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MEDEAS
MODELING THE RENEWABLE ENERGY TRANSITION IN EUROPE

Project Nr: 691287

Guiding European Policy toward a low-carbon economy. Modelling sustainable Energy system Development under Environmental And Socioeconomic constraints

Annex 1: Task 2.2.a Rates of increase of electricity infrastructure and associated energetic cost (Global and European)

Version 2.0.0

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Document info sheet

Lead Beneficiary: BSERC

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Task: 2.2.a.1 Rates of increase of electricity infrastructure and associated energetic cost (Global and European)

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List of abbreviations and acronyms

BAU	Business As Usual
CAAGR	Compound Average Annual Growth Rate
CCS	Carbon Capture and Storage
CO_2	Carbon Dioxide
CPS	Current Policies Scenario
CSP	Concentrated Solar Power
DLR	Dynamic Line Rating
DRT	Demand Response Technologies
DSM	Demand –side Management
EC	European Commission
EC-GA	European Commission – Grant Agreement
EDT	Electricity Demand Technologies
EIA	U.S. Energy Information Administration
ENTSO-e	European Network of Transmission System Operators for electricity
EST	Electricity Storage Technologies
EU	European Union
GHG	Greenhouse gases
GDP	Gross Domestic Product
GW	Gigawatt
GWh	Giga Watt/hour
IEA	International Energy Agency
IEO 2016	International energy Outlook 2016
INDCs	Intended Nationally Determined Contributions
LCOE	Levelized cost of energy
LEAP	Long-range Energy Alternatives Planning System
LV	Low Voltage
MW	Megawatt
NPS	New Policies Scenario

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NPV	Net Present Value
OECD	Organization of Economic Cooperation and Development
PV	Photovoltaic
PWh	Petawatt hour
R2011	Reference case 2011
R2016	Reference case 2016
RES	Renewable Energy Sources
SA	System Adequacy
S0, … S6	Scenario 0, … Scenario 6
T&D	Transmission and Distribution
TGT	Transmission Grid Technologies
TWh	Terawatt hour
USA	United States of America
USD	United States Dollars
VRE	Variable resources of energy
WB	World Bank
WEC	World Energy Council
WEO	World Energy Outlook
WoLim	World Limits Model
WP	Work Package

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Power system

Given the leading role of electricity in the transition towards emissions-free energy sector, the importance of the power system is constantly growing. The substitution of the primary resource – fossil fuels, with intermittent sources, introduces drastic changes in the operational conditions and requirements to the electricity systems, which must meet them. In addition, the emergence of non-existent till recently mass consumers (transport) will increase the demand and the need of new investments. This means a transformation of the more than 100-year history of the power system in line with the new requirements for performance, flexibility and sustainability.

The exchange of electricity between the national systems in Europe started in the beginning of the 1920-ies. The first union for coordination of the electricity systems' operation was the *Union internationale des producteurs et distributeurs d'énergie électrique* (UNIPEDE), established on May 23rd, 1925 in Paris by the electrical industries of Italy, France and Belgium.

In order to foster the more efficient use of energy resources through an interconnection of electricity networks, on May 23rd, 1951 in Paris was founded UCPTE - *Union de Coordination de Production et Transport de l'Energie.*

To face the new prospects connected with the introduction of an organized electricity market and the fall off of the coordinated generation, in 1999 UCPTE became UCTE.

On December 19th, 2008 in Brussels was established, and on July 1st, 2009 became operational ENTSO-E - an association of 42 TSOs, which inherited six regional associations of electricity transmission system operators.

The accelerating development of distributed generation from variable resources of energy (VRE) /intermittent sources in contrast to the existing in the past and still concentrated in large regulated power plants generation imposes significant changes on the structure and control of electrical systems. The time of the passive medium and low voltage grids that bring the electricity generated by large power plants to the consumers, is passing. They become active and generate electricity, which needs to be controlled in the low-voltage grid.

The main impediment arises from the volatility of the primary resource: solar radiation and wind, and from the need of new grid and system technologies, which allow for controlling of the systems at a variable resource and multiple generation sources.

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A serious challenge is the necessity to control power flows in active networks. Of course, the Kirchhoff's laws cannot be changed; the distribution of flows is determined by the parameters of the grid, hence they need to be adapted during the operation of the system, depending on a number of variable regime dimensions and injected capacities. The aim is to reach higher resilience of the system, lower costs and redundancies, and safer operation. This requires high automation of power networks and systems, equipped with new devices, protection and control systems.

Electrification of life activities constantly increases and energy carriers and resources are being substituted by electricity, including in areas, considered until now reserved for liquid fuels. This requires rational utilization of surrounding areas, available materials and reduction of the technological losses of energy.

Operation control technologies should be largely introduced in practice:

1. Technologies for control of steady states, but also of transient processes and emergency regimes;
2. Technologies for demand control; and
3. Technologies for control of generation.

The first category consists of various types of system technologies: cables, including superconducting, transformers including phase-shifting, compensators, overhead lines, reactors, substations, capacitors, protection systems, current limiters, DLR, monitoring systems etc. The control of transient processes requires system automation that is able to work under conditions of meshed network, selective protectors and information systems.

Demand control comprises smart metering and smart devices for controlling demand, demand-side managing systems (DSM) and demand response (DR) technologies. Electric vehicles could be assigned to DSM, allowing for charging of batteries during the night minimum of electric load.

The third category refers mainly to

1. Wind power plants/farms;
2. Photovoltaic (PV) power plants;
3. Concentrated Solar Power (CSP) plants;
4. Biomass power plants.

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There should be explicitly emphasized the importance of storage technologies, which development has been speeded up during the last years in connection with the increasing need of control of power systems, networks and especially – with regard to the emerging road electric mobility. Power storage facilities, along with the economic constraints, determine to a great extent the possibilities for RE-e generation development. Unfortunately, they do not yet meet the flexibility and efficiency requirements, but given the intensive efforts put in this technological direction, they are expected to reach better indicators.

Strategic energy research examines the development of power systems in a too general manner, considering that technical issues could be solved through a specialized research on the basis of the already defined requirements to the electricity production and demand[1]. To a large extent, the decisions about the structure of electrical grids depend on the conditions in the countries the system operates on. Therefore, it goes without saying that research like MEDEAS, which covers the whole world, could find principal technical solutions and common economic evaluations only.

As concerns Europe, however, due to the interconnected power system, the issues related to the development of electricity systems are a subject to consistent specialized research (GRIDTECH, SUSPLAN, Realisegrid, e-highway2050 etc.).

The aim of MEDEAS, as it is defined in the Grant Agreement, is "*to solve the current needs of integration and transparency by developing a leading-edge policy modelling tool based on WoLiM, TIMES and LEAP models and incorporating Input-Output Analysis that allows for accounting of environmental, social and economic impacts*".

This research should cover both Europe and the World. In conformity with this scale, the Contract requires suggesting "***Rates, improvement and management of the electricity infrastructure***". It is clear that power systems could be described by their economic characteristics, but reflecting the needs of the developing economy and the indispensable technical progress.

This is the reason to ground this document on reporting data and the latest prospective studies made by different institutions, i.e. EU, IEA, EIA, World Bank, WEC etc.

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[1]Electricity demand is defined as a total gross electricity generated minus own use in generation, plus net trade (imports less than exports), minus transmission and distribution losses.

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Historical development

Power consumption depends to the greatest extent on the economic growth, represented through the GDP. Until 20 years ago the curves of their development had been almost parallel.

Detailed historical information about the global electricity consumption by countries for the period 2000 – 2015 is provided by the World Bank and other sources.

During the last years however, the active policy orientation towards climate protection has led to decoupling of the energy consumption in the World and in the EU are from the respective GDP, as it is illustrated in Figure 1 and Figure 2.

The historical information is somewhat uncertain for the needs of forecasting, due to the significant changes taking place in the energy policy of the EU and the biggest countries – USA, China and India – towards renewable electricity. This policy has been underway for several years now and will continue in the future.

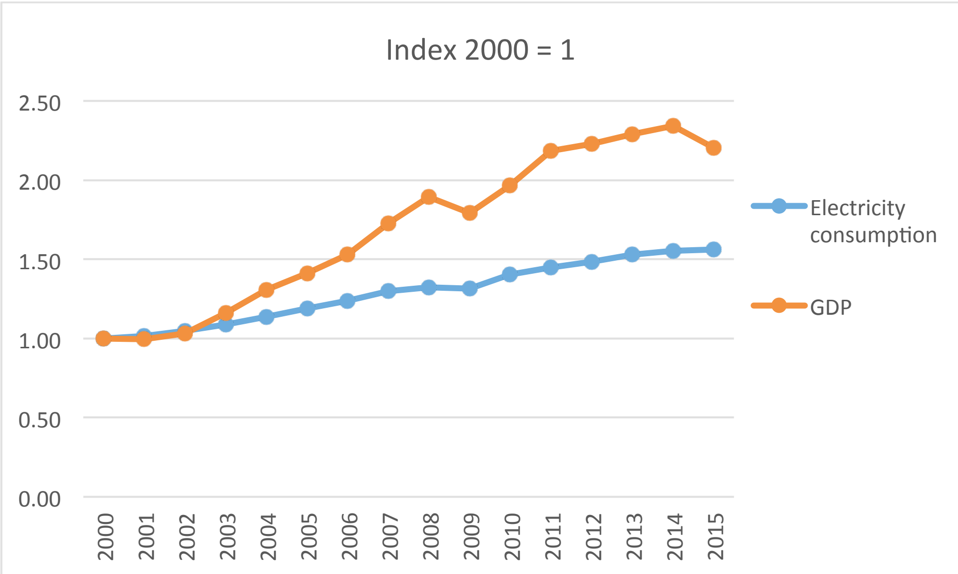

Figure 1: World electricity demand versus GDP

Source: World Bank 2016a, Enerdata 2016

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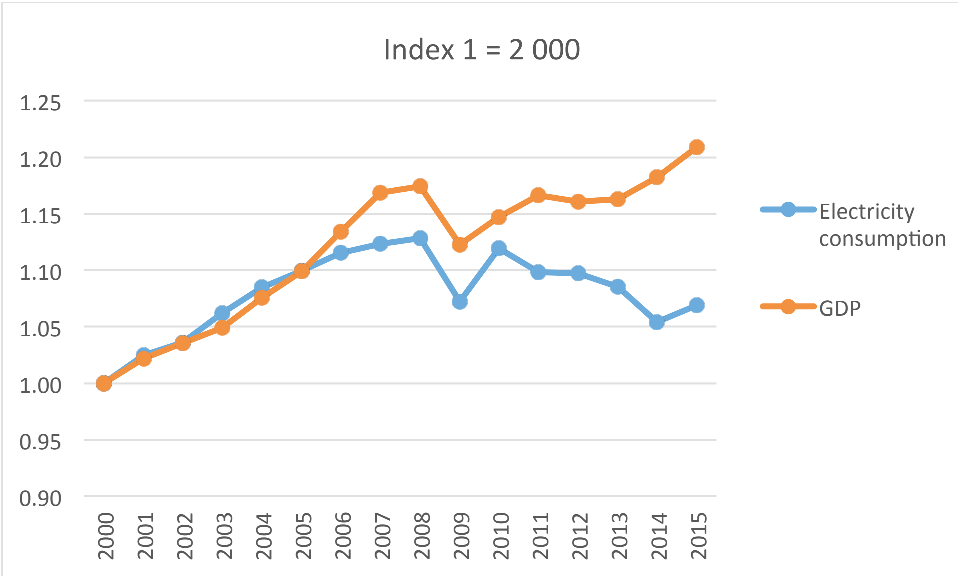

Figure 2: EU electricity demand versus GDP

Source: EUROSTAT 2016, Enerdata 2016

The difference between the patterns of the electrical energy consumption in the World and EU is indicative: while it marks an increase in the world, in Europe it remains almost parallel to the x-axis. Of course, this picture reflects also the economic stagnation in Europe, which has started in 2008.

