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

## **Deliverable 3.3**

**Transition Pathways: the rates of change in BAU, MLT and OT scenarios.**

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## Document info sheet

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## Scope of document

The previous D 3.2 explored some of the variables at global and European level (GHG carbon budget, energy/capita, investment in Renewable Energy sectors) that should be taking into account to achieve a global low carbon society within 2050. These variables also focus the constraints to attain the transition in terms of the carbon budget that is left to burn without exceeding the 2°C, within the year 2100, according to the estimation from IPCC. Thus, starting from these assumptions, the D 3.3 has the aim to explore the possible pathways toward that goals by means narrative, qualitative and quantitative scenarios at Global and European levels.



## List of abbreviations and acronyms

BAU: Business as usual

DDE delay differential equation  
CSP: Concentrated solar power

EEU: Central & Eastern Europe  
EROI Energy return on energy invested

FF Fossil Fuel

GAINS: GHG-Air pollution Interaction and Synergies

GHG Greenhouse Gases

GLOBIOM: The Global Biosphere Management Model

GP: Greenpeace

GP-AdER Scenario: Greenpeace Advanced Energy Revolution Scenario

GP-ER Scenario: Greenpeace Energy Revolution Scenario

IAM: Integrated assessment modelling

IEA: International Energy Agency

IEA 450 Scenario: International Energy Agency 450 Scenario

IEA CP Scenario: International Energy Agency Current Policies Scenario

IEA NP Scenario: International Energy Agency New Policies Scenario

IPCC: Intergovernmental panel on climate change

IRENA: International Renewable Energy Agency

MESSAGE: Model for Energy Supply Strategy Alternatives and their General Environmental Impacts



MLT: Mid-level Transition

OT: Optimum Transition

PV: photovoltaics

RE Renewable Energy

RCP: Representative Concentration Pathway

SRES: The Special Report on Emissions Scenarios

SSP: Shared Socioeconomic Pathway

WEU: Western Europe



## Executive summary

The Deliverable 3.3 has the aim to explore the possible pathways toward a decarbonized society, pathways described in term of the main key variables that can drive the transition, both at global and European levels.

The document is organized in 3 main contributions:

- Narrative and semiquantitative Socioeconomic scenarios at World and European levels for the rate of changes in BAU scenario, and in other alternative scenarios (IIASA)
- Qualitative and quantitative analysis of Optimal Transition scenario for UE and at with an example of country level (USA), keeping the ratio secondary energy / capita constant along the way up to 2050. (CSIC)
- Qualitative and quantitative estimation of the World total energy demand and the energy demand by sector, splitted also by energy sources, in MLT-2020 and MLT 2030 (CIRCE).

IIASA reports the results of the implementation of the Shared Socioeconomic Pathway 2 (SSP2) scenarios. The SSPs are part of a new framework that the climate change research community has adopted to facilitate the integrated analysis of future climate impacts, vulnerabilities, adaptation, and mitigation. The SSP2 presents a middle-of-the-road development in the mitigation and adaptation challenges space. In other words, the SSP2 marker implementation reflects an extension of the historical experience, particularly in terms of carbon and energy intensity improvements in its baseline. Without stringent climate policies throughout the world, this pathway, (that can be seen as a sort of BAU pathway) would lead to a steady emissions increase over the 21st century, with projected end-of-century warming nearing 4°C relative to preindustrial levels. It would be possible to meet the target of Paris Agreement (warming by less than 2°C) under SSP2 **only if stringent climate policies were implemented throughout the world**. However, even with the stringent climate policies throughout the world under SSP2, the reduction extents of CO<sub>2</sub> emission and Kyoto Gases emission in the EU region over 1990-2050 will be 64% and 61%, respectively, significantly less than those put in the EU's Low-carbon Economy Roadmap for 2050, which asked for a reduction by 95%. The carbon price under the stringent climate policies will increase by US\$ 85 (2005 US\$) from 2010 to 2050. The implication of the SSP2 implementation for MEDEAS is that MEDEAS project should pay much more attention to SSP1 (e.g., taking the green



road) and should explicitly specify technological breakthroughs in designing Optimum Transition pathway so as to substantially reduce GHG emission levels before 2050.

Another important analysis has provided by CSIC. They propose, at European level, a model to analyse the energy consumption and the investment in RE, keeping constant the ratio of energy per capita and taking into account the available predictions for the population in Europe. This theme is strictly connected with the importance of energy/capita as indicator of the society welfare.

CIRCE provides the analysis of the pathways for MLT scenarios (2020 and 2030) mainly based on global level analysis of the energy demand by sectors and by source. The approach is to simulate the two different MLT scenarios taking into account the emissions provided by the previous deliverable. A mathematical solution for these scenarios is proposed and a possible energy mix to accomplish each of the scenarios is developed analysing the situation of the main sectors: power generation, buildings, industry and transport.

Each study evidences, under different point of view, the urgency to formulate and to apply stringent climate policies were implemented throughout the world.



## Introduction

### Introduction: Rate of change for BAU

#### Storylines of Shared Socioeconomic Pathways

The SSP storylines serve as the starting point for the development of the quantitative SSP elements. Each storyline provides a brief narrative of the main characteristics of the future development path of an SSP. The storylines were identified at the Workshop on The Nature and Use of New Socioeconomic Pathways for Climate Change Research held at National Center for Atmospheric Research (NCAR), Boulder, CO, USA, on November 2-4, 2011. A brief summary of the storylines presented here is taken from the corresponding summary parts of the meeting report dated March 12, 2012. For further details and extended descriptions of the storylines, see O'Neill et al. (2014).

**SSP1 - Sustainability:** This is a world making relatively good progress towards sustainability, with sustained efforts to achieve development goals, while reducing resource intensity and fossil fuel dependency. Elements that contribute to this are a rapid development of low-income countries, a reduction of inequality (globally and within economies), rapid technology development, and a high level of awareness regarding environmental degradation. Rapid economic growth in low-income countries reduces the number of people below the poverty line. The world is characterized by an open, globalized economy, with relatively rapid technological change directed toward environmentally friendly processes, including clean energy technologies and yield-enhancing technologies for land. Consumption is oriented towards low material growth and energy intensity, with a relatively low level of consumption of animal products. Investments in high levels of education coincide with low population growth. Concurrently, governance and institutions facilitate achieving development goals and problem solving. The Millennium Development Goals are achieved within the next decade or two, resulting in educated populations with access to safe water, improved sanitation, and medical care. Other factors that reduce vulnerability to climate and other global changes include, for example, the successful implementation of stringent policies to control air pollutants and rapid shifts toward universal access to clean and modern energy in the developing world.



**SSP2 - Middle of the Road** (or Dynamics as Usual, or Current Trends Continue, or Continuation, or Muddling Through): In this world, trends typical of recent decades continue, with some progress towards achieving development goals, reductions in resource and energy intensity at historic rates, and slowly decreasing fossil fuel dependency. Development of low-income countries proceeds unevenly, with some countries making relatively good progress while others are left behind. Most economies are politically stable with partially functioning and globally connected markets. A limited number of comparatively weak global institutions exist. Per-capita income levels grow at a medium pace on the global average, with slowly converging income levels between developing and industrialized countries. Intra-regional income distributions improve slightly with increasing national income, but disparities remain high in some regions. Educational investments are not high enough to rapidly slow population growth, particularly in low-income countries. Achievement of the Millennium Development Goals is delayed by several decades, leaving populations without access to safe water, improved sanitation, medical care. Similarly, there is an only intermediate success in addressing air pollution or improving energy access for the poor as well as other factors that reduce vulnerability to climate and other global changes.

**SSP3 - Fragmentation** (or Fragmented World): The world is separated into regions characterized by extreme poverty, pockets of moderate wealth and a bulk of countries that struggle to maintain living standards for a strongly growing population. Regional blocks of countries have re-emerged with little coordination between them. This is a world failing to achieve global development goals, and with little progress in reducing resource intensity, fossil fuel dependency, or addressing local environmental concerns such as air pollution. Countries focus on achieving energy and food security goals within their own region. The world has de-globalized, and international trade, including energy resource and agricultural markets, is severely restricted. Little international cooperation and low investments in technology development and education slow down economic growth in high-, middle-, and low-income regions. Population growth in this scenario is high as a result of the education and economic trends. Growth in urban areas in low-income countries is often in unplanned settlements. Unmitigated emissions are relatively high, driven by high population growth, use of local energy resources and slow technological change in the energy sector. Governance and institutions show weakness and a lack of cooperation and consensus; effective leadership and capacities for problem solving are lacking. Investments in human capital are low and inequality is high. A regionalized world leads to reduced trade flows, and institutional development is unfavorable, leaving large numbers of people vulnerable to climate change and



many parts of the world with low adaptive capacity. Policies are oriented towards security, including barriers to trade.

**SSP4 - Inequality** (or Unequal World, or Divided World): This pathway envisions a highly unequal world both within and across countries. A relatively small, rich global elite is responsible for much of the emissions, while a larger, poorer group contributes little to emissions and is vulnerable to impacts of climate change, in industrialized as well as in developing countries. In this world, global energy corporations use investments in R&D as the hedging strategy against potential resource scarcity or climate policy, developing (and applying) low-cost alternative technologies. Mitigation challenges are therefore low due to some combination of low reference emissions and/or high latent capacity to mitigate.

Governance and globalization are effective for and controlled by the elite, but are ineffective for most of the population. Challenges to adaptation are high due to relatively low income and low human capital among the poorer population, and ineffective institutions.

**SSP5 - Conventional Development** (or Conventional Development First): This world stresses conventional development oriented toward economic growth as the solution to social and economic problems through the pursuit of enlightened self-interest. The preference for rapid conventional development leads to an energy system dominated by fossil fuels, resulting in high GHG emissions and challenges to mitigation. Lower socio-environmental challenges to adaptation result from the attainment of human development goals, robust economic growth, highly engineered infrastructure with redundancy to minimize disruptions from extreme events and highly managed ecosystems.

Figure 1 presents the relative position of SSPs 1-5 in the mitigation-adaptation space.



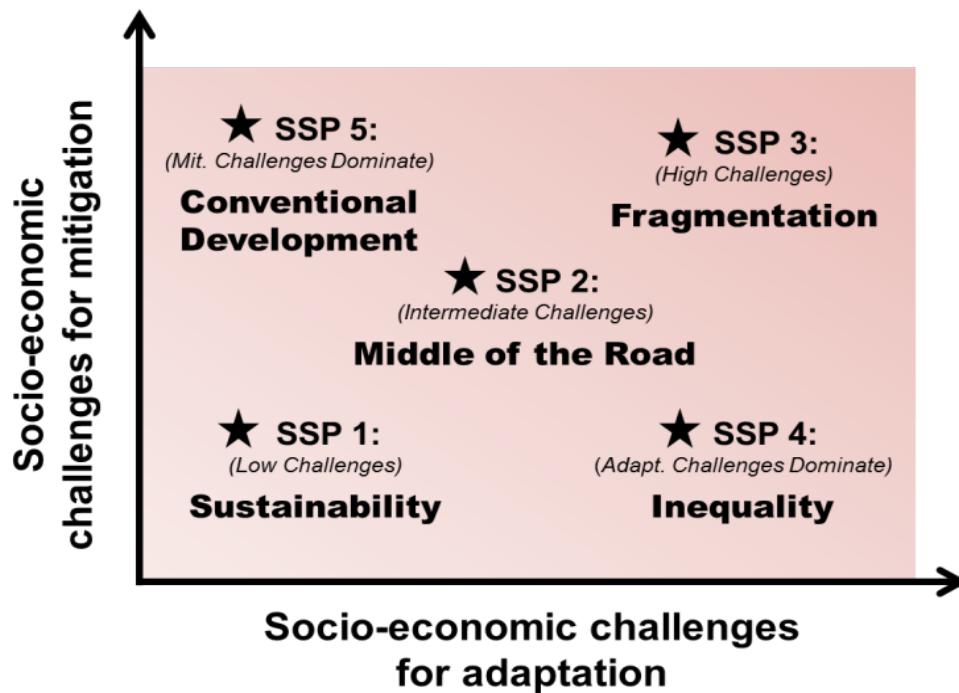


Figure 1 : Characterizing the SSPs in the mitigation-adaptation space

**Literature Context for SSP2:** The SSP2 follows the tradition of earlier dynamics-as-usual or middle-of-the-road scenarios, such as the SRES B2 (Riahi and Roehrl, 2000) or the IS92a scenario (Pepper et al., 1992). Dynamics-as-usual (or business-as-usual) scenarios often share intermediate assumptions about basic drivers of global change, such as intermediate assumptions for demographic and population change as well as economic growth. They are generally useful for exploring the response of the system assuming central trends for the determinants of greenhouse gas emissions. For example, the SRES B2 and the IS92a scenario both resulted in GHG emissions trends close to the median of the literature. While SSP2 features intermediate levels of GHG emissions, an important distinction from the earlier scenarios is that SSP2 has been designed primarily to lie in the center with respect to socio-economic challenges for mitigation and adaptation. The intermediate GHG emissions in SSP2 are thus an outcome or finding from the scenario analysis rather than an input to the scenario design. For a mapping of the SSPs to different other archetypical scenarios from the past see also van Vuuren and Carter (2013).

## SSP Implementation Framework of IIASA

Figure 2 depicts the iterative process about how the SSP2 (also SSP1 and SSP3) narrative was translated into the quantitative scenario that serves as the marker implementation for the evolution of the future global energy and land system in an SSP2 world.

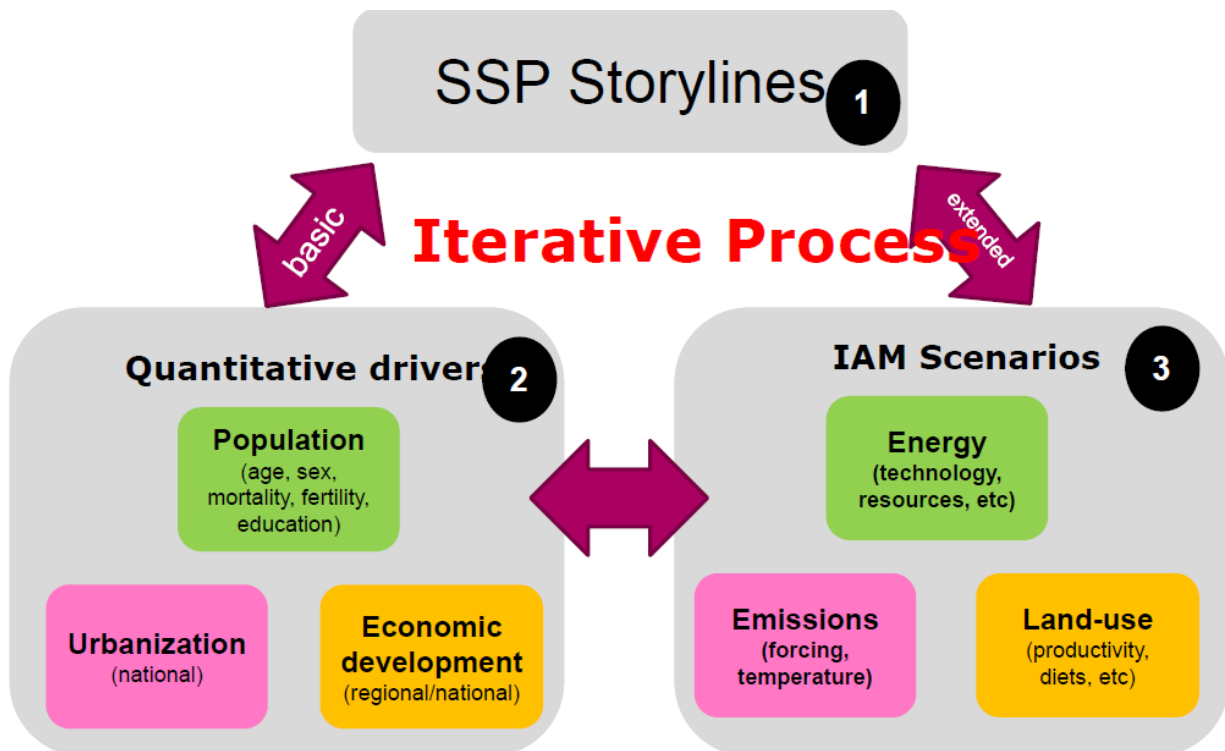


Figure 2 : SSP Implementation Framework of IIASA

In the “Quantative Drivers” box, the estimated total population size, as well as the age and sex structure for each country in the starting year 2010, was taken from the UN estimates and projections (the 2010 assessment). Age- and sex- specific proportions in the different educational attainment categories are taken from the IIASA data base of human capital reconstruction and projections (Samir and Lutz, 2014). The urbanization projections were developed at NCAR using an approach that produces three scenarios (fast, central, and slow) for each country of the world with



the population greater than 1 million and the land area greater than 1000 km<sup>2</sup> in 2010. Projections extend from 2010 to 2100 and consist of the projected percent urban population for each country. The economic projections for the SSPs concentrate on projecting Gross Domestic Product (GDP) and per capita income (GDP per capita) for each of the SSPs. Three modeling teams (led by OECD Environment Directorate, The Potsdam Institute for Climate Impact Research, and IIASA, respectively) have made projections for GDP and GDP per capita. All three models share a basic assumption that macroeconomic growth is driven by a combination of (i) increases in primary inputs (labor and capital, and for OECD also natural resources), (ii) labour-augmenting (human capital) efficiency improvements, and (iii) total factor productivity improvements. The three teams harmonized the interpretation of the SSP storylines for the main drivers of economic growth. Specifically, the models use as the basis for their interpretation of the SSPs (i) the speed of economic growth at the frontier (i.e. for the most advanced countries), and (ii) the speed of convergence of countries towards the frontier. Under SSP2, the middle-of-the-road assumptions are made about population growth, urbanization, technological change, and economic growth. High-income countries continue their practices in urban development; developing countries generally follow the historical urbanization experiences of the more developed countries. All countries follow the central urbanization pathway, with various forms and patterns depending on their current practices and their stages of urbanization.

In the “IAM Scenarios” box, a coupling between three IIASA’s global models – Model for Energy Supply Strategy Alternatives and their General Environmental Impacts (MESSAGE), the Global Biosphere Management Model (GLOBIOM), and the GHG-Air pollution INTERaction and Synergies (GAINS) model – was established. Figure 3 depicts the information flows in this model coupling process.



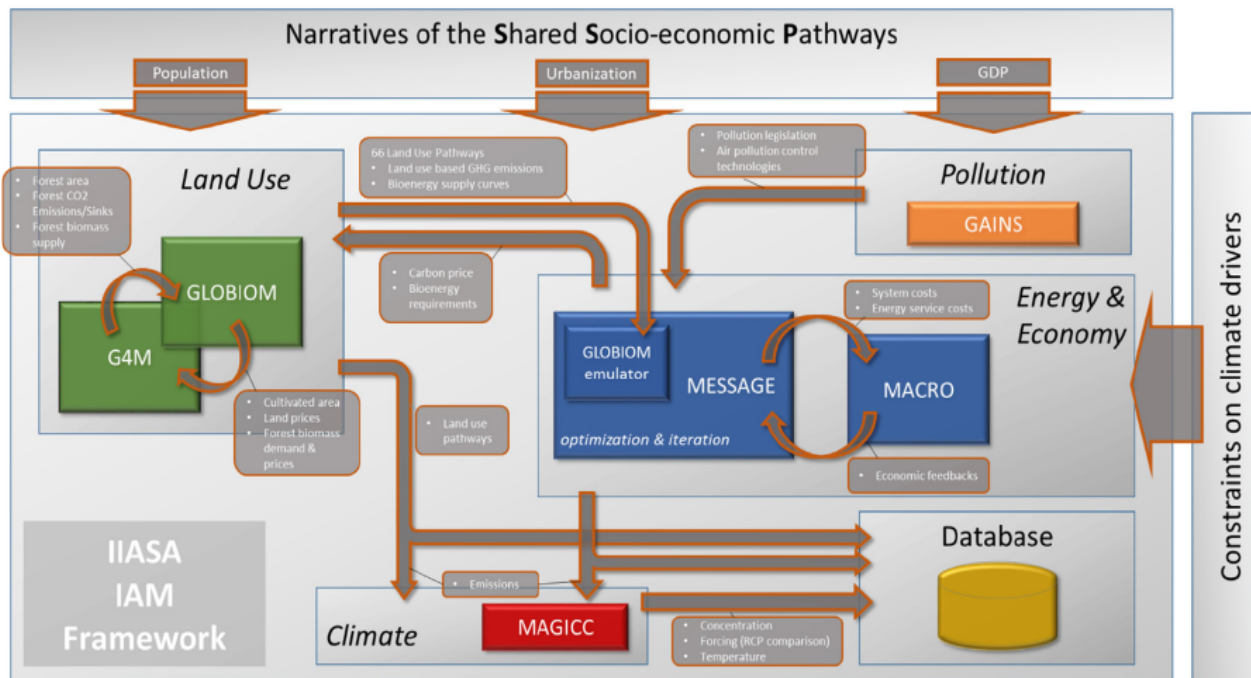


Figure 3 : Flowchart of IIASA's Integrated Assessment Modeling (IAM) Procedure

MESSAGE is an energy engineering model based on a linear programming (LP) optimization approach and designed for medium- to long-term energy system planning and policy analysis. The model minimizes total discounted energy system costs, and provides information on the utilization of domestic resources, energy imports and exports and trade-related monetary flows, investment requirements, the types of production or conversion technologies selected (technology substitution), pollutant emissions, and inter-fuel substitution processes, as well as temporal trajectories for primary, secondary, final, and useful energy. In addition to the energy system, the model also includes generic representations of agriculture and forestry, which allows incorporation of emissions and mitigation options for the full basket of greenhouse gasses and other radiatively active substances. MESSAGE is linked to a macro-economic model -MACRO. In MACRO, capital stock, available labor, and energy inputs determine the total output of the economy according to a nested constant elasticity of substitution (CES) production function. Through the linkage to MESSAGE, internally consistent projections of GDP and energy demand are calculated in an iterative fashion that takes price-induced changes in demand and GDP into



account. MESSAGE is in addition coupled to GLOBIOM for consistent projections of land-use. GLOBIOM is a partial-equilibrium model represents various land-use based activities, including agriculture, forestry and bioenergy sectors. The model is built following a bottom-up setting based on detailed grid-cell information, providing the biophysical and technical cost information. This detailed structure allows taking into account a rich set of environmental parameters. Its spatial equilibrium modeling approach represents bilateral trade based on cost competitiveness. The model was initially developed mostly for integrated assessment of climate change mitigation policies in land based sectors, including biofuels, and is increasingly being implemented also for agricultural and timber markets foresight, and economic impacts analysis of climate change and adaptation (Havlík et al. 2011, 2014). MESSAGE has also been linked to the GAINS model (Amann, et al., 2009) to provide estimates of air pollution. Additional extensive model documentation can be found at <http://www.iiasa.ac.at/web/home/research/researchPrograms/Energy/Download-MESSAGE.en.html> and <https://wiki.ucl.ac.uk/display/ADVIAM/MESSAGE>.



## Demographic and Economic Drivers

The predictions of total global population sizes of the SSPs cover a wide range at both the country and global level. Consistent with the narratives, the global population is lowest in the SSP1 and SSP5 reaching about 7 billion people by 2100 and the highest in SSP3 reaching 12.6 billion in 2100. The middle of the road scenario (SSP2) depicts a population peaking at 9.4 billion. Figure 4 shows the population projections under SSP2 for Central & Eastern Europe (EEU) and Western Europe (WEU) up to 2100.<sup>1</sup> The population of the EU region will increase moderately from 611.5 million in 2010 to 675.2 million in 2050, indicating an annual growth rate of 0.25%. It is worth noting the different demographic dynamics between EEU and WEU. While the population of EEU will decrease by 0.2% per year between 2010 and 2015, the population of WEU will increase by 0.35% per year over the same period. Population decrease in EEU results from both a low fertility rate and migration from EEU to WEU.

The highest SSP GDP projection (SSP5) depicts a very rapid development and convergence among countries with per-capita GDP approaching almost 140,000 US\$(2005) per year by 2100. In contrast, the lowest projection (SSP3) depicts a development failure with strong fragmentation, leading to slow growth or long-term stagnation in most countries of the world. Under the SSP3, per-capita GDP will stay around US\$20,000 (2005 US\$) per year by 2100, which represents the lowest long-term economic projections in the literature. In all scenarios, economic growth is projected to slow down over time, with average growth rates in the second half of the century roughly half of those in the first half (Riahi et al., 2016). Figure 5 shows the project of total GDP under SSP2 for EEU and WEU up to 2100. The total GDP of the EU region will be doubled from 15.5 trillion (2005) US\$ in 2010 to 31 trillion (2005) US\$ in 2050, implying an annual growth rate of more than 1.7%. In the economic growth process, EEU will catch up with an annual growth rate of about 2.2%, whereas the corresponding GDP growth rate in WEU will be less than 1.7%.

