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Supporting the deployment of selected low-carbon technologies in Europe

Implications of techno-economic assumptions. An energy system perspective with the JRC-EU-TIMES model

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Abstract
This report aims at supporting the identification of technological options that could facilitate an efficient and effective transition to a low-carbon energy technology portfolio in the EU for the medium term (2030). It also aims at improving the reader's understanding on how uncertainty of cost and efficiency parameters impact technologies' competiveness as well as affordability, security and sustainability of the entire energy system.

Title How does the techno-economic performance of low-carbon technologies affect their deployment?

- Technology improvements, on top of the projected learning, could accelerate deployment of established technologies (PV and wind onshore and offshore). In contrast, even with a more pessimistic technology outlook, deployment of additional capacity will continue until 2030.
- Emerging technologies (e.g. second-generation biofuels, tidal stream and carbon capture and storage) take up a role in 2030 only under optimistic scenario assumptions.
- The overall impact on security of supply, affordability and environmental sustainability is generally proportional to technology deployment. Technologies that are still marginal, like tidal stream energy, require strong improvements, which might be difficult to achieve in the medium-term without significant additional R&I efforts.

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Executive summary

Policy context

Technological research and innovation (R&I) for the energy system, one of the five pillars of EU's Energy Union strategy, is essential in determining future low-carbon energy trajectories. Substantial R&I is required to further reduce costs of low-carbon technologies and improve their performance.

The main objective of this report is to help decision-makers in identifying technological options that could facilitate an efficient and effective transition to a low-carbon energy technology portfolio in the EU for the medium term (2030). Furthermore, this report aims at improving the reader's understanding on how uncertainty of cost and efficiency parameters impact technologies' competiveness as well as affordability, security and sustainability of the entire energy system. To this end, we use the JRC-EU-TIMES model, representing the energy systems of EU28 member States plus Iceland, Norway and Switzerland (EU28+) from 2005 to 2050.

The analysis focuses on seven distinctive technology groups: solar photovoltaic (PV) and concentrated solar power (CSP), onshore and off-shore wind power, tidal and ocean wave power, carbon capture and sequestration (CCS) in the power sector as well as second generation biofuels and hydrogen production.

Key conclusions

For all technologies already in the market today (PV, wind onshore and offshore) additional improvements in cost and/or efficiency, on top of the already projected learning, would further accelerate their deployment. In contrast, even with a more pessimistic technology outlook for PV as well as onshore and offshore wind, deployment of additional capacity will continue until 2030.

Emerging technologies, namely second-generation biofuels, tidal stream and CCS for the power sector, take up a role as low-carbon technologies in 2030 only under optimistic scenario assumptions.

The overall impact of different techno-economic assumptions on the energy system in terms of security of supply, affordability and environmental sustainability, is generally proportional to their impact on technology deployment.

Cost variation for PV and onshore and off-shore wind demonstrate the largest potential impact on the energy system, despite the fact that these technologies are relatively mature. Consequently, investing in R&I of PV and wind would be cost-effective, if this R&I leads to a reduction in costs. This points to the need for an in-depth analysis of potential bottlenecks in the supply chains, including the impact of critical materials.

Technologies that are still marginal, like tidal stream energy, have a less significant impact on the energy system by 2030. However, strong improvements in their techno-economic performance could positively impact the energy systems. Such improvements are however high, might thus be difficult to achieve in the medium-term without significant R&I efforts.

