemented at lower TRL are not later repeated at higher TRL.

- *RES Generation:* The CAPEX to be financed for Wind, bio (including transport), solar PV, hydro and other renewables[17] can be estimated to be around EUR 15 bn[18]. One could argue that RES estimates are at the upper range, as some part of the Research, Development and Demonstration (RDD) may also be carried out autonomously (in particular for the main stream RES wind and solar).
- *RES Transmission/Distribution/Storage:* The CAPEX to be financed for transmission ('hybrid systems' of renewable electricity generation plus storage) and distribution (innovative management in the distribution grid) could be estimated as around EUR 8 bn[19].

Top-down and bottom-up estimates for ***total first-of-a-kind investment needs for all projects for all sectors included in the IF are estimated to be somewhere between EUR 21 bn and EUR 68 bn.*** The upper limit can be characterised as relatively comfortable and broad coverage of the main investment needs.

Due to the necessary significant assumptions used to calculate these investment estimates, further analysis needs to be conducted to determine the distribution of Innovation Fund resources over the sectors. We undertook, for the following analysis, a more detailed technical analysis of a smaller subset of investments (based on the expert survey and technological information available in the energy system models FORECAST Industry and ENERTILE (see Appendices). This subset has the advantage of being fairly comprehensive (see below) - though still limited - and detailed in technological description. The subset is characterised by the following:

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[15] The table has severe limitations. The upper limit is likely to be underestimated because the table does not capture all innovations (some sector associations were more active than others in answering the Expert Survey), and because it assumes that all innovations would just be demonstrated once and because it ignores innovations below TRL 5. Insights from sectoral roadmaps and other studies/publications on innovation needs (from sector associations) have not consistently been taken into account when preparing this table.

[16] Source for RES investments: International Energy Agency (2014). World Energy Investment Outlook. Key technologies from Roundtable Results. R&D intensities from SETIS as follows: https://setis.ec.europa.eu/system/files/Technology_Information_Sheet_Wind_Energy_Generation.pdf for wind (2.6-3.0%), https://setis.ec.europa.eu/sites/default/files/Capacities%20Map%202009_0.pdf for solar (2.2-2.5%), https://setis.ec.europa.eu/sites/default/files/Capacities%20Map%202009_0.pdf for biofuels (3.6-4.5%), https://setis.ec.europa.eu/sites/default/files/Capacities%20Map%202009_0.pdf for producers of electrical components and equipment (3.4%) and industrial machinery (2.6%) as a proxy for distribution and transmission.

[17] Based on estimates from Ocean Energy Strategic Research Agenda, http://oceanenergy-europe.eu/images/Publications/TPOcean-Strategic_Research_Agenda_Nov2016.pdf, and Renewable Heat Cooling – Platform, http://www.rhc-platform.org/fileadmin/user_upload/members/Downloads/RHC_SRA_epo_final_lowres.pdf, the value for the category other renewables may be significantly underestimated.

[18] Top-down estimation based on average annual investments in the EU in the New Policies Scenario 2021-2030, multiplied by observed sector specific R&D intensities. R&D intensities from SETIS as follows: https://setis.ec.europa.eu/system/files/Technology_Information_Sheet_Wind_Energy_Generation.pdf for wind (2.6-3.0%), https://setis.ec.europa.eu/sites/default/files/Capacities%20Map%202009_0.pdf for solar (2.2-2.5%), https://setis.ec.europa.eu/sites/default/files/Capacities%20Map%202009_0.pdf for biofuels (3.6-4.5%), https://setis.ec.europa.eu/sites/default/files/Capacities%20Map%202009_0.pdf for producers of electrical components and equipment (3.4%). For comparison: An estimated EUR 7,5 bn to EUR 18 bn is needed for first of a kind commercial demonstration projects in solar PV, wind and bioenergy up to 2020 (JRC, 2013).

[19] Top-down estimation based on average annual investments in the EU in the New Policies Scenario 2021-2030, multiplied by observed sector specific R&D intensities, using https://setis.ec.europa.eu/sites/default/files/Capacities%20Map%202009_0.pdf for producers of electrical components and equipment (3.4%) and industrial machinery (2.6%) as a proxy for distribution and transmission.

- Compared to the investment estimates provided in Table 2, the innovative set of technologies chosen for further analysis focuses for each major technology route only on one representative innovative technology. For example for the iron/steel sector, one representative technology for example is considered for CCS, for hydrogen-based steel and for direct electricity use. The rationale for this is that on a first approach, industrial stakeholders would not be able to handle and develop a number of variants for one route in parallel; hence, the investment volume calculated for the impacts is based on a realistic view of how many technologies could develop in parallel.
- A further difference is that Table 2 also includes a large investment volume of around EUR 8 bn in the category RES transmission and distribution, which is not included in the present data set.
- Finally, for the very heterogeneous sector of chemicals (and to some degree also for the bio-based processes in refineries) only a limited set of products could be represented here in the set of innovative technologies.
- Summarizing, the investment volumes used in the following are to be seen as a minimum investment need, based on a subset selected for deeper analysis. *This approach leads to lower investment volumes compared to Table 2: in the range of EUR 14 bn compared to EUR* 55-68 *bn estimated for Table 2, where a certain diversity and competition is admitted for individual process routes (i.e. that for several technology routes multiple innovative technologies are included; roughly a "redundancy" of a factor of 3).*
- *Overall, the subset can be characterized as a minimum investment volume to be covered, if the IF intends to cover the main sectors at least once.*

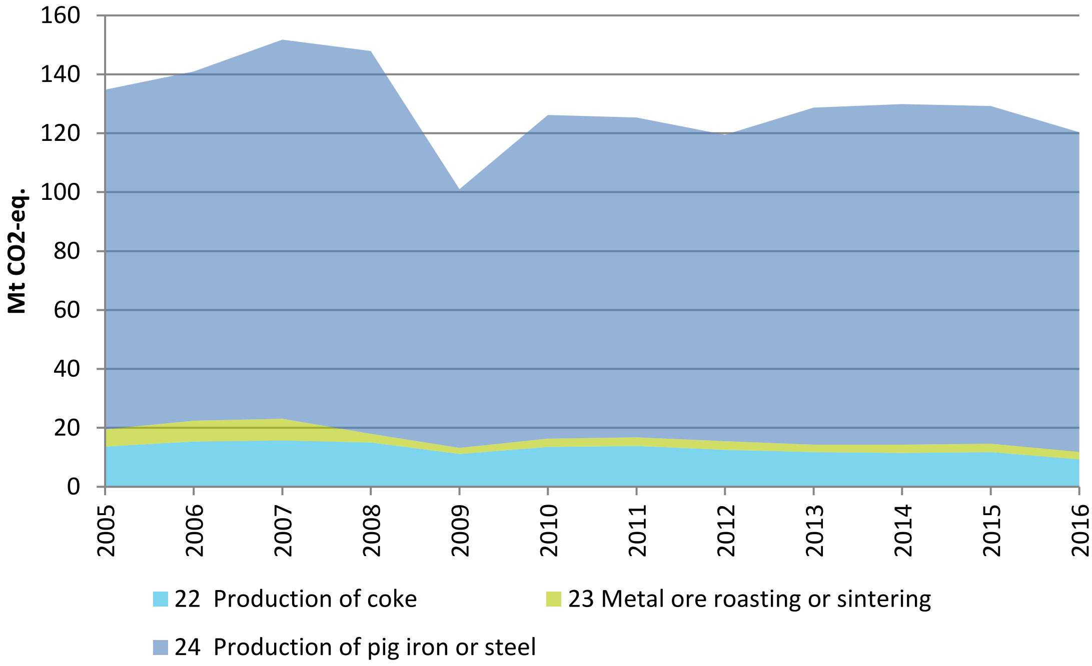
The subset of innovative low-carbon technologies is described in detail in the chapters 3 to 5, and analysed in sections 6.1 to 6.4.

One important question during the assessment is how the total volume of required investment for the exemplary IF compares to the volume of the IF under the assumption of current carbon prices. This is discussed in section 6.5.

3 Illustrative technological innovations for the Innovation Fund (IF) in the field of energy-intensive industries[20]

3.1 Iron/steel industry

As an energy-intensive industry the European steel industry accounted in 2016 for around 7% of the verified emissions of all stationary installations of the European Union and around 22% of its industrial emissions excluding combustion (Figure 1, EEA (2017)).



Source: EEA (2017)

Figure 1: Verified historical emissions EU28 iron and steel sub-sector as reported in the EU ETS

In addition to energy-related emissions from fossil fuel combustion, process emissions due to chemical reactions during the reduction of iron ore arise in the steel industry. In crude steel production two main process routes can be distinguished: primary steel production from iron ore (BOF: basic oxygen furnace) and the much less energy-intensive steel production using scrap and electricity as main inputs (EAF: electric arc furnace). To further decarbonise the steel industry "breakthrough" technologies and true paradigm shifts will be necessary [RT].

In the following section, a selection of such breakthrough technologies is presented stating the current level of development of the technology (Table 3) as well as selected characteristics (Table 4).

[20] This chapter is based on information gathered at the Commissions Roundtables [RT] „Finance for Innovation: Towards the ETS Innovation Fund", the following Expert Survey [ES], public literature [PL] and own estimations [e]. For many of the technologies the consortium has been able to build upon inputs from the expert survey, and the expert roundtables, while also adding its own expert judgement. References to the expert survey, and towards the consortium's expert opinion are not included further to respect the confidentiality clause from the expert survey.

In addition to the selected mitigation options there exists a variety of additional technologies that could also contribute to the reduction of future CO_2-emissions in the steel industry [RT]:

- direct reduction based on natural gas,
- the use of biomass in steel production
- low quality scrap melting for basic oxygen furnaces
- more recycling of steel
- carbon capture and storage
- waste heat recovery (e.g. blast furnace slag, electric arc furnace)

Table 3: Technology readiness levels of selected mitigation options in the iron/steel sub-sector

Clusters of mitigation options	TRL 6	TRL 7	TRL 8	TRL 9
Integrated process improvement	Bath smelting	Top gas recycling		
- Energy Efficiency - Reduction in process-related emissions			Near net shape casting	
Fuel switch - towards renewable energy sources		Hydrogen-based steel production		
- towards decarbonised electricity	Electricity-based steel production			
End-of-pipe (CCS/ CCU)	Carbon capture and usage			
Recycling and re-use (innovative recycling processes)				
Material efficiency (in production and downstream)				
Material substitution (downstream)				

Source: [RT]

(Green) Hydrogen based steel production

Hydrogen based steel production is used to replace carbon in metallurgical processes with hydrogen produced via renewable electricity sources. The needed hydrogen could be e.g. produced via a PEM electrolyser and then be used for the reduction of iron oxide instead of e.g. coal or other fossil fuels replacing conventional blast furnaces (BF). In a second stage it could be even possible to melt the pre-reduced iron ore with hydrogen plasma directly into liquid steel. (EUROFER 2017; Voestalpine AG et al. 2017; SSAB AB 2017)

Table 4: Main characteristics of selected mitigation options iron/steel sub-sector

Technology option	Examples	TRL	Max. emissions reductions	Market entry
DRI RES-H2	HYBRIT, GrINHy, H2Future, SuSteel, SALCOS[21]	7	up to 80%	2030/2035
DRI RES-Electrolysis	SIDERWIN, ULCOWIN	6	up to 90%	2025/2030
Bath smelting[22]	HIsarna	5[23]-6[24]	up to 20%	2025[e]
Top gas recycling[25]	ULCOS-BF, IGAR	7	up to 30%	2020/2025
Carbon capture and usage	Carbon2Chem, Steelanol	5-7	case specific: an LCA is needed for each project to determine the GHG reduction potential.	2025/2030
Near net shape casting	Castrip, Salzgitter, ARVEDI ESP	8-9	up to 60%	2015

Source: [RT], Pardo und Moya (2013), WSP Parsons Brinckerhoff (WSP) und DNV-GL (2015c), Fleiter et al. (2013b), own estimations [e]

Electrolysis based steel production

Alkaline electrolysis is used to produce direct reduced iron from iron ore using only electrical energy replacing conventional blast furnaces and as a consequence fossil fuels in steel production. The reduction of the iron oxide takes place at the cathode, while at the anode oxygen emerges as gas. (Pardo und Moya 2013; EUROFER 2017; www.ulcos.org)

Bath smelting

Bath smelting combines coal preheating and partial pyrolysis incorporating a reactor, a melting cyclone for ore melting and a smelter vessel for final ore reduction and iron production. The current process still uses fossil fuels like e.g. coal as energy source but on a significantly lower level compared to a conventional blast furnace. In addition, the

[21] SALCOS plans to proceed by steps: (1) add a natural gas based direct reduction plant for iron ores to the actual plant layout at the integrated site in Salzgitter. The direct reduced iron from this plant is to be fed to the existing blast furnaces (CO_2 reduction: 10%, as natural gas used for reduction has a certain amount of hydrogen content). (2) Additionally, large amounts of hydrogen may be fed to the process, replacing the needed natural gas partly. The hydrogen will be produced via electrolyzers operated with power from renewable resources. (CO_2 reduction: 18%). (3) Addition of an electric arc furnace plant, to be fed with the direct reduced iron from the then already existing direct reduction plant (CO_2 reduction: 25%). (4) Further steps are principally based on the same approach as the steps before, leading to the complete transformation of steelmaking from the blast furnace/basic oxygen technology to direct reduction/electric arc furnace route in the decades to come. The maximum CO_2 reduction possible by the SALCOS concept in this ultimate configuration is 82%. (5) As a last step, the addition of CCU is a possibility, as the direct reduction technology under consideration offers CO_2 separation as a standard feature). Realisation of (1)-(3) may require investments in the range of 1.25 billion Euro.

[22] Higher potentials with CCU/S: up to 80%.

[23] Pilot plant in the Netherlands IJmuiden.

[24] Information from [RT]

[25] Higher potentials with CCU/S. up to 60%.

process would allow partial substitution of coal by other energy carriers (e.g. biomass, natural gas, hydrogen). (EUROFER 2014; Pardo und Moya 2013; EUROFER 2017)

Top gas recycling

Top gas recycling removes via a capture system the CO_2 from the top gas of the Blast Furnace and recovers useful components such as carbon and hydrogen. The reducing gas is then recycled back into the reactor allowing a reduction of the coke rates compared to a conventional blast furnace (BF).To facilitate the CO_2 removal, the system is operated on pure oxygen instead of hot blast. (EUROFER 2014; Pardo und Moya 2013; EUROFER 2017)

Carbon capture and usage

Carbon capture and usage is the use of steel mill waste gases for the production of bio fuels (e.g. ethanol) and/or basic chemicals (e.g. naphtha) using CO_2 emissions to get access to carbon as feedstock (ES). The mitigation potential of this technology depends on the substituted product and the type of usage/binding (permanent vs. temporary). The energy demand of the conversion process (and H2 generation) has to be provided by renewable energy sources. (EUROFER 2017; thyssenkrupp 2017; ArcelorMittal 2017).

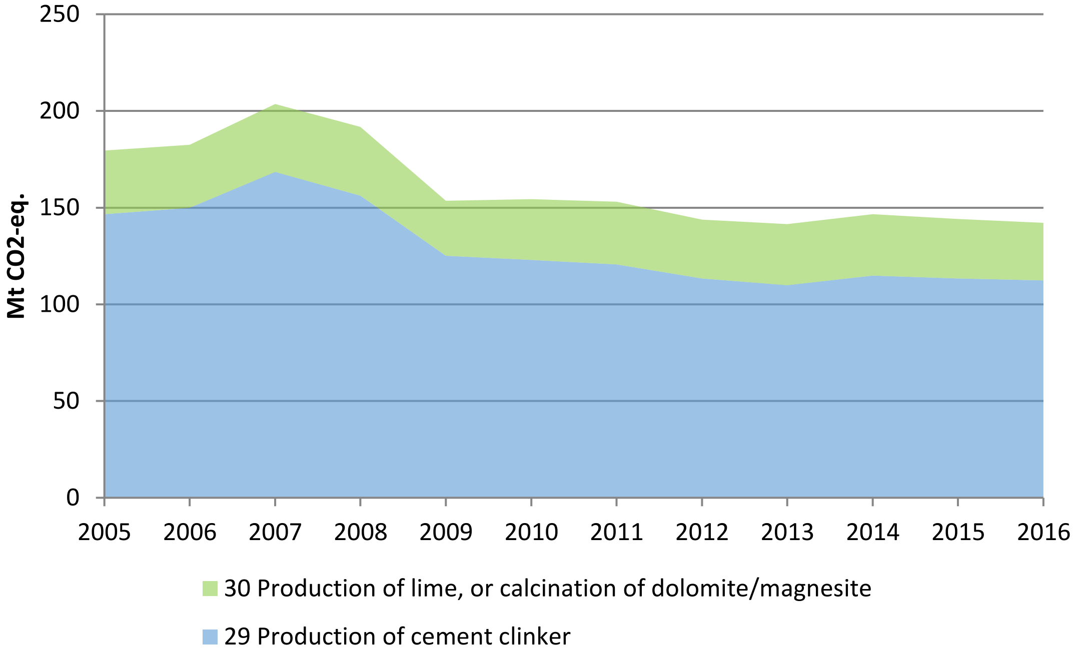
Near net shape casting

Near net shape casting encompasses various technologies that lead to a considerable shortening of the process-chain from liquid steel to the final steel product. Therefore it can substitute conventional continuous casting plants, reheating furnaces and part of the roll stands. New efficient casting processes offer high saving potentials as they reduce the need for repeated reheating and consequently energy demand. (Fleiter et al. 2013b)

3.2 Cement / lime industry

Together, the cement and lime sectors accounted for about 8% of total greenhouse gas (GHG) emissions in the scope of the EU Emissions Trading Scheme (ETS) in 2016 and for about 28% of the industrial sector emissions within the ETS (see Figure 2). In 2016, CO_2 emissions in the cement industry were about 112 Mt, while they were at about 30 Mt in the lime industry.

Two main sources of CO_2 emissions are important in the cement and lime industry: First, the emission from the burning of fossil fuels in the clinker/lime furnace (< 0.5 t CO_2/t clinker) and, second, the process related emissions from the decarbonation of the limestone (~0.52 t CO_2/t clinker). Today's mitigation efforts concentrate on three main pillars. These include improving energy efficiency, switching to low-carbon/renewable fuels and reducing the clinker content in the cement by using e.g. fly ash or blast furnace slag. By using today's best available technologies, mitigation potentials along these three lines are limited. E.g. incremental technologies for energy efficiency improvement of today's standard cement production process (dry kiln with cyclone preheaters and precalciners) are expected to achieve limited efficiency and CO_2 savings only in the coming decades. For example the CSI und ECRA (2017) expect less than 10% remaining thermal efficiency potential until 2050. Similarly, the cement sector's official roadmap to 2050 states that to achieve an 80% CO_2 reduction by 2050 compared to 1990 breakthrough technologies are needed (Cembureau 2013). Accordingly, without innovations, mitigation potentials are limited to a reduction of about 30-40%.



Source: EEA (2017)

Figure 2: Verified historical emissions EU28 cement and lime sub-sector as reported in the EU ETS (Source: EEA 2017)

Both sectors show a huge degree of R&D activities directed towards reduction of CO_2 emissions. The options range from fuel switching, to new raw materials, new cement alternatives towards carbon capture and storage or use. Along the value chain, even more options are available, including a more efficient use of concrete in the construction sector.

In the following, selected important break-through mitigation options with potentially high impact are described and characterised. This document does not aim to list all options currently in development. The objective of the scenario analysis is to learn about the entire portfolio of mitigation options. It will not be used to derive conclusions about individual mitigation options.

New binders based on other raw materials than calcicarbonate (limestone) can substantially reduce CO_2 emissions as they reduce process related emissions from the decarbonation of the limestone but also often allow for lower process temperatures and less demand for thermal energy. Various concepts are under development using different technologies and materials. For modelling the impact on GHG emissions and energy demand, it is less relevant, which material composition is used. Thus, cement binder innovations are not grouped according to material composition as often done, instead they are grouped according to the potential CO_2 mitigation effect. The following groups of new binders are included in the scenario analysis. The reference technology is always production of Ordinary Portland Cement (OPC).