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<sup>1</sup> EEU includes Albania, Bosnia and Herzegovina, Bulgaria, Croatia, Czech Republic, Estonia, The former Yugoslav Rep. of Macedonia, Latvia, Lithuania, Hungary, Poland, Romania, Slovak Republic, Slovenia, and Yugoslavia. WEU includes Andorra, Austria, Azores, Belgium, Canary Islands, Channel Islands, Cyprus, Denmark, Faeroe Islands, Finland, France, Germany, Gibraltar, Greece, Greenland, Iceland, Ireland, Isle of Man, Italy, Liechtenstein, Luxembourg, Madeira, Malta, Monaco, Netherlands, Norway, Portugal, Spain, Sweden, Switzerland, Turkey, and United Kingdom.



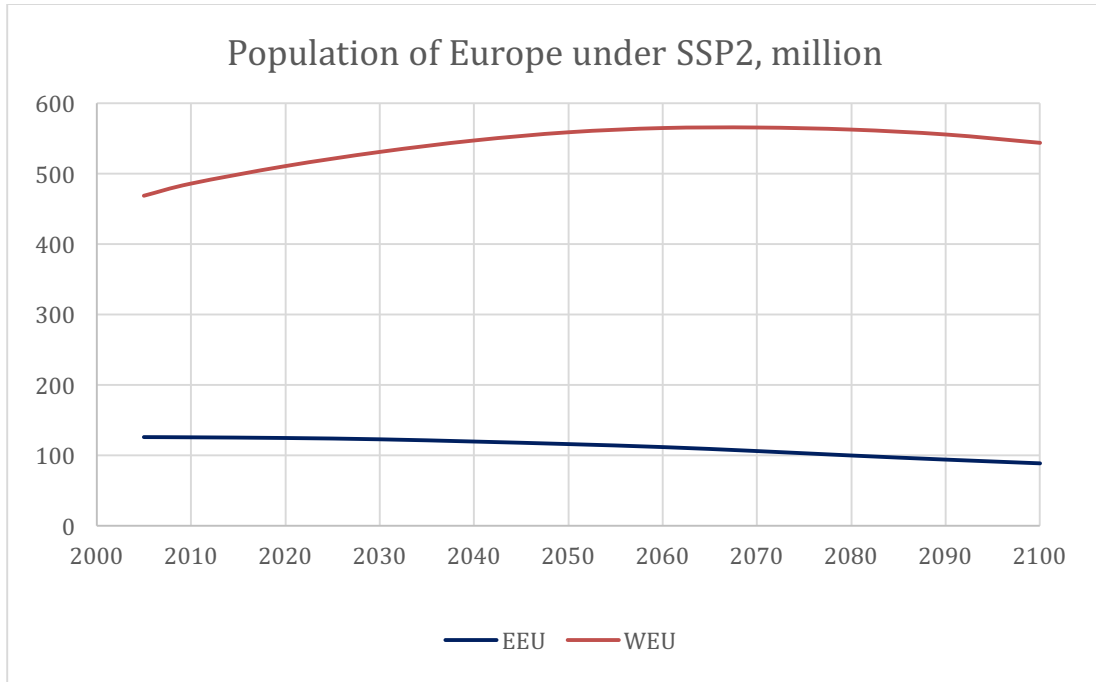


Figure 4 : Population projections under SSP2 for EEU and WEU

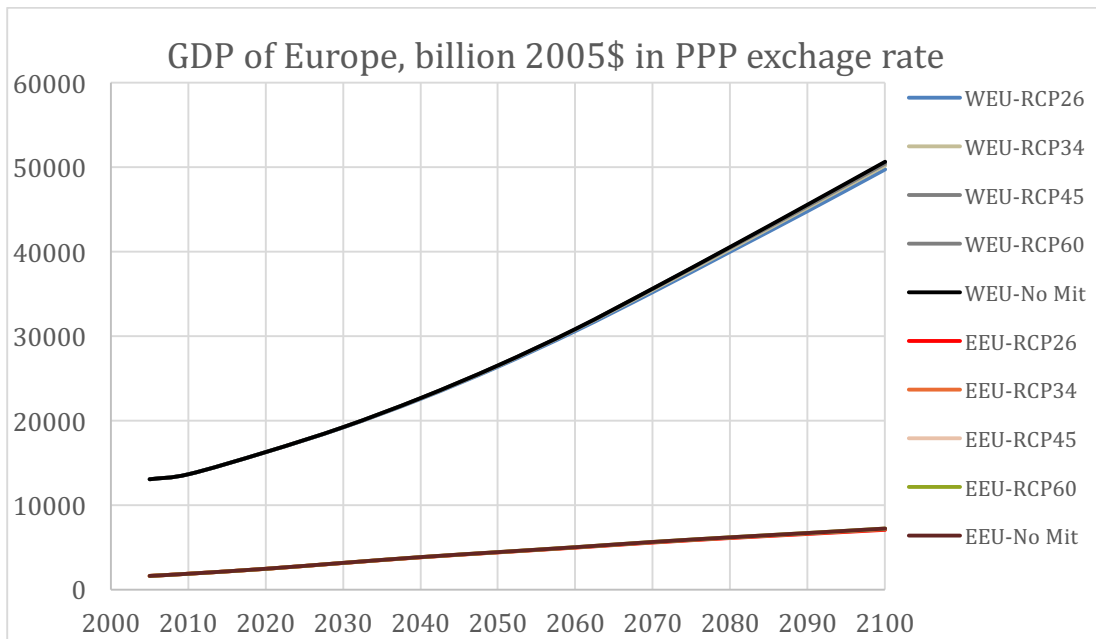


Figure 5: GDP projections under SSP2 for EEU and WEU



## Introduction: Rate of change for Optimal Transition

In this study, CSIC follows the suggestion to keep the ratio secondary energy / capita constant along the way up to 2050. The dynamics of this macroeconomic parameter is a subject of multiple studies (see Seifritz and Hodgkin, 1990; Lei and Zhou, 2012). We assume that sustainable living standards are related directly to energy consumption, and this will hold at least until 2050 (for a discussion on the topic see Brown et al, 2011). Along the way, the fractions of energetic production from fossil and nuclear fuels are supposed to approach 0 (or at least 10-15%, which is the current uncertainty level in our analysis), while the renewables (first of all, sun and wind energy) will take the rest, i.e 85-100%. In order to reach this state, huge investments into the technology, material base and infrastructure of renewables are required. The study will be based on the data of the EU-28, being the most relevant base and, on the other hand, the most convenient one from the statistical viewpoint (in particular, due to the fact that RE fraction is the highest in Europe among the most important economic regions in the world).

## Introduction: Rate of change Mid Level Transition

CIRCE proposed two different MLT scenarios: MLT-2020, in which the emissions follow the current trend until 2020 (Business as Usual Scenario) and then they decrease; MLT-2030, in which the current trend is maintained without taking any measure until 2030 and decreases since then. The total CO<sub>2</sub> emission of both scenarios emission is restricted by the CO<sub>2</sub> carbon budget.

The CO<sub>2</sub> carbon budget is the amount of carbon dioxide emission that can be emitted having a likely chance of limiting global temperature rise. The IPCC published CO<sub>2</sub> equivalent carbon budgets until 2100 for different rises in the temperature and with different probabilities (IPCC 2014). Meinshausen et al. (2009) published the CO<sub>2</sub> budget from 2000 to 2049 with different probabilities. From the latter, 1170 Gt CO<sub>2</sub> was selected as the carbon budget from 2000 to 2050 not to overtake 2°C with a 67% chance. This value is in agreement with the value calculated from the data provided in IEA 450 scenarios.

On the basis of this CO<sub>2</sub> constraint and the value provided for 2020 and 2030 in the BAU scenario (IEA-CP), a mathematical solution for MLT-2020 and MLT-2030 scenarios is proposed. Then a bottom-up approach follows and each sector is analysed individually to form a whole scenario that



achieves the required reduction in CO<sub>2</sub> emission. This way, a full description of the restrictions needed in both scenarios (MLT-2020 and MLT-2030) to accomplish the CO<sub>2</sub> budget is developed. The energy demand and energy mix of each sector are studied worldwide with the help of the data provided in the different scenarios from the IEA and GP.

IEA, GP, and IRENA provide scenarios that follow the actual trend and scenarios in which measures needed not to increase the global average temperature up to 2°C are taken.

The IEA provides annually analyses of the energy situation worldwide. The last one, World Energy Outlook 2016 (IEA 2016), reflects the post-Paris expectations for international co-operation on climate change. Three main global scenarios are developed:

Current Policies Scenario (IEA CP): based on policy announcements and plans, and reflects the way that governments see their energy sectors developing over the coming decades. It takes into account the policies or measures already supported by specific implementation measures in place as of mid-2016.

New Policies Scenario (IEA NP): the starting points are the policies and measures that are already in place, but it also takes into account the aims, targets, and intentions that have been announced.

450 Scenario (IEA 450): it has the objective of limiting the average global temperature increase in 2100 to 2 degrees Celsius above pre-industrial levels. In this scenario, it is fixed where the energy sectors need to end up and then work back to the present.

Greenpeace uses IEA data for its Reference Scenario and describes two Energy Revolution scenarios (Greenpeace., Global Wind Energy Council., and SolarPowerEurope. 2015).

The energy revolution scenario (GP-ER): is an update of the Energy Revolution scenario published in 2012, which followed the key target to reduce worldwide carbon dioxide emissions from energy use down to a level of around 4 gigatonnes per year by 2050 in order to hold the increase in global temperature under +2°C. A second objective is the global phasing out of nuclear energy

The Advanced Energy Revolution Scenario (GP-AdER): stronger efforts to transform the energy systems of all world regions towards a 100% renewable energy supply is done.



The Current Policy Scenario of the IEA was chosen as the Business as usual (BAU) scenario for 2020 and 2030, as it seems the most reliable projection worldwide.

Figure compares the total CO<sub>2</sub> emission calculated for the different scenarios. Data until today was obtained from the IEA. The BAU scenario corresponds with the IEA-CPS, which is similar to GP-RS.

Only IEA-450 and GP-ER accomplish the CO<sub>2</sub> emissions level that is supposed to limit the increase in the global temperature up to 2°C. GP-AdR goes even further and limits, even more, the CO<sub>2</sub> emissions. As it can be observed, a drastic decrease in the CO<sub>2</sub> evolution is essential. If the measures are delayed until 2030 and Business As Usual trend continues, even a more drastic decrease in the CO<sub>2</sub> emission would be needed not to exceed the carbon budget.

The CO<sub>2</sub> emissions in IEA 450 are higher than in the GP-ER scenario. Although both scenarios limit the increase in the temperature to 2°C, the probability in IEA 450 is lower than in GP-ER, this restricts, even more, the CO<sub>2</sub> budget.

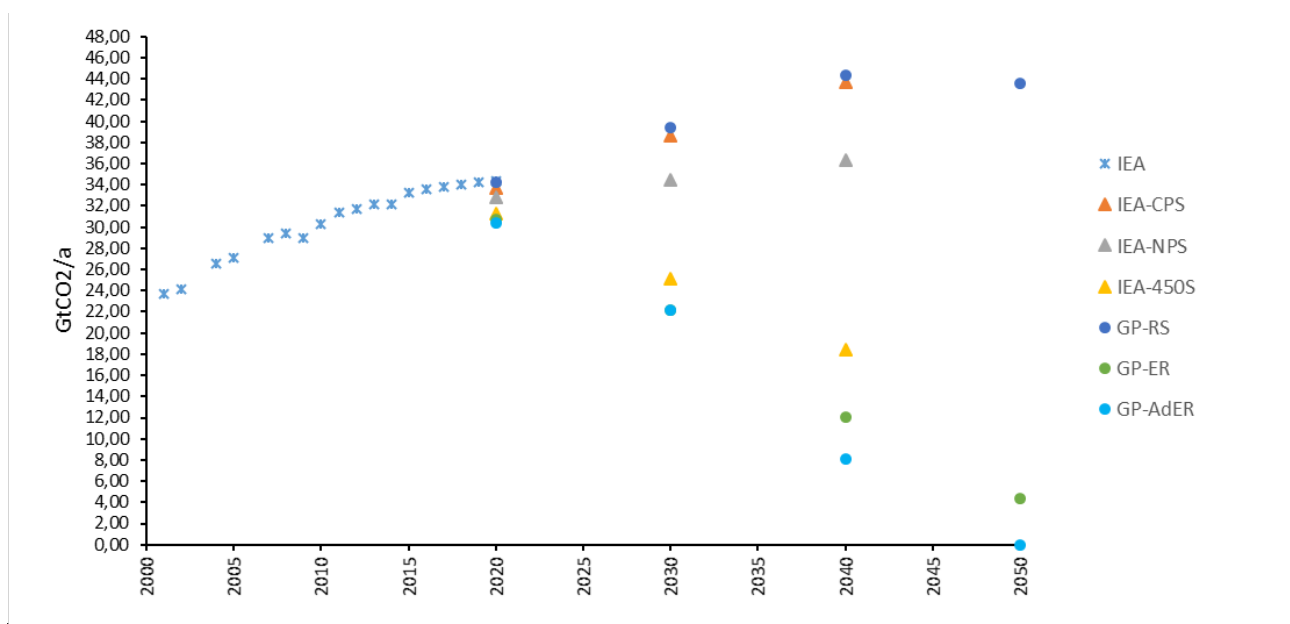


Figure 6 : CO<sub>2</sub> emission evolution projected in the different scenarios.

## Methodology

### Methodology for rate of change in BAU scenario

#### Methods for Estimating Future Energy Demand

As explained in Fricko et al. (2016), the baseline future energy demands under the SSPs were derived from the population and GDP projections as well as historical data regarding population (UN, 2010), GDP in purchasing power parity (World Bank, 2012), and final energy (IEA, 2012). The derivations take into account historical developments of final energy intensity, sectorial final energy shares for the industrial, buildings and transport sectors as well as non-energy use (mostly as feedstock in petrochemical industry) and electrification rates in industry and buildings for the period 1971 to 2010. Quantile regressions were run using the combined cross-sectional and time series data at the country level for final energy intensity, sectorial shares and electrification rates against GDP (PPP) per capita, respectively. For final energy intensity, IIASA team utilizes a linear functional form in log-log space, for the sectorial shares the team follows development patterns as identified by Schaefer (Schäfer, 2005) (e.g., a humpback shape for industry, growing share of transportation), and for electrification rates a logistic (S-shaped) functional form. Across the SSPs, it is assumed that regions converge to a certain quantile at a particular income per capita level in the future. For example, while final energy intensity converges quickly to the lowest quantile in SSP1, it converges more slowly to a larger quantile in SSP3.

Energy intensity improvements are the leading feature of the assumptions in implementing the SSP scenarios. These improvements are driven by advances in energy efficiency and evolving behavioral/lifestyle preferences, historical tracks of which are quantified by the above-mentioned quantile regressions. Historically, the intensity of total final energy (FEI; final energy at the end-use level per dollar of GDP) improved at a rate of about 1.2% globally over 1971–2010. Without this improvement, energy use, and by extension greenhouse gas emissions, would be much higher today than they currently are. Energy intensity improvements thus have important implications for the anticipated challenges for mitigation. Figure 7 summarizes the baseline assumptions for SSP1, SSP2, and SSP3 in terms of their energy intensity evolution over the 21<sup>st</sup> century (globally and for the North and South, respectively), highlighting the middle-of-the road position (SSP2) within this



set. The narrative of SSP2 prescribes that technological trends do not shift markedly from historical patterns. In the SSP2 baseline (i.e., when no climate mitigation efforts are assumed), final energy intensity is therefore assumed to continue to improve at approximately the abovementioned average historical rate (i.e., 1.3%). In contrast, SSP1 and SSP3 assume more extreme evolutions that imply lower and higher challenges to mitigation. The SSP1 no-climate-policy baseline assumes global FEI improvements of 1.7% annually while in the SSP3 baseline FEI is assumed to improve more slowly (0.2% annually). Figure 7 also presents historical energy intensity data for key countries, which shows how the future energy intensity improvement rates of the global North and South in the SSP2 baseline compare to historical trends. The Figure further shows how regional convergence in terms of economic and technological development is either facilitated (in SSP1) or frustrated (in SSP3), with SSP2 providing a middle ground.

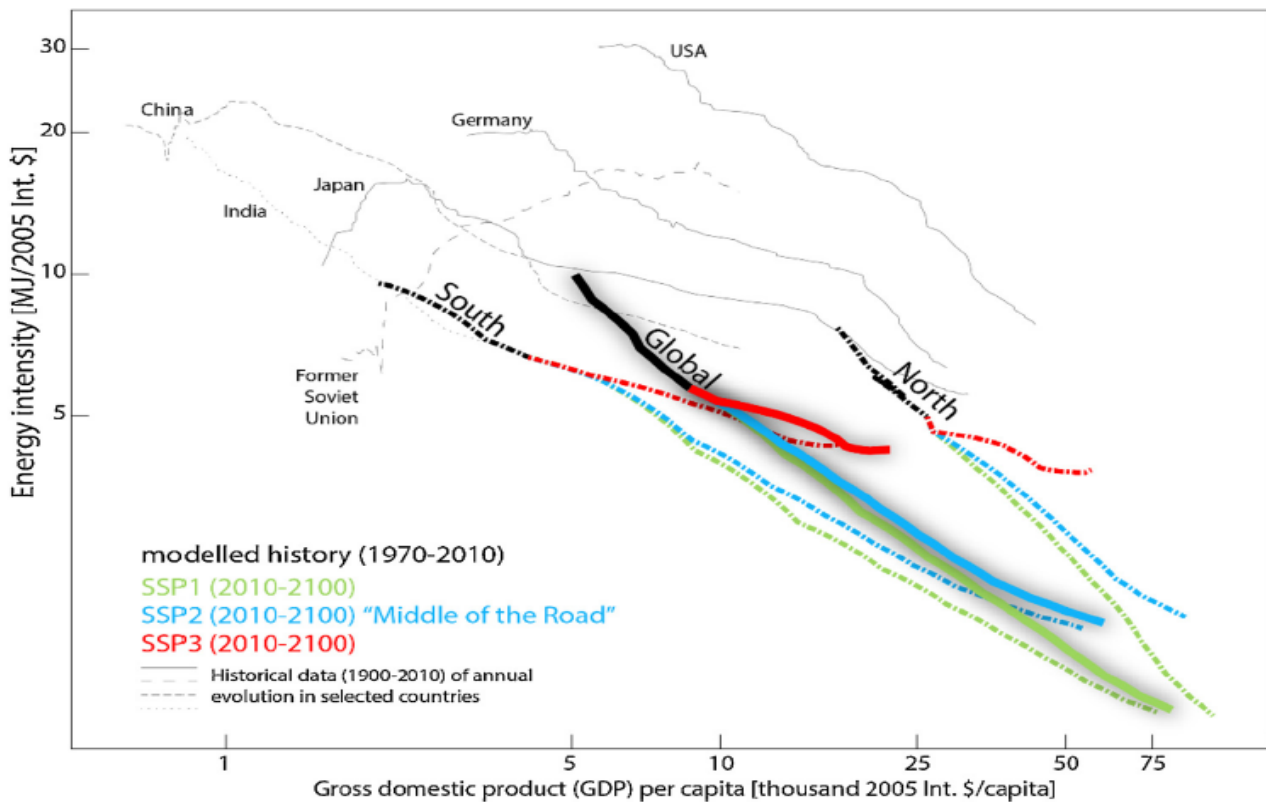


Figure 7: Historic and future final energy intensity (total final energy use over GDP PPP) development plotted against gross domestic product (GDP PPP) per capita (Fricko et al., 2016).

Note: Thin lines represent annual historical data from 1900 to 2010 for selected countries based on Maddison (2010). Original GDP data from this source has been deflated from 1990 to 2005 using a US GDP deflator and a 10 year moving average has been applied to the energy intensity numbers to smooth high-frequency fluctuations. Global model data (thick solid lines) is provided for SSP1, SSP2 and SSP3 (green, blue, red, respectively) as well as regionally aggregated data for the global North and South (thick dashed lines). Historical data for these regions for the period 1970–2010 originated from World Bank (2012). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article).

Tables 1 and 2 lists all major storyline elements in the energy sector and agricultural and land-use sector. The two tables then report the quantitative translations of these storyline elements in SSP1, SSP2, and SSP3 baselines. All indicators in these two tables apply to 2010–2100 and intensity improvements are in FE/GDP annually. Together with economic and population developments, energy intensity improvements and other technological progress as specified in Tables 1 and 2 translates into varying levels of energy demand, which are both inputs into and output of the IIASA IAM implementation.



Table 1: Major storyline elements in the energy sector and their quantitative translations in SSP1, SSP2, and SSP3 baselines (Fricko et al., 2016)

<b>Energy</b>			
	<b>SSP1</b>	<b>SSP2</b>	<b>SSP3</b>
<b>Energy demand</b>	Total final energy intensity improvement is approx. 1.7% <i>(Regional range from 1.3% to 2.45%)</i>	Total final energy intensity improvement is approx. 1.2% <i>(Regional range from .9% to 2%)</i>	Total final energy intensity improvement is approx. 0.3% <i>(Regional range from .2% to .9%)</i>
<b>Transport</b>	High electrification <i>(max. 75% of total transport possible)</i>	Medium electrification <i>(max. 50% of total transport possible)</i>	Low electrification <i>(max. 10% of total transport possible)</i>
<b>Residential &amp; Commercial</b>	High electrification rate: 1.44% <i>(Regional range from .35% to 4%)</i>	Medium electrification rate: 1.07% <i>(Regional range from .23% to 3%)</i>	Low electrification rate: .87% <i>(Regional range from .37% to 2%)</i>
<b>Industry+ Feedstocks</b>	High electrification rate: 0.56% <i>(Regional range from .2% to 1.2%)</i> High feedstock reduction rate: -0.33% <i>(Regional range from -0.51% to 0.59%)</i>	Medium electrification rate: 0.47% <i>(Regional range from .07% to 1.08%)</i> Medium feedstock reduction rate: -0.27% <i>(Regional range from -0.45% to 0.64%)</i>	Low electrification rate: .12% <i>(Regional range from -.03% to 0.71%)</i> Low feedstock reduction rate: -0.24% <i>(Regional range from -0.38% to 0.51%)</i>
<b>Traditional Fuel Use</b>	Phase-out by 2040	Phase-out by 2080	Continued use of traditional biomass
<b>Fossil Energy Resource</b>			
<b>Coal</b>	High Cost Assumption	Medium Cost Assumption	Low Cost Assumption
<b>Other Hydrocarbons</b>	Medium source availability <i>(56 ZJ)</i>	High source availability <i>(77 ZJ)</i>	Low source availability <i>(41 ZJ)</i>
<b>Energy supply</b>			
<b>Conventional and Unconventional Fossil Fuel Conversion</b>	Low technology learning rate and slow market penetration <i>(limited cost reduction (0-30% by 2100; 30% for gas only))</i>	Medium assumptions <i>(cost reduction between 10% (coal syn-liquids) and 30% (for other coal and gas))</i>	High learning rate for coal; medium for others; hydrogen is unavailable <i>(cost reductions from 15-20% (for coal-synthetic liquids gas) and (up to 50% for coal))</i>
<b>Commercial Biomass Conversion</b>	High technology improvements <i>(cost reductions of 30%-50%)</i>	Medium assumptions <i>(cost reductions of 20%-40%)</i>	Low technology improvements <i>(cost reductions of 10%-30%)</i>
<b>Non-bio Renewables Conversion</b>	High technology improvements <i>(cost reductions of 20%-90%)</i>	Medium assumptions <i>(cost reductions of 18%-70%)</i>	Low technology improvements <i>(cost reductions of 10%-30%)</i>
<b>Nuclear Power</b>	Low assumptions <i>(cost reductions of 15%)</i>	Medium assumptions <i>(Cost reductions of 30%)</i>	No learning
<b>CCS (under climate policy only)</b>	Low technology development for fossils; High for biomass <i>(Cost reduction of 0%-50%)</i>	Medium assumptions <i>(Cost reductions of 10-40%)</i>	Low technology development <i>(Cost reductions of 10%-27%)</i>

Table 2: Major storyline elements in the agricultural and land-use sector and their quantitative translations in SSP1, SSP2, and SSP3 baselines (Fricko et al., 2016)

<i>Agriculture and land use</i>			
	SSP1	SSP2	SSP3
Net deforestation	Afforestation (No net deforestation by 2050, +3% forest area by 2100 compared to 2010)	Deforestation/Afforestation (Forest loss of 1% by 2050, back to 2010 area by 2100)	Deforestation (Net forest loss of 3% by 2050 and 6% by 2100 compared to 2010)
<b>Land Productivity growth</b>			
Crops: Yields	High yield growth (Annual yield growth from 0.51% p.a. in the North to 0.66% in the South)	Moderate yield growth (Annual yield growth from 0.46% p.a. in the North to 0.60% in the South)	Slow yield growth (Annual yield growth from 0.35% p.a. in the North to 0.35% in the South)
Crops: Input intensity	Low intensity (Elasticity of variable inputs incl. fertilizer use wrt technological change: 0.75)	Medium intensity (Elasticity of variable inputs incl. fertilizer use wrt technological change: 1.00)	High intensity (Elasticity of variable inputs incl. fertilizer use wrt technological change: 1.25)
Livestock: Feed conversion efficiency	Enhanced efficiency growth (Annual feed conversion efficiency change from 0.10% in the North to 0.26% in the South)	Moderate efficiency growth (Annual feed conversion efficiency change from 0.10% in the North to 0.24% in the South)	Slow efficiency growth (Annual feed conversion efficiency change from 0.07% in the North to 0.14% in the South)
Livestock: Endogenous productivity growth	High livestock systems transition (Annually up to 5% of livestock production systems can be converted to an alternative system or the activity can be abandoned )	Medium livestock systems transition (Annually up to 2.5% of livestock production systems can be converted to an alternative system or the activity can be abandoned )	Low livestock systems transition (No adjustment in the ruminant production system structure)
<b>Environmental impact of food consumption</b>			
Food demand	Slow consumption growth and more sustainable and healthy diets (Calorie consumption per capita growing - North: 1%, South: 16%. Livestock product share decreases in North by one third but increases in South, leading to a stable share of 15% globally)	Moderate consumption growth and increasing share of livestock products in the diet (Calorie consumption per capita growing by 11% in the North, and 22% in the South. Livestock product share in the diet growing from 15% to 18.)	Substantial consumption growth but lagging demand for animal proteins in diet in the South (Calorie consumption per capita growing by 5% in the North and 15% in the South. Livestock product share stays at 15%)
Losses & Wastes	Fast reduction of losses & wastes (L&W) (L&W in the processing chains reduced from 12% to 7% in the Oilseed and Pulses sector and from 7% to 2.5% in the dairy sector over 2000 and 2050)	Medium reduction of losses & wastes (L&W) (L&W in the processing chains reduced from 12% to 7.5% in the Oilseed and Pulses sector and from 7% to 3% in the dairy sector over 2000 and 2050)	Slow reduction of losses & wastes (L&W) (L&W in the processing chains reduced from 12% to 9% in the Oilseed and Pulses sector and from 7% to 4.5% in the dairy sector over 2000 and 2050)

## Methodology to calculate the rate of change in OT scenario

The rate of change in Optimal transition can be quantified as a share of the current energy production that must be retained from the use to be invested. Let us proceed in the following manner:

### Variables and functions

- $t$ : time (in years from 2014, where  $t=0$ ; this is the reference year for the currently available statistics);
- $F(t)$ : net power of the fossil+nuclear origin;
- $R(t)$ : net power from the renewables;
- $I(t)$ : power, invested to the renewables;
- $T(t)$ : “target” total net power, available to consumers;
- $S$ : time delay for investments to turn into actual power in the grid (i.e. construction time);
- $L$ : mean lifetime of a renewable power plant (e.g.  $L=30$  – typical lifetime of a wind facility);
- $e$ : EROI of the renewable power source (e.g.  $e=20$  for a wind facility)
- $p$ : fraction of immediate (capital) investment for a renewable power plant (e.g. a typical value for a wind facility is  $p=0.7$ ).

