asset

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Technology pathways in decarbonisation scenarios

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About ASSET

ASSET (Advanced System Studies for Energy Transition) is an EU funded project, which aims at providing studies in support to EU policymaking, including for research and innovation. Topics of the studies will include aspects such as consumers, demand-response, smart meters, smart grids, storage, etc., not only in terms of technologies but also in terms of regulations, market design and business models. Connections with other networks such as gas (e.g. security of supply) and heat (e.g. district heating, heating and cooling) as well as synergies between these networks are among the topics to study. The rest of the effort will deal with heating and cooling, energy efficiency in houses, buildings and cities and associated smart energy systems, as well as use of biomass for energy applications, etc. Foresight of the EU energy system at horizons 2030, 2050 can also be of interests.

The ASSET project will run for 36 months (2017-2019) and is implemented by a Consortium led by Tractebel with Ecofys and E3-Modelling as partners.

TABLE OF CONTENT

1 INTRODUCTION

The European Commission is working, among others, with the PRIMES model (operated by Energy Economy Environment Modelling Lab - E3M) to deliver the scenarios that illustrate the potential impact of energy and climate policies, long-term targets and decarbonisation pathways on the operation of the European energy system.

Modelling scenarios for development of the energy system is highly dependent on the assumptions. An essential input to any modelling exercise, and one which has a high influence on modelling results, are assumptions about the development of technologies - both in terms of performance and costs. While these assumptions have been traditionally developed by the modelling consultants (E3M), based on a broad and rigorous literature review, the Commission is increasingly seeking a review of these technologies by industrial stakeholders to make them even more robust and representative of the current projects as well as experts' and stakeholders' expectations.

The definition of technologies and their developments far into the future (PRIMES model has currently the time-horizon up to 2070) is a complex exercise.

While today one cannot have complete knowledge of all technologies that will be deployed on the pathway towards decarbonisation of the energy system, we have already some indication of the technologies that are currently being developed, their current costs and performance as well as their likely evolution in the future. Private companies and public authorities have already made investments in research and demonstration projects as well as, in some case, full-scale industrial activities on these technologies.

Some of the novel technologies currently considered as viable options for full decarbonisation relate to synthetic fuels/e-fuels (CH_4 and more complex hydrocarbons as well as H_2 produced from (increasingly decarbonised) electricity), networks and refuelling stations necessary for their distribution as well as storage options. For synthetic fuels, conversion technologies have to be carefully considered starting with CO_2 capturing, H_2 production, methanation or processes for production of even more complex hydrocarbons suitable for use in transport.

Mapping of these technologies and, more importantly, knowledge about their current and future cost and performance – while obviously subject to many uncertainties – are crucial for envisaging decarbonisation pathways.

The revised, draft version (compared to the latest set underpinning the Reference scenario 2016[1]) of assumptions was compiled by E3M in early 2018, through extensive literature research – see Appendix 2.

[1] Please see: https://ec.europa.eu/energy/sites/ener/files/documents/ref2016_report_final-web.pdf.

2 GOAL OF THE STUDY

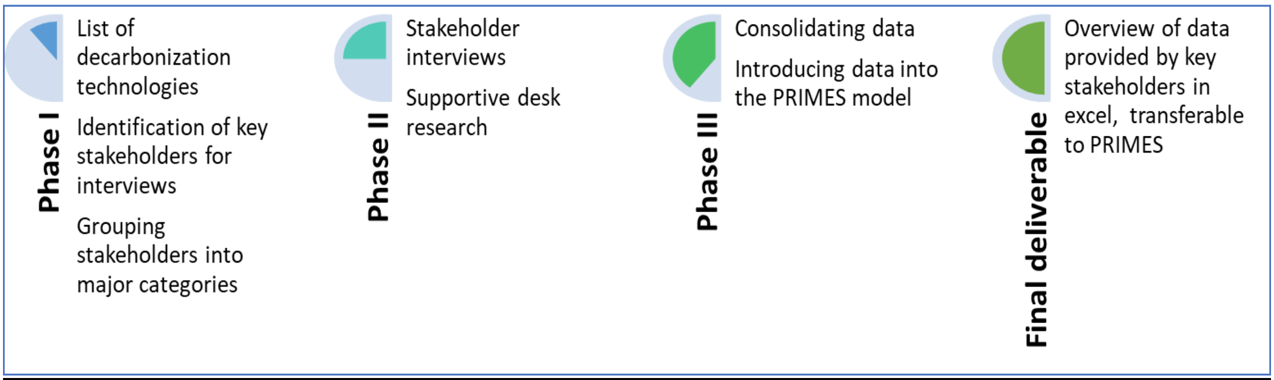
The purpose of this study was to ensure robustness and representativeness of the technology assumptions by reaching out to relevant experts, industry representatives and stakeholders, who are in possession of the most recent data in the different sectors.

The study thus undertook to confirm and - if necessary - adjust the assumptions for PRIMES modelling for the technologies relevant for long term (decarbonisation) pathways in the EU that have been compiled by E3M (both in terms of technology pathways selected and costs). This objective was achieved by identifying and reaching out to relevant experts, industry representatives and stakeholders and using internal expertise.

3 APPROACH

A 3-step approach was followed, leading to the final deliverables, as presented in Figure 1.

Figure 1: Study approach



<u>Phase I</u>

In the first phase, the technologies were grouped into several categories. Next, the list of key potential stakeholders to be interviewed in Phase II was identified and consultants grouped these stakeholders in major categories, following the technologies subject to the review.

<u>Phase II</u>

In phase II, consultants developed a form, which they populated with selected data, tailor-made l for each stakeholder. Supported with a letter from the European Commission, they reached out to stakeholders on bilateral basis, requesting them to review the provided selected data. They also invited the stakeholders to extend the list of the reviewed data, depending on their expertise.

The process included:

a. Sending the forms, tailor-made for each stakeholder
b. Two reminder-rounds, when necessary

c. Working level support and consultation to reviewers by phone and email. In several cases, consultants also organised phone conferences to clarify more complex questions on the specifics of the PRIMES model and technology assumptions presentation.
d. Receiving the reviews and discussing them with the modelling team.

The stakeholder review process peaked ahead of the stakeholder consultation workshop, organised by the Commission on 16th May 2018. Some bilateral exchanges continued also after the workshop.

Phase III

In the third phase, all the data received by the stakeholders was checked and reviewed again by the modelling team with available literature and complemented with further desk-top research, where necessary.

The reviewed assumptions were presented to the European Commission for final review and assessment. Upon agreement with the EC, the modified data was then introduced into the PRIMES model.

4 Decarbonisation technologies

The decarbonisation technologies, subject to the review were divided in five categories:

- Domestic appliances and equipment
- Renovation costs
- Industry
- Power and heat
- New fuels

The complete overview of the technologies is presented below.

Table 1: Summary overview of technologies

Category				
Domestic appliances and equipment	**Renovation costs**	**Industry**	**Power and heat**	**Novel technologies**
1. Residential 1.1. Electric appliances 1.1.1. Dryers 1.1.2. Dishwashers 1.1.3. Refrigerators 1.1.4. Washing machines 1.1.5. Lighting 1.2. Cooking 1.2.1. Cooker 1.3. Space heating 1.3.1. Boilers gas 1.3.2. Boilers condensing gas 1.3.3. Boilers oil 1.3.4. Boilers condensing oil 1.3.5. Wood stoves or Boiler pellets 1.3.6. Heat Pump Air 1.3.7. Heat Pump Hydro 1.3.8. Heat Pump	1. Light renovation (light windows) 2. Light renovation (med. windows) 3. Light renovation (med. windows, light wall) 4. Light renovation (med. windows, light wall/roof) 5. Medium renovation (med. windows, med. wall/roof/basement) 6. Medium renovation (med. windows, med. wall/roof/basement) 7. Deep renovation (deep. windows, med. wall/roof/basement) 8. Deep renovation (deep. windows, deep wall/roof/basement) 9. For four difference climatic zones: north, south, centre-west and east	1. Horizontal processes 1.1. Motors large scale 1.2. Motors midsize 1.3. Motors small 1.4. Cooling refrigeration 1.5. Lighting 1.6. Air conditioning 2. Glass annealing 2.1. Glass annealing (electric) 2.2. Glass annealing new glass thermal (solids) 2.3. Glass annealing new glass thermal (fuels) 2.4. Glass annealing recycled glass thermal (fuels) 3. Iron and Steel basic processing 3.1. Electric Arc (Iron and steel) 3.2. Blast furnace (Iron and steel) solids 4. Direct heat	1. Steam turbines 1.1. Steam Turbine Coal Conventional 1.2. Steam Turbine Lignite Conventional 1.3. Steam Turbine Coal Supercritical 1.4. Steam Turbine Lignite Supercritical 1.5. Fluidized Bed Combustion Coal 1.6. Fluidized Bed Combustion Lignite 1.7. Integrated Gasification Combined Cycle Coal 2. Gas turbines 2.1. Gas Turbine Combined Cycle Gas Conventional 2.2. Gas Turbine Combined Cycle Gas Advanced 2.3. Steam Turbine	1. Hydrogen 1.1. Hydrogen from natural gas steam reforming centralised - Large Scale (per 1 kW or 1 MWh H2 HHV) 1.2. Hydrogen from natural gas steam reforming centralised - Large Scale with CCU(per 1 kW or 1 MWh H2 HHV) 1.3. Hydrogen from natural gas steam reforming de-centralised - Medium Scale (per 1 kW or 1 MWh H2 HHV) 1.4. Hydrogen from low temperature water electrolysis PEM centralised - Large Scale (per 1

Geothermal 1.3.9. Heat Pump Gas 1.3.10. Electric Resistance 1.3.11. Gas individual 1.3.12. Solar Thermal 1.3.13. CHP ICE 1.3.14. CHP micro CCGT 1.3.15. CHP FC 1.3.16. District heating 1.4. Water heating 1.4.1. Water heating boiler (diesel) 1.4.2. Water heating boiler (electricity) 1.4.3. Water heating boiler (natural gas) 1.4.4. Solar collector 1.4.5. Water heating heat pump 1.4.6. Water heating boiler (heat)		4.1. Direct heat use in food and other industries - electric 4.2. Direct heat use in food and other industries - fuels 5. Drying and separating 5.1. Drying and separating fuels(cement) 5.2. Drying and separating electric 5.3. Drying and separating thermal 6. Furnaces 6.1. Electric furnace (ALS, COP ZNC) 6.2. Electric furnace (ALP) 7. Electric processes 7.1. Electric process in IS 7.2. Electric process in Fertilisers 7.3. Electric process in Petrochemical 7.4. Electric process in inorganic chemicals 7.5. Electric process in low energy chemicals 7.6. Electric process in paper and pulp	Fuel Oil Conventional 2.4. Gas turbine with heat recovery 2.5. Very small-scale Gas Plant 3. CCS 3.1. Pulverised Lignite Supercritical CCS post combustion 3.2. Integrated Gasification Coal CCS pre-combustion 3.3. Integrated Gasification Lignite CCS pre-combustion 3.4. Pulverised Coal Supercritical CCS oxyfuel 3.5. Pulverised Lignite Supercritical CCS oxyfuel 3.6. Gas combined cycle CCS post combustion 3.7. Gas combined cycle CCS oxyfuel 4. Biomass 4.1. Steam Turbine Biomass Solid Conventional 4.2. Biogas Plant with	kW or 1 MWh H2 HHV) 1.5. Hydrogen from low temperature water electrolysis PEM de-centralised at a refuelling station (per 1 kW or 1 MWh H2 HHV) 1.6. Hydrogen from low temperature water electrolysis Alkaline centralised - Large Scale (per 1 kW or 1 MWh H2 HHV) 1.7. Hydrogen from low temperature water electrolysis Alkaline de-centralised at a refuelling station (per 1 kW or 1 MWh H2 HHV) 1.8. Hydrogen from low temperature water electrolysis SOEC centralised (per 1 kW or 1 MWh H2 HHV) 1.9. Hydrogen from

1.5. Air conditioning 1.5.1. Electric Air-conditioning 1.5.2. Electric Air-conditioning central 2. Service 2.1. Electric appliances 2.1.1. Office lighting 2.2. Space heating 2.2.1. Large scale Boilers 2.2.2. Large scale Boilers condensing 2.2.3. Large scale Heat Pumps 2.2.4. District heating 2.3. Air conditioning 2.3.1. Air-conditioning (electricity) 2.3.2. Air-conditioning (natural gas) 2.3.3. Air-conditioning (heat)		8. Electric refining 8.1. Paper and pulp electric refining 9. Foundries (non-ferrous alloys) 9.1. Electric foundries 9.2. Foundries (non-ferrous alloys) - fuels 9.3. Thermal foundries 10. Kilns 10.1. Electric kilns for copper 10.2. Kilns for other non-ferrous (fuels) 10.3. Kilns cement (fuels) 10.4. Electric kilns (ceramics) 10.5. Kilns materials (fuels) 10.6. Tunnel kiln (ceramics) 11. Thermal processes 11.1. Fertilisers thermal process 11.2. Petrochemical thermal process 11.3. Inorganic chemistry thermal process 11.4. Low energy chemistry thermal process	Heat recovery 4.3. Small Waste burning plant 4.4. Biomass Gasification CC 4.5. MBW incinerator CHP 5. Nuclear 5.1. Nuclear III gen. (incl. economies of scale) 5.2. Nuclear III gen. (no economies of scale) 6. Fuel cells 6.1. Fuel Cell Gas (large scale) 6.2. Fuel Cell Gas (small scale) 7. Wind onshore 7.1. Wind onshore-Low 7.2. Wind onshore-Medium 7.3. Wind onshore-high 7.4. Wind onshore-very high 7.5. Wind small scale rooftop 8. Wind offshore 8.1. Wind offshore - low potential 8.2. Wind offshore - medium potential	low temperature water electrolysis SOEC de-centralised at a refuelling station (per 1 kW or 1 MWh H2 HHV) 2. Conversion technologies 2.1. Methanation (per 1 kW or 1 MWh CH4 HHV) 2.2. CH4 Liquefaction plant (per 1 kW or 1 MWh gas HHV) 2.3. Gas Liquefaction plant (per 1 kW or 1 MWh gas HHV) 2.4. Regasification Plant including LNG storage (per 1 kW or 1 MWh gas HHV) 2.5. Power to liquid via the methanol route (per 1 kW or 1 MWh CH4 HHV) 2.6. Power to liquid via the Fischer Tropsch route (per 1 kW or 1 MWh CH4 HHV)

			8.3. Wind offshore - high potential 8.4. Wind offshore - very high (remote) 9. PV 9.1. Solar PV low potential 9.2. Solar PV medium potential 9.3. Solar PV high potential 9.4. Solar PV very high potential 9.5. Solar PV small scale rooftop 9.6. Solar Thermal with 8 hours storage 10. Tidal and waves 11. Hydro 11.1. Lakes 11.2. Run of river 12. Geothermal 12.1. Geothermal High Enthalpy 12.2. Geothermal Medium Enthalpy 13. Electric boilers 14. District heating 14.1. District heating Boilers Gas 14.2. District heating Boilers Fuel Oil 14.3. District heating Boilers Biomass	2.7. Power to liquid via High temperature co-electrolysis and Fischer Tropsch (per 1 kW or 1 MWh CH4 HHV) 2.8. Capture CO2 from air (Absorption technology) (per 1 tCO2) 2.9. Capture CO2 from air (Adsorption technology) (per 1 tCO2) 2.10. CO2 Liquefaction plant (per 1 ton CO2) 3. Refuelling technologies 3.1. H2 compression station (per 1 kW or 1 MWh H2 HHV) 3.2. Hydrogen Liquefaction plant (per 1 kW or 1 MWh H2 HHV) 3.3. H2 liquid to gas refuelling station (per 1 kW or 1 MWh H2 HHV) 3.4. H2 refuelling station Small (per