Table 5: Technology readiness levels (TRL) of selected mitigation options in the cement and lime sub-sector

<table>
<tr><th>Clusters of mitigation options</th><th>TRL 6</th><th>TRL 7</th><th>TRL 8</th><th>TRL 9</th></tr>
<tr><td rowspan="2">Integrated process improvement
- Energy Efficiency
- Reduction in process-related emissions</td><td>Low carbon cement (-50%)</td><td></td><td></td><td></td></tr>
<tr><td colspan="2">Less carbon cement (-30%)</td><td></td><td></td></tr>
<tr><td rowspan="2">Fuel switch
- towards renewable energy sources
- towards decarbonised electricity</td><td></td><td></td><td></td><td></td></tr>
<tr><td></td><td></td><td></td><td></td></tr>
<tr><td>CCS and CCU</td><td>CCS (direct separation)</td><td></td><td>Low Carbon cement (-70%)</td><td>Post combustion CCS</td></tr>
<tr><td>Recycling and re-use
(innovative recycling processes)</td><td></td><td></td><td></td><td></td></tr>
<tr><td>Material efficiency
(downstream)</td><td></td><td></td><td></td><td></td></tr>
<tr><td>Material substitution
(downstream)</td><td></td><td></td><td></td><td></td></tr>
</table>

Source: [Roundtables]

Table 6: Main characteristics of selected mitigation options cement/lime sub-sector

Technology option	Examples	TRL	Max. GHG emissions reductions	Market entry
Low carbon cement (-50%) (new binder)	Celitement	6	50%	2022
Less carbon cement (-30%) (new binder)	Aether	6-7	30%	2020
CCS Post combustion		8-9	95%	2022
CCS (direct separation)	LEILAC project	5-6	~70%*	2025
Low Carbon cement (-70%) (CCU: CO_2 absorbing concrete)	Solidia	8	70%	2020

* only process related emissions

Sources: Round tables, Cembureau Communication,

Low carbon cement (-30%)

Aether cement is an innovative type of clinker based on the same raw materials (limestone, clay, iron and bauxite) as conventional and produced in the same (but slightly adapted) rotary kilns as OPC. The production of Aether, however, uses less limestone than OPC and takes place at lower temperatures (1300°C compared to

1450°C), which results in reduced emissions and energy demand. GHG savings of 20-30% compared to OPC are reported. A similar performance as OPC makes this product widely applicable. TRL is estimated at 6-7, because first industrial trials with small volumes were made. (http://www.aether-cement.eu/)

Low carbon cement (-50%)

A hydraulic binder currently under development is Celitement, which is produced around 200°C temperature in autoclave process instead of 1450°C. The lower process temperature results in about 50% lower energy demand. Also process related emissions are reduced by about 50% down to 0.23 t CO_2/ t cement. (Cembureau communication) (Stemmermann et al. 2010)

Low carbon cement (-70%)

Calcium silicates based binders have the potential to replace Portland Cement in large quantities by providing similar product qualities (CSI und ECRA 2017). An example for a calcium silicate based binder is the Solidia Cement presented at the expert roundtables. Resulting from a new raw material mix and a lower process temperature, Solidia cement production shows about 30% lower CO_2 emissions than cement based on Portland Clinker. Further, it absorbs CO_2 during the concrete's curing process, which takes place in special curing chambers at 40-60°C and high concentrations of CO_2. The CO_2 absorption during the curing is estimated to save about 30% or 300 kg CO_2 per tonne of cement. While the curing chambers allow a very fast hardening (~1day), they also limit applications of Solidia to pre-cast concrete elements. The TRL is estimated at 8 to 9, as industrial demonstration has taken place in 2014. [Expert Roundtables]

Other potentially new binders might also be based on concrete from demolition waste. Demolition waste is currently mostly recycled for use as aggregate in road sub-base, where it does not replace CO_2-intense production of new cement. Recycled concrete is less used for production of new concrete, but can up to a certain share be used with today's technology. Using recovered concrete as raw material for the production of new cement is a yet unexploited but potentially huge mitigation option. Ongoing research projects report that a new cement type based on construction wastes would be able to reduce CO_2 emissions by about 70% resulting from replacement of limestone raw materials as well as a lower process temperature. The TRL is estimated relatively low at 6-7. (Communication with Cembureau)

CCS Post combustion

Due to the high specific CO_2 emissions of cement plants, CCS is a highly discussed mitigation technology for the cement industry. Principally, alternative designs are feasible including post combustion, oxyfuel process, pre combustion and carbon looping. They all have different advantages and disadvantages and are differently mature today. While for post combustion a few pilot and demonstration plants have been implemented already, oxyfuel and carbon looping technologies are still less mature and require more R&D activities. Pre-combustion is less attractive for the cement production, because it does not allow capturing the process related emissions from the carbonation of limestone (CSI und ECRA 2017).

CCS direct separation

A CCS technology specifically adjusted for the cement and lime production is currently developed in the frame of the EU Horizon 2020 project LEILAC. Its core technology is based on direct separation, which separates the calcination of the limestone from the combustion of fuels and, thus, generates a pure stream of CO_2 emissions from calcination. Compared to other CO_2 capture technologies (oxyfuel or post-combustion), this technology has the advantage that it does not require large amounts of additional energy for the CO_2 capture. A pilot plant is planned in the frame of the project LEILAC in an existing cement plant in Belgium. Results of the pilot testing phase are expected for 2020. While the technology is proven for magnesium oxide, it is estimated as TRL5 for lime and cement, because a pilot plant is not yet running. [Roundtables] (Vincent et al. 2016)

Carbon capture and use (CCU)

Carbon capture and use (CCU) is today still less developed and researched than CCS. There are various possibilities for the use of the CO_2 including enhanced oil/gas recovery, mineral recarbonation, raw material for the production of chemical products in combination with hydrogen, growing of algae and others (CSI und ECRA 2017). **CO_2 absorbing concrete** captures ambient CO_2 during the strength development or life. An example is the above described Solidia cement (see new binders).

Additional options

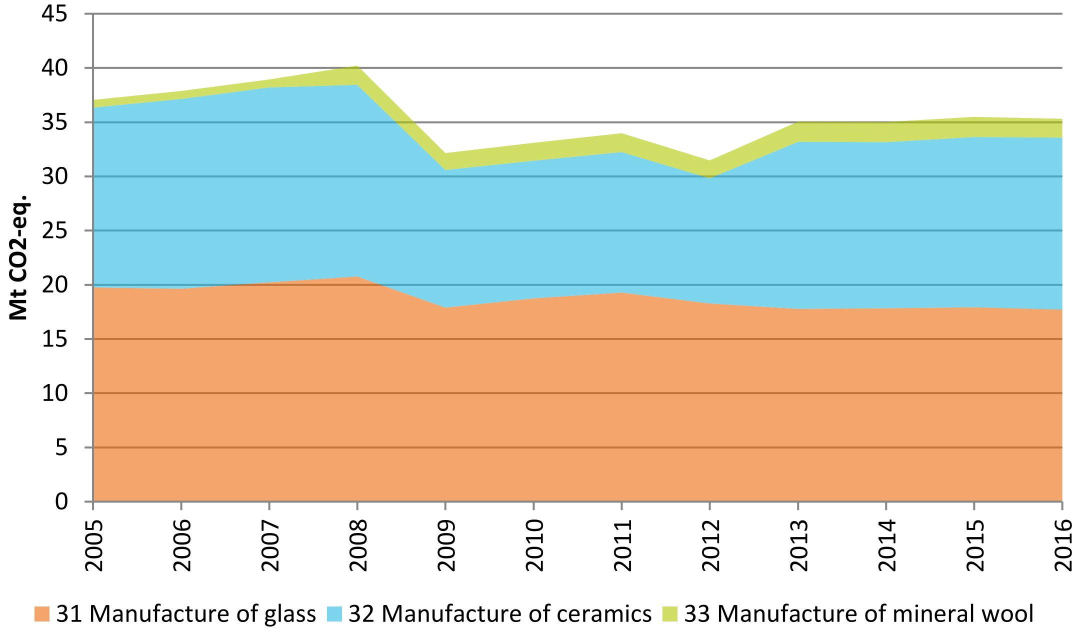
Additional innovations that might become relevant in the future but are not included in the analysis are:

- The **oxyfuel technology** uses pure oxygen instead of air in the combustion chamber combined with a flue gas recirculation. This increases the CO_2 content in the flue gas substantially and thus allows more efficient CO_2 capture. The principle has been proven in lab scale and currently a pilot plant is prepared by ECRA. It might be constructed in 2020. Estimated TRL is While principally it is also possible to use oxyfuel capture only for the precalciner (which would be less complex to implement). (CSI und ECRA 2017). [Roundtables], (CSI und ECRA 2017)
- Improved **building insulation cements** that save energy during the lifetime. An example is the Mineral foam Airium as presented at the expert roundtables.
- **Nano engineering** of concrete for high durability and strengths, which is still at TRL 3 to 4 (Abdolhosseini Qomi et al. 2014)
- New binders based on **calcined clays and limestone fillers**: While both are promising raw material substitutes due to their abundant availability and first research results report high mitigation potentials, the project is still at TRL4-5 and thus out of the scope of this study (Cembureau communication)
- "**Design for disassembly**": Re-use of building components after demolition of buildings in the construction of new buildings without destroying their structure (WBCSD 2015).

3.3 Glass/ceramics industry

The European glass and ceramics industry accounted in 2016 for around 2% of the verified emissions of all stationary installations of the European Union and around 6% of its industrial emissions excluding combustion (Figure 3, EEA (2017)).

Both industries transform mineral raw materials into a variety of different products using different production techniques. In addition to energy related emissions, both sectors emit process emissions which are linked to the raw materials themselves [RT].



Source: EEA (2017)

Figure 3: Verified historical emissions EU28 glass and ceramics sector as reported in the EU ETS (Source: EEA 2017)

In the following section, a selection of relevant technologies for the decarbonisation of the branch is presented stating the current level of development of the technology (Table 7) as well as selected characteristics (Table 8).

RES Electrification

Using electricity instead of natural gas could be an option to reduce future CO_2 emissions and increase thermal efficiency in both industries. However, the viability of this option is depending on future cost and availability of RES electricity. For the glass industry, this technology is already available in large scale (British Glass 2014; Cerame Unie 2013). Currently smaller sized furnaces apply this process, which uses the resistance of the molten glass itself (conductivity of molten glass increases and allows the use of resistant heating) (IPPC (2013, 50f) cited in Fleiter et al. (2016)).

Oxygen-fuel combustion (incl. heat recovery)

Oxy-fuel combustion burns the fuel using more oxygen instead of combustion air in the current furnace atmosphere thereby increasing efficiency and decreasing fuel demand. In addition, oxy-fuel combustion needs smaller heat recovery systems and can reach higher temperatures without emitting NOx as a side product. (British Glass 2014) Praxair (2016) has developed an advance heat recovery system for oxy-fuel fired glass furnaces which allows further energy consumption reductions compared to conventional oxy-fuel and air-regenerative furnaces (20%-30%) and further emissions reductions. (Kobayashi 2017; Praxair 2016; Libbey 2017)

Table 7: Technology readiness levels of selected mitigation options glass/ceramics

<table>
<tr><th>Clusters of mitigation options</th><th>TRL 6</th><th>TRL 7</th><th>TRL 8</th><th>TRL 9</th></tr>
<tr><td rowspan="3">Integrated process improvement

- Energy Efficiency
- Reduction in process-related emissions</td><td></td><td></td><td></td><td>Batch preheating</td></tr>
<tr><td></td><td>Heat recovery from oxy-fuel combustion</td><td></td><td></td></tr>
<tr><td colspan="2"></td><td colspan="2">Waste heat recovery</td></tr>
<tr><td rowspan="2">Fuel switch
- towards renewable energy sources
- towards decarbonised electricity</td><td colspan="4"></td></tr>
<tr><td colspan="3">Electrification</td><td></td></tr>
<tr><td>End-of-pipe
(CCS/ CCU)</td><td colspan="2"></td><td></td><td></td></tr>
<tr><td>Recycling and re-use (innovative recycling processes)</td><td></td><td></td><td></td><td>Closed-loop recycling</td></tr>
<tr><td>Material efficiency
(in production and downstream)</td><td></td><td></td><td></td><td></td></tr>
<tr><td>Material substitution
(downstream)</td><td></td><td></td><td></td><td></td></tr>
</table>

Source: [RT]

Table 8: Main characteristics of selected mitigation options glass/ceramics

Technology option	Examples	TRL	Max. emissions reductions 26	Market entry
RES Electrification	-	5-8[27]	up to 80%	2015/2020 [e]
Oxy-fuel combustion incl. heat recovery[28]	OPTIMELT	7[e]	up to 60%	2025[e]
Waste heat Recovery	Organic Rankine Cycle	8-9[29]	up to 15%[30]	-
Batch preheating		8	up to 15% [e]	-
Recycling[31]	-	9	up to 60%	-

Source: [RT], [ES], British Glass (2014), WSP Parsons Brinckerhoff (WSP) und DNV-GL (2015b), Cerame Unie (2013), WSP Parsons Brinckerhoff (WSP) und DNV-GL (2015a), Praxair (2016), Kobayashi (2017), Libbey (2017), (IPPC (2013, S. 102) cited in Fleiter et al. (2016)) own estimations [e]

[26] Reductions partly lower for ceramic industry (e.g. gasification of biomass up to 29%, oxy-fuel firing/oxygen enrichment up to 12.5%).

[27] Lower TRL in the ceramic industry (5-6). Higher TRL in the glass industry (8).

[28] Mainly for glass industry. Example for container glass.

[29] Lower TRL in the ceramic industry for special projects e.g. DRYficiency project (around TRL 5).

[30] Mainly for glass industry.

[31] Mainly for glass recycling.

Waste heat recovery

Waste heat recovery can be used to pre-heat the input air to the furnace in order to reduce energy demand to heat up the kiln (British Glass 2014). This takes place in regenerative furnaces, which are either cross-fired or end-fired. End-fired furnaces are more energy efficient than cross-fired furnaces, due to the longer path of the flames (IPPC (2013, 311f) cited in Fleiter et al. (2016)). The potential of this saving option is medium compared to other options like fuel switch or oxy-fuel combustion (British Glass 2014). In the ceramic industry excess heat can be also used to preheat dryer air in addition to preheating the combustion air (Cerame Unie 2013).

Batch preheating

In glass making raw materials used are normally introduced into the furnace at ambient temperature or slightly warmer. Using waste heat based pre-heaters can reduce fuel consumption up to approx. 15% warming the batch and cullet to 275-325°C and increase output by around 20%. By now, some pre-heaters are already in operation. (British Glass 2014).

Recycling

Another possibility to reduce energy consumption and CO_2 emissions in the glass industry is closed-loop recycling, where cullet is returned to the manufacturer for re-melting. In addition, glass that is deemed to contaminate could be re-melted into other uses (British Glass 2014).

In the ceramic industry recycling has a limit due to the chemical transformation that occurs when firing raw materials, however products like bricks can be crushed into brick chips and unfired clay can be reused. Imperfect ceramic products could be crushed and used in other industries (e.g. construction industry). (Cerame Unie 2013)

Additional options

In addition to the modelled focus technologies other technologies like e.g. the fuel switch to bio fuels and EE-methane could also be an option for the glass and ceramics industry. However, fuel switch especially to bio fuels and EE-methane provides several challenges. It would need major technical changes to the system as current glass melting furnaces are designed to burn oil or gas (British Glass 2014). It is also reliant to high uncertainties concerning future bio fuels availability - due to competition with other sectors like e.g. the transport sector - and future price uncertainties concerning the use of EE-methane instead of bio fuels.

In addition to the selected mitigation options there exists a variety of additional technologies that could also contribute to the reduction of future CO_2-emissions in the steel industry [RT]:

- Furnace/kiln design improvements
- Fuel flexibility/switch
- Heat exchanger in kiln stack
- Combined heat and power; heat pumps
- Process optimisation
- Increased material efficiency (optimised product design, light weight, 3D-printing for prototyping)
- Design of non-/low fired products (mainly ceramics)
- Batch reformulation/pelletisation
- Carbon capture and usage/storage

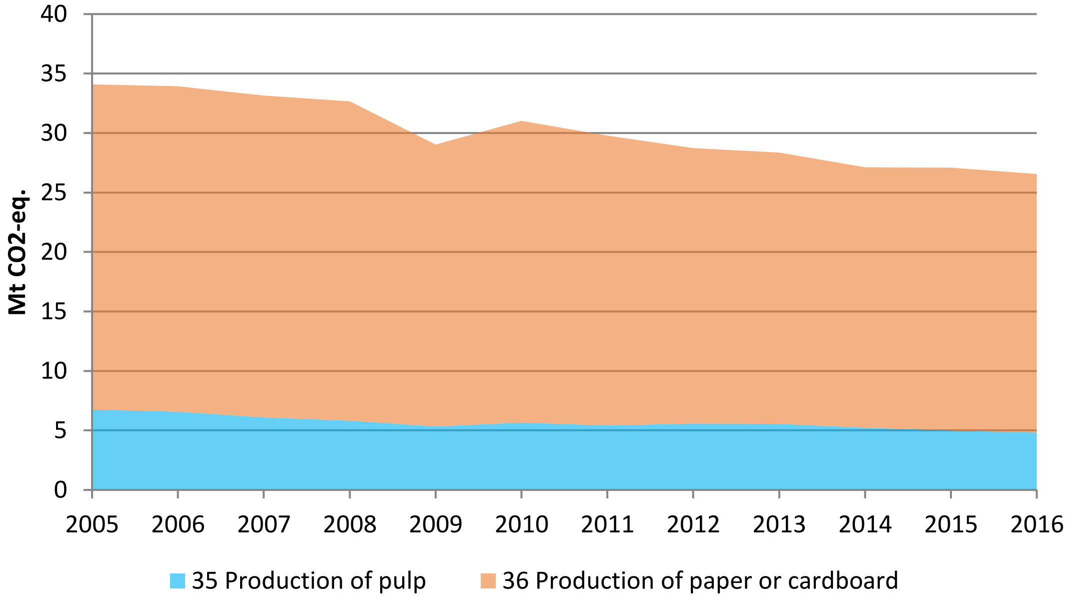
3.4 Pulp/paper industry

The European pulp and paper industry accounted in 2016 for around 1.5% of the verified emissions of all stationary installations of the European Union and around 5% of its industrial emissions excluding combustion (Figure 4, EEA (2017)).

The paper industry covers both the production of the required chemical pulp, mechanical pulp and recovered fibres as well as the production of paper and cardboard. It characterized by its differently integrated paper production sites and a high share of integrated electricity generation and combined heat and power generation (Fleiter et al. 2013b).

In the past the European pulp and paper industry in has already made noteworthy efforts towards decarbonisation. Nevertheless, the industry still has potential for innovation either directly via process innovations or indirectly via the substitution through new products [RT].

A selection of relevant technologies for the decarbonisation of the branch is presented stating the current level of development of the technology in Table 9, as well as selected characteristics in Table 10.



Source: EEA (2017)

Figure 4: Verified historical emissions EU28 pulp/paper sector as reported in the EU ETS (Source: EEA 2017)

Table 9: Technology readiness levels of selected mitigation options pulp and paper industry

Clusters of mitigation options	TRL 5	TRL 6	TRL 7	TRL 8	TRL 9
Integrated process improvement - Energy Efficiency - Reduction in process-related emissions		Enzymatic pre-treatment			Black liquor gasification
	Foaming of fibrous materials				Waste heat recovery
				New drying techniques	
Fuel switch - towards renewable energy sources - towards decarbonised electricity					
End-of-pipe (CCS/ CCU)					
Recycling and re-use (innovative recycling processes)					
Material efficiency (in production and downstream)					
Material substitution (downstream)					

Source: [RT]

Table 10: Main characteristics of selected mitigation options pulp and paper industry

Technology option	Examples	TRL	Max. emissions reductions	Market entry
New drying techniques	Impulse drying[32]	8-9	up to 20%	2020[e]
Foaming of fibrous materials		5	n.a.	2025
Black liquor gasification		8-9[e]	up to 11%	2020[e]
Enzymatic pre-treatment		6-8	up to 5%	2025[e]
Heat recovery	e.g. paper[33]	9	up to 5%	-

Source: [RT], WSP Parsons Brinckerhoff (WSP) und DNV-GL (2015d), Fleiter et al. (2013b), Fleiter et al. (2012b), own estimations [e]

New drying techniques

Drying the paper web is the major energy-consuming process in a paper mill. Literature discusses various new drying techniques that might result in energy efficiency improvements and CO_2-emission reductions as a consequence. The actual possible energy saving potential is currently not clearly known, as is the time of earliest commercial application.

[32] Selected options like for example "superheated steam drying" can have lower TRLs (e.g. 3-5 in WSP Parsons Brinckerhoff (WSP) und DNV-GL 2015d). The example shown here is for "impulse drying".

[33] Also modelled for mechanical pulp.

Examples for such innovative drying techniques are steam/air impingement drying, condensing belt drying and impulse drying. (Fleiter et al. 2012b).

Black liquor gasification

Black liquor gasification (BLG) is a technique used in pulp mills to generate surplus electricity or bio fuel. In the black liquor gasification process concentrated black liquor is converted into inorganic compounds (mainly sodium and sulphur) suitable for the recovery of cooking chemicals and combustible fuel gas comprising primarily hydrogen and carbon monoxide. (Suhr et al. 2015).