If the investment is split into the “immediate” part  $p$  and the “distributed” part  $(1-p)$  (maintenance and similar expenditures), then let us consider the “immediate” investment  $X$  that introduces new power  $Y$  after the particular time delay  $S$ .



The total investment is, therefore,  $X/p$ , and the “distributed” part is  $(1-p)X/p$ , that translates into the power cost  $(1-p)X/(p*L)$ ; also,  $Y=(X/p)*(e/L)$

The net new power output will be, therefore,  $Y-(1-p)X/(p*L) = X/(p*L)*(e+p-1)$ .

For the sake of simplicity, we'll use the constant

$$- \quad A = (e+p-1)/(p*L)$$

Equations

(1)  $T(t) = F(t)+R(t)-I(t)$ : total balance

(2)  $R'(t+s) = I(t)*(e+p-1)/(p*L)$  : the increase in RE power output on the range  $[t+s, t+s+dt]$  would be  $R(t+s+dt)-R(t+s)$ , which is equivalent to the net output stemming from the investment of energy  $I(t)dt$ .

Eq. (2) integrated with the limits  $[0,t]$  yields:

$$(2') R(t+s)-R(s) = A*\int[0,t] (F+R-T) dz = -A*\int[0,t](T-F)dz + A*\int[0,t]R(z)dz$$

This is the integral form of an inhomogeneous delay differential equation (DDE).

Clearly, in order to make this solvable, we should define  $R(t)$  on the initial period  $[0,s]$  – since the investments before the moment 0 are unknown.

The model in the given formulation doesn't account for the retirement of the power facilities, that is, we assume all the newly introduced power to “survive” until 2050; we will introduce this correction into the model in the last chapter. Nevertheless, even in this form, the lifetime (parameter  $L$ ) affects the solution through the product with EROI.

The standard numerical approach is the so-called “step method”: the function  $R(t)$  is computed first for the period  $[s,2s]$ , based on the integration of the given  $R(t)$  on  $[0,s]$ . Then it is computed for  $[2s,3s]$ , and so on. A typical feature of solutions of DDEs is a possible discontinuity of the solution  $R(t)$  or its derivative at the points  $s,2s,3s$ , etc; there is, in general, no absolutely reliable numerical recipe to solve DDEs; each solver should be thoroughly checked for robustness.



CSIC group implemented the solver for the equation with the “step method” and cross-checked it against a freeware solver PyDelay wrote in Python (licensed under the MIT License, see <https://arxiv.org/pdf/0911.1633.pdf>).



## Methodology to calculate the rate of change in MLT scenario

To develop different energy scenarios a bottom-up approach was followed. The first stage consisted in gathering basic input variables, such as population growth, energy intensity, GDP projections, etc. These variables determine the energy demand in each energy sector under study, industry, buildings, transport and other. Each one of these sectors consumes different types of final energy. For instance, the building sector consumes electricity, heat, fossil-fuels and renewable energy. Most of the final energy sources are primarily converted into useful energy at energy conversion centers where primary energy is the necessary input. The energy mix in each scenario determines thus the final emissions. If the given energy mix results in global CO<sub>2</sub> emissions greater than the target, a new energy mix is proposed. This process continues until the target is achieved. The proposed energy mixes are built according to reasonable assumptions specific for each sector and in accordance with historical tendencies and published scenarios. The emission target procedure is described in Figure 8.



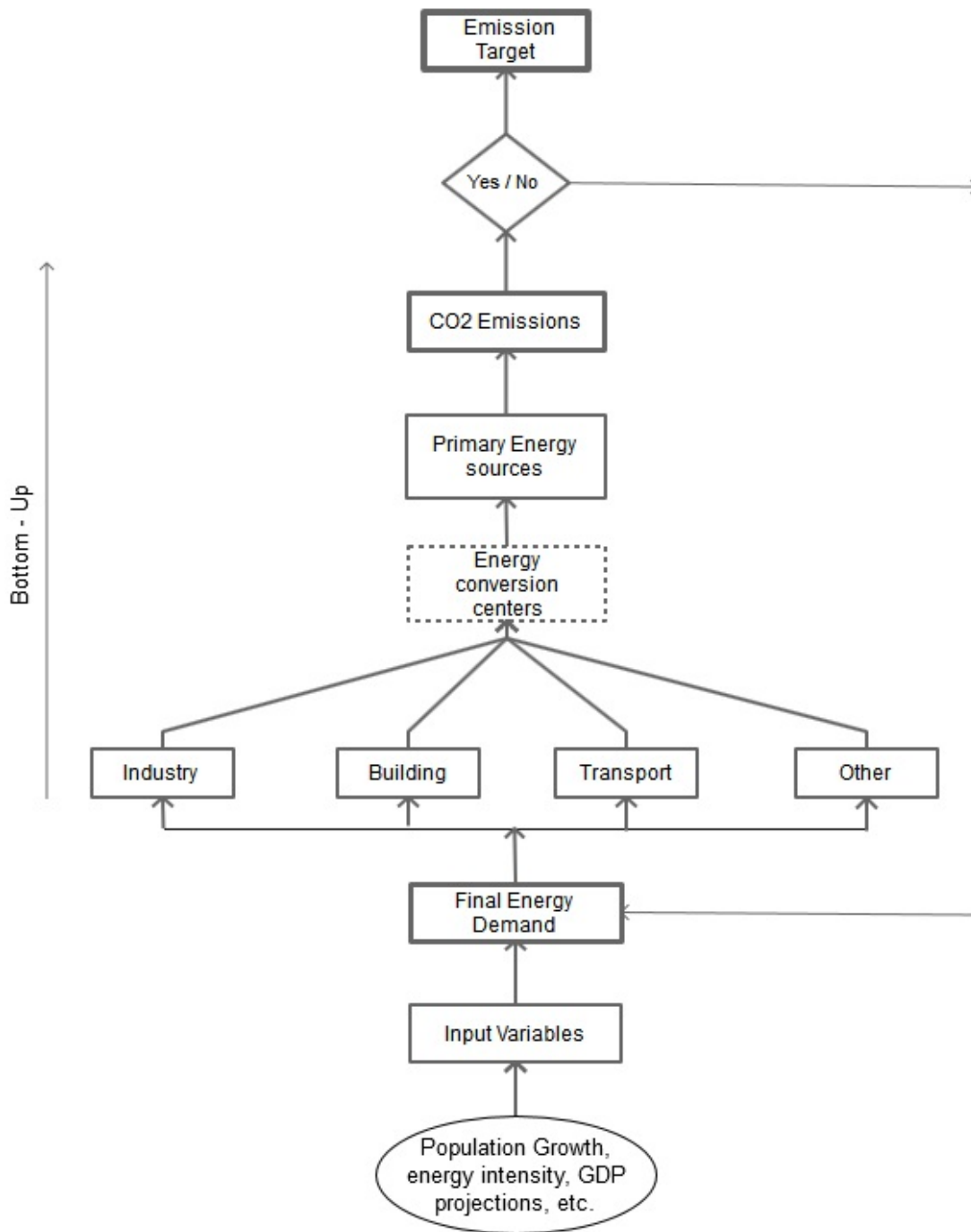


Figure 8 : Energy scenarios information flow diagram



Knowing the CO<sub>2</sub> carbon budget and the initial emission point in each scenario (emission in 2020 for the MLT-2020 and emission in 2030 for the MLT-2030 according to IEA Reference scenario in both cases) the CO<sub>2</sub> total emission are adjusted to a mathematic expression:

$$y(t) = a + b \left(1 - \frac{t}{T}\right)^n \quad (1)$$

Where:

a: lowest emission value in 2050 for both scenarios, MLT 2020 and MLT 2030 is 4.4 GtCO<sub>2</sub>. This value was chosen similar to GP-ER scenario because a low value is needed not to overpass the CO<sub>2</sub> budget but also to set an adequate tendency for the following years.

b: CO<sub>2</sub> emission decrease between initial and final values. In MLT 2020 and MLT 2030 these values are 29.3 and 34.2 GtCO<sub>2</sub>, respectively.

t: year in which emissions will be determined

T: total of number of years, 30 years for MLT 2020 and 20 years for MLT 2030

n: equation coefficient to adjust the curve to different scenarios



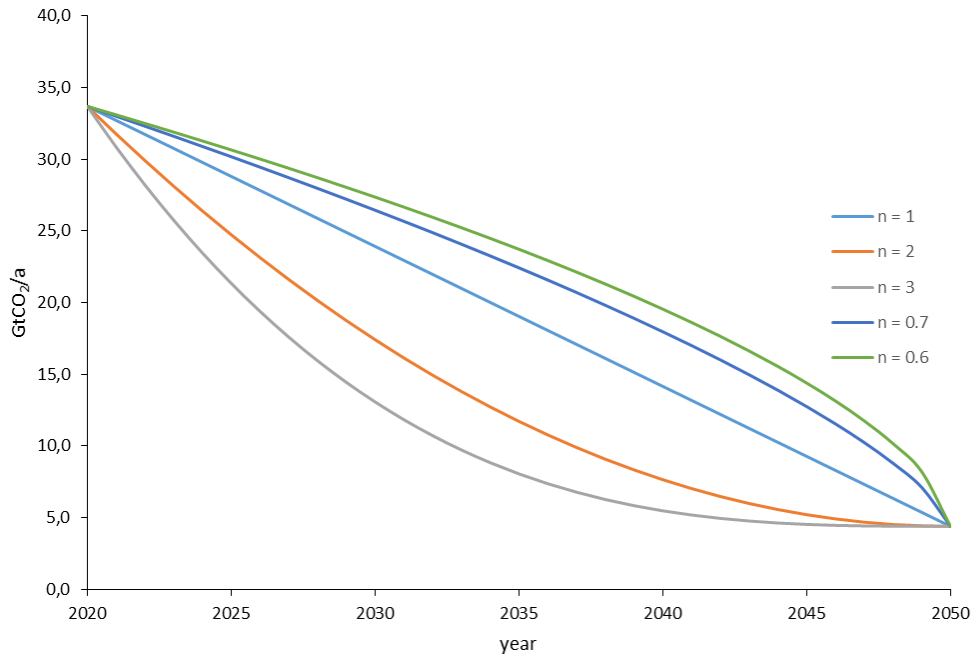


Figure 9 : Possible pathways to achieve the emission target for MLT-2020

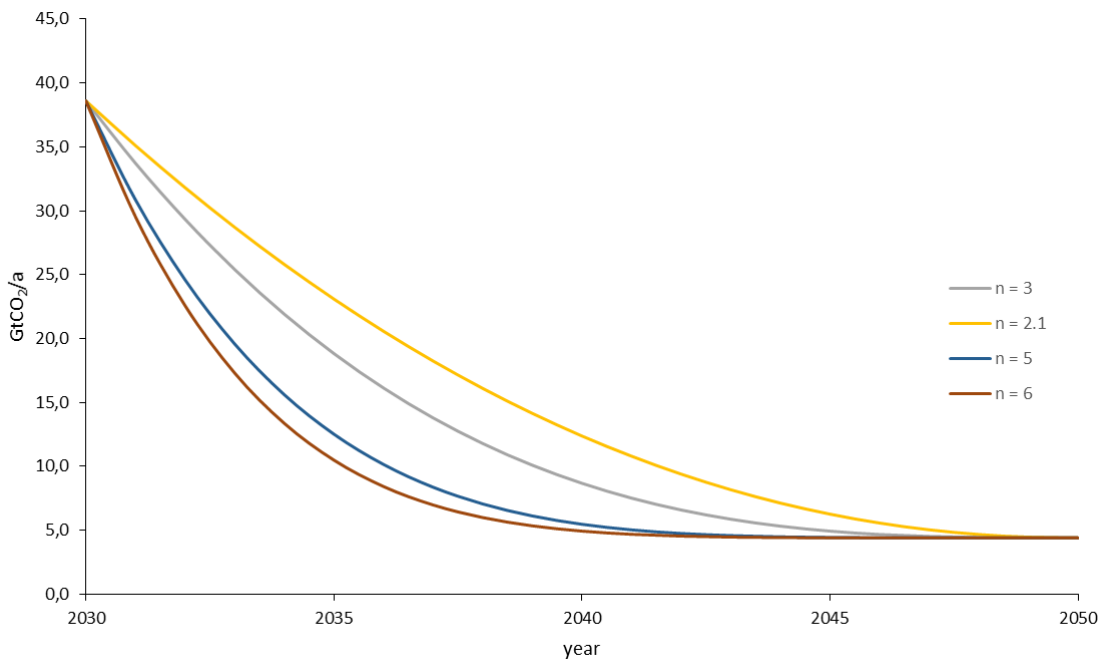


Figure 10 : Possible pathways to achieve the emission target for MLT-2030



Figure 9 and 10 show possible pathways to achieve the emission target of 1170 GtCO<sub>2</sub> between 2000 and 2050. Fig. 9 focuses on scenario MLT 2020, whereas Fig. 10 focuses on MLT 2030.

Note that for MLT-2020, the minimum pathway that still allows not to overpass the CO<sub>2</sub> carbon budget is achieved with  $n=0.6$ . Such scenario implies a moderate gradual CO<sub>2</sub> reduction at the initial years, allowing for a feasible penetration of renewable sources, but still maintaining a level of non-renewable sources. The remaining curves shown in Fig. 9 would imply achieving an even greater renewables penetration and thus an emission budget that would lead likely to a temperature increase lower than 2°C. In this respect, the linear pathway ( $n=1$ ) would be also a feasible option.

In figure 10 possible pathways for the MLT-2030 scenario are plotted. In this case, the minimum pathway needed is achieved with  $n=2.1$ . As it is observed a more drastic CO<sub>2</sub> reduction is necessary for this scenario, meaning a very rapid penetration of renewable sources and maintaining as small as possible, the share of fossil fuel use. Note that the linear pathway would be not possible for this scenario, as the carbon budget would be largely surpassed.

The scenarios MLT-2020 and MLT-2030 were developed considering a systemic approach in which each sector under study (industry, building, transport, other) will have a direct influence on the primary energy sources. Our approach was made following general guidelines of the energy balance of the International Energy Agency (IEA 2005).

Previous works on possible future energy-emissions scenarios from IEA and GP were studied to determine a possible energy mix and consumption curve for each sector, then they were assembled to form a primary energy scenario that was limited by the CO<sub>2</sub> emission curve determined with the mathematical equation 1.



## MLT-2020 and MLT-2030. General aspects

Figure 11 shows the total CO<sub>2</sub> emissions obtained for MLT-2020 and MLT-2030 scenarios in comparison with the BAU (IEA-CPS), IEA-450S and GP-ER.

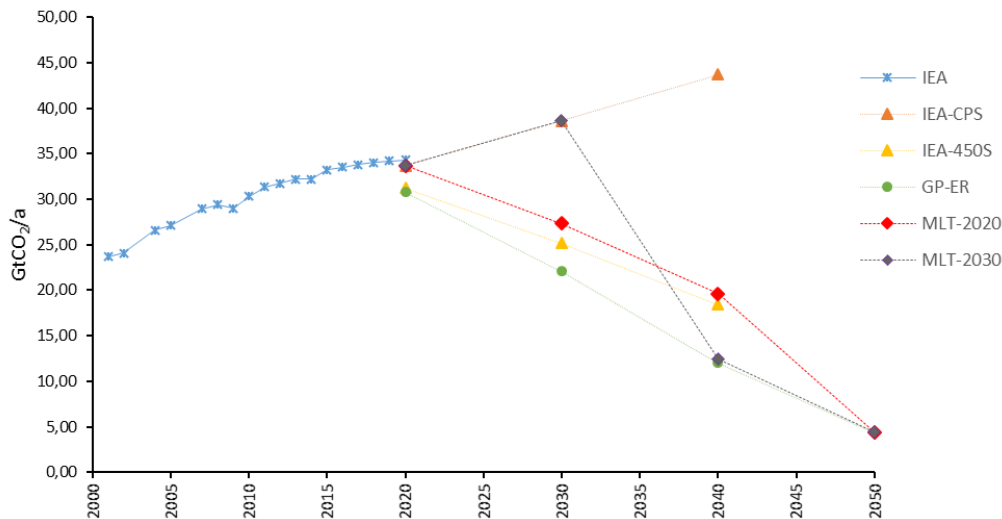


Figure 11 : Total CO<sub>2</sub> emissions including MLT 2020 and MLT 2030 scenarios.

In MLT 2020 the BAU trend continues until 2020, and from 2020-2050 the emissions decrease following the pathway explained in the previous section to accomplish the CO<sub>2</sub> budget in 2050. Even in this scenario an important change in the current trend is needed. The average annual reduction is 4.7%. This trend is softer from 2020 to 2040 (with a minimum reduction of 1.8%) and then a significantly larger reduction by 2050 should occur (reaching a 19% reduction in the last years). The average value of 4.7% is in agreement with the result obtained in Task 3.1.d. Although that report considered the total GHG emissions and in this report only CO<sub>2</sub> emission are taken into account.

This path in CO<sub>2</sub> emissions was obtained with the mathematical expression 1. The energy demand obtained for this scenario (Figure 12) follows a type-S curve with a decrease at the beginning, a stabilization in the middle and a stronger decrease at the end. The decrease in the beginning is due to the actions taken that have an immediate effect. However, due to the increase in the



population, this trend suffers a stabilization. Then, the actions taken with a long term effect give results during last decade.

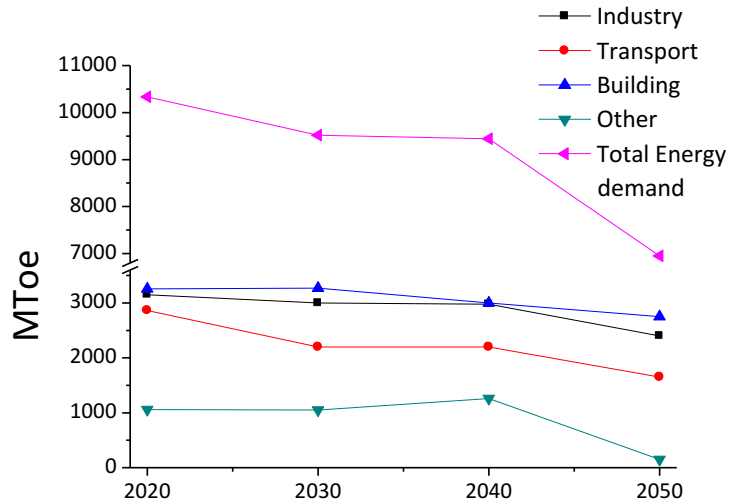


Figure 12 : Total energy demand and energy demand by sectors in MLT-2020.

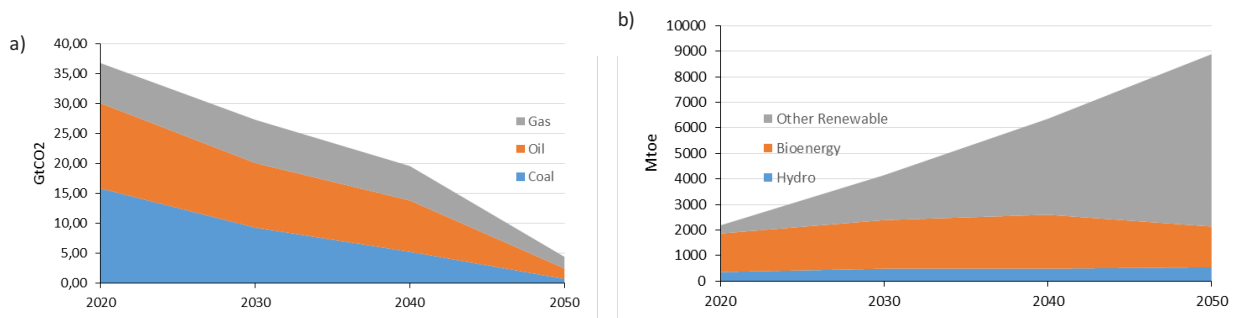


Figure 13 : a) CO<sub>2</sub> emission by fuel type in MLT-2020. b) Energy produced by renewable energy sources in MLT-2020.

Figure 13 shows the evolution of the total emissions by type of fuel. Only the emissions of oil, coal, and gas are considered in this approximation. The use of coal needs to be drastically reduced from 2020, becoming almost negligible in 2050. The use of oil gradually decreases until 2040 and then more severely from 2040 to 2050. Finally, the use of gas is maintained during the first 20 years, it can even be a substitute of carbon in some processes, but is reduced afterward.

In contrast, the use of renewable energy increases gradually, specifically “other renewables” that include wind and solar, which are the ones estimated to have a larger potential. This trend can be observed in Fig. 14, where the final energy consumption normalized with what was consumed in 2014 is represented by renewable energy, fossil fuels, nuclear and total final consumption.

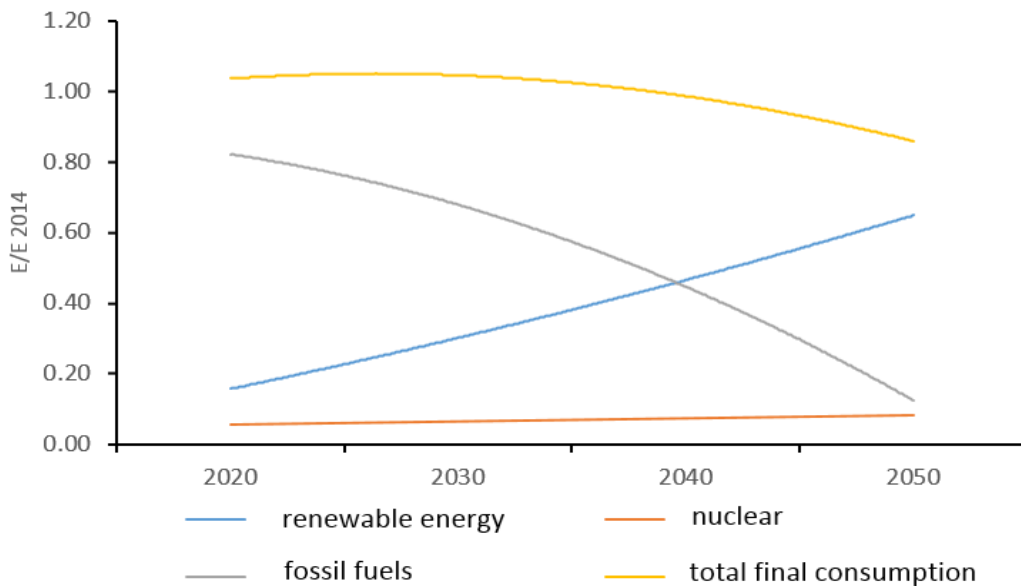


Figure 14 : Final energy consumption projection in MLT-2020.