			14.4. District heating Boilers Coal 14.5. District heating Boilers Lignite 14.6. MBW incinerator district heating 14.7. District Heating Electricity 14.8. District Heating Geothermal 14.9. District Heating Heat Pump 14.10. District Heating Solar 15. Industrial power generation 15.1. Industrial Boilers Coal 15.2. Industrial Boilers Lignite 15.3. Industrial Boilers Gas 15.4. Industrial Boilers Fuel Oil 15.5. Industrial Boilers Biomass	1 kW or 1 MWh H2 HHV) 3.5. H2 refuelling station Medium (per 1 kW or 1 MWh H2 HHV) 3.6. H2 refuelling station Large (per 1 kW or 1 MWh H2 HHV) 3.7. ELC recharging points - Semi Fast recharging (per 1 kW or 1 MWh ELC) 3.8. ELC recharging points - Fast recharging (per 1 kW or 1 MWh ELC) 3.9. CNG compression station (per 1 kW or 1 MWh gas HHV) 3.10. CNG refuelling station (per 1 kW or 1 MWh gas HHV) 3.11. LNG refuelling station (per 1 kW or 1 MWh gas HHV) 4. Distribution technologies

				4.1. NGS Transmission Network (per MWh) (per MWh) 4.2. NGS Distribution Network (per MWh) 4.3. H2 pipeline 60bar (per MWh H2 HHV) 4.4. H2 pipeline 10 bar (per MWh H2 HHV) 5. CO2 transmission network 5.1. 6. Hydrogen transport 6.1. Road transport of liquid H2 6.2. Road transport of gaseous H2 7. Storage technologies 7.1. Compressed Air Energy Storage (per 1 kW or 1 MWh electricity) 7.2. Flywheel (per 1 kW or 1 MWh electricity) 7.3. Large-scale batteries (per 1 kW or 1 MWh

				electricity) 7.4. Small-scale batteries (per 1 kW or 1 MWh electricity) 7.5. Pumping (per 1 kW or 1 MWh electricity) 7.6. Underground Hydrogen Storage (per 1 kW or 1 MWh H2) 7.7. Pressurised tanks - Hydrogen storage (per 1 kW or 1 MWh H2) 7.8. Liquid Hydrogen Storage - Cryogenic Storage (per 1 kW or 1 MWh H2) 7.9. Metal Hydrides - Hydrogen Storage (per 1 kW or 1 MWh H2) 7.10. Thermal Storage Technology (per 1 kW or 1 MWh Heat) 7.11. LNG Storage Gas (per 1

				kW or 1 MWh Gas) 7.12. Underground NGS Storage (per 1 kW or 1 MWh Gas) 8. Liquid CO_2 storage tank

5 PRESENTATION OF DATA TO STAKEHOLDERS

A template for data survey presented to stakeholders on bilateral basis was established in the Phase II of the study. It consisted of the following worksheets:

- Guidance: instructions how to use the form
- Introduction: basic information about the reviewer organisation and technology category reviewed
- Technology data overview: specific set of data to be reviewed
- Additional information: further information which the reviewer would like to provide
- All technology categories: the overview of all technologies to be reviewed - for information only

The data survey template is presented in Appendix 1: Survey template.

6 LIST OF STAKEHOLDERS

Consultants agreed with the Commission to contact maximum 100 key stakeholders on bilateral basis. The list of key stakeholders was established in early April and once consolidated 94 organisations were indeed to be contacted on bilateral basis, as presented in Table 2.

Furthermore, the European Commission directly approached over 300 stakeholders with a request to review the datasets alongside the invitation to the workshop on 16th May.

The complete overview of stakeholders contacted on bilateral basis is presented below.

Table 2: List of stakeholders requested for reviewing the data

Organization		Type of technology				
		Domestic	Renovation costs	Industry	Power and heat	Novel technologies
1.	Abengoa					X
2.	AEBIOM				X	
3.	AFHYPAC					X
4.	Agora Energiewende				X	X
5.	Air Liquide					X
6.	AkuoEnergy				X	
7.	AkzoNobel			X		
8.	Alstom					X
9.	Arcellor Mittal			X		
10.	Association of the European Heating Industry				X	
11.	Audi					X
12.	Bosch					X
13.	BP					X
14.	CEA					X
15.	Coalition for Energy Savings	X				X
16.	COGEN Europe				X	
17.	Covestro			X		
18.	Credit Suisse					X
19.	DCP Fuel Cell PowerTrain				X	
20.	E.ON				X	
21.	EASE					X
22.	ECN				X	
23.	EDF				X	
24.	EDSO				X	
25.	EERA					X
26.	EIT InnoEnergy	X	X	X	X	X

Organization		Type of technology				
		Domestic	Renovation costs	Industry	Power and heat	Novel technologies
27.	ENAGAS					X
28.	ENEA				X	
29.	ENEL					X
30.	Energinet					X
31.	Engie Research					X
32.	ENTSO-E				X	
33.	ERTAC/BMW					X
34.	ESTELA				X	
35.	ESTIF				X	
36.	ETIP					X
37.	Eurelectric				X	
38.	Eurima		X			
39.	EUROBAT					X
40.	Eurogas					X
41.	European Biogas Association				X	
42.	European Climate Foundation				X	
43.	European Council for an Energy Efficient Economy	X	X	X		
44.	European Heat Pump Association	X				
45.	European Steel Technology Platform			X		
46.	FCH Platform					X
47.	Fertilizers Europe					X
48.	Fiat					X
49.	Friends of the Super grid					X
50.	Fuel Cells and					X

Organization		Type of technology				
		Domestic	Renovation costs	Industry	Power and heat	Novel technologies
	Hydrogen Joint Undertaking (FCH JU)					
51.	Fuels Europe					X
52.	Gas Connect Austria					X
53.	GasUnie					X
54.	GEODE	X				
55.	GERG					X
56.	Glen Dimplex					X
57.	GRT Gas					X
58.	HKS					X
59.	Hydrogen Europe					X
60.	Hydrogenics					X
61.	HyEnergy					X
62.	IEA Renewable Industry Advisory Board				X	
63.	IRENA				X	
64.	KIC InnoEnergy - Smart grids and Storage					X
65.	Lanzatech					X
66.	Michelin					X
67.	Mitsubishi Hitachi Power systems					X
68.	Nawa technologies					X
69.	NEK					X
70.	NEL Hydrogen					X
71.	NGVA Europe					X
72.	NOW					X
73.	Ocean Energy Europe				X	
74.	OCI Nitrogen					X

Organization		Type of technology				
		Domestic	Renovation costs	Industry	Power and heat	Novel technologies
75.	Port of Rotterdam					X
76.	Red Electridad Espania					X
77.	SAFT Groupe					X
78.	Salzgitter Flachstahl					X
79.	Shell					X
80.	Siemens				X	
81.	SmartEn	X				
82.	Solar Heat Europe				X	
83.	Solar Power Europe				X	
84.	Sunfire					X
85.	Symbio					X
86.	TERNA					X
87.	Total				X	
88.	Transelectrica				X	
89.	Uniper Energy				X	
90.	Vattenfall				X	
91.	VERBUND Solutions GmbH				X	
92.	Wind Europe				X	
93.	Yara International					X
94.	Zinium					X

7 STAKEHOLDER DATA REVIEW PROCESS AND RESPONSES

7.1 Bilateral stakeholder consultation organised by the Consortium

Out of the 94 agreed organisations, the consultants contacted 92. In two cases, the actual contact details of the key expert could not be identified in due time.

All 92 organisations were approached by email in the period 09-17.04.2018. Reminders were sent between 24-26.04.2018.

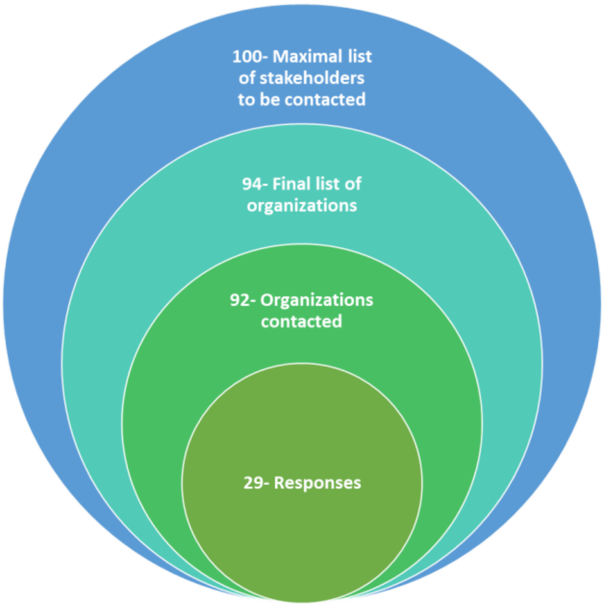
Most stakeholders requested, both by email and over the phone, some clarification of the data provided to be able to clearly understand the data presented for the review. In some cases, short teleconferences were held to discuss the needs of PRIMES and recommendations for modellers.

29 organisations provided feedback, including the proposals for revision of technology costs. The organisations who provided their reviews were:

1. AEBIOM
2. Agora Energiewende
3. Air Liquide
4. Association of the European Heating Industry
5. Coalition for Energy Savings
6. COGEN Europe
7. EASE
8. ECN
9. ESTELA
10. Eurelectric
11. European Biogas Association
12. European Climate Foundation
13. European Heat Pump Association
14. Fuel Cells and Hydrogen Joint Undertaking
15. Hydrogen Europe
16. IRENA
17. KIC Innogy
18. Lanzatech
19. Mitsubishi Hitachi Power
20. NEL Hydrogen
21. NOW
22. OCE Nitrogen
23. Ocean Energy Europe
24. Siemens
25. SmartEn
26. Solar Heat Europe
27. Solar Power Europe
28. Sunfire
29. Vattenfall

Figure 2 summarizes the level of engagement from stakeholders.

Figure 2: Summary of stakeholder engagement in the process

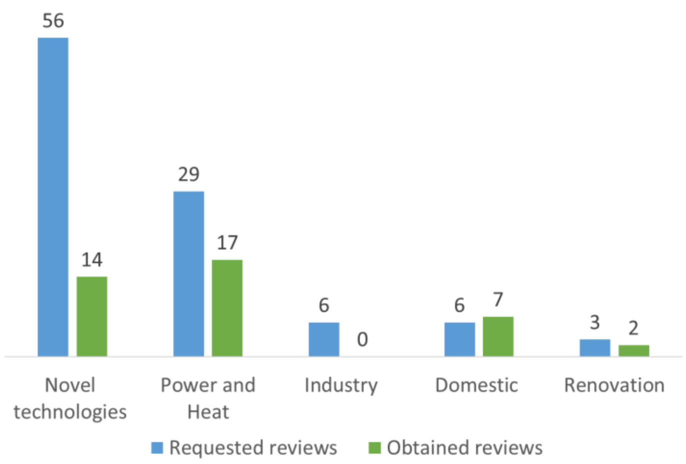


In four cases, the stakeholders expressed their interest to review a broader scope of data than originally requested and provided a broad scope of reviews, covering the full range of technologies under the review.

The key element of the bilateral stakeholder consultation was the stakeholders' request to clarify the technology developments as presented in PRIMES draft assumptions, especially for novel technologies. Some 100 requests for clarifications were made by the 93 stakeholders and there were 56 requests regarding novel technologies parameters, followed by 36 category specific responses from the 29 reviewers.

Figure 3 presents the detailed split of requested clarification and the subsequently obtained reviews.

Figure 3: Overview of requested – and obtained category-specific reviews



7.2 Stakeholders that provided information directly to the Commission

An even larger group of stakeholders provided their feedback both bilaterally and to the European Commission as they were invited to do so alongside the participation in the workshop organised by the Commission on 16 May. All feedback was considered, as presented in Table 3.

Table 3: Overview of feedback streams

	Name of the organisation	Feedback to the EC	Feedback to consortium
1.	AEBIOM	X	X
2.	Agora Energiewende		X
3.	Air Liquide		X
4.	Association of the European Heating Industry		X
5.	Business Europe	X	
6.	CAN Europe	X	
7.	CEEP	X	
8.	CEFIC	X	
9.	Cembureau	X	
10.	Coalition For Energy Savings		X
11.	COGEN	X	X
12.	CZ industry	X	
13.	Danish Energy	X	X
14.	Danish Energy Agency	X	
15.	ECOS	X	
16.	EASE		X
17.	ECN		X
18.	EGEC	X	
19.	EHPA	X	
20.	ENTSO-G	X	
21.	Estela		X
22.	Eugine		X
23.	Eurelectric	X	X
24.	Eurofer	X	
25.	Eurofuel	X	
26.	Eurogas	X	
27.	European aluminium	X	
28.	European Biogas Association		X
29.	European Climate Foundation		X
30.	European Heat Pump Association		X
31.	Foratom	X	
32.	Fuel Cells and Hydrogen Joint Undertaking		X
33.	FuelsEurope	X	X
34.	Greenpeace	X	
35.	Hydrogen Europe		X
36.	IDDRI	X	
37.	IRENA		X
38.	KIC Innogy		X

39.	Lanzatech		X
40.	Mitsubishi Hitachi Power		X
41.	NEL Hydrogen		X
42.	NOW		X
43.	OCE Nitrogen		X
44.	Ocean energy	X	X
45.	Siemens		X
46.	Smart En		X
47.	Solar Heat Europe		X
48.	Solar Power Europe		X
49.	Sunfire		X
50.	Vattenfall		X
51.	Windeurope	X	
52.	WWF	X	

8 Report from the workshop on 16 May 2018

The meeting was organised by the Commission as part of the study and in order to increase the stakeholder outreach.

In the **opening remarks**, the Commission explained the project that is led by ASSET consortium and consists of three phases:

1) Bilateral outreach to some 100 stakeholders, selected by consultants, in order to obtain their feedback on draft technology assumptions.
2) The meeting held on 16/5 (and the written feedback the Commission solicited prior to the meeting), which was an opportunity to engage with a large group of stakeholders interested in such exchanges (invitations to over 300 stakeholders were sent and additional stakeholders were also invited to join).
3) Finalisation of the technology assumptions by modellers and the Commission, taking into account all bilateral exchanges, written comments and feedback and discussions on 16/5.

Importantly, the project itself is the final phase of preparation of technology assumptions. PRIMES modelling experts from E3M explained during the meeting the broad and rigorous literature review and the methodology of establishment of the cost curves, which is the standard academic approach in such a work.

The Commission welcomed high level of participation and interest in modelling inputs and acknowledged that stakeholders have significant expertise that can be shared with the Commission and that can be useful input into modelling. The Commission wanted the meeting to be an opportunity to have a discussion about technology assumptions used in model PRIMES and to obtain a clearer picture of technology developments as expected by stakeholders. Enhanced exchanges around modelling aspects were meant to be an opportunity to learn from each other. Many stakeholders congratulated the Commission on the initiative to increase transparency around Commission modelling. PRIMES experts were grateful for feedback that reflects the most recent information about state of development and prospects of technologies (otherwise difficult to obtain from academic literature).

The Commission also stressed that this is a technical meeting aimed to discuss the specific topic of technology assumptions in PRIMES. Still some related questions were raised notably concerning the

Commission's Long Term Strategy (scheduled for adoption in November), the scenarios that the Commission plans to develop and their level of ambition. The Commission referred to the upcoming public consultation on the Long Term Strategy where stakeholders should bring all relevant expertise and debate the level of ambition as well as pathways.