Enzymatic pre-treatment

Pre-treating wood chips using enzymes reduces the mechanical energy needed for wood processing. A variety of processes and enzymes have been discussed since the 1980s, but no single dominant process design has evolved so far. New approaches combine the use of enzymes with low-intensity refining to improve the penetration of the enzymes into the wood. Electricity savings are expected of 10-40%, depending on the type of enzymes and the process design. (Fleiter et al. 2012b).

Heat recovery

Heat recovery and the use of waste heat are widespread in the paper industry. Large potentials are found in the use of waste heat from refiners and grinders, but also from the dryer section in the paper machine and the effluent water. In particular, the use of low temperature heat still shows further potential, but also the steam system is often not adequately optimized. (Fleiter et al. 2012b).

Additional innovations

In addition to the modelled focus technologies other technologies which have not been chosen for deeper analysis e.g. due to their too low TRL levels – for example deep eutectic solvents and new materials replacing paper and plastic (e.g. Paptic) - could also be relevant for the future emission reduction ambitions of the pulp and paper industry.

Such technologies could be [RT]:

- Deep eutectic solvents,
- New materials replacing paper and plastics,
- On-site bio energy production,
- New recycling technologies without wetting and drying,
- Lightweight products,
- New materials replacing paper and plastic,
- Improved dewatering and retention via chemical treatments,
- CCS/CCU,
- and others.

3.5 Chemicals industry + bio-based industry

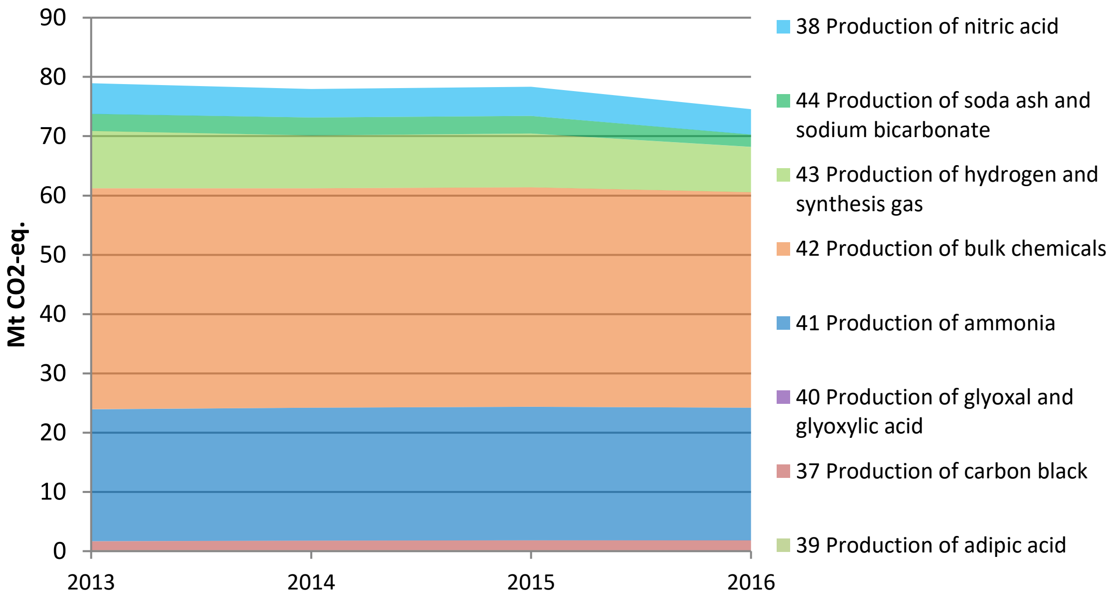
The European chemicals industry accounted in 2016 for around 4% of the verified emissions of all stationary installations of the European Union and 14% of the industrial emissions excluding combustion (Figure 5, EEA 2017)[34].

With a workforce of 1.2 million and sales of € 519 billion (2015), it is one of the largest industrial sectors and an important source of direct and indirect employment in many regions of the European Union. Annual CAPEX remain around € 20 billion and annual investments in R/D are around € 9 billion [RT]. The chemical industry is very heterogeneous, with many intermediates being used within the chemical industry itself as raw material for other products; the energy and carbon intensity vary strongly over products and processes. High Value Chemicals (HVC – the products of an ethylene plant) and ammonia are two of the most energy intensive products, and used in the production of many others.

DG CLIMA has chosen to combine the bio-based industry in one expert roundtable with the chemical industry, and this combination is followed here. The bio-based industry, again, consists of a large variety of processes and products, which can be classified as:

- Drop-ins: A traditional (platform) chemical, such as ethylene or ammonia, is replaced and used as basis for the production of other products);
- New structures: A new molecule is made with new functionality replacing another molecule with the (more or less) the same functionality).

Differently than many other industry sub-sectors, the chemical and the bio-based sub-sectors do not only use hydrocarbons in their energy mix (fuel, electricity), but also as feedstock (naphtha, natural gas, biomass, …).



Source: EEA (2017)

Figure 5: Verified historical emissions EU28 chemical sector as reported in the EU ETS

[34] Some chemical company data are reported under the fuel combustion category; hence, actual emissions of the chemical industry may be higher.

Below, a selection of relevant technologies for the decarbonisation of the branch is presented stating the current level of development of the technology (Table 11) as well as selected characteristics (Table 12).

Bio-based

There are many bio-based routes, a few of which were described in the expert survey and in the expert roundtable. These however represent just a small fraction of the wide variety of processes and products, at different TRL and with different energy and greenhouse gas savings. To illustrate, [WSP, 2015] reports TRLs varying from 1-6 for the use of biological pathways (e.g. fermentation and biocatalysis). While bio-based production can also lead to fuel savings (in case a complicated fossil route is replaced by a more straightforward bio-based route; for quite some bio-based routes, the energy use is higher than for the alternative fossil route [Dechema 2017] ; the total LCA effect is in these cases often still beneficial as the gain from the feedstock switch outweighs the effect of the increased energy use. [Dechema 2017] describes several bio-based routes for producing platform chemicals (methanol, ethylene, propylene, BTX) – which have not been modelled here.

CCU

There are many different CCU technologies and many CCU of these are intensely researched. There are CCU options in the chemical industry with various TRLs, including the production of polymers, Power2Fuel, Power to methanol (CO_2 + H_2 from electrolysis), and using CO_2 from steel plants for the production of chemicals. [Dechema 2017] describes several CCU routes for producing platform chemicals (ammonia, methanol, ethylene, propylene, BTX); this data has been taken into account for the modelling of the production of methanol. Energy and carbon savings are obviously technology and product dependent, but also depend heavily on the reference conditions (for example: in many of the CCU options, the combustion reaction is reversed, requiring high energy input, which is delivered by electrolysis to produce hydrogen; these CCU technologies only lead to a reduction of fossil CO_2 emissions in case the emission factor of the power used is sufficiently low); therefore, assessing the GHG savings thoroughly is important (LCA). Furthermore, it is important to determine "who gets the CO_2 savings", the CO_2 consumer, or the supplier of CO_2 (the one who is no longer emitting it); refer to the paragraph of the steel sector. Note that in the modelling the CO_2 savings have been allocated to the chemical industry (and most likely to the steel sector, so currently there is double counting of emissions savings).

CCS on ammonia

CCS in industry would logically start in plants emitting pure CO_2 streams; ammonia plants emit such streams, in relatively high amounts. This, in combination with the limited alternatives to reduce emissions from ammonia production [Stork 2015], makes application of CCS to ammonia plants logical demonstration projects. According to [WSP 2015] the TRL is 6-7; currently the carbon price in EU ETS is insufficiently high to make any CCS business case attractive without policy support only on the basis of financial drivers. Saving for CCS for ammonia are based on 90% capture efficiency for the process emissions, i.e. two thirds of the CO_2 emissions / tonne of ammonia. A CAPEX of 364 Euro/tonne ammonia includes the full CCS chain (capture of process emissions, transport, storage). If we just account for capturing, the CAPEX would be of the order of 130 Euro/tonne ammonia. This is very much dependent on the actual set-up, and that range of investment costs is likely to be an underestimation. If we would scope this measure as total capture (process and combustion emissions), the investment costs would be >500 euro/ton ammonia.

Table 11: Technology readiness levels selected mitigation options chemicals sub-sector

<table>
<tr><th>Clusters of mitigation options</th><th>TRL 5</th><th>TRL 6</th><th>TRL 7</th><th>TRL 8</th><th>TRL 9</th></tr>
<tr><td>Integrated process improvement
- Energy Efficiency
- Reduction in process-related emissions</td><td></td><td></td><td></td><td></td><td></td></tr>
<tr><td>Fuel switch
- towards renewable energy sources
- towards decarbonised electricity</td><td></td><td>Hydrogen to produce ammonia</td><td></td><td></td><td></td></tr>
<tr><td rowspan="2">End-of-pipe

(CCS/ CCU)</td><td colspan="3">CCU Methanol</td><td>CCU: Functionality-driven</td><td></td></tr>
<tr><td colspan="3">CCS for ammonia</td><td></td><td></td></tr>
<tr><td>Recycling and re-use (innovative recycling processes)</td><td></td><td></td><td></td><td></td><td></td></tr>
<tr><td>Material efficiency (in production and downstream)</td><td></td><td></td><td></td><td></td><td></td></tr>
<tr><td>Material substitution (downstream)</td><td></td><td></td><td></td><td></td><td></td></tr>
</table>

Source: [RT], [WSP, 2015]

Table 12: Main characteristics of selected mitigation options chemicals / bio-based sub-sector

Technology option	Examples	TRL	Max. emissions reductions	Market entry
CCU – Methanol	Carbon International Iceland	6-7	Eliminates (almost) all emissions, if renewable power is used[35] and depending on the (accounting of the) source of CO_2, and the energy used to capture the CO_2.	2030[36]
CCS for ammonia	Capturing of process emissions from syngas production already happening.	6-7	(Almost) all process emissions, which forms typically 2/3 of the CO_2 emissions of ammonia production	2025
Hydrogen based ammonia	Renewable electricity → H_2, turned into NH_3	6	(Almost) all emissions	In the near future

Source: [RT], [WSP, 2015]

[35] The emissions for methanol production include emissions in the plants producing methanol plus the emissions associated with the carbon that is included in the methanol (and which is released end-of-life). This is needed to compare CCU in a fair manner with other process routes.

[36] Moderate plant already operational in Iceland.

Additional innovations

Additional innovations that might become very relevant in the future but are not included in the analysis are (note that this list is intended to be illustrative rather than exhaustive):

- **Recycling** is an integral part of the circular economy (chemical recycling). It can take place within, but also outside the chemical industry (mechanical recycling), in its current definition. Chemical recycling can again take place in many different ways, ranging from the Vinyl loop process (in which selective dissolution and filtration eliminates contaminations in PVC without breaking down the molecule structure) to production of syngas by plasma gasification or catalytic cracking (in which the molecules in plastic waste is completely broken down – to be built up later again) [Elser 2015]. LCA approaches can be used to assess whether reuse, mechanical recycling, chemical recycling or energy recovery are the better options, taking future developments (such as the electricity emission factor) into account.
- [Dechema, 2016] reports several "**modular plants**" initiatives, of which several in the pilot phase. Drivers for modularization in small scale continuous production are the faster time to market, savings in procurement (known parts and vendors), increased flexibility (amongst others offering the possibility to produce close to feedstock / clients), the possibility of multi-purpose continuous plants and sequential numbering-up of modular plants following market demands, with the potential for lower OPEX, CAPEX, logistics and energy consumption [Dechema, 2016].
- Many new applications are developed for **hydrogen electrolysis** (including demand side management), and new technologies are also developed, like nuclear high temperature electrolysis for ammonia and solid state ammonia synthesis [Stork 2015 and WSP 2015]. Hydrogen plays a key role in the production of ammonia (emitting a significant share of the chemical industries GHG's, see Source: EEA (2017)
- Figure 5) and opens the road for many CCU options (by which, as potential but still far away future, olefin platform chemicals could be made (hydrogen + CO_2 → methanol → Methanol to Olefins), apart from its applications in other sectors of the society (refineries, steel?, transport fuel, …). The CO_2 footprint of its application depends strongly on the electricity emission factor.
- Increasing efficiency in production through **digitisation and advanced processes** [RT];
- **Methane pyrolysis** as a new technology for hydrogen production with lower CO_2 emissions [RT];
- **Electrification**, next to using electricity for CCU, it can also be used to optimize the heat household, or just as a boiler. Work is ongoing on many innovations in this field.
- **Process Intensification** (including membrane technology) is already featuring in the modular plant designs, but can also be used as technology toolbox in itself. [WSP, 2015] indicates TRL 3-5, which may well apply to some of the process intensification technologies, but others are at different stages of development.
- More robust and tolerant production systems [RT]
- Integration of advanced process modelling, control technologies and digitization [RT]
- Industrial symbiosis [RT]

- Materials "breakthroughs" including better eco-design of materials, development of advanced sustainable recycling process, high performance functional materials for low-carbon energy, mobility and housing [RT]
- Catalytic high temperature cracking for olefins / integrating gas turbines with the cracking furnace [WSP, 2015]
- Methanol to olefins [WSP, 2015]
- Biomass gasification / waste / decarbonized methane as fuel [WSP, 2015]
- Improvements in catalysis [IEA, 2013]
- Power 2 Heat / Power 2 Fuels
- Many bio-based processes are / have been developed, aimed at making a wide variety of chemicals. Bio-based processes either aim at delivering platform chemicals (such as ethylene from sugar or from bio-naphtha), or at delivering new chemicals with apt functionalities (for example lactic acid). Uptake of platform chemicals is easier (as the market is already used to processing these), but there are many routes to new chemicals, which could (in future) have a competitive advantage against fossil-based chemicals.
- Many CCU processes are being developed, again aimed at making a wide variety of chemicals, and other products. Either traditional chemicals (such as methanol), or new chemicals delivering the desired functionality (such as polyols) are produced. In many, but not in all, cases significant amounts of energy are required (traditionally, CO_2 is formed when combusting hydrogen carbons; many CCU processes aim at reducing the share of oxygen and increasing the share of hydrogen in the molecules, which could be seen as the opposite of the combustion reaction, thus requiring energy).

3.6 Non-ferrous metals industry

As an energy but also electricity-intensive industry the European aluminium industry accounted in 2016 for around 1% of the verified emissions of all stationary installations of the European Union and around 2% of its industrial emissions excluding combustion (Figure 6, EEA (2017)). In aluminium production two main process routes can be distinguished: primary aluminium production from bauxite and the much less energy-intensive aluminium production using scrap and electricity as main inputs.

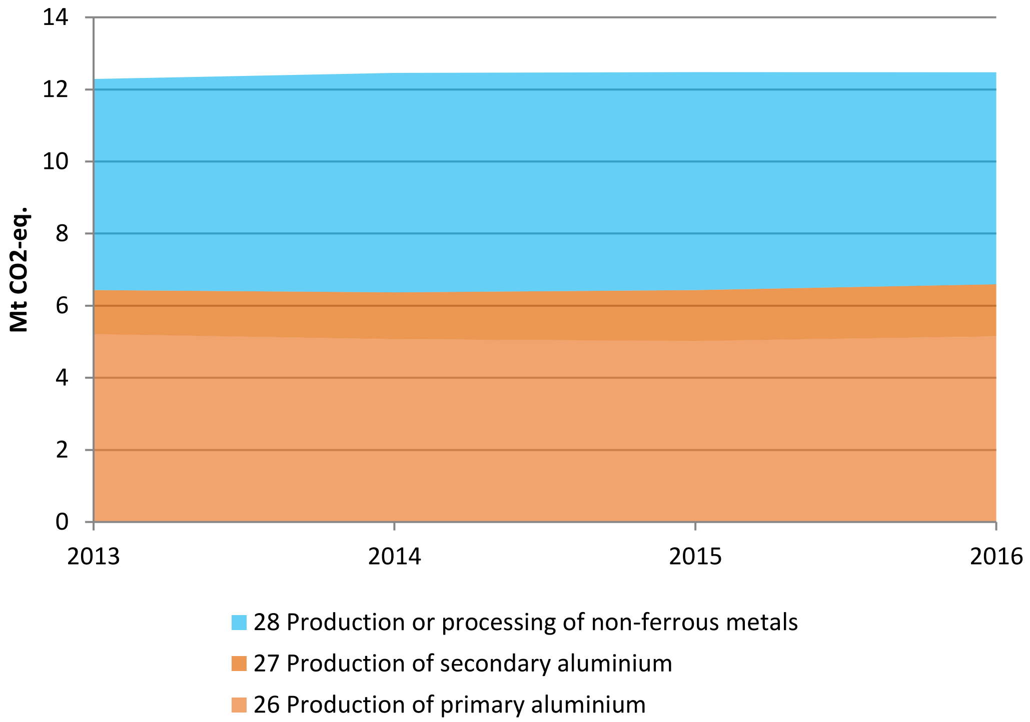
In the following section, a selection of such "breakthrough" technologies is presented stating the current level of development of the technology (Table 13) as well as selected characteristics (Table 14).

Low-emission electrolysis

HAL4e is an example of an energy efficient, low-emission electrolysis in which several saving options (e.g. millivolt chasing & bottleneck removal, operate at shorter interpolar distance, improved process control & stability, etc.) are combined. (http://www.hydro.com/globalassets/1-english/investor-relations/other-presentations/2015/hydro-technology-update.pdf)

Inert anodes in combination with wetted drained cathodes

From the use of inert and dimensionally stable non-carbon anodes substantial energy efficiency increases can be expected, especially when the anode is combined with a stable wettable cathode. The combination of those can reduce energy requirements in the electrolysis and anode manufacturing processes as well as reduce CO_2 emissions by approximately 1.65 t CO_2eq./t compared to the Hall-Héroult technology (Choate, 2003; HWWI, 2005 cited from Moya et al. 2015). Fuel consumption would also be reduced as the anode baking facility is no longer required. (Moya et al. 2015)



Source: EEA (2017)

Figure 6: Verified historical emissions EU28 aluminium industry reported in the EU ETS

Table 13: Technology readiness levels of selected mitigation options in non-ferrous metals industry

Clusters of mitigation options	TRL 5/6	TRL 7	TRL 8	TRL 9
Integrated process improvement - Energy Efficiency - Reduction in process-related emissions	HAL4e			
	Inert anodes/wetted cathodes		Waste heat recovery	
Fuel switch - towards renewable energy sources - towards decarbonised electricity	Magnetic billet heating			
End-of-pipe (CCS/ CCU)				
Recycling and re-use (innovative recycling processes)				
Material efficiency (in production and downstream)				
Material substitution (downstream)				

Source: [RT]

Table 14: Main characteristics of selected mitigation options non-ferrous metals industry

Technology option	Examples	TRL	Max. emissions reductions	Market entry
Low emission electrolysis	HAL4e	5-6	n.a.	2023
Inert anodes/wetted drained cathodes		5	up to 35%	2020/2025
Magnetic billet heating		5-9[37]	n.a.	2010/2020[38]
Waste heat recovery[39]		8-9	n.a.	-

Source: [RT], Fleiter et al. (2013b)

Magnetic billet heating

Induction melting furnaces enable a much better utilization of the final energy as fuel-driven furnaces having the disadvantage of a high use of primary energy in the conversion process for power supply. But, using superconducting coils for generating the magnetic field leads to lower final energy demand. Currently the technology used as a pre-treatment of heat in metal forming. However, the basic principle of superconducting coils can be used in all areas where at present Induction techniques can be used Kellers et al. 2009). (Fleiter et al. 2013b)

Additional innovations

In addition to the selected mitigation options there exists a variety of additional technologies that could also contribute to the reduction of future CO_2-emissions in the non-ferrous metals industry [RT]:

- Carbothermic reduction,
- Balancing the electricity demand in aluminium smelters,
- Innovative recovery processes,
- New materials with improved conductivity,
- and others.