The trend of divergence of the curves of GDP and the uses of electricity will continue in the future as a result of the :

- increase of efficiency of consumption and
- grid technologies' development

At the same time there are two factors that will soften this effect:

- increasing role of electricity in transport: electricity intensity of transport, and
- transition to renewable energy: the ratio RES-e/Electricity Demand

The gradual transition towards a low-carbon economy requires accelerated pace of renewable energies production and consumption (IRENA 2015, IRENA 2016), which is inevitably associated with an increased role of electricity. Processes that have been traditionally tightly connected with the utilization of fossil fuels, must now switch to electricity. This leads to electrification of the economy. The process will require more intensive development of power systems, structural changes and new forms of control.

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It is expected that the investments in low and medium voltage grids will increase with higher pace than the investments in transmission grids. On the other hand, it is not necessary to go into technical details of power system structure, having in mind the character of the model that will use this information. The economic models for energy development focus mainly on consumption and production, and reflect the technical infrastructure in general. This approach is correct as far as these types of models do not have the possibility to investigate technical solutions, typical for grids.

Power grid is infrastructure, which cannot be included in any other way in the economic model, except for with the cost of transformation, storage and transmission of electricity.

Basic information

The MEDEAS project aims to create a model for long-term planning of the transition to low-carbon global and EU economy.

Energy conversion and consumption are the main pollutants, emitting carbon emissions in the atmosphere. In seeking ways to emissions-free economy, the research carried out has shown that the only right decision is the transition to renewable sources' utilization, which inevitably leads to an increased share of the power sector in the global energy balance.

This process is not independent. On the contrary – it is part of the social transition, which considers environment, life-style, economy and transport as integral elements of it.

Power energy is the bridge to the emissions-free economy, because it allows for the utilization of the main natural resources – wind, water and solar radiation. The crucial difference between the use of fossil fuels and VRE lies within their availability over time and the possibilities to be controlled.

The tools for control of modern power systems are inadequate and require introduction of changes both in structure and in technologies. These involve sound investments. In accordance with the initial definition of the MEDEAS model, set in WP2, there is an obvious need of information regarding the costs for enhancement of electricity infrastructure - power lines, transformers, equipment and systems.

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In the known studies these assessments are made on the basis of production and consumption, taking into account the existing network structure, its performance and the need of substitution with new systems.

This is the reason to dedicate the next chapters to the overview of the available studies and projections, which are devoted mainly to demand, the necessary generation and its influence on the environment. Based on these projections, the needed infrastructure will be evaluated.

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Global projections

Electricity generation and consumption

The projections for energy development in the world included in the major analytical documents, cover a period of 25 years (IEA 2016c, IEA 2015, IEA 2014b, EIA 2016), or even more (WEC 2016). They comprise research by regions, international organizations (like OECD, etc.), continents and separate large countries.

There are also single studies devoted to projections of the development of individual important components, such as solar and wind electricity, which will also be considered here for comparison and possible adjustments.

Given the different approach or form of the data to be compared, there might become necessary to make certain assumptions, which should be explicitly underlined.

IEA World Energy Outlook 2016 (WEO 2016)

Energy consumption is closely connected with the economic development. Historically it has grown even more because residential consumers usually look for more comfort, which apparently requires more energy.

In the recent years, as a result of the more active policy orientation towards climate protection, the intensity of energy consumption, especially in Europe but also in the rest of the World, is not proportional to GDP. Energy demand decreases its contribution to the GDP growth. Markets offering energy services become more efficient thanks to the introduction of more efficient technologies and adoption of respective policies. A significant part of the world's economy is undergoing a structural change, including a burst of less energy–intensive forms of activities. (IEA 2015b)

In 2015 the global energy intensity of GDP decreased with 1,8%, which is mainly due to the obligatory regulatory rules, covering about 30% of the energy consumption (IEA 2016c). This process will continue in the future (Figure 3).

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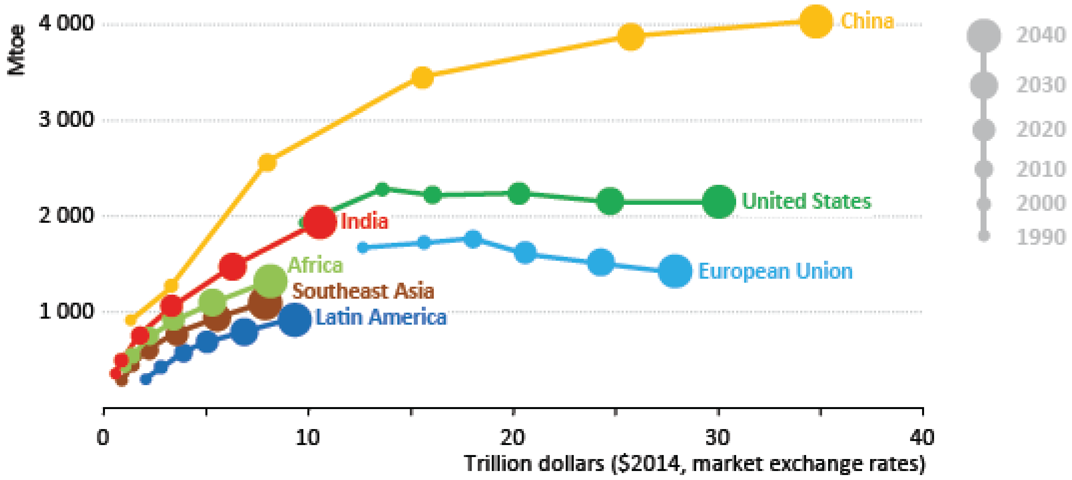

Figure 3: Primary energy demand and energy intensity of GDP in the New Policies Scenario

Source: IEA 2015b

There may be expected the same effect for the electricity, as a component of the energy balance, but there occur other strong factors.

To protect climate it is not enough to ensure effective consumption, but also to switch to new energy sources, whereby electricity is assigned a major role. Processes that have been traditionally tightly connected with the utilization of fossil fuels, now must switch to electricity, which leads to electrification of the economy. This process will require more intensive development of the power systems, new ways of construction and above all – new forms of control.

Three are three main scenarios elaborated in the studies of IEA - World Energy Outlook: Current Policy Scenario (CPS), New Policy Scenario (NPS) and 450S Scenario (450S), which differ significantly.

The ***Current Policy Scenario*** takes into account the policy in the field of climate protection, which has entered into force as of mid of 2016. It serves as a benchmark for measuring the results of other two scenarios.

The ***New Policies Scenario*** is built upon CPS with added new measures based on the COP21. It includes "*programmes to support renewable energy and improve energy efficiency, to promote alternative fuels and vehicles, carbon pricing, reform of energy subsidies, and the introduction, expansion or phase out of nuclear power*".

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The ***450 Scenario*** is based on the definition of the goal to limit the rise in the long-term average global temperature to two degrees Celsius (2°C), compared to the pre-industrial levels and the means to achieve it. It enhances NPS with a set of policies which are expected to contribute to the stabilization of the GHG concentration after 2100 at around 450 parts per million. This scenario includes also an assessment of the possible implementation of a 1,5°C target (IEA 2016c). 450S is developed in more details in *Energy and Climate: World Energy Outlook Special Report* (IEA 2015a) for the needs of COP21 and is being used in the two outlooks - WEO2015 and WEO2016.

The projections are based on several pre-conditions concerning the following parameters (IEA 2016c):

- annual growth of electricity consumption by 2% - 1,4% less than the annual economic growth projection;
- increased share of electricity in energy balance;
- increase of RE from 6 to 20%;
- One third less emission of CO2 per unit of electricity generation;
- 40% more power capacity per unit of electrical energy generated (due to the lower capacity factor of renewable energy generators);
- reduction of CO2 emission growth to 6%; etc.

Stronger preconditions are imposed on the 450 scenario, for instance

- energy efficiency policy to slowing total electricity demand to 30% less than NPS;
- reduction of fossil fuels based generation to about 15% in 2040, compensated by renewables, nuclear, and CCS;
- power sector emission reduced to ¼ of the current levels; etc.

The best understanding of the relation between GDP, demand of electricity and emissions under the different scenarios is given in the following Figure 4.

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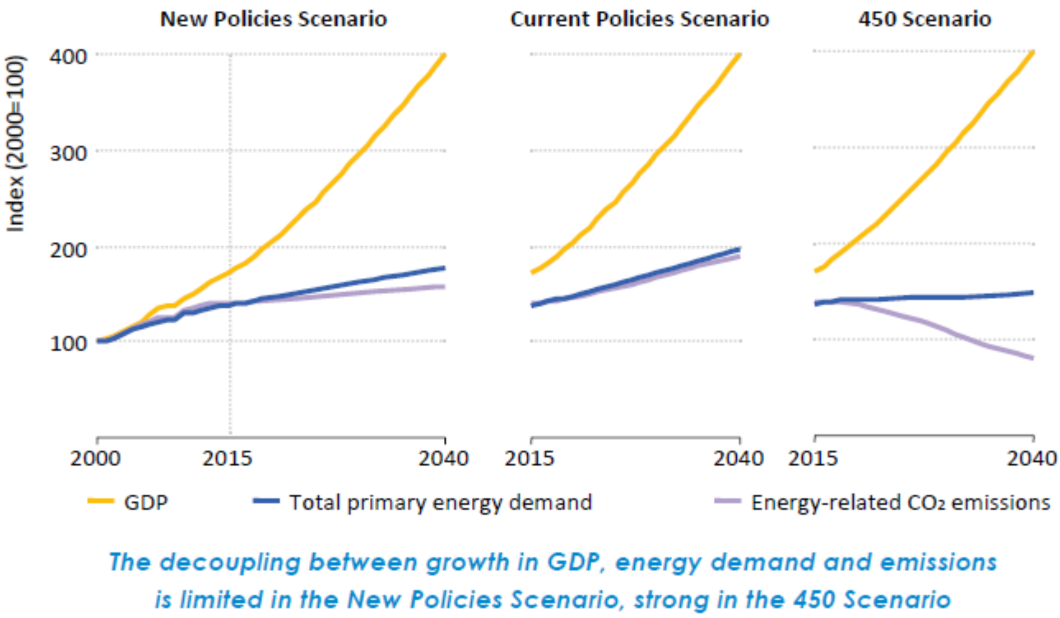

Figure 4: Global GDP, energy demand and energy-related CO2 emissions trajectories by scenario

Source: IEA 2016c

In order to make the comparison of results possible, the scenarios are developed under the condition of equal energy demand.

The world's electricity demand is presented in the next Table 1 where the three scenarios in WEO 2016 are analysed. The reference case scenario slows its increase especially more close to 2050 as the energy efficiency will grow and the economy structure will be less energy intensive. The overall trend is to reach larger share of low-carbon energy sources as they increasingly replace the fossil fuels.

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Table 1: World electricity demand[2] by scenarios, TWh

	2000	2014	CAAGR[1] 2000-2013, %	2020	2025	2030	2035	2040	CAAGR 2013-2040, %
NPS	13 199	20 557	3,2	23 186	25 755	28 612	31 521	34 250	2,0
CPS								37 037	2,3
450S								30 374	1,5

Source: IEA 2016c

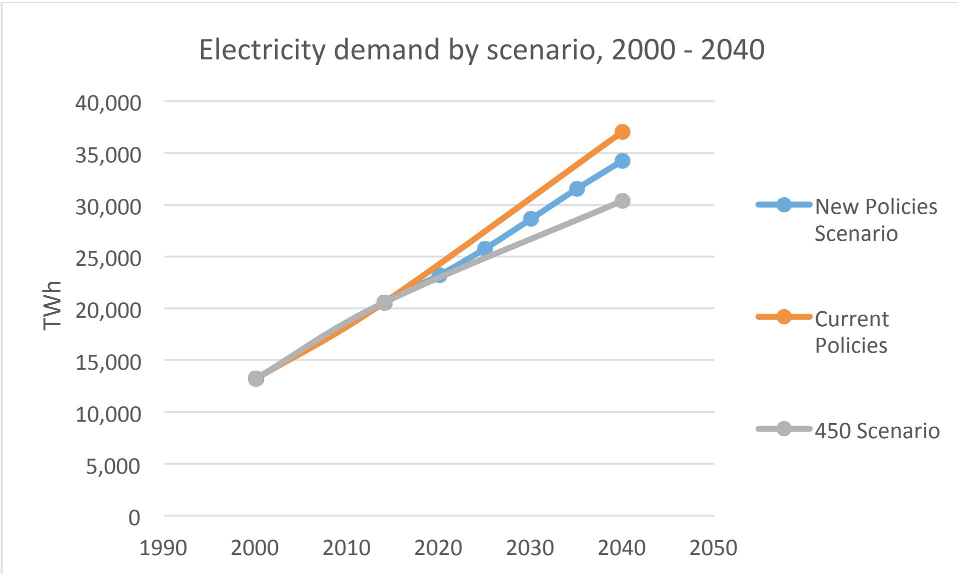

Figure 5: Electricity demand by scenario, 2000 – 2040

Source: IEA 2016c

[2] Electricity demand is defined as the total gross electricity generated minus the own use in generation, plus net trade (imports minus exports), minus transmission and distribution losses.

