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

D4.3. MEDEAS Model implementation at country level (Austria and Bulgaria). Case Studies for TIMES and LEAP.

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Document info sheet

Lead Beneficiary: University of Valladolid

WP: 4, Model building and models implementation

Task: 4.1c. Country-level model; 4.2. Implementation of the scenarios and pathways proposed in WP3 on the TIMES model for Austria; 4.3. Implementation of the scenarios and pathways proposed in WP3 on the LEAP model for Bulgaria

Authors:

UVa: David Álvarez Antelo, Ignacio de Blas, Iñigo Capellán-Pérez, Óscar Carpintero, Carlos de Castro, Fernando Frechoso, Luis Fernando Lobejón, Pedro L. Lomas, Margarita Mediavilla, Luis Javier Miguel, Jaime Nieto, Gonzalo Parrado, Paula Rodrigo González

BSERC: Angel Nikolaev, Lulin Radulov

AEA: Martin Baumann, Lukas Eggler, Angela Holzmann, Christoph Ploiner

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Abstract

This document describes the case studies of the models implemented at the country level. The structure of the MEDEAS models developed for the world and for Europe have been applied for two country cases: Austria and Bulgaria. On the other hand, the case of Austria has been implemented in TIMES and the case of Bulgaria has been implemented in LEAP.

The MEDEAS-country level models are integrated energy-economy-environment assessment models that have been developed with the systems dynamics methodology. These models, which have been programmed with the Vensim software, use as input the results of the simulation of the MEDEAS_w and MEDEAS_eu models, with which they are linked. The structure of these models are similar and consists of 7 modules: Economy, Energy, Infrastructures, Materials, Land Use, Social and Environmental Impacts Indicators and GHG Emissions. Among the main novelties of this model with respect to other IAMs are the integration of input-output matrices, feedback between vaiables of the environmental, economic and energy modules and the estimation and feedback of the EROI. As well as the EU case, the adaptation to the country level includes the representation of trade (at both final goods/services and primary energy level) with the rest of the world and the other countries from Europe, as well as a simplified representation of the land-use system. Different scenarios established in WP3 have been developed for Austria and Bulgaria 2050 using MEDEAS country-level models.

Also, three different scenarios (BAU, MLT, and OLT) for Austria up to 2050 have been developed according with WP3, using the Austrian TIMES (The Integrated MARKAL-EFOM System) energy system model. These scenarios explore the structure and requirements of Austrian energy system keeping the GHG emissions within the given carbon budgets.

Finally, the applied methodology, scenarios concept, assumptions (dynamics of the partially aggregated variables - PAVs), and results related to the 3 decarbonisation scenarios for Bulgaria by 2050 are presented, using the LEAP (Long Range Energy Alternatives Planning System) model. Thus, it can be identified feasible or at least possible projections to achieve the carbon budget (accumulated GHG emissions until 2050) for Bulgaria in the different scenarios.

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List of abbreviations and acronyms

2RIOT	Two-region Input-Output tables
3RIOT	Three-region Input-Output tables
AQUASTAT	United Nations-Food and Agriculture Organization Water information system
AUT	Austria
BAU	Business as Usual
BG	Best guess
BGR	Bulgaria
BGS	British Geological Survey
BP	British Petroleum
CAP	Capital compensation
CGE	Computable general equilibrium
CHP	Combined heat and power generation
Cp	Capacity factor
CSP	Concentrated solar power
EC	European Commission
EJ	Exajoules
EROI	Energy return on energy invested (also EROEI)
EROIext	EROI extended
EROIpou	EROI point of use
EROIst	EROI standard

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EU	European Union
EU27	European Union 27 countries
EU28	European Union 28 countries
EUROSTAT	European Union Statistical Survey
EV	Electric Vehicle
EXP	Exports
FAO	United Nations-Food and Agriculture Organization
FAOSTAT	United Nations-Food and Agriculture Organization Statistical Survey
FD	Final demand
FEC	Final energy consumption
FED	Final energy demand
FES	Final energy supply
GDP	Gross domestic product
GDPpc	Gross domestic product per capita
GE	Government expenditures
GFCF	Gross fixed capital formation
GHG	Greenhouse Gases
Gm^2	Square gigameters (10^9 m^2)
GWP	Global warming potential
HDI	Human Development Index
HH	Households
HVDC	High voltage direct current

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IAM	Integrated Assessment Model
IEA	International Energy Agency
IIASA	International Institute for Applied Systems Analysis
IMF	International Monetary Fund
IMP	Imports
INVENT	Stock changes
IOA	Input-output analysis
IOT	Input-output table
IPCC	United Nations Intergovernmental Panel on Climate Change
IRWR	Internal renewable water resources
JRC	European Union Joint Research Center
km^2	Square kilometers
km^3	Cubic kilometers
ktoe	Thousands tons of oil equivalent
kWh	Kilowatt-hour
LAB	Labor compensation
LEAP	Long Range Energy Alternatives Planning System
LPG	Liquefied petroleum gases
MEDEAS_at	MEDEAS-Austria IAM
MEDEAS_bg	MEDEAS-Bulgaria IAM
MEDEAS_eu	MEDEAS_eu IAM
MEDEAS_w	MEDEAS_w IAM

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Mha	Million hectares
MLT	Mid-level Transition scenario
MRIO	Multi-regional input-output
Mt	Million tons
Mtoe	Million tons of oil equivalent
NEEAP	National Energy Efficiency Action Plan in Bulgaria
NRE (NR)	Non-renewable energy
NSI	National Statistics Institute of Bulgaria
NZEB	Nearly Zero Energy Buildings
OECD	Organisation for Economic Co-operation and Development
OLT	Optimum-Level Transition scenario
PAV	Partially Aggregated Variable
PBL	Netherlands Environmental Assessment Agency
PES	Primary energy sources
PV	Solar photovoltaic energy
RCP	Representative Concentration Pathways
RES	Renewable energy sources
RF	Radiative forcing
RoEU	Rest of Europe (including non-EU countries)
RoW	Rest of the world
RURR	Remaining ultimate recoverable resources
SDA	Structural decomposition analysis

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SSP	Shared socio-economic pathways
TAX	Taxes
TFEC	Total Final Energy Consumption
TFEF	Total Final Energy Footprint
TFEI	Total Final Energy Intensity
TIMES	The Integrated MARKAL-EFOM System
toe	Tons of oil equivalent
TPES	Total primary energy supply
TWe	Electric Terawatt
TWh	Terawatt-hour
UK	United Kingdom
UN	United Nations Organization (also UNO)
UNFCCC	United Nations Framework Convention on Climate Change
UNESCO	United Nations, Educational, Scientific and Cultural Organization
URR	Ultimate recoverable resources
USD	United States Dollars
USGS	United States Geological Survey
VA	Value Added
WIOD	World input-output database
WIOT	World input-output tables
WP	Work Package

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Executive summary

The objective of the MEDEAS project is to provide simulation tools that facilitate the design of energy policies in the European Union to achieve a low-carbon economy. One of these key tools is the integrated assessment model (IAM) for European countries, which is part of the Deliverable 4.3 of the MEDEAS project described in this document.

The MEDEAS country-level models are not completely independent models of the MEDEAS_w and MEDEAS_eu model, because many of the variables that affect the European countries are global or regional variables (for example, global oil resources or the increase in the average temperature of the planet). Therefore, the starting point of the simulations of the MEDEAS country-level models will be the data obtained from the simulation of the MEDEAS_w and MEDEAS_eu models for the corresponding scenarios. The MEDEAS_w and MEDEAS_eu models were described in the documents corresponding to deliverables 4.1 and 4.2, respectively, and they have been taken as reference to build the country-level models. These models have been built with the methodology of systems dynamics integrating the economic structure through the Input-Output Tables (IOT). The initial programming of the models has been developed with the Vensim DSS software, but it wiil be translated to python, in order to provide a model in open-source software.

By default, the simulation model of each country is designed to be run in the 1995-2050 time window, being the year the unit of time, although internally the simulation has a lower sampling period. Conceptually, the MEDEAS country-level models are structured in 7 modules:

- Economy and population: the economy of MEDEAS is modelled following a post-Keynesian approach assuming disequilibrium (i.e. non-clearing markets), demand-led growth and supply constraints. The economic structure is capture by the integration of IOA (35 industrial sectors and households).
- Energy: this module includes the renewable and non-renewable energy resources potentials and availability taking into account biophysical and temporal constraints. In total, 5 final fuels are considered (electricity, heat, solids, gases and liquids) and a diversity of energy technologies is modelled. A net energy approach has been followed.
- Energy infrastructures represent the infrastructures of power plants to generate electricity and heat.
- GHG Emissions: this module projects the GHG emissions in the European Union generated by human activities.

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- Materials: estimation of the materials required for the construction and Operation & Management of the alternative energy infrastructures.
- Land-use: it is a simple model oriented to obtain information to estimate the potential for biomass and the potential for solar energy.
- Social and environmental impacts: this module translates the “biophysical” results of the simulations into metrics related with social and environmental impacts. The objective of this module is to contextualize the implications for human societies in terms of well-being for each simulation.

These modules have been programmed in approximately 100 simulation windows and using more than 5,000 variables. The modules of economy and energy are the most extensive and reach the highest degree of disaggregation. The model consists of a modular and flexible structure, where each module can be expanded/simplified/replaced by another version or submodel, new modules can be added, etc.

The scope of the model covers all the challenges that were proposed in the project. Some of these relevant challenges are:

a) Use of information generated by the MEDEAS_w and MEDEAS_eu simulation models.
b) Integration of Input-Output Matrices (IOT) in the Economy module.
c) Modeling the commercial relations of Europe through the IOT.
d) EROI estimation and its feedback.
e) Socio-economic indicators model implementation.
f) Supply-demand closures model implementation. The energy shortage determines the feedback between the energy and the economic module.
g) The effects of climate change are feedback into energy consumption.
h) Two standard scenarios have been modelled and implemented. Three other scenarios have been programmed.

Figure 1 shows the flow chart of the working mode of the country-level models. The model has shown robustness and consistency in the experimental tests carried out. The first results show a behavior of the country-level models similar to that obtained in the results of the world or European models.

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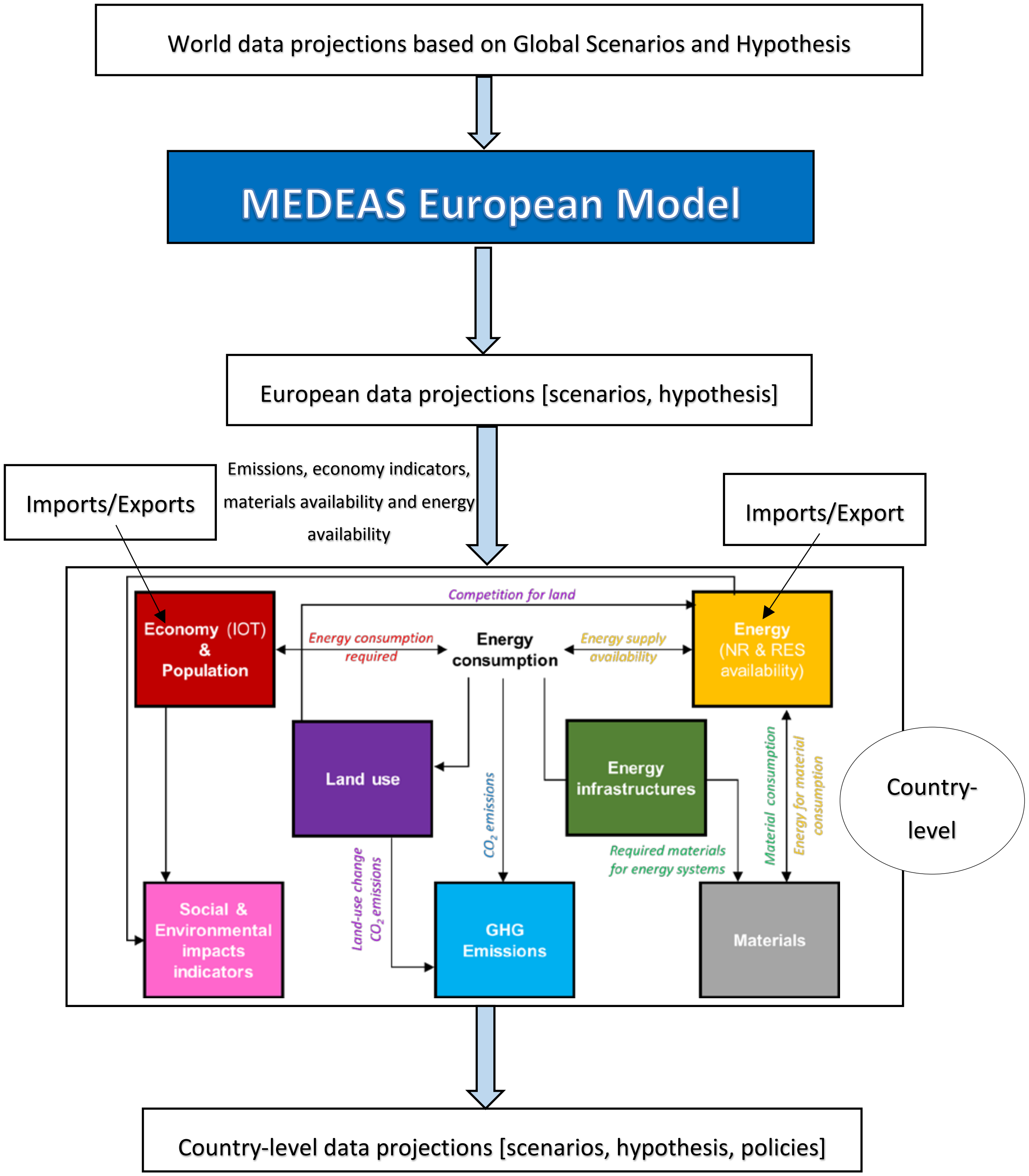

Figure 1. Flow chart representing the working mode of the country-level models.

In addition, another important result of the project is the comparison and benchmarking of the MEDEAS model. In this Deliverable, we use results of applying MEDEAS to BAU and OLT scenarios

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previously defined for comparison purposes with two other models: TIMES-Austria and LEAP-Bulgaria.

For MEDEAS, the generation of energy from RES increases steadily until 2040s in Austria for both scenarios, although the BAU scenario is higher; in the case of Bulgaria, both scenarios increases the generation of energy from RES, although the OLT scenario present higher generation since Bulgaria starts from previous low renewables production values. The consumption of non-renewable energies declines in the early 2020s in Austria, with an OLT scenario slightly more intensive in non-renewable primary energy. In the case of Bulgaria, the decrease starts in the late 2020s or the early 2030s, reaching similar values to those of Austria, although the BAU scenario presents higher levels of non-renewables due to the starting point of Bulgaria. The share of renewables in the energy mix increases to almost reach 60%-70% in the Austrian BAU and OLT scenarios, respectively; also, reaches 40%-60% in the case of Bulgarian BAU and OLT scenarios, respectively. GHG emission present similar patters to the non-renewables consumption. Lastly, both the Total Final Energy Consumption (TFEC) and Gross Domestic Product (GDP) show a similar trend for both scenarios and countries roughly maintaining current levels up to 2025-2030, and a declining thereafter due to the strong climate change impacts coming from the MEDEAS-W and MEDEAS_eu in both scenarios.

For TIMES-Austria, three scenarios have been implemented In the BAU scenario, it can be seen that GHG missions are slightly decreasing, although final energy and gross domestic consumption are slightly increasing until 2050. Already in this scenario, the trend towards energy efficiency and renewable energy continues, but energy efficiency cannot keep pace with economic growth. The sectorial results show the industrial energy consumption outweighs energy savings in transport and buildings. Thus, the share of renewable energy is also only slightly increasing.

The OLT scenario assumes that after 2020, policies leading to a renewable and low carbon energy transition come into effect. The main impact of these policies that intent to stay within a carbon budget of 1.4 Gt CO2eq is that electricity becomes the main fuel in all energy sectors. This starts from households and services (for appliances and heat pumps), goes over to transport (battery electric vehicles) and industry (where a lot of appliances are switched to electricity) and finally also to the iron and steel production (using electricity for electric arc furnaces and for hydrogen production for the new steel production processes).

As electricity production more than doubles until 2050 and exceed the growth of the production capacities, huge electricity imports will be necessary to satisfy the demand. As the production capacity nearly triples, huge challenges for storage and the grid have to be tackled.

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In general the development can be described as a massive switch towards renewable and low carbon fuels, supported by energy efficiency measures and demand reduction.

The analysis of the GHG emissions in the case of the MLT scenario shows that due to the slow decrease of the annual emissions from today until 2030, the remaining carbon budget is actually less than zero. This shows that a feasible MLT scenario requires a significantly higher carbon budget, and an earlier deviation from the baseline scenario or a baseline scenario with significant emissions reduction from as early on as possible.

Finally, regarding LEAP-Bulgaria. The scenario results demonstrate that the carbon budget has been aligned. It appeared, however, that the compliance with the limited carbon budget for Bulgaria is a very difficult task, mainly due to the projected high economy growth (the GDP in 2050 is 2.5 times the one in 2015), combined with limited resources to undertake ambitious (and expensive) policies.

In both OLT and MLT, the only feasible solution to comply with the carbon budget is to implement comprehensive measures in all demand and supply sectors. These involve mainly serious energy efficiency improvement combined with abrupt fuel switch to less carbon intensive fuels.

As expected, the most feasible approach to comply with the carbon budget is to implement the decarbonization measures as soon as possible, i.e. to achieve most of the energy savings and fuel switch shortly after 2020 in OLT and shortly after 2030 in MLT.

In this sense, it is obvious that it is much more difficult and expensive to achieve the carbon budget in MLT, compared to OLT. In MLT, the sharp technological changes in 2030 - 2035, such as replacement of energy plants and energy demand equipment (transport vehicles, heating and electricity appliances, etc.) would require discarding operating technologies and massive investment in new equipment and infrastructure, causing economic shock.

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1. General introduction

The objective of the MEDEAS project is to provide simulation tools that facilitate the design of energy policies in the European Union to achieve a low-carbon economy. One of these key tools is the integrated assessment model (IAM) for European countries.

In section 2 of this deliverable, we present the methodological basis of the IAM (main assumptions and structure of the different modules of which it is composed) and some tested experimental results and scenarios for this country-level model applied to two case studies: Austria and Bulgaria. Scenarios have been developed using a Bussiness as Usual scenario (BAU), considering current patterns of variables analyzed, and a green growth scenario (OLT), considering a large share of renewables starting by 2020. The MLT is assumed to be an intermediate situation between the others.

In addition, another important result of the project is the comparison and benchmarking of the MEDEAS model. In this Deliverable, we use results of applying MEDEAS to BAU and OLT scenarios previously defined for comparison purposes with two other models: TIMES-Austria and LEAP-Bulgaria.

In section 3, the TIMES-Austria model methodological basis are presented, and the model is tested for the scenarios previously defined with Austrian particular assumptions for the relevant variables to be compared with MEDEAS_at results for these variables.

In section 4, the LEAP-Bulgaria model is presented. First, some methodological basis are established. Then, main scenario assumptions for Bulgaria are illustrated. Finally, the model is tested for the relevant variables to be compared with MEDEAS_bg results.

Finally, section 5 present main conclusions of the model and scenario tested in this deliverable.

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2. Country models with MEDEAS methodology. Cases of Austria and Bulgaria.

2.1. Introducción

As in the case of World (MEDEAS_w) and European models (MEDEAS_eu), country models have been programmed in the Vensim software for this first version. The simulation model can be read and run with a Model Reader software that is freely distributable at no cost, licensed by Ventana Systems, Inc.

Conceptually, the models have been divided into 7 submodules: Economy, Energy, Infrastructures, Materials, Land Use, Social and Environmental Impacts Indicators and Emissions. These submodules have been programmed in approximately 100 simulation windows and using more than 5000 variables. The modules of economy and energy are the most extensive and reach the highest degree of disaggregation. The scope of the models covers all the challenges that were proposed in the project. Some of these relevant challenges are:

a) Integration of Input-Output Matrices in the Economy sub-model.

b) EROI estimation and feedback.

c) Socio-economic indicators model implementation.

d) Supply-demand closures model implementation. The energy shortage determines the feedback between the energy and the economic submodule.

e) The effects of climate change are feedback into energy consumption.

f) Two standard scenarios have been modelled and implemented. Three other scenarios have been programmed.

The models obtained can still be modified and expanded, depending on the availability of new data or new information, but the current version provides a solid enough basis to serve as a framework for country-level scale models.

Despite the challenges encountered, there are still many limitations and uncertainties. For this reason, the interpretation of the results must be done with caution. This model is not intended to

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predict the future, but rather to guide qualitatively the best options for the energy transition towards a low-carbon economy. It is a tool to explore strategies, not specific policies, since the latter are applied at a different (reduced) political scale. Despite these limitations, the qualitative interpretation of the results, supported by tools such as the sensitivity analysis, allows guiding the decision making to guide the best possible energy transition.

2.2. Methodology

2.2.1. Integration of World, European (EU-28) and country-levels in MEDEAS

2.2.1.1. General framework

MEDEAS-Europe model was built for the European Union (EU-28) spatial context, considering the EU-28 space as a whole. In this deliverable, two EU member countries have been modelled in relation with the other two MEDEAS models (MEDEAS_eu and MEDEAS_w).

MEDEAS_w and MEDEAS_eu presented differences but were related. MEDEAS_eu model (for more details about EU model, see Deliverable 4.2) was conceptually integrated in the World model (for more details about world model, see Deliverable 4.1). In the same framework, MEDEAS-Bulgaria and MEDEAS-Austria are linked to the European and World Models, as represented in the next flow chart (Figure 2).

First, the global hypothesis and scenarios considered in WP3 are introduced to the MEDEAS World model. The results of the World level are the World data projections based on the previous scenarios and hypothesis. These projections, represented here as vectors, are introduced, along with data obtained by the World model, into the MEDEAS European model. The results are the European data projections needed to feed the country-level models in a top-down structure.

At this stage we need to take also into account trade and energy exchanges. In order to do so, imports and exports in economic and energy terms are introduced in the country-level models. In the economy module, imports and exports are introduced through the Input-Output matrix using, at the same time, four submatrices.

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As in the case of the European model, the climate change module does not exist; therefore, we consider the GHG emissions module instead. The results are the country-level data projections taking into consideration the scenarios, hypothesis and the related policies.

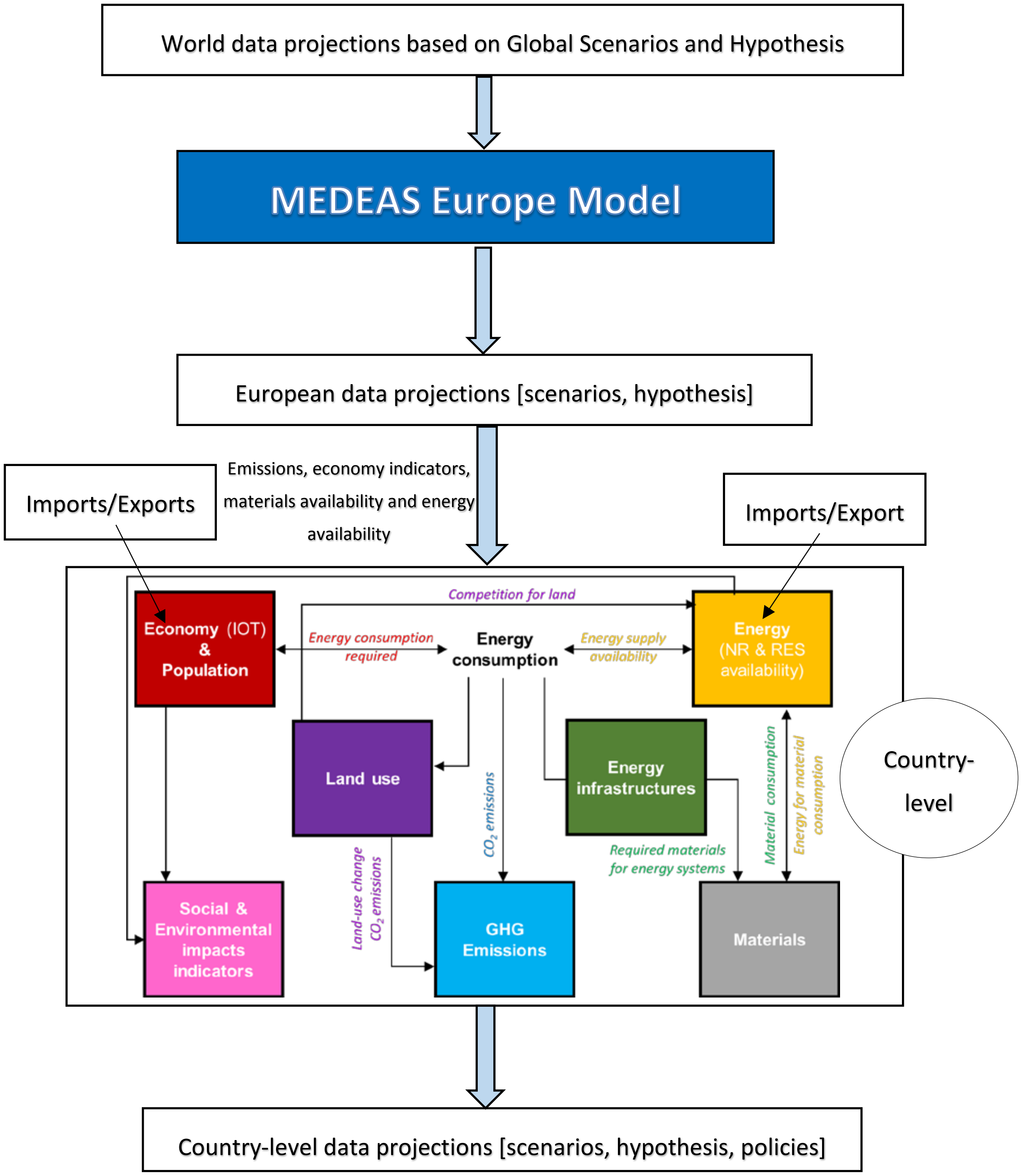

Figure 2. Flow chart representing the working mode of the country-level models.

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The country-level models structure are mainly based on the world and European models. Although the deliverables 4.1 and 4.2 give a detailed description of the general structure of these models, we will explain the main ideas of each submodule for the country-level models.

MEDEAS country-level models, whose timeframe is 2050, are conceptually structured as shown in Figure 3, with different interrelated modules (represented by boxes). The main variables connecting the different modules are also represented by arrows. Hence, the relationships and feedback in MEDEAS country-level may evolve in the future.

MEDEAS estimates the future "Energy consumption" as a result of confronting the "Final energy consumption required" from the economy (demand side) and the "Final energy supply availability" from the energy systems (supply side). Thus, this adjustment runs feedback over variables in all the modules that eventually have an impact on the economy and energy systems. The feedback-rich structure of the model creates inputs and outputs to the modules.

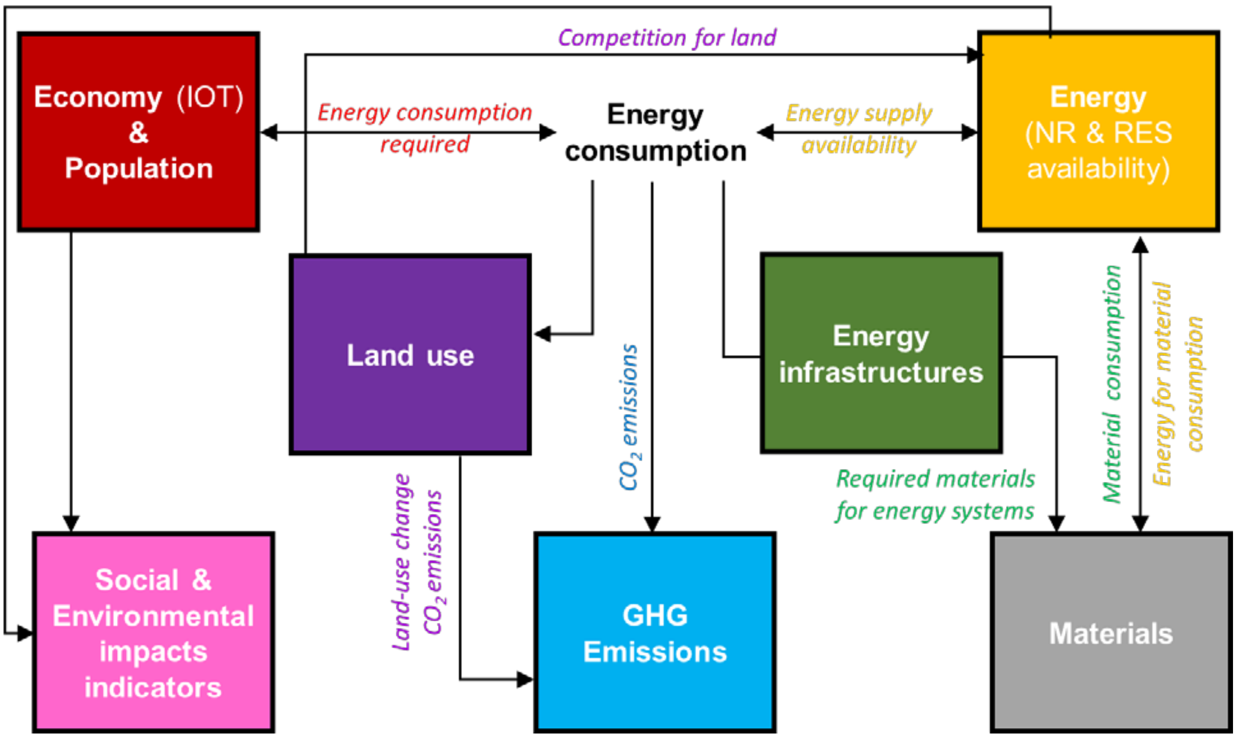

Figure 3. Schematic module interactions within MEDEAS-country-level models.

Furthermore, we have to consider imports and exports in the economy and energy modules for the country-level models. Consequently, "Final energy supply availability" results from the domestic resources or from abroad (from the rest of the world and Europe as a result of imports). Energy consumption is disaggregated in different types of renewable (RES) and non-renewable (NR) energy resources. At the same time, the model computes the Energy Return On Energy

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Investment (EROEI), the net energy available after discounting the energy invested in its generation. This is a novelty in the field of energy modelling, since most models consider EROEI instead as an exogenous input.

Input-Output Analysis (IOA) is the core of the Economy module. Throughout the Input Output Tables (IOT) and an econometric sectoral demand function, sectorial requirements of consumption and production are going to be estimated. Therefore, Energy consumption is not only expressed by type of energy, but also by economic sectors. In addition, energy intensities will be forecasted for each sector and final energy type, according to the technological and economic development.

The land-use module will consider the required land for renewable sources of energy.

Social and environmental impact indicators will also be obtained for each simulation, which could eventually provide feedback for the economy module. The model takes into account the CO_2 emissions. These emissions are the main input for the GHG emissions module. The materials required for deploying RES and NR technologies will be an important input for the Energy module, as well. In fact, the model is flexible enough to allow any user to apply the data and trends, as they prefer.

Although policies are not represented in Figure 2, they will ultimately be relevant for the models. Policies will provide the framework in which each module develops and let the model run different scenarios.

Generally, the structure of the variables included in each module will follow a similar outline to the ones described for the world and European models in the Deliverables 4.1 and 4.2.

2.2.1.2 Indicators

In this section, we will go through some indicators related to the European Union and the two countries selected, according to the Figure 1. The main goal is to compare both in a quantitative way in order to estimate the countries' share of each indicator with respect to the European Union. The following indicators have been considered in total and per capita values:

- Population
- Gross Domestic Product
- Total primary energy consumption
- Oil consumption

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- Gas consumption
- Coal consumption
- Electricity consumption
- Wind energy production
- Solar energy production
- Oil reserves
- Gas reserves
- Coal reserves
- CO_2 emissions

The latest available data for these indicators is shown below with a table and a figure representing the countries' share or EU values for each of them.

Population

The first indicator considered is the population of the EU, Austria and Bulgaria. The total population of a country consists of all people falling within the scope of the census. In the broadest sense, the total may comprise either all the usual residents of the country and all the people present in the country at the time of the census (OECD, 2005). Data for the period between 2010 and 2015 are presented in the Table 1.

Table 1. Population of EU-28, Austria and Bulgaria.

Time	2010	2011	2012	2013	2014	2015	Percentage
EU-28 (million people)	503.65	504.77	505.96	506.94	508.13	509.67	100 %
Austria (million people)	8.36	8.39	8.43	8.48	8.54	8.57	1.7 %
Bulgaria (million people)	7.40	7.35	7.31	7.27	7.22	7.17	1.4 %

Source: OECD iLibrary

As shown in the table, the Austrian and Bulgarian population represent 1.7% and 1.4% out of the total EU-28 population. These data are illustrated in the Figure 4, in which the blue area represents the world, while the orange and grey represent Austria and Bulgaria, respectively.

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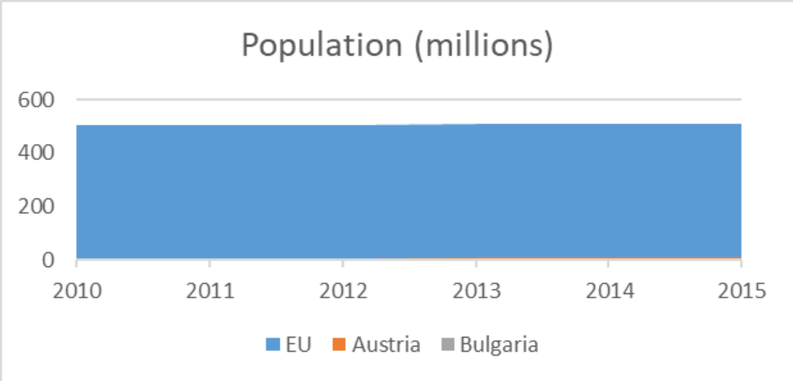

Figure 4. Evolution of the population for the EU-28, Austria and Bulgaria.

Gross Domestic Product (GDP)

The GDP is an aggregate measure of production, and it equals to the sum of the gross values added by all resident institutional units engaged in production (plus any taxes, and minus any subsidies, on products not included in the value of their outputs) (OECD, 2005).

Gathered data shows the period 2010-2015 (Table 2). In this case, Austria accounts for the 2.3 % of total EU-28 GDP while Bulgaria does for the 0.3 % in the 2014. The data are shown in the Figure 5.

Table 2. GDP of EU-28, Austria and Bulgaria.

Time	2010	2011	2012	2013	2014	2015	Percentage (2014)
EU-28 (billion 2010 USD using exchange rates)	16,945.4	17,243.8	17,161.55	17,195.93	17,426.82	n.a.	100%
Austria (billion 2010 USD using exchange rates)	390.21	401.17	404.21	405.51	406.94	410.45	2.30 %
Bulgaria (billion 2010 USD using exchange rates)	49.94	50.73	50.85	51.50	52.30	n.a.	0.30 %

Source: OECD iLibrary; n.a. = not available.

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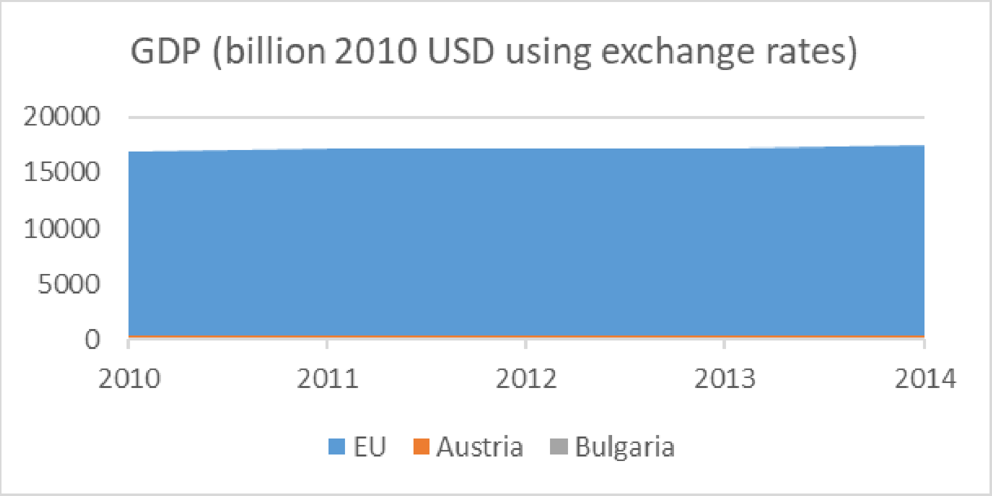

Figure 5. Evolution of the GDP for EU-28, Austria and Bulgaria.

Total primary energy consumption

Primary energy comprises commercially traded fuels, including modern renewables used to generate electricity. Oil remains the world's dominant fuel, making up roughly a third of all energy consumed (BP, 2017). Gathered data for the period from 2010 to 2015 measured in million tons of oil equivalent.

Table 3. Total primary energy consumption data for the EU-28, Austria and Bulgaria.

Time	2010	2011	2012	2013	2014	2015	Percentage
EU-28 (Mtoe)	1,755.36	1,696.19	1,681.67	1,670.05	1,605.70	1,630.93	100%
Austria (Mtoe)	35.92	33.83	35.35	35.10	33.94	34.05	2.1%
Bulgaria (Mtoe)	17.83	19.11	18.06	16.69	17.89	18.93	1.2%

Source: BP.

As seen in the table 3 and the Figure 6, Austria and Bulgaria consume 2.1% and 1.2% out of the total European primary energy consumption, respectively.

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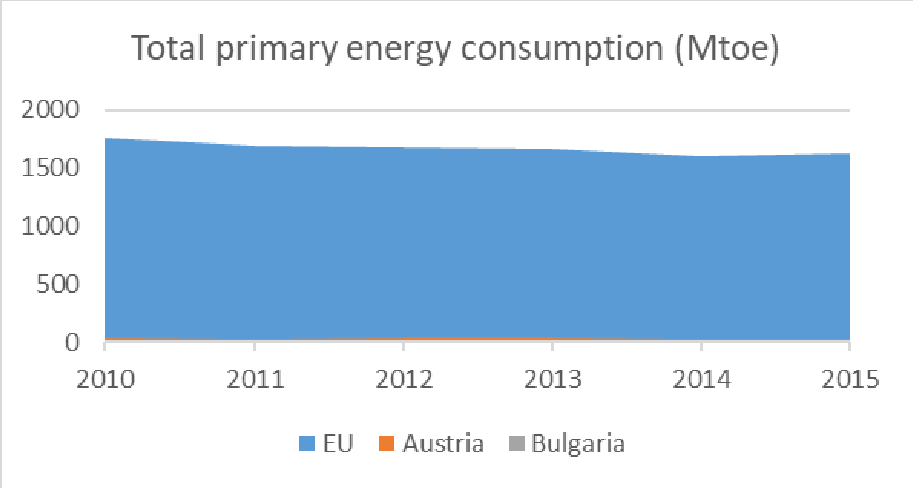

Figure 6. Evolution of the Total Primary Energy consumption in the EU-28, Austria and Bulgaria.

Oil consumption

Oil remained the world's leading fuel, accounting for a third (33.3%) of global energy consumption. Inland demand plus international aviation and marine bunkers and refinery fuel and loss. Consumption of biogasoline (such as ethanol), biodiesel and derivatives of coal and natural gas are also included (BP, 2017). Data for years 2010 to 2015 are given in millions of metric tons (Table 4).

Table 4. Oil consumption data for the EU-28, Austria and Bulgaria.

Time	2010	2011	2012	2013	2014	2015	Percentage
EU-28 (Mt)	665.07	644.78	618.42	601.96	591.18	600.22	100%
Austria (Mt)	13.38	12.67	12.47	12.71	12.53	12.63	2.1%
Bulgaria (Mt)	3.89	3.78	3.90	3.62	3.88	4.18	0.7%

Source: BP.

Austria and Bulgaria account for 2.1% and 0.7% out of the total EU-28 oil consumption, respectively (Figure 7).

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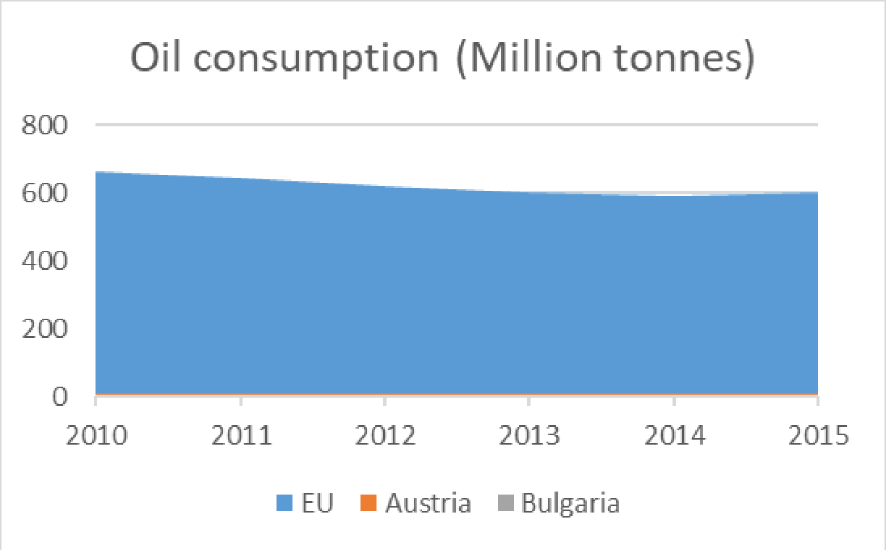

Figure 7. Evolution of the oil consumption in the EU-28, Austria and Bulgaria.

Gas consumption

Natural gas consumption excludes natural gas converted to liquid fuels, but includes derivatives of coal as well as natural gas consumed in gas-to-liquids transformation (BP, 2017). Gathered data for the period between 2010 and 2015 expressed in million tons of oil equivalent (Mtoe) (Table 5).

Table 5. EU-28, Austrian and Bulgarian gas consumption data.

Time	2010	2011	2012	2013	2014	2015	Percentage
EU-28 (Mtoe)	449.68	405.43	395.85	389.17	346.03	361.88	100%
Austria (Mtoe)	8.97	8.44	8.05	7.72	7.08	7.51	2.1%
Bulgaria (Mtoe)	2.30	2.63	2.45	2.37	2.35	2.58	0.7%

Source: BP.

As it can be seen in the table, Austria and Bulgaria represent 2.1% and 0.7% out of the total EU-28 natural gas consumption. Data about natural gas consumption is represented in the Figure 8.

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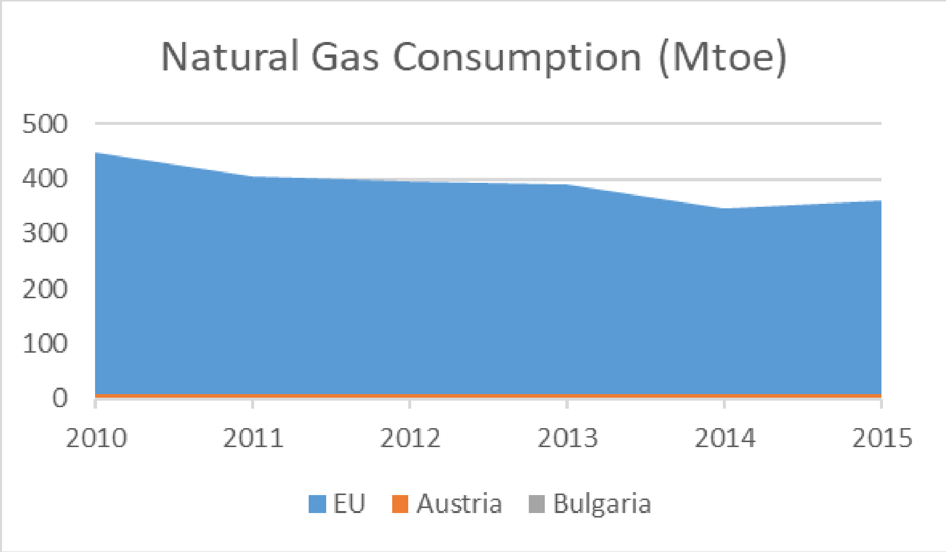

Figure 8. Evolution of Natural gas consumption in the EU-28, Austria and Bulgaria.

Coal consumption

Coal consumption includes data for solid fuels only. Included in the hard coal category are bituminous and anthracite. The sub-bituminous coal includes lignite and brown coal. Other commercial solid fuels are also included (BP, 2017). We have collected data for the period between 2010 and 2015 expressed in million tons of oil equivalent (Mtoe) (Table 6).

Table 6. Coal consumption data for the EU-28, Austria and Bulgaria.

Time	2010	2011	2012	2013	2014	2015	Percentage
EU-28 (Mtoe)	279.30	287.31	293.66	287.15	267.25	262.39	100%
Austria (Mtoe)	3.39	3.48	3.24	3.28	3.02	3.24	1.2%
Bulgaria (Mtoe)	6.89	8.11	6.93	5.93	6.40	6.67	2.5%

Source: BP.

In this case, Austria and Bulgaria represent 1.2% and 2.5% out of the total EU-28 coal consumption, and the data is illustrated in the Figure 9.

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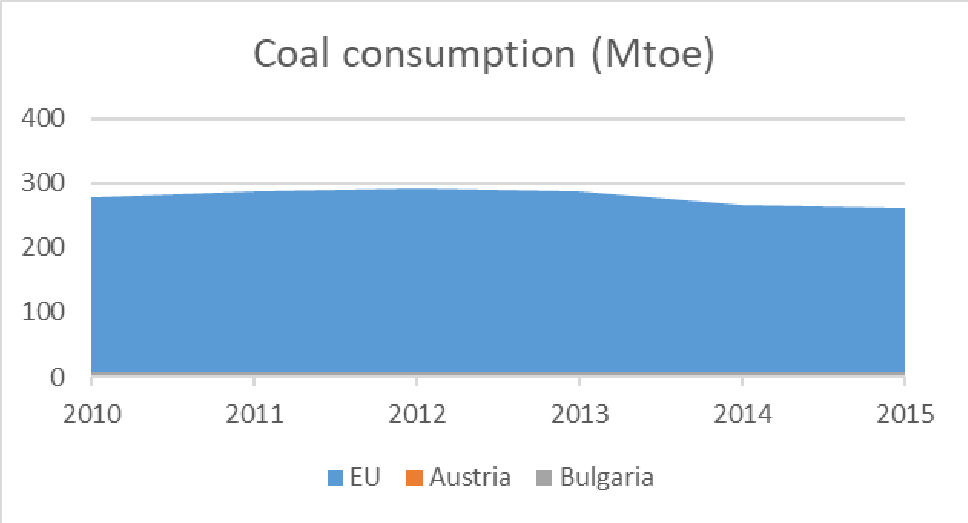

Figure 9. Evolution of Coal consumption in the EU-28, Austria and Bulgaria.

Electricity consumption

Electricity consumption increased almost 13% worldwide during the five-year period (2010-2015). However, this balance is negative in the European Union, where electricity consumption has decreased by 4%. In the following table, we can see the data collected for the period between 2010 and 2015 in TWh (Table 7).

Table 7. EU-28, Austria and Bulgaria electricity consumption data.

	2010	2011	2012	2013	2014	2015	Percentage 2014
EU-28 (TWh)	3,161.73	3,099.84	3,104.99	3,072.85	3,002.59	n.a.	100%
Austria (TWh)	70.11	70.70	72.07	72.16	71.41	72.07	2.4%
Bulgaria (TWh)	33.73	35.74	34.79	33.71	34.02	n.a.	1.1%

Source: OECD iLibrary; n.a. = not available.

Austria and Bulgaria represent 2.4% and 1.1% out of the total EU-28 electricity consumption in 2014. This proportion is pictured in the next figure (Figure 10), taking into account data gathered in the table.

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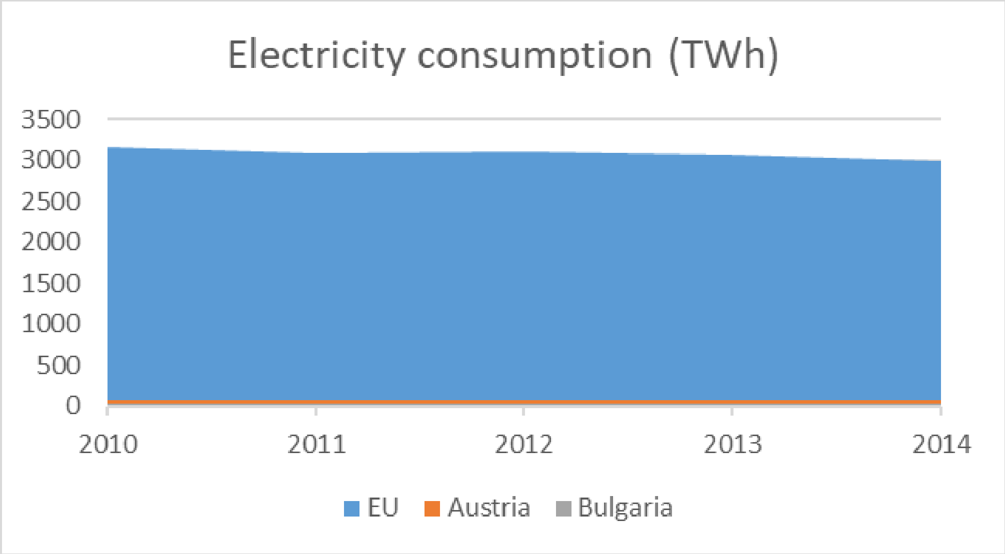

Figure 10. Evolution of the Electricity consumption in the EU-28, Austria and Bulgaria.

Wind energy production

The next indicator is wind energy production. Regarding the collected data, world wind production has more than doubled in five years (2010-2015). This trend is shared by the European Union, where wind production doubled in the same period (2010-2015). Collected data shown in the next table are presented in thousand tons of oil equivalent (ktoe) (Table 8).

Table 8. World and European Union wind energy production data.

	2010	2011	2012	2013	2014	2015	Percentage
EU-28 (ktoe)	12,844.70	15,451.88	17,717.63	20,364.46	21,771.50	n.a.	100%
Austria (ktoe)	177.50	166.50	211.73	271.07	330.76	416.50	1.6%
Bulgaria (ktoe)	58.57	74.05	105.01	118.16	114.47	n.a.	0.5%

Source: OECD iLibrary; n.a. = not available.

Austria and Bulgaria represent 1.6% and 0.5% out of the total EU-28 wind production in 2014. This proportion is represented in the Figure 11.

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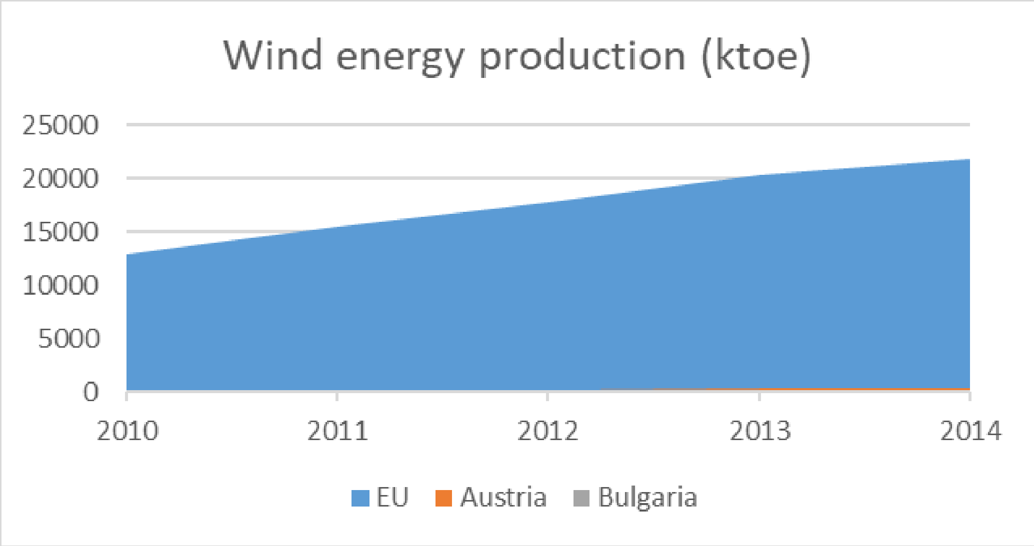

Figure 11. Evolution of Wind energy production in the EU-28, Austria and Bulgaria.

Solar energy production

Solar energy production has had a substantial increase from 2010 to 2014 both in the world and in the European Union. In the European Union solar production has increased 3.2 times during the same period, Austria 1.5 times and Bulgaria 11 times. This information is shown in the next table where the data is given in thousand tons of oil equivalent (ktoe) (Table 9).

Table 9. European Union, Austria and Bulgaria solar energy production data.

Time	2010	2011	2012	2013	2014	Percentage
EU-28 (ktoe)	3,716.94	6,037.63	9,009.01	10,643.07	12,008.67	100%
Austria (ktoe)	167.51	183.25	203.35	227.86	249.69	2.1%
Bulgaria (ktoe)	11.51	22.51	85.41	136.10	127.35	1.1%

Source: OECD iLibrary.

Solar production represents 2.1% and 1.1% out of the total world solar production in Austria and Bulgaria, respectively. It can be seen in the Figure 12.

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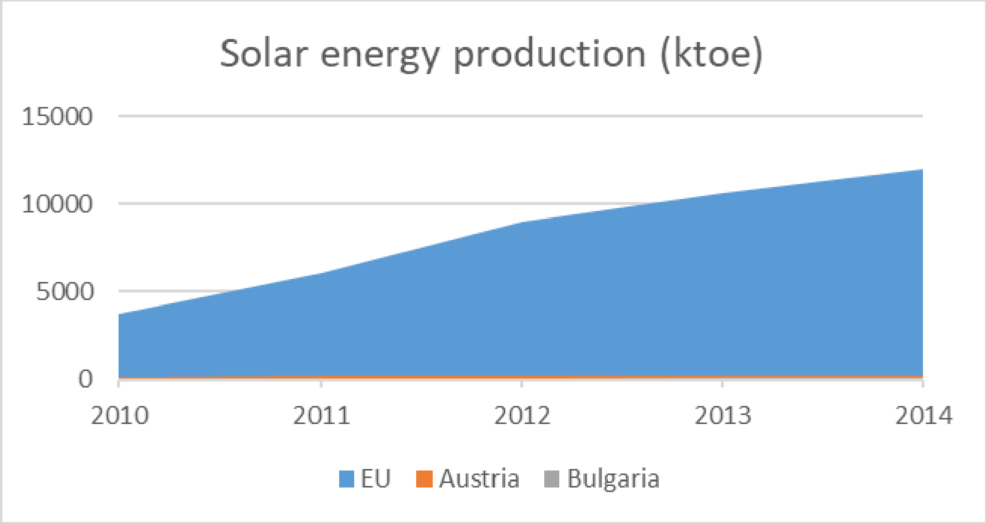

Figure 12. Evolution of Solar energy production in the EU-28, Austria and Bulgaria.

Oil reserves

Total proved reserves of oil are generally taken to be those quantities that geological and engineering information indicates with reasonable certainty can be recovered in the future from known reservoirs under existing economic and geological conditions. Oil reserves include field condensate and natural gas liquids as well as crude oil (BP, 2017). In the following table, data for the period between 2010 and 2016 are represented (Table 10).

Table 10. EU-28, Austria and Bulgaria oil reserves data.

Time	2010	2011	2012	2013	2014	2015	Percentage
EU-28 (1000 million barrels)	6.00	6.17	5.95	5.83	5.64	5.56	100%
Austria (1000 million barrels)	0	0	0	0	0	0	-
Bulgaria (1000 million barrels)	0	0	0	0	0	0	-

Source: BP.

As it can be seen in the table, the EU-28 oil reserves decrease around 7.4% in the period 2010-2015 (Figure 13).

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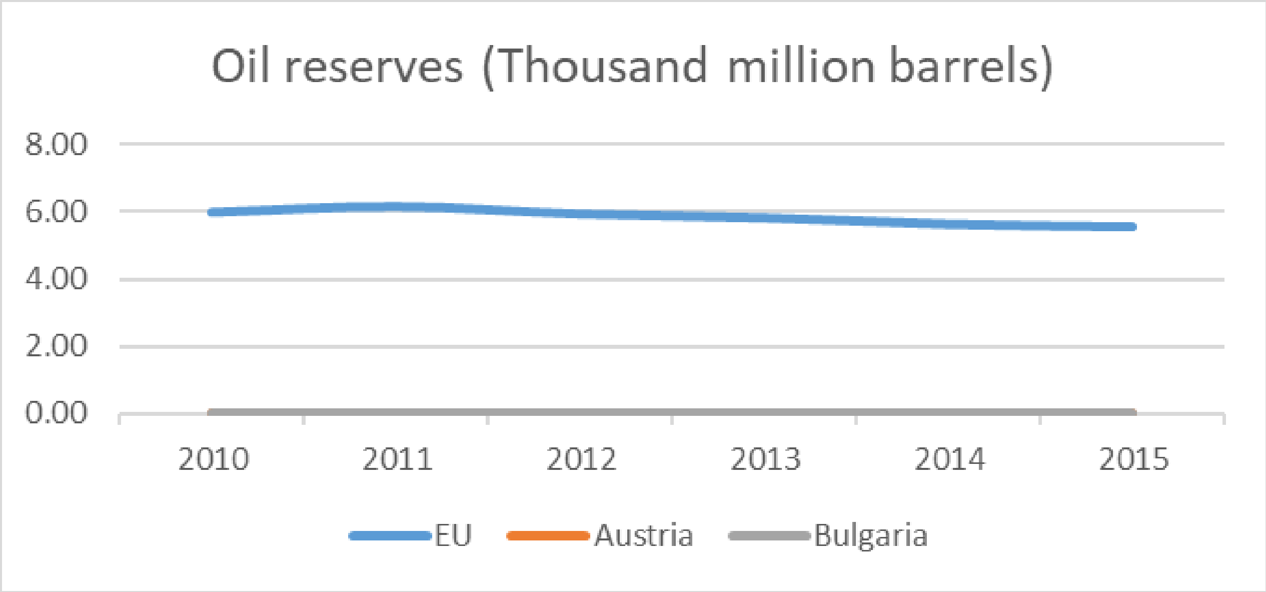

Figure 13. Evolution of Oil reserves in the World and the EU-28.

Gas reserves

Total proved reserves of natural gas are generally taken to be those quantities that geological and engineering information indicates with reasonable certainty can be recovered in the future from known reservoirs under existing economic and operating conditions (BP, 2017).

Data are measured in trillion cubic meters, and they have been represented for the period between 2010 and 2016 (Table 11).

Table 11. EU-28, Austria and Bulgaria gas reserves data.

Time	2010	2011	2012	2013	2014	2015	Percentage
EU-28 (trillion cubic metres)	2.36	1.78	1.52	1.44	1.32	1.30	100%
Austria (trillion cubic metres)	0	0	0	0	0	0	-
Bulgaria (trillion cubic metres)	0	0	0	0	0	0	-

Source: BP.

As shown in the table and in the Figure 14, gas natural reserves decrease more than 45 % in the period 2010-2015 in the context of the EU-28.

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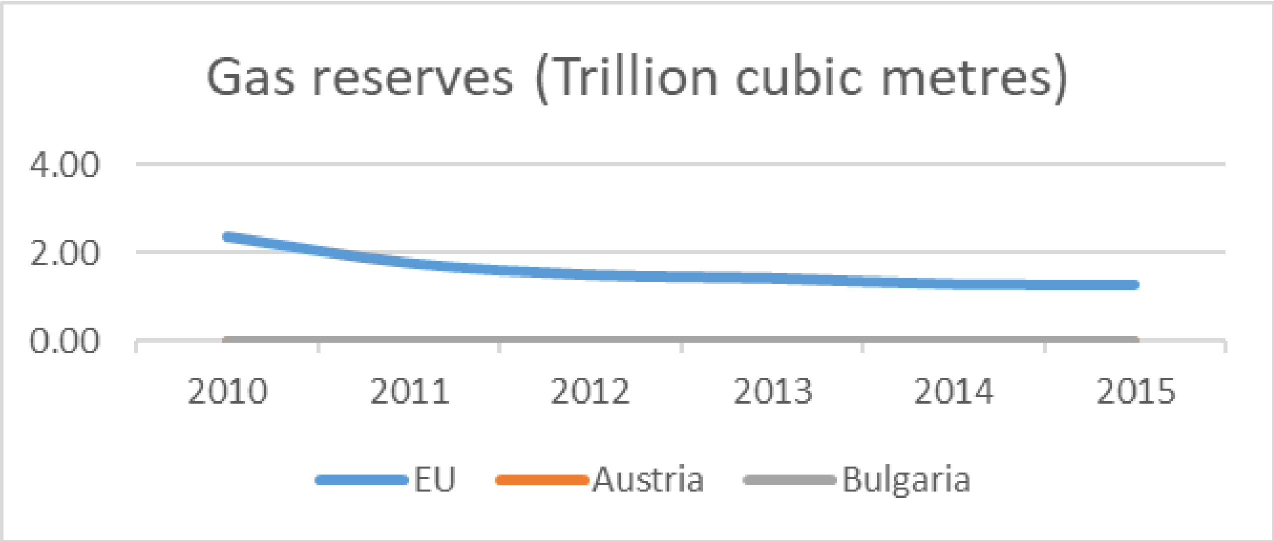

Figure 14. Evolution of Gas reserves in the EU-28, Austria and Bulgaria.

Coal reserves

Total proved reserves of coal are generally taken to be those quantities that geological and engineering information indicates with reasonable certainly can be recovered in the future from known deposits under existing economic and operating conditions. Total proved coal reserves are shown for anthracite and bituminous (including brown coal) and sub-bituminous and lignite (BP, 2017). Coal reserves data are presented in million tons and given for the end of 2015 (Table 12).

Table 12. EU-28, Austria and Bulgaria coal reserves.

Time	2015	Percentage
EU-28 (Mt)	56,082	100%
Austria (Mt)	0	-
Bulgaria (Mt)	2,366	4.2%

Source: BP.

The Bulgarian coal reserves represent about 4.2% of total EU-28 proved reserves. Data are represented by a barcode in this case (Figure 15).

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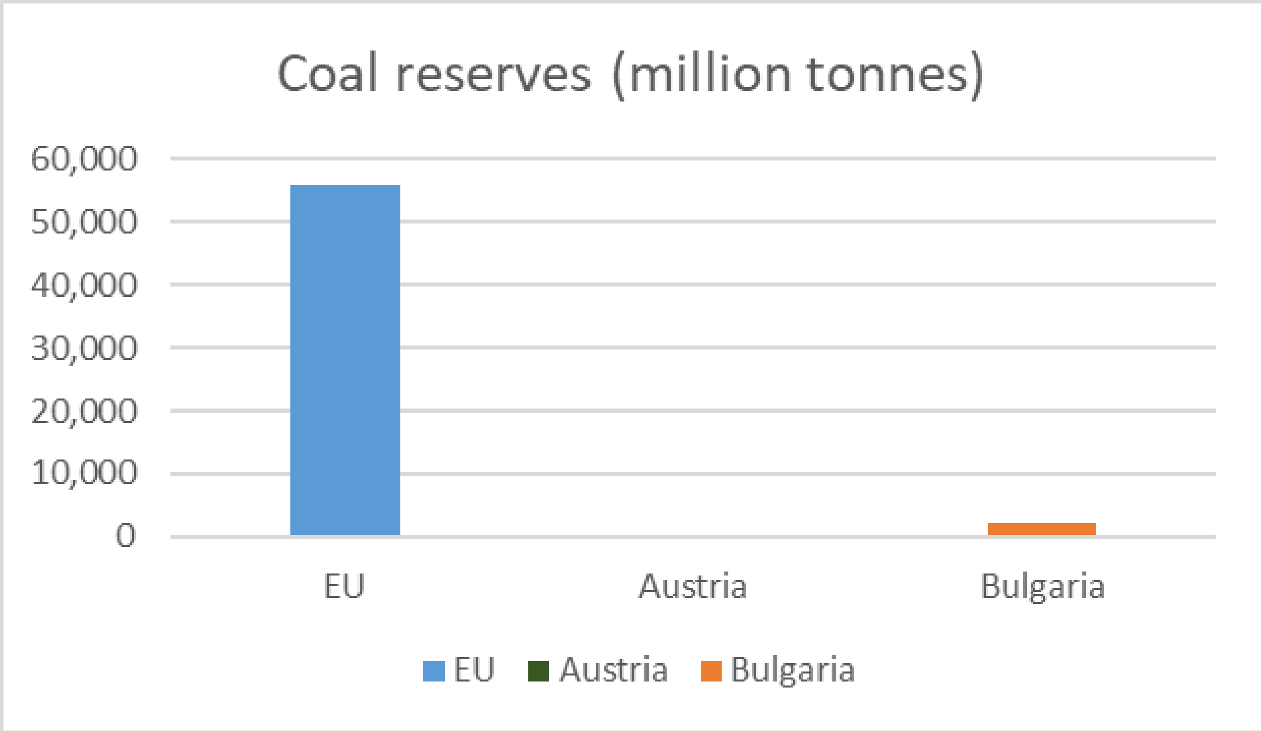

Figure 15. Coal reserves in 2016 for the EU-28, Austria and Bulgaria.

CO_2 emissions

In this case, world carbon dioxide emissions have increased by 6% during the last seven years (2010-2015), whereas European Union CO_2 emissions have decreased by 11%. These data are shown in the Table 13.

Table 13. EU-28, Austria and Bulgaria CO_2 emissions data.

Time	2010	2011	2012	2013	2014	2015	Percentage
EU-28 (Mt CO_2)	3,931.13	3,803.28	3,736.06	3,653.76	3,446.16	3,489.77	100%
Austria (Mt CO_2)	69.73	66.97	64.20	64.11	60.63	62.82	1.8%
Bulgaria (Mt CO_2)	44.97	50.35	45.33	39.94	42.54	45.15	1.2%

Source: BP.

Austrian and