In MLT 2030, CO<sub>2</sub> emission follows the evolution of the BAU scenario until 2030 (figure 11) and only then the evolution is adjusted to accomplish the CO<sub>2</sub> budget. Due to the increase in emissions from 2020 to 2030, the remaining CO<sub>2</sub> budget is only 330 Gton CO<sub>2</sub>. This, in addition with the higher initial point, is the reasons of the need to drastically decrease the CO<sub>2</sub> emissions. The average annual reduction in this scenario is around 11% and range from 13% during the first part to 1.8% in the last part when the tendency is stabilized. The changes associated with reducing CO<sub>2</sub> emission so drastically will be very difficult to accomplish. These results are in agreement with the statement made by the IPCC ((IPCC 2014)): “Delaying additional mitigation to 2030 will substantially increase the challenges associated with limiting warming over the 21st century to below 2°C relative to pre-industrial levels (high confidence).”

Figure 15 shows the total energy demand and the energy demand by sector in MLT-2030. The energy demand in all the sectors starts gradually to decrease from 2030 but not in a drastic form. The reason is that most of the policy measures that promote efficiency show its mitigation potential in the long term and not immediately. As a consequence, and due to the high level of energy demand that is reached in 2030, a faster decrease in the energy demand would be difficult to accomplish.

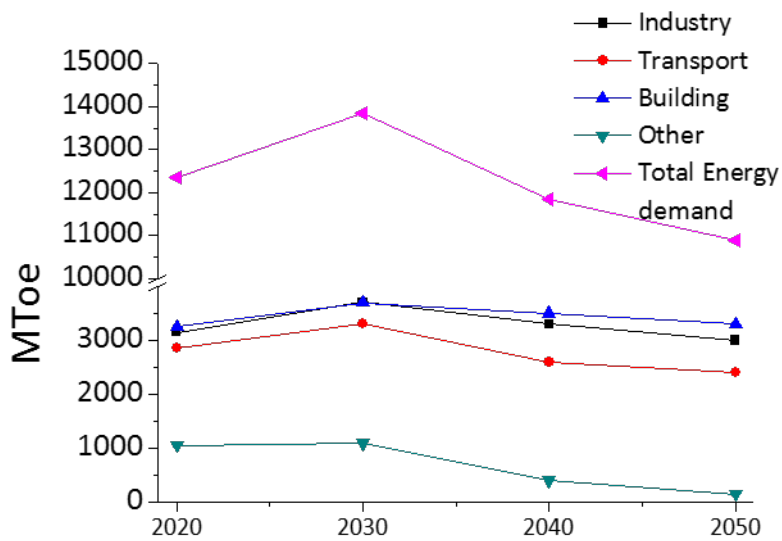


Figure 15 : Total energy demand and energy demand by sectors in MLT-2030.

In this scenario the only solution not to overtake the CO<sub>2</sub> carbon budget is a drastic decrease in the use of fossil fuels and an inversely drastic increase in the use of RES (figures 16 and 17). The approach to solve this scenario is maybe not realistic but it remains as the only solution possible to fix the CO<sub>2</sub> emissions. As it can be observed in figures 16, coal emissions are cut down from 2030 to 2040 and totally eliminated in 2050. Gas and oil follow a similar evolution with a small remaining amount in 2050.

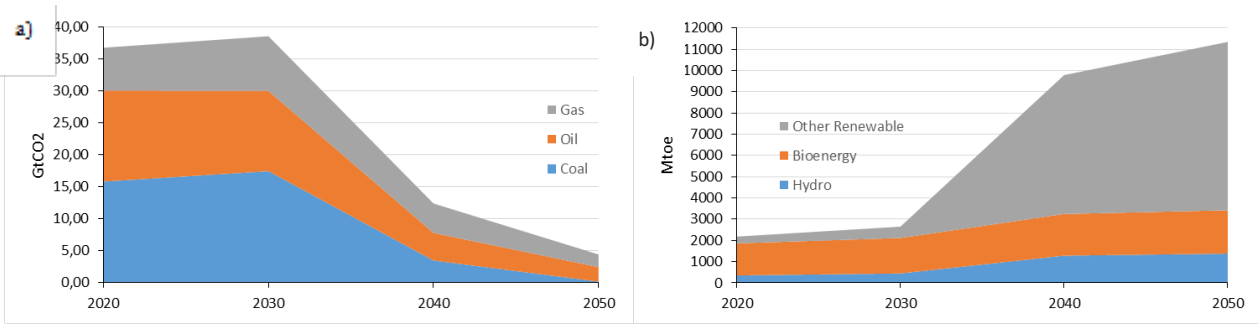


Figure 16 : a) CO<sub>2</sub> emission by fuel type in MLT-2030. b) Energy produced by renewable energy sources in MLT-2030.

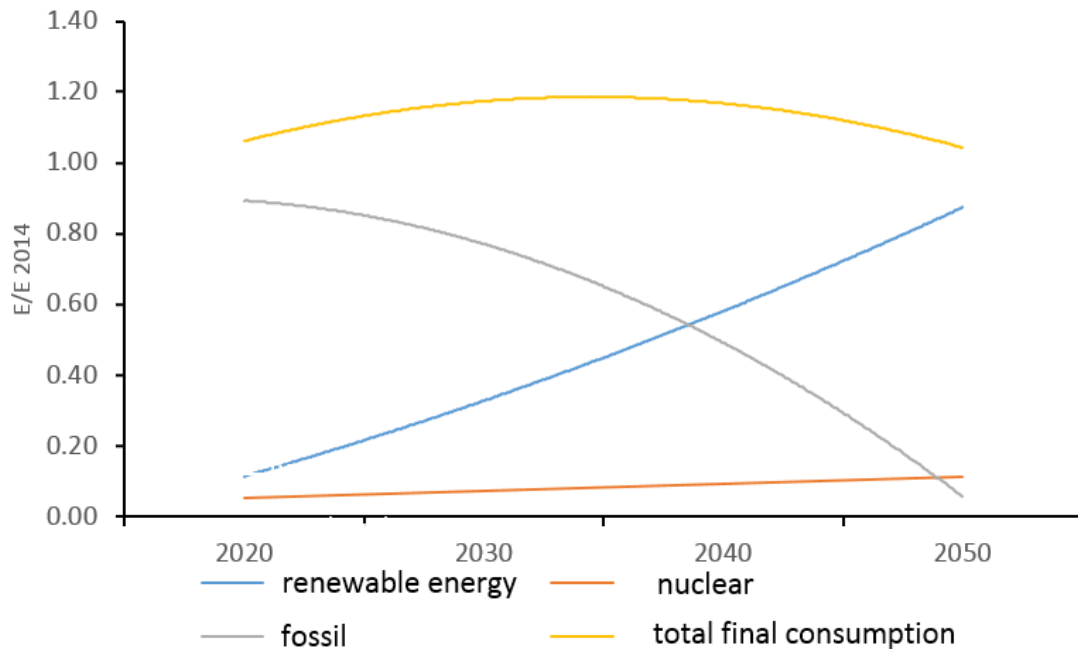


Figure 17 : Final energy consumption projection in MLT-2030.

In both scenarios, the transport sector is the sector that emits more CO<sub>2</sub> in 2050 (40% in MLT-2020 and 55% in MLT-2030). Buildings and industry account for 8 and 18%, respectively, in both scenarios. This is in agreement with the estimations made for Europe in task D.3.1.ab. However, in our scenarios the power generation sector is not totally decarbonized, meaning a 31% and a 17% of CO<sub>2</sub> emission in 2050 in MLT-2020 and MLT-2030, respectively.

Note that the assumption of keeping final energy per capita constant as described in internal deliverable 3.1c OT scenarios does not apply to the MLT scenarios as there is no room for manoeuvre. Hence, together with increasing the renewable penetration rate, primary and secondary energy consumption also needs to be reduced. This is in accordance with IEA and GP scenarios. Fig. 18 shows the per capita final energy demand projections for MLT 2020 and 2030.

The energy consumption per capita is higher in MLT-2030 because the total energy demand expected is higher (population is considered the same in both scenarios). As explained previously the reasons are a faster growth until 2030 and a delay in the mitigation actions, most of them with a long term potential.

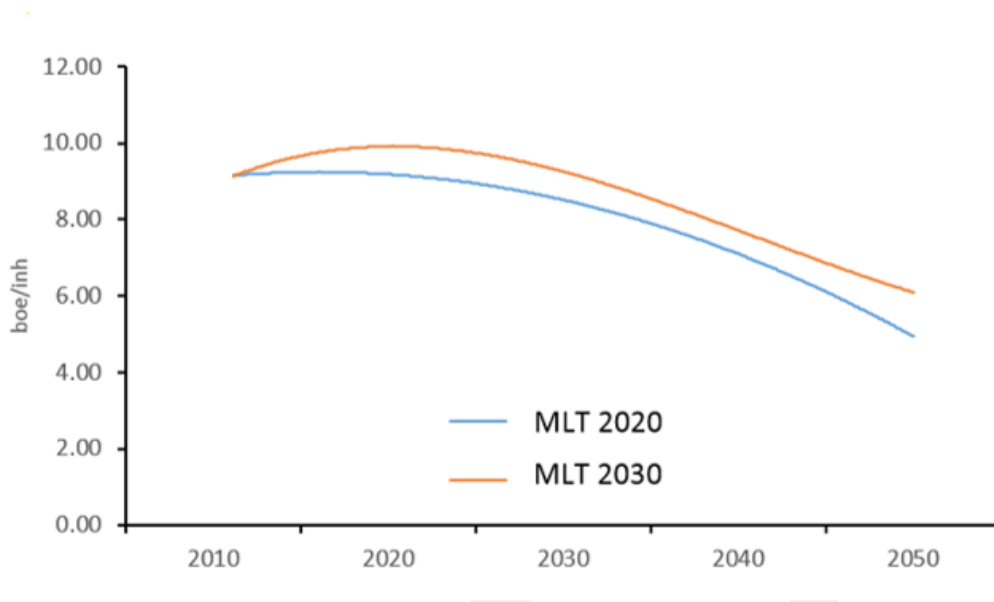


Figure 18 : Final energy consumption per capita for MLT 2020 and MLT 2030 scenarios

## Results

### Results for rate of change in BAU scenario

In this section, we report the major findings for the IIASA study.

Figure 19 shows the demand for final energy in EEU, under the scenarios of SSP2-RCP2.6 (meaning that the stringent climate policies will be implemented throughout the world), SSP2-RCP3.4 (with moderately stringent climate policies), SSP2-RCP4.5 (with moderate climate policies), and SSP2-RCP6.0 (with weak climate policies), respectively. The figure indicates that only under SSP2-RCP2.6, the level of demand for final energy in 2050 will be moderately higher than that of 2010, by a margin of 2.4%. In contrast, demand for final energy in 2050 under SSP2-RCP3.4, SSP2-RCP4.5, SSP2-RCP6.0 will be 9.5%, 17%, and 21% higher than the level of 2010, respectively. This means that SSP2-RCP2.6 is more relevant to the objective of MEDEAS.



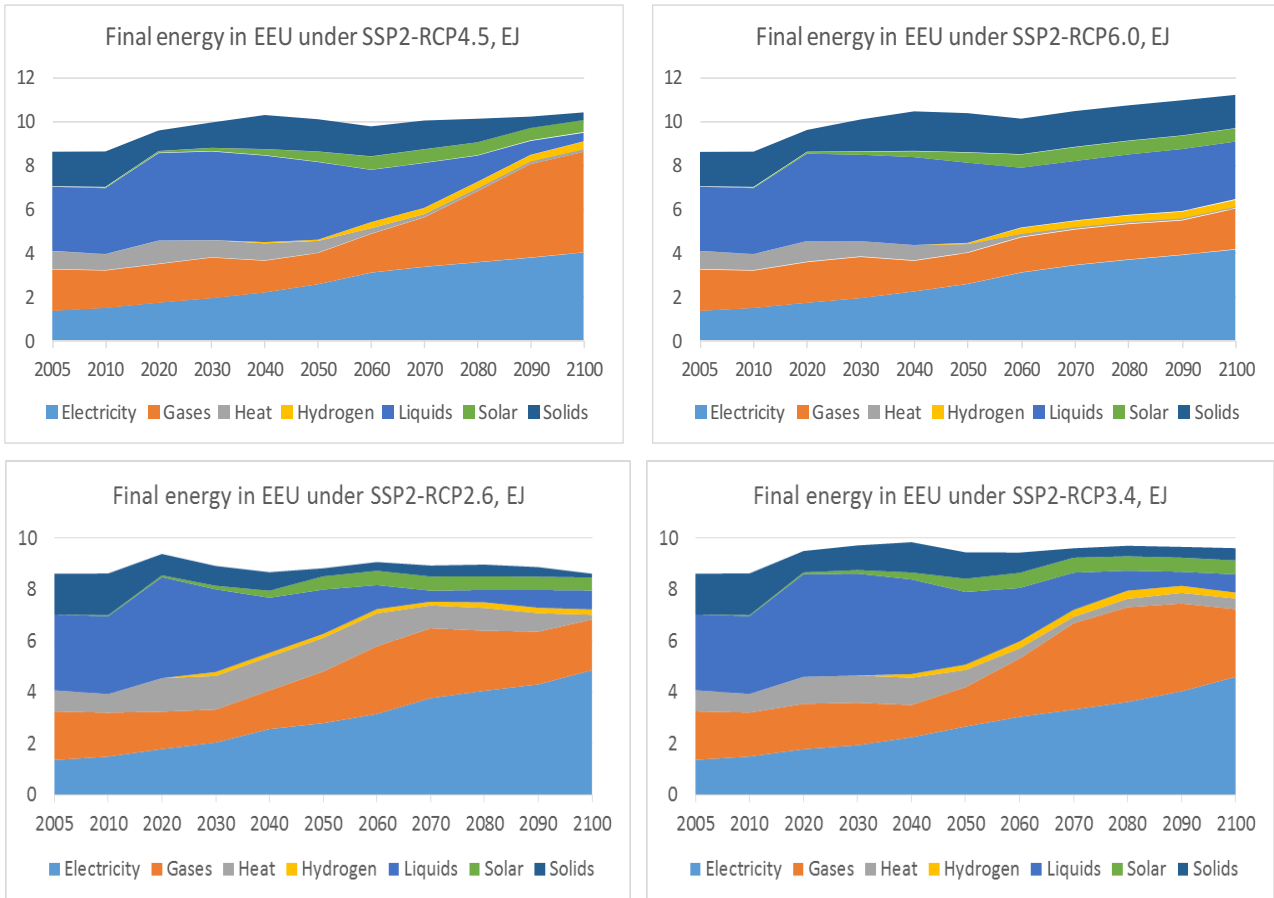


Figure 19. Demand for final energy in Central and Eastern Europe (EEU) under SSP2



Figure 20 shows the demand for final energy in WEU under the scenarios of SSP2-RCP2.6, SSP2-RCP3.4, SSP2-RCP4.5, and SSP2-RCP6.0, respectively. Similar to the case of EEU, Figure 17 indicates that only under SSP2-RCP2.6, the level of demand for final energy in WEU by 2050 will return to the level of 2010. Demand for final energy in 2050 under SSP2-RCP3.4, SSP2-RCP4.5, SSP2-RCP6.0 will be 12%, 20% and 23% higher than the level of 2010, respectively. This comparison also indicates that SSP2-RCP2.6 is more relevant to the objective of MEDEAS. Therefore, in the rest part of this section, we will focus on the results under SSP2-RCP2.6.

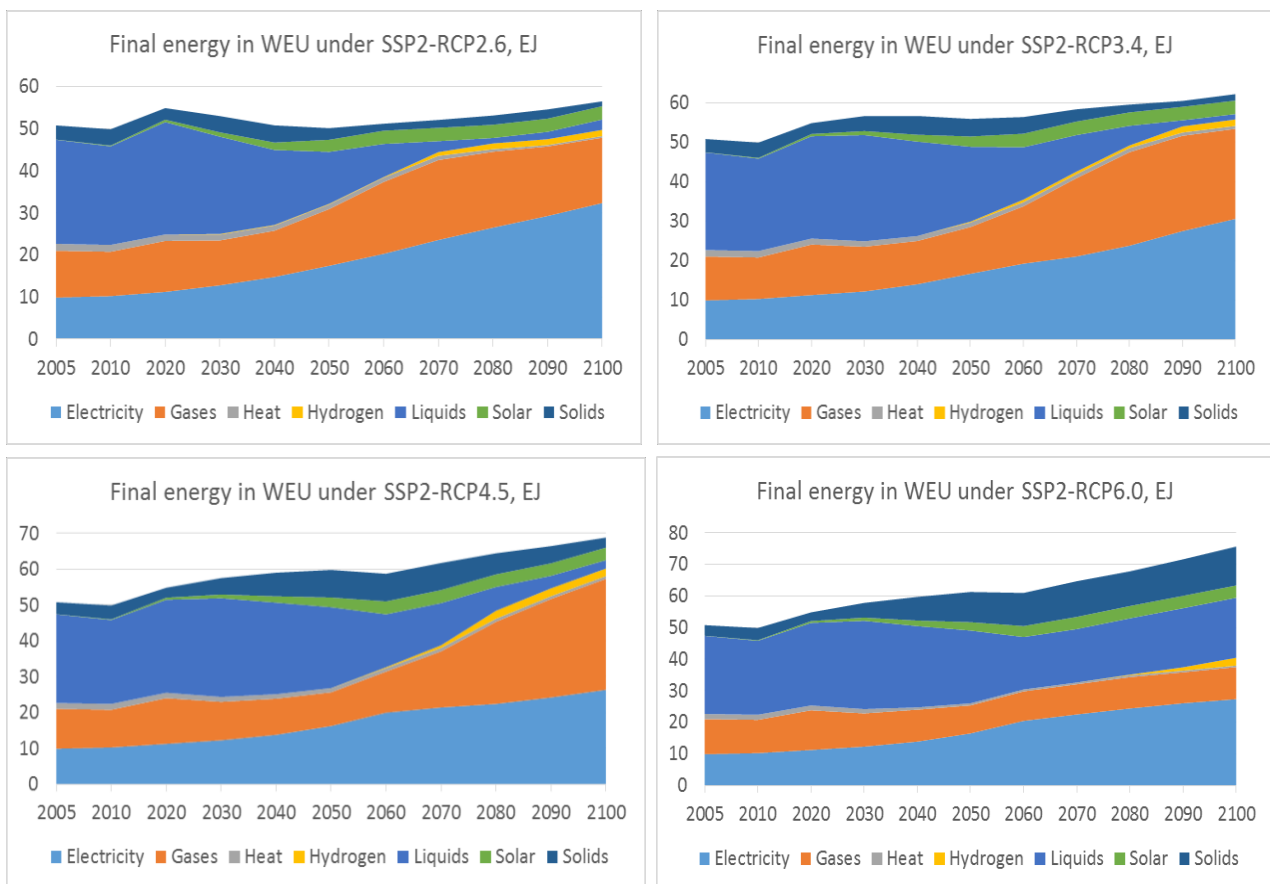


Figure 20 : Demand for final energy in Western Europe (WEU) under SSP2



Figure 21 reports the demand for primary energy under SSP2-RCP2.6 in EEU and WEU, respectively. The figure shows a U-shaped dynamic over 2010-2050 in EEU and that the level in 2050 will be about 1% lower than that in 2010. In contrast, the demand for primary energy in WEU will have an increasing trend over 2010-2050 and the level in 2050 will be 14% higher than the level in 2010. Because the demand in WEU is typically 5.5-6.0 times higher than that in EEU, at the EU aggregation, the total demand for primary energy in 2050 will be 12% higher than that in 2020.

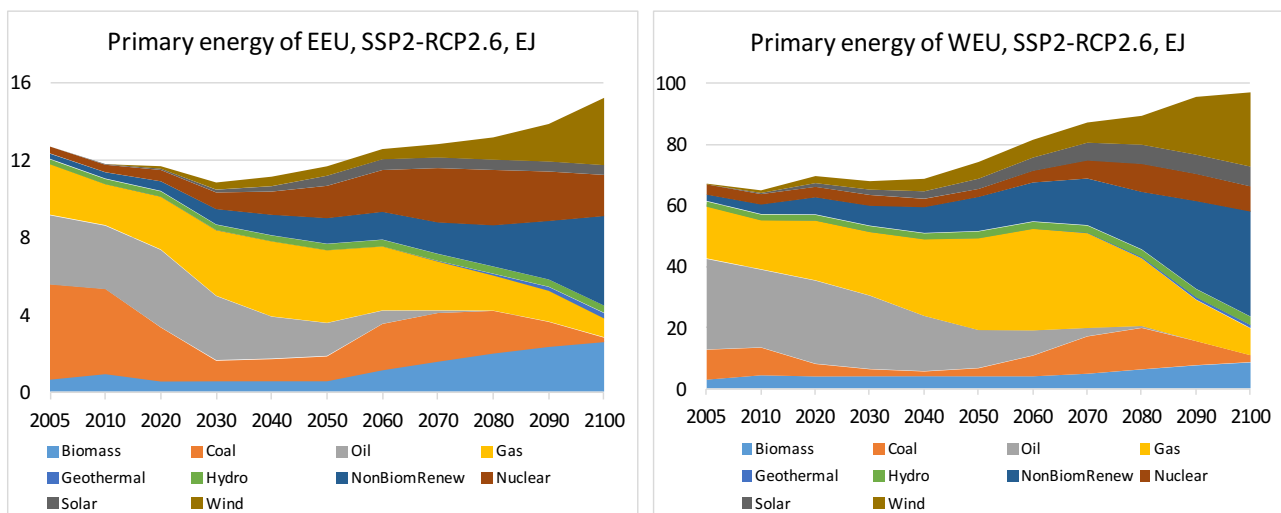


Figure 21 : Demand for primary energy under SSP2-RCP2.6 in EEU (left) and WEU (right)

Despite the continuous increase in demand for primary energy, Figure 21 shows a significant reduction in demands for coal and oil and correspondingly, a remarkable increase in demands for gas, non-biomass renewables, nuclear, wind, and solar energy. As a consequence, the emissions of both CO<sub>2</sub> and Kyoto gases will decline over the period of 2010-2050, as shown in Figure 22. However, the extent of the decline is far less than the expectation of the EU's Low-Carbon Economy Roadmap for 2050, which expects a reduction extent by 80%-95% over the period of 1990-2050. In more detail, the 2050 levels of CO<sub>2</sub> emission and Kyoto Gases emission in the EU region will be about 39% and 42% of the corresponding levels in 2005, or 36% and 39% of the corresponding levels in 1990.

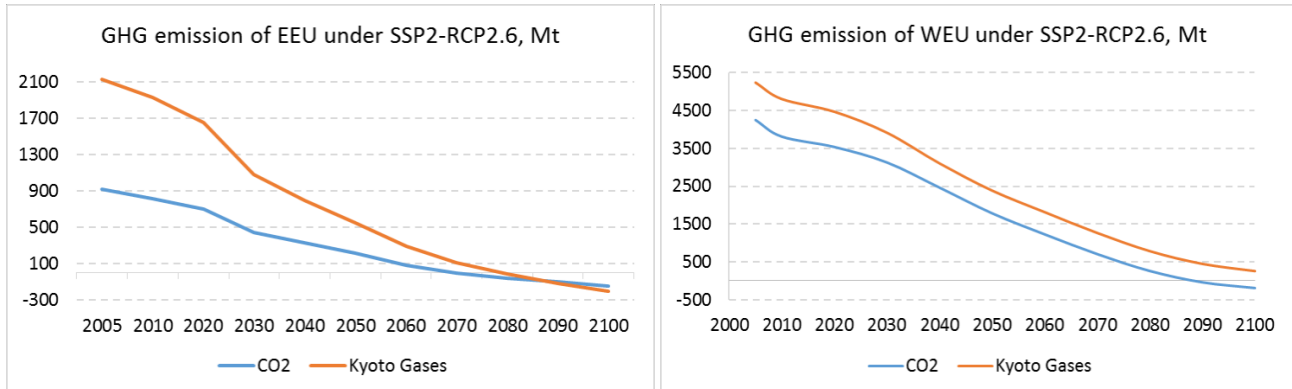


Figure 22 : Emission levels of CO<sub>2</sub> and Kyoto gases under SSP2-RCP2.6 in EEU (left) and WEU (right).  
Note: Kyoto gases are in CO<sub>2</sub> equivalent.

Although the reduction extent of 61% and 64% over 1990-2050 under SSP2-RCP2.6 is far less than the expectation of the EU's Low-Carbon Economy Roadmap for 2050, it still implies a high level of mitigation cost for achieving it. Figure 23 compares this cost implication across the scenarios of SSP2-RCP2.6, SSP2-RCP3.4, SSP2-RCP4.5, and SSP2-RCP6.0. It shows that the carbon price under the stringent climate policies (SSP2-RCP2.6) will increase by US\$ 85 (2005 US\$) per ton from 2010 to 2050. The corresponding figures under SSP2-RCP3.4, SSP2-RCP4.5, and SSP2-RCP6.0 are US\$ 30, 12, and 2.35 per ton respectively.