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Table 2 below depicts the amount of electricity produced in conformity with the above scenarios.

Table 2: Global electricity generation by source and scenario, TWh

	Historical		New policies		Current policies		450 Scenario	
	2000	**2014**	**2025**	**2040**	**2025**	**2040**	**2025**	**2040**
Total generation	15 476	23 809	29 540	39 047	30 886	42 511	27 688	34 092
Fossil fuels	10 017	15 890	17 175	20 243	19 183	26 246	14 113	8 108
Nuclear	2 591	2 535	3 405	4 532	3 319	3 960	3 685	6 101
Hydro	2 619	3 894	4 887	6 230	4 817	5 984	4 994	6 891
Other renewables	250	1 489	4 074	8 041	3 567	6 320	4 896	12 992

Source: IEA 2016c

The difference between production and demand determines the losses and auto-production shown in Table 3.

Table 3: Auto-production calculation, TWh

	Historical		New policies		Current policies		450 Scenario	
	2000	**2013**	**2020**	**2040**	**2020**	**2040**	**2020**	**2040**
Electricity generation	15 476	23 809	29 540	39 047	30 886	42 511	27 688	34 092
Electricity demand	13 199	20 557	25 755	34 250		37 037		30 374
Losses + own use	2 277	3 252	3 785	4 797		5 474		3 718
Percentage	14,70	13,66	12,81	12,28		12,88		10,91

Source: IEA 2016c

The losses of electricity in power systems in the world are around 8% (WB 2016), the rest are own needs.

It is natural to expect that the differences depend both on the amount of energy consumed, and the type of generating sources. Renewable energy has the advantage that large quantities are produced near the user and even by the user itself. There should be added that renewable sources are characterized by very low own needs.

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The following Table 4 presents projections of generating capacities under the different scenarios. The differences are minimal; only in 450S they are slightly larger, despite the significantly lower production and consumption. The reason lies in the significantly lower capacity factors of wind and solar generating plants – about 15% and 25% respectively.

Table 4: Global electrical capacities by scenarios, GW

	Electrical capacity, GW						CAAGR (%)
	2014	2020	2025	2030	2035	2040	2013 - 2040
New Policy Scenario	6 117	7 479	8 371	9 349	10 299	11 168	2,3
Current Policy Scenario		7 436		9 303		11 161	2,3
450S Scenario		7 447		9 554		11 766	2,5

Source: IEA 2016c

International Energy Outlook 2016 (EIA 2016)

EIA (US Energy Information Administration) focuses on a reference scenario and introduces a series of alterations in it. The EIA's approach in composing of projections becomes clear from the next quotation:

„The Reference case projection is a business-as-usual trend estimate, given known technology and technological and demographic trends. EIA explores the effects of alternative assumptions in other scenarios with different macroeconomic growth rates and world oil prices. The IEO 2016 cases generally assume that current laws and regulations are maintained throughout the projections. Thus, the projections provide policy-neutral baselines that can be used to analyse international energy markets." (EIA 2016)

And further: *„EIA has endeavoured to make these projections as objective, reliable, and useful as possible. They are intended to serve as an adjunct to, not a substitute for, a complete and focused analysis of public policy initiatives". (EIA 2016)*

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The energy production according to the reference scenario is presented in Table 5.

Table 5: Reference case, Net electricity generation, PWh

Energy source by region	2012	2020	2025	2030	2035	2040	CAAGR, 2012–2040
Total World	**21,6**	**25,8**	**28,4**	**30,8**	**33,6**	**36,5**	**1,9**
Fossil fuels	14,5	15,9	17,1	18,2	19,7	21,3	-2,2
Nuclear	2,3	3,1	3,4	3,9	4,3	4,5	2,3
RES	4,27	6,05	6,83	7,4	8,19	8,99	2,6
Wind	0,52	1,31	1,60	1,86	2,19	2,45	2,4
Solar	0,1	0,45	0,60	0,72	0,85	0,96	2,9
Others	0,53	0,75	1,07	1,30	1,42	1,72	4,1

Source: EIA 2016

The increase of electricity demand is less than 2%, which is lower than the average expected growth of the world economy. It could be seen that this projection relies on renewable sources and nuclear power plants, but at the same time the use of fossil fuels increases, except for oil.

Table 6 presents the projection of electricity production by sources under the reference scenario.

Table 6: Projection of capacities by sources, Reference scenario, GW

	2011	2012	2020	2025	2030	2035	2040	CAAGR (2012 – 2040) %
Total capacities	**5 201**	**5 439**	**6 577**	**6 982**	**7 422**	**7 924**	**8 456**	**1,7**
Fossil fuels	3 479	3 600	3 932	4 030	4 154	4 330	4 542	0,9
Nuclear	369	373	414	461	532	570	602	1,7
RES	1 353	1 466	2 231	2 491	2 736	3 024	3 312	3,1
Wind	220	269	569	656	750	867	961	4,7
Solar	69	95	293	364	427	491	551	6,5

Source: EIA 2016

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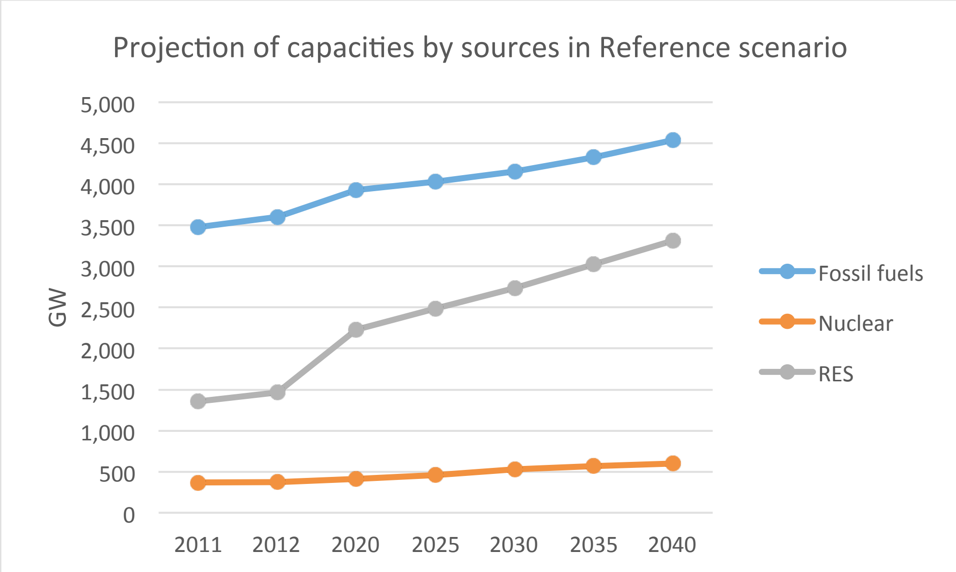

Figure 6: Projection of capacities by sources in Reference scenario, GW

Source: EIA 2016

EIA presents several scenarios with different characteristics – low and high oil prices, low and high economic growth – which affects the consumption, but there are no alternative scenarios for production.

World Energy Scenarios 2016, World Energy Council (WEC 2016)

The new World Energy Council's perspective towards energy transition until 2060 generates three distinct scenarios – Modern Jazz, Unfinished Symphony and Hard Rock. The Modern Jazz is based on fast-paced economic growth and constantly changing energy landscape due to rapid technology innovation. The Unfinished Symphony emphasis on the climate change policy and the civil society support. The Hard Rock scenario explores the energy transition through local level policies without consideration of global impacts, based on the conflicts in some parts of the world. (WEC 2016)

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The following table presents the electricity generation by fuels and scenarios from 2014 to 2060.

Table 7: Electricity generation by fuels and scenarios according to WEC 2016, TWh

Electricity generation	2014	2020	2030	2040	2050	2060	CAGR
Unfinished Symphony (USy)							
Total	**23 816**	**26 216**	**30 854**	**35 453**	**39843**	**44 474**	**1,4%**
Fossil	15 885	15 804	8 306	13 408	10 561	8 660	-1,3%
Nuclear	2 535	3 299	4 367	5 496	6 546	7 617	2,4%
RES	5 395	1 489	11 175	12 792	20 800	21 105	3%
Wind	717	132	2 918	4 928	7 431	9 326	5,7%
Solar	198	501	1 694	3 760	5 802	7 943	8,4%
Hard Rock (HR)							
Total	**23 816**	**26 728**	**30 605**	**35 559**	**40 191**	**44 914**	**1,4%**
Fossil fuels	15 885	16 571	11 191	1 464	20 963	20 401	0,5%
Nuclear	2 535	3 267	3 864	4 510	5 411	6 661	2,1%
RES	5 395	6 889	8 586	10 861	13 816	13 226	2%
Wind	717	1 264	1 983	2 946	4 063	5 608	4,6%
Solar	198	472	793	1 262	2 037	327	6,3%
Modern Jazz (MJ)							
Total	**23 816**	**27124**	**32 171**	**37 724**	**43 090**	**48 491**	**1,6%**
Fossil fuels	15 885	16 964	10 768	19 949	19 843	9 487	-1,1%
Nuclear	2 535	317	3 327	3 681	4 219	4 908	1,4%
RES	5 395	6 990	7 726	12 888	17 333	24 545	3,3%
Wind	717	1 316	254	4 257	6 433	8 818	5,6%
Solar	198	482	1 369	2 746	4 068	5 718	7,6%

Figure 6 proposes a comparison of the energy generation according to the three different scenarios until 2060.

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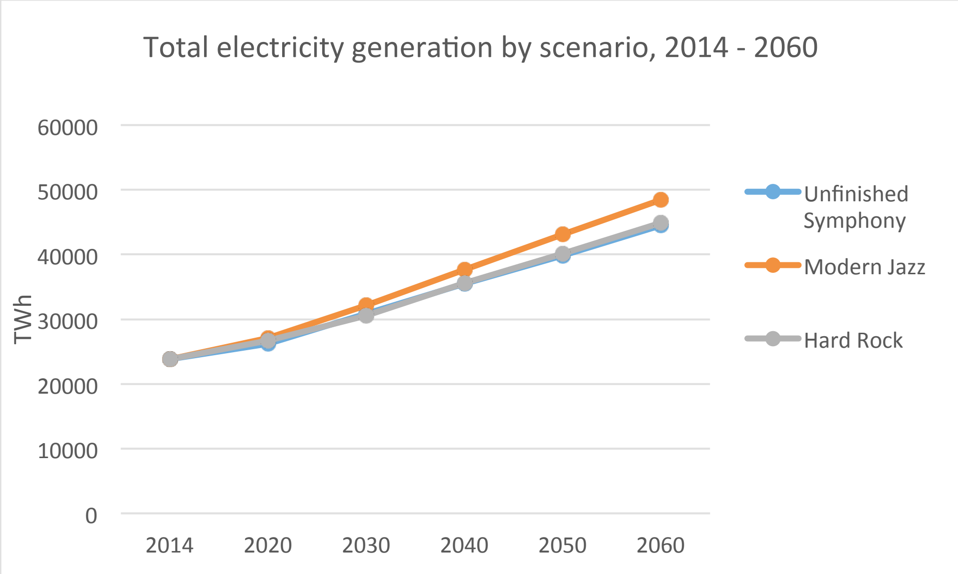

Figure 6: Electricity generation by scenario, 2014 – 2060

Source: WEC 2016

The projections – USy and HR – have identical curves, but the next Figure 7 shows that they are completely different from the point of view of generation types. USy has very high RE and low fossil fuel component, while HR is characterized by an exactly opposite combination – low RE and high fossils.