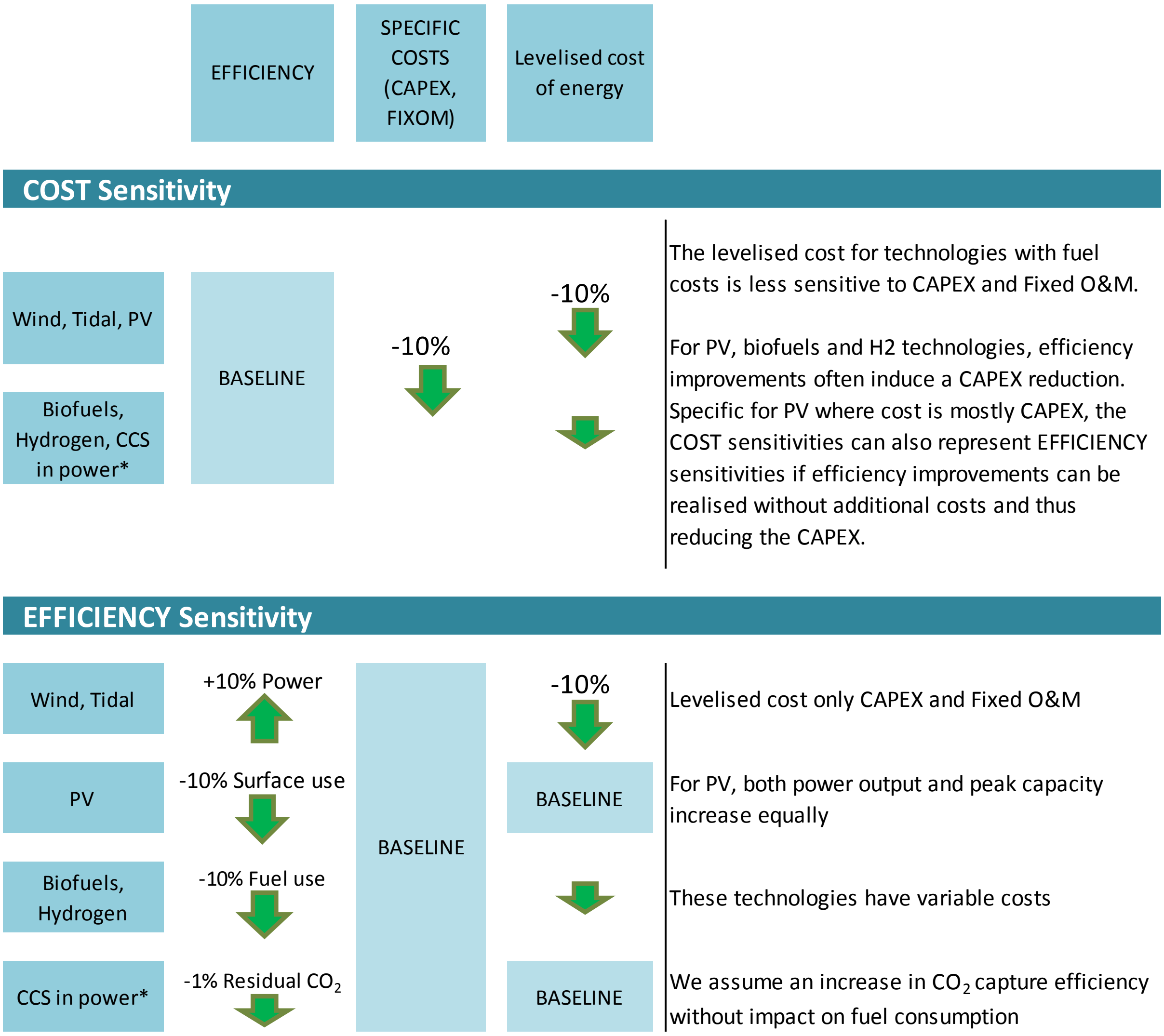
Related and future JRC work

The main areas for further development and research include deriving sensitivity ranges from a review of past and ongoing R&D efforts, as well as enlarging the analysis to more than one technology simultaneously for a deeper understanding of cross-sensitivities among technologies. An assessment of how key exogenous drivers could significantly affect the European energy system would also shed additional light on how a cost-effective and efficient transition to low-carbon energy could be fostered. Such an analysis could, for instance, include import prices of fossil fuels (coal, oil, gas) and demand for energy services

1. Introduction

Technological innovation for the energy system, one of the five pillars of EU's Energy Union strategy, is essential in determining future low-carbon energy trajectories. The 2015 Communication on A Framework Strategy for a Resilient Energy Union with a Forward-Looking Climate Change Policy [1] sets out key priorities to make energy more secure, affordable and sustainable. Among the objectives of the European Energy Union are the diversification of energy sources, the reduction of energy imports, and ensuring the EU continues to play a leading role in energy efficiency and low carbon energy technologies development and deployment. Energy Research and Innovation (R&I) is recognised as a critical building, driving economic growth, creating highly qualified jobs, and contributing to all dimensions of the Energy Union. The implementation of the energy transition thus requires substantial R&I to further reduce costs of low-carbon technologies and improve their performance. In this context, the main objective of this report is to help decision-makers in identifying technological options that could facilitate an efficient and effective transition to a low-carbon energy technology portfolio in the EU for the medium term (2030). Furthermore, this report aims at improving the reader's understanding on how uncertainty of cost and efficiency parameters impact technologies' competiveness as well as affordability, security and sustainability of the entire energy system.