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The **event was divided into three sessions dedicated to clusters of technologies**:

(1) technologies related to synthetic fuels, Carbon Capture and Storage, sector coupling and storage

(2) renewable technologies in power generation and nuclear power generation

(3) technologies related to energy efficiency in buildings, appliances and industry

Each of the sessions was started by **short explanations by ECOFYS/Tractebel** of the process of bilateral contact with stakeholders. It was explained that 100 stakeholders were selected by consultants (based on their expert knowledge). In total 95 stakeholders were contacted, 28 stakeholders provided 33 reviews on technology assumptions. A lot of the bilateral exchanges required also additional explanations which were provided by the PRIMES experts especially in terms of methodology and precise meaning of different categories.

The Commission explained that over 300 stakeholders were invited to the meeting; that all additional stakeholders who signalled their wish to participate were invited and if there was an omission, an additional week was allowed for questions/comments.

The **presentation from the PRIMES team** was partly common and partly adapted to specific technologies and relevant modelling parts discussed at each session. In the first part, PRIMES team was explaining the model, its structure combining the micro-economic foundations with engineering representation, mathematical foundations, typical inputs and outputs as well as issues it can cover. The difference between PRIMES and bottom-up models was explained. The modellers stressed that the model is not a forecasting tool but can answer "*what if*" questions, i.e. how the energy system will develop assuming given technology prospects, global fossil fuels prices and macro-economic developments, and is well suited to simulate medium/long term transitions, less for short term changes. The other part of the presentation was tailored to the specific technologies discussed at each session listing the literature sources that were the main references, explaining the technology definitions and categories reported, as well as explaining the relevant module of PRIMES in more detail. It was stressed that while indeed technologies often come already today in rich variations, they necessarily have to be aggregated/simplified as models as such are by definition a simplified version of the real life. Also technologies that are expected to have little penetration of the market or on which literature has only scarce information are often omitted for simplification reasons.

Modellers explained that in the table with draft assumptions units of measurement can be different from those most commonly used and, for example, expressing costs in EUR/kWh was only used for illustrative purposes. Importantly the EUR/kWh (produced or stored – LCOE or LCOS) which are reported in the circulated file on assumptions are illustrative only as model calculates such metrics dynamically (notably taking into account dynamic projections of fuels costs and utilisation factors); they are endogenous and differ for each scenario. It was also explained that *overnight investment costs* (CAPEX) are the costs of constructing a project if no interest was incurred during construction, as if the project was completed "overnight”. In the session-specific parts of the presentation modellers explained the technologies concerned and parts of PRIMES model which are relevant, as well as providing the clarifications to most frequent questions received during the written consultation.

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In the Q&A session, the following issues were discussed and clarified:

Electricity price for e-fuels (synthetic fuels produced with electricity): the electricity price considered as cost element in e-fuels production is the electricity price paid by heavy industry not the whole-sale prices; these are endogenous in the model and are scenario dependent. On the supply side, different generation costs for different technologies are derived.

Power-to-Gas (PtG) generation possibilities: Several options/streams are considered in the model (SMR with CCS, electrolysis and methanation, different sources of CO_2 sources (but not from fossil fuels)). Heat recovery within the process of e-fuel production is considered, however excess heat production is not considered to be used. It was stressed again that LCOE is only illustrative as it will be changing e.g. alongside electricity prices. Therefore, comments should focus on more concrete elements of technology assumptions like CAPEX.

Full costs of PtG: Impact on infrastructure of the higher use of e-fuels is considered in the model. While costs of electrolysers/steam reformers are not directly reported they are included in system-wide analysis, and are visible e.g. in increased fuels prices for consumers, which may therefore decide to increase or decrease the quantities used.

Types of gas, its storage and network representation: Natural gas is well represented in PRIMES but also all types of renewable gases. A number of types of storages is represented in PRIMES (hydro, batteries, e-fuels, heat as well as classical gas storage). Both natural gas and H_2 network is considered although both transmission and distribution only via parametrisation (PRIMES is not a spatial model). The refurbishment option to allow carrying higher amounts of hydrogen in the existing network is also considered in the model. PRIMES has a gas module (PRIMES gas supply) allowing for more modelling results, e.g. sources of imports but it is not run as a part of standard PRIMES modelling suite. The question was raised about reflecting the European legislation imposing requirement of readiness for extreme weather conditions (i.e. preparedness for "one in 20 years" type of extreme conditions - referring to gas availability). Currently this is not reflected in PRIMES.

However, the system reliability constraints for the electricity system are fully respected. Currently the legislation applies only to gas storage availability, however it has not yet been applied to the electricity system in view of high levels of heating being dependent on electricity. Such an option could however be modelled in PRIMES - if required - as a sensitivity. The use of backup systems for heating are already now considered in the modelling (i.e. use of gas boilers or electrical resistance type of equipment together with heat pumps for a certain number of hours a year, simulating the drop of temperatures).

Electricity markets representation and possibility to reflect "excess" electricity production: Hourly resolution of the electricity market is now part of standard PRIMES model run as it was implemented for the analytical work underpinning Market Design Initiative proposals (Unit commitment module). The approach to consider only "excess" (i.e. once demand is covered) electricity supply as the one that qualifies for storage and production of e-fuels is, however, overly simplified. The decision to store electricity or produce e-fuels depends on many factors: balancing needs, the market prices of storage and electricity as well as final demand for e-fuels.

Assumptions on bio-energy: PRIMES has a biomass module (PRIMES biomass supply) which is part of standard model run and which defines dynamically the supply (taking into account global availability of feedstock according to current knowledge – based on interactions with the GLOBIOM team at IIASA and the CAPRI team at Eurocare- and demand for bio-energy projected by the main PRIMES model). The model then defines which feedstock provides the bio-energy supply and at which cost.

2nd generation/advanced biofuels (as defined by the ILUC Directive) are represented with high granularity with 35 conversion chains (pyrolysis is an option but cellulosic sources are predominant). The costs of feedstock are not consulted as a part of this project.[2]

Biomass boilers for industrial use are also represented in PRIMES.

Different GHG emissions reduction levels and construction of scenarios: PRIMES can model different levels of GHG reductions that are constraints for the scenarios – both consistent with the ambition of limiting the temperature change to 2°C and the aspirational goal of Paris for 1.5°C. Together with the GAINS model that covers also non-CO_2 emissions and the knowledge of land use from GLOBIOM, all GHG emissions and sinks from the EU economy are modelled. For a given level of GHG emissions reduction (at a given time horizon), PRIMES can produce an “infinite” number of pathways of how to achieve the given target. Such pathways will vary in terms of policies pursued, technology developments and, as a consequence, costs. It is possible to construct the scenarios where the predominant energy carrier would be H_2 or electricity. Still the model provides a realistic representation and the change is progressive, taking into account the vintages representation whereas equipment gets replaced progressively. More "ambitious" scenarios can be also developed reflecting premature scrapping of equipment but this would most likely lead to higher cost. PRIMES model can also be used to perform sensitivity analysis (e.g. assuming different prospects of technology development) and can present ranges/absolute numbers.

Demand side response: such measures are represented in PRIMES but implicitly by modifying the demand curve (smoothening "peaks" and "valleys") and thus influencing energy costs. PRIMES cannot, however, capture explicit investments into such services.

Costs representation: Investments and entire system costs are reported for the entire EU-28 and country by country. Taxes and subsidies are an important component of cost calculation. For the past, they are obtained from energy taxation tables from TAXUD as well as from the process of MS consultation in the preparation of the Reference scenario. For the future, they are assumed to continue unchanged in real terms throughout projection period – this is an assumption, however, that could be changed if required, as taxation is an exogenous input to the model.

National costs of technologies are sometimes applicable e.g. for buildings but not for technologies that have harmonised performance/costs at EU (or even sometimes global) level such as PVs.

Technologies that have CCS aspect (e.g. gas turbines with CCS) include cost of carbon storage and transport, albeit there is currently a simplification that only transport (and thus storage) within each country is assumed.

[2] Costs and availability of feedstock are regularly consulted with the EUCLIMIT consortium (www.euclimit.eu) with the CAPRI and GLOBIOM teams. Also recently E3M has participated in a study specifically on advanced biofuels in which the Costs and availability of feedstock where updated (https://publications.europa.eu/en/publication-detail/-/publication/448fdae2-00bc-11e8-b8f5-01aa75ed71a1/language-en)

Technologies that have a need for transmission (remote RES in power generation) also have these costs added to their capital costs.

The wind and solar potentials reflect wind velocity and solar irradiation, as well as spatial limitations to the extent possible in PRIMES and have impact on costs. Resource potential classes, referring to different resource intensities, are then coupled with cheaper/more expensive equipment that is suitable to the resource intensity for each class.

Life-cycle assessment is not performed; only investment and operation costs are accounted for, as well as emissions in use. In addition to CAPEX, in the system costs the financing costs are reflected. PRIMES considers converging financing conditions across MS – again this is an assumption for the model which could be modified.

Storage: Different technologies of storage are considered (see above) and their use: ancillary services, reserve and seasonal storage. PRIMES uses a fully-fledged unit commitment algorithm, taking into account all the technical constraints of the power plants (cyclic operation, technical minimums) and the system requirements for each type of reserve and balancing. Storage in the form of e-fuels (Hydrogen, gas, liquids) is well represented in the model: batteries are also represented in the model (large and small) to capture the different storage characteristics linked to battery size and type. Importantly, remuneration of storage is not aimed at storage itself but at operation of the entire power system - on the assumption that well-operating market will find a way to finance storage. It was also explained that batteries costs reported in the assumption file circulated referred to stationary uses. Batteries for mobile uses are part of transport assumptions. Transport assumptions were not consulted as part of ASSET project as the Commission has consulted them extensively for the purpose of the recent Mobility packages and the report with relevant assumption is now publicly available[3].

Hydrogen: Both electrolysers and steam reformers are represented albeit the latter (if not equipped with CCS) will be increasingly less competitive in scenarios with increasing (ETS) carbon prices. Different gas pressures alongside sizes of refuelling stations are represented in PRIMES. The transmission and decompression stages are considered and reflected in the costs. Both decentralised (local electrolysers) and centralised (with networks carrying H_2) infrastructure can be assumed and its respective costs are accounted for and fully passed through to energy costs. Electricity for electrolysers operation can come from dedicated capacity or from the grid.

H_2 (if such a pathway is pursued) will not only be produced when prices are low, an equally strong driver is the demand for H_2 notably in the industry (that in certain scenarios can be very high). For finding the market equilibrium price of H_2 (and any other energy carrier) PRIMES performs iterations of simultaneous decisions in order to find the market equilibrium.

Sector coupling: it can be well reflected in PRIMES. The complexity of sector coupling is that transformation of one sector is heavily dependent on the other (e.g. gas decarbonisation, if to be achieved via e-fuels, requires decarbonisation of electricity generation), therefore a system-wide model such as PRIMES is very well placed for this kind of analysis.

[3]Please see:
https://ec.europa.eu/clima/sites/clima/files/transport/vehicles/docs/ldv_co2_technologies_and_costs_to_2030_en.pdf

Prices projections: both electricity prices and CO_2 prices are fully endogenous and result from interaction of all sectors. CO_2 prices and the carbon allowance market follow the requirements of the ETS legislation. Conversely, global fossil fuel price projections are an output of another model of E3M (Prometheus) and exogenous for the PRIMES model.

Wind: the question was raised how the link between CAPEX and capacity factor (CF) could be better reflected because currently PRIMES associates high CAPEX with high CF but there could also be lower cost in exploiting high resources (where CF is high). In the feedback received during the consultation phase, it has been pointed out by multiple stakeholders that costs should be higher in the case of onshore installations for very low potential sites and lower for very high potential sites, as the former require plants with larger blades in order to maximise the use of limited resource, and the latter need stronger foundations.

It was indicated that the capacity factors shown in the assumptions are taken into perspective together with the potential of the available potential classes, i.e. even though the low potential class for wind have very low CF, these zones have very limited potential – implying that there are relative few areas in Europe classified in this very low potential area. Therefore, the model utilises in most cases areas with high or very high availability of wind, thus it is the CF of these two classes that is used by the model mostly. In general, CF were criticised as too low (also for the high/very high classes) and PRIMES team agreed to review these assumptions. The need for better labelling of technologies was underlined (identifying notably the floating and fixed bottom technologies). It was explained that offshore CAPEX cost reflect the electricity connection which is important especially for remote locations.

On-site generation: such possibility is important for big industrial players and is reflected in PRIMES model, which splits between utility and industrial applications.

Nuclear: Nuclear CAPEX was discussed in light of recently announced costs (e.g. Hinckley Point C reactors) that are much higher than draft assumptions and opinion of nuclear industry expecting lower costs. It was stressed that the development of nuclear depends not only on the cost of equipment but also on the costs resulting from safety regulations, national legislation and public perception and that assumptions are made for development of European technology in Europe (different from global trends). It was suggested to reflect the learning effects for Generation III reactors considering economies of scale as well as addition, in technology menu, of second generation Small Modular Reactors.

PRIMES already reflects lower costs for Lifetime Operation extensions. For nuclear sites, the PRIMES modelling team has undertaken an analysis to verify where life time extension and brownfield investments are possible.

Back-up capacity for renewables: the requirements of back-up capacity in power generation that increase alongside higher variable renewables penetration are reflected in PRIMES. These requirements are likely to increase with higher demand for electricity coming from transport/heating and even higher deployment of variable renewables. Back-up capacity is represented for peak demand, ancillary services and necessary reserve requirements. PRIMES also reflects that inter-connections contribute to stability of the system. The unit commitment simulator runs all EU countries simultaneously, thus resulting to the optimal allocation of interconnector capacities using flow-based allocation.

Ocean and hydro energy: Further differentiation of technology would be needed for ocean energy, but currently PRIMES represents the technology in aggregated manner only. For hydro, hydro- pumping (for storage), lakes and run of the river are differentiated.

Electricity interconnections: PRIMES reflects commissioning of interconnectors as currently scheduled by ENTSO-E. The main operating mode of PRIMES is perfectly functioning internal market and thus flow-based allocation of interconnection. Utilisation of interconnections is endogenous in the model. Imperfect functioning of markets can also be represented in PRIMES and has been already performed as input to Commission's Impact Assessments.

Engine-based power plants: are represented in PRIMES.

Extreme weather conditions: are not standard consideration in PRIMES beyond what is required by the EU/national legislation (see the preparedness requirement for gas sector described above).

Further transparency of the modelling input: a lot of criticism in the past concerned demand-side technologies and solutions. The current project is a steep improvement (notably concerning costs of renovations) – it is also reminded that a new module has been recently developed in order to better reflect the residential and services. Further work is needed and stakeholders voiced interest in seeing also the databases and reviewing them. It is important that experts can have their questions answered by modelling experts in order to better understand the end result. However, it was also stressed that consistent data on the residential and particularly the services sector for all MS, is much more difficult to obtain.

Consistency with eco-design: Eco-design preparatory studies are considered in preparation of technology assumptions, but product categories do not always fully match. There were some reporting bugs in the draft assumption file circulated, including a problem with the unit of measurement for lighting. The revised assumptions have been fully checked again with eco-design legislation and modified accordingly. Related to lighting there was a problem of unit of measurement in the file sent for consultation, this has been corrected in the final file. The methodology for deriving technology progress in the future was explained as well as how "ultimate" status for technology is established (i.e. the floor costs) and the difficulty of doing the latter for the immature technologies. It was also explained that costs are sometimes reported per household rather than unit of appliances as this is more practical for the model – however, for the appliances the units have been adjusted. Labour costs for installing equipment are part of equipment costs. Potential for smart appliances is currently considered only implicitly (smoothening load curve).

Renovations costs: PRIMES has information on national costs from different projects (e.g. ENTRANZE) but as data is not covering all MS, it was necessary to create groups of similar countries. Renovation costs shown do not cover the costs such as scaffolding or other preparatory works which indeed are real life costs and are included in PRIMES. PRIMES differentiates between income groups in terms of their disposable income and thus willingness to conduct renovations. The standards that come from EPBD implementation are reflected. The model does not aim to capture best practices but have figures representative of the practice across the EU

Industry: Currently the PRIMES technology assumptions are expressed per kW of useful energy required in production whereas industry would prefer to convert it into purchasing costs per unit of industrial output**.** Such a conversion can be done.