The discussion of this section indicates that MEDEAS project should pay much more attention to the combination of SSP1 (e.g., taking the green road) and RCP2.6 (with stringent climate policies across the globe) and should explicitly specify technological breakthroughs in designing Optimum Transition pathway so as to substantially reduce GHG emission levels in the EU region before 2050.

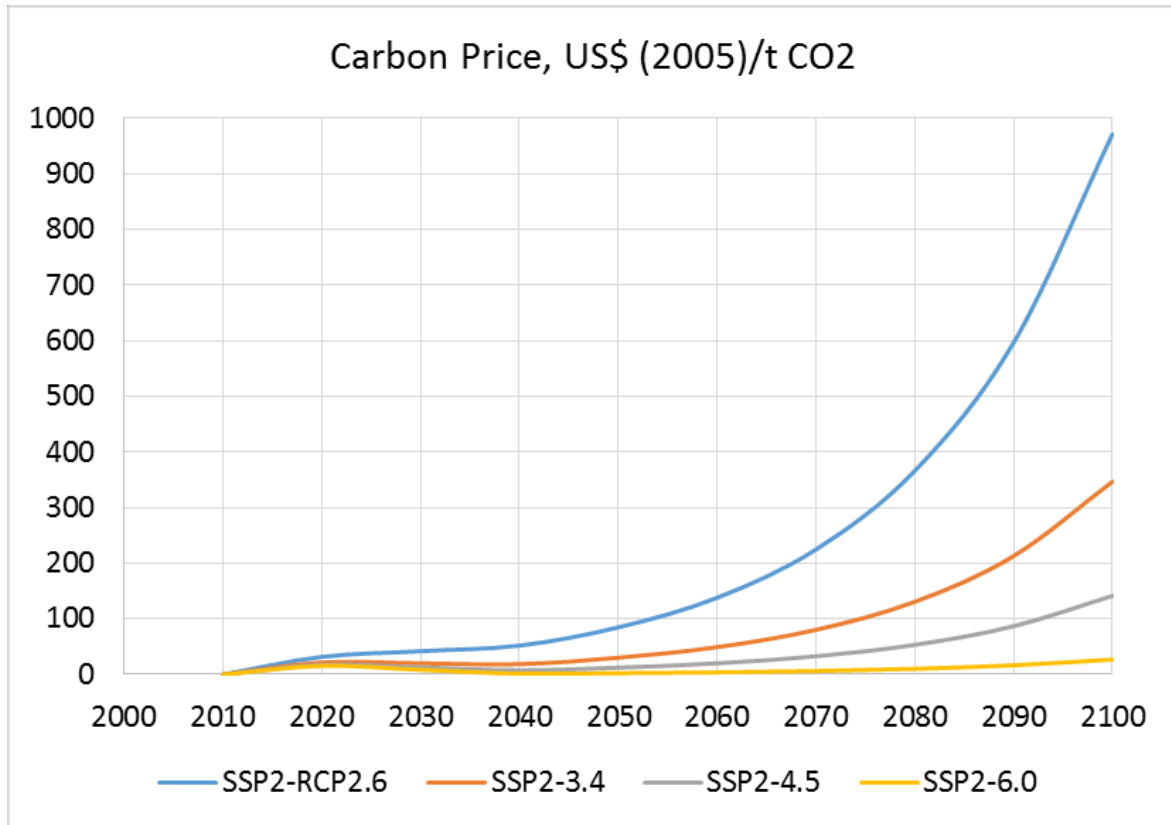


Figure 23 : Carbon prices under the scenarios of SSP2-RCP2.6, SSP2-RCP3.4, SSP2-RCP4.5, and SSP2-RCP6.0 in the EU region



## Results of the Rate of Change in OT scenario

### Analysis of the solution

To begin with, we can consider a simple analytically integrable system. We can look for analytical solutions that have the same functional form for  $R(t)$  as in the first period  $[0,S]$ .

Let us define the units in terms of the initial energy consumption (at  $t=0$ ), that is,  $T(t=0) = 1$ .

### Exponential model

Considering our previous estimate for the growth of total secondary energy as 20% (in accordance with the growth of the population) we can start with the following assumptions, supposing  $t=36$  corresponds to the year 2050 = 2014+36:

$$S = 1 \text{ (1 year is a typical construction period for a wind power facility)}$$

$$T(36) = 1.2$$

$$T(t) = 1.0 * \exp(0.005064 * t)$$

$$R(0) = 0.159$$

$$I(0) = 0.01$$

$R(t < S) = 0.159 * \exp(0.0557 * t)$  (these parameters are approximately in line with the statistics of the general expansion of consumption of renewables in Europe, see [http://ec.europa.eu/eurostat/index.php/Renewable\\_energy\\_statistics](http://ec.europa.eu/eurostat/index.php/Renewable_energy_statistics))

It can be shown that for these parameters the solution of Eq. (2) stays the same

$$R(t) = 0.159 * \exp(0.0557 * t),$$

reaching 1.18 in 2050. The yearly investment rate, on the other hand, ascends from 1% in 2014 to 6% in 2050, when virtually all the fossil fuel fraction is spent to produce new RE (see Figure 24).



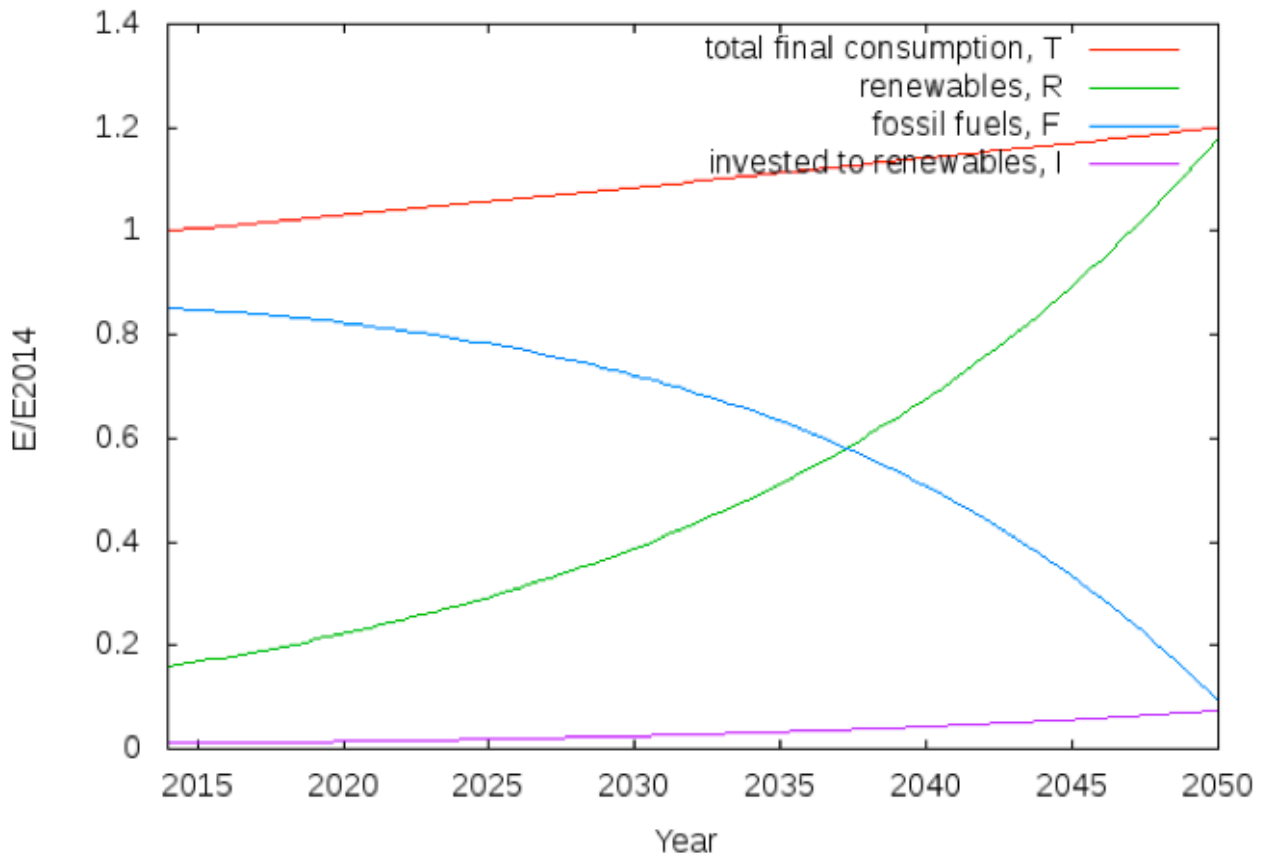


Figure 24 : Energy consumption projections.

Notice that the objective 20% for the fraction of renewables in 2020, which is the current EU-28 objective, is reached within this model.

The code, developed in the group, implementing the numerical solution of Eq.(2) and applied to the same initial data, provides the same answer. It is also noticed that the solution is highly sensitive to the initial data, especially, the form of the investment  $R(t)$  in the first period  $[0,S]$ . This is clearly a mathematical artifact of the model that must be improved to introduce factors, mitigating this kind of “instability”. The target function  $T(x)$  and the final objectives for F and R should have the heaviest weight on the final transition scenario.



## Linear model

We can look for a solution in a linear form, assuming the investments being constant along the way up to 2050. Assuming the same initial conditions and a mean yearly investment in terms of energy (0.03 in E2014, or roughly 3% until 2050) being unchanged, the following scenario is predicted (see Figure 25). The difference with respect to the Scenario (1) is that initially the energy is invested in a much more intensive way in order to reduce the fossil fuel fraction. The total reduction in the consumed FF (or their proportional GHG emissions), i.e. the difference in areas beneath the F (blue) curves, is around 25%.

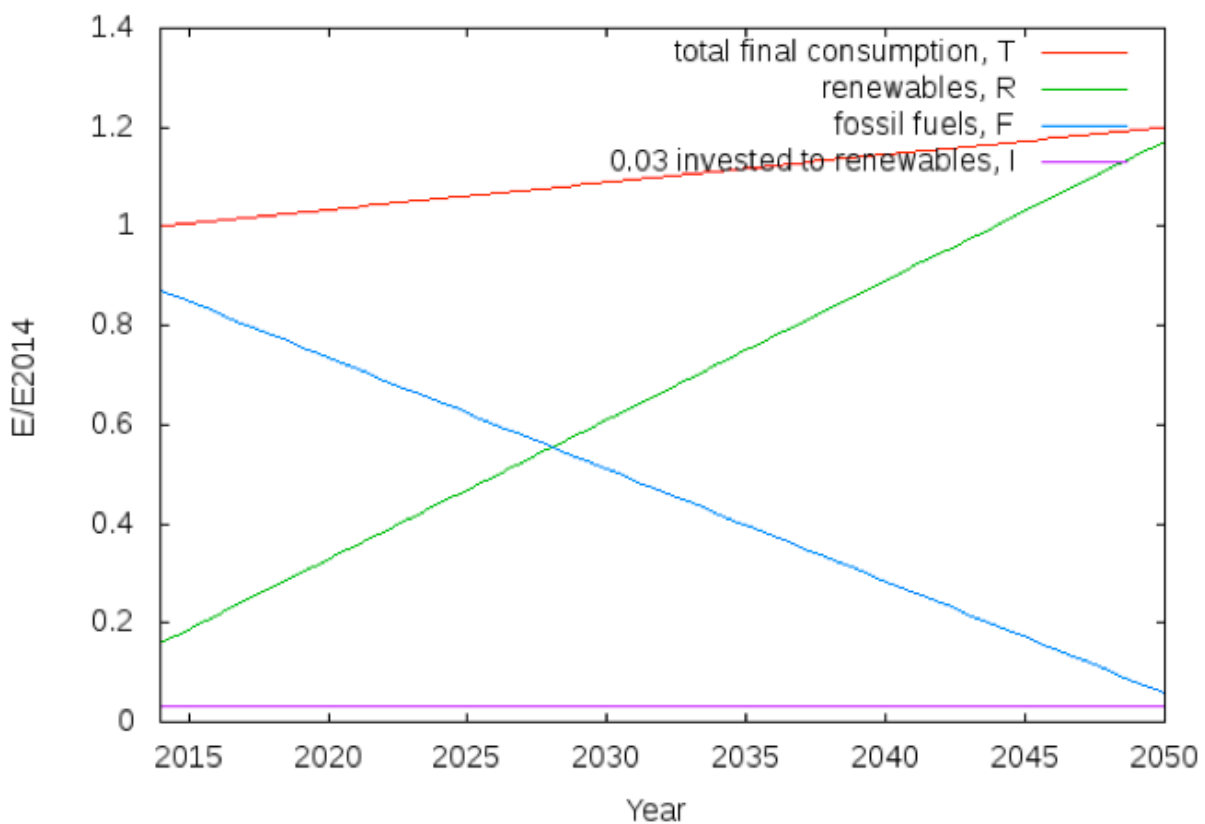


Figure 25 : Energy consumption projections : linear

## Sigmoid target final consumption

Some projections related to European population (in particular, UN medium scenario published in 2015, see [https://esa.un.org/unpd/wpp/publications/files/key\\_findings\\_wpp\\_2015.pdf](https://esa.un.org/unpd/wpp/publications/files/key_findings_wpp_2015.pdf)) predict a particular saturation of population by mid-century. If we stick to the assumption of a constant energy/capita factor, then it might be useful to take a function for the target, that has a similar sigmoid form. This scenario, assuming the same exponential growth of renewables, leads us to the following dynamics (see Figure 26).

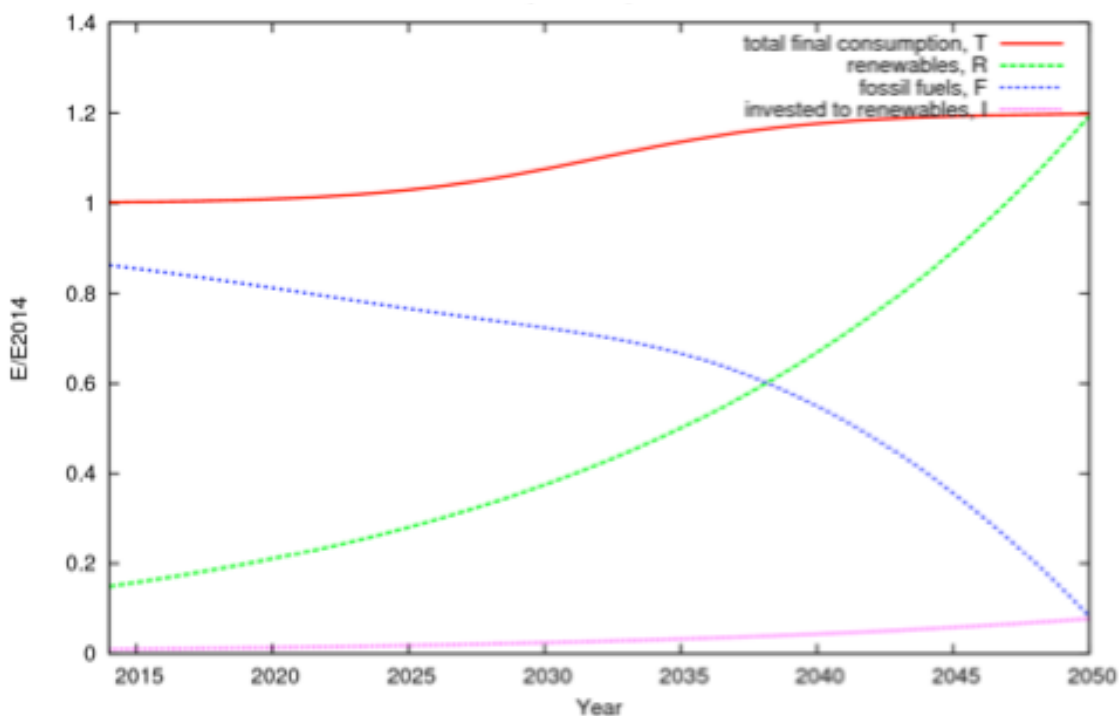


Figure 26 : Energy consumption projection : sigmoid. RE growth : exponential

It can be seen, that in this case in order to cope with the growing demand the reduction of the fossil fuel fraction must be maintained nearly linear and relatively slow at least until 2035, and later on a more aggressive reduction can be applied.

## Model with Retirement

In order to expand the model, we can take into account the retirement of the power facilities, that is, modifying Eq.(2) by subtracting the power of renewables, introduced L years before:

$$(2'') R'(t+s) = I(t) \cdot (e+p-1)/(p \cdot L) - R'(t+s-L)$$

The expenditures associated with the withdrawal of a retired facility are supposed to be a part of the total investment, distributed over the lifetime of the facility.

We can also look for a solution in a more general way, as a linear combination of a linear and an exponential function:

$$(3) I(t) = b_1 e^{it} + c_1$$

$$(4) R(t) = a_2 t + b_2 e^{it} + c_2$$

$$(5) T(t) = t_0 e^{kt}$$

$$(6) F(t) = T(t) + I(t) - R(t)$$

with the following parameters:

$$t_0 = 1$$

$$k = \ln(1.2)/36 = 0.0050645 \text{ (i.e. assuming } T(36) = 1.2)$$

$$(7) b_1 + c_1 = i_0 = 0.01 \text{ (i.e. initial investment rate 1\%)}$$

$$(8) b_2 + c_2 = r_0 = 0.159 \text{ (i.e. initial renewables' fraction 15.9\%)}$$

Using these functional forms, we can readily find the possible range for the parameter in Eq. 3, taking the upper bound for the investments as 10 % and  $b_1 = 0.01$ , that is,

$$(9) i < \ln(10)/36 = 0.064.$$

In order to reduce the dimensionality of the free parameter space, we can define the «target» final value for



$$R(t)=1.19,$$

so almost all the user demand is covered by RE, and the fossil fuels only power the introduction of new RE.

At this point, we can vary one parameter and have the solution fully defined. For the sake of simplicity let us take it as  $i$ , that is, the rate of growth of investments into RE (see Eq. 3). Variation of  $i$  will lead to the different functional forms of  $F(t)$ , that translates into different total consumption of fossil fuels (which is the area beneath the line  $F(t)$ ). Minimization of this area gives the minimum rate

$i_{min}=0.03$ ,  $b_i=0.0307$ , with the rest of the parameters computed in accordance with Eq. (7) and (8).

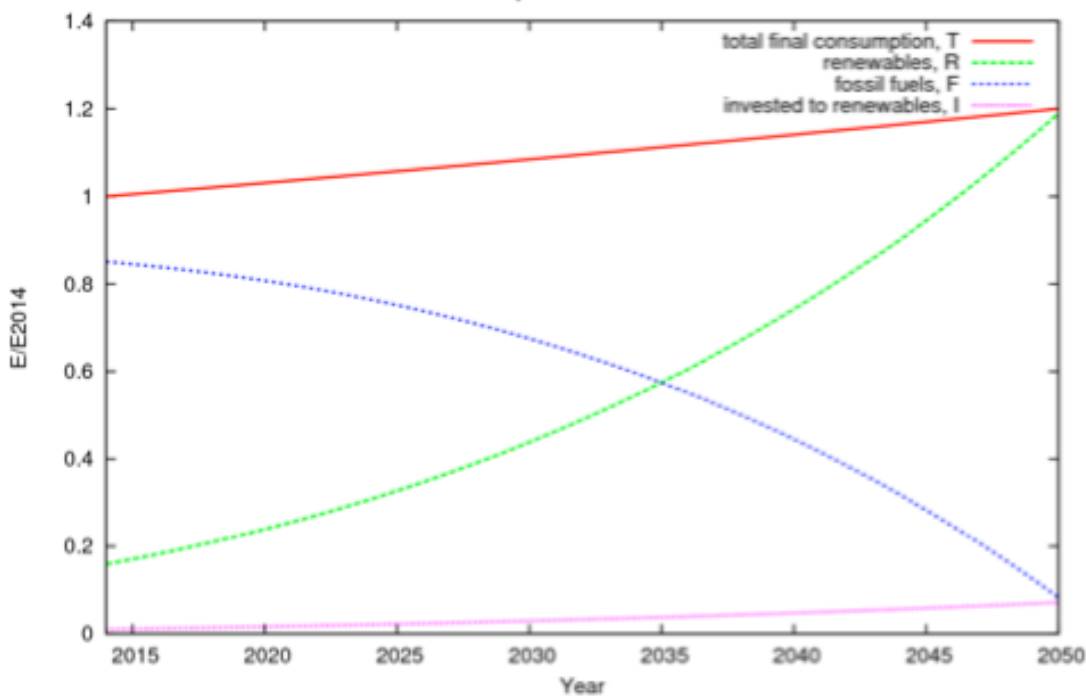


Figure 27 : Energy consumption projection : Exp+Linear solution

The dependence of the basic functions on time is presented in Figure 27. The final investment rate is expected to be 7%; as in the previous scenarios, we assume that by 2050 virtually all the energetic end-user demand is covered by the renewable energy, while the fossil fuels are spent almost entirely as investments into RE sector.



## Results rate of change MLT: Analysis by sectors

### Electricity sector

In the BAU scenario, power generation would increase by 60% to 2030 and the total renewable energy share in power generation would reach 30%, up from 23% in 2014. Wind share will go from 3% to 7%, with solar PV expected to remain below 3%. The share of natural gas and coal combined would still account for the majority of power generation by 2030 (IRENA 2016).

There is a large uncertainty in how much renewables in the electricity sector could grow and also in how the share of electricity used in total final energy demand is found in the mitigation scenarios. Depending on the level of energy efficiency improvements and deployment of electrification technologies, the evolution of the electricity sector could differ significantly. The deployment of renewable energy to the extent projected in the 2°C scenarios will require a significant enhancement of system integration measures. This may encompass various technical, institutional, policy and market design aspects to enable the cost-effective uptake of large amounts of RES in the power system.

The electricity demand is expected to grow in most 2°C scenarios due to the increasing living standards and the electrification of other sectors (transport, building, industry). At the same time, efficiency measures are needed. In the Greenpeace Energy Revolution scenario, the total electricity demand will rise from about 18,860 TWh/a to 37,000 TWh/a by 2050. Compared to the Reference scenario, efficiency measures avoided the generation of about 16,700 TWh/a.

Global electricity consumption increases by around 2% per year in the New Policies Scenario, with the expansion in renewables accounting to meet more than half of the increase. In the 450 Scenario, electricity becomes the largest form of energy supply in industry and increases in buildings and transport sectors. Despite the expansion in electrification in end-use sectors, global electricity demand is 11% lower than in the New Policies Scenario in 2040 (but still nearly 50% higher than today).

Figure 28 shows the power generation expected in the different scenarios. Power generation includes electricity and heat generation. As in the electricity demand, in spite of the increase in the



use of electricity, the evolution of power generation decreases or is maintained in comparison with the BAU Scenario.

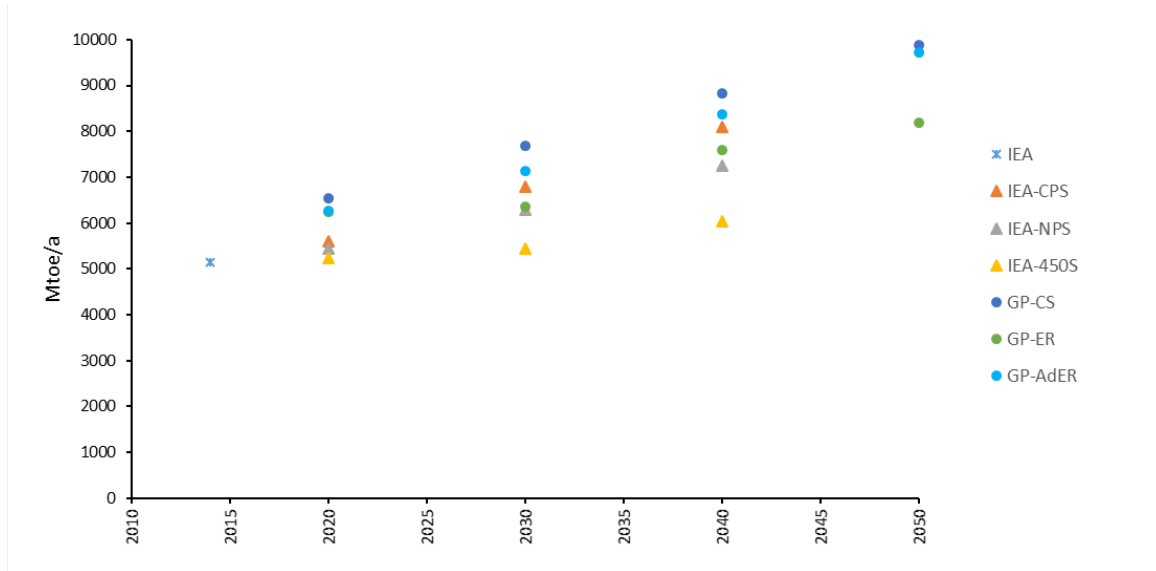


Figure 28: Power generation in the different scenarios.

The share of RES in the electricity sector is a matter of great discrepancy among the different scenarios.