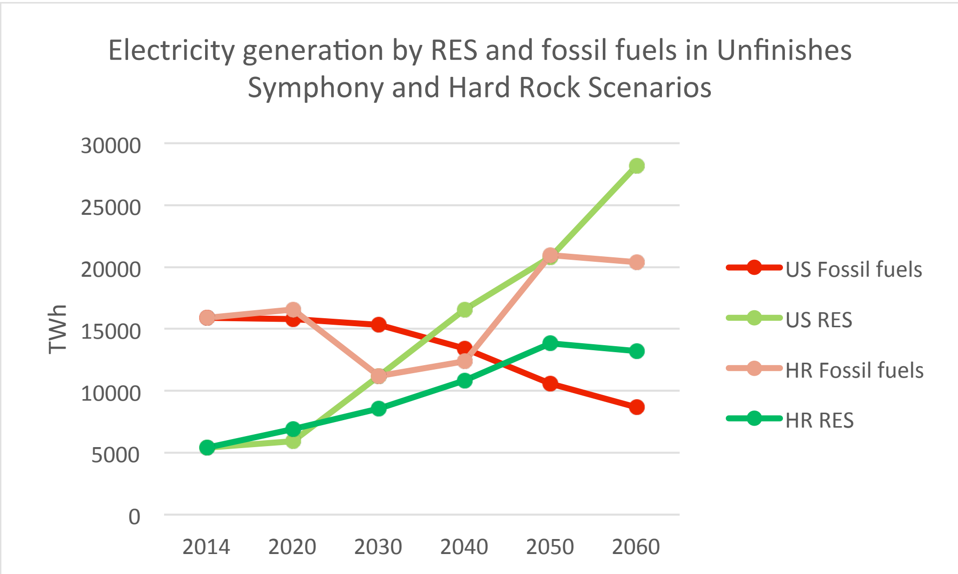

Figure 7: Electricity generation by fossil fuels and RES in Hard Rock and Unfinished Symphony (USy) scenarios, 2014 – 2060

Source: WEC 2016

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Comparison between sources

The IEA WEO's projections, which are the most complete, extend the horizon to the year 2040. NPS was developed in more details with projection for every 5 years. CPS and 450S are presented primarily with estimates of the baseline year (2013) and the final year (2040). In order to carry out comparisons between the scenarios, approximations are made where necessary.

The IEO 2016 elaborates one projection till 2040. Based on that, a number of variations in the oil prices and the economic development are made in order to establish their influence. The projections do not include changes in power capacities and generation. All analyses were made on the net amount of energy produced. In order to compare the results of EIA with those of the other sources, an assessment of own needs and losses in transmission network are added to the net energy amount.

As presented in Table 3, during the period 2013 - 2040 the losses and own use of electricity production differentiate between 12,65% and 14,80%. Those values are used to calculate the gross electricity production in the IEO 2016's Reference scenario in order to compare the IEA's, WEC's and EIA's data and forecasts (Table 8 and Figure 8). WEC has developed two projections, one of them (Jazz) could be considered conservative, less caring for the low-emission generation and, hence, for climate.

Table 8 presents 3 scenarios, which could be considered BAU under certain conditions. These scenarios are:

- WEO Current policy scenario
- IEO scenario
- WEC Jazz scenario

For the scenarios, which do not include projections for 2050, a linear extrapolation has been made. IEO disposes of information about net generation only. For the needs of the comparison, an assessment of own needs and of network losses was added. (See Table 3)

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Table 8: World total electricity generation by energy source. Reference case, 2013 - 2050, TWh

Year		TWh							Shares (%)		CAAGR (%)
		1990	2013	2014	2020	2030	2040	2050	2020	2040	2020 - 2040
WEO 2016	Fossil fuels	7 495	n/a	15 890	16 367	18 202	20 242	23 494	61	52	1,1
	Nuclear	2013	n/a	2 535	3 053	3 720	4 532	4 727	11	12	2
	RES	2 3196	n/a	5 383	7 280	10 192	14 270	15 157	27	37	3,4
	Total generation	11 863	n/a	23 809	26 698	32 287	39 045	44 534	100	100	1,9
IEO 2016	Fossil fuels	n/a	8 861	n/a	9 727	10 121	10 621	11 314	38	29	0,4
	Nuclear	n/a	2 455	n/a	3 051	3 946	4 501	5 354	12	12	2
	RES	n/a	4 948	n/a	6 874	8 682	10 628	12 772	27	29	2,2
	Total generation	n/a	22 123	n/a	25 765	30 842	36 455	41 618	100	100	1,8
	Above + AP + Losses	n/a	25 134	n/a	29 145	34 614	41 067	46 425	100	100	1,8
WEC Modern Jazz	Fossil fuels	n/a	n/a	15 885	16 964	10 768	19 994	19 843	63	20	0,6
	Nuclear	n/a	n/a	2 535	3 170	3 327	3 681	4 219	12	10	1,4
	RES	n/a	n/a	2 395	6 990	7 726	12 888	17 333	26	40	3,3
	Total generation	n/a	n/a	23 816	27 961	35 198	44 454	53 647	100	100	2,7

Source: WEC 2013, IEA 2016c, EIA 2016

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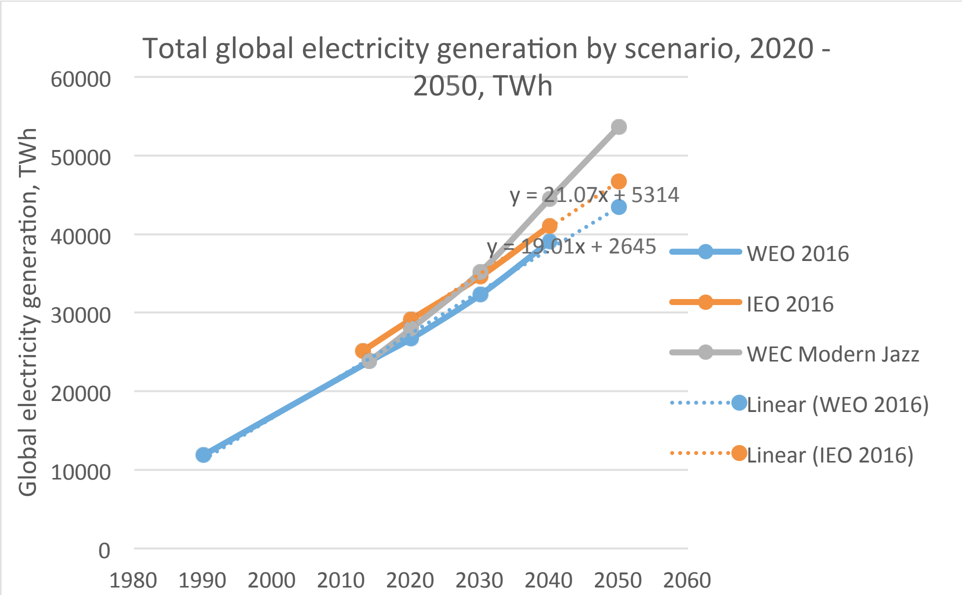

Figure 8: BAU scenarios of WEO and WEC, and the basic scenario of IEO

Source: WEC 2016, IEA 2016c, EIA 2016

Figure 9 depicts the three scenarios, which have climate protection as their main target. These include the two WEO's scenarios - New Policy and 450S, and WEC's Symphony scenario.

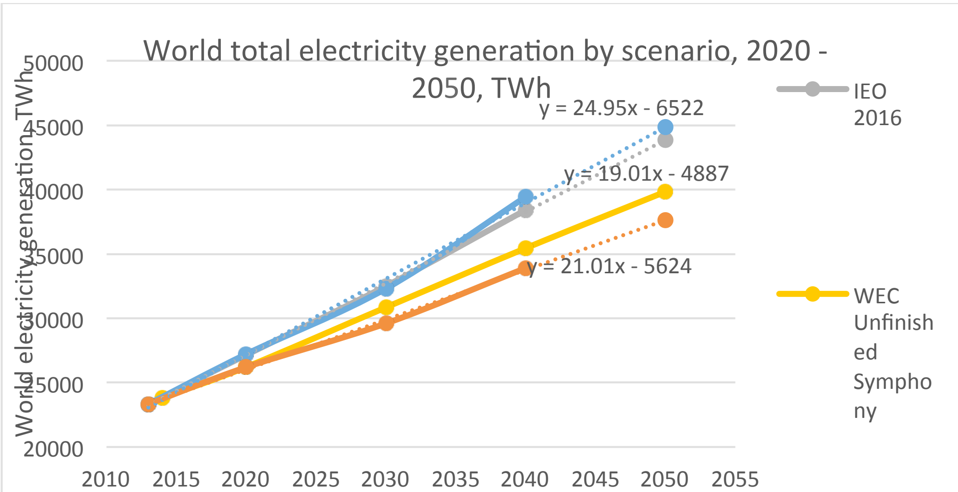

Figure 9: Scenarios aiming at the speeding up of the transition to low-carbon economy

Source: WEC 2016, IEA 2016c, EIA 2016

The following tables present the solar and wind energy projections, which are included in the various sources and scenarios.

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Table 9: World installed wind-powered generating capacity by source, GW

SCENARIO	2010	2014	2020	2030	2040	2050	Growth (2010/'13-2050), %
IEO 2016 Reference Sc.	173	n/a	569	750	961	n/a	5,9
WEC Jazz	191	n/a	404	621	1 290	1 824	5,8
WEC Symphony	191	n/a	667	1 059	1 274	1 654	5,5
WEO 2016, New policies	n/a	351	670	1 119	1 504	1 978	5,8
WEO 2016, Current policies	n/a	351	621	940	1 214	1 518	4,9
WEO 2016, 450S	n/a	351	710	1 572	2 312	3 133	7,5
IEA Energy Technology Perspectives to 2050	n/a	n/a	671	1 024	1 572	2 016	3,7

Source: EIA 2016, WEC 2013, IEA 2016c, IEA 2010

Table 10: World installed solar-powered generating capacity by source, GW

SCENARIO	2010	2014	2020	2030	2040	2050	Growth (2010/'13/'20-2040), %
IEO 2016 Reference Sc.	37	n/a	293	427	551	n/a	6,5
WEC Jazz	39	n/a	255	326	445	1 654	9,8
WEC Symphony	39	n/a	437	1 451	3 585	4 439	12,8
WEO 2016, New policies	n/a	176	481	949	1 405	1 887	8,3
WEO 2016, Current policies	n/a	176	424	708	991	1 275	6,9
WEO 2016, 450S	n/a	176	517	1 278	2 108	2 892	10,02
IEA Energy Technology Perspectives to 2050	n/a	n/a	511	1 632	2 895	4 512	9

Source: EIA 2016, WEC 2013, IEA 2016c, IEA 2010

The WEO scenarios are analysed in much more details, while the IEO's study focuses on the impact of oil prices and of the economic development.

Under the current circumstances and given the nature of the preliminary available information regarding the requirements of the MEDEAS model under development, **WEO's model might be preferred**, and in case of need to combine several characteristics from both scenarios.

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Investments in network construction

The information about grid development, and particularly concerning the involved costs, is very limited. There should be followed carefully the appearance of new specialized studies on the expected development of electricity production, similar to the recently published study by the Global Wind Energy Council (GWEC 2016) which covers the period till 2050 and contains detailed information about wind global projections and the corresponding costs for integration.

Table 11 presents the global investments needed by energy types till 2050 separated in two periods 2016 – 2025 and 2026 – 2050 as provided by the WEO New Policies Scenario.

Table 11: Cumulative global investment in power sector by energy type in the New Policies Scenario, 2016-2050, USD2015 billion

	2016 - 2025					
	Fossil fuels	Nuclear	Renewables	Total Plant	T&D	Total
World	1 148	529	2 544	4 220	2 989	**7 210**

	Continued 2026 - 2040						2015-2050
	Fossil fuels	Nuclear	Renewables	Total Plant	T&D	Total	Total
World	2 743	1 586	8 096	12 425	9 054	**21 479**	**34 354**

Source: IEA 2016c

Better understanding of the interrelations between the investments in Transmission&Distribution and Generation could be obtained from the next Figure 10.