Heat pumps: PRIMES numbers are within the range but at the upper bounds particularly in the short term and PRIMES team would like to re-consider them. Hybrid technologies are currently not within the modelling scope, nevertheless back-up systems are considered when necessary (e.g. air source heat pumps with a gas heater). It is difficult to capture seasonal efficiency and variation in outside temperature. For air-source heat-pumps which are the most affected by outside temperatures, regional efficiencies are considered in PRIMES, and they generally are installed with back-up systems. PRIMES team use FEC not PEC (ex-post calculation is possible).

Solar thermal collectors: PRIMES represents them. The efficiency is calculated as per kWh thermal output (heat) divided by kWh thermal input (which is captured from the sun in the solar thermal collector). This is nevertheless adjusted on a country by country level, considering the average intensity of solar irradiation in each Member State.

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In the concluding remarks, the Commission thanked all participants in the meeting as well as those who engaged in bilateral exchanges stressing that it was a very useful exercise for the Commission striving for the best modelling tools and inputs and therefore, the most robust results of modelling. Next steps were explained:

(1) circulation of presentations from the meeting in the next days and

(2) publication of the final report from the project that will also feature final version of technology assumptions (as soon as technology assumptions can be finalised considering some feedback received only during the meeting and the need for further bilateral exchanges).

List of stakeholders who participated in the workshop (based on registrations) is presented in the table below.

Table 4: Stakeholders who participated in the workshop on 16 May 2018

1.	AEBIOM
2.	Amprion
3.	APPLiA
4.	Aurubis Belgium / ECI / Eurometaux
5.	BASF SE
6.	BDR THERMEA
7.	Bruegel
8.	BUSINESSEUROPE
9.	CEDEC
10.	CEEP
11.	CEFIC
12.	CEMBUREAU, the European Cement Association
13.	CEPI
14.	Cerame-Unie
15.	CEZ
16.	Chance for Buildings
17.	Climate Action Network (CAN) Europe
18.	CMI Energy
19.	COGEN
20.	E.V.V.E.
21.	ECOS
22.	EDP - ENERGIAS DE PORTUGAL
23.	EGEC-geothermal
24.	ENTSOG
25.	EPPSA
26.	ESTELA
27.	EUGINE - European Engine Power Plants Association
28.	EURELECTRIC
29.	Eurima
30.	EUROFUEL / INFORMAZOUT
31.	Eurogas
32.	EUROHEAT & POWER
33.	EUROMETAUX
34.	EuropaInsights
35.	European Aluminium
36.	European Copper Institute
37.	European Environmental Bureau
38.	European Heating Industry (EHI)
39.	European Steel Association (EUROFER)

40.	FECER - CEC
41.	Federation of Austrian Industries (IV)
42.	Federation of German Industries (BDI)
43.	Fern
44.	FORATOM
45.	Fraunhofer ISI
46.	FuelsEurope
47.	GAS NATURAL FENOSA
48.	GdW
49.	German Chemical Industry Association (VCI)
50.	Glass for Europe
51.	Global CCS Institute
52.	Greenpeace
53.	Heinrich Böll Foundation
54.	Hydrogen Europe
55.	IBTC
56.	Interel EU (on behalf of ChargePoint)
57.	International Union of Property Owners
58.	MaREI UCC
59.	MHPSE
60.	Ocean Energy Europe
61.	OpenExp
62.	Prognos AG
63.	Renewables Grid Initiative
64.	Robert Bosch GmbH
65.	ROCKWOOL International
66.	Saint-Gobain
67.	smartEn
68.	Solar Heat Europe
69.	SolarPower Europe
70.	The Coalition for Energy Savings
71.	The European Association for Storage of Energy - EASE a.i.s.b.l.
72.	Thüga Aktiengesellschaft
73.	thyssenkrupp AG
74.	TOTAL
75.	Tractebel
76.	Transport & Environment

77.	UN Environment - Finance Initiaitve
78.	Valmet Technologies
79.	VDMA
80.	Veolia
81.	Wind Europe
82.	WirtschaftsVereinigung Metalle e.V.
83.	WWF

9 Final Data Set

The final data set of PRIMES technology assumptions was modified based on the comments received and additional literature review. The final data set was internally reviewed and established in agreement with the European Commission and is presented in the next pages.

© E3Mlab - PRIMES model - 2018 Industry	Investment cost EUR/kW - the figures include learning by doing - kW measures plant's capacity in energy terms for the ordinary technology - the ratio kW per ton of output product (not shown in the table) differs by sector and by process type							Energy Efficiency Index (equal to 1 in 2015) - includes learning by doing - measured as useful output per energy input - the useful output is measured in physical units or a physical production proxy - an increase implies higher efficiency						
	Current	2030			Ultimate			Current	2030			Ultimate		
Technology		From		To	From		To		From		To	From		To
Horizontal processes														
Motors large scale	91	82	105	245	73	80	191	1.00	1.01	1.07	1.13	1.01	1.15	1.22
Motors midsize	114	102	232	588	91	179	330	1.00	1.02	1.06	1.13	1.03	1.15	1.21
Motors small	143	129	362	988	114	235	375	1.00	1.03	1.07	1.11	1.05	1.15	1.20
Cooling refrigeration	155	139	320	510	124	294	445	1.00	1.05	1.13	1.15	1.09	1.27	1.34
Lighting	220	201	454	545	120	128	145	1.00	1.16	1.30	1.34	1.26	1.39	1.49
Air Ventilation	215	193	254	350	172	198	279	1.00	1.09	1.26	1.35	1.15	1.44	1.66
Heating (low temperature)	135	121	278	578	118	194	440	1.00	1.07	1.18	1.30	1.15	1.29	1.43
Integrated steelworks														
Sintering	681	604	1000	1498	552	905	1179	1.00	1.06	1.19	1.25	1.10	1.28	1.35
Blast Furnace	1021	919	1170	1412	817	1019	1357	1.00	1.06	1.15	1.18	1.10	1.20	1.25
Process Furnace	378	340	612	985	302	518	728	1.00	1.04	1.11	1.15	1.06	1.18	1.25
Casting and Rolling	983	873	1037	1238	797	903	1197	1.00	1.02	1.06	1.08	1.04	1.09	1.12
Scrap processing - electric arc														
Smelters	958	863	1176	1377	765	1037	1374	1.00	1.06	1.17	1.22	1.10	1.24	1.30
Electric Arc	2458	2212	2592	3114	1966	2385	2990	1.00	1.04	1.10	1.12	1.06	1.13	1.16
Process Furnace	378	336	634	981	307	515	757	1.00	1.04	1.11	1.15	1.06	1.18	1.25
Casting and Rolling	894	804	1005	1216	715	884	1168	1.00	1.02	1.06	1.08	1.04	1.09	1.12
Alumina														
Digestion	575	518	915	1259	459	824	1081	1.00	1.03	1.09	1.12	1.06	1.14	1.19
Cyclones	280	249	927	1681	227	678	1129	1.00	1.04	1.11	1.15	1.06	1.17	1.22
Precipitation	225	203	386	552	180	280	452	1.00	1.04	1.10	1.12	1.07	1.14	1.19
Calcination	175	160	330	450	138	275	391	1.00	1.04	1.10	1.12	1.06	1.13	1.15

© E3Mlab - PRIMES model - 2018 Industry	Investment cost EUR/kW - the figures include learning by doing - kW measures plant's capacity in energy terms for the ordinary technology - the ratio kW per ton of output product (not shown in the table) differs by sector and by process type							Energy Efficiency Index (equal to 1 in 2015) - includes learning by doing - measured as useful output per energy input - the useful output is measured in physical units or a physical production proxy - an increase implies higher efficiency						
	Current	2030			Ultimate			Current	2030			Ultimate		
Technology		From		To	From		To		From		To	From		To
Primary Aluminium														
Alumina refining	391	347	716	1247	317	549	860	1.00	1.03	1.09	1.12	1.04	1.14	1.20
Smelting	534	481	1978	3457	427	1875	3048	1.00	1.05	1.15	1.20	1.08	1.21	1.25
Casting and Rolling	670	603	750	883	536	660	874	1.00	1.02	1.06	1.08	1.04	1.09	1.12
Primary Copper														
Pyrometallurgy	1820	1640	2189	2563	1454	1926	2562	1.00	1.05	1.13	1.16	1.09	1.18	1.22
Fire refining	790	711	878	1015	632	724	960	1.00	1.04	1.10	1.12	1.07	1.14	1.18
Electrorefining	2178	1986	2615	3205	1719	2321	3069	1.00	1.03	1.09	1.12	1.06	1.14	1.20
Secondary Aluminium														
Srap processing	293	260	654	1074	238	545	881	1.00	1.03	1.09	1.11	1.05	1.13	1.18
Melting Refining	567	511	945	1401	453	859	1147	1.00	1.03	1.09	1.12	1.04	1.13	1.16
Casting and Rolling	421	379	571	834	337	548	822	1.00	1.02	1.06	1.08	1.03	1.09	1.12
Ferro-alloys														
Pyrometallurgy	874	786	1187	1645	699	985	1531	1.00	1.05	1.13	1.16	1.09	1.18	1.22
Fire refining	771	703	1127	1548	609	872	1368	1.00	1.04	1.10	1.12	1.07	1.14	1.18
Electrorefining	1512	1361	1722	2300	1210	1525	2176	1.00	1.03	1.09	1.12	1.06	1.14	1.20
Casting and Rolling	655	582	908	1203	531	820	1042	1.00	1.02	1.07	1.09	1.03	1.10	1.12
Fertilizers														
Electric Processes	810	729	1187	1558	648	987	1308	1.00	1.03	1.08	1.10	1.05	1.12	1.15
Steam	136	121	447	797	110	345	676	1.00	1.03	1.08	1.10	1.04	1.12	1.16
Thermal Processes	333	295	875	1457	270	751	1154	1.00	1.04	1.15	1.22	1.07	1.24	1.30
Petrochemicals														
Electric Processes	845	761	1137	1587	676	1021	1337	1.00	1.03	1.08	1.10	1.05	1.12	1.15

© E3Mlab - PRIMES model - 2018 Industry	Investment cost EUR/kW - the figures include learning by doing - kW measures plant's capacity in energy terms for the ordinary technology - the ratio kW per ton of output product (not shown in the table) differs by sector and by process type							Energy Efficiency Index (equal to 1 in 2015) - includes learning by doing - measured as useful output per energy input - the useful output is measured in physical units or a physical production proxy - an increase implies higher efficiency						
	Current	2030			Ultimate			Current	2030			Ultimate		
Technology		From		To	From		To		From		To	From		To
Steam	136	123	410	874	109	394	664	1.00	1.03	1.08	1.10	1.04	1.12	1.16
Thermal Processes	423	381	818	1498	339	798	1407	1.00	1.05	1.16	1.22	1.09	1.24	1.30
Inorganic and basic chemicals														
Electric Processes	681	613	953	1428	544	862	1128	1.00	1.02	1.07	1.10	1.03	1.11	1.12
High Enthlapy Heat	136	121	748	1317	110	345	672	1.00	1.03	1.08	1.10	1.04	1.12	1.16
Thermal Processes	333	299	748	1317	266	697	1297	1.00	1.05	1.16	1.22	1.09	1.24	1.30
Pulp														
Pulping	635	572	945	1281	508	774	1115	1.00	1.04	1.10	1.13	1.07	1.14	1.18
Refining bleaching	529	476	835	1183	423	725	1029	1.00	1.04	1.10	1.12	1.06	1.14	1.19
Drying and Separation	857	761	1159	1789	695	1005	1677	1.00	1.05	1.14	1.18	1.09	1.20	1.25
Papermaking	571	514	1274	2016	457	1179	1670	1.00	1.05	1.15	1.20	1.09	1.23	1.33
Paper making														
Pulping	529	476	846	1105	423	666	1054	1.00	1.03	1.08	1.10	1.06	1.11	1.16
Refining bleaching	287	262	603	978	227	554	853	1.00	1.04	1.10	1.12	1.06	1.14	1.17
Drying and Separation	514	463	850	1245	411	768	1003	1.00	1.05	1.14	1.18	1.09	1.20	1.25
Cement														
Milling	308	281	529	853	243	413	639	1.00	1.03	1.06	1.07	1.04	1.08	1.10
Prehating Drying	190	169	330	845	154	303	632	1.00	1.02	1.05	1.11	1.04	1.10	1.15
Cement Kiln	373	336	587	918	299	399	776	1.00	1.03	1.06	1.08	1.05	1.09	1.12
Grinding	385	342	795	1260	312	592	879	1.00	1.03	1.08	1.10	1.06	1.12	1.15
Basic Glass														
Batch	350	315	646	1235	280	488	766	1.00	1.04	1.09	1.12	1.06	1.15	1.22
Melting Glass	420	373	508	778	341	433	595	1.00	1.03	1.07	1.10	1.04	1.13	1.19

© E3Mlab - PRIMES model - 2018 Industry	Investment cost EUR/kW - the figures include learning by doing - kW measures plant's capacity in energy terms for the ordinary technology - the ratio kW per ton of output product (not shown in the table) differs by sector and by process type							Energy Efficiency Index (equal to 1 in 2015) - includes learning by doing - measured as useful output per energy input - the useful output is measured in physical units or a physical production proxy - an increase implies higher efficiency						
	Current	2030			Ultimate			Current	2030			Ultimate		
Technology		From		To	From		To		From		To	From		To
Forehearth	420	378	673	1188	336	549	797	1.00	1.03	1.10	1.13	1.06	1.16	1.22
Annealing	580	522	704	938	464	627	825	1.00	1.02	1.07	1.10	1.04	1.11	1.16
Ceramics														
Milling Calcinating	821	729	916	1158	666	803	1059	1.00	1.03	1.07	1.09	1.04	1.10	1.12
Drying and Separation	205	184	364	582	164	299	432	1.00	1.04	1.11	1.14	1.06	1.16	1.21
Firing	350	315	588	1014	280	457	701	1.00	1.03	1.10	1.13	1.06	1.16	1.22
Treatment	327	294	439	672	261	397	516	1.00	1.02	1.07	1.10	1.04	1.11	1.16
Other non metallic minerals														
Drying	158	143	383	693	127	232	453	1.00	1.05	1.10	1.13	1.09	1.15	1.22
Milling	293	264	459	782	234	349	543	1.00	1.03	1.08	1.10	1.05	1.13	1.19
Kiln	360	324	463	682	288	352	533	1.00	1.05	1.08	1.10	1.07	1.12	1.19
Grinding	293	268	438	619	232	349	518	1.00	1.03	1.09	1.11	1.06	1.12	1.17
Food drink and tobacco														
Refrigeration	232	209	758	1454	186	542	813	1.00	1.05	1.19	1.27	1.09	1.29	1.34
Drying and Separation	590	538	1548	2712	466	875	1467	1.00	1.11	1.28	1.39	1.18	1.45	1.67
Steam	227	201	560	1094	184	459	732	1.00	1.02	1.07	1.10	1.04	1.12	1.15
Direct Heat	681	613	790	1225	544	635	912	1.00	1.04	1.09	1.12	1.07	1.15	1.22
Textiles and leather														
Machinery	643	586	1406	2166	507	986	1247	1.00	1.03	1.09	1.12	1.06	1.13	1.15
Steam processing	681	613	911	1364	544	825	1151	1.00	1.02	1.07	1.10	1.04	1.12	1.16
Drying	735	662	1247	1795	587	1011	1477	1.00	1.05	1.12	1.15	1.09	1.18	1.25
Finishing	635	564	1138	1822	515	867	1346	1.00	1.03	1.08	1.10	1.06	1.12	1.17
Engineering and equipment industry														

© E3Mlab - PRIMES model - 2018 Industry	Investment cost EUR/kW - the figures include learning by doing - kW measures plant's capacity in energy terms for the ordinary technology - the ratio kW per ton of output product (not shown in the table) differs by sector and by process type							Energy Efficiency Index (equal to 1 in 2015) - includes learning by doing - measured as useful output per energy input - the useful output is measured in physical units or a physical production proxy - an increase implies higher efficiency						
	Current	2030			Ultimate			Current	2030			Ultimate		
Technology		From		To	From		To		From		To	From		To
Refrigeration	232	209	488	781	186	448	679	1.00	1.05	1.19	1.27	1.09	1.28	1.34
Machinery	643	579	1417	2132	514	1005	1521	1.00	1.03	1.09	1.12	1.06	1.13	1.15
Steam processing	635	572	902	1202	508	746	1011	1.00	1.02	1.06	1.08	1.04	1.09	1.12
Foundries	718	638	800	1038	582	703	924	1.00	1.03	1.07	1.09	1.05	1.10	1.12
Other industries														
Machinery	643	571	1346	2050	521	946	1241	1.00	1.03	1.09	1.12	1.06	1.13	1.27
Steam processing	227	204	617	1096	181	459	761	1.00	1.02	1.07	1.10	1.04	1.12	1.16
Drying Wood Rubber Plastics	650	593	954	1280	513	859	1110	1.00	1.03	1.09	1.12	1.06	1.14	1.18
Refrigeration	232	209	855	1559	186	543	790	1.00	1.05	1.19	1.27	1.09	1.29	1.34
Fire heaters	681	613	743	1246	544	712	1066	1.00	1.02	1.06	1.10	1.04	1.11	1.14

Notes

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In the table above, which shows a summary of the model's data, there is matching between purchasing costs and efficiency rates over time.

b) The first column of the data refers to an estimation of current costs and efficiencies. The second column refers to a technology category which is the most cost-efficient in the medium term, as the more efficient technologies are not yet fully mature. The third column refers to the ultimate possibilities of the most advanced technology, as included in the model's dataset.