In the IEA-NP scenario (IEA 2016) an acceleration in the share of RES in the electricity sector is expected due to the latest policy announcements; renewables will account for 37% of the electric sector in 2040 (with a total demand of 39000 TWh). However this is not enough to achieve less than a 2°C increase in the temperature; the 450 Scenario increases the share of RES in the electric sector to 58% in 2040 (with a total demand of 34000 TWh).

In the GP-ER scenario (Greenpeace. et al. 2015) the share of renewable sources is 58% by 2030 and 92% by 2050, reaching 100% in the GP-AdER Scenario (23,600 GW installed generation capacity in 2050). The increase in the share of renewable electricity will compensate for the phasing out of nuclear power production and the reducing number of fossil fuel-fired power plants. In these scenarios, electricity is used for electric vehicles, but also for the generation of synthetic fuels for fossil fuel substitution including hydrogen.

IRENA sets a middle position and assumes a 45% share of RES in power generation in 2030 and 80% in 2050 (IRENA 2016). The higher power generation will be provided mainly by more solar PV,



the wind, geothermal and ocean energy, although differences in the share of each source are observed among the different scenarios.

The Renewable energy mix of IEA 450 in 2040, that supply 58% of 34000 TWh, is: 20% is Hydro, 18% wind, 9% solar PV and 11% other renewables. All renewables see substantial capacity growth in the IEA 450 Scenario, but wind power and solar PV see the biggest scale-up. The power generation mix of this scenario is filled out with 18% nuclear, 16% fossil fuels and 8% of CCS. The use of CCS rises rapidly, both to reduce emissions and as an important protection strategy for fossil-fuel assets that have recently been built and whose investment costs have still not been recovered. Nevertheless, around 675 GW of coal-fired power generation capacity is retired prior to the end of its lifetime in the 450 Scenario.

IRENA REmap scenario projects an increase in wind power from 3% in 2014 to 14% in 2030 (reaching nearly 2 000 GW). Solar PV jumps from less than 1% in 2014 to almost 7% in 2030 (1760 GW). The share of hydropower is not expected to grow as fast because it starts from a higher base, but would still account for the largest share of renewable power generated by 17%.

In Greenpeace scenarios wind, PV, CSP and geothermal energy will contribute to 68% to the total electricity generation.

Solar PV and wind power share increases in all the scenarios but a wide range of outcomes are observed. By 2030, IRENA REmap solar potential estimates the IEA 450 by a factor of two and by 30% for wind. Greenpeace ER increases the IEA 450 solar potential by a factor of three and almost doubles the wind capacity (Figure 29).



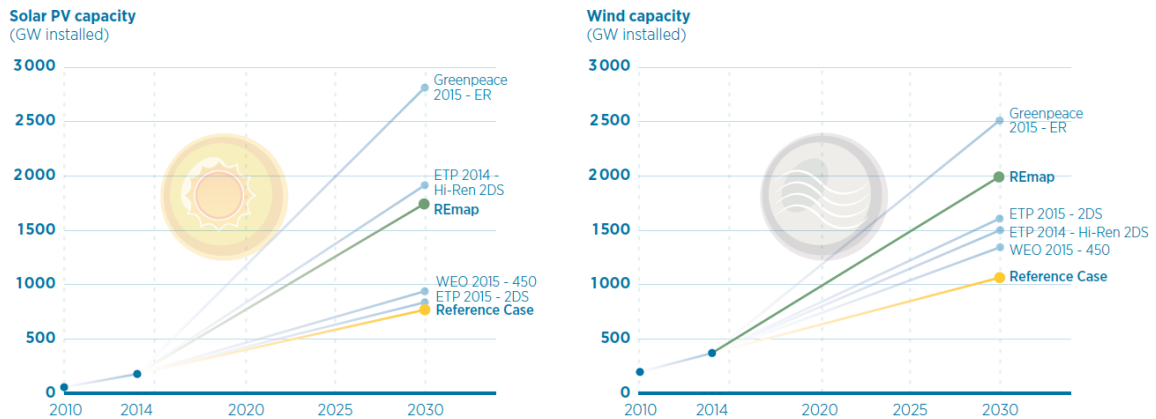


Figure 29: Solar and wind capacity projections according to different scenario analyses. Extracted from IRENA Roadmap for a renewable energy future (IRENA 2016).

The deployment of RES technologies to levels even consistent with the 450 Scenario requires a significant upgrade in technical, institutional, policy and market design, collectively known as system integration measures. In the absence of these measures that increase the flexibility of the system, there is a risk that the wind or solar capacity would face significant curtailment during times of abundant generation, which could undermine the economics of projects, the investments and make these technologies less effective as emissions abatement options (IEA 2016). If RES technologies are increased to higher levels, as in the Energy [R]evolution scenarios (GP-ER and GP-adER), it will lead to a high share of fluctuating power generation sources (PV, wind and ocean). Therefore, smart grids, demand side management (DSM), energy storage capacities and other options need to be expanded in order to increase the flexibility of the power system for grid integration, load balancing and a secure supply of electricity (Greenpeace. et al. 2015).

## Electricity Sector in MLT 2020

As it can be observed in Fig. 30, the demand in the energy sector rises as a result of the increase in the use of electricity in the remaining sectors (this is, in fact the only sector where energy demand is expected to increase). In the MLT-2020 scenario, the total power generation obtained for 2030 and 2040 is between the ones proposed by the IEA 450 and GP-ER. For 2050 it is slightly higher than in GP-ER scenario.

As can be seen in Fig. 31, the use of coal decreases rapidly at around 50% until 2040 and is almost absent in 2050. The use of oil decreases fast until 2030, then it is maintained until 2040 and decreases again in 2050 to reach the restrictive limit needed for that year. Natural gas share is maintained in the first decade of the transition because the priority is to decrease the use of coal and oil, but its use drops from 2030 to 2050 (Table 3).

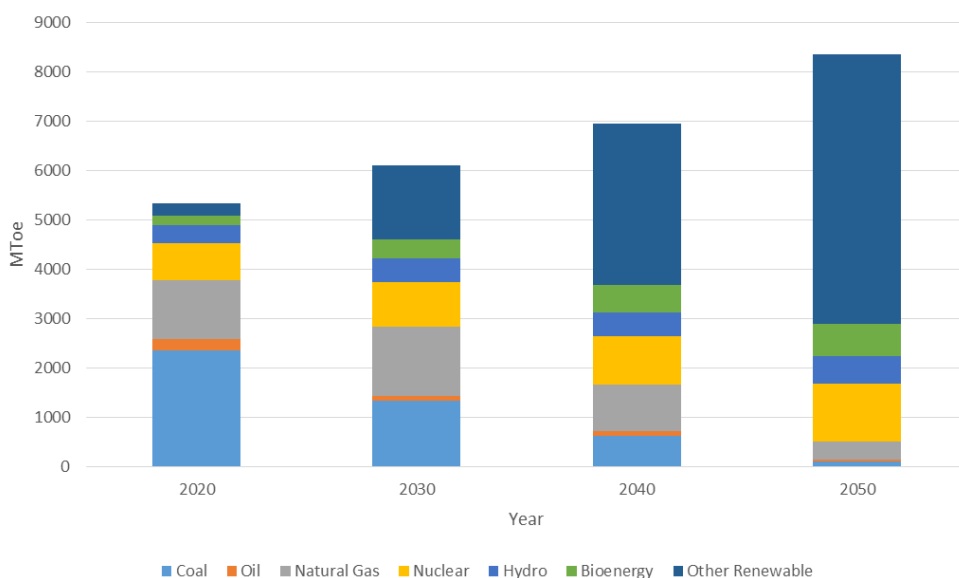


Figure 30: Power generation in MLT-2020.

In order to compensate the decrease in the use of these carbon-technologies and the increase in the demand, the contribution of non-carbon technologies has to increase necessarily (Fig. 31 and Table 3). Nuclear and renewable energies are the possible replacement. In the MLT-2020 scenario, the share of nuclear energy is maintained, which means that its power generation increases slightly as the total power generation increases. The GP approach eliminates the nuclear energy by



2030, while IEA- 450 scenario increases its share to 23% in 2030 and 26% in 2040. In order to remove the nuclear energy from the MLT-2020 scenario, the renewable options need to be further increased as carbon-technologies cannot be an option to avoid exceeding the 2°C budget.

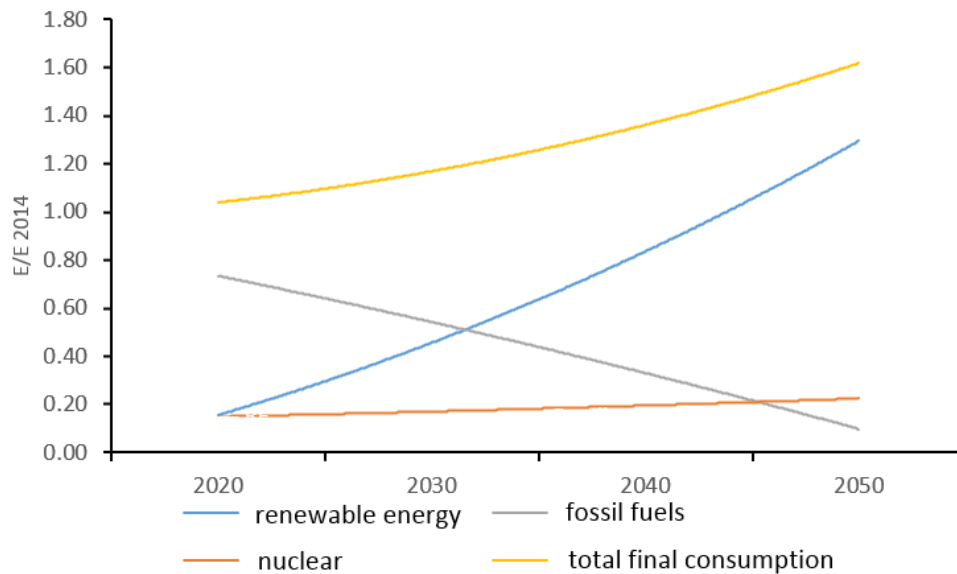


Figure 31 : Power generation demand in MLT-2020.

Table 3 : Power generation share in MLT-2020

	2020	2030	2040	2050
<b>Coal (%)</b>	44,2	22	9	1,2
<b>Oil (%)</b>	4,2	1,4	1,3	0,5
<b>Natural Gas (%)</b>	22,4	23	13,7	4,5
<b>Nuclear (%)</b>	14,2	15	14	14
<b>Hydro(%)</b>	6,7	8	7	6,5
<b>Bioenergy(%)</b>	3,7	6	8	8
<b>Other Renewable (%)</b>	4,7	24,6	47	65,3
<b>Total power Generation (Mtoe)</b>	5332	6090	6944	8354

Hydropower generation increases slightly until 2030 and then is maintained so its share slightly decreases. The reason is that an important capacity of hydropower generation already exists but a



sustainable expansion of this technology is limited if large hydropower stations with large dams and flooding areas want to be avoided (according to GP estimations) (Greenpeace. et al. 2015).

The use of bioenergy for power generation increases slowly. Values are in agreement with the estimations provided in GP-ER and IEA 450 scenario.

The main increase in power generation is attributed to other renewables. In the MLT-2020 scenario this value (Table 1) is higher than in the IEA 450 scenario (14,5% in 2030, 24,7% in 2040) but lower than GP-ER (25,3% in 2030; 61.2% in 2040 and 75.8% in 2050). The increase in the use of other renewables is essential to achieve the 2°C budget if CCS is not considered and if nuclear power is limited.

The composition associated with “Other renewables” could be similar to the GP-ER scenario. As it can be seen in figure 32, ocean and geothermal energy increase its generation but its potential is considered limited. The main sources of renewable energy considered are the wind and solar.

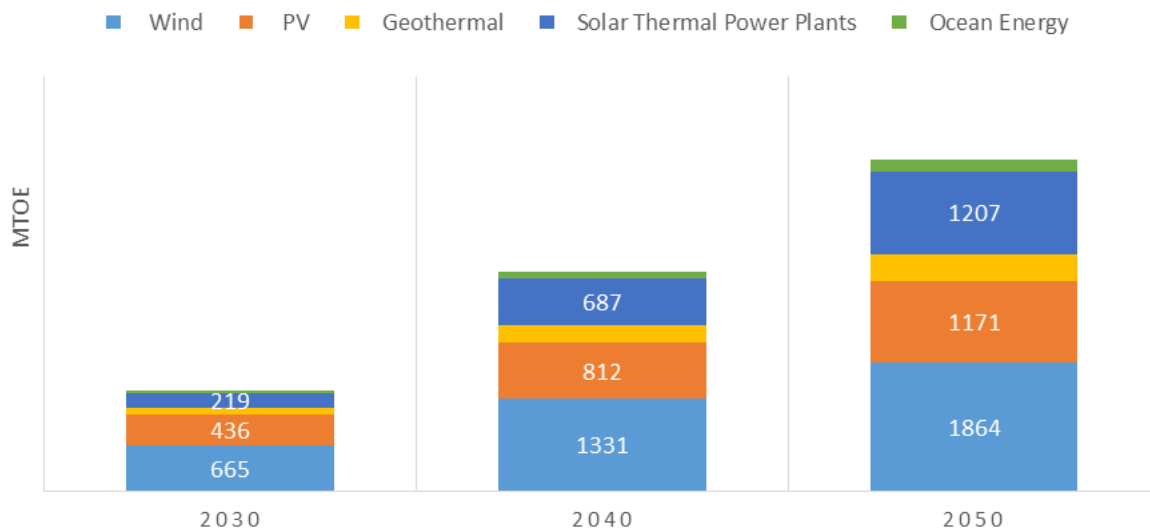


Figure 32: GP-ER other renewables composition in the electric sector.

## Electricity Sector in MLT-2030

As explained previously, in this scenario really drastic measures and changes need to be done in order not to exceed the carbon budget.

As it can be observed in Figure 33, the consumption in the power sector largely increases in 2040 and 2050, as a result of the increase in the electricity share in other sectors. This was also observed in MLT-2020 scenario, but in this case, the increase is even higher.

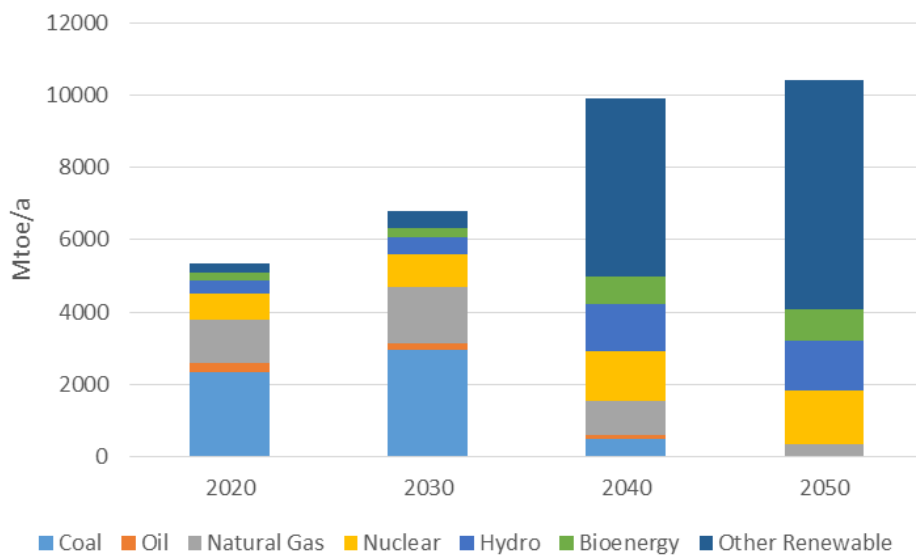


Figure 33 : Power generation in MLT-2030.

In addition to the increase in the consumption, the power sector needs to be rapidly decarbonized. The use of coal needs to be reduced to a 5% in 2040 and be null in 2050, with a similar path for oil and natural gas. It is important to highlight the difficulties associated with such a drastic increase in renewable energies (see Fig. 34 and table 4).

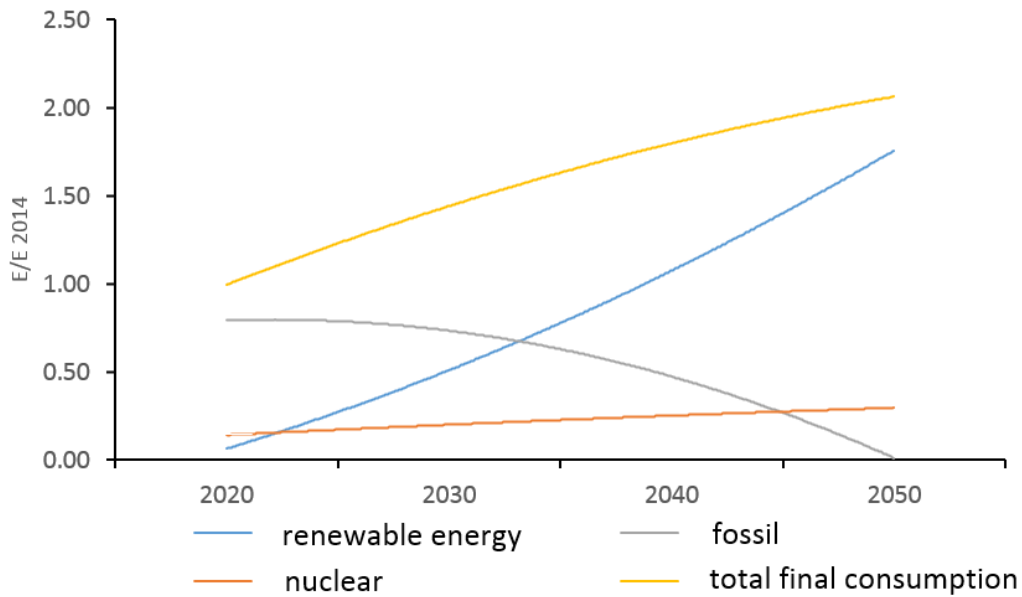


Figure 34: Power generation demand in MLT-2030.

Table 4 :Power generation share in MLT-2030.

	2020	2030	2040	2050
<b>Coal (%)</b>	44,2	43,8	5	0
<b>Oil (%)</b>	4,2	2,7	1	0
<b>Natural Gas (%)</b>	22,4	22,6	9,5	3,3
<b>Nuclear (%)</b>	14,2	13,8	14	14
<b>Hydro(%)</b>	6,7	6,6	13	13
<b>Bioenergy(%)</b>	3,7	4	8	8
<b>Other Renewable (%)</b>	4,7	6,6	49,5	59,5
<b>Total power Generation (Mtoe)</b>	5332	6777	9900	10643



## Building sector

Today, the building sector accounts for one-third of global energy consumption. Almost three-quarters are consumed in households: 33% is used for heating spaces, 30% for cooking and 20% for heating water. Renewables already account for a large share (about 35% in 2010) but 60% of it is due to traditional uses of bioenergy for cooking and heating leading to indoor air pollution detrimental to human health. Modern renewable energy share accounts for only 13% (IRENA 2016).

Energy demand from the building sector is going to grow due to the rising number of residential and commercial buildings in response to the expanding global population. IEA predicts an energy demand growth in services of 1.6 % annually to 2040 and about half of it in households because economic growth is faster in the services sector. Furthermore, the population is expected to decline in some regions of the world in the later part of the projection period (IEA 2016). In contrast, final energy use may stay constant by mid-century if today's cost-effective best practices and technologies are widely applied. The building sector has a great potential to reduce its energy demand. Improving building insulations to reduce heating and cooling needs and using more efficient equipment, for example in heating and lighting. This can be accomplished with stringent energy-savings requirements for new buildings and retrofits of existing ones. Strong barriers hinder the market uptake of cost-effective opportunities and adequate policies supporting them are key.

The objective set in MEDEAS project of limiting the average global temperature increase in 2100 to 2°C is in accordance with the objective of the IEA 450 and GP-ER scenarios. In these scenarios, the least-efficient categories of appliances (e.g. refrigerators, freezers, washing machines and dryers) and all incandescent light bulbs (including halogens) are totally phased out by 2030 reducing significantly the growth of electricity demand. In some cases, such measures are already justified by the market, but consumers need additional incentives. Furthermore, requirements in the building codes for new buildings are imposed, leading to a decrease in the energy demand for space heating and cooling. As a result, in the IEA 450 scenario, direct CO<sub>2</sub> emissions from the buildings sector fall to 2.3 Gt in 2040, while indirect emissions from an increasingly decarbonised power sector fall by two-thirds below today's level. As can be observed in figure 35 the energy demand for these scenarios decreases significantly in comparison with the Business as Usual Scenario (IEA-CPS). In the case of GP-ER, the energy demand for 2030 and 2040 is even lower.



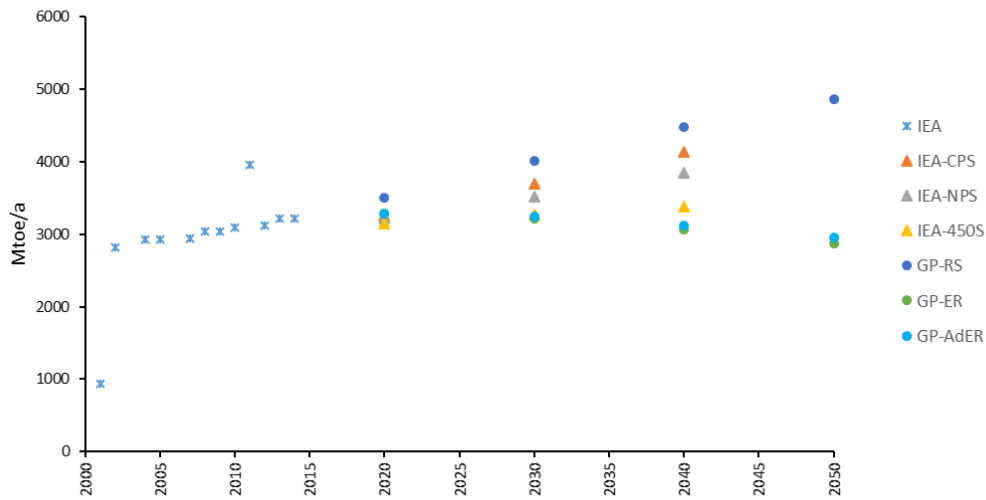


Figure 35. Energy demand in the building sector for different scenarios. Data from IEA (include building and service sector) and GP provided as other sector (include agriculture, building and service sector).

In all mitigation scenarios, a significantly larger reduction potential by 2050 than by 2030 can be observed in comparison with the reference scenario. The building infrastructure modernization driven by the policy planning does not have an immediate effect. The large mitigation potentials of this sector can only be achieved with policy permanence starting as soon as possible (IPCC 2014).

The share of each type of energy to satisfy the energy demand varies from one projection to another. The IRENA scenario (IRENA 2016), projected only until 2030, supposes a 38% share of renewables in that year, taking into account the reduction in traditional uses of bioenergy. Bioenergy will remain the main source of renewable energy in the sector, coming mainly from solid biofuels, biogas and liquid biofuels instead of traditional sources. Compared to open fires, advanced biomass stoves provide fuel savings of 30 – 60 % and reduce indoor air pollution levels by 80 – 90 % for models with chimneys. Solar thermal will increase fivefold between 2010 and 2030. Renewables-based district heating/cooling offers an important opportunity and must be at the core of urban planning.

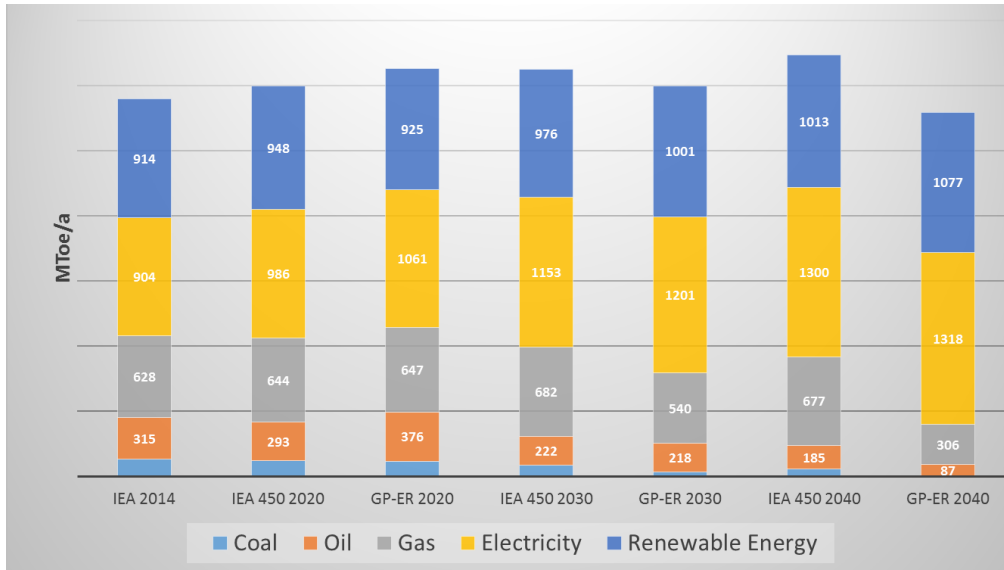


Figure 36 : Final energy demand in the building sector in IEA 450 and GP-ER scenarios.