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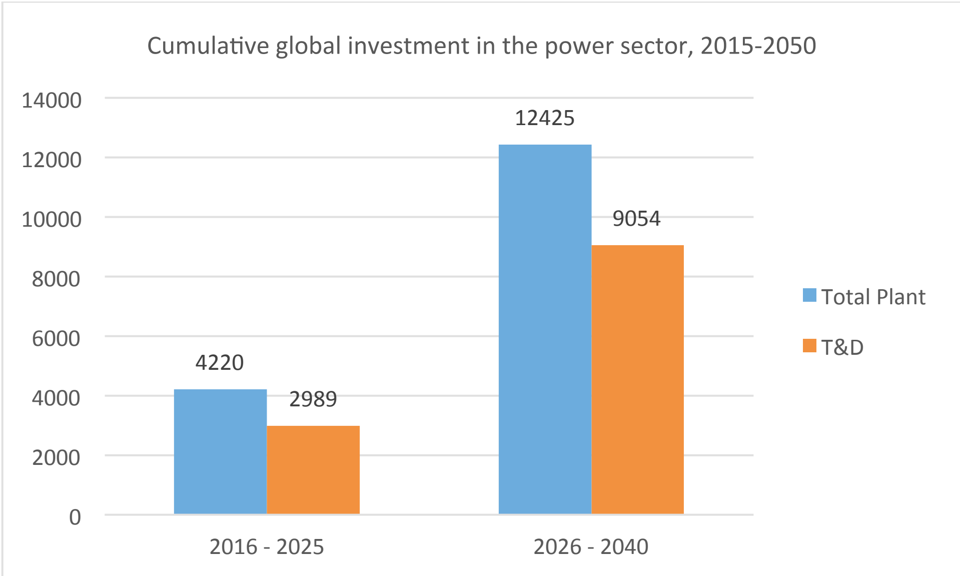

Figure 10: Cumulative investment in power production and T&D sectors in the New Policies Scenario, 2016 - 2050 (USD2015 billion)

Source: IEA 2016c

It is interesting to see that the costs related to infrastructure are very similar to those of the generating system, despite the established opinion that they usually do not affect the strategic decisions.

Under the considered perspective this is expected because the completely new generation characteristics impose a revision of the concept regarding the network and the introduction of new technologies for its control and protection.

As it was already mentioned, the **450 Scenario** has fixed outcomes: no more than 2°C long-term average global temperature. NPS does not satisfy this requirement and a set of additional measures and corresponding investments are necessary to achieve the target. The assessment of IEA about the investments in generation and infrastructure are presented in Table 12 and Table 13 below.

Table 12: Cumulative global power generation and T&D investment in the 450 Scenario, 2016-2040, USD2015 trillion

	Fossil and Nuclear	Dispatchable Renewables	Variable Renewables	TOTAL
Generation	4,2	4,5	6,5	15,5

Source: IEA 2016

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Table 13: Cumulative global T&D investment in the 450 Scenario, 2016-2040, USD2015 trillion

	Transmission	Distribution	VRE integration	TOTAL
Infrastructure	1,5	4,7	1	7,2

Source: IEA 2016

It is interesting to compare the investment in NPS and 450S projections, as shown in Table 14.

Table 14: Comparison of investment in NPS 450S projections, 2016-2040, USD2015 trillion

	Fossil and Nuclear	Renewables	T&D	Total
NPS	4,1	7,1	8,1	19,3
450S	4,2	11	7,2	22,4

Source: IEA 2016c

As expected, the investments in renewable generation are higher (about 35%), but those in transmission and distribution are lower (about 11%) due, most probably, to the distributed generation.

Special attention shall be paid to energy storage technologies, which are indispensable for the large application of the active scenarios towards low carbon energy. These should be divided into two types according to the place of their application:

- System (network)-oriented
- Consumer-oriented

The projections for the development of electricity system do not provide particular figures regarding the accumulating technologies. It is considered here that these costs are included in the costs of the network.

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European Union projections

Strategic documents

The "Climate and energy package 2020" defines three key targets in conformity with the European Strategy (EC 2010):

- 20% reduction of greenhouse gas emissions (compared to 1990 levels)
- 20% of EU energy from renewables
- 20% higher energy efficiency

The package encompasses a set of binding legislative documents to ensure the attainment of these targets.

The existing framework on energy development and climate protection till 2030 foresees:

- At least 40% reduction of GHG emissions compared to 1990
- At least 27% renewable energy
- At least 27% improved energy efficiency

The EU policy in 2050 should be directed towards reduction of GHG emissions by 80 – 95% compared to the 1990 levels, while the target for 2040 is 60%.

These targets should be attained through internal measures without relying on loans outside the EU.

A key factor in this process is the production and consumption of electricity. It will be generated almost exclusively through low-carbon technologies: RES, nuclear, fossil fuel power stations equipped with carbon capture and storage technologies.

Projections for the power sector development at a global and European scale are being made systematically by consistent consideration of the emerging opportunities and needs. For the needs of the MEDEAS project only the most recent ones will be used: EU 2011a, EC 2013a, e-highway2050 2016, IEA 2016c, EIA 2016.

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Electricity generation and consumption

e-highway 2050 (E-highway 2015a, 2015b)

The study e-Highway2050 supported by the Seventh Framework Programme of the EU is intended to develop a methodology for the planning of a Pan-European Transmission Network, by considering the main strategic guideline of the EU energy sector: climate protection under energy market conditions. The study focuses on construction of the main power network – high and ultra-high voltage by 2050, based on the already approved steady development by 2020.

The following five scenarios are thoroughly investigated:

- **100% RES**: stop of using fossil fuels
- **Big & Market**: leading rule is the expansion of power and CO_2 markets
- **Large fossil fuel with CCS, and nuclear**
- **Large scale RES & no emission**
- **Small and local:** bottom-up strategy mainly based on small-scale/local solutions to reach this target

The methodology does not study BAU scenarios. All scenarios meet the EU targets of 80-95% GHG reduction, in different ways (EC 2011c). The investigations are very technical and specific, and are not convenient for inclusion directly in models like MEDEAS. They however may be used as benchmarking of MEDEAS results.

IEA World Energy Outlook 2016, 2015 and 2014

The 3 scenarios for Europe – New Policy, Policy As Usual and 450 Scenario – have already been described shortly in the Global projection chapter. The parameters of EU projections are similar to the ones listed in that chapter.

The projections for electricity demand according to the three scenarios are presented in the following

Table 15. Compared with the global projections they are much more modest which is normal for developed countries.

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Table 15: Electricity demand in the EU by scenarios, TWh

	1990	2014	CAAGR 1990 – 14, %	2020	2025	2030	2035	2040	CAAGR 2013 – 40, %
NPS				2 861	2 931	2 966	3 024	3 047	0,4
CPS	2 605	2 836	0,94	2 896		3 152		3 384	0,8
450S				2 814		2 861		2 977	0,4

Source: IEA 2016c

There should be reminded that CPS serves as a reference scenario, which helps in assessing the characteristics and achievements of NPS and 450S. The attention is focused on NP scenario more than on 450S, but this will most probably change in the future.

Table 16 shows the structure of electricity generation in accordance with NPS. The three main components of generation – fossil, nuclear and RES - are presented as well.

Table 16: Electricity generation in the EU New policy scenario, TWh

	Electricity generation, TWh								Shares (%)		CAAGR (%)
	1990	2014	2020	2025	2030	2035	2040	2050	2013	2050	2014 - 2050
Total generation	**2 577**	**3 155**	**3 299**	**3 355**	**3 379**	**3 416**	**3 427**	**3 681**	**100**	**100**	**0,36**
Fossil fuels	1 467	1 355	1 304	1 284	1 137	1 003	883	952	46	24	-0,95
Nuclear	795	876	839	731	720	727	719	707	27	21	-0,28
RES, among them	315	920	1 156	1 342	1 522	1 686	1 824	2 125	29	54	2,29
wind	1	253	416	542	666	771	851	998	8	25	3,78
solar	0	97	136	160	180	205	226	279	3	7	8,09

Source: IEA 2016c

For the sake of comparison the next Table 17 illustrates the calculation of electricity demand. Information from the World Bank database is used. Electricity losses in the EU power systems represent about 6,5%[3] (WB 2016), which are supposed to go down, although without expecting significant decrease, except for in the Eastern European countries. Normally, electricity losses in high-voltage systems are very low – below 2%, hence the direction of losses' percentage in future

[3]About 6% according to IEA WEO, 2015 (page 317) (IEA 2015b)

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will depend on the distribution of RES-e production and correspondingly – on the flows in low- and medium-voltage grids.

The difference between generation and demand determines the losses and auto-production shown in Table 17.

Table 17: Auto-production calculation in the EU, TWh

			New policies		Current policies		450S Scenario	
	1990	2014	2020	2040	2020	2040	2020	2040
Electricity generation	2 576	3 225	3 266	3 408	3 334	3 829	3 195	3 291
Electricity demand	2 163	2 710	2 861	3 047	2 896	3 384	2 814	2 977
Losses+ own use	430	389	359	327	3 334	382	3 195	302
Percentage	16,03	15,97	12,4	10,59	13,14	11,62	11,92	9,54

Source: IEA 2016c

The next Table 18 presents the projections of generating capacities according to the different scenarios. The differences are negligible, only in 450S they are greater despite the lower production and consumption. The reason could be found in the lower capacity factors of wind and solar generating installations – about 15% and 25% respectively.

Table 18: European Union: Electrical capacities by scenarios, GW

	Electrical capacity, GW						CAAGR (%)
	2013	2020	2025	2030	2035	2040	2013 - 2040
New Policy Scenario	976	1 066	1 123	1 176	1 228	1 265	1,0
Current Policy Scenario		1 064		1 171		1 275	1,0
450S Scenario		1 060		1 181		1 312	1,1

Source: IEA 2016c

Gridtech project

The project GridTech (GridTech 2015) analysed projections for the development of the European power transmission network till 2050 in order to define the opportunities to increase the system's flexibility through the introduction of technical solutions, which would allow for the integration of intermittent generation. It covered Transmission Grid Technologies (TGT), Energy Storage Technologies (EST) and Electricity Demand Technologies (EDT).

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The project studied one main scenario (S0) for the development of the European transmission system, including Turkey, and different scenarios for increasing its flexibility through technological solutions, in order to meet the constantly growing capacities by 2050. The alternative scenarios differed by their focus on particular technologies.

It was accepted for 2020 to start with the plan by ENTSO-e (ENTSO-e 2013) with consideration of different European documents, e.g. national plans and studies. The next stages – 2030, 2040 and 2050 – were built upon consideration of various EU and national strategic documents for emissions' reduction, RES development etc. (EC 2013b, ENTSO-e 2014).

The results of Gridtech will not be used for further analyses because of the serious differences of concepts of GRIDTECH and MEDEAS.

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Energy Roadmap 2050

Roadmap 2011 information

The foundations of this energy strategy were laid down in 2011 (EC 2011a, EC 2011b, EC 2011c) on the basis of already existing strategic documents, for instance "Europe 2020: A strategy for smart, sustainable and inclusive growth." (EC 2010) A Reference scenario and several alternative decarbonisation scenarios were developed. They differ one from another by the way in which the aim of 85% CO_2 emissions reduction will be attained, as it is shown in Table 19.

Table 19: Roadmap 2011 scenarios main characteristics

Scenario	Reference	Current trends and recent Eurostat
1bis	Current Policy Initiatives (CPI)	Additional to Reference initiatives reflecting the new EU documents in 2012
S2	Energy Efficiency	Very high primary energy savings by 2050 and a very stringent implementation of the Energy Efficiency Plan
S3	Diversified supply technologies	All energy sources can compete on a market basis without specific support measures
S4	High RES	Higher overall RES share and very high RES penetration in power generation
S5	Delayed CCS	Difficulties for CCS regarding storage sites
S6	Low nuclear	The public perception of nuclear safety remains low

Source: EC 2011c

The European Network of Transmission System Operators proposed "the setting-up of a **EC Masterplan** ***for Electricity Highway Implementation*** *as a community tool enabling us to keep up with the objectives of the EC related to the establishment of the electricity* ***Highway System*** *and to achieve the EU's energy policy targets.*" (ENTSO-e 2012) The idea was realised later by the e-highway 2050 project. (e-highway 2015)

The initial political documents were just the beginning of a comprehensive strategy that develops systematically a stream of various regulatory and policy materials – from Directives to Opinions (EC 2013a, EC 2013b, EC 2013c).