The work's methodology introduces sensitivity analysis on main techno-economic parameters of key emerging technologies within a consistent energy modelling framework for the 28 EU member states. These include technology-specific costs (investment costs, CAPEX, and fixed operation and maintenance costs, FIXOM) and conversion efficiency. We investigate whether strong technology performance improvements or cost reductions can make a technology sufficiently competitive to capture market share and to what extent. Conversely, we analyse the systemic impact of uncertain trajectories of technology and cost parameters. In this way, our results provide useful insights on prioritising the efforts to foster technological deployment. The report can be in the interest of policy makers, technology developers, power marketers, transmission system operators as well as researchers.



*CCS can also deployed in the industrial sector. In this report, the focus in however on the power sector

Figure 1: Overview of the sensitivities and impact on levelised cost of energy (the example is given only for improvements of cost and efficiency)

1.1 Scope

For studying the role of technology cost and efficiency, our analysis focuses on seven distinctive technology groups: solar photovoltaic (PV) and concentrated solar power (CSP), onshore and off-shore wind power, tidal and ocean wave power, carbon capture and sequestration (CCS) in the power sector as well as second generation biofuels and hydrogen production. For each technology group, we design sensitivity scenarios entailing variations of investment (CAPEX) and fixed operation and maintenance (FIXOM) costs. For technology efficiencies, the range of variations is narrower (as it is constrained by technological and physical limitations. Second generation biofuels and solar PV are assumed to have the highest improvement potential on technical efficiency. Also, when varying technology efficiencies, we assume that costs remain unchanged and vice-versa.

We use the JRC-EU-TIMES model, representing EU28 plus Iceland, Norway and Switzerland from 2005 to 2050 [2]. The model ensures the satisfaction of all energy services and materials demands in three sectors – namely industry, buildings and transport - while minimising the total supply cost under a climate-constraint, which includes the 2030 Climate and Energy Policy Framework (40% – 27% - 27% targets), as well as a long term target of 80% reduction of CO_2 in 2050 compared to 1990 levels.

2. The baseline energy system trends for 2030

Achieving ambitious CO_2 emission reduction in the European energy system is technically possible, beyond the currently agreed 20-20-20 climate and energy policy package ([3], [4], [5], and [6]). It does require, however, a significant change in the energy consumption mix and technological deployment. Key findings, on the 2030 trends of the EU energy system, indicate that the (total EU) imports of energy decrease by 3%, mainly because the share of renewables in total primary energy consumption increases to a level of 22% in 2030, relative to just 10% in 2010; while primary energy consumption decreases by 16% over the same time period. Final energy decreases by 3% despite the overall growth in energy services and material demands. In 2030, 27% of final energy is provided by renewable resources – consists mainly of biomass for heat and combined heat and power (12%), RES-e (10%), solar and ambient heat (4%) and biofuels (1%).

Electricity production grows by 2% between 2010 and 2030, while the total installed capacity almost doubles. This is due the share of variable low-availability wind and solar energy in the total electricity production that also more than doubles in that same period, from 12% to 26%. In the same period, the total RES-e share increases from 21% to 46%. Due to this sharp growth of RES-e, the carbon intensity of electricity production reduces from 0.42 to 0.16 t of CO_2/MWh.

	2030 main technology		COST: 2030 CAPEX [€/kW]	EFFICIENCY: Definition	EFFICIENCY: 2030 Efficiency	EFFICIENCY: Max. increase
Solar PV	Thin film	Min	272 - 371	Conversion efficiency - surface use Example: multijunction cells	11%	+ 50%
			544 - 744		16%	
		Max	816 - 1114		24%	

For solar PV, where cost is mostly CAPEX, the COST sensitivities can also represent EFFICIENCY sensitivities (of 32% and 11% compared to the baseline 16%) if efficiency improvements can be realised without additional costs and thus reducing the CAPEX.