As shown in figure 36, in the GP-ER Scenario the direct use of renewables provides 31% of the final energy demand in the building sector in 2030 and 35% in 2050. The demand is lower than in the IEA 450 scenario, and this allows the total elimination of coal by 2040 and a large reduction in the use of gas and oil. In the IEA 450 scenario, the Mtoe/year of renewables directly used in the building sector is similar to the GP-ER scenario, accounting for 30% of the final energy-demand in 2030 and 2040. In both scenarios, the main contribution to the direct use of renewables is due to the advance use of bioenergy, with an increasingly important contribution of solar energy and geothermal energy.



## Building sector in MLT-2020.

In the BAU scenario, the final energy demand in the building sector increases. However, in the MLT-2020 scenario (figure 37) the demand of energy in the building sector follows the same trend than in the IEA 450 and GP-ER scenarios. The demand is maintained until 2030 and then it slowly decreases. In order to accomplish this trend, in spite of the increase in the global population, severe policies and measures must be applied.

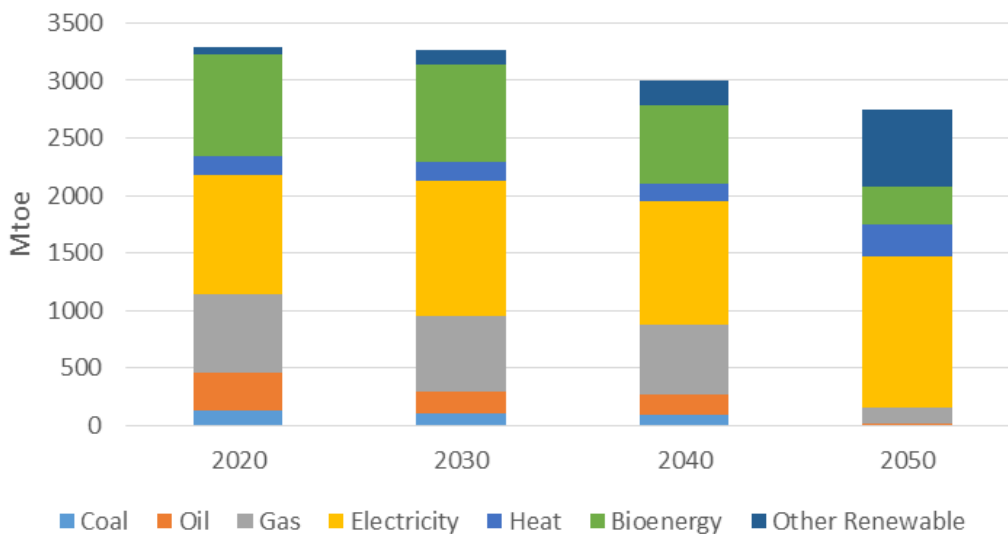


Figure 37 : Building sector in MLT-2020.

In this sector, the share of coal, oil and gas decreases in favor of electricity and other renewables (Fig. 38 and table 5). The main decarbonisation is due to the evolution of the electricity sector, that has a large share in buildings. The composition of the sector changes slowly and in 2030 and 2040 it is similar to the IEA 450 scenario. However, to achieve the strict limit needed in 2050, a more severe decarbonization is needed, and coal and gas use has to become almost inexistent while gas has to decrease by around 75%.

Electricity and renewables are the main responsible of this replacement. Solar and biothermal are the renewables with the larger potential to be used in this sector.

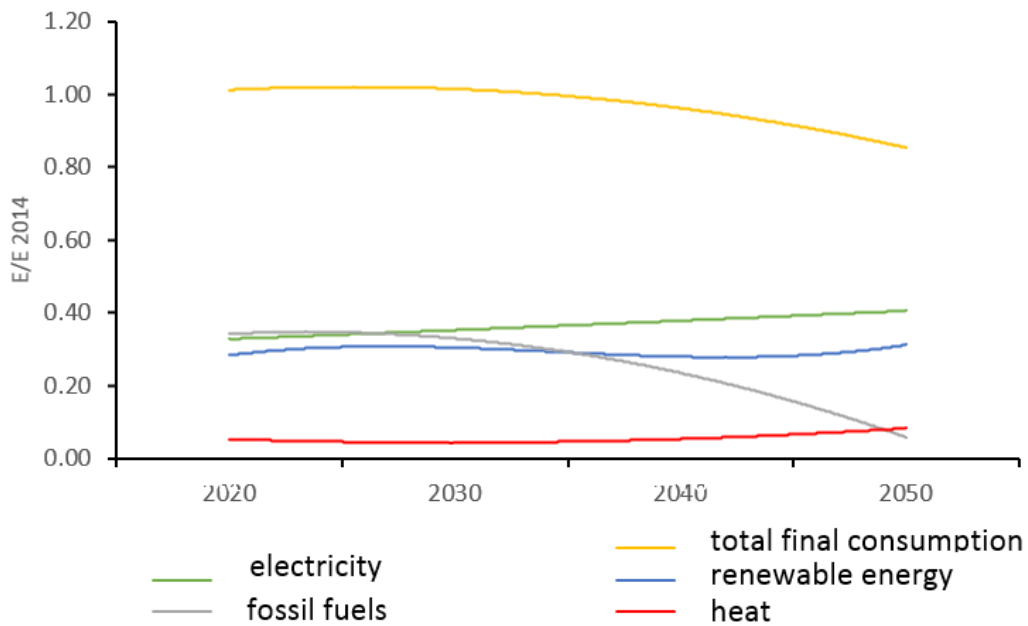


Figure 38 : Final energy demand in the building sector in MLT-2020.

Table 5 : Building sector share in MLT-2020.

	2020	2030	2040	2050
<b>Coal (%)</b>	4	3	3	0,1
<b>Oil (%)</b>	10	6	6	0,4
<b>Gas (%)</b>	21	20	20	5
<b>Electricity (%)</b>	32	36	36	48
<b>Heat (%)</b>	5	5	5	10
<b>Bioenergy(%)</b>	27	26	23	12
<b>Other Renewable (%)</b>	2	4	7	24,5
<b>Total energy demand (Mtoe)</b>	3259	3269	3000	2750



## Building Sector in MLT-2030.

In all the mitigation scenarios the decrease in the demand of the building sector is driven by policy measures that promote the building infrastructure modernization. Additionally, the mitigation potential is achieved in a period of 30 years after these policies are applied. In this scenario the delay in the actions restricts the decrease in the consumption and the tendency of the consumption decreases slowly during the first 20 years, achieving values slightly higher than in MLT-2020. So, as it can be observed in figure 39 and 40, the expected energy demand of the sector remains high.

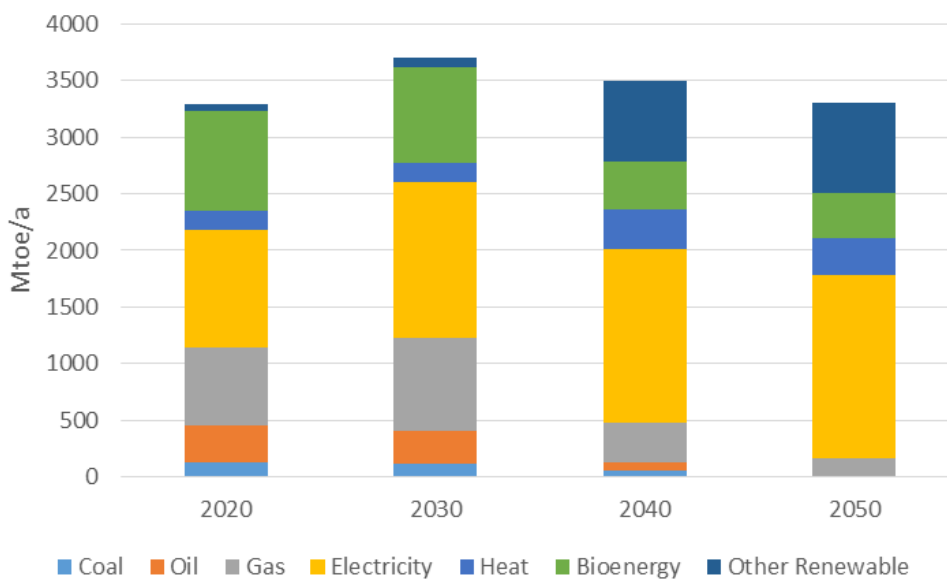


Figure 39 : Building sector in MLT-2030.

Table 6 show the building sector share in MLT-2030. In order to meet the CO<sub>2</sub> budget, decarbonization needs to be done rapidly, increasing the share of electricity and renewable sources, mainly solar. Bioenergy shares in 2020 and 2030 come from traditional bioenergy uses and these need to evolve to modern bioenergy. Such a fast change is considered difficult and this is the reason of its decrease in this scenario.

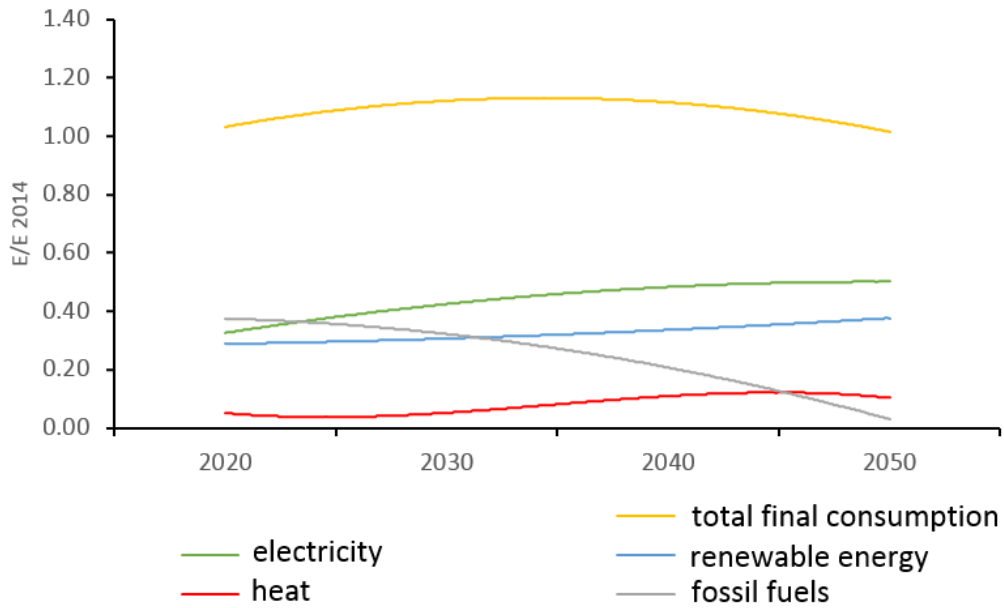


Figure 40 : Final energy demand in the building sector in MLT-2030.

Table 6 : Building sector share in MLT-2030.

	2020	2030	2040	2050
<b>Coal (%)</b>	4	3,2	1,5	0,1
<b>Oil (%)</b>	10	7,8	2	0,3
<b>Gas (%)</b>	21	22,1	10	4,5
<b>Electricity (%)</b>	32	37,3	44	49
<b>Heat (%)</b>	5	4,5	10	10
<b>Bioenergy(%)</b>	27	22,9	12	12
<b>Other Renewable (%)</b>	2	2,2	20,5	24,1
<b>Total energy demand (Mtoe)</b>	3259	3702	3500	3300



## Industry

Worldwide emissions from industry are larger than the emissions from the buildings or transport end-use sectors and represented just over 30 % of global GHG emissions in 2010. The largest energy consuming sectors in the industry are chemical and petrochemical industry, iron and steel and nonmetallic minerals. Together these sectors consume about 45% of industrial energy demand.

Current Policy Scenario (IEA 2016) projects an increase in the share of industry from 38 to 39 % by 2040. Energy demand in the industry has increased by 2.0% per year since 1990, but this rate of growth is expected to slow down by 1.2% per year over the period to 2040. On the other hand, energy efficiency is projected to continue to improve over the next decades. Regulatory efforts to reduce the carbon intensity in the industry sector typically focus on improving energy efficiency. The degree to which regulatory action is being pursued has been increasing in recent years, in particular in China, where the industry sector is responsible for one-third of the total energy demand today and uses more energy than the industry sectors of all OECD countries combined (IEA 2016).

The energy intensity of the sector could be reduced by approximately 25 % compared to current level through widescale upgrading, replacement and deployment of best available technologies, particularly in countries where these are not in practice and for non-energy intensive industries. According to the IPCC through innovation, additional reductions of approximately up to 20 % in energy intensity may potentially be realized before approaching technological limits in some energy intensive industries. Barriers to implementing energy efficiency relate largely to the initial investment costs and lack of information. Systemic approaches and collaboration within and across industrial sectors at different levels, e. g., sharing of infrastructure, information, waste and waste management facilities, heating and cooling, may provide further mitigation potential in certain regions or industry types. The formation of industrial clusters, industrial parks, and industrial symbiosis are emerging trends in many developing countries, especially with SMEs (IPCC 2014).



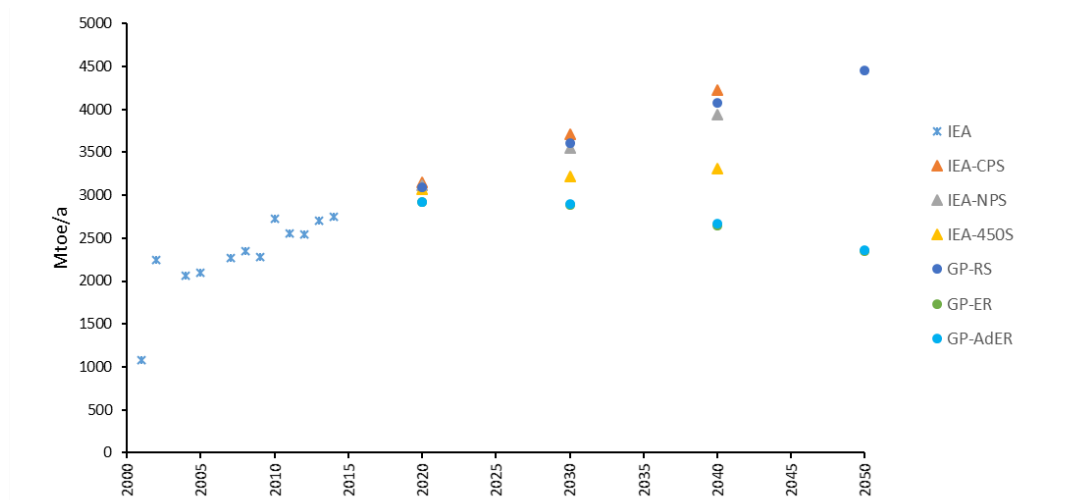


Figure 41: Final energy demand of the Industry sector for different scenarios.

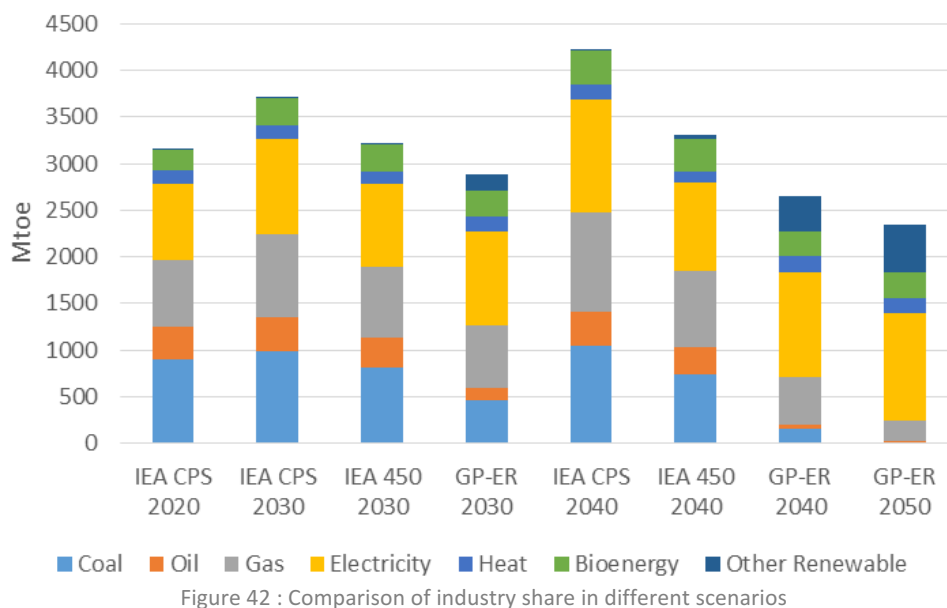
Figure 41 compares the final energy demand projected for the different scenarios. In the New Policies Scenario, the final energy demand is slightly reduced and the emission intensity of fuel demand in the industry sector falls by 0.6 % per year due to policies that encourage the uptake of low-carbon options. However, CO<sub>2</sub> emissions continue to increase because a significant part of the energy efficiency potential in the industry remains untapped. In the IEA 450 scenario, the final energy demand is reduced almost by 25%. CO<sub>2</sub> emission in 2040 are almost 30% lower than in the New policies scenario, a large part, almost 50%, due to the energy efficiency, fuel switching and demand reduction account for around 18% and the rest is due to CCS. To accomplish such estimations there is a need for further research, development and deployment to increase the uptake of renewables-based options. For example, to produce heat for the industry sector, and to improve the commercialisation prospects for CCS (IEA 2016).

Greenpeace revolution scenarios put the final energy demand even lower than IEA 450. In comparison to 2012, global fuel use in industry decreases from 78 to 50% and electricity use shows an increase from 29 to 48% as a result of the substitution of fuel with electric heating systems for heating. Energy revolution scenarios do not include CCS in their projections but they include the use of hydrogen in different sectors. For the industry sector, hydrogen serves as an additional renewable fuel option for high-temperature applications, supplementing biomass in industrial processes, whenever direct use of renewable electricity is not applicable. In addition to hydrogen, solar collectors, geothermal energy (including heat pumps) and electricity from



renewable sources are increasingly substituting for fossil fuel-fired systems in the industry. Due to all that, the share of RES in the industry sector in GP-ER accounts for 33% (80% taking into account the electricity) in 2050 and 25% in 2040 (60% taking into account the electricity). The share of coal, oil and gas are drastically reduced, being 27% in 2040 and 10% in 2050 (Greenpeace. et al. 2015) (figure 26).

In the IEA 450 scenario (figure 42) coal, oil and gas share is 60% in 2030 and 56% in 2040 and RES accounts only for 10 and 12%, respectively. In this scenario, CCS is essential to decrease the amount of CO<sub>2</sub> emitted.



## Industry in MLT-2020

In this scenario, a conservative approach regarding the energy demand in 2030 and 2040 is chosen with values not as low as in the GP scenarios but lower than in IEA-450 scenario. However, to accomplish the emissions level in 2050, the energy demand of the industry sector must be reduced to values close to GP scenarios. In order to meet this decrease, energy efficiency in the sector must be a priority since the beginning.

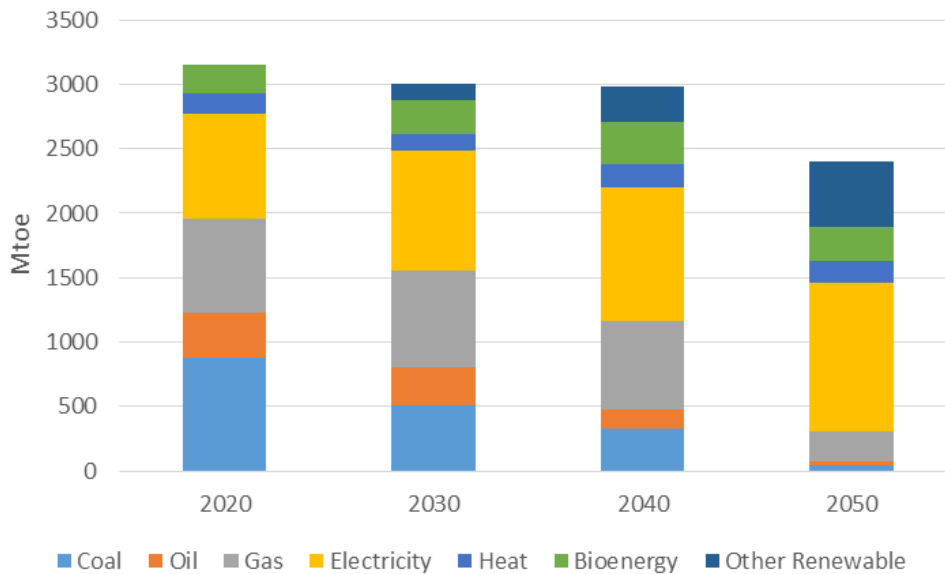


Figure 43 : Industry sector in MLT-2020

As it can be observed, in figures 43, 44 and table 4, the sector is progressively decarbonized, with coal and oil as the main priorities and gas in the last decade. Note that in Fig. 44, “renewables” stands for direct renewable energy use as is the case for fossil fuels. Heat and electricity can, in turn stem from renewable and non-renewable sources, with the final budget for all sectors presented in Fig. 14.

Electricity use increases as a result of the substitution of fuel use for heating with electric heating systems. In addition, bioenergy solar collectors and geothermal energy are the main sources of renewable energy.

It is also important to mention that even using 100% renewables, a fully decarbonized industry will never be achieved in the absence of carbon capture and storage, as several industrial processes produce CO<sub>2</sub> as a consequence of chemical reactions, i.e. during the linkerization process of cement, where limestone is converted into calcium oxide, thereby liberating CO<sub>2</sub>. A given quantity of coal or petroleum will also be likely required, as different processes use coke as reducing agent.

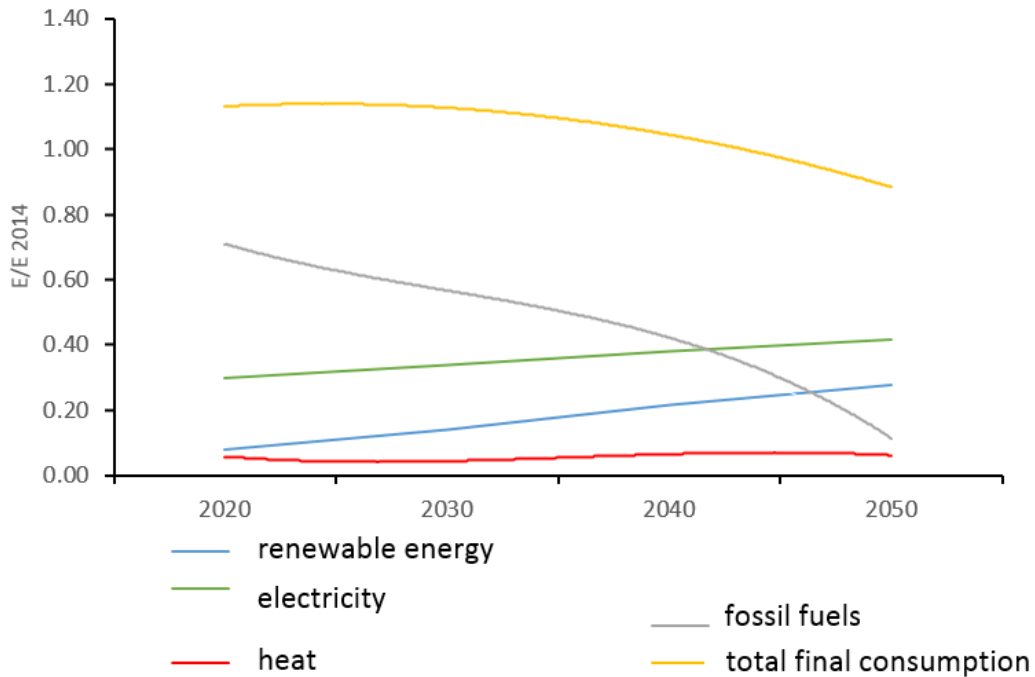


Figure 44 : Final energy demand in the industrial sector in MLT-2020

Table 7: Industry sector share in MLT-2020.

	2020	2030	2040	2050
<b>Coal (%)</b>	28	17	11	2
<b>Oil (%)</b>	11	10	5	1
<b>Gas (%)</b>	23	25	23	10
<b>Electricity (%)</b>	26	31	35	48
<b>Heat (%)</b>	5	4	6	7
<b>Bioenergy(%)</b>	7	9	11	11



<b>Other Renewable (%)</b>	0	4	9	21
<b>Total energy demand (Mtoe)</b>	3151	3000	2980	2400

## Industry in MLT-2030

A similar effect as observed in the building sector takes place in the industry sector. If no measures are taken until 2030 and the consumption continues increasing until then, the values of energy demand in 2040 and 2050 are higher than in MLT-2020 scenario and again a faster decarbonization of the sector is needed (figures 45 and 46).