© E3Mlab - PRIMES model - 2018	Purchasing cost							Efficiency						
Domestic	Current	2030			Ultimate			Current	2030			Ultimate		
		From		To	From		To		From		To	From		To
	in EUR/appl							kWh/appliance						
Electric Appliances														
Dryers	554	495	685	803	387	680	791	316	280	226	214	272	175	144
Dishwashers	489	470	543	765	436	539	753	249	235	214	185	232	200	133
Refrigerators and freezers	574	547	733	867	496	728	854	219	215	171	152	210	115	72
Washing machines	585	539	604	795	454	538	783	212	198	176	144	195	155	84
	in EUR/appl							kWh/Household						
Lighting	5	4	6	11	2	5	11	43	38	31	25	37	26	14
	Current	2030			Ultimate			Current	2030			Ultimate		
		From		To	From		To		From		To	From		To
Technology	in EUR/kW							%						
Cooking														
Cooker, oven and hobs (electric)	183	171	187	260	150	180	231	0.79	0.80	0.82	0.87	0.80	0.87	0.93
Cooker, oven and hobs (gas)	191	179	195	258	157	188	240	0.42	0.42	0.44	0.45	0.43	0.46	0.47
Space Heating														
Boilers Gas	157	154	180	220	148	179	217	0.79	0.81	0.85	0.87	0.81	0.89	0.94
Boilers condensing Gas	195	191	224	273	171	210	237	0.87	0.89	0.93	0.96	0.90	0.98	1.03
Boilers Oil	162	158	185	226	153	174	223	0.77	0.79	0.83	0.85	0.79	0.87	0.94
Boilers condensing Oil	201	196	230	281	176	216	244	0.85	0.87	0.92	0.94	0.88	0.97	1.02
Wood stoves or Boiler pellets	410	401	471	610	373	442	590	0.72	0.74	0.77	0.79	0.74	0.79	0.81
Heat Pump Air														
in South Countries								2.65	2.86	3.29	3.58	2.88	4.19	4.90
in Middle South countries								2.38	2.56	2.95	3.21	2.58	3.75	4.39
in Middle North countries	784	603	835	1080	267	673	1030	2.17	2.33	2.69	2.93	2.35	3.42	4.00
in North countries								1.98	2.13	2.45	2.67	2.14	3.12	3.65
Heat Pump Water	1036	847	1104	1428	487	960	1287	3.30	3.55	4.10	4.52	3.58	4.98	5.73
Heat Pump Ground	1695	1385	1805	2335	1203	1570	1774	3.60	3.88	4.47	4.93	3.90	5.43	5.94
Heat Pump Gas	1176	904	1194	1512	400	942	1339	1.30	1.40	1.61	1.78	1.41	1.96	2.14
Electric Resistance (e.g. convectors)	60	60	76	80	60	69	79	0.99	0.99	1.00	1.00	0.99	1.00	1.00
Gas individual (autonomous heater)	134	133	168	221	132	161	218	0.82	0.87	0.91	0.93	0.88	0.95	1.03
Solar Thermal	1250	1158	1383	1635	955	1200	1347	0.58	0.59	0.61	0.62	0.60	0.63	0.65
CHP ICE	2800	2345	2840	3145	1945	2450	2975	0.65	0.66	0.68	0.69	0.66	0.70	0.71

© E3Mlab - PRIMES model - 2018 Domestic	Purchasing cost							Efficiency						
	Current	2030			Ultimate			Current	2030			Ultimate		
		From		To	From		To		From		To	From		To
Technology	in EUR/kW							%						
CHP micro CCGT	4000	3631	4208	4825	2945	3825	4232	0.60	0.63	0.66	0.69	0.63	0.72	0.75
CHP Fuel Cell	10000	8456	9945	11467	3502	4576	5600	0.65	0.69	0.71	0.73	0.71	0.73	0.75
District heating	91	88	107	133	83	100	131	0.72	0.73	0.74	0.75	0.74	0.76	0.78
Water Heating														
Water heating boiler (diesel)	342	334	392	479	323	390	492	0.70	0.72	0.75	0.77	0.72	0.77	0.80
Water heating boiler (electricity)	110	109	122	149	92	110	140	0.90	0.91	0.93	0.95	0.92	0.96	0.99
Water heating boiler (natural gas)	188	183	224	264	174	207	260	0.77	0.81	0.86	0.88	0.82	0.90	0.99
Solar collector	254	240	290	343	215	288	338	0.58	0.59	0.61	0.63	0.60	0.63	0.65
Water heating heat pump	318	311	352	382	298	300	319	2.40	2.60	2.88	3.01	2.64	3.08	3.60
Water heating combined with district heating	85	82	94	117	68	76	92	0.72	0.73	0.74	0.75	0.74	0.76	0.78
Air Conditioning														
Electric Air conditioning	195	189	262	353	177	250	348	2.34	2.42	2.93	3.34	2.56	3.75	4.32
Electric Air conditioning central	434	421	584	786	395	557	775	2.50	2.59	3.13	3.57	2.73	3.67	4.34

Notes

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c) Purchasing Costs are total acquisition costs, where for geothermal heat pumps also the drilling costs are included.

d) The efficiencies indicated are nominal efficiencies and not seasonal energy efficiencies.

e) Back-up systems are considered in the model, and where applicable are part of the purchasing costs and reflected in the average efficiency rates. This explains the difference of heat pump efficiencies across regions in Europe.

f) The efficiency rates for cogeneration (CHP) systems refers to both electricity and heat outputs.

g) In case of combined space and water heaters, the purchasing costs for water heating apply to the additional purchasing costs to cover water heating.

© E3Mlab - PRIMES model - 2018 Services	Purchasing cost							Efficiency						
	Current	2030			Ultimate			Current	2030			Ultimate		
		From		To	From		To		From		To	From		To
Technology	EUR/kW							kWh/appliance						
Electric Appliances														
Office lighting	9	8	12	23	4	12	22	16.97	16.47	14.98	11.79	16.38	10.98	5.59
	EUR/kW							%						
Space Heating														
Large scale Boilers	118	115	135	165	105	127	163	0.79	0.81	0.85	0.87	0.81	0.89	0.94
Large scale Boilers condensing	156	153	179	219	136	167	205	0.87	0.89	0.93	0.96	0.90	0.98	1.03
Heat Pump Air														
in South Countries								2.65	2.86	3.29	3.58	2.88	4.19	4.90
in Middle South countries								2.38	2.56	2.95	3.21	2.58	3.75	4.39
in Middle North countries	549	422	585	756	187	471	669	2.17	2.33	2.69	2.93	2.35	3.42	4.00
in North countries								1.98	2.13	2.45	2.67	2.14	3.12	3.65
Heat Pump Water	725	593	773	999	341	672	837	3.30	3.55	4.10	4.52	3.58	4.98	5.73
Heat Pump Ground	1187	970	1264	1635	842	1099	1153	3.60	3.88	4.47	4.93	3.90	5.43	5.94
District heating	73	60	78	101	72	92	105	0.72	0.73	0.74	0.75	0.74	0.76	0.78
Air Conditioning														
Air-conditioning (electricity)	137	126	177	229	105	160	226	2.75	2.90	3.36	3.72	2.94	4.09	5.28
Air-conditioning (natural gas)	578	501	524	574	335	351	388	1.30	1.32	1.48	1.60	1.35	1.71	2.14
Air-conditioning (heat)	155	149	163	187	144	151	154	0.71	0.72	0.73	0.74	0.73	0.75	0.77

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g) In case of combined space and water heaters, the purchasing costs for water heating apply to the additional purchasing costs to cover water heating.

© E3Mlab - PRIMES model - 2018 Renovation for residential buildings				
Regions	Type of renovation measure (building envelope refurbishment)	Energy savings (%)	Investment Costs (Euro/Household)	Investment Costs (Euro/square meter)
Centre/West	Light renovation (light windows)	12%	5565	77
	Light renovation (med. windows)	16%	6115	85
	Light renovation (med. windows,light wall)	44%	10449	145
	Light renovation (med. windows, light wall/roof)	61%	13757	191
	Medium renovation (med. windows, med.wall/roof/basement)	69%	16505	230
	Medium renovation (deep windows, med.wall/roof/basement)	73%	18679	260
	Deep renovation (deep. windows, med.wall/roof/basement)	76%	21204	295
	Deep renovation (deep. windows, deep wall/roof/basement)	78%	23932	333
North	Light renovation (light windows)	8%	2797	33
	Light renovation (med. windows)	22%	6814	80
	Light renovation (med. windows,light wall)	37%	11164	132
	Light renovation (med. windows, light wall/roof)	55%	15076	178
	Medium renovation (med. windows, med.wall/roof/basement)	67%	17221	203
	Medium renovation (deep windows, med.wall/roof/basement)	74%	19164	226
	Deep renovation (deep. windows, med.wall/roof/basement)	82%	22465	265
	Deep renovation (deep. windows, deep wall/roof/basement)	87%	25702	303
South	Light renovation (light windows)	10%	4142	58
	Light renovation (med. windows)	16%	4675	65
	Light renovation (med. windows,light wall)	36%	7226	101
	Light renovation (med. windows, light wall/roof)	49%	10368	144
	Medium renovation (med. windows, med.wall/roof/basement)	56%	13128	183
	Medium renovation (deep windows, med.wall/roof/basement)	65%	16169	225
	Deep renovation (deep. windows, med.wall/roof/basement)	69%	17741	247
	Deep renovation (deep. windows, deep wall/roof/basement)	75%	20603	287
East	Light renovation (light windows)	8%	2832	41
	Light renovation (med. windows)	13%	3420	50
	Light renovation (med. windows,light wall)	34%	5620	82
	Light renovation (med. windows, light wall/roof)	48%	7155	105
	Medium renovation (med. windows, med.wall/roof/basement)	56%	8563	125
	Medium renovation (deep windows, med.wall/roof/basement)	62%	10096	148
	Deep renovation (deep. windows, med.wall/roof/basement)	65%	11332	166
	Deep renovation (deep. windows, deep wall/roof/basement)	69%	13233	194

Notes

a) Investment costs are the energy related expenditures needed to implement the indicated deepness level of building renovation, excluding usual renovation expenditures needed for other purposes (structure, finishing materials, decoration etc.)

b) The energy savings rate refers to a typical building as in the current stock of existing buildings (not savings in new constructions, which follow the buildings codes' insulation standards)

c) The data in the table are a summary of the data in the model which are more detailed and include several house types, house ages and geographical categories

©E3Mlab PRIMES model-2018 Power generation technologies	Overnight Investment Costs in a greenfield site, excluding financial costs during construction time				Fixed Operation and Maintenance costs, annually				Variable non fuel cost				Electrical Efficiency (net) in optimal load operation				Self-Consumption of electricity			
	EUR/kW				EUR/kW				EUR/MWh				ratio				%			
	2020	2030	2040	2050	2020	2030	2040	2050	2020	2030	2040	2050	2020	2030	2040	2050	2020	2030	2040	2050
Steam Turbine Coal Conventional	1600	1600	1600	1600	25.6	25.6	25.6	25.6	2.40	2.40	2.40	2.40	0.38	0.42	0.43	0.43	0.09	0.09	0.09	0.09
Steam Turbine Lignite Conventional	1800	1800	1800	1800	32.5	32.5	32.5	32.5	3.00	3.00	3.00	3.00	0.37	0.38	0.37	0.37	0.12	0.12	0.12	0.12
Steam Turbine Coal Supercritical	1700	1700	1700	1700	41.5	35.7	31.7	30.9	3.63	3.51	3.38	3.35	0.45	0.46	0.47	0.47	0.07	0.07	0.07	0.07
Steam Turbine Lignite Supercritical	2000	2000	2000	2000	46.8	42.4	39.4	38.8	4.16	4.01	2.85	2.70	0.41	0.42	0.43	0.44	0.10	0.10	0.10	0.10
Fluidized Bed Combustion Coal	1900	1900	1900	1900	35.2	35.2	35.2	35.2	2.83	2.83	2.83	2.83	0.40	0.41	0.42	0.42	0.06	0.06	0.06	0.06
Fluidized Bed Combustion Lignite	2280	2280	2280	2280	42.2	42.2	42.2	42.2	4.40	4.40	4.40	4.40	0.38	0.39	0.40	0.40	0.12	0.12	0.12	0.12
Integrated Gasification Combined Cycle Coal	2400	2300	2250	2150	46.8	44.9	43.9	41.9	5.16	4.96	4.78	4.60	0.46	0.48	0.49	0.50	0.09	0.09	0.09	0.09
Gas Turbine Combined Cycle Gas Conventional	720	690	660	640	15.0	15.0	15.0	15.0	2.31	2.31	2.31	2.31	0.57	0.58	0.59	0.59	0.03	0.03	0.03	0.03
Gas Turbine Combined Cycle Gas Advanced	820	770	750	750	15.0	15.0	15.0	15.0	1.99	1.90	1.81	1.73	0.60	0.61	0.62	0.63	0.02	0.02	0.02	0.02
Steam Turbine Fuel Oil Conventional	1200	1200	1200	1200	20.7	20.7	20.7	20.7	2.76	2.76	2.76	2.76	0.35	0.35	0.35	0.35	0.05	0.05	0.05	0.05
Gas turbine with heat recovery	800	700	650	600	15.0	15.0	15.0	15.0	3.50	3.50	3.50	3.50	0.35	0.37	0.39	0.40	0.01	0.01	0.01	0.01
Very small scale Gas Plant	939	921	917	913	23.5	20.0	18.8	17.6	0.71	0.71	0.71	0.71	0.35	0.36	0.36	0.37	0.01	0.01	0.01	0.01
Pulverised Lignite Suprcritical CCS post combustion	3600	3420	3250	3200	68.6	65.0	61.6	60.6	6.24	6.02	4.28	4.04	0.32	0.33	0.34	0.35	0.33	0.30	0.28	0.28
Integrated Gasification Coal CCS pre combustion	3550	3350	3250	3150	69.8	65.9	63.9	61.9	7.74	7.44	7.17	6.91	0.37	0.39	0.40	0.41	0.32	0.27	0.25	0.25
Integrated Gasification Lignitel CCS pre combustion	3950	3750	3650	3550	77.6	73.6	71.6	69.6	6.38	6.15	5.95	5.75	0.34	0.37	0.38	0.39	0.35	0.29	0.26	0.26
Pulverised Coal Suprcritical CCS oxyfuel	3400	3150	2890	2850	75.5	64.7	55.5	53.9	6.06	5.86	5.64	5.59	0.36	0.37	0.38	0.38	0.32	0.27	0.24	0.24
Pulverised Lignite Suprcritical CCS oxyfuel	3800	3550	3350	3300	72.6	67.6	63.6	62.6	6.94	6.70	4.76	4.50	0.32	0.33	0.34	0.35	0.34	0.28	0.25	0.25
Gas combined cycle CCS post combustion	1750	1625	1500	1500	41.0	38.2	35.0	34.3	3.10	2.99	2.88	2.78	0.43	0.46	0.48	0.49	0.22	0.18	0.16	0.16
Gas combined cycle CCS oxyfuel	2013	1820	1650	1628	46.3	42.1	38.0	36.8	3.45	3.34	3.20	3.07	0.40	0.46	0.49	0.50	0.27	0.19	0.15	0.14
Steam Turbine Biomass	2000	1800	1700	1700	47.5	40.1	39.2	38.4	3.56	3.56	3.56	3.56	0.35	0.39	0.40	0.40	0.10	0.10	0.10	0.10