3.7 Refineries industry

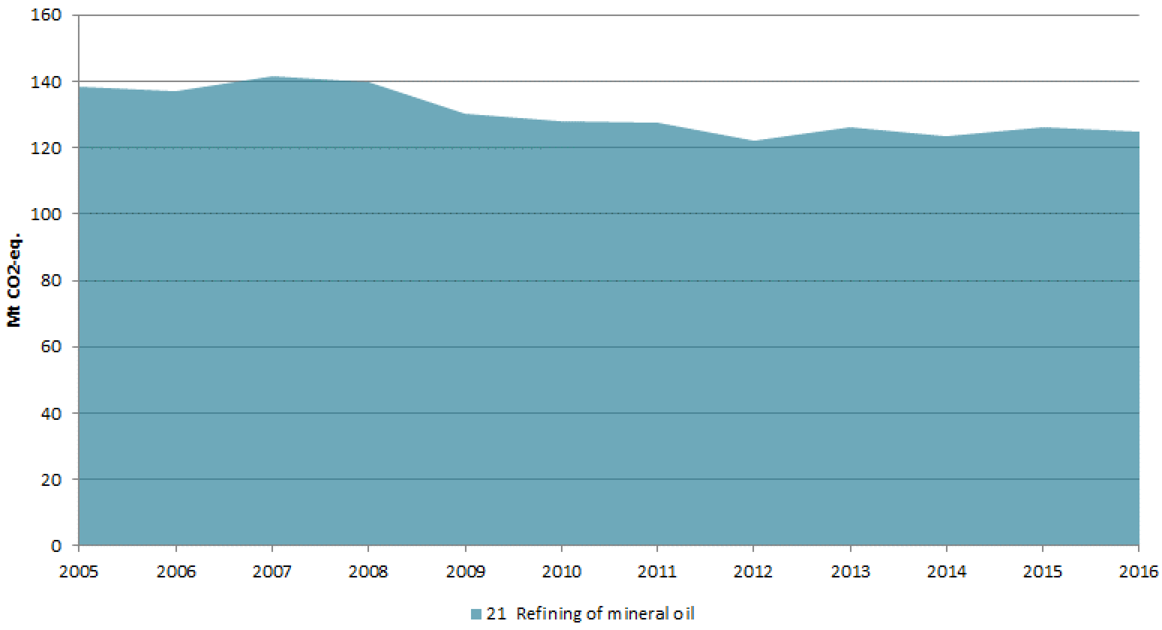
As an energy-intensive large industry the European refinery industry accounted in 2016 for around 7% of the verified emissions of all stationary installations of the European Union and around 23% of its industrial emissions excluding combustion (Figure 7, EEA (2017)). In refineries, crude oil is converted via various physical, physical-chemical and

[37] Lower TRLs in the copper industry (5), higher TRLs in the aluminium industry (8-9).

[38] 2020 for the copper industry.

[39] Example for copper.

chemical processes into different products such as fuels for transport, combustion fuels for the generation of heat and power, raw materials for the petrochemical and chemical industries, products such as lubricating oils, paraffin and bitumen. Main GHG emitting processes are furnace units in the production of process heat, electricity and steam from fuels (fuel gas, heating oil and liquid gas), coke combustion in the catalytic converters (catalytic crackers and reformers), Production of hydrogen and synthesis gas. To further decarbonise the refinery sector breakthrough technologies and true paradigm shifts will be necessary.



Source: EEA (2017)

Figure 7: Verified historical emissions EU28 refinery industry reported in the EU ETS

However, refineries are facing multiple challenges:

- Quite some refineries (17 out of 100 since 2008) have been closed in Europe in the past years (FuelsEurope, 2017)[40], while their utilization rate has also decreased (indicating that more closure might well come);
- There is pressure on the continued use of fossil fuels in transport see for example:
  - IEA WEO 2016, 450 scenario, for OECD Europe: share of oil in transport decreasing from 89% (2020) to 52% (2040; with further 18% electricity and 23% biofuels and 7% other fuels).
  - In the EU Commission's low carbon roadmap, emissions from the transport sector will significantly decrease between now and 2050[41].
- Electric vehicles: Structural shift from gasoline car to electric mobility. On the future energy sources for transport, many options are open; see for example Shell (2017)[42]:

[40] https://www.fuelseurope.eu/dataroom/static-graphs

[41] (https://ec.europa.eu/clima/policies/strategies/2050_en)

- Pressure to insulate houses and shift to heat pumps and solar heating/cooling
- Pressure from investor side on fossil-fuel based investments

All in all, this leads to an increasingly uncertain environment. However, one issue is clearly that the oil markets are shrinking (the open question is to which degree) and moving towards innovative technologies, compatible with the 2050 sustainable energy systems provides unique opportunities to the sector to reinvent itself.

In the following section, a selection of such breakthrough technologies is presented stating the current level of development of the technology (Table 15) as well as selected characteristics (Table 16).

Table 15: Technology readiness levels of selected mitigation options refinery industry

Clusters of mitigation options	TRL 5/6	TRL 7	TRL 8	TRL 9
Integrated process improvement				
- Energy Efficiency - Reduction in process-related emissions				
Fuel switch - towards renewable energy sources	Biorefining	Renewable hydrogen		
- towards decarbonised electricity	Power to Gas/Liquid (via RES-H2)		Carbon Capture and Storage CCS / CCU	
End-of-pipe (CCS/ CCU)				
Recycling and re-use (innovative recycling processes)				
Material efficiency (in production and downstream)				
Material substitution (downstream)			Advanced biofuels	

Source: [RT]

Table 16: Main characteristics of selected mitigation options refinery industry

Technology option	Examples	TRL	Max. emissions reductions	Market entry
Carbon Capture and Storage	Lacq/TOTAL	8-9	60% (net; 90% gross reduction)	2025
RES-H2		7	up to 50%	2020
Bio-based refinery	REPSOL approach	6	up to 30%	2025
Power to Gas/Liquid (synthetic fuels)		6	80%	2025
Advanced biofuels		8-9	n.a.	2020

Source: [RT]

[42] http://www.shell.com/energy-and-innovation/the-energy-future/future-transport.html

Carbon Capture and Storage CCS/Carbon Capture and Use CCU

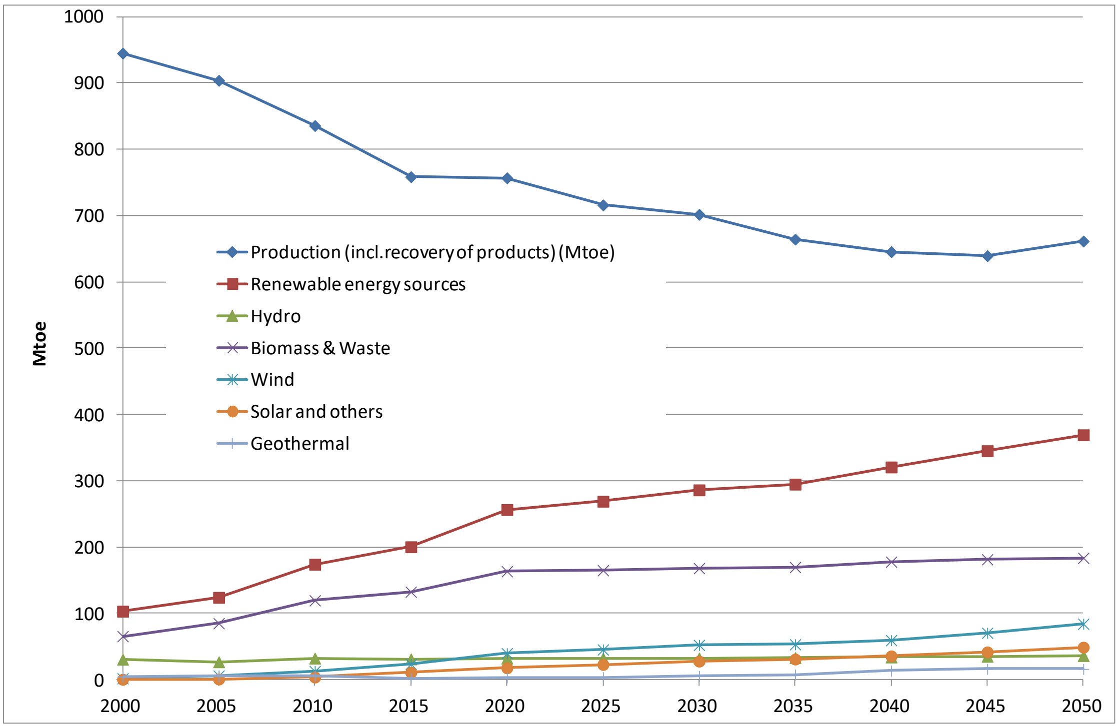
CCS/CCU is in principle an interesting option for refineries given the fact that these are large emitters and there are relatively few entities. Typical processes are for example for CCS are described by van Straelen et al. (2009)[43]. CCS/CCU can be applied to refineries as they are, i.e. based on crude oil as an input or on bio-refineries. The latter would lead possibly to negative emissions (to be verified by Lifecycle Analysis LCA). In both cases, an increase in energy consumption occurs, both for electricity and heat, for the extraction of the CO_2.

[43] http://www.sciencedirect.com/science/article/pii/S1876610209000277

4 Illustrative technological innovations for the Innovation Fund (IF) in the field of renewables (RES) and energy storage

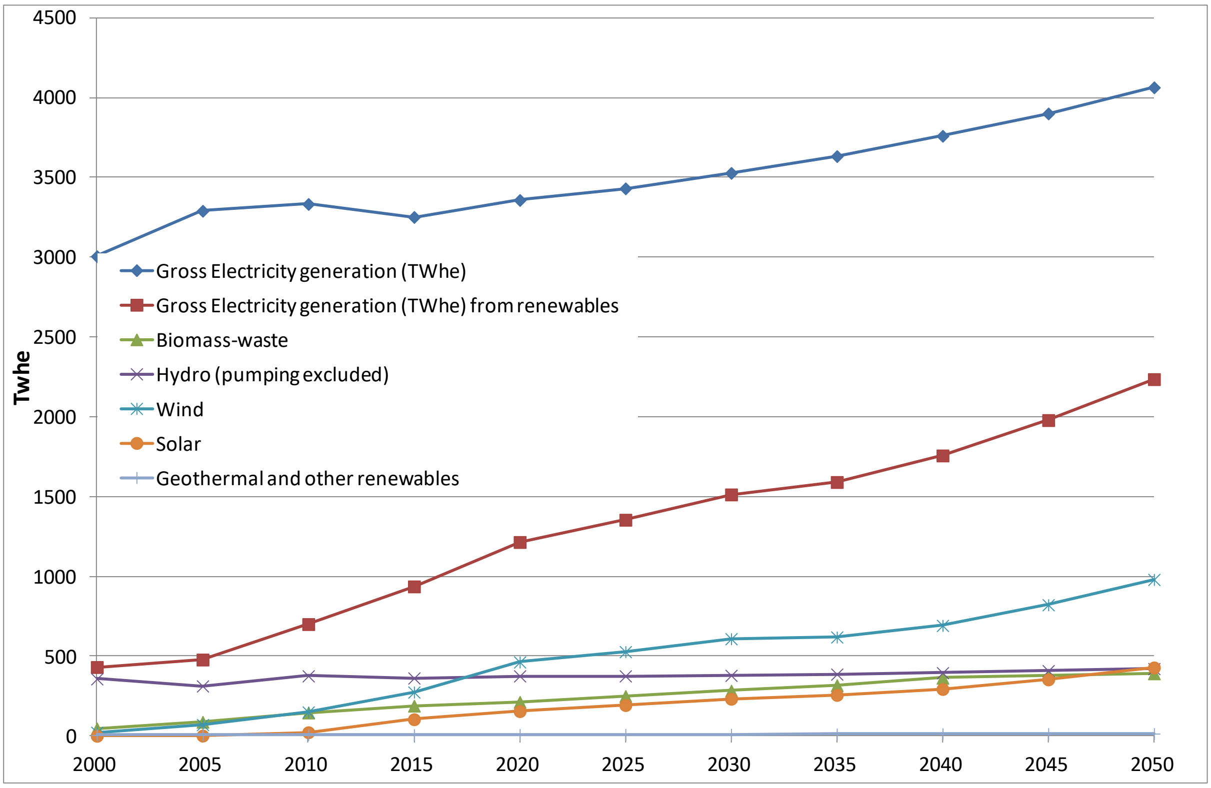
Renewable energy sources (RES) have already strongly penetrated energy production and consumption, see Figure 8, Figure 9 and Table 17:

- Overall RES: measured as the share of RES in Gross Final Energy Consumption (16.1% in 2015, 21% expected in 2020 compared to a target of 20%, 24.7% expected in 2030 compared to a target of minimum 32% presently, with a clause for an upwards revision by 2023).
- Subsector RES electricity (share of RES electricity in Gross Electricity Consumption): 28.2% in 2015, 35.5% expected in 2020, 42.5% expected in 2030.
- Subsector RES heating/cooling (share of RES heating/cooling energy in Final Energy Consumption for Heating/Cooling): 17.4% in 2015, 22.2% expected in 2020, 24.7% expected in 2030.
- Subsector RES transport (share of RES transport energy in Transport Final Energy Consumption): 6.9% in 2015, 11.2% expected in 2020, 14.1% expected in 2030.



Source: PRIMES (2016), Eurostat

Figure 8: Primary energy production from renewable energy sources for EU28 (historical and baseline projection to 2050)



Source: PRIMES (2016), Eurostat

Figure 9: Gross electricity generation from renewable energy sources for the EU28 (historical and baseline projection to 2050[44])

Table 17: Shares of renewables (overall, electricity, heating/cooling, transport) for the EU28 (historical and projection to 2050)

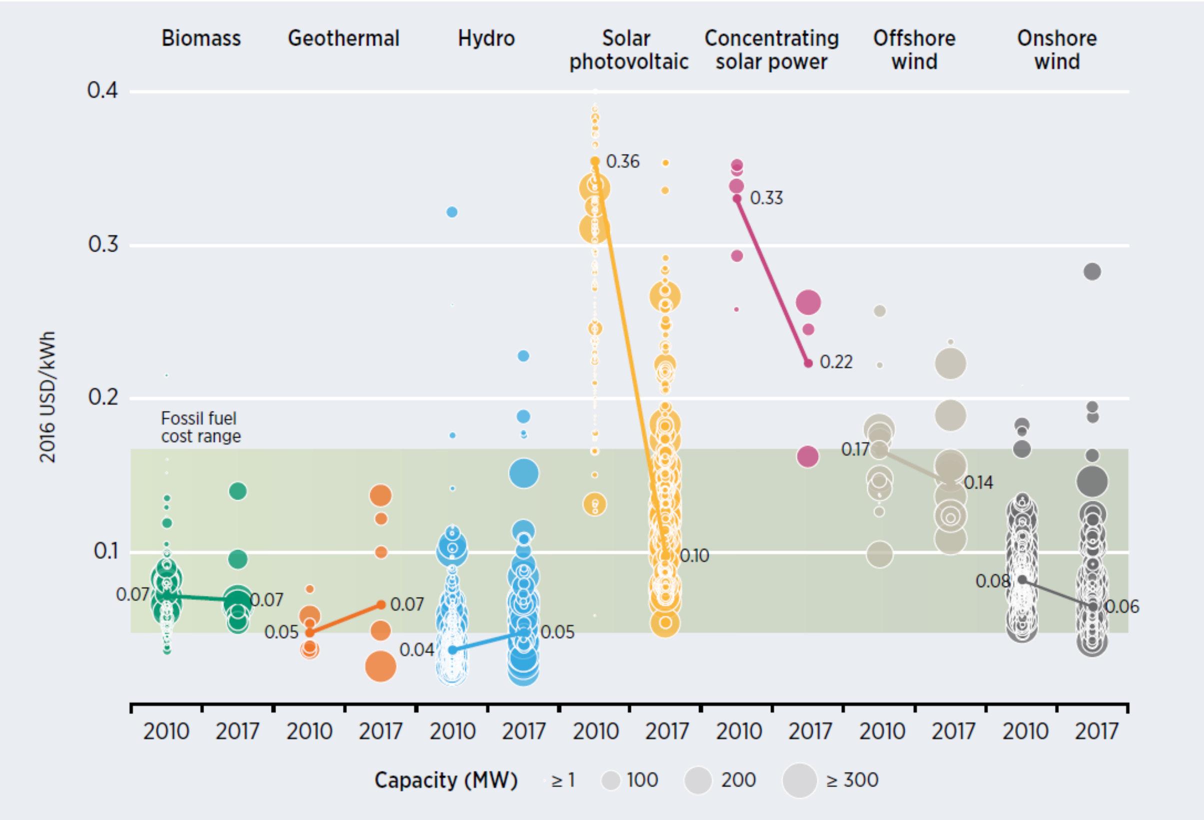
%	2000	2005	2010	2015	2020	2025	2030	2035	2040	2045	2050
Renewables (RES) share in Gross Final Energy Consumption	**7.5**	**8.7**	**12.4**	**16.1**	**21.0**	**22.4**	**24.3**	**25.3**	**27.2**	**29.2**	**31.2**
RES heating/cooling (RES H&C)	9.0	10.3	14.0	17.4	22.2	23.1	24.7	26.2	28.1	29.5	30.4
RES electricity (RES-E)	13.3	14.8	19.7	28.2	35.5	38.9	42.5	43.4	46.4	50.4	54.8
RES transport (RES-T) (1)	0.9	1.7	5.2	6.9	11.2	12.5	14.1	15.3	16.8	19.0	21.1
(1) based on Indirect Land-use Change (ILUC) formula											

Source: PRIMES (2016), Eurostat

In this, RES differ from energy-intensive industries because this massive diffusion of RES technologies, driven by the regulatory framework at EU and national levels accompanied

[44] The baseline projection for 2050 is far from reaching 100%. However, the targets set for 2050, in particular the required greenhouse gas reduction of 80-95% require a nearly 100% decarbonisation of the power sector in Europe. We therefore base our considerations on 100% RES share for 2050.

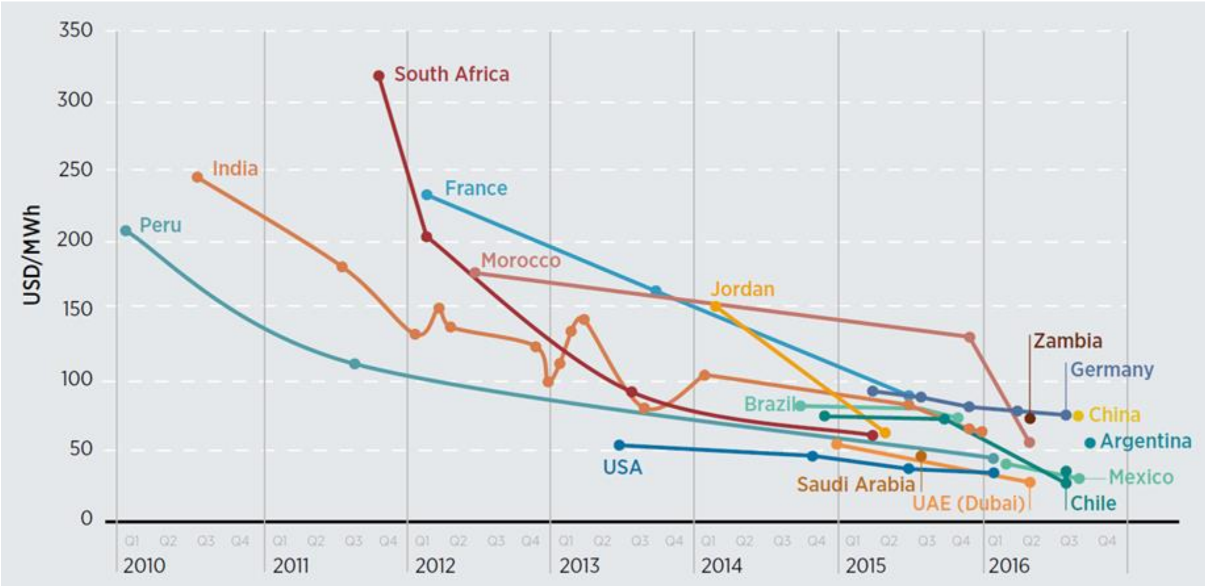
by strong policy support at national level, has led to a large spread of innovative RES technologies. In addition, the size of wind converters and solar plants has become considerably larger than 15 years ago, costs especially for solar PV has dropped dramatically (see Figure 10 to Figure 13). The most recent auctions in Germany have now reached in 2017 LCOE levels of about 55 Euro/MWh for solar PV, wind on- and offshore while sun-rich countries like the Emirates, Saudi-Arabia or Chile are at below 20 Euro/MWh for PV with further rapidly falling prospects (see Figure 11 for PV). The present auction price for renewable energy sources indicate the forth-coming price range to 2022 (Figure 12). There are cost differences among countries which are due to differences in the potential of renewable energy sources but also still due to the efficiency of the penetration of renewables into the main electricity markets. Ocean and tidal technologies, as still rather early technologies show still comparatively high LCOEs (see Figure 13). However, the prospects - to which the IF could contribute - are good that the technology cost could come down by scaling up units.



Note: The diameter of the circle represents the size of the project, with its centre the value for the cost of each project on the Y axis. The thick lines are the global weighted average LCOE value for plants commissioned in each year. Real weighted average cost of capital is 7.5% for OECD countries and China and 10% for the rest of the world. The band represents the fossil fuel-fired power generation cost range.