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Table 20 shows the different demand according to the 6 scenarios.

Table 20: R2011, Electricity final demand, TWh

	2005	2050						
		Ref	1bis	S2	S3	S4	S5	S6
Final energy demand	2 762	4 130	3 951	3 203	3 618	3 377	3 585	3 552
Industry	1 134	1 504	1 426	1 109	1 211	1 169	1 201	1 191
Households	795	1 343	1 230	913	1 026	938	1 019	1 013
Tertiary	759	1 184	1 041	518	707	605	696	677
Transport	74	100	255	663	675	664	669	671

Source: EC 2011c

The differences between the scenarios are presented in the following figure, comparing the 2005 scenario with the six scenarios for 2050.

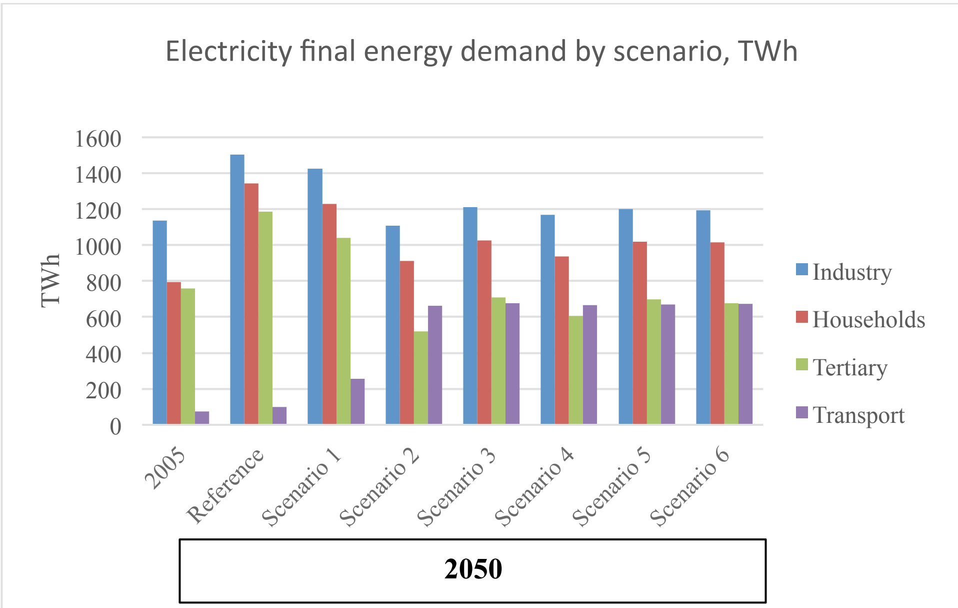

Figure 11: R2011 Final electricity demand in 2050 by scenario, TWh

Source: EC 2011c

Electricity production is presented in the following

Table 21. The variety of scenarios offers the possibility to make a subsequent evaluation of the necessary regulatory framework.

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Table 21: European Union: Electricity generation, TWh, %

Electricity generation		2005	2050						
			Ref	1bis	S2	S3	S4	S5	S6
Total	**TWh**	**3 274**	**4 931**	**4 620**	**4 281**	**4 912**	**5 142**	**4 872**	**4 853**
Nuclear energy	**Shares (%)**	30,5	26,4	20,6	14,2	16,1	3,5	19,2	2,5
Renewables		14,3	40,3	48,8	64,2	59,1	83,1	60,7	64,8
Hydro		9,4	7,6	8,5	9,2	8	7,7	8,1	8,1
Wind		2,2	20,1	24,7	33,2	31,6	48,7	32,4	35,6
Solar, tidal, etc.		0	5,1	7	10,6	9,9	16,4	9,9	10,8
Fossil fuels		55,2	33,3	30,6	21,6	24,8	9,6	20,1	32,7
Other fuels (hydrogen, methanol)		0	0	0	0	0	3,9	0	0

Source: EC 2011c

A clear view of the differences in electricity generation by the various scenarios could be got from the Figure 12 that follows.

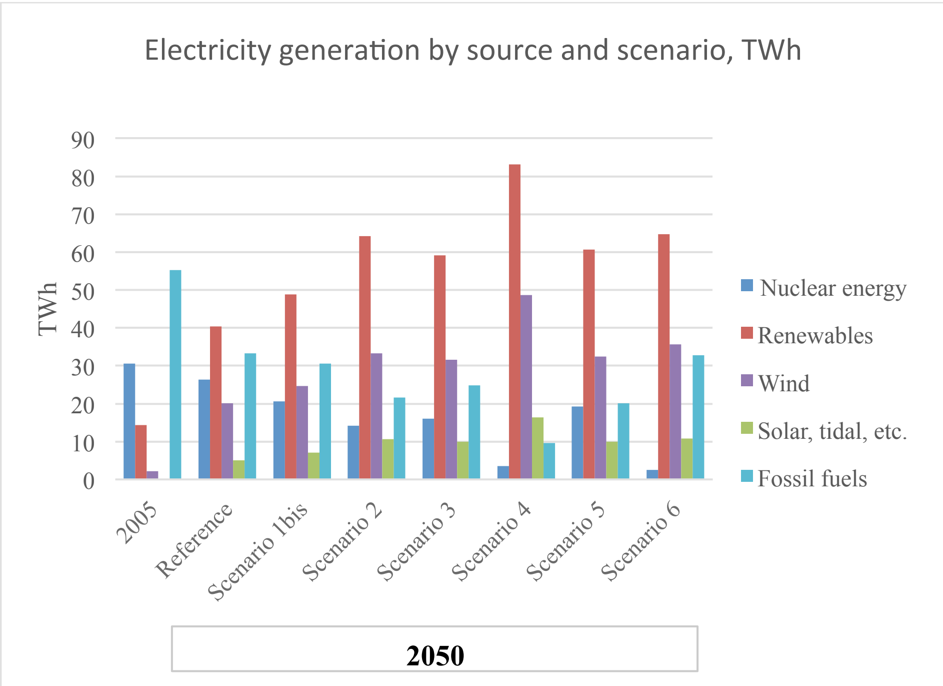

Figure 12: R2011 Electricity generation by source and scenario, TWh

Source: EC 2011c

The necessary power capacities are presented in Table 22.

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Table 22: Necessary power capacities, MW

	2005	2050						
		Ref	1bis	S2	S3	S4	S5	S6
Net Installed Power Capacity	**715**	**1 454**	**1 502**	**1 473**	**1 621**	**2 219**	**1 639**	**1 721**
Nuclear energy	134	161	117	79	102	41	127	16
Renewables (excluding biomass/geothermal), of them	147	681	784	1 012	1 081	1 749	1 093	1 193
Hydro (pumping excluded)	105	121	122	125	126	131	126	127
Wind power	41	382	432	548	595	984	609	674
Solar	2	171	224	330	351	603	348	381
Thermal power	434	613	601	382	439	429	419	513

Source: EC 2011c

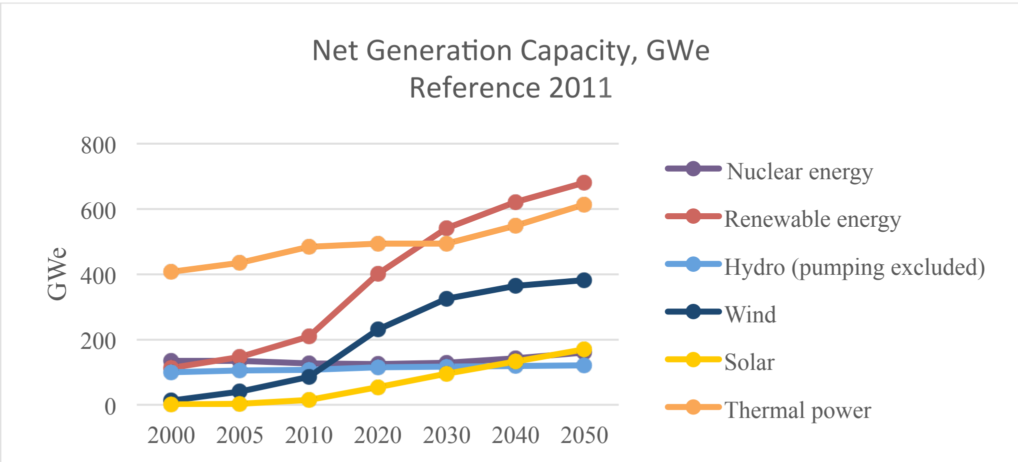

Figure 13: Net electricity generation capacities, R2011, Reference scenario

Source: EC 2011c

Roadmap 2016 information

In 2013, the European Commission published a projection of the reference scenario with consideration of the changed economic situation in the EU and the development of the technologies (EC 2013a, EC 2013b and EC 2013c). After the new projection made in 2016 (EC 2016), the earlier one has been considered an intermediate stage.

The projection from 2016 elaborates the reference scenario taking into account the most current (by 2015) macroeconomic development of the World and Europe, technological achievements and

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regulatory framework[4]. The document considers the energy sector in close relationship with the mutually interrelating transport sector and climate.

Table 23 and Table 24 show projections of the power generation and installed capacities according to the last edition of the Roadmap.

Table 23: R2016, Energy generation projection, TWh

	2000	2005	2010	2020	2030	2040	2050
Gross electricity generation by source	**3 006**	**3 290**	**3 333**	**3 358**	**3 528**	**3 760**	**4 064**
Nuclear energy	945	997	917	772	778	734	737
Fossil fuels	1 629	1 814	1 715 937	1 370	1 237	1 269	1 092
Renewable energy, of which	431	478	700	1 215	1 513	1 757	2 235
Wind	22	70	149	463	608	692	980
Solar	0,1	1,5	22	155	232	293	429

Source: EC 2016

[4] *The projections are based on a set of assumptions, including on population growth, macroeconomic and oil price developments, technology improvements, and policies. Regarding policies, projections show the impacts of the full implementation of existing legally binding 2020 targets and EU legislation. As such, they also show the continued impact post 2020 of policies such as the EU Emissions Trading System Directive (including the Market Stability Reserve), the Energy Performance of Buildings Directive, Regulations on eco-design and on CO2 emission standards for cars and vans, as well as the recently revised F-gas Regulation. Such policies notably influence current investment decisions, with impacts on the stock of buildings, equipment and cars, which have long-lasting effects post-2020 on GHG emissions or energy consumption.* (EC 2016)

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Table 24: R2016, Generation capacity projection

	2000	2005	2010	2020	2030	2040	2050
MW							
Net Generation Capacity	**683 507**	**739 589**	**858 628**	**1 029 680**	**1 059 230**	**1 088 931**	**1 283 315**
Nuclear energy	139 595	136 829	132 606	114 204	109 905	97 243	92 824
Renewable energy	128 990	162 194	238 638	475 177	570 572	628 282	807 312
Hydro (pumping excluded)	115 841	119 177	122 922	131 473	133 190	136 576	142 001
Wind	12 730	40 485	85 701	207 219	255 388	279 259	367 622
Solar	178	2292	29 774	135 999	180 956	210 126	294 710
TWh							
Thermal power	414 922	440 565	487 384	440 299	378 753	363406	383 178

Source: EC 2016

Figure 14 illustrates the sharp increase of RE in comparison to the reference scenario from 2011.