©E3Mlab PRIMES model-2018 Power generation technologies	Overnight Investment Costs in a greenfield site, excluding financial costs during construction time				Fixed Operation and Maintenance costs, annually				Variable non fuel cost				Electrical Efficiency (net) in optimal load operation				Self-Consumption of electricity			
	EUR/kW				EUR/kW				EUR/MWh				ratio				%			
	2020	2030	2040	2050	2020	2030	2040	2050	2020	2030	2040	2050	2020	2030	2040	2050	2020	2030	2040	2050
Solid Conventional																				
Steam Turbine Biomass Solid Conventional w. CCS	3800	3450	3090	3000	81.5	69.1	63.0	61.4	5.99	5.91	5.82	5.80	0.27	0.31	0.32	0.32	0.34	0.29	0.27	0.26
Biogas Plant with Heat recovery	1300	1250	1150	1050	28.8	24.3	23.8	23.3	2.56	2.56	2.56	2.56	0.38	0.38	0.39	0.39	0.03	0.03	0.03	0.03
Small Waste burning plant	2030	2013	2005	1997	52.3	44.5	41.8	39.2	0.82	0.82	0.82	0.82	0.33	0.34	0.34	0.34	0.01	0.01	0.01	0.01
Biomass Gasification CC	4380	3600	3250	3150	27.1	22.9	22.4	21.9	2.76	2.76	2.76	2.76	0.37	0.43	0.47	0.48	0.09	0.09	0.09	0.09
MBW incinerator CHP	5630	5240	4870	4540	40.5	32.2	28.3	27.6	2.84	2.65	2.46	2.84	0.31	0.34	0.37	0.42	0.10	0.10	0.10	0.10
Nuclear III gen. (incl. economies of scale)	5300	5050	4750	4700	120	115	108	105.0	6.40	7.40	7.60	7.80	0.38	0.38	0.38	0.38	0.05	0.05	0.05	0.05
Nuclear III gen. (no economies of scale)	6000	6000	6000	6000	120	115	108	105.0	6.40	7.40	7.60	7.80	0.38	0.38	0.38	0.38	0.05	0.05	0.05	0.05
Fuel Cell Gas (large scale)	4447	3090	2871	2668	66.7	46.4	43.1	40.0	1.04	1.04	1.04	1.04	0.68	0.68	0.68	0.69	0	0	0	0
Fuel Cell Gas (small scale)	13000	6000	4500	3090	66.7	46.4	43.1	40.0	1.04	1.04	1.04	1.04	0.68	0.68	0.68	0.69	0	0	0	0
Wind onshore-Low	1395	1261	1110	1043	13.0	13.0	13.0	12.0	0.15	0.15	0.15	0.15	1.00	1.00	1.00	1.00	0	0	0	0
Wind onshore-Medium	1295	1161	1010	943	14.0	14.0	13.0	12.0	0.18	0.18	0.18	0.18	1.00	1.00	1.00	1.00	0	0	0	0
Wind onshore-high	1080	988	840	782	18.0	18.0	17.0	16.0	0.23	0.23	0.23	0.23	1.00	1.00	1.00	1.00	0	0	0	0
Wind onshore-very high	1200	1066	915	848	22.0	21.0	21.0	20.0	0.25	0.25	0.25	0.25	1.00	1.00	1.00	1.00	0	0	0	0
Wind small scale rooftop	2850	1850	1750	1650	25.0	21.0	18.0	17.0	0.10	0.10	0.10	0.10	1.00	1.00	1.00	1.00	0	0	0	0
Wind offshore - low potential	2223	1804	1763	1749	33.0	27.0	26.0	26.0	0.39	0.39	0.39	0.39	1.00	1.00	1.00	1.00	0	0	0	0
Wind offshore - medium potential	2778	2048	1929	1891	42.0	31.0	29.0	28.0	0.39	0.39	0.39	0.39	1.00	1.00	1.00	1.00	0	0	0	0
Wind offshore - high potential	3206	2454	2292	2240	48.0	37.0	35.0	34.0	0.39	0.39	0.39	0.39	1.00	1.00	1.00	1.00	0	0	0	0
Wind offshore - very high (remote)	3684	2843	2689	2640	55.0	43.0	40.0	39.0	0.39	0.39	0.39	0.39	1.00	1.00	1.00	1.00	0	0	0	0
Solar PV low potential	721	690	567	495	22.0	15.0	13.0	11.0	0.00	0.00	0.00	0.00	1.00	1.00	1.00	1.00	0	0	0	0
Solar PV medium potential	710	663	519	454	12.6	10.8	10.0	9.2	0.00	0.00	0.00	0.00	1.00	1.00	1.00	1.00	0	0	0	0
Solar PV high potential	700	645	477	431	13.0	12.2	11.5	10.8	0.00	0.00	0.00	0.00	1.00	1.00	1.00	1.00	0	0	0	0
Solar PV very high potential	690	627	455	407	15.9	13.5	12.1	10.8	0.00	0.00	0.00	0.00	1.00	1.00	1.00	1.00	0	0	0	0

©E3Mlab PRIMES model-2018 Power generation technologies	Overnight Investment Costs in a greenfield site, excluding financial costs during construction time				Fixed Operation and Maintenance costs, annually				Variable non fuel cost				Electrical Efficiency (net) in optimal load operation				Self-Consumption of electricity			
	EUR/kW				EUR/kW				EUR/MWh				ratio				%			
	2020	2030	2040	2050	2020	2030	2040	2050	2020	2030	2040	2050	2020	2030	2040	2050	2020	2030	2040	2050
Solar PV small scale rooftop	1435	930	745	610	24.0	17.0	15.0	13.0	0.00	0.00	0.00	0.00	1.00	1.00	1.00	1.00	0	0	0	0
Solar Thermal with 8 hours storage	5500	4237	3437	3075	121.0	113.0	99.0	77.0	0.10	0.10	0.10	0.10	1.00	1.00	1.00	1.00	0	0	0	0
Tidal and waves	6100	3100	2025	1975	39.6	33.3	28.0	23.5	0.10	0.10	0.10	0.10	1.00	1.00	1.00	1.00	0	0	0	0
Lakes	3000	3000	3000	3000	25.5	25.5	25.5	25.5	0.32	0.32	0.32	0.32	1.00	1.00	1.00	1.00	0	0	0	0
Run of River	2450	2400	2350	2300	8.9	8.2	8.2	8.1	0.00	0.00	0.00	0.00	1.00	1.00	1.00	1.00	0	0	0	0
Geothermal High Enthalpy	3901	3198	2897	2613	90.0	95.0	100.0	105.0	0.32	0.32	0.32	0.32	0.10	0.10	0.10	0.10	0	0	0	0
Geothermal Medium Enthalpy	4970	4586	3749	3306	95.0	95.0	92.0	92.0	0.32	0.32	0.32	0.32	0.10	0.10	0.10	0.10	0	0	0	0
Boilers Electricity	344	333	333	333	5.0	5.0	5.0	5.0	0.50	0.50	0.50	0.50	1.00	1.00	1.00	1.00	0	0	0	0
district heating Boilers Gas	137	158	158	158	1.2	1.2	1.2	1.2	0.44	0.44	0.44	0.44	0.89	0.96	0.96	0.96	0	0	0	0
district heating Boilers Fuel Oil	229	264	264	264	1.3	1.3	1.3	1.3	0.53	0.53	0.53	0.53	0.86	0.95	0.95	0.95	0	0	0	0
district heating Boilers Biomass	791	850	850	850	1.3	1.3	1.3	1.3	1.41	1.41	1.41	1.41	0.82	0.90	0.90	0.90	0	0	0	0
district heating Boilers Coal	351	405	405	405	1.3	1.3	1.3	1.3	1.41	1.41	1.41	1.41	0.82	0.90	0.90	0.90	0	0	0	0
district heating Boilers Lignite	419	483	483	483	1.4	1.4	1.4	1.4	1.57	1.57	1.57	1.57	0.79	0.90	0.90	0.90	0	0	0	0
MBW incinerator district heating	961	948	936	923	16.6	16.2	15.7	15.3	1.41	1.41	1.41	1.41	0.82	0.90	0.90	0.90	0	0	0	0
District Heating Electricity	850	850	850	850	1.1	1.1	1.1	1.1	0.50	0.50	0.50	0.50	0.99	0.99	0.99	0.99	0	0	0	0
District Heating Geothermal	2321	2209	2209	2209	77.8	80.4	88.7	97.6	1.14	1.22	1.35	1.50	0.10	0.10	0.10	0.10	0	0	0	0
District Heating Heat Pump	3019	2806	2806	2806	5.0	3.7	3.7	3.7	0.00	0.00	0.00	0.00	2.50	3.33	3.33	3.33	0	0	0	0
District Heating Solar	970	910	910	910	10.0	10.0	10.0	10.0	0.70	0.70	0.70	0.70	1.00	1.00	1.00	1.00	0	0	0	0
Industrial Boilers Coal	340	373	373	373	1.3	1.3	1.3	1.3	1.41	1.41	1.41	1.41	0.82	0.92	0.92	0.92	0	0	0	0
Industrial Boilers Lignite	406	445	445	445	1.4	1.4	1.4	1.4	1.57	1.57	1.57	1.57	0.79	0.92	0.92	0.92	0	0	0	0
Industrial Boilers Gas	114	124	124	124	1.2	1.2	1.2	1.2	0.44	0.44	0.44	0.44	0.89	0.98	0.98	0.98	0	0	0	0
Industrial Boilers Fuel Oil	222	243	243	243	1.3	1.3	1.3	1.3	0.53	0.53	0.53	0.53	0.86	0.96	0.96	0.96	0	0	0	0
Industrial Boilers Biomass	737	807	807	807	1.3	1.3	1.3	1.3	1.41	1.41	1.41	1.41	0.82	0.90	0.90	0.90	0	0	0	0

©E3Mlab PRIMES model-2018 Power generation technologies (cont'd)	Technical Lifetime	Capacity Factor (equivalent full load operation) %				Annual growth of O&M costs with plant age
	Years	2020	2030	2040	2050	
Steam Turbine Coal Conventional	40	0.80	0.80	0.80	0.80	2.87%
Steam Turbine Lignite Conventional	40	0.80	0.80	0.80	0.80	2.59%
Steam Turbine Coal Supercritical	40	0.80	0.80	0.80	0.80	2.46%
Steam Turbine Lignite Supercritical	40	0.80	0.80	0.80	0.80	2.33%
Fluidized Bed Combustion Coal	40	0.80	0.80	0.80	0.80	2.54%
Fluidized Bed Combustion Lignite	40	0.80	0.80	0.80	0.80	2.54%
Integrated Gasification Combined Cycle Coal	30	0.80	0.80	0.80	0.80	2.28%
Gas Turbine Combined Cycle Gas Conventional	30	0.35	0.35	0.35	0.35	1.65%
Gas Turbine Combined Cycle Gas Advanced	30	0.35	0.35	0.35	0.35	1.62%
Steam Turbine Fuel Oil Conventional	40	0.40	0.40	0.40	0.40	2.70%
Gas turbine with heat recovery	25	0.24	0.24	0.24	0.24	0.91%
Very small scale Gas Plant	20	0.30	0.30	0.30	0.30	0.41%
Pulverised Lignite Suprcritical CCS post combustion	40	0.80	0.80	0.80	0.80	2.45%
Integrated Gasification Coal CCS pre combustion	30	0.80	0.80	0.80	0.80	2.25%
Integrated Gasification Lignitel CCS pre combustion	30	0.80	0.80	0.80	0.80	2.25%
Pulverised Coal Suprcritical CCS oxyfuel	40	0.80	0.80	0.80	0.80	2.41%
Pulverised Lignite Suprcritical CCS oxyfuel	40	0.80	0.80	0.80	0.80	2.45%
Gas combined cycle CCS post combustion	30	0.80	0.80	0.80	0.80	1.92%
Gas combined cycle CCS oxyfuel	30	0.80	0.80	0.80	0.80	1.97%
Steam Turbine Biomass Solid Conventional	40	0.80	0.80	0.80	0.80	2.91%
Steam Turbine Biomass Solid Conventional w. CCS	40	0.80	0.80	0.80	0.80	2.41%
Biogas Plant with Heat recovery	25	0.20	0.20	0.20	0.20	1.60%
Small Waste burning plant	20	0.10	0.10	0.10	0.10	0.73%
Biomass Gasification CC	30	0.70	0.70	0.70	0.70	7.20%
MBW incinerator CHP	35	0.65	0.65	0.65	0.65	4.46%
Nuclear III gen. (incl. economies of scale)	60	0.85	0.85	0.85	0.85	1.76%
Nuclear III gen. (no economies of scale)	60	0.85	0.85	0.85	0.85	1.76%
Fuel Cell Gas (large scale)	20	0.28	0.28	0.28	0.28	2.61%
Fuel Cell Gas (small scale)	20	0.28	0.28	0.28	0.28	3.99%

©E3Mlab PRIMES model-2018 Power generation technologies (cont'd)	Technical Lifetime	Capacity Factor (equivalent full load operation) %				Annual growth of O&M costs with plant age
	Years	2020	2030	2040	2050	
Wind onshore-Low	25	0.20	0.20	0.21	0.22	5.00%
Wind onshore-Medium	25	0.20	0.23	0.24	0.25	5.00%
Wind onshore-high	25	0.26	0.29	0.29	0.31	5.00%
Wind onshore-very high	25	0.36	0.40	0.41	0.42	5.00%
Wind small scale rooftop	20	0.19	0.21	0.23	0.25	5.00%
Wind offshore[4] - low potential	25	0.28	0.32	0.39	0.45	5.00%
Wind offshore - medium potential	25	0.33	0.35	0.44	0.52	5.00%
Wind offshore - high potential	25	0.39	0.41	0.49	0.56	5.00%
Wind offshore - very high (remote)	25	0.47	0.47	0.53	0.59	5.00%
Solar PV low potential	25	0.10	0.10	0.10	0.10	5.00%
Solar PV medium potential	25	0.12	0.13	0.14	0.15	5.00%
Solar PV high potential	25	0.16	0.17	0.17	0.17	5.00%
Solar PV very high potential	25	0.21	0.24	0.25	0.26	5.00%
Solar PV small scale rooftop	25	0.12	0.14	0.16	0.17	5.00%
Solar Thermal with 8 hours storage	25	0.23	0.26	0.28	0.28	5.00%
Tidal and waves	80	0.24	0.33	0.36	0.36	5.00%
Lakes	60	1.00	1.00	1.00	1.00	0.00%
Run of River	50	0.22	0.22	0.22	0.22	5.00%
Geothermal High Enthalpy	35	0.65	0.65	0.65	0.65	0.00%
Geothermal Medium Enthalpy	30	0.45	0.45	0.45	0.45	0.00%
Boilers Electricity	25	0.40	0.40	0.40	0.40	0.00%
district heating Boilers Gas	25	0.35	0.35	0.35	0.35	4.51%
district heating Boilers Fuel Oil	25	0.35	0.35	0.35	0.35	6.12%
district heating Boilers Biomass	25	0.35	0.35	0.35	0.35	10.48%
district heating Boilers Coal	25	0.35	0.35	0.35	0.35	7.49%

[4] The capacity factors of wind resource presented in this table are averaged values over different wind classes for Europe.
In addition to these values, the model adjusts capacity factors per Member State based on TSO operation data so as to reflect local conditions and observed performance of installed capacities. Investment decisions are based on these Member State-specific values.