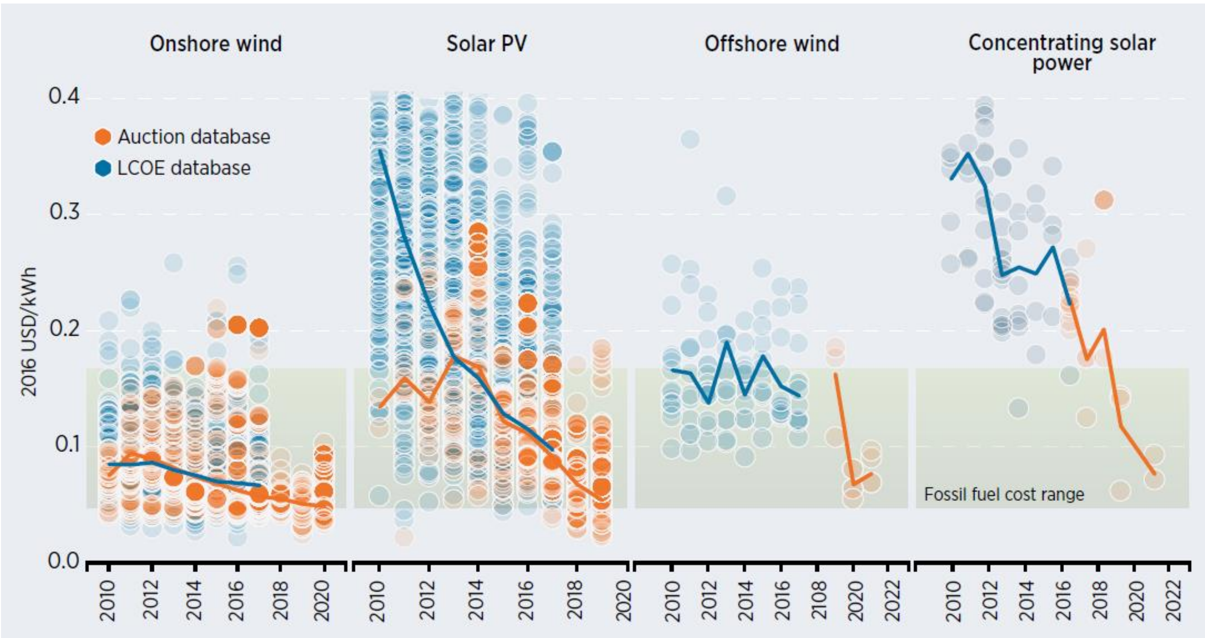
Source: IRENA (2018)

Figure 10: Global levelised cost of electricity from utility-scale renewable power generation technologies, 2010-2017



Source: IRENA (2017)

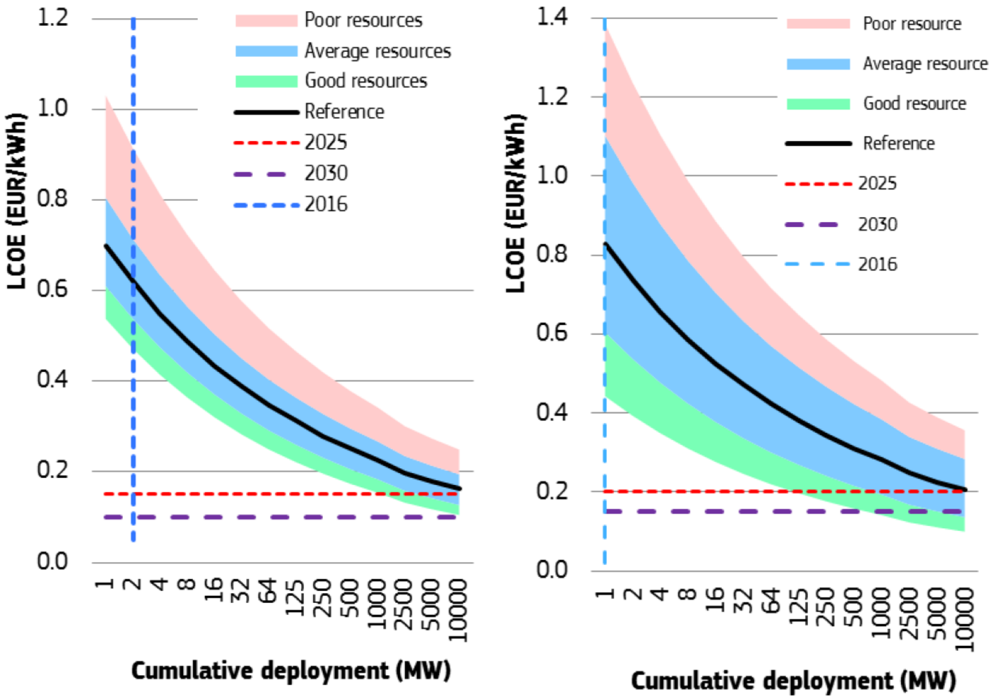
Figure 11: LCOE for solar PV in different countries



Note: Each circle represents an individual project or an auction result where there was a single clearing price at auction. The centre of the circle is the value for the cost of each project on the Y axis. The thick lines are the global weighted average LCOE, or auction values, by year. For the LCOE data, the real WACC is 7.5% for OECD countries and China, and 10% for the rest of the world. The band represents the fossil fuel-fired power generation cost range.

Source: IRENA (2018)

Figure 12: Levelised cost of electricity for projects and global weighted average values for CSP, solar PV, onshore and offshore wind, 2010-2022



Source: JRC (2016)

Figure 13: LCOE today and predictions with cumulative power for tidal arrays (left) and wave arrays (right)

In this context, the Innovation Fund will mainly have the following impacts:

- Increase the potential for the main stream renewable such as wind, solar PV. This will mainly occur at the more cost-intensive part of the cost curves for renewables (example: floating foundations for wind energy). The low cost part will be dominated by the mass production, especially with respect to solar PV and the world-wide development. This implies also that the Innovation Fund would have a stronger focus on TRL5-7 technologies in this field rather than for TRL 8-9 which would mainly be promoted by the industries own and continued research activities. Overall, compared to the main stream penetration of renewable the additional impacts of the innovation fund for the main stream renewables could mainly occur beyond 2030
- Increase in the potential (scale and cost) for the minority renewables such as geothermal, ocean/tidal but also small scale hydro (the potentials for large installations being exhausted in Europe), including pumped hydro. Here, the innovation fund could lead to a substantial relative increase of the renewable installations, however, from a relatively low absolute level. Nevertheless, these hydro plants are important contributors of flexibility services to a renewable electricity grid with high shares of renewable. For these renewable technologies, the focus of the IF would be for all TRLs.
- Increase in the potential of renewables with a medium-size potential and still relatively high cost, in particular concentrating solar power. This concept can only be applied in Southern European countries (in particular Spain). However, this technology is much for relevant for export markets given the more favourable conditions in other parts of the world (e.g. the MENA region).

- Biomass applications for power generation are seen in some studies[45] for 2050 to have a limited potential for electricity generation. There are also debates on the availability of sustainable biomass (although it could be increased with targeted action). Sustainable biomass may need to be prioritized for purposes where there are no / little alternatives, for example in the field of renewable materials. The same argument holds for biomass for heating purposes. On the other hand, a number of ambitious decarbonisation scenarios see a need for biomass in combination with CCS in order to achieve negative emissions.
- The Light Duty Vehicles (LDVs) in the transport sector could strongly shift towards electricity. However, (sustainable) biofuels from third generation, in combination with strong energy efficiency measures in transport, could make substantial contributions, especially for Heavy Duty Vehicles (HDVs) and aviation. [Source: presentation by .Concawe at the expert round table for refineries] The same for synthetic fuels (fuels made from CCU processes). However, the later could mainly play a role beyond 2030, in deep decarbonisation scenarios.
- The IF could also stimulate RES for heat such as innovative heat pumps, heat storage, solar collectors,etc.

In the following sections, a selection of such breakthrough technologies is presented stating the current level of development of the technology as well as selected characteristics.

The technologies are grouped according to whether they:

- enhance the potential for the resource
- reduce costs for the technology
- enhance technological performance
- provide the basis for new technologies
- allow for conversions bio energy to liquid / bioenergy to gas

In addition to the selected mitigation options there exists a variety of additional technologies that could also contribute to the reduction of future CO_2-emissions through the deployment of renewables [RT].

We provide in the following sections indications on the necessary FOAK ("First-of-a-kind") investment needs (see further Table 26 and Table 27). They should be understood, as already previously emphasized, as a set of technologies which present only one-in-kind plant for major single technology lines. This differentiates the figures also from the estimates of ICF (2016).

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[45] see for example:

Öko-Institut e.V.; Fraunhofer ISI (Eds.) (2016): Climate Protection Scenario 2050. Summary of second final report. Study conducted on behalf of the German Federal Ministry for the Environment, Nature Conservation, Building and Nuclear Safety. Berlin: Öko-Institut (contributing authors of Fraunhofer ISI: Braungart, S.; Eichhammer, W.; Elsland, R.; Fleiter, T.; Hartwig, J.; Kockat, J.; Pfluger, B.; Schade, W.; Schlomann, B.; Sensfuß, F.)

Langfrist- und Klimaszenarien BMWi, available online at: https://www.bmwi.de/Redaktion/DE/Artikel/Energie/langfrist-und-klimaszenarien.html

Fraunhofer ISI (2014): Optimized pathways towards ambitious climate protection in the European electricity system (EU Long-term scenarios 2050 II), Karlsruhe, September 2014. Available online at: https://www.isi.fraunhofer.de/de/competence-center/energiepolitik-energiemaerkte/projekte/eu-longterm-scenarios-2050-ii_33092.html#tabpanel-3

4.1 Wind Energy

Wind energy was already target of the NER300 Calls 1/2. Under these two calls 8 projects were awarded in the field of wind energy. Maximum funding range was 11-113 MEuro per project. ICF (2016) estimates project sizes for wind energy (fixed onshore, fixed offshore) of 50-300 MEuro (with indicative investment needs estimated at 250 - 3,000 MEuro) and for floating offshore turbines of 125-300 MEuro (with indicative investment needs estimated at 625-3,000 MEuro). Innovative wind energy technologies are listed in the following table.

Based on our selected technology set, we estimate the FOAK investment needs to 2030 for wind onshore with 170 MEuro and for wind offshore with 1,150 MEuro. For wind onshore, most of the technological development is supposed to be driven by market evolution, which is justified by the recent cost decrease observed in renewables auctions.

Table 18: Technology readiness levels of selected mitigation options wind energy

Clusters of mitigation options RES Technologies	TRL 5/6	TRL 7	TRL 8	TRL 9
Wind energy				
Enhance potential for resource	Floating foundations (a semi-submersible floater, light, competitive, adapted to mass production, easily towable connectable/disconnectable)		Mountainous region (e.g. Austria) Cold climate (e.g. heated blades in Sweden)	
Reduce costs for the technology	> 12 MW offshore wind turbines and > 40m water depth foundation solutions			
Enhance technolo-gical performance				
Provide basis for new technologies				

Source: [RT]

4.2 Solar Energy

Solar energy was already target of the NER300 Calls 1/2. Under these two calls 7 projects were awarded in the field of solar energy (of these 6 for CSP and 1 for PV). Maximum funding range was 40-70 MEuro per project (CSP), 8 MEuro for PV. ICF (2016) estimates project sizes for solar energy (CSP) of 185-330 MEuro (with indicative investment needs estimated at 925 - 3,300 MEuro), PV generation of 35-50 MEuro (with indicative investment needs estimated at 175 - 500 MEuro) and for PV Manufacturing of 45-250 MEuro (with indicative investment needs estimated at 135-1,250 MEuro). Innovative solar energy technologies are listed in the following table.

Based on our selected technology set, we estimate the FOAK investment needs to 2030 for CSP with 800 MEuro and for solar PV with 150 MEuro. Also for solar PV, most of the technological development is supposed to be driven by market evolution, justified again by the recent large cost decrease observed in renewables auctions.

Table 19: Technology readiness levels of selected mitigation options solar energy

Clusters of mitigation options RES Technologies	TRL 5/6	TRL 7	TRL 8	TRL 9
Solar energy				
Enhance potential for resource				
Reduce costs for the technology			Large scale Stirling dish power plant (scale-up)	Scale-up of CSP tower concepts Scale up of concentrating PV.
Enhance technological performance				Improve efficiency of tower concepts Innovative thermal storage concept for towers (graphite thermal storage) Building integrated PV
Provide basis for new technologies				

Source: [RT]

4.3 Bio energy

Bio-energy was already target of the NER300 Calls 1/2. Under these two calls 14 projects were awarded in the field of bio-energy. Maximum funding range was 4-199 MEuro per project. ICF (2016) estimates project sizes for 2[nd] generation biofuels of 150-600 MEuro (with indicative investment needs estimated at 750-6,000 billion Euro); for biomass for energy generation in the order of 8-100 MEuro (with indicative investment needs estimated at 80-2,000 MEuro). Innovative bio-energy technologies are listed in the following table.

Table 20: Technology readiness levels of selected mitigation options bio-energy

Clusters of mitigation options RES Technologies	TRL 5/6	TRL 7	TRL 8	TRL 9
Bio energy				
Enhance the potential for the resource		Use of lower quality biomass Waste to biofuels (e.g. SEKAB CelluAPP)		
Reduce costs for the technology			Large-scale production of synthetic gas	
Enhance technological performance		More integrated bioenergy production Integration with pulp/paper mill		
Provide basis for new technologies				
Bio energy to liquid / bioenergy to gas			Biodiesel, bionaphta Second generation ethanol Bio-Methanol Synthetic natural gas (injection in gas pipeline) Pyrolisis oil	

Source: [RT]

Based on our selected technology set, we estimate the FOAK investment needs to 2030 for biomass for energy generation at 310 MEuro.

4.4 Ocean/Wave Energy

Ocean/wave energy was already target of the NER300 Calls 1/2. Under these two calls 5 projects were awarded in the field of ocean/wave. Maximum funding range was 9-72 MEuro per project. ICF (2016) estimates project sizes for Ocean energy (comprising tidal stream, wave energy and tidal lagoons) of 20-100 MEuro (with indicative investment needs estimated at 100-1,000 MEuro).

Based on our selected technology set, we estimate the FOAK investment needs to 2030 for ocean/wave energy at 270 MEuro. Innovative ocean/wave energy technologies are listed in the following table.

Table 21: Technology readiness levels of selected mitigation options ocean/wave energy

Clusters of mitigation options RES Technologies	TRL 5/6	TRL 7	TRL 8	TRL 9
Ocean/wave energy				
Enhance the potential for the resource	floating ocean thermal energy conversion system			
Reduce costs for the technology			Up-scaling of ocean/wave energy plants	
Enhance technological performance				
Provide basis for new technologies				

Source: [RT]

4.5 Geothermal Energy

Geothermal energy was already target of the NER300 Calls 1/2. Under these two calls 3 projects were awarded in the field of geothermal energy. Maximum funding range was 15-39 MEuro per project. ICF (2016) estimates project sizes for geothermal energy of 75-120 MEuro (with indicative investment needs estimated at 225-720 MEuro).

Based on our selected technology set, we estimate the FOAK investment needs to 2030 for geothermal energy at 280 MEuro. Innovative geothermal energy technologies are listed in the following table.

Table 22: Technology readiness levels of selected mitigation options geothermal energy

Clusters of mitigation options RES Technologies	TRL 5/6	TRL 7	TRL 8	TRL 9
Geothermal Energy				
Enhance the potential for the resource	Use of Organic Rankin Cycle (enhance potential)		Hot dry rock process (more locations)	
Reduce costs for the technology				
Enhance technological performance				
Provide basis for new technologies	Semi-open underground loop (e.g. CloZEd Loop Energy)	)		

Source: [RT]

4.6 Energy Storage/Intelligent Grids

Intelligent grids were already target of the NER300 Calls 1/2 while energy storage was not. Under these two calls 3 projects were submitted in the field of intelligent grids. Maximum funding range was 8-85 MEuro per project. ICF (2016) estimates project sizes for Advanced electricity networks (AEN) of 10-50 MEuro (with indicative investment needs estimated at 140-1,400 MEuro), and for Large-scale energy storage solutions, including pumped-storage hydropower (LES) of 15-350 MEuro (with indicative investment needs estimated at 75-3,500 MEuro).

It should be noted that energy storage and intelligent grids are enablers for renewable energy sources to penetrate the market. They can therefore not be considered independently from RES penetration and are therefore modelled in conjunction with the penetration of RES technologies. Innovative energy storage / intelligent grid technologies are listed in Table 23.

Table 23: Technology readiness levels of selected mitigation options energy storage/intelligent grids

Clusters of mitigation options RES Technologies	TRL 5/6	TRL 7	TRL 8	TRL 9
Energy storage/intelligent grids				
Enhance the potential for the resource				
Reduce costs for the technology			Reduction in storage technology cost	
Enhance technological performance			Upscaling and enhancement of storage technologies	
Provide basis for new technologies				

Source: [RT]

5 ILLUSTRATIVE TECHNOLOGICAL INNOVATIONS FOR THE INNOVATION FUND (IF) IN THE FIELD OF CCS

1st-generation capture technologies (i.e. the commercial separation processes) in the power sector are based on amine-based chemical absorption technologies (that have reached TRL8 - 9 in the power sector) and cryogenic air separation technologies used to deliver O_2 to an oxygen blown gasifier or oxy combustion systems (TRL7-9 for the power sector). In the power generation sector, CO_2 capture processes are traditionally classified as post-combustion CO_2 capture, pre-combustion CO_2 capture and oxy combustion. The first generation of these technologies is fully ready for wide-spread deployment in the immediate future, although there is likely still scope for improvement in cost, performance and/or flexibility (to make the technologies more compatible with the integration of fluctuating renewable energy sources).

According to Zero Emission Platform 2017 Future CCS technologies report[46], the capture of CO_2 based on post-combustion CO_2 capture has realised full commercial scale demonstration[47] and pre-combustion is about to be commercial. Oxy-combustion technology has achieved a mini-demonstration status.

These are the technologies that could in principle be rapidly scaled. However, regulatory uncertainty and cost will probably impede that these technologies could penetrate, aside renewable energy sources that are already cheaper today[48]. Already coal without CCS is now more expensive than a number of renewables and by 2020 all renewables will generate electricity at cheaper cost than coal. This is why on a worldwide level, more and more plans for coal-fired plants are put on hold. Table 24 shows LCOEs for power plants with and without CO_2 capture.

With CO_2 capture, LCOEs are in the range of 71 to 91 EUR/MWh in 2013 (excluding transport and storage). This is compared with LCOEs for main-stream renewables (solar PV, wind onshore/off shore) of 55 Euro/MWh in 2017 and down to 20 Euro/MWh in sun-rich locations (see Figure 14). It can be certainly expected that CCS from the power sector could benefit from cost reduction[49] but so can renewables with a faster drop in

[46] http://www.zeroemissionsplatform.eu/news/news/1665-zep-publishes-future-ccs-technologies-report.html

[47] Examples include:
Boundary Dam Unit #3 (Saskatchewan, Canada), a large-scale demonstration project capturing 1 Mtpa CO_2 from 115 MWe coal fired power plant using the amine based Cansolv Solvent. There have been discussions on the cost of the unit which could be around 140 USD/MWh (http://www.cbc.ca/news/canada/saskatchewan/carbon-capture-critics-1.4388026 and https://www.cbc.ca/news/canada/saskatchewan/saskpower-carbon-capture-unlikely-future-1.4386411).
The government of Saskatchewan continues support to the project (https://www.cbc.ca/news/canada/saskatchewan/sask-government-carbon-capture-1.4390371)
The Petra Nova Unit #8 (Texas, USA), 1.4 Mtpa CO_2 from a slip stream (equivalent to 240MWe) of a coal fired power plant (using MHI's KS1 hindered amine solvent). Together with the Boundary Dam project, these are the two large scale power projects at a worldwide level, using CCS on a commercial basis (https://www.eia.gov/todayinenergy/detail.php?id=33552).
The ROAD (Rotterdam, Netherlands) demonstration project in the power generation industry. This project involves the capture of 1.1 Mtpa CO_2 from a slip stream (equivalent to 250MWe) of a coal fired power plant using Fluor's Econamine solvent. Two main power generators, Uniper and Engie announced their retirement from the project mid-2017 which was not pursued by then (https://www.rijksoverheid.nl/binaries/rijksoverheid/documenten/publicaties/2017/01/27/road-project/ROAD-project.pdf)

[48] https://www.forbes.com/sites/energyinnovation/2017/05/03/carbon-capture-and-storage-an-expensive-option-for-reducing-u-s-co2-emissions/#6c44440b6482

[49] According to Race, Julia (2017), in 2013, the UK CCS Cost Reduction Task Force21 estimated that generation and capture costs could drop approximately 17% for plants reaching FID (Financial Investment Decision) in 2020, instead of in 2013. In the late 2020s generation and capture costs could drop a further 25%. This would lead to LCOEs for power sector CCS in the range of 44-57 Euro2013/MWh.

LCOE, enhancing possibly the gap, if no massive penetration of power sector CCS occurs. Hence, from a pure cost perspective, renewables will provide electricity at a lower LCOE.