	2030 main technology		COST: 2030 CAPEX [€/kW]	EFFICIENCY: Definition	EFFICIENCY: 2030 Efficiency	EFFICIENCY: Max. increase
Wind ON	Variable rotor speed, three blades	Min	252 - 660	Power coefficient - electricity production for given capacity Example: advanced control methods	20%	+ 30%
			1050 - 1320			
		Max	1575 - 1980		26%	
Wind OFF		Min	900 - 1650		35%	+ 30%
			1800 - 3300			
		Max	2700 - 4950		46%	
Tidal	Tidal stream	Min	1687	Power coefficient Example: optimise power take-off	40%	+ 25%
			3375			
		Max	5062		50%	
CCS in power	CCS on coal power plants	Min	100 - 330	CO_2 capture efficiency - residual CO_2 Improved absorption	88% - 90%	+ 3%
			200 - 660			
		Max	300 - 990		91% - 93%	
Biofuels	2nd generation biokerosene	Min	869	Conversion efficiency - biomass use Example: increased acitivity enzymes	24%	+ 100%
			1738		36%	
		Max	2607		72%	

24%, 36% and 72% is equivalent to 0.10, 0.15 and 0.30 w/w efficiency

	2030 main technology		COST: 2030 CAPEX [€/kW]	EFFICIENCY: Definition	EFFICIENCY: 2030 Efficiency	EFFICIENCY: Max. increase
H2	Electrolyser	Min	3276	Conversion efficiency - fuel use Example: increased pressure	64%	+ 20%
		Baseli	6552		71%	
		Max	9828		83%	

Figure 2: Overview of the inputs for the 7 technology groups and their main technologies in 2030

3. The role of cost and efficiency: main highlights

An important finding of the sensitivity analysis is that for all technologies already in the market today (photovoltaic, wind and hydrogen production) additional improvements in cost and/or efficiency, on top of the already projected learning, would further accelerate their deployment. In contrast, when technology expectations are lower than foreseen, deployment remains relevant but yet lower than projected. This is an indication of inertia in the energy system, preventing already established technologies from leaving the market even in the face of unforeseen techno-economic barrier as those explored in this report. Furthermore, even with a more pessimistic technology outlook for PV as well as onshore and offshore wind, deployment of additional capacity will continue until 2030. Emerging technologies, namely second-generation biofuels, tidal stream and CCS for the power sector, take up a role as low-carbon technologies in 2030 only under optimistic scenario assumptions. However, CSP and wave power, despite their significant technical potential, are not cost-competitive before 2030 even under the most optimistic assumptions.