©E3Mlab PRIMES model-2018 Power generation technologies (cont'd)	Technical Lifetime Years	Capacity Factor (equivalent full load operation) % 2020	2030	2040	2050	Annual growth of O&M costs with plant age
district heating Boilers Lignite	25	0.35	0.35	0.35	0.35	7.89%
MBW incinerator district heating	35	0.35	0.35	0.35	0.35	2.66%
District Heating Electricity	20	0.35	0.35	0.35	0.35	0.00%
District Heating Geothermal	25	0.30	0.30	0.30	0.30	0.00%
District Heating Heat Pump	20	0.35	0.35	0.35	0.35	0.00%
District Heating Solar	25	0.16	0.16	0.16	0.16	0.00%
Industrial Boilers Coal	25	0.40	0.40	0.40	0.40	7.49%
Industrial Boilers Lignite	25	0.40	0.40	0.40	0.40	7.89%
Industrial Boilers Gas	25	0.40	0.40	0.40	0.40	3.98%
Industrial Boilers Fuel Oil	20	0.40	0.40	0.40	0.40	6.43%
Industrial Boilers Biomass	25	0.40	0.40	0.40	0.40	10.38%

©E3Mlab PRIMES model-2018 Conversion technologies - Revised	Investment cost per unit of capacity (EUR/kW-output)			Fixed O&M costs (EUR/kW-output)			Capital and fixed cost per unit of output (EUR/MWh-output)			Variable, fuel and emissions cost per unit of output (EUR/MWh-output or per tCO2)			Total levelized cost per unit of output at a 8.5% discount rate (EUR/MWh-output or per tCO2)		
	2015	2030	Ultimate	2015	2030	Ultimate	2015	2030	Ultimate	2015	2030	Ultimate	2015	2030	Ultimate
Hydrogen from natural gas steam reforming centralised - Large Scale (per 1 kW or 1 MWh H2 HHV)	550	500	450	22.0	20.0	18.0	11.8	10.7	9.7	36.0	49.0	176.0	48.0	60.0	186.0
Hydrogen from natural gas steam reforming centralised - Large Scale with CCU (per 1 kW or 1 MWh H2 HHV)	900	850	800	36.0	34.0	32.0	19.3	18.3	17.2	88.0	115.0	249.0	107.0	133.0	267.0
Hydrogen from natural gas steam reforming de-centralised - Medium Scale (per 1 kW or 1 MWh H2 HHV)	1978	1598	1450	57.0	31.0	28.0	48.0	36.2	33.0	40.0	55.0	196.0	88.0	91.0	229.0
Hydrogen from low temperature water electrolysis PEM centralised - Large Scale (per 1 kW or 1 MWh H2 HHV)	1400	340	200	49.0	15.0	10.0	26.6	6.9	4.2	72.5	78.0	86.0	99.0	85.0	90.0
Hydrogen from low temperature water electrolysis PEM de-centralised at a refuelling station (per 1 kW or 1 MWh H2 HHV)	2200	750	350	77.0	34.0	18.0	41.8	15.2	7.3	78.2	82.0	87.0	119.9	97.0	95.0
Hydrogen from low temperature water electrolysis Alkaline centralised - Large Scale (per 1 kW or 1 MWh H2 HHV)	1100	300	180	28.0	14.0	9.0	19.5	6.1	3.8	73.0	83.0	87.0	92.0	89.0	90.0
Hydrogen from low temperature water electrolysis Alkaline de-centralised at a refuelling station (per 1 kW or 1 MWh H2 HHV)	1650	380	300	41.0	17.0	15.0	29.3	7.7	6.3	73.0	83.0	88.0	102.0	91.0	94.0
Hydrogen from high temperature water electrolysis SOEC centralised (per 1 kW or 1 MWh H2 HHV)	1595	804	600	55.8	36.2	39.0	30.3	16.3	13.6	89.8	98.1	86.7	120.1	114.3	100.4
Hydrogen from high temperature water electrolysis SOEC de-centralised at a refuelling station (per 1 kW or 1 MWh H2 HHV)	2711.5	1407	750	94.9	63.3	48.8	51.5	28.5	17.0	91.4	99.7	88.2	142.8	128.2	105.2

©E3Mlab PRIMES model-2018 Conversion technologies - Revised	Investment cost per unit of capacity (EUR/kW-output)			Fixed O&M costs (EUR/kW-output)			Capital and fixed cost per unit of output (EUR/MWh-output)			Variable, fuel and emissions cost per unit of output (EUR/MWh-output or per tCO2)			Total levelized cost per unit of output at a 8.5% discount rate (EUR/MWh-output or per tCO2)		
	2015	2030	Ultimate	2015	2030	Ultimate	2015	2030	Ultimate	2015	2030	Ultimate	2015	2030	Ultimate
Methanation (per 1 kW or 1 MWh CH4 HHV)	1200	633	263	42.0	22.0	9.0	22.8	12.0	5.0	1.0	1.0	1.0	23.0	13.0	6.0
CH4 Liquefaction plant (per 1 kW or 1 MWh gas HHV)	450	450	450	18.0	18.0	18.0	7.7	7.7	7.7	9.0	13.0	40.0	17.0	20.0	47.0
Gas Liquefaction plant (per 1 kW or 1 MWh gas HHV)	200	200	200	20.0	20.0	20.0	4.8	4.8	4.8	2.0	3.0	4.0	7.0	8.0	9.0
Regasification Plant including LNG storage (per 1 kW or 1 MWh gas HHV)	175	175	175	5.0	5.0	5.0	2.7	2.7	2.7	0.0	0.0	2.0	3.0	3.0	5.0
Power to liquid via the methanol route (per 1 kW or 1 MWh CH4 HHV)	1000	620	364	50.0	31.0	18.0	20.9	12.9	7.6	7.0	10.0	34.0	28.0	23.0	41.0
Power to liquid via the Fischer Tropsch route (per 1 kW or 1 MWh CH4 HHV)	1556	1143	673	54.0	40.0	24.0	29.5	21.7	12.8	2.0	2.0	6.0	31.0	24.0	19.0
Power to liquid via High temperature co-electrolysis and Fischer Tropsch (per 1 kW or 1 MWh CH4 HHV)	2332	1511	965	163.0	106.0	68.0	54.5	35.3	22.5	111.0	118.0	165.0	165.0	153.0	188.0
Capture CO2 from air (Absorption technology) (per 1 tCO2)	770	648	518	26.9	22.7	18.1	116.9	98.4	78.7	0.2	0.2	0.2	117.0	99.0	78.9
Capture CO2 from air (Adsorption technology) (per 1 tCO2)	1260	894	495	44.1	31.3	17.3	191.3	135.8	75.2	0.1	0.1	0.2	191.0	136.0	75.4
CO2 Liquefaction plant (per 1 ton CO2)	174	174	174	3.0	3.0	3.0	3.2	3.2	3.2	0.0	0.0	0.0	3.0	3.0	3.0

©E3Mlab PRIMES model-2018 Refuelling technologies - Revised	Investment cost per unit of capacity (EUR/kW-output)			Fixed O&M costs (EUR/kW-output)			Capital and fixed cost per unit of output (EUR/MWh-output)			Variable, fuel and emissions cost per unit of output (EUR/MWh-output or per tCO2)			Total levelized cost per unit of output at a 8.5% discount rate (EUR/MWh-output or per tCO2)		
	2015	2030	Ultimate	2015	2030	Ultimate	2015	2030	Ultimate	2015	2030	Ultimate	2015	2030	Ultimate
H2 compression station (per 1 kW or 1 MWh H2 HHV)	114	102	91	0.4	0.4	0.4	2.30	2.10	1.80	3.60	4.60	5.10	5.90	6.60	7.00
Hydrogen Liquefaction plant (per 1 kW or 1 MWh H2 HHV)	761	635	457	23	23	23	12.10	10.60	8.40	1.10	1.40	1.50	13.20	11.90	9.90
H2 liquid to gas refuelling station (per 1 kW or 1 MWh H2 HHV)	855	759	568	1.6	1.4	1.1	16.90	15.00	11.20	3.70	4.60	5.20	20.60	19.60	16.40
H2 refuelling station Small (per 1 kW or 1 MWh H2 HHV)	1009	867	822	4.1	4.1	4.1	20.30	17.60	16.70	3.60	4.60	5.10	24.00	22.20	21.80
H2 refuelling station Medium (per 1 kW or 1 MWh H2 HHV)	542	412	379	1.7	1.7	1.7	10.80	8.30	7.60	3.60	4.60	5.10	14.50	12.90	12.80
H2 refuelling station Large (per 1 kW or 1 MWh H2 HHV)	325	247	151	0.7	0.7	0.7	6.40	4.90	3.10	3.60	4.60	5.10	10.10	9.50	8.20
ELC recharging points - Semi Fast recharging (per 1 kW or 1 MWh ELC)	240	168	149	9.6	6.7	6.0	5.79	4.05	3.59	0.00	0.00	0.00	5.79	4.06	3.59
ELC recharging points - Fast recharging (per 1 kW or 1 MWh ELC)	900	567	486	36.0	22.7	19.4	21.71	13.68	11.73	0.00	0.00	0.00	21.72	13.68	11.73
CNG compression station (per 1 kW or 1 MWh gas HHV)	89	89	89	5.7	5.7	5.7	2.70	2.70	2.70	1.20	1.50	2.00	3.90	4.20	4.70
CNG refuelling station (per 1 kW or 1 MWh gas HHV)	197	197	197	4.3	4.3	4.3	6.80	6.80	6.80	0.00	0.00	0.00	6.80	6.80	6.80
LNG refuelling station (per 1 kW or 1 MWh gas HHV)	120	120	120	3.9	3.9	3.9	4.50	4.50	4.50	0.00	0.00	0.10	4.50	4.50	4.60

Notes

a) Primes endogenously calculates electricity prices, therefore variable costs will be different from scenario to scenario. The variable costs in the table use base load electricity prices, carbon prices and fuel prices of a decarbonisation scenario for the respective years.

b) Costs of installation, land cost and grid connection is included in the investment costs of Large Scale Batteries.

c) Costs of the technology "Methanation" refer only to plants that comprise the second stage (inputs: Hydrogen and CO_2, output: CH_4) of a Power- to-Gas pathway. Similar for the "Power-to-Liquids" costs. The costs for capturing CO2 or producting hydrogen are not included.

©E3Mlab PRIMES model-2018 Distribution technologies - Revised	Investment cost per unit of capacity (EUR/kW-output)			Fixed O&M cost per unit of capacity (EUR/kW-output)			Variable Cost EUR/MWh			Levelized cost per unit of product transported, at a 8.5% discount rate (EUR/MWh-output)		
	2015	2030	Ultimate	2015	2030	Ultimate	2015	2030	Ultimate	2015	2030	Ultimate
NGS Transmission Network (per MWh) (per MWh)	126	126	126	5.0	5.0	5.0	0.7	0.7	0.7	2.7	2.7	2.7
NGS Distribution Network (per MWh)	552	552	552	22.0	22.0	22.0	3.2	3.2	3.2	19.2	19.2	19.2
H2 pipeline 60bar (per MWh H2 HHV)	178	173	166	7.0	7.0	7.0	1.0	1.0	1.0	3.8	3.7	3.6
H2 pipeline 10 bar (per MWh H2 HHV)	723	723	723	29.0	29.0	29.0	4.1	4.1	4.1	25.2	25.2	25.2
	Investment cost per unit of capacity (EUR/ton CO2 per year)			Fixed O&M cost per unit of capacity (EUR/ton CO2 per year)			Variable Cost EUR/kWh			Levelized cost per unit of product transported, at a 8.5% discount rate (EUR/MWh-output)		
	2015	2030	Ultimate	2015	2030	Ultimate	2015	2030	Ultimate	2015	2030	Ultimate
CO2 Transmission network (per tCO2)	23	23	23	1.3	1.3	1.3	1.0	1.0	1.0	4.4	4.4	4.4
	Investment cost per unit of capacity (EUR/kW-output)			Fixed O&M cost per unit of capacity (EUR/kW-output)			Variable Cost EUR/kWh			Levelized cost per unit of product transported, at a 8.5% discount rate (EUR/MWh-output)		
	2015	2030	Ultimate	2015	2030	Ultimate	2015	2030	Ultimate	2015	2030	Ultimate
Road transport of liquid H2	74	68	55	7.0	7.0	7.0	0.3	0.3	0.3	3	2.8	2.5
Road transport of gaseous H2	344	324	284	58.0	58.0	58.0	3.6	3.6	3.6	19	18.5	17.5

©E3Mlab PRIMES model-2018 Storage technologies - Revised	Investment cost per unit of energy stored per year (EUR/MWh)			Fixed O&M costs (EUR/kW)			Variable, fuel and emissions cost per unit of stored energy (EUR/MWh)			Total levelized cost per unit of stored energy, at a 8.5% discount rate (EUR/MWh-stored)		
	2015	2030	Ultimate	2015	2030	Ultimate	2015	2030	Ultimate	2015	2030	Ultimate
Compressed Air Energy Storage (per 1 kW or 1 MWh electricity)	125000	112500	110931	38.5	34.7	34.2	0.0	0.0	0.0	225.0	203.0	200.0
Flywheel (per 1 kW or 1 MWh electricity)	1750000	1575000	1553029	52.5	47.3	46.6	0.0	0.0	0.0	1127.0	1015.0	1000.0
Large-scale batteries (per 1 kW or 1 MWh electricity)	600000	253000	225484	40.5	15.0	13.1	0.0	0.0	0.0	311.0	122.0	108.0
Small-scale batteries (per 1 kW or 1 MWh electricity)	270000	114000	101619	16.9	6.3	5.5	0.0	0.0	0.0	74.0	31.0	27.0
Pumping (per 1 kW or 1 MWh electricity)	100000	90000	88745	22.5	20.3	20.0	0.0	0.0	0.0	155.0	140.0	138.0

Underground Hydrogen Storage (per 1 kW or 1 MWh H2)	5340	3936	3821	0.0	0.0	0.0	0.6	0.7	0.8	2.8	2.4	2.4
Pressurised tanks - Hydrogen storage (per 1 kW or 1 MWh H2)	6000	4800	4659	0.0	0.0	0.0	0.6	0.7	0.8	3.0	2.7	2.7
Liquid Hydrogen Storage - Cryogenic Storage (per 1 kW or 1 MWh H2)	8455	6800	4000	0.0	0.0	0.0	0.7	0.9	1.0	4.1	3.6	2.6
Metal Hydrides - Hydrogen Storage (per 1 kW or 1 MWh H2)	12700	11430	11271	0.0	0.0	0.0	0.5	0.7	0.8	5.7	5.3	5.3
Thermal Storage Technology (per 1 kW or 1 MWh Heat)	100000	90000	88745	100.0	97.2	95.8	0.0	0.0	0.0	78.6	70.7	69.7
LNG Storage Gas (per 1 kW or 1 MWh Gas)	135	135	135	0.0	0.0	0.0	0.6	0.7	0.8	1.9	2.1	2.1
Underground NGS Storage (per 1 kW or 1 MWh Gas)	33	33	33	0.0	0.0	0.0	0.6	0.7	0.8	4.4	4.5	4.6

	Investment cost per ton CO2 stored per year (EUR/tCO2)			Investment cost per ton CO2 (EUR/tCO2)			EUR/tCO2 liquefaction cost			Total levelized cost per unit of stored energy, at a 8.5% discount rate (EUR/CO2-stored)		
	2015	2030	Ultimate	2015	2030	Ultimate	2015	2030	Ultimate	2015	2030	Ultimate
Liquid CO2 storage tank	1000	1000	1000	15.0	15.0	15.0	3.18	3.18	3.18	4.14	4.43	4.02

Notes

a) Primes endogenously calculates electricity prices, therefore, variable costs will be different from scenario to scenario. The variable costs in the table use base load electricity prices, carbon prices and fuel prices of a decarbonisation scenario for the respective years.

b) Costs of installation, land cost and grid connection is included in the investment costs of Large Scale Batteries.

c) Costs of the technology "Methanation" refer only to plants that comprise the second stage (inputs: Hydrogen and CO_2, output: CH_4) of a Power- to-Gas pathway. Similar for the "Power-to-Liquids" costs. The costs for capturing CO2 or producting hydrogen are not included.