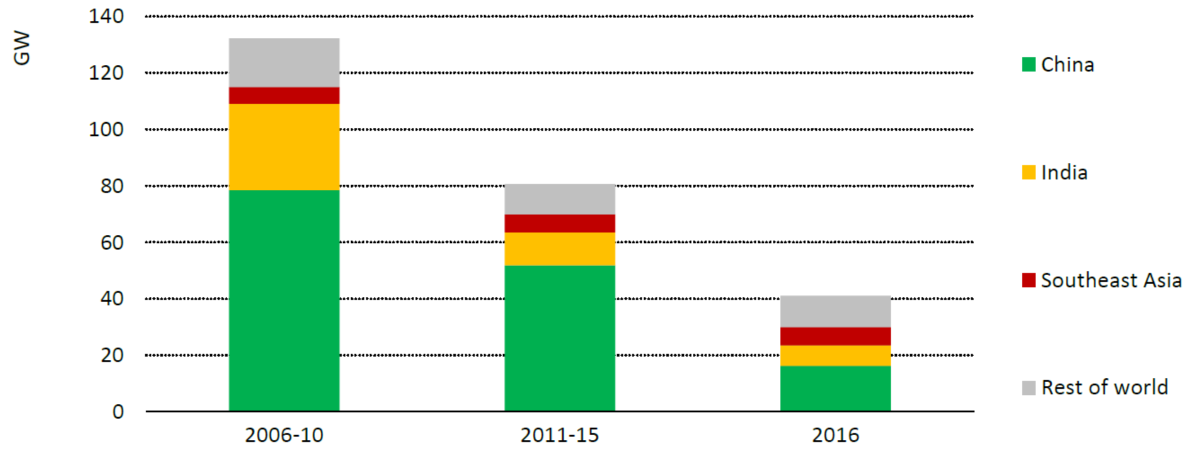
Table 24: Representative values of cost measures for power plants with/out CO_2 capture

Performance and Cost Measure	Post – Combustion	Pre- Combustion	Oxy Combustion	
Fuel	Bituminous coal	Natural gas[19]	Bituminous coal	Bituminous/Sub -bituminous coal
Reference plant	SCPC	NGCC	IGCC	SCPC
Total capital requirement w/o capture (2013€/kW)	2,012	806	2,445	1,990
Total capital requirement w/ capture (2013€/kW)	3,520	1,584	3,356	3,796
LCOE w/o capture (2013€/MWh)	54	49	69	49
LCOE w/ capture (2013€/MWh)	87	71	92	85
Cost of CO_2 captured (2013€/t CO_2)	35	57	26	40
Cost of CO_2 avoided[20] (2013€/t CO_2)	48	67	[33 – 48][10]	48

Notes in the table: (19) The gas CCS costs are very dependent on the fuel price and fuel price sensitivities should be included in evaluations; (20) Excluding Transport and Storage.

Source: Race, Julia (2017)

Figure 14: Average annual final investment decisions (FIDs) for new coal-fired power capacity



Source: IEA, World Energy Investment 2017 (2017)

Further information on CCS cost provided during the expert workshops and further sources shows quite a lot of variation and deserves further exploration:

- The ***capture costs*** on a Norwegian CCS Demonstration project showed capture CAPEX ranging from around 440 Euro/tonne CO_2 captured yearly for the capturing of a CO_2 stream to around 900-1600 Euro/tonne for the capturing of other CO_2 streams. Annual OPEX ranged from 7 Euro/tonne captured CO_2 for the capturing of the pure CO_2 stream to 45-90 Euro/tonne for the capturing of other CO2 streams. This implies that for this project the capture costs are higher than used in the modelling, e.g. in the case of ammonia (324 Euro/tonne).
- The ***transport & storage costs*** estimated in November 2017 by Port of Rotterdam for a project in Rotterdam would be between 20-30 euro/ton CO_2.
- A presentation during the expert workshop with indicative costs prepared for the Ervia CCS project shows that CAPEX for CCS ranges from around 2 MEuro/MWe electricity capacity to around 6.5 MEuro/MWe electricity capacity.
- Lawrence Irlam[50] shows FOAK CCS costs (values for Germany and Poland, based on a levelisation period of 30 years):
- Power generation:
    - PC supercritical: US$ 70-121 / tonne of CO_2 avoided
    - IGCC: US$ 87-148 / tonne of CO_2 avoided
    - NGCC: US$ 92-138 / tonne of CO_2 avoided

  CCS on industrial streams:
    - US$ 26-27 / tonne of CO_2 avoided (for biomass to ethanol or natural gas plants)
    - US$ 29-33 / tonne of CO_2 avoided (for fertilizer plants)
    - US$ 72-113 / tonne of CO_2 avoided (for iron and steel plants)
    - US$ 130-188 / tonne of CO_2 avoided (for cement plants).

Nevertheless, in a deep decarbonsation perspective of 2050 (95% reduction in GHG), the question of larger increase in electricity demand is raised[45]. While direct electricity uses (such as for electric cars or heat pumps) will moderately increase the electricity demand in Europe due to high efficiencies of electric uses and electricity savings with present uses, electricity demand could rise more strongly, however, by 2050, due to hydrogen production and the production of synthetic fuels (e.g. for goods transport on roads), given the low chain efficiencies of those processes. In such a scenario, the RES potentials in Europe may be insufficient and need possibly to be enhanced by potentials in sun-rich countries (coupled with imports of hydrogen, synthetic fuels or RES electricity), raising issues of supply security.

Emerging power sector CCS is still in a stage which is early for the IF but are briefly mentioned here given the longer term prospects. Emerging power sector CCS technologies are usually classified by their gas separation principles which are at the core of every CO_2 capture system.

Table 25 provides an overview of different classes of 2nd and 3rd generation (emerging or novel) capture technologies that are proposed for capturing CO_2 from power plants. These are characterised by their potential to achieve substantial improvement either with respect to the functional material, the reactor/contactor design or in the gas separation concept. This table presents the progress of their development towards their scale up

[50] The global CCS Institute, Global Costs of Carbon Capture and Storage, 2017 update, June 2017.

and commercialisation goals. A number of these technologies are still at a rather low TRL compared to the technologies which are relevant for the IF though some are at TRL 5-6.

Table 25: Emerging CCS mitigation options in the power sector

Separation Process	TRL 2015
Precipitating solvents	5
Biphasic solvents	4-5
Enzyme catalysed enhanced solvents	5
Vacuum Pressure Swing Adsorption (post combustion)	5
++Temperature Swing Adsorption (post combustion)	3-4
CO_2 liquefaction/partial condensation	6
Chemical looping combustion of solid fuels	6
Calcium looping, post combustion	6
Metallic membranes for H2	4-5
Polymeric membranes for CO_2	5-6
Ceramic membranes for O2	4

Source: adapted from European Zero Emission Technology and Innovation Platform (2017) Future CCS[51]

[51] https://pure.strath.ac.uk/portal/en/publications/future-ccs-technologies(a57b85a8-2f93-4cb4-ad4d-03a4e94db6df)/export.html

6 ASSESSMENT OF THE TECHNOLOGICAL INNOVATIONS FOR THE INNOVATION FUND (IF)

This section provides quantitative and qualitative assessment of the impacts of the Innovation Fund, i.e. mainly in the perspective of 2030, until the end of the now envisaged period for the IF. The quantitative analysis is centred on the exemplary set of innovative technologies as described in the previous sections (which in turn has been feeded by the outcome from the expert survey, presentations and discussions during the sectoral workshops as well as literature and databases from industrial and power sector models run by Fraunhofer ISI, such as FORECAST Industry or ENERTILE, see Appendix 2 and 3). We focus on their immediate impacts (i.e. assuming no technology diffusion). Mechanisms such as industrial symbiosis that can kick-start further diffusion will nevertheless discussed qualitatively.

This section includes the following issues:

- Distribution of TRLs in the exemplary set of innovative technologies. Risk for technologies is supposed to be linked to the TRL level.
- Percentage reduction achievable as compared to the reference technology and hence to the benchmarks
- Overall potential GHG reduction by the exemplary technologies and the innovation fund. Differences arising from the design elements and policy packages will be considered if the impact of the design element can be quantified. Otherwise, the influence of the design elements will be discussed qualitatively.
- Investments triggered directly by the (exemplary) fund.
- Volume of the grants (based on the suggested volume of 450 Million allowances and current carbon prices of around 15 Euro/tonne CO_2. Future increases in carbon prices, e.g. to 25 Euro/tonne, are discussed in terms of additional available volume but would not be speculated for the future though projections show that carbon prices could rise to 25 Euro/tonne CO_2[52].
- Gap to cover the required investment volume with grants only. This needs, however, taking into account that in particular higher TRL-levels are not necessarily in need of grants but overcoming other, non-economic, barriers could be the major issue.
- The gap provides then the required volume for further financing from financial instruments to cover the investment needs for the fund. Financing instruments may be needed as grant scheme are not sufficient to cover all needs, in particular as higher TRLs may better be addressed by financial instruments, for example loan guarantees to overcome barriers.

Before entering the discussion of the different impacts listed above, the set of illustrative technologies for the industrial sector is summarised in Table 26 (Part 1 and 2), which presents a summary for innovative renewables and CCS technologies. It should be recalled that the set represents in a stylised manner a number of concrete technologies which have been presented and discussed during the sector workshops and the survey. On one hand it simplifies a number of variants, which have been presented for individual innovative processes, on the other hand the information was completed and brought into

[52] see for example https://www.carbontracker.org/eu-carbon-prices-could-double-by-2021-and-quadruple-by-2030/, suggesting carbon prices of 55 Euro per tonne of CO_2 by 2030.

a synthetic harmonised technology representation with the help of the industry model FORECAST and the ENERTILE model for the power sector (see Appendix 2 and 3). Though the technology set is not pretending to predict the outcome of the IF selection process it is a fair cross-cutting view across the different low-carbon technologies discussed.

The table presents the following information:

- a brief characterisation of the technologies: technology name, sector, product, add-on technology or new process (the main difference being that the first considers the cost of the add-on only while the later need to consider the full cost of a new plant).
- TRL levels.
- Estimated capacity of early stage, industrial or power sector plants.
- Estimated range of full or differential cost (differential costs refer to the additional cost as compared to a reference plant). For the innovative power technology we present full cost only
- Relative GHG reduction compared to a reference plant, once evaluating indirect emissions from electricity with present (2015) emission factors and once evaluating them with an emission factor close to zero, which can be expected for 2050, once the power sector is largely decarbonised. For the power sector the reference technology are the remaining fossil fuel mix which by 2050 could be essentially based on natural gas, if any.
- A characterisation of the reference technology, which is usually a modern but conventional process: direct specific emissions (and how they compare with the benchmarks for industrial emitters according to the ETS Benchmarking Decision[53]), indirect specific emissions and total emissions[54]. For the innovative power technologies no benchmark exists under the ETS.
- Overall GHG emission reduction related to the set of innovative technologies.

[53] http://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:32011D0278&from=EN

[54] It can be seen from the table that the direct specific emissions as stated in the reference technology and the benchmarks are in most cases in good agreement. some differences, e.g. for the blast furnace, are related to specific issues, e.g. in this case the product used for the reference technology is the tonne of steel, while for the benchmark it is the molten metal.

Table 26: Overview of illustrative innovative technologies in the field of industry (Part 1)

Technology name	Sector	Product	Add-on technology or new process	TRL	Estimated average capacity of industrial installation (t/a)	Estimated range of initial full investment per installation (€/t product)	Estimated range of initial differential investment per installation (€/t product)	Maximum emissions reduction (up to ... %)	CO2-emission reduction per tonne of product (direct and indirect (2015 emission factor)	CO2-emission reduction per tonne of product (direct and indirect (100% RES))
Top gas recycling BF	Iron and steel	Steel (primary)	add-on	7	2.000.000	≤ 50	≤ 50	-30 %	-10%	-15%
Near net shape casting	Iron and steel	Rolled steel	add-on	8-9	1.000.000	≤ 50	≤ 50	-60 %	-52%	-60%
Black liquor gasification	Pulp and paper	Chemical pulp	add-on	8-9	500.000	101-500	101-500	-11 %	-54%	-62%
Enzymatic pre-treatment	Pulp and paper	Mechanical pulp	add-on	6-8	500.000	101-500	101-500	-5 %	-25%	n.a.
New drying techniques	Pulp and paper	Paper	add-on	8-9	500.000	51-100	51-100	-20 %	-5%	-63%
Batch preheating	Non-metallic minerals	Container glass	add-on	8	100.000	≤ 50	≤ 50	-15 %	-7%	-33%
Recycling/increase of cullets	Non-metallic minerals	Container glass	add-on	9	100.000	≤ 50	≤ 50	-60 %	-15%	-41%
Oxy-fuel combustion incl. waste heat recovery	Non-metallic minerals	Container glass	add-on	7	100.000	≤ 50	≤ 50	-60 %	-20%	-46%
Oxy-fuel combustion incl. waste heat recovery	Non-metallic minerals	Flat glass	add-on	7	100.000	≤ 50	≤ 50	-60 %	-17%	-46%
HAL4e	Non-ferrous metals	Primary aluminium	add-on	5-6	250.000	101-500	101-500	-5 %	-11%	-79%
Inert anodes (incl. wetted cathodes)	Non-ferrous metals	Primary aluminium	add-on	5	250.000	501-1000	501-1000	-35 %	-15%	-79%
Magnetic billet heating	Non-ferrous metals	Copper	add-on	5	250.000	≤ 50	≤ 50	n.a.	39%	-57%
Foaming of fibrous materials	Pulp and paper	Paper	add-on	5	500.000	101-500	101-500	-100 %	-30%	-71%
Smelting reduction (CO2-concentration in off-gas)	Iron and steel	Steel (primary)	add-on	5-6	500.000	51-100	51-100	-25 %	-41%	-45%
DRI RES H2	Iron and steel	Steel (primary)	new process	7	2.000.000	501-1000	101-500	-80 %	-8%	-91%
DRI RES Electrolysis	Iron and steel	Steel (primary)	new process	5-6	2.000.000	501-1000	101-500	-90 %	-20%	-100%
RES Electrification	Non-metallic minerals	Container glass	new process	5-8	100.000	501-1000	101-500	-80 %	-31%	-92%
Less-carbon cement - 30%	Non-metallic minerals	Cement	new process	6-7	1.000.000	501-1000	≤ 50	-30 %	-19%	-23%
Low-carbon cement - 70% (recarbonating)	Non-metallic minerals	Cement	new process	8	1.000.000	501-1000	≤ 50	-70 %	-71%	-76%
Low-carbon cement - 50%	Non-metallic minerals	Cement	new process	6	1.000.000	501-1000	51-100	-50 %	-45%	-50%
Hydrogen based ammonia	Chemical industry	Ammonia	new process	6	500.000	>1000	501-1000	-90 %	n.a.	-94%
Methanol production from hydrogen and CO2 (CCU)	Chemical industry	Methanol	new process	5-7	500.000	>1000	>1000	carbon sink (-0.67 to 1.23 tCO2 eq. per tonne of product)	n.a.	-94%
CCS: Add-on CO2 capture (add-on to ULCOS-BF, IGAR)	Iron and Steel	Steel (primary)	new process	5-7	2.000.000	101-500	101-500	-60 %	-79%	-82%
CCS: Smelting reduction plus CO2 capture (add-on to in bath smelting reduction)	Iron and Steel	Steel (primary)	new process	5-6	500.000	101-500	101-500	-80 %	-79%	-82%
CCS: Post-combustion	Non-metallic minerals	Clinker	add-on	7-9	1.000.000	101-500	101-500	-95 %	-60%	-68%
CCS: Direct separation	Non-metallic minerals	Lime	add-on	5	70.000	51-100	51-100	-99 %	n.a.	n.a.
CCS Ammonia	Chemical industry	Ammonia	add-on	6-7	500.000	101-500	101-500	-90 %	-90%	-90%
CCS: Post-combustion	Refinery sector		add-on	8-9	1.000.000 reference plant emission	101-500	101-500	-80 %	-90%	-90%
CCS: Oxyfuel	Refinery sector		add-on	8-9	1.000.000 reference plant emission	101-500	101-500	-80 %	-96%	-96%
						Total full investments (billion Euro)	**Total diff. investments (billion Euro)**			
						9,5	**4,5**			

Table 26 continued (Part 2)

Technology name	Reference technology	Reference technology: direct CO2-emissions per tonne of product (CO2/t)	Benchmark CO2-emissions (allowance/t)	Reference technology: indirect CO2-emissions per tonne of product (CO2/t)	Reference technology: direct and indirect CO2-emissions per tonne of product (CO2/t)	GHG Savings (min) (Kt CO2eq.)	GHG Savings (max) (Kt CO2eq.)	Source
Top gas recycling BF	Conventional blast furnace	1,19	1,328	0,06	1,25	252	370	capacity from Pardo (2012) Prospective Scenarios Iron&Steel p.27
Near net shape casting	Continous casting + rolling	0,14	0	0,06	0,20	101	116	according to FORECAST, Fleiter et al. no additional costs would occur
Black liquor gasification	Conventional chemical pulping process	0,14	0.06-0.12	0,23	0,37	99	114	costs from FORECAST; Fleiter et al.; capacity own estimate
Enzymatic pre-treatment	Conventional mechanical pulping process (e.g. ground wood pulp and thermomechanical pulp)	-0,05	0,02	0,78	0,73	92	#WERT!	costs from FORECAST; Fleiter et al.; capacity own estimate
New drying techniques	Conventional paper mill	0,14	0,318	0,19	0,33	8	103	costs from FORECAST; Fleiter et al.; capacity own estimate
Batch preheating	Conventional glass furnace (container glass)	0,40	0.382-0.306	0,14	0,54	4	18	costs from FORECAST; Fleiter et al.; capacity own estimate
Recycling/increase of cullets	Conventional glass furnace (container glass)	0,40	0.382-0.306	0,14	0,54	8	22	costs from FORECAST; Fleiter et al.; capacity own estimate
Oxy-fuel combustion incl. waste heat recovery	Conventional glass furnace (container glass)	0,40	0.382-0.306	0,14	0,54	11	25	own estimation based on WSP (2015), Fleiter et al. 2016
Oxy-fuel combustion incl. waste heat recovery	Conventional glass furnace (flat glass)	0,80	0,453	0,33	1,13	19	52	0
HAL4e	Primary aluminium electrolysis	1,55	1,514	5,70	7,25	199	1.424	costs own estimation based on FC; capacity from Moya (2015) Energy Efficiency and GHG Emissions: Prospective Scenarios for the Aluminium Industry (JRC Scientific and policy report)
Inert anodes (incl. wetted cathodes)	Primary aluminium electrolysis	1,55	1,514	5,70	7,25	272	1.424	costs and capacity from Moya (2015) Energy Efficiency and GHG Emissions: Prospective Scenarios for the Aluminium Industry (JRC Scientific and policy report)
Magnetic billet heating	Copper further treatment	0,11	no Benchmark for copper	0,37	0,49	-48	69	FORECAST; Fleiter et al.
Foaming of fibrous materials	Conventional paper mill	0,14	0,318	0,19	0,33	49	115	DG Clima Survey
Smelting reduction (CO2-concentration in off-gas)	Sinter plant + coke oven + blast furnace	1,78	1,785	0,08	1,86	386	416	capacity from Pardo (2012) Prospective Scenarios Iron&Steel p.27
DRI RES H2	Sinter plant + coke oven + blast furnace	1,78	1,785	0,08	1,86	303	3.375	costs from Fischedick (2014); capacity estimated
DRI RES Electrolysis	Sinter plant + coke oven + blast furnace	1,78	1,785	0,08	1,86	749	3.722	costs from Fischedick (2014); capacity estimated
RES Electrification	Conventional glass furnace (container glass)	0,40	0.382-0.306	0,14	0,54	17	49	estimated from Fleiter et al. 2016: Mapping Heat WP2
Less-carbon cement - 30%	Preperation of limestone + clinker burning + cement grinding	0,77	0,766	0,05	0,81	157	186	estimate Fraunhofer ISI
Low-carbon cement - 70% (recarbonating)	Preperation of limestone + clinker burning + cement grinding	0,77	0,766	0,05	0,81	581	620	estimate Fraunhofer ISI
Low-carbon cement - 50%	Preperation of limestone + clinker burning + cement grinding	0,77	0,766	0,05	0,81	369	409	estimate based on Cembureau material
Hydrogen based ammonia	Ammonia production based on steam reforming (natural gas)	1,83	1,619	0,05	1,88	#WERT!	879	DECHEMA, 2017, Low carbon energy and feedstock for the European Chemical industry; Brunke, 2017, Dissertation; DECC, 2015, Chemicals Appendices
Methanol production from hydrogen and CO2 (CCU)	Integrated methanol production	2,10	no Benchmark for methanol	0,00	2,10	#WERT!	989	DECHEMA, 2017, Low carbon energy and feedstock for the European Chemical industry; DECC, 2015, Chemicals Appendices; Perez-Fortes (2016)
CCS: Add-on CO2 capture (add-on to ULCOS-BF, IGAR)	Sinter plant + coke oven + blast furnace	1,78	1,785	0,08	1,86	2.922	3.045	Eurofer 2013; RT; Fischedick (2014); Pardo Moya 2012
CCS: Smelting reduction plus CO2 capture (add-on to in bath smelting reduction)	Sinter plant + coke oven + blast furnace	1,78	1,785	0,08	1,86	730	761	Eurofer 2017; Eurofer 2013; RT; Fischedick (2014); Pardo Moya 2012
CCS: Post-combustion	Clinker burning	0,77	0,766	0,05	0,81	485	558	Technology template FT: Innovation Fund; Capacity and costs from Kuramochi et al. 2012
CCS: Direct separation	Lime burning	0,79	0	0,01	0,80	#WERT!	#WERT!	Technology template FT: Innovation Fund
CCS Ammonia	Ammonia production based on steam reforming (natural gas)	1,83	1,619	0,05	1,88	563	563	DECHEMA, 2017, Low carbon energy and feedstock for the European Chemical industry; Brunke, 2017, Dissertation; DECC, 2015, Chemicals Appendices; Leitstudie Assumptions REH. Measure applies to process emissions only.
CCS: Post-combustion	Reference Emissions	n.a.	unclear which benchmark to use	n.a.	3,10	#WERT!	#WERT!	Pardo Moya 2012; Solbin Kim 2017
CCS: Oxyfuel	Reference Emissions	n.a.	unclear which benchmark to use	n.a.	3,10	#WERT!	#WERT!	Pardo Moya 2012/ Solbin Kim 2017
						8.329	**19.424**	