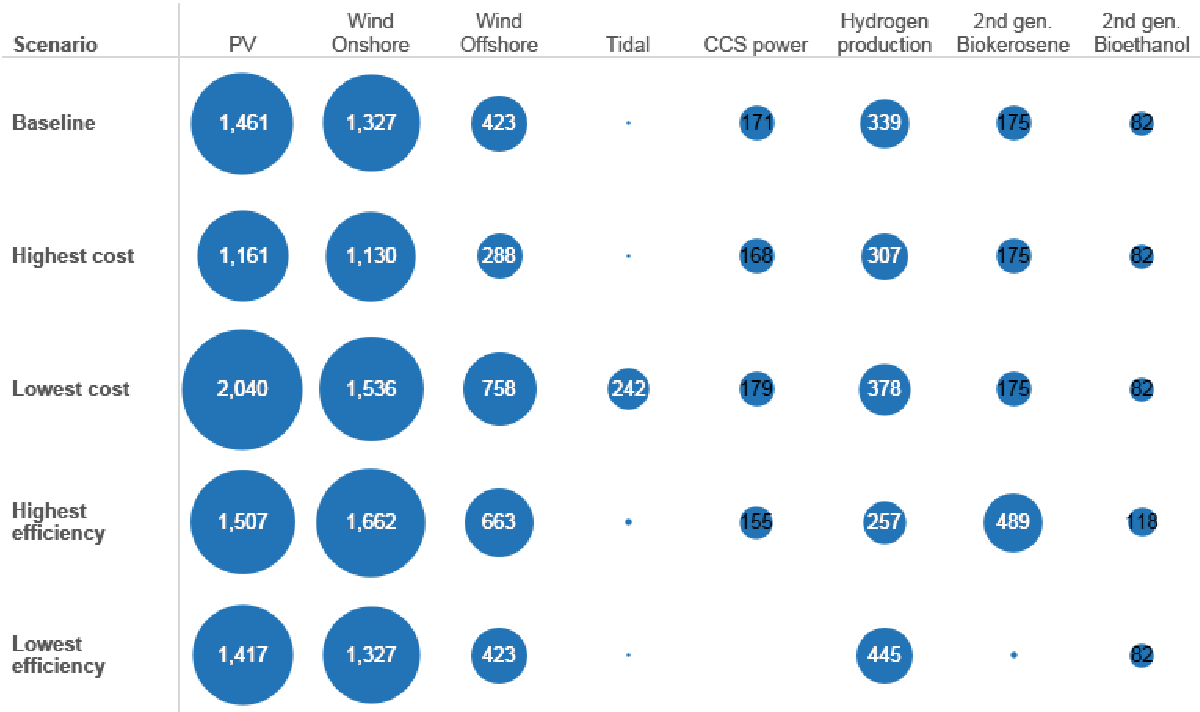


Figure 3: Energy production (PJ) and the role of cost and efficiency for key low-carbon technologies in 2030. For comparison, the consumption of primary energy in the EU28 reaches 62,356 PJ (equivalent of 1488 mtoe).

3.1 The role of cost and efficiency on the deployment of specific technologies

Photovoltaic (PV) systems' installed capacity quadruples on average from 2014 to 2030, mainly driven by the projected gradual cost reduction of 25% in that same period. With a yearly growth of 10%, the total installed capacity reaches a level above 350 GW. This requires an average installation rate of 18 GW per year that is comparable to the 2012 installation rate. Under baseline assumptions, from the land surface available for PV deployment, as accounted in the model's current version, more than 50% of the totals is used for most of the EU countries. When PV cost assumptions are sensitized, the share of PV generated electricity in 2030 ranges from 9% to 16%. Indeed, every 100

EUR/kW reduction in the 2030 PV cost adds 30GW of PV capacity in the EU. As it consists mainly of CAPEX, the specific cost of PV can also be reduced by improving the PV efficiency when assuming this improvement does not involve additional costs. Under this assumption, the cost sensitivities can also represent efficiency sensitivities. Improving the PV efficiency by 2.2 percentage points, as this results in a 100 EUR/kW reduction in the PV cost, will also add 30GW of PV capacity. However, efficiency improvements that involve proportional additional costs, while they significantly reduce land use requirements, only demonstrate a marginal impact on the PV deployment trajectory and energy system cost.

Concentrated Solar Power (CSP), despite the very high physical potential in southern Europe, stands below the expectations of the industry in 2030 (the Strategic Research Agenda estimates a global installed capacity of 10 GW by 2015 and 30 GW by 2020, including 7 GW installed in EU countries in 2020). Specifically, cost reductions that bring CAPEX within the range of 1000-2000 EUR/kW make CSP competitive for Cyprus, Spain, Greece and Portugal.

Onshore wind power installed capacity totals at 337GW by 2030. Total installed capacity for **offshore wind** at the same time reaches 117 GW. The deployment of both onshore and off-shore wind in the EU accelerates significantly between 2020 and 2030. Onshore wind generation almost treble in 2030 relative to 2010 under the baseline scenario of this analysis, and more than doubles even under the most pessimistic cost assumptions (+50% increase in CAPEX and FIXOM). Under the most optimistic cost assumptions, off-shore wind technologies could increase by a factor 8 in 2030 with respect to 2010. For both onshore and offshore wind, the impacts on electricity generation of increasing capacity factors with 30% are comparable to reductions in costs by 50%. Reducing the costs with 50% has a larger impact on the levelised cost of electricity than increasing the capacity factors with 30%. However, in several countries the wind installed capacity reaches the limit of the resource potential and so the cumulative EU28 capacity is less sensitive. For this reason, increasing the capacity factor allows to harvest more electricity in all countries whereas decreasing cost does not impact all countries. Overall, wind energy develops into an essential component of the European energy mix by 2030 and beyond, even under the most pessimistic scenarios.