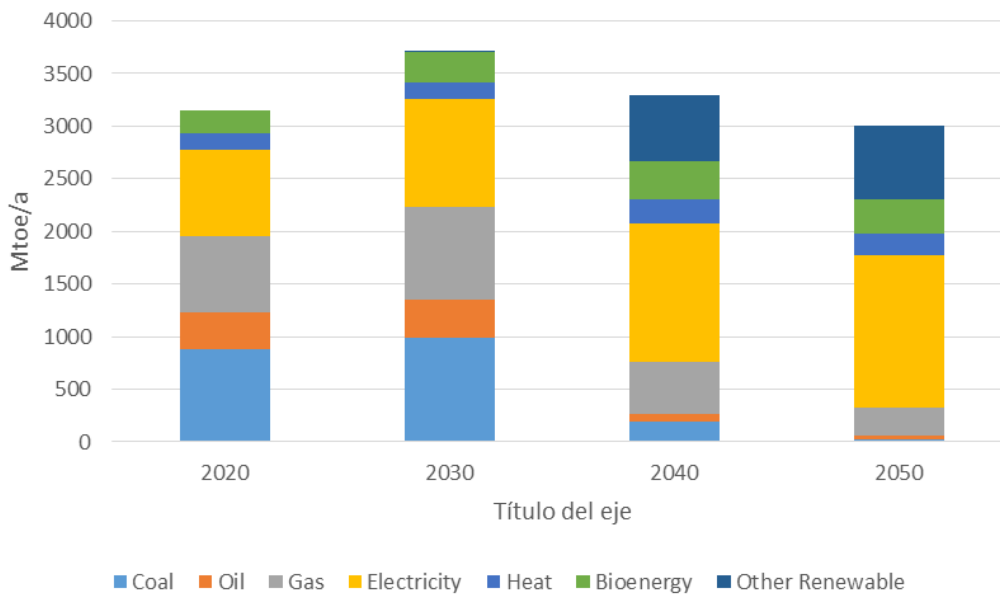


Figure 45 : Industry sector in MLT-2030

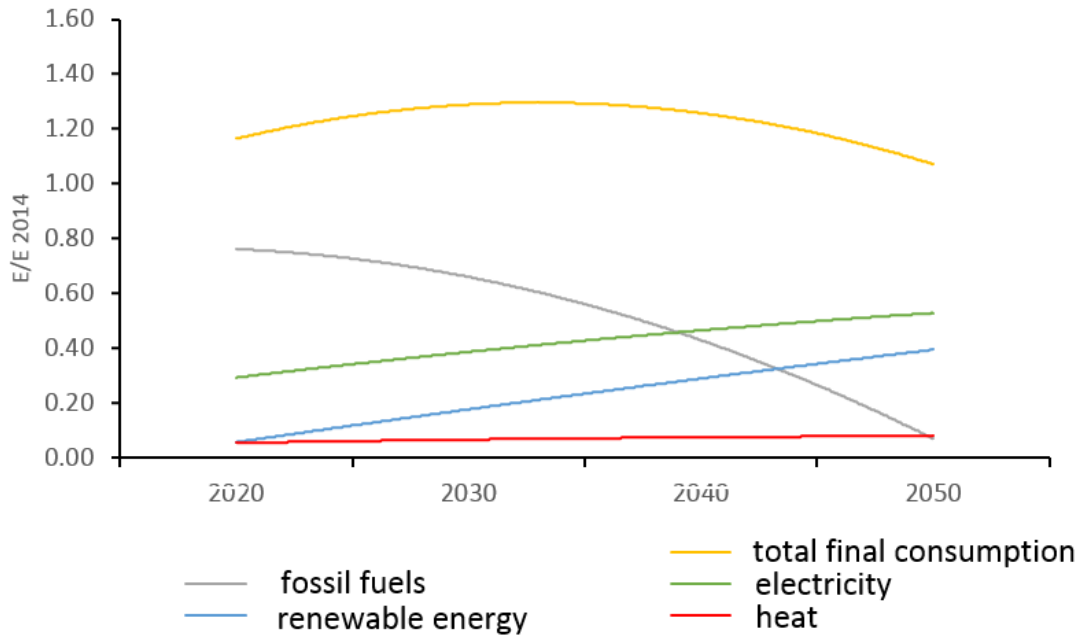


Figure 46 : Final energy demand in the industrial sector in MLT-2030

Table 8: Industry sector share in MLT-2030.

	2020	2030	2040	2050
<b>Coal (%)</b>	28	17	6	1
<b>Oil (%)</b>	11	10	2	1
<b>Gas (%)</b>	23	24	15	9
<b>Electricity (%)</b>	26	28	40	48
<b>Heat (%)</b>	5	4	7	7
<b>Bioenergy(%)</b>	7	8	11	11
<b>Other Renewable (%)</b>	0	0	19	23
<b>Total energy demand (Mtoe)</b>	3151	3708	3300	3000

Electricity is the main substitute of carbon-based fuels (table 8), but with the support of other renewables, bioenergy, and heat.



Industry sector is a complex sector that is composed of different types of industries. In some of them, the decarbonization could be difficult, i.e. in the metallurgical sector where very high temperatures are required for smelting. Two different approaches are included in the different scenarios analysed to achieve this. IEA opts for CCS while GP chooses the use of hydrogen as fuel. Any of them will need significant technological improvement to be implemented and even then a complete decarbonization of the sector would be difficult. This is in agreement with task. 3.1.ab where the limit for the industry sector was 25% of the final emissions.



## Trasport

Nowadays, the transport sector requires over one-fourth of current energy use, including road and rail, aviation and sea transport. Most of all the transport energy demand is provided by oil products (92.7 % in 2013) (IEA 2016). Increasing the share of renewables in the transport sector, directly or via synthetic fuels, to phase-out carbon emissions would require considerable effort.

The mounting policy focused on fuel-economy standards in road transport of recent years moderates some of the possible growth in oil demand to 2040 but current policy efforts appear insufficient to reduce the oil dependency of transport (IEA 2016). In the New Policies Scenario, the emission intensity of transport fuel use drops at a slower rate than in any other sector and emissions rise in 2040 to 9.4 Gt (7.5Gt today) (figure 47). The main reason is because of the increase in demand in the different sub-sectors: mobility, freight transport, aviation and international shipping.

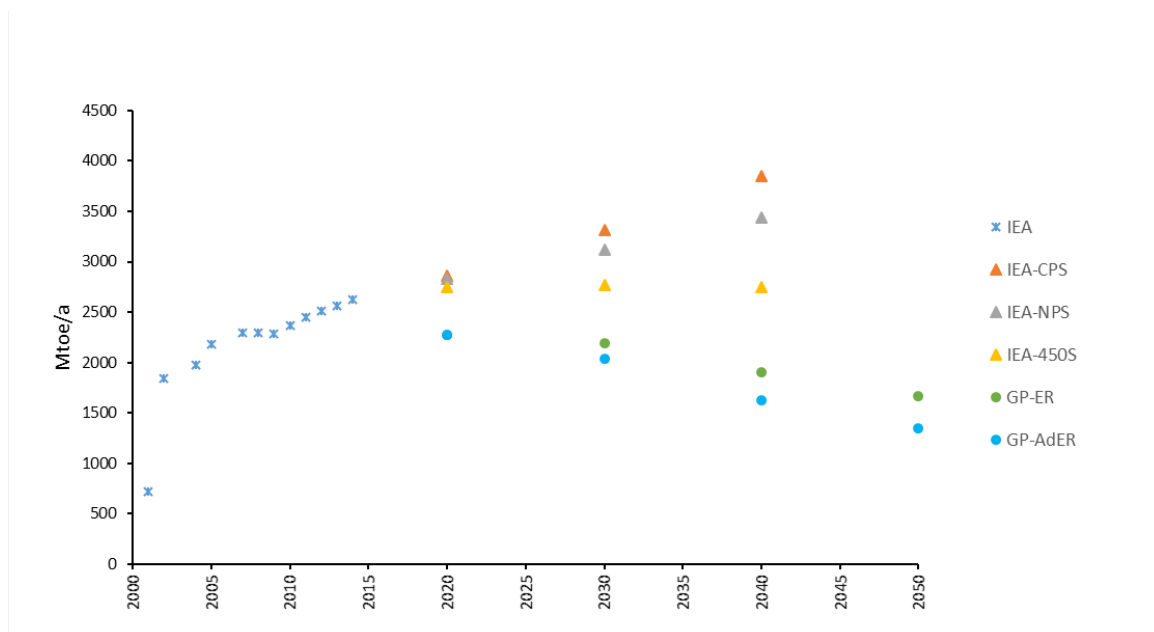


Figure 47 : Final energy demand of the transport sector. Comparison of different scenarios.

Efficient measures are considered key to reduce the demand. For example, the GP-ER scenario reduces the energy demand from the sector by 53% in 2050 in comparison to the Reference scenario. The GP-AdER scenario leads to even higher energy savings, 62% (Figure 47). A key target is to introduce incentives for people to drive smaller cars and buy new and more efficient vehicle concepts. In addition, it is vital to shift transport use to efficient modes like rail, light rail and buses, especially in the expanding large metropolitan areas. Along with the increase in prices for fossil fuels, these changes reduce the further growth in car sales projected under the Reference scenario.

In the IEA450 scenario, energy efficiency is also key. The energy demand of the sector decreases by 28% in 2050 in comparison with the reference scenario (figure 48). In addition, switching to biofuels and electrification is essential. In this scenario oils share of total transport, demand drops from over 90% to under 65% in 2040. As a result, CO<sub>2</sub> emissions from transport peak just before 2020 and then drop in 2040 to 20% below today level. By 2040, the global stock of electric vehicles grows to over 710 million.

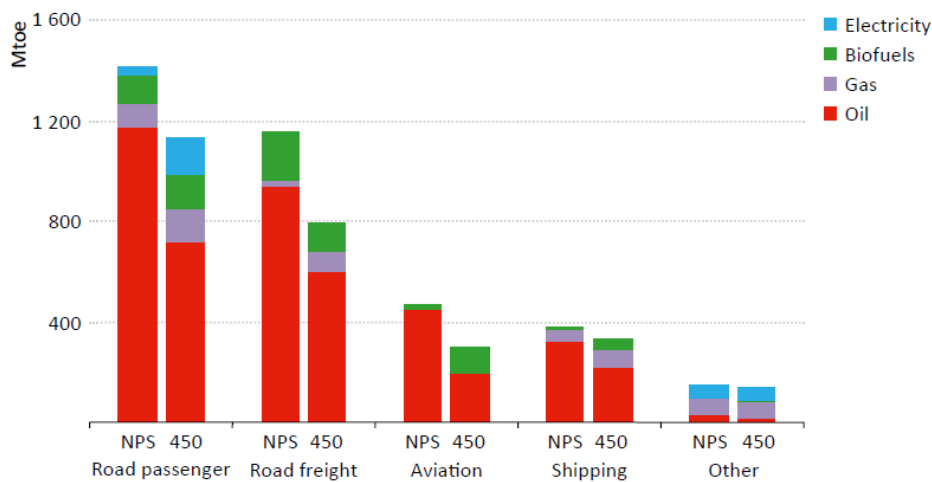


Figure 48 : Global transport fuel demand in the New Policies and 450 Scenarios in 2040. Extracted from (IEA 2016).

In the Greenpeace ER scenario, electricity provides 9% of the transport sectors total energy demand in 2030, while in 2050 the share is 39%. Hydrogen and other synthetic fuels generated using renewable electricity are complementary options to further increase the renewable share in the transport sector. GP scenarios increasingly rely on hydrogen as a renewable fuel because



battery supported electric vehicles are considered to reach their limitations and biomass potentials are restricted. However, future application of hydrogen might not suffice to replace all fossil fuel demand, especially in aviation, heavy duty vehicles and navigation. Thus these scenarios also considered the introduction of synthetic hydrocarbons from renewable hydrogen, electricity and biogenic/atmospheric CO<sub>2</sub>. More research and development is needed to achieve commercialization at the scale of synfuels (also called advanced biofuels) as they are considered the main option to decarbonize aviation and maritime sectors.

Synfuels is an alternative approach to overcome the limit of decarbonization of the transport sector, without considering it this sector will be the one that generates most emission of CO<sub>2</sub> in 2050 according to the limits settled in task D3.1. ab.



## Transport in MLT-2020

As in the other sectors commented previously, the energy demand of the transport sector in MLT-2020 for 2030 and 2040 is a middle value, lower than in IEA 450 scenario but not as low as GP-ER. In 2050, due to the strict limit needed, the energy demand is restricted in accordance with GP-ER scenario. To accomplish this trend efficient measures, need to be taken, for example, incentives to buy new smaller cars or to use public transport or even change the taxation system of fossil fuels.

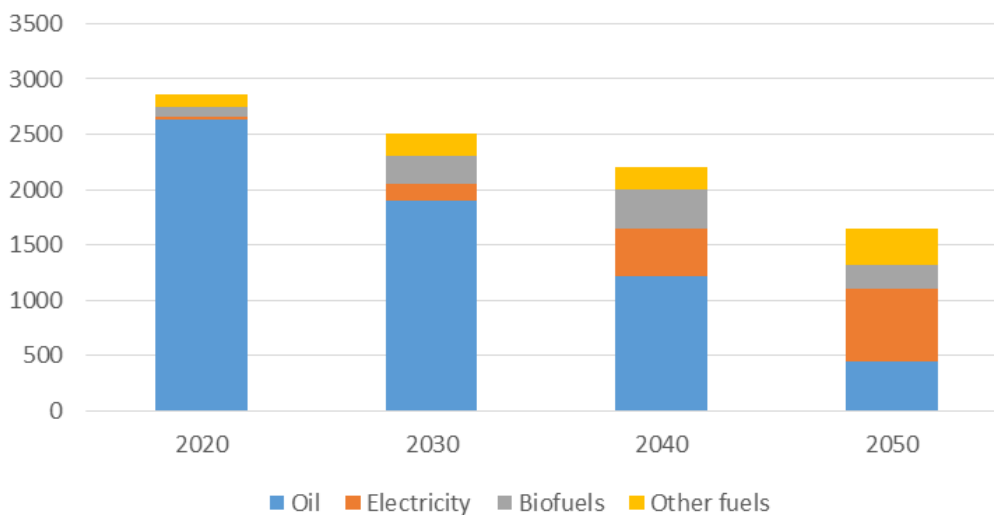


Figure 49 : Transport sector in MLT-2020.

The sectors dependence on oil hampers its decarbonization. As it can be observed in Fig. 50 and table 5, biofuel and electricity are the main alternatives to oil. Electric vehicles account for around 40% share in 2050 as they are mainly useful only for road passenger (Figure 49). On the other hand, biofuel potential is limited, with a share of only 13% in 2050. Road freight, aviation and shipping depend mainly on the development of advanced biofuels or hydrogen, considered as other fuel sources.



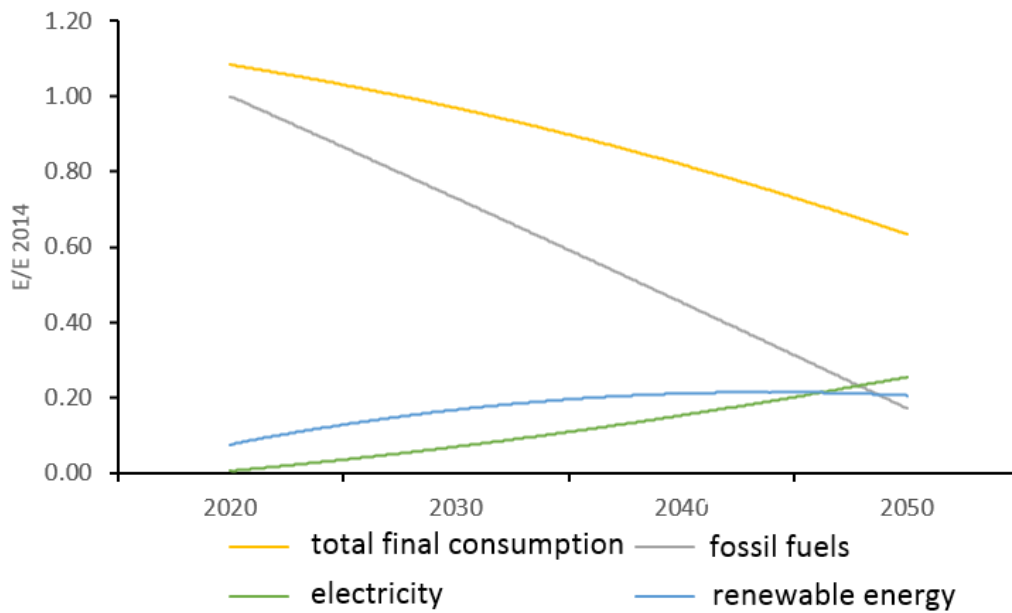


Figure 50. Final energy demand in the transport sector in MLT-2020.

Table 9: Transport sector share in MLT-2020.

	2020	2030	2040	2050
<b>Oil (%)</b>	92	76	55	27
<b>Electricity (%)</b>	1	6	20	40
<b>Biofuels (%)</b>	3	10	16	13
<b>Other fuels (%)</b>	4	8	9	20
<b>Total energy demand (Mtoe)</b>	2863	2500	2200	1650



## Transport in MLT-2030

As in the previous sectors, the delay in adopting policies to improve the efficiency of the sector and decrease the demand leads to a higher energy consumption in 2040 and 2050 than in MLT-2020.

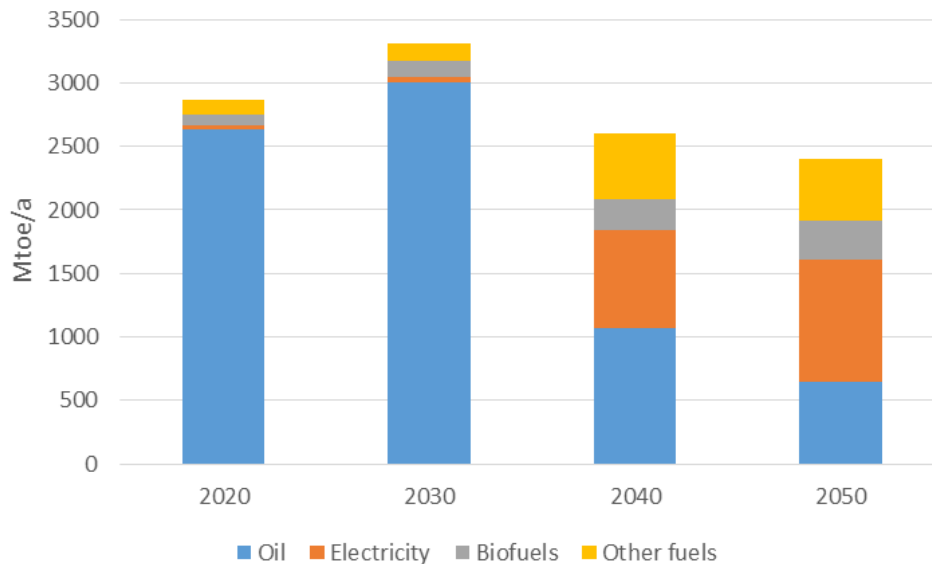


Figure 51 : Transport sector in MLT-2030.

Once more a faster decarbonization is needed and the share of oil has to decrease drastically in 2040 and 2050 (figure 51, 52, table 10). As a result, the use of electricity in the transport sector increases by 40% in 20 years. Biofuels and other fuels have the same share in the composition than in MLT-2020.

This drastic change in the composition is the only possibility not to overpass the CO<sub>2</sub> budget in 2050. Despite this, this sector accounts for 55% of the CO<sub>2</sub> emissions in 2050 (40% in MLT-2020) being the sector that is decarbonized to a lower extend.

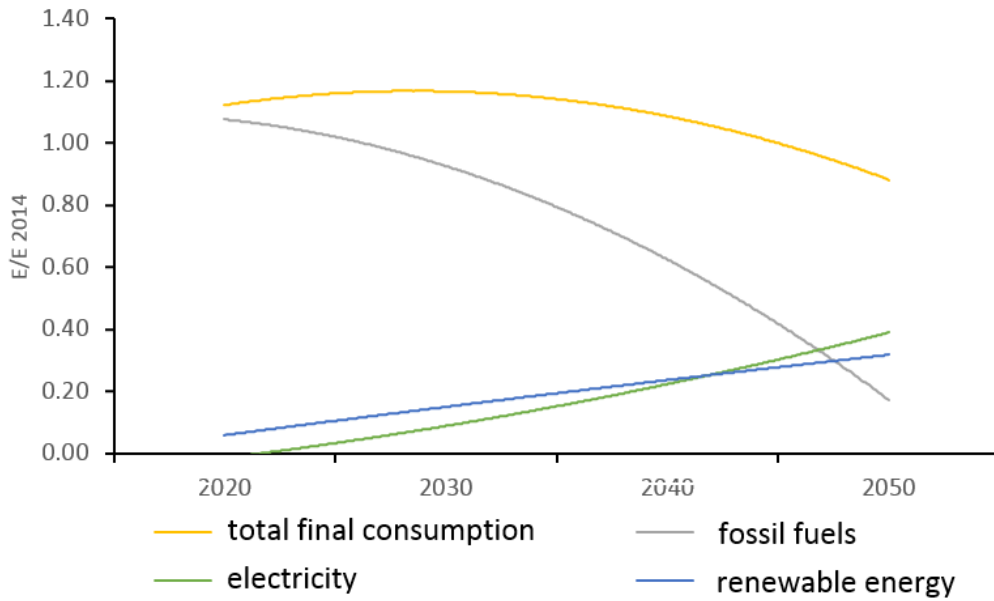


Figure 52 : Final energy demand in the transport sector in MLT-2030.

Table 10 :Transport sector share in MLT-2030.

	2020	2030	2040	2050
<b>Oil (%)</b>	92	91	41	27
<b>Electricity (%)</b>	1	1	30	40
<b>Biofuels (%)</b>	3	4	9	13
<b>Other fuels (%)</b>	4	4	20	20
<b>Total energy demand (Mtoe)</b>	2863	3315	2600	2400



## Conclusions

### Conclusion for BAU scenario

This document reports the EU-focused results of these implementations with an emphasis on the middle-of-the-road development scenario (i.e., SSP2). The SSP2 marker implementation reflects an extension of the historical experience, particularly in terms of carbon and energy intensity improvements in its baseline. At the global level, the results of SSP2 implementation indicate that it is possible to limit global warming within 2°C by the end of this century (relative to preindustrial levels) only if stringent climate policies were implemented throughout the world.

However, even with the stringent climate policies throughout the world under SSP2, the reduction extents of CO<sub>2</sub> emission and Kyoto Gases emission in the EU region over 1990-2050 will be 64% and 61%, respectively, significantly less than those put in the EU's Low-carbon Economy Roadmap for 2050, which asked for a reduction by 95%. The carbon price under the stringent climate policies will increase by US\$ 85 (2005 US\$) from 2010 to 2050. The implication of the SSP2 implementation for MEDEAS is that MEDEAS project should pay much more attention to SSP1 (e.g., taking the green road) and should explicitly specify technological breakthroughs in designing Optimum Transition pathway so as to substantially reduce GHG emission levels before 2050.



## Conclusion from OT scenario

CSIC proposes a model of energy consumption and investment, based on a constant ratio energy per capita and on the available predictions for the population in Europe. The mathematical model was developed and a software tool, based on it, was implemented using Python+Numpy/Scipy stack, which was cross-checked against an available freeware Python package. Several possible basic scenarios were proposed, and their preliminary analyses were given in the methodology sections. This approach can be readily extended to other local (e.g. USA, Asia) or global systems.



## Conclusion from MLT scenario

CIRCE propose the analysis of two different MLT scenarios, from 2020 and from 2030. Based on the CO<sub>2</sub> budget limit and the initial CO<sub>2</sub> expected in 2020 and 2030 a mathematical equation that leads to different pathways is obtained and shown. Then, a bottom-up approach follows to describe a possible composition for each sector that leads to a primary energy mix restricted by the CO<sub>2</sub> pathway developed.

As opposed to Optimum Transition scenarios, both medium transition scenarios imply a necessary reduction of per capita final consumption, if the 2°C temperature increase is not to be surpassed. This applies to all sectors with the exception of electricity generation, which is assumed to increase.

In MLT-2020 the energy demand obtained follows a type-S curve with a decrease at the beginning, a stabilization in the middle and a stronger decrease at the end. In this scenario, an increase in RES is essential in all the sectors not to overpass the CO<sub>2</sub> carbon budget. A small quantity of nuclear energy is assumed, in accordance with IEA scenarios. Non-nuclear scenarios would imply a sharper increase of renewable penetration as initially assumed. This applies to both MLT-2020 and MLT-2030.

In MTL-2030 the energy demand is stabilized from 2030 to 2040 and then starts to decrease. In this scenario the increase in the use of RES is so pronounced that it seems really difficult to be accomplished. Delaying additional mitigation to 2030 will substantially hamper the process of not overpassing the limiting warming below 2°C relative to pre-industrial levels.



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***MEDEAS Internal Deliverables***

Bardi, U., Falsini, S. and Perissi, I. 2017. Report 3.1.d MLT Scenarios. Internal Deliverable of WP3 within MEDEAS Project. Nr. 691287

Ballabrera, J. et al. 2017. Report 3.1.c OT scenarios. Internal Deliverable of WP3 within MEDEAS Project. Nr. 691287

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Osychenko, O. and Solé, J. 2017. Report 3.2.b: Rates of change for OT (fast rate of change). Internal Deliverable of WP3 within MEDEAS Project. Nr. 691287