Table 27: Overview of illustrative innovative technologies in the field of power sector technologies (Part 1)

Technology name	Sector	Product	Add-on technology or new process	TRL	Estimated average capacity of industrial installation MW)	Estimated range of initial full investment per installation (€/kW electric power)	Estimated range of initial differential investment per installation (€/kW electric power)	Maximum emissions reduction (up to ... %)	CO2-emission reduction per kWh (2015 emission factor)	CO2-emission reduction per kWh (100% RES))
Hydro	Renewables	Renewable electricity	new process	0	60	1.679	-	-100 %	-100%	-100%
Wind onshore	Renewables	Renewable electricity	new process	8	100	1.696	-	-100 %	-100%	-100%
Wind offshore	Renewables	Renewable electricity	new process	5-6	300	3.825	-	-100 %	-100%	-100%
Photovoltaics	Renewables	Renewable electricity	new process	8-9	120	1.245	-	-100 %	-100%	-100%
Solarthermal	Renewables	Renewable electricity	new process	8-9	100	8.035	-	-100 %	-100%	-100%
Biomass	Renewables	Renewable electricity	new process	7-8	100	3.112	-	-100 %	-100%	-100%
Ocean/tidal	Renewables	Renewable electricity	new process	5-6, 8	60	4.500	-	-100 %	-100%	-100%
Geothermal	Renewables	Renewable electricity	new process	5-6, 8	60	4.735	-	-100 %	-100%	-100%
Power Sector CCS	CCS	Low carbon electricity	add-on	8-9	300	5.000	-	-60 %	-60%	-60%
						Total full investments (billion Euro)	**Total diff. investments (billion Euro)**			
						4,7	**-**			

Note on power sector CCS: the emission reduction reaches 90% for the relevant streams. On average, the CCS projects discussed during the expert workshops reached 60% on average for the overall project emissions which is used here for achievable projects by 2030.

Table 27 continued (Part 2)

Technology name	Reference technology	Reference technology: direct CO2-emissions per TWh 2015 (Mt CO2/TWh)	Benchmark CO2-emissions (allowance/t CO2)	Reference technology: direct CO2-emissions per TWh 2050 (Mt CO2/TWh)	Reference technology: total CO2-emissions per per TWh (Mt CO2/TWh)	GHG Savings (2015 emission factor) (Kt CO2eq.)	GHG Savings (2050 emission factor) (Kt CO2eq.)
Hydro	Average fossil power generation mix 2015	0,81	no electricity benchmark	0,36	0,81	195	86
Wind onshore	Average fossil power generation mix 2015	0,81	no electricity benchmark	0,36	0,81	203	90
Wind offshore	Average fossil power generation mix 2015	0,81	no electricity benchmark	0,36	0,81	977	432
Photovoltaics	Average fossil power generation mix 2015	0,81	no electricity benchmark	0,36	0,81	117	52
Solarthermal	Average fossil power generation mix 2015	0,81	no electricity benchmark	0,36	0,81	285	126
Biomass	Average fossil power generation mix 2015	0,81	no electricity benchmark	0,36	0,81	488	216
Ocean/tidal	Average fossil power generation mix 2015	0,81	no electricity benchmark	0,36	0,81	293	130
Geothermal	Average fossil power generation mix 2015	0,81	no electricity benchmark	0,36	0,81	293	130
Power Sector CCS	Average fossil power generation mix 2015	0,81	no electricity benchmark	0,36	0,81	952	422
						3.804	**1.684**

Note on the reference technology in 2050 for power generation: According to the PRIMES (2016) baseline it is assumed that the remaining fossil fuel power plants in 2050 are based on gas-fired technology. The reference scenario derived from PRIMES 2016 does NOT reach 100% RES in 2050; however, most of the fossil fuel remaining is based on gas.

6.1 Distribution of TRLs in the exemplary set of innovative technologies

Table 28 shows the distribution of TRL levels in the exemplary set of innovative technologies, split by the two groups TRL 5-7 (which represent the earlier stage technologies) and TRL 8-9 (technologies relatively close to industrial applications. In terms of investments, technologies close to industrial applications present around 16-26% (depending on whether full or differential investments are considered). In terms of GHG savings they present 16% with 2015 emission factors for the power system and 8% with 2050 emission factors. The reason for the difference is that the early stage technologies present a massive switch to electricity which impacts more strongly on GHG emissions once the power sector is largely decarbonised. A grant schemes would mainly focus on the TRL 5-7 levels and would then have to cover in the range of 83% of the necessary total full investments into innovative industrial low-carbon technologies.

For renewables on the contrary, only one third of the innovative power sector low carbon technologies are in lower TRL ranges (mainly for technologies such as ocean, wave, tidal, geothermal or advanced wind-offshore technologies e.g. with floating foundations, see Table 29).

Table 28: Distribution of investment (billion Euro) and of GHG emissions (kt CO_2eq.) for innovative industrial low-carbon technologies by TRL

Distribution of investment (billion Euro) by TRL		Distribution of GHG savings (kt CO2eq.) by TRL	
Full investment	Differential investment	GHG Savings (min)	GHG Savings (max)
TRL5-7	TRL5-7	TRL5-7	TRL5-7
7,97	3,47	6.988	17.849
TRL 8-9	TRL 8-9	TRL 8-9	TRL 8-9
1,57	0,99	1.341	1.575
16%	22%	16%	8%

Table 29: Distribution of investment (billion Euro) and of GHG emissions (kt CO_2eq.) for innovative power sector low-carbon technologies by TRL

Distribution of investment (billion Euro) by TRL	
Full investment	Differential investment
TRL5-7	TRL5-7
1,58	-
TRL 8-9	TRL 8-9
3,16	-
67%	-
Distribution of GHG savings (kt CO2eq.) by TRL	
GHG Savings (min)	GHG Savings (max)
TRL5-7	TRL5-7
670	1.514
TRL 8-9	TRL 8-9
1.014	2.290
60%	60%

6.2 Percentage reduction achievable as compared to the reference technology and to the benchmarks

Figure 15 shows the cumulated GHG emission reductions (kt CO_2 eq.) versus GHG reduction compared to the reference technology (%) with 2015 (upper graph) / 2050 emission factors (lower graph) for indirect emissions. The two graphs show what would happen, if the cut-off criteria for innovative industrial low-carbon technologies under the IF would be set at 10%, 20% or 40% of the ETS benchmarks (which are represented by the reference technologies). In the case of 2015 emission factors the impact would be quite large: a 10% cut-off criteria would mean that 3% of the emission reduction of the innovative technologies could not be realised, a 20% cut-off criteria that 14% of the emission reduction could not be realised, a 40% cut-off criteria that 24%, hence nearly a quarter of emission reductions, are not eligible. However, if the 2050 emission factors are used to evaluate the GHG reduction of innovative technology set, even with a 40% cut-off criteria only 3% of the GHG reduction could not be realised.

For innovative renewable technology no such cut-off criteria could be defined, as by definition, renewable technology would save 100% of emissions compared to the ETS.

For CCS, there is also no benchmark available under the EU ETS, but the average of newly installed fossil power plants provides a natural benchmark. CCS captures usually 85-90% of the emission streams collected. However, not all streams are collected. On average, during the expert workshops, projects were suggested with a net overall emission reduction in the range of 60%, though in some cases, CCS technologies with only 30% net emission reduction have been proposed in the sector workshops.

Figure 15: Cumulated GHG emission savings (kt CO_2 eq.) with 2015 (upper graph) / 2050 emission factors (lower graph) for indirect emissions versus GHG reduction per process compared to the reference technology (%)

6.3 Overall potential GHG reduction by the exemplary technologies and fund

According to Table 30 the overall GHG reduction potential for the innovative set of industrial technologies representing the IF is of the order of 8.3 Mt CO_2eq. (with 2015 emission factors for electricity) and about twice, 19.4 Mt CO_2eq. (with 2050 emission factors for electricity). The latter presents about 2-2.5% of the overall industrial emissions under the ETS of today. As stated in the introduction to this chapter, no diffusion is, however, assumed for the innovative low carbon technologies after their introduction. Grants alone could realise mostly the lower TRL levels, hence about 85-92% of the GHG reductions in case the IF is large enough to provide the corresponding funds (see discussion below).

For innovative power sector low-carbon technologies (Table 30) the overall GHG reduction is of the order of the order of 3.8 Mt CO_2eq. (with 2015 emission factors for fossil fuel based electricity generation which is supposed to be replaced by the innovative technology in 2030) and 1.7 Mt CO_2eq. (with 2050 emission factors for fossil fuel based electricity generation which still is supposed to be the reference technology by 2050[55], however, with a considerably lower emission factor compared to 2015, as natural gas would be the main remaining fossil fuels).

Table 30: Overall potential GHG reduction (Mt CO_2eq.) by the exemplary technologies and fund

Unit: Mt CO_2eq.	with 2015 emission factors	with 2050 emission factors
Innovative Industrial Low Carbon Technologies	8.3	19.4
Innovative Power Sector Low Carbon Technologies	3.8	1.7
Overall	12.1	21.1

[55] In reality, some of the innovative technologies would replace other less attractive RES technology, e.g. onshore wind replaced by offshore or ocean energy, but then impacts would even be smaller.

6.4 Investments triggered directly by the (exemplary) Innovation Fund

Table 31 shows that the total investments to be triggered by the exemplary IF is about EUR 9.5 bn for innovative industrial low carbon technologies in terms of full investments, and roughly half or EUR 4.5 bn in terms of differential investments, i.e. compared to the reference technology.

According to Table 31 the total investments related to innovative power sector low carbon technologies are about EUR 4.7 bn.

In total around EUR 14.2 bn full investments are to be covered by the exemplary IF in order to realise the set of innovative low carbon technologies. The split by TRL levels was provided in a previous section.

Table 31: Overall investment (billion Euro) triggered by the exemplary technologies and fund

Unit: billion Euro	Total full investments	Total diff. investments (compared to reference technology)
Innovative Industrial Low Carbon Technologies	9.5	4.5
Innovative Power Sector Low Carbon Technologies	4.7	-
Overall	14.2	-

6.5 Gap to cover required investment volume with grants only

This section discusses the gap which, potentially, cannot be covered by a grant-only scheme and which should be tackled further by additional funding sources, including financing instruments. Though grants are supposed to be the main funding source under the IF, it must, however, be emphasized that grants may not be the only support required for certain type of projects, in particular at the TRL 8-9 level, which may, in addition, require financing instruments to reduce risks, such as loan guarantees.

The Innovation Fund shall be based on 400 million allowances reserved from 2021 onwards for the purpose of the technology support. In addition, a further 50 million of unallocated allowances from 2013-2020 will be added, together with, as early as 2019; any possible un-used or remaining funds from the NER 300 Programme. Further 50 million allowances could be added to the fund post 2025, if these are not used for free allocation to industry.

The ETS Directive and the end of 2017 agreed features for the Innovation Fund set a number of key design elements, in particular:

- Up to 60% of the relevant costs of projects may be supported,
- Project selection will be done based on objective and transparent criteria, including, among others, the potential for emission reductions, potential for wide application or significant lowering of transitioning costs towards a low-carbon economy in the concerned sectors,

- Technologies to be supported are not yet commercially available, but represent breakthrough solutions or are sufficiently mature to be ready for demonstration at pre-commercial scale,
- Up to 40% of the IF support for eligible projects (that is up to 24% of projects' relevant costs) may be pre-financed (may not depend on achieved reduction of greenhouse gas (GHG) emissions) provided that pre-determined project milestones are met,
- Projects in all Member States, including small-scale projects, are eligible to apply.

An important parameter in estimating the gap to cover beyond grants is the definition of relevant cost. Under NER300, relevant costs were defined as follows (no definition exists for energy intensive industry, as they were not part of the NER300):

- The relevant costs of CCS demonstration projects shall be those investment costs which are borne by the project due to the application of CCS net of the net present value of the best estimate of operating benefits and costs arising due to the application of CCS during the first 10 years of operation.
- Relevant costs of RES demonstration projects shall be those extra investment costs which are borne by the project as a result of the application of an innovative renewable energy technology net of the net present value of the best estimate of operating costs and benefits arising during the first 5 years compared to a conventional production with the same capacity in terms of effective production of energy.

Under NER300 relevant cost were about 56% on average of the total investment cost. Now, NER300 was, de facto, mainly promoting renewable projects (NER 300 aimed at both RES and CCS, but 38 out of 39 projects were awarded in the RES sector). In the second call under the NER300 one CCS project was awarded (the UK CCSoxy White Rose[56]). However, finally it was not realised until completion due to decision of the UK government, not to follow up the national CCS call[57]. The definition of relevant cost for renewables are compared to a conventional production. The relevant cost for CCS are the costs due to the introduction of CCS technologies in the power plant[58] and includes revenues from the avoided CO_2-emissions. For the industry sector no definition existed under NER300, as industrial processes were not included in NER300 calls (apart from industrial CCS). For industrial process much depends on whether

[56] Award Decision under the second call for proposals of the NER 300 funding programme. Brussels, 8.7.2014, C(2014) 4493 final. Available at:: https://ec.europa.eu/clima/sites/clima/files/lowcarbon/ner300/docs/c_2014_4493_en.pdf and https://ec.europa.eu/clima/sites/clima/files/lowcarbon/ner300/docs/c_2014_4493_annex_en.pdf (Annex 1)

[57] https://infrastructure.planninginspectorate.gov.uk/projects/yorkshire-and-the-humber/white-rose-carbon-capture-and-storage-project/

[58] see the definition of relevant costs for CCS from the Commission Decision 2010/670/EU: "The relevant costs of CCS demonstration projects shall be those investment costs which are borne by the project due to the application of CCS net of the net present value of the best estimate of operating benefits and costs arising due to the application of CCS during the first 10 years of operation." and explanations in the Frequently Asked Questions: "Application Form C, Annex 2, provides guidance on the investment costs and operating costs and benefits to be considered for the establishment of the relevant costs. Please note that the additional costs associated with the application of CCS for post combustion, oxyfuel and industrial CCS projects can be identified straightforward and there is no need to refer to a reference plant. In contrast, the additional costs for pre-combustion CCS" https://ec.europa.eu/clima/sites/clima/files/ner300/docs/faq_1_en.pdf

differential or full investments are considered: in the first case, industrial low carbon processes could be treated in a similar manner as CCS and hence they would be close to 100% of the (additional) investment cost also. The reason for this is that while for the power sector the fossil fuel alternative continue to exist for the new RES alternatives, the innovative industrial processes are based to a large degree on totally new principles (e.g. hydrogen-based processes instead of coal-based processes); they are usually not merely a scaling up of existing technologies or add-ons to existing processes. This is also justified by the expert survey in which for nine relevant industry-sector projects the ratio between “additional CAPEX” and “total CAPEX” could be determined, with around 90%. On average, the revenues were around equal to the expenses[59]. If full investments are considered, revenue streams from products are to be considered.

We therefore apply a factor of 56% for RES projects only, taking into account the comparison with conventional production. Since then the cost of renewables has been further dropping. Standard RES technologies are now at the same cost (LCOE) as the conventional alternatives. However, innovative technologies still come at extra cost.

Figure 16 presents the financing needs and the financing gap for the exemplary IF discussed here, if it is based on grants only.

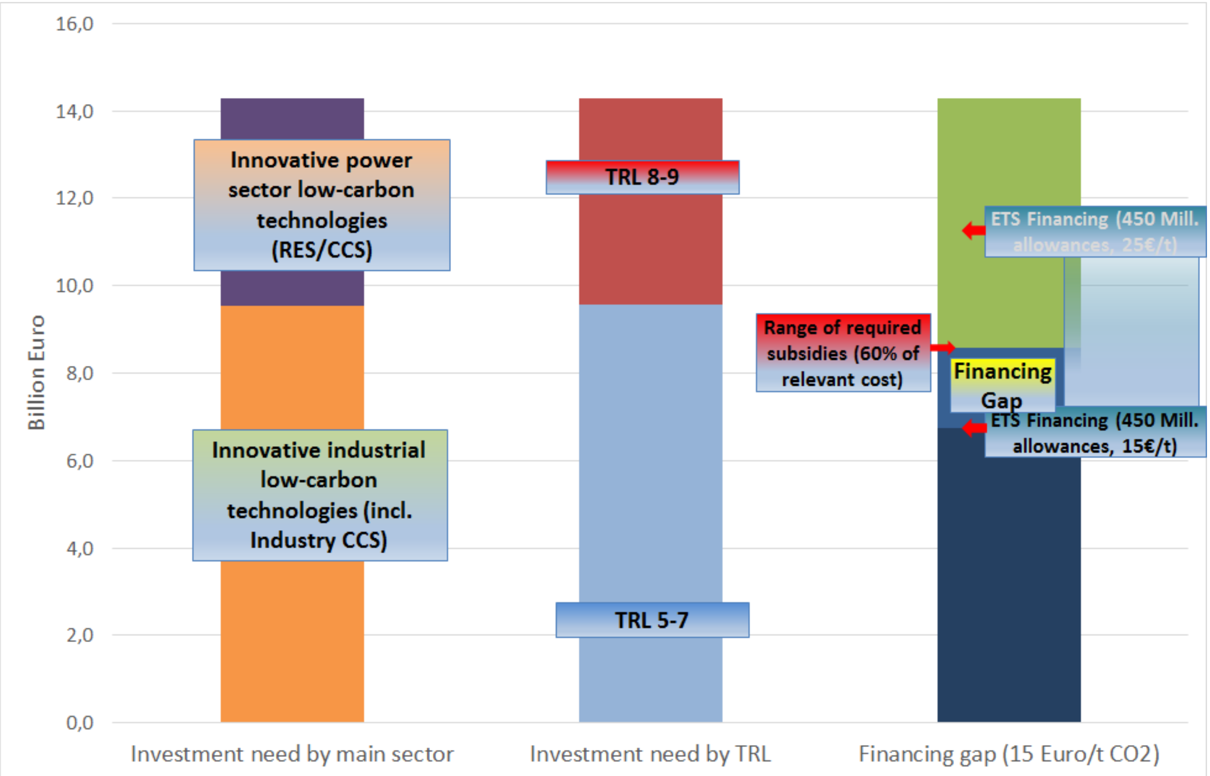


Figure 16: Financing needs and financing gap for the exemplary IF

[59] This refers to the following two questions in the questionnaire to stakeholders in the expert survey:
Revenue (Levelized revenue in million EUR / year):
- What is the revenue of the project (according to your current prospects)? In case the project leads to an economic loss (i.e. negative revenue) please indicate a negative value.
Expenses (Levelized revenue in million EUR / year):
- What is the total OPEX of the project (according to your current prospects)?Please specify if there are remarkable changes of OPEX during the lifetime of the project.