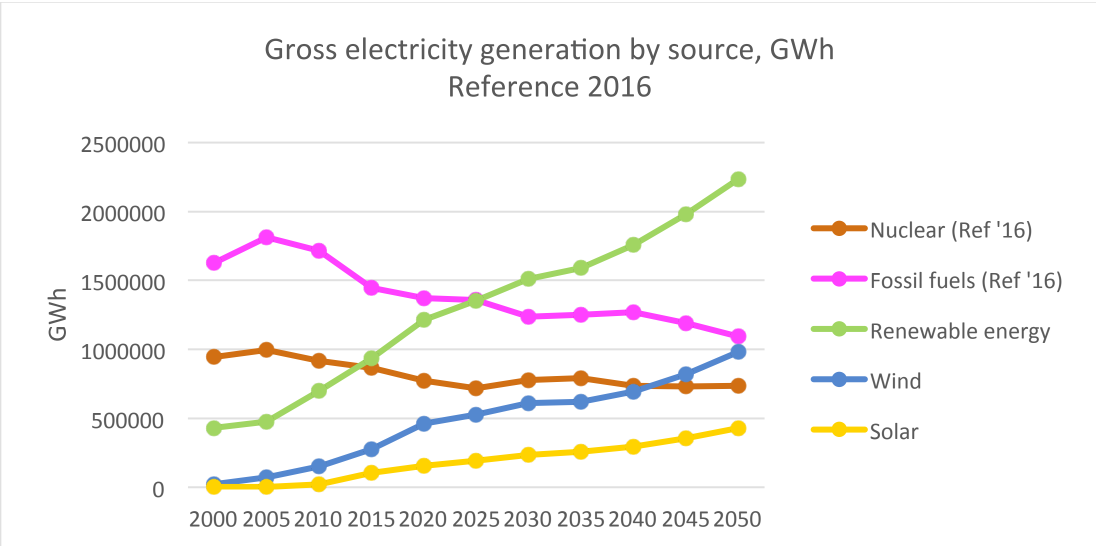

Figure 14: Gross electricity generation by source, Reference Scenario 2016

Source: EC 2016

It is interesting to see the difference between the two reference scenarios as regards the total generating capacity on the following Figure 15. WEO's New Policies Scenario is added to the graphic for the needs of the comparison.

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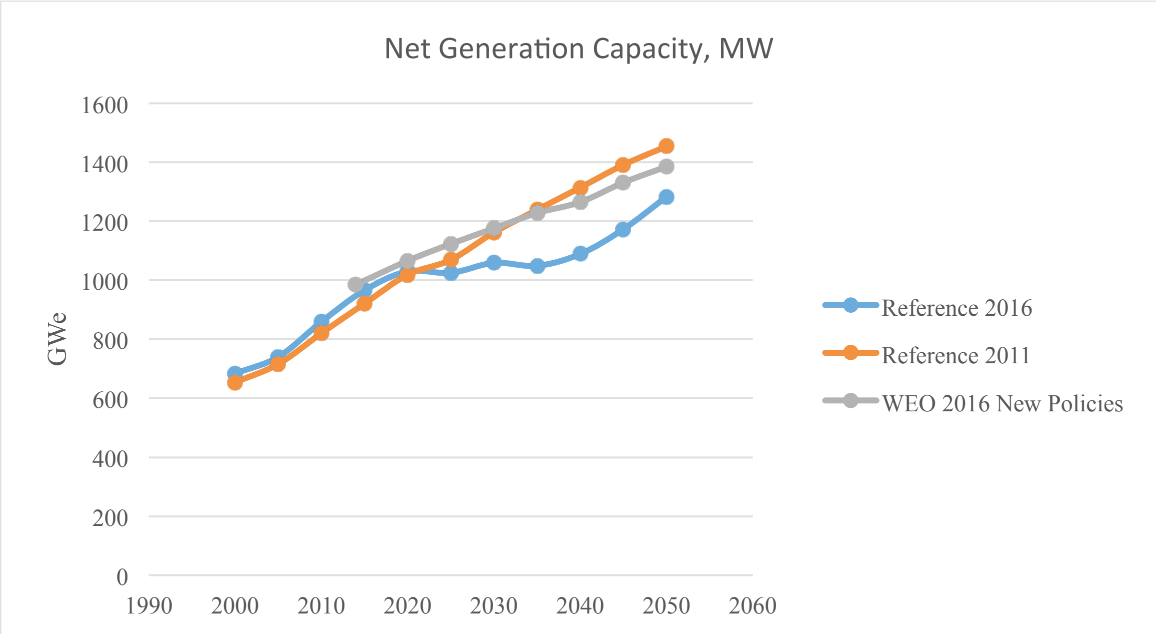

Figure 15: Comparison of generation capacity of Reference Scenario 2011, Reference Scenario 2016 and WEO 2016 New Policies Scenario

Source: EC 2011c, EC 2016

The production of electricity after 2020 according to both the Roadmap 2016 and the WEO 2016 scenarios is expected to be lower than the initially foreseen in the Roadmap 2011 scenario, probably as a result of a set of factors, the most important of which is the energy efficiency.

Figure 16 compares the projections for gross electricity generation from nuclear and renewable energy according to the Reference scenarios from 2011 and 2016. In the last study there could be observed a sharp change in the importance of RES utilization and its share, which is almost two times higher than the projected in 2011 one.

These drastic differences show that the 2011 projections are reappraised, but detailed information is still missing.

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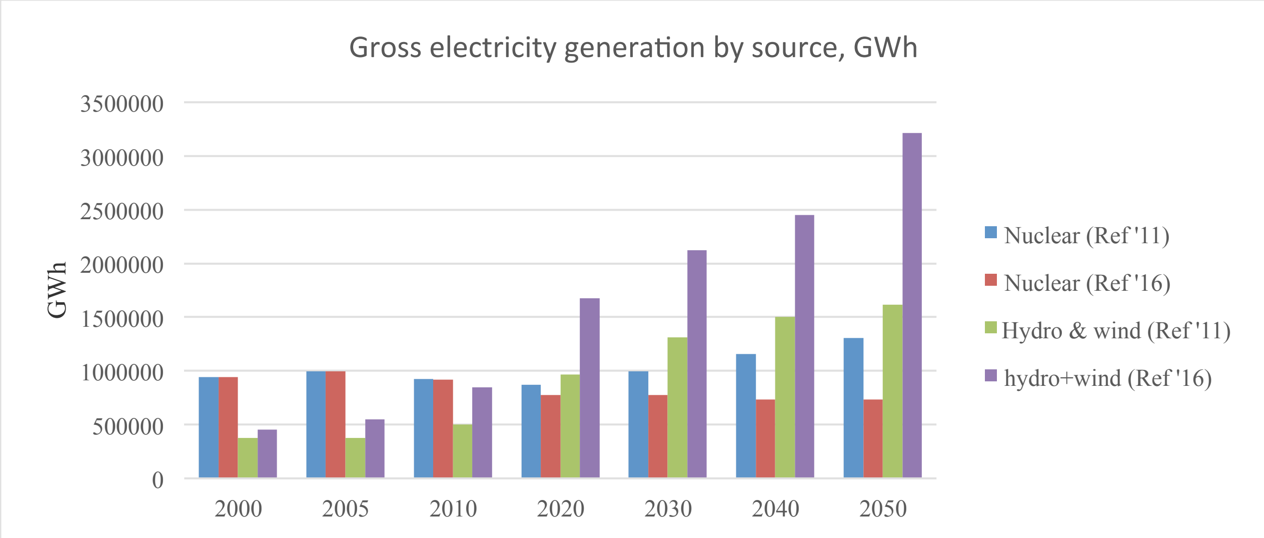

Figure 16: Projection of gross electricity generation in 2050 by sources

Sources: EC 2011c, EC 2016

Comparison between sources

The EC FP7 project e-Highway focuses exclusively on ultrahigh voltage power networks. The study bases on 6 scenarios, each of them fulfilling the requirement for CO_2 emissions' reduction by 80-85%. For the needs of MEDEAS, it could serve as a comparison and navigation through the process of the particular research of the electricity grid due in WP7.

The project GridTECH studies the influence of 3 groups of technologies - Transmission Grid Technologies (TGT), Energy Storage Technologies (EST) and Electricity Demand Technologies (EDT) – on the building of power network till 2050. The results are of high interest from the point of view of the requirements towards the future technological development and they could be used at a later stage of the MEDEAS implementation. As far as this project covers the whole European network, including Turkey, it is difficult to compare the information with that for the EU.

The study developed by WEC analyses two scenarios: Symphony (sustainability) and Jazz (energy affordability) by 2050 and covers the whole territory of Europe, including Russia (without mentioning which part of the Russian Federation has been considered).

WEO presents an excellent analysis and detailed information in 3 different scenarios: CPS, NPS and 450S. The following Figure 17 illustrates the comparison between the three scenarios.

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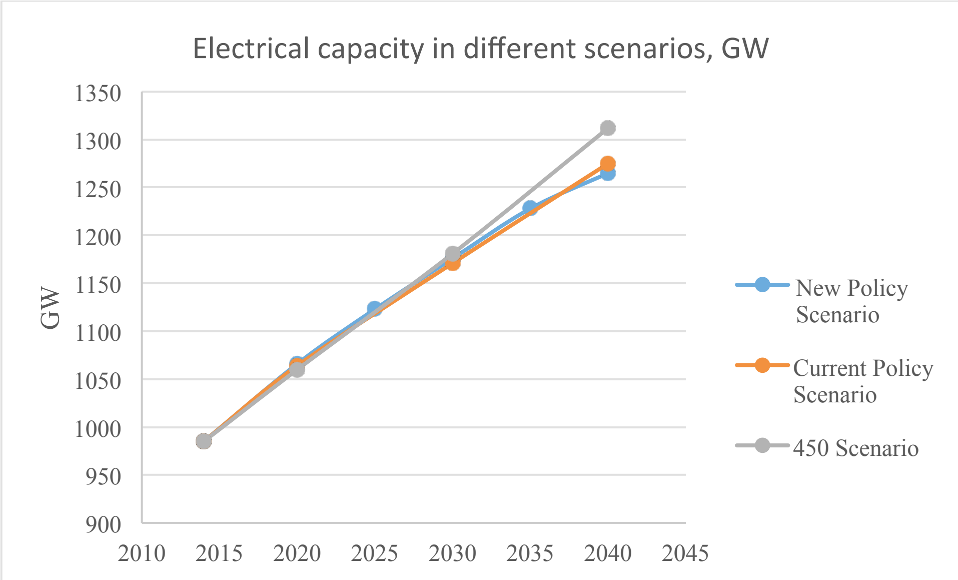

Figure 17: Electrical capacity in EU according to the three scenarios of WEO 2016 – Current policies scenario, New policies scenario and 450 scenario

Source: IEA 2016c

EU Roadmap is a project of the European Union. It is being constantly developing through systematic changes in the legal and regulatory framework by taking into account the already achieved results and the changed situation. The initiative is supported by targeted projects, funded by the EU research programmes within Horizon 2020 and the programmes for Coordination and Support, as well as others.

The development of the energy sector is analysed and assessed in the context of the development and needs of the economy as a whole (EC 2011a,b,c; EC 2013a,b,c; EC 2016 etc.).

The most comprehensive is the information contained in the EU documents and it should be used for the modelling by the MEDEAS project.

Costs for network construction

In connection with the drastic transformation of the generating system from centralized to distributed, a corresponding modification of the power network is needed. This applies primarily to the power system's control –power plants, substations and dispatch centres. Serious changes lie ahead in the low-voltage network. With respect to the emerging of numerous producers at low-voltage, the grid should transform from passive – receiving energy from medium-voltage grid, to active – self-producing, exporting, importing and controlling. It is not enough already to have basic relaying protection, but also control systems, especially in relation to the intelligent

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networks, which should be able to operate autonomously, i.e. to undertake all control functions that are common to the existing large systems.

In relation to these changes it is expected that in the next years the main components of the European power system, which operational life is expiring, will be replaced, and by this the costs for the rehabilitation of the network will appear to be the prevailing part of the total power system's investments.

The projections of the generating system development are quite frugal in providing information about the needed investments in power networks.

Cost projections of IEA

The following Table 25, along with the projection of the necessary financial sources for power generation, there is an assessment of the grid – transmission and distribution - needed costs, by 2025 and 2040 in the New Policies Scenario made by (IEA 2016c).

Table 25: Cumulative investment in the power sector in the EU by type in the New Policies Scenario, 2016 -2050 (USD2015 billion)

	2016 - 2025					
	Fossil fuels	Nuclear	Renewables	Total Plants	T&D	Total
European Union	86	59	410	554	325	879

	2026 - 2040						2015 - 2050
	Fossil fuels	Nuclear	Renewables	Total Plants	T&D	Total	Total
European Union	207	334	1 346	1 905	727	2 632	4 202

Source: IEA 2016c

The allocation of investments in the EU among the separate components is quite different according to WEO. Not surprisingly, the leading direction is oriented to the generating capacities as a result of the rigid policy towards the attainment of the climate protection targets till 2050. At the same time the projection of the investments in the grid is also high in accordance with the new tasks which the electrical system faces: control of intermittent capacities and distributed generation including smart grids.