Tidal and wave energy deployment in the medium-term is below the industry's expectations (projections for 2020 are in the range of 240 MW according to [7]), despite the very high potential. With both cost reductions and/or efficiency improvements, tidal stream and wave energy do not become competitive in 2030. Wave energy doesn't become cost-competitive in Europe even in the longer term, due to the competition with the also variable but cheaper solar and wind power. For tidal stream however, cost reductions of more than 40% (below 2500 EUR/kW) bring market penetration forward from 2040 to 2030, allowing for 16-19 GW. Similarly, efficiency improvements of 25%, inflating the capacity factor to the projected maximum of 50%, accelerate deployment, reaching 0.5GW of installed capacity in the EU in 2030. Off-shore wave energy in contrast requires at least 50% cost reductions to become competitive in Europe by 2040.

Carbon Capture and Storage (CCS) in the baseline reaches a level of 8 GW out of 488 GW of thermal capacity by 2030 in the EU 28. Coal power plants first deploy CCS, generating in the medium-term over 90% of the total power output with CCS. Capacity of CCS in the power sector is expected to further increase rapidly, reaching 195 GW in 2050. In the long-run, biomass-fuelled plants with CCS take over from coal based generation. Our results indicate that neither costs, capture rate efficiency nor the availability of storage sites are a significant barrier to the large uptake of CCS in all our sensitivity scenarios.

Second generation biofuel production technologies can play a role to help decarbonising the energy system. However under baseline assumptions, and without target for renewable energy in transport after 2020, a negligible amount of 2nd generation (2G) biofuels is only used in road transport while first generation biofuel production is totally phased out. Only aviation continues consuming biofuels, though 2G generation biodiesel blended with kerosene account for only 2% of the total transport energy use. Biodiesel is used for air transport where, in contrast to road transport, no alternative emission reduction options exist in the JRC-EU-TIMES. Replacing fossil fuels for heat production with solid biomass results in more significant energy savings than replacing oil based fuels with 2G biofuel; competition for biomass thus shifts biomass use in the sector that yields the highest benefits under the climate and energy policies in 2030 and beyond. Process efficiency has a much stronger influence in the competitiveness of 2G biofuels than their cost. However, even under the most optimistic efficiency assumptions, electrification of road transport will only be slightly reduced by the increase in bioethanol production. On the other hand, biodiesel could have a much more significant role in the air transport. The analysis highlights that woody biomass availabilitye and its price as well as the CO_2 emission accounting approach for biomass with CCS, all play a very significant role in influencing in the deployment of 2G biofuel.

Hydrogen production represents 0.8% of total final energy consumption for the baseline scenario in 2030. Electrolysis represents 64% of total production, while 25% comes from gasifiers and the remaining 11% is a by-product of the industrial sector. This trend is driven by the substantial penetration of intermittent renewables, namely solar PV and wind, in the generation portfolio. The deployment of gasifiers is not particularly sensitive to changes of techno-economic assumptions. Steam reformers, while relatively important in the short term, do not have an important role to play in hydrogen production under a stringent CO_2 cap, while: only with very high efficiency improvements – or significant cost and efficiency deterioration for gasification technologies – could biomass steam reforming remain competitive in 2030. However, the relative contribution to total hydrogen production would remain very small.

4. The role of cost and efficiency on affordability, security and sustainability

An Energy System Index (ESI) is derived (based on the methodology presented in [8]) in order to assess the role of technologies cost and efficiency on affordability, security and sustainability of the European Energy System. The ESI is built on proxy indicators for each of the dimensions identified in the European Commission's Communication on the Energy Union [1], as shown in Figure 4. It is a summary measure of the potential role of each technology group and of improvements or deterioration in their prospective development, on the three key objectives of the Energy Union overall, and separately. In this regard, the ESI provides an easy entry point for more detailed analyses, as well as useful insights to target R&I policies on the basis of the most important objective.