The gap is to be covered by other financing instruments. The main observations are the following:

- Total investment needs for the exemplary set of innovative technologies amount to around EUR 14 bn (initial full cost investment for a first-of-a-kind plant). The approach in the present report leads to a minimum investment volumes compared to the range of EUR 55-68 bn estimated in Chapter 2, where a certain diversity is admitted for individual process routes (i.e. that for individual technology routes several innovative technologies are included with a certain "redundancy"). For the detailed discussion see section 2.
- The financing needs of the exemplary set of technologies are composed to about two thirds by lower TRL (5-7) and one third by higher TRL (8-9).
- Assuming that the exemplary IF would have to be covered by grants only and based on the 60% maximum requirement for subsidies, the required range of subsidies is in the order of 5.7 - 8.6 billion Euro. Total prefinancing required could be EUR 3.4 bn (based on 40% pre-financing). The lower subsidy level is valid, if the subsidies are mainly required for the lower TRL only, the upper limit if all TRL are to be subsidised. The upper limit is therefore a theoretical limit, as a number of projects may not be in need of subsidies but rather of risk mitigation.
- On the other hand, based on an amount of 450 million allowances and the present carbon price of 15 €/t (average over the last year), the gap to be covered for the exemplary IF by grants, compared to the available EUR 6.75 bn, is not existing (lower TRLs subsidised only) or up to EUR 1.8 bn (all TRL subsidised). It should be noted that financing instruments may, in principle, also be relevant for the investments in low-carbon technologies with higher TRLs while lower subsidies might be granted for high TRLs.
- From this comparison it appears that given current carbon prices, the exemplary fund could be largely or totally covered with grants. However, as stated previously, the exemplary IF modelled here with investments in the range of EUR 14 bn should be compared to the EUR 55-68 bn estimated in Chapter 2, where a certain technology diversity is admitted for individual process routes (i.e. for individual technology routes multiple innovative technologies are included). This implies a considerably gap compared to the supposed available subsidies in 2020, and raises the issue of additional financing instruments beyond grands, even of only part of the enlarged technology pool is to be covered.
- In recent times the carbon price has been increasing and is at present reaching levels of around 15 €/t (peaking at over 20 €/t). The expectation is that the carbon price will rise over the next decade[60]. We carry out a sensitivity calculation with a carbon price of 25 €/t which may be relevant for the start of the next decade while, at the end of the decade, the price could be well beyond 25 €/t (some project more than 50 €/t[61]). If the carbon price reaches 25 €/t (EUR 11.3 bn available for grants), the subsidy requirements of the exemplary technology set is by far exceeded, and a larger number of innovative technologies could be subsidised (with investments in the range of EUR 19 bn)). However, even then, in order to cover largely the enlarged technology pool additional financing instruments are required, complementing the grants.

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[60] EU Reference Scenario 2016 Energy, transport and GHG emissions. Trends to 2050 https://ec.europa.eu/energy/sites/ener/files/documents/20160713%20draft_publication_REF2016_v13.pdf

[61] https://www.carbontracker.org/eu-carbon-prices-could-double-by-2021-and-quadruple-by-2030/

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APPENDIX 1: DEFINITION OF TECHNOLOGY READINESS LEVELS TRL

Technology Readiness Levels TRL are defined by Horizon2020 as follows[62]:

TRL 1 – basic principles observed

TRL 2 – technology concept formulated

TRL 3 – experimental proof of concept

TRL 4 – technology validated in lab

TRL 5 – technology validated in relevant environment (industrially relevant environment)

TRL 6 – technology demonstrated in relevant environment (industrially relevant environment)

TRL 7 – system prototype demonstration in operational environment

TRL 8 – system complete and qualified

TRL 9 – actual system proven in operational environment (competitive manufacturing; First-of-a-kind commercial plant)

Research Grants (H2020 and successors)

Focus of Grants under the IF

Focus of Financial Instruments FI

Financial Instruments focus typically on TRL 8/9 which is close to the commercial application, Grants under the IF are mainly aiming at TRL 6-8, with some uncertainty however, and adjacent TRLs 9 and TRL5 (if relevant for the IF period 2020/2030) are also interesting to consider. TRL definitions are not exactly defined and there can be differences in judgement. TRL 1-5 are mainly targeted by research funds such as H2020 and successors.

[62] Source: https://ec.europa.eu/research/participants/data/ref/h2020/wp/2014_2015/annexes/h2020-wp1415-annex-g-trl_en.pdf

APPENDIX 2: SHORT DESCRIPTION OF THE FORECAST MODEL FOR THE INDUSTRY SECTOR (WWW.FORECAST-MODEL.EU)

For support to the evaluation of the exemplary set of innovative low-carbon industrial technologies the bottom-up model FORECAST-Industry is used. On one hand, its database provided additional information on innovative low-carbon technologies; on the other hand, the information collected through the survey in the project and the Round Tables was integrated into the model. The updated model was then used to evaluate the set of industrial technologies in terms of emission reduction and cost for the 2030 perspective.

The FORECAST modelling platform aims to develop long-term scenarios for future energy demand. It is based on a bottom-up modelling approach considering the dynamics of technologies and socio-economic drivers. The model allows addressing research questions related to energy demand including scenarios for the future demand of individual energy carriers like electricity or natural gas, calculating energy saving potentials and the impact on greenhouse gas (GHG) emissions as well as abatement cost curves and ex-ante policy impact assessments (http://www.forecast-model.eu).

Figure 17 shows the simplified structure of FORECAST-Industry. Main macro-economic drivers are industrial production for more than 70 individually modelled basic materials products, gross value added for less energy-intensive sub-sectors and the number of employment as input for the space heating sub-module. Five sub-modules are distinguished: basic materials processes, space heating, electric motor systems, furnaces and steam systems.

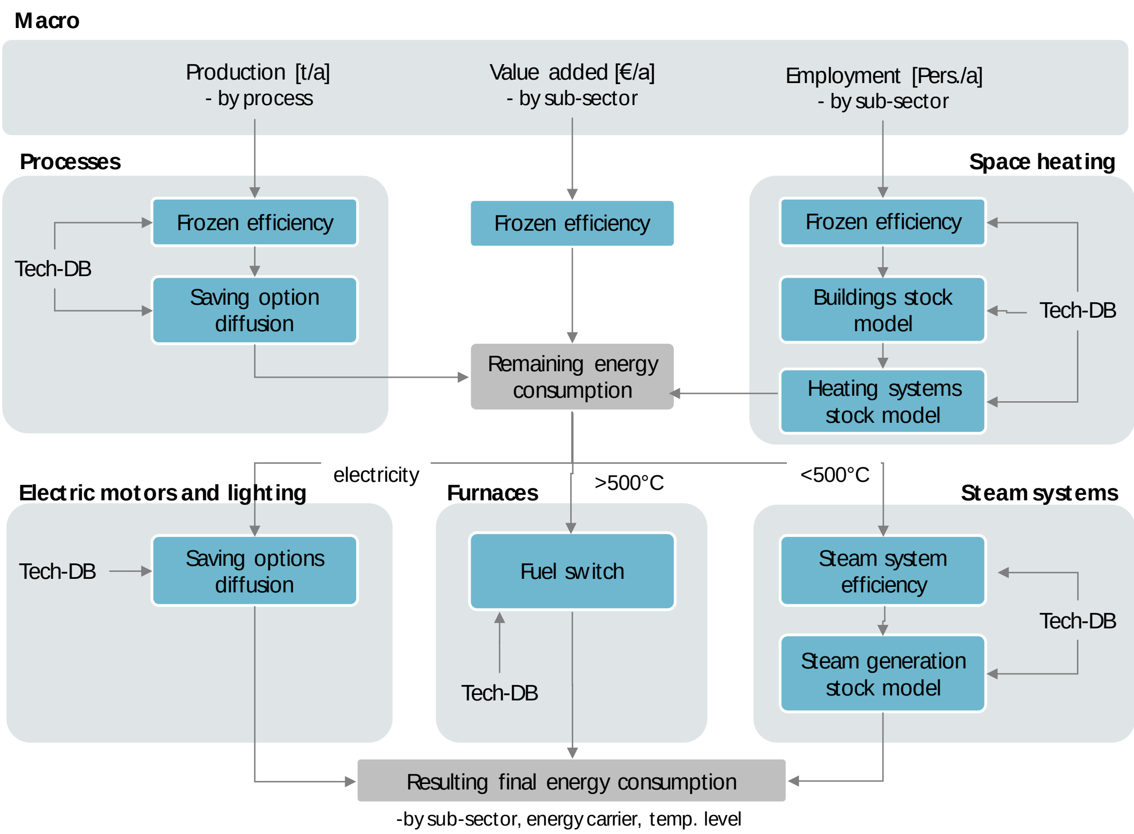

Figure 17: Overview of the bottom-up model FORECAST-Industry

Accordingly, the model distinguishes five sub-modules:

1. **Energy-intensive processes**: this module presents the core of the bottom-up quantity structure of FORECAST. 64 individual processes are considered via their (physical) production output and specific energy consumption (SEC). The diffusion of about 200 individual saving options is modelled based on their payback period (Fleiter et al. 2013a; Fleiter et al. 2012a). Saving options can represent energy efficiency measures (EEMs), but also internal use of excess heat, material efficiency or savings of process-related emissions. They can be of incremental as well as radical nature.
2. **Space heating**: space heating accounts for about 9% of final energy demand in the German industry. We use a vintage stock model for buildings and space heating technologies. The model distinguishes between offices and production facilities for individual sub-sectors. It considers construction, refurbishment and demolition of buildings as well as construction and dismantling of space heating technologies. The investment in space heating technologies such as natural gas boilers or heat pumps is determined based on a discrete choice approach (Biere et al. 2014).
3. **Electric motor systems and lighting**: these cross-cutting technologies (CCTs) include pumps, ventilation systems, compressed air, mechanical equipment, cold appliances, other motor appliances and lighting. The module captures the individual units as well as the entire motor-driven system including losses in transmission between conversion units. The electricity demand of the individual CCTs is estimated based on typical shares by sub-sector. The diffusion of energy efficiency measures (EEMs) is modelled similarly to the approach used for process specific EEMs.
4. **Fuel switch in furnaces**: energy demand in furnaces is a result of the bottom-up estimations from the module "energy-intensive processes". Furnaces are found across most industrial sub-sectors and are very specific to the production process. Typically they require heat on a very high temperature level. While EEMs for individual furnaces are modelled in the module "energy-intensive processes" the module on furnaces simulates price-based substitution between energy carriers (i.e. fuel switch). The method is based on a random utility model (logit model). The model is calibrated using revealed preferences data gained from regression analysis of historic time series (a similar method is used by Kesicki und Yanagisawa (2015)).
5. **Steam systems**: the remaining process heat (<500°C) is used in steam (and hot water) systems throughout most sub-sectors. The module comprises both the distribution of steam and hot water as well as its generation. As very little information is available about the performance of existing steam distribution systems, we assume exogenous efficiency improvements. Steam generation on the other hand is modelled based on a detailed bottom-up vintage stock model simulating the replacement of the entire steam generation technology stock. More than 20 individual technologies are taken into account ranging from natural gas boilers to all kinds of CHP units, biomass boilers, large scale heat pumps, electric boilers and fuel cells. Fuel switch is a result of competition among the individual technologies as discrete choice model where the utility is defined as the total cost of ownership.

To summarize, how the earlier mentioned groups of mitigation options relate to the individual sub-models is depicted in Table 32.

Table 32: Relation matrix of sub-models and mitigation options

	Energy-intensive processes	**Cross-cutting technologies**	**Space heating and cooling**	**Steam systems**	**Furnaces: Fuel switch**
Energy efficiency	Endogenous diffusion of saving options (incremental and radical)	Endogenous diffusion of EEMs	Endogenous stock model for refurbishment and replacement of buildings	Exogenous steam system efficiency	-
Fuel switch	Exogenous structural change	-	Endogenous discrete choice model	Endogenous discrete choice model	discrete choice utility model
Recycling and circular economy	Exogenous assumption	-	-	-	-
Material efficiency and substitution	Exogenous assumption	-	-	-	-

Technological change is modelled in this sub-model via the diffusion of so called saving options. Saving options can represent small incremental improvements in existing technologies as well as radically new processes. Saving options are related to individual processes. By diffusing through the technology stock, saving options reduce the specific energy consumption (SEC) of the process. In a few cases, they can also reduce the specific process related greenhouse gas (GHG) emissions. FORECAST currently considers about 200 saving options allocated to the 68 processes. Due to the high degree of heterogeneity and the diversity as well as low data availability, the simulation of saving options is based on a simplified approach that follows S-shaped diffusion curves and takes profitability into account, but is not based on detailed vintage stock approach or technology competition models. For a more detailed description it is referred to Fleiter et al. (2012). A similar approach is used in the sub-model for electric motor systems and lighting.

Saving options unfold their impact on energy consumption and GHG emissions by diffusing through the technology stock and, thus, reducing the specific energy consumption or specific process related emissions of individual production processes. Saving options can be incremental changes as well as radically new production processes. The diffusion of saving options is based on the payback time, which depends on energy savings, energy prices and the carbon price.

APPENDIX 3: SHORT DESCRIPTION OF THE ENERTILE MODEL FOR THE RENEWABLE, CCS AND ENERGY STORAGE SECTORS (WWW.ENERTILE.EU)

For support to the evaluation of the exemplary set of innovative low-carbon power sector technologies the European electricity sector Modell ENERTILE is used. On one hand, its database provided additional information on innovative low-carbon technologies; on the other hand, the information collected through the survey in the project and the Round Tables was integrated into the model. The updated model was then used to evaluate the set of power sector technologies in terms of emission reduction and investment cost for the 2030 perspective.

RES and CCS impacts were modelled with the ENERTILE model (www.enertile.eu) which covers the electricity sectors of the whole of the EU and the MENA region.

Enertile optimisation is an energy system optimization model developed at the Fraunhofer Institute for System and Innovation Research ISI. The model focuses on the power sector, but also covers the interdependencies with other sectors, especially heating/ cooling and the transport sector. It is a used mostly for long-term scenario studies and is explicitly designed to depict the challenges and opportunities of increasing shares of renewable energies. A major advantage of the model is its high technical and temporal resolution.

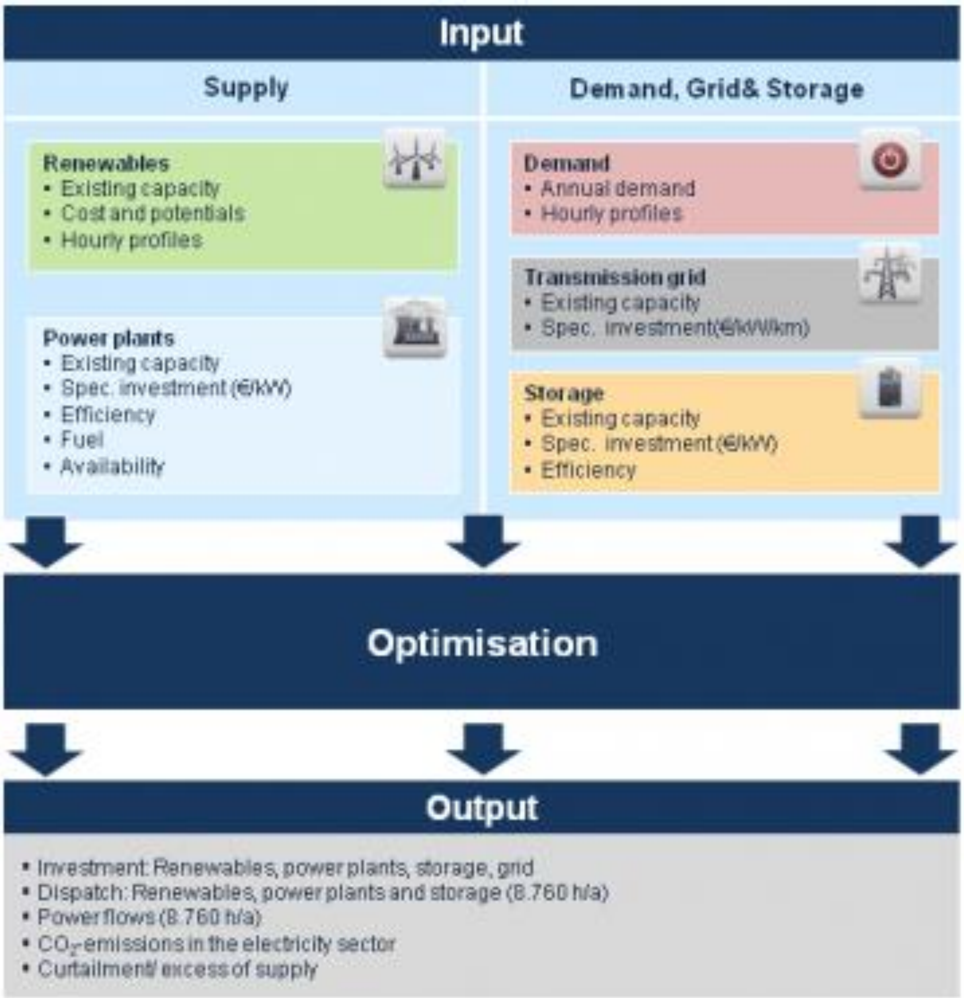

Figure 18: Simplified structure of the ENERTILE model

Integrated optimization of investments and dispatch

Enertile optimizes the investments into all major infrastructures of the power sector, including conventional power generation, combined-heat-and-power (CHP), renewable power technologies, cross-border transmission grids, flexibility options, such demand-side-management (DSM) and power-to-heat storage technologies. The model chooses the optimal portfolio of technologies while determining the utilization of these for in all hours of each analysed year.

High spatial coverage

The model currently depicts and optimizes Europe, North Africa and the Middle East. Each country is usually represented by one node, although in some cases it is useful to aggregate smaller countries and split larger ones into several regions. Covering such a large region instead of single countries becomes increasingly necessary with high shares of renewable energy, as exchanging electricity between different weather regions is a central flexibility option.

High temporal resolution

The model features a full hourly resolution: In each analysed year 8,760 hours are covered. Since real weather data is applied, the interdependencies between weather regions and renewable technologies are implicitly included.

Detailed picture of renewable energy potential and generation profiles

The potential sites for renewable energy are calculated on the basis of several hundred thousand regional data points for wind and solar technologies with consideration of distance regulations and protected areas. The hourly generation profile is based on detailed regional weather data.

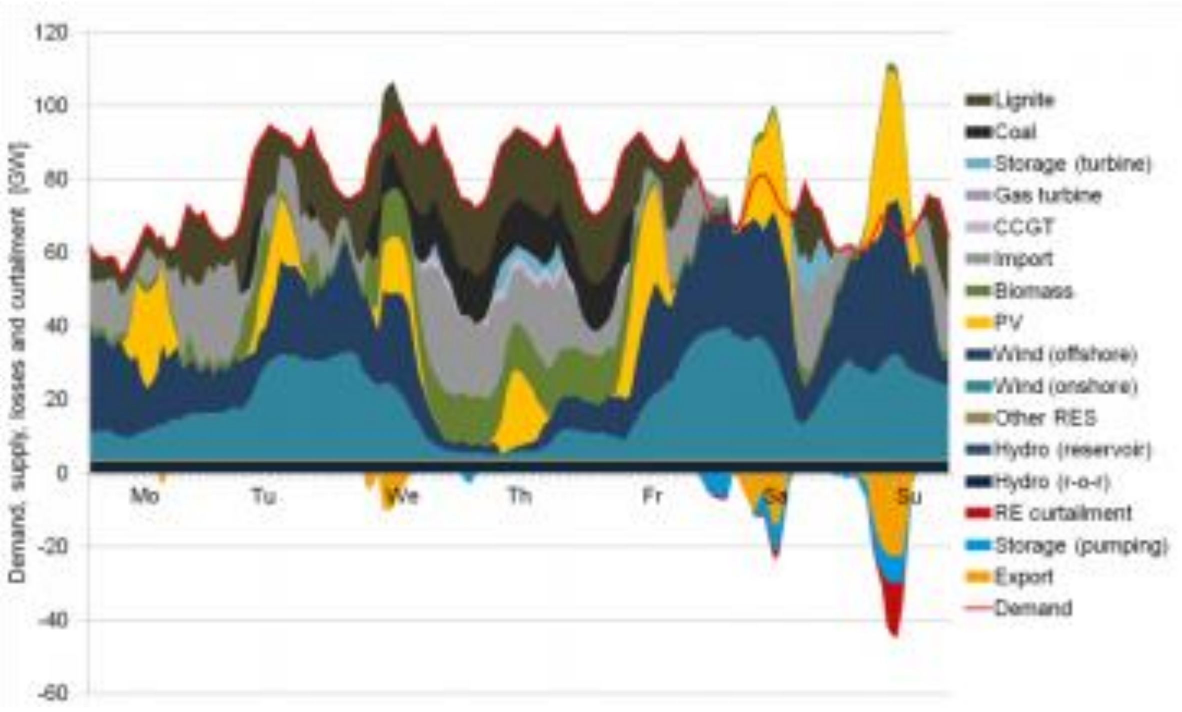

Figure 19: Example of the hourly matching of supply and demand in the ENERTILE model

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