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Costs Projections according to the Energy Roadmap 2050

The amounts of the investments, according to the various projections of Roadmap2050 are shown in the next Table 26 (EC 2011c).

Table 26: Grid investment costs, Bn Euro'95

Scenario	2011-2020	2021-2030	2031-2050	2011-2050
Reference	292	316	662	1 270
Current Policy Initiatives (CPI)	293	291	774	1 358
Energy Efficiency	305	352	861	1 518
Diversified supply technologies	337	416	959	1 712
High RES	336	536	1 323	2 195
Delayed CCS	336	420	961	1 717
Low nuclear	339	425	1 029	1 793

Source: EC 2011c

As a rule it could be expected that the costs will be increasing after 2020 due to the need to replace the existing infrastructure, limiting of development of the nuclear energy (according to the last scenario) or because of the emerging RE generation. With the advancing of the substitution of the controllable generators (of fossil fuels) and the increasing of intermittent renewable energy installations, more investments are needed in new grid technologies, storages, automation and system control.

As the European policy is oriented towards and follows scenarios for high RES shares, the grid requires more and more investments, as it was outlined above, then the High RES scenario is the most likely to be the implemented one.

The next three tables show the projections of investments in power system and separately for the transmission, distribution grid and the interconnectors.

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Table 27: Transmission grid investment costs, Bn Euro'95

Scenario	2011-2020	2021-2030	2031-2040	2041-2050	2011-2050
Reference	47,9	52,2	53,5	52	205,6
Current Policy Initiatives (CPI)	47,1	49,6	64,8	66,6	228,1
Energy Efficiency	49	63,1	80,3	80,1	272,5
Diversified supply technologies	52,8	70,2	88	86,8	297,8
High RES	52,8	95,5	137,8	134,4	420,5
Delayed CCS	52,7	71,1	88,6	87,6	300,0
Low nuclear	52,9	73,8	95,2	94,8	316,7

Source: EC 2011c

Table 28: Distribution grid investment costs, Bn Euro'95

Scenario	2011-2020	2021-2030	2031-2040	2041-2050	2011-2050
Reference	243,7	263,5	280,5	276	1063,7
Current Policy Initiatives (CPI)	245	239,3	317,6	325,9	1127,8
Energy Efficiency	256,3	289,1	408,4	291,8	1245,6
Diversified supply technologies	284,2	345,9	454,3	329,8	1414,2
High RES	283,5	440	619,8	431,5	1774,8
Delayed CCS	283,4	349,4	445,1	339,6	1417,5
Low nuclear	286,4	350,8	472,5	366,5	1476,2

Source: EC 2011c

Table 29: Investments in new electricity interconnections, BnEuro

Scenario	2006-2020	2021-2030	2031-2050
Reference	13,1	0,3	0,0
Current Policy Initiatives (CPI)	21,9	9,7	0,6
Energy Efficiency	21,9	9,7	0,6
Diversified supply technologies	21,9	9,7	0,6
High RES	21,9	21,2	50,8
Delayed CCS	21,9	9,7	0,6
Low nuclear	21,9	9,7	0,6

Source: EC 2011c

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The next Figure 18 presents the total costs for development of the grid by 2050 according to the different scenarios.

The EU Reference Scenario 2016 (EC 2016) does not include an analysis of the investments and the reference scenario considerably differs from that in Energy Roadmap 2050 (EC 2011c) as regards the RES projection, so there should be respective changes in the expected investments.

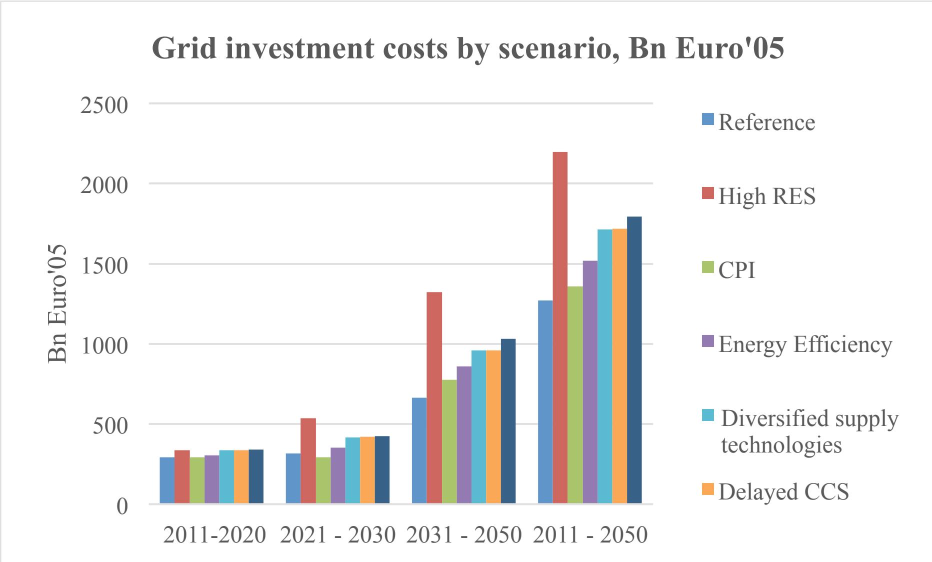

Figure 18: Grid investment costs by scenario, Bn Euro'05

Source: EC 2011c

As it has already been mentioned, these projections will be modified in the new 2016 projection. For the time being, however, the reference scenario from 2016 does not provide information about the various parameters, including with regard to the designed capacities, their exploitation, investments etc., which are expected to be published in the nearest future.

Investments in grid development to 2050

The data provided in this chapter will be used for the development of scenarios within WP3. This information shall be considered as a basis for coordination with all sub-tasks within D2.2, and with the data required by the model, when these will be disclosed by the model developers.

The projected grid development investments at global and European levels are presented in the next two tables.

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Table 30: Grid development investments in EU by year until 2050, Bn Euro'05

	Year	Reference	CPI	Energy Efficiency	Diversified supply technologies	High RES	Delayed CCS	Low nuclear
Grid investment costs	**2011-2020**	**292**	**293**	**305**	**337**	**336**	**336**	**339**
	2011	29,2	29,3	30,5	33,7	33,6	33,6	33,9
	2012	29,2	29,3	30,5	33,7	33,6	33,6	33,9
	2013	29,2	29,3	30,5	33,7	33,6	33,6	33,9
	2014	29,2	29,3	30,5	33,7	33,6	33,6	33,9
	2015	29,2	29,3	30,5	33,7	33,6	33,6	33,9
	2016	29,2	29,3	30,5	33,7	33,6	33,6	33,9
	2017	29,2	29,3	30,5	33,7	33,6	33,6	33,9
	2018	29,2	29,3	30,5	33,7	33,6	33,6	33,9
	2019	29,2	29,3	30,5	33,7	33,6	33,6	33,9
	2020	29,2	29,3	30,5	33,7	33,6	33,6	33,9
	2021-2030	**316**	**291**	**352**	**416**	**536**	**420**	**425**
	2021	31,6	29,1	35,2	41,6	53,6	42	42,5
	2022	31,6	29,1	35,2	41,6	53,6	42	42,5
	2023	31,6	29,1	35,2	41,6	53,6	42	42,5
	2024	31,6	29,1	35,2	41,6	53,6	42	42,5
	2025	31,6	29,1	35,2	41,6	53,6	42	42,5
	2026	31,6	29,1	35,2	41,6	53,6	42	42,5
	2027	31,6	29,1	35,2	41,6	53,6	42	42,5
	2028	31,6	29,1	35,2	41,6	53,6	42	42,5
	2029	31,6	29,1	35,2	41,6	53,6	42	42,5
	2030	31,6	29,1	35,2	41,6	53,6	42	42,5
	2031-2050	**662**	**774**	**861**	**959**	**1323**	**961**	**1029**
	2031	33,1	38,7	43,1	48	61,7	48,1	51,5
	2032	33,1	38,7	43,1	48	61,7	48,1	51,5
	2033	33,1	38,7	43,1	48	61,7	48,1	51,5
	2034	33,1	38,7	43,1	48	61,7	48,1	51,5
	2035	33,1	38,7	43,1	48	61,7	48,1	51,5

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	Year	Reference	CPI	Energy Efficiency	Diversified supply technologies	High RES	Delayed CCS	Low nuclear
	2036	33,1	38,7	43,1	48	61,7	48,1	51,5
	2037	33,1	38,7	43,1	48	61,7	48,1	51,5
	2038	33,1	38,7	43,1	48	61,7	48,1	51,5
	2039	33,1	38,7	43,1	48	61,7	48,1	51,5
	2040	33,1	38,7	43,1	48	61,7	48,1	51,5
	2041	33,1	38,7	43,1	48	61,7	48,1	51,5
	2042	33,1	38,7	43,1	48	61,7	48,1	51,5
	2043	33,1	38,7	43,1	48	61,7	48,1	51,5
	2044	33,1	38,7	43,1	48	61,7	48,1	51,5
	2045	33,1	38,7	43,1	48	61,7	48,1	51,5
	2046	33,1	38,7	43,1	48	61,7	48,1	51,5
	2047	33,1	38,7	43,1	48	61,7	48,1	51,5
	2048	33,1	38,7	43,1	48	61,7	48,1	51,5
	2049	33,1	38,7	43,1	48	61,7	48,1	51,5
	2050	33,1	38,7	43,1	48	61,7	48,1	51,5
	2011-2050	**1 270**	**1 358**	**1 518**	**1 712**	**2 195**	**1 717**	**1 793**

Source: EC 2011c

Table 31: Global grid development investments by year until 2050, USD2015

Period/Year	Total generation	Transmission and Distribution
2015 -2025	**4 220**	**298,9**
2015	422,2	298,9
2016	422,2	298,9
2017	422,2	298,9
2018	422,2	298,9
2019	422,2	298,9
2020	422,2	298,9
2021	422,2	298,9
2022	422,2	298,9

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Period/Year	Total generation	Transmission and Distribution
2023	422,2	298,9
2024	422,2	298,9
2025	422,2	298,9
2026 - 2050	**12 425**	**9 054**
2026	497	362
2027	497	362
2028	497	362
2029	497	362
2030	497	362
2031	497	362
2032	497	362
2033	497	362
2034	497	362
2035	497	362
2036	497	362
2037	497	362
2038	497	362
2039	497	362
2040	497	362
2041	497	362
2042	497	362
2043	497	362
2044	497	362
2045	497	362
2046	497	362
2047	497	362
2048	497	362
2049	497	362
2050	497	362
2015 - 2050	**16 645**	**12 043**

Source: IEA 2016c

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Conclusions

This report presents an overview of the various projections to 2040 – 2050 and their comparison from different perspectives. Given the different times they were developed in, various databases used and targets pursued, it becomes evident that there exist serious differences between them, both in scope and in results. In order to enable the comparisons, it became necessary to make extrapolations for some of them.

As a result of the analysis and comparisons, two projections are proposed for consideration within the MEDEAS project:

- WEO projections for the World (IEA 2016c), and
- EU Roadmap2050 for the European Union (EC 2011a).

Of course, the current level of information requires further checks and supplementation with a combination of different sources.

With the increasing generation and consumption of VRE, further transformations of power systems should take place in order to make them more flexible in integrating VRE without compromising their reliability and security of supply. IEA carries out regular studies in this direction (IEA 2014a, 2016b, 2016c),

ENTSO-e is actively working to ensure the System Adequacy (SA) of each country's power system to face the new challenges. The analyses, assessments and recommendations are presented each year in a report (ENTSO-e 2015, 2016). With the advancing of the VRE penetration, the SA methodology of ENTSO-e will be further strengthened and supplemented with new requirements.

Given the absence of specific demands from the side of the expected Dynamic model of the MEDEAS project, parts of the information contained in this report might appear useless or incomplete.

Hopefully, during the course of specifying the information necessary for the Model, the proposed report will be improved.

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