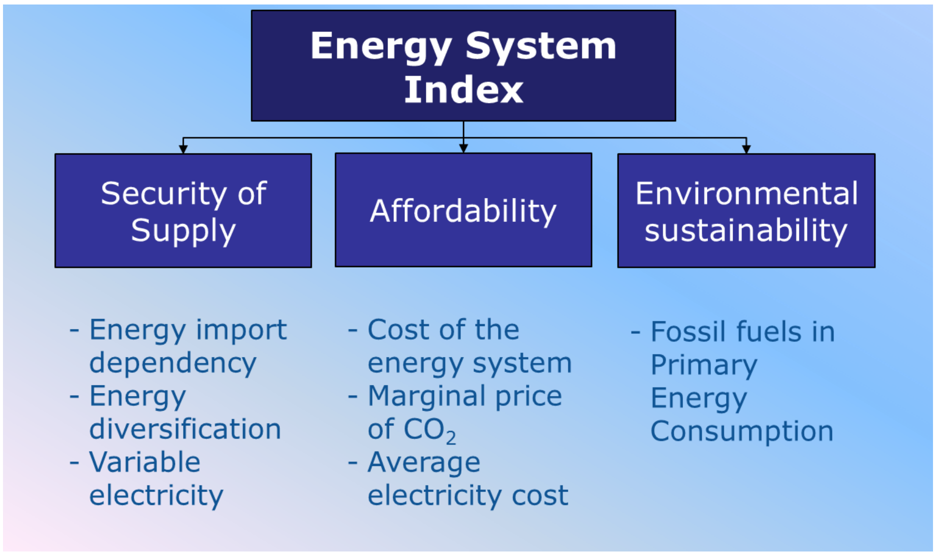


Figure 4: Theoretical framework for the development of the Composite Indicator

The ESI points out that cost variation for solar photovoltaics and onshore and off-shore wind demonstrate the largest potential impact on the energy system, despite the fact that these technologies are relatively mature. At the same time, efficiency variation of 2G biofuels, onshore and offshore wind, and hydrogen production significantly influence the energy system as well. The cost of PV and wind technologies has the highest impact on the affordability of the energy system in 2030, as both technologies are particularly capital intensive. Specifically, reducing technology costs by 50% results in a reduction in the total energy system cost of up to 12 billion Euros per annum. Consequently, investing in R&I of PV and wind would be cost-effective for the system as a whole, if this R&I is effective in reducing technology costs. This points to the need for an in-depth analysis of potential bottlenecks in the supply chain for PV and wind onshore, including the impact of critical materials, in determining the overall specific investment costs of the technologies.

Technologies that are still marginal, like tidal stream energy, have a less significant impact on the energy system by 2030. However, strong improvements in their techno-economic performance could positively impact the energy systems. Such improvements are in the range of more than 40% compared to the expectations of the industry, and might thus be very difficult to achieve in the medium-term without significant R&I efforts and breakthroughs in technological options.

In general terms, focusing on improving the investment and fixed costs of low-carbon technologies seems to be more effective in improving the energy system than enhancing technological efficiency in the medium term. There are some exceptions however.

Improving the capacity factor of wind (both onshore and offshore) would have very strong positive impact on ESI, in particular by reducing the system costs. This is mostly driven by a decoupling of installed capacity and electricity generation: a 3% increase in installed capacity in wind onshore leads to an increase in electricity generated of over 25%. This effect is even stronger for wind offshore: while installed capacity increases by over 20% with higher efficiency, the electricity generated increases by almost 60% compared to the baseline.

Finally, changes in the evolution of specific investment costs of 2nd generation (2G) biofuels have a negligible impact on the energy system in 2030. Biomass availability and cost seems to be much more important in determining the overall impact of 2G technologies: indeed, when the input:outpt ratio of 2G biofuel generation processes *deteriorates*, there is a strong negative impact on the overall performance of the energy system. The impact is not symmetrical for similar improvements. The result is driven by the impact that higher biomass requirements for biofuel production would have on both energy security and on environmental sustainability.

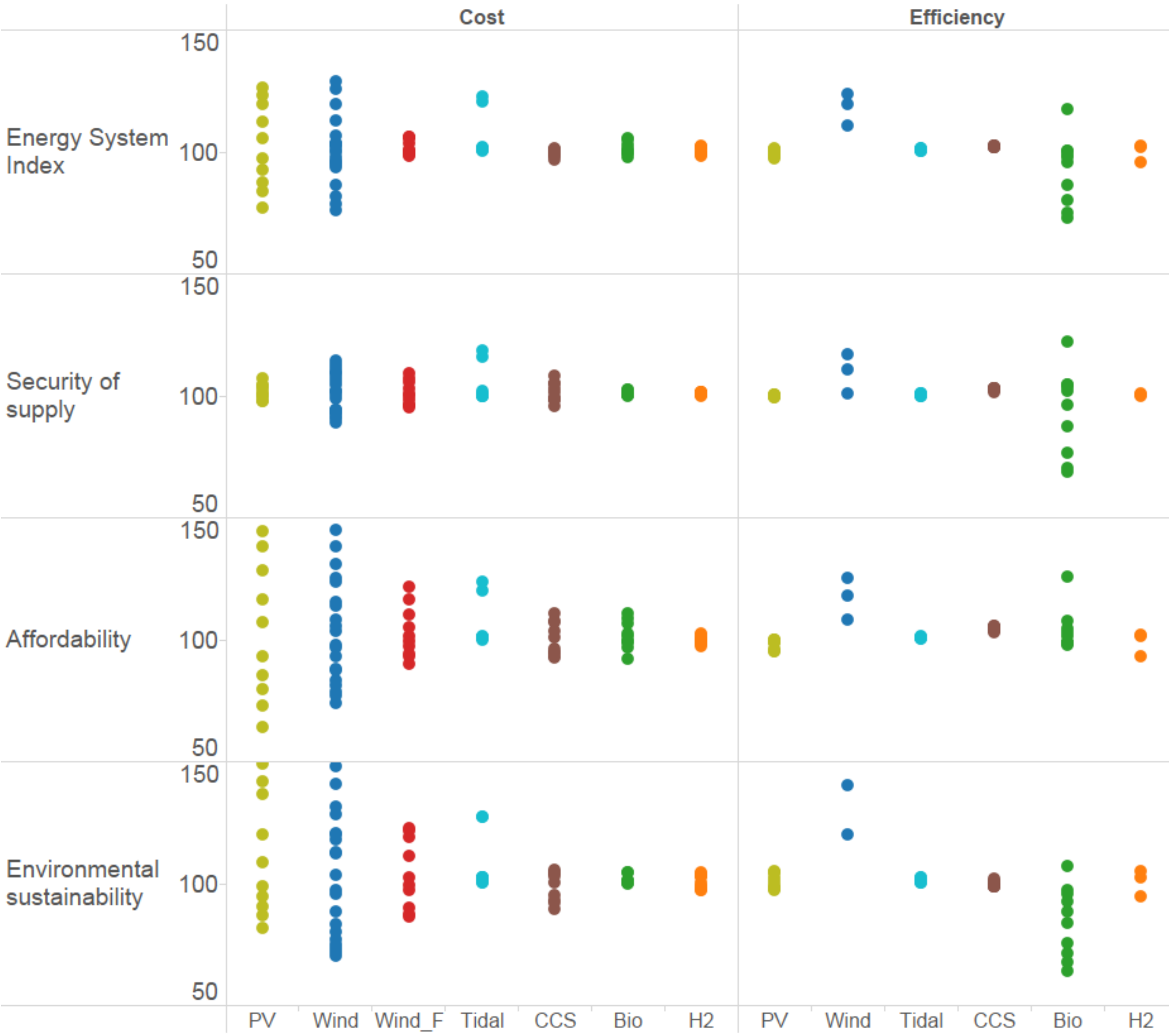


Figure 5: Spread of the values of the energy security, security of supply, affordability and environmental sustainability dimension

For more detailed information about the study, please contact the JRC-EU-TIMES team at:
JRC-EU-TIMES@ec.europa.eu

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List of abbreviations

2G	Second generation biofuel production technologies
CAPEX	Overnight investment cost, usually expressed in Eur/Kw
CCS	Carbon capture and storage
CSP	Concentrated Solar Power
EU28	EU 28 member States
FIXOM	Fixed operation and maintenance costs, usually expressed in Eur/Kw
PV	Photovoltaics
R&I	Research and Innovation

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