10 APPENDIXES

APPENDIX 1: SURVEY TEMPLATE

Worksheet 1: Guidance

Guidance

We kindly ask you to work with **three** worksheets in **nine** steps:

I **Introduction**

1 Please, verify your contact data

2 We have pre-defined the technologies for your review in rows 6-7; detailed overview of parameters for these technologies is found in the worksheet "Technology data overview"

3 Should you be interested in reviewing a broader scope of technologies, please, check the list of technologies in the worksheet "all technology categories" and connect to Izabela.Kielichowska@Navigant.com with the proposed list

4 Based on your request, we will send you the extended datasets

II **Technology data overview**

5 Please, go to "Technology data overview" worksheet and analyse the proposed parameters

6 Please mark your changes in green, f.ex.

	Overnight Investment Costs EUR'13/kW			
	2020	*2030*	*2040*	*2050*
Steam Turbine Coal Conventional	*1600*	*1600*	*1600*	*1600*
Steam Turbine Lignite Conventional	*1800*	*1800*	*1800*	*1800*
Steam Turbine Coal Supercritical	*1700*	*1700*	*1700*	*1700*
Steam Turbine Lignite Supercritical	*2000*	*2000*	*2000*	*2000*

III **Additional information**

7 Please, provide us with additional information, supporting the proposed changes:

List of sources for updated data

Is any major technology option in your category to be added?

Are there any pre-requisites to consider (is a technology can develop only under certain conditions?

Which technology pathways are most likely to develop?

Please, limit your input to max. 500 signs per topic

9 Please, send the updated form by **30th April EOB** to: Izabela.Kielichowska@navigant.com

In case of any questions, please, contact: Izabela.Kielichowska@navigant.com

Worksheet 2: Introduction

Name	
Organisation	
Type of technologies discussed	
- main category	
- subcategories	
Contact details	

Worksheet 3: Technology data overview

	Overnight Investment Costs EUR'13/kW				Fixed O&M EUR'13/kW				Variable non fuel cost EUR'13/MWh				Electrical Efficiency (net) ratio				Self Consumption %				Technical Lifetime	Capacity Factor %				Annual growth of
	2020	2030	2040	2050	2020	2030	2040	2050	2020	2030	2040	2050	2020	2030	2040	2050	2020	2030	2040	2050	Years	2020	2030	2040	2050	O&M
Industrial Boilers Coal	340	373	373	373	1	1	1	1	1,41	1,41	1,41	1,41	0,82	0,92	0,92	0,92	0	0	0	0	25	0,40	0,40	0,40	0,40	7,49%
Industrial Boilers Lignite	406	445	445	445	1	1	1	1	1,57	1,57	1,57	1,57	0,79	0,92	0,92	0,92	0	0	0	0	25	0,40	0,40	0,40	0,40	7,89%
Industrial Boilers Gas	114	124	124	124	1	1	1	1	0,44	0,44	0,44	0,44	0,89	0,98	0,98	0,98	0	0	0	0	25	0,40	0,40	0,40	0,40	3,98%
Industrial Boilers Fuel Oil	222	243	243	243	1	1	1	1	0,53	0,53	0,53	0,53	0,86	0,96	0,96	0,96	0	0	0	0	20	0,40	0,40	0,40	0,40	6,43%
Industrial Boilers Biomass	737	807	807	807	1	1	1	1	1,41	1,41	1,41	1,41	0,82	0,90	0,90	0,90	0	0	0	0	25	0,40	0,40	0,40	0,40	10,38%

Worksheet 4: Additional information

	ADDITIONAL INFORMATION	
1	List of sources for updated data	*(max. 500 signs)*
2	Is any major technology option in your category to be added?	*(max. 500 signs)*
3	Are there any pre-requisites to consider (is a technology can develop only under certain conditions?	*(max. 500 signs)*
4	Which technology pathways are most likely to develop?	*(max. 500 signs)*

Worksheet 5: All technology categories - for information only

	FOR INFORMATION ONLY	
	Main category	Supporting category
1	Domestic	Electric appliances
2	Domestic	Cooking
3	Domestic	Space heating
4	Domestic	Water heating
5	Domestic	Air conditioning
6	Domestic - services	Electric appliances
7	Domestic - services	Space heating
8	Domestic - services	Air-conditioning
9	Renovation Costs	Centre/West
10	Renovation Costs	North
11	Renovation Costs	South
12	Renovation Costs	East
13	Industry	Horizontal processes
14	Industry	Glass annealing
15	Industry	Iron and Steel basic processing
16	Industry	Direct heat
17	Industry	Drying and seperating
18	Industry	Furnaces
19	Industry	Electric processes
20	Industry	Electric (pulp and paper) refining
21	Industry	Foundries (non-ferrous alloys)
22	Industry	Heat
23	Industry	Kilns
24	Industry	Lighting
25	Industry	Machinery
26	Industry	Process furnaces
27	Industry	Raw material in petrochemical
28	Industry	Space heating
29	Industry	Sinter making
30	Industry	Steam uses
31	Industry	Coating
32	Industry	Thermal processes
33	Industry	Glass tanks
34	Industry	Smelters
35	Power&heat	Steam turbine and Fluidized Bed combustion
36	Power&heat	Gas plants
37	Power&heat	Supercritical/CCS/gasification combustion
38	Power&heat	Biomass/biogas applications
39	Power&heat	Nuclear
40	Power&heat	Fuel cells
41	Power&heat	Wind
42	Power&heat	Solar
43	Power&heat	Hydro, tidal and waves
44	Power&heat	Geothermal
45	Power&heat	Electric boilers
46	Power&heat	District heating heat-only-boilers technologies
47	Power&heat	Industrial boilers
48	Novel technologies	Conversion technologie s- Hydrogen
49	Novel technologies	Conversion technologies - Power-to-X
50	Novel technologies	CO2 capture and CO2 capture
51	Novel technologies	Refuelling technologies
52	Novel technologies	Distribution technologies
53	Novel technologies	CO2 and H transmission network
54	Novel technologies	Storage options

APPENDIX 2: LITERATURE REVIEW LIST

A non-exhaustive list of literature used for the preparation and review of all the technologies is presented below.

Electrolysis, Methanation, power to gas and power to liquids

- IEA-RETD, "Non-individual transport - Paving the way for renewablepower-to-gas (RE-P2G)", 2016
- IEA-RTD, "Policies for Storing Renewable Energy, A scoping study of policy considerations for energy storage (RE-Storage)", 2016
- Power-to-Gas Roadmap for Flanders; Brussels, October 2016
- ENEA, "The potential of Power to gas",2016
- E4tech, "Development of Water Electrolysis in the European Union", 2014
- Shell, "Energy of the Future?", 2017
- IEA, "Technology Roadmap. Hydrogen and Fuel Cells",2015
- Power-to-Gas: technology and Business Models, Markus Lehner et al., Springer, 2014
- Renewables in Transport 2050, FVV – FORSCHUNGSVEREINIGUNG VERBRENNUNGSKRAFTMASCHINEN E.V., Report 1086, 2016
- Power to Liquids, German Environment Agency, September 2016
- Electrochemical production of chemicals, DNV, December 10,2012
- What role is there for electrofuel technologies in European transport's low carbon future?, Dr Chris Malins, Cerulogy, Noovember 2017
- Power to methanol solutions for fexible and sustainable operations in power and process industries, C. Bergins et al., Mitsubishi, 2015
- Application of Power to Methanol Technology to Integrated Steelworks for Profitability, Conversion Efficiency, and CO2 Reduction, G. Harp et al.
- Electrochemical Conversion of Carbon Dioxide to Hydrocarbon Fuels, EME 580 Spring 2010
- Techno-economic and environmental evaluation of CO2 utilisation for fuel production, JRC, 2016
- Methanol synthesis using captured CO2 as raw material: Techno-economic and environmental assessment, Ma Perez-Fortes et al. Applied energy 161, 2016
- "Catalytic CO2 conversion: a techno-economic analysis and theoretical study, Thomas Savaete , Master's dissertation, University Gent, 2015-2016"
- Renewable Power-to-Gas: A technological and economic review, Manuel Gotz et al., Renewable Energy, 85, 2016
- "Technology data for high temperature solid oxide electrolyser cells, alkali and PEM electrolysers, Mathiessen Brian et al, Aalborg University, 2013"
- Transition of Future Energy System Infrastructure; through Power-to-Gas Pathways, Azadeh Maroufmashat and Michael Fowler , Energies, 1 June 2017
- Systems Analyses Power to Gas, KEMA, June 20, 2013
- "A comparison between renewable transport fuels that can supplement or replace biofuels in a 100% renewable energy system, D. Connomy et al, Energy, 73, 2014"

Storage Technologies

- IEA, "Technology Roadmap. Hydrogen and Fuel Cells",2015
- EASE,EERA, "European energy Storage Technology Development Roadmap",2017
- Hydrogen-based Energy Conversion, SBC Energy Institute, Schlumberger, February 2014
- Lazard's levelized cost of storage analysis, version 3, LAZARD, November 2017
- A review at the role of storage in energy systems with a focus on power to gas and long term storage, Herib Blanco, Andre Faaij, Renewable and Sustainable Energy Reviews, 81 (2018)
- Electric Energy Storage, Technology Assessments, US DOE, 2015
- Dunn, Kamath, Tarascon, "Electrical Energy Storage for the Grid : A Battery of Choices", 2016
- IEA, "Prospects for Large-Scale Energy Storage in Decarbonised Power Grids",2009
- EPRI, "Electricity energy Storage Technology Options" Awhite paper primer on applications, costs amd benefits,2010
- IEA, "Technology Roadmap", Energy Storage, 2014
- IRENA, "Battery Storage for Renewables: Market Status and technology outlook", 2015
- IRENA, "Renewables and Electricity Storage Atechnology roadmap for Remap 2030", 2015
- IRENA, IEA, ETSAP,"Electricity Storage. Technology Brief", 2012
- NREL, "Large Scale Energy storage",2015
- NREL,"Cost and performance data from power generation technologies",2012
- Deloitte, "Energy storage" Tracking the technologies that will transform the power sector",2013
- LAZARD, "Levelised Cost of Storage"-version 2, 2016
- Bllomberg, https://about.bnef.com/blog/lithium-ion-battery-costs-squeezed-margins-new-business-models/
- World Energy Council, "World Energy Resources E-storage",2016
- World Energy Council, "World Energy Resources E-storage: Shifting from cost to value wind and solar Applications",2016
- IRENA, "Electricity storage and renewables: Costs and markets to 2030",2017

Hydrogen - Transmission and Distribution to the network

- Power-to-Gas Roadmap for Flanders; Brussels, October 2016
- ENEA, "The potential of Power to gas",2016
- IEA, "Technology Roadmap. Hydrogen and Fuel Cells", 29 June 2015

Recharging infrastructure

- Cambridge Econometrics, Low-carbon cars in Europe: A socio-economic assessment, February 2018
- McKinsey, A portfolio of power-trains for Europe: a fact-based analysis: The role of Battery Electric Vehicles, Plug-in Hybrids and Fuel Cell Electric Vehicles, 2012

CO_2 capture

- Henriette, "Economics of carbon dioxide capture and utilization-a supply and demand perspective", Springer, 2016
- Economics of carbon dioxide capture and utilization, Environ Sci Pollut Res, 2016, 23:22226-22241

- Carbon capture and storage, SBC Energy Institute, Schlumberger, January 2013, update
- Carbon dioxide capture and storage, UNEP, 2005, Cambridge University Press
- Direct Air Capture of CO2 with Chemicals, APS physics, June 1, 2011
- Putting costs of direct air capture in context, Yuki Ishimoto et al., FCEA Working Paper 002, June 2017
- The CO2 economy: review of CO2 capture and reuse technologies, Efthymia Ioanna Koytsoumpa et al., J. of Supercritical Fluids, 23-1-2017
- Biophysical and economic limts to negative CO2 emissions, Pete Smith et al., Nature Climate Change, 7 December 2015
- The costs of CO2 transport, Zero emissions platform
- CO_2 utilization pathways, Mar Perez-Fortes et al., Energy Procedia, 63, 2014
- CO_2 utilization developments in conversion processes, Erdogan Alper et al., Petroleum, 3, 2017

Power generation –with focus on Renewable energy technologies

Reports and surveys from various stakeholders:

- IRENA – Renewables power generation costs
- SET-plan
- IEA – World Energy Outlook
- IEA – Energy Technology Perspectives
- IEA – Medium Term Renewable Market Outlook
- EIA – Annual energy outlook
- IEA Wind Implementing Agreement
- Frontier economics
- BNEF – New energy outlook
- National Renewable Energy Laboratory
- Wind Europe, Solar PV association
- Private stakeholders

Scientific literature in order to cross-check estimations for the costs in the long-run:

- Challenges to the adoption and large-scale diffusion of emergent energy technologies, University of California
- The Learning-by-doing Effects in the Wind Energy Sector, International Association for Energy Economics
- Learning by Doing and Spillovers in Renewable Energy, MIT
- A Spatial-Economic Cost Reduction Pathway Analysis for U.S. Offshore Wind Energy Development from 2015–2030, NREL

Industry

- Best Available Techniques (BAT) Reference Documents for (previously IPPC):
- Production of Cement, Lime,and Magnesium Oxide
- Ceramic Manufacturing Industry

- Manufacture of Glass
- Large Volume Inorganic Chemicals- Ammonia, Acids and Fertilisers
- Iron and Steel Production
- Non-Ferrous Metals Industries
- Large Volume Organic Chemical Industry
- Production of Pulp, Paper and Board
- OECD GLOBAL FORUM ON ENVIRONMENT Focusing on SUSTAINABLE MATERIALS MANAGEMENT
- ETSAP Technology briefs on all available technologies
- ECO-Design studies for elements covered by Eco-design regulations
- DECC studies by Ricardo
- Industrial associations websites and documents (CEFIC)

Residential and services

Heating and cooling technologies

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- ENER Lot 20 – Local Room Heating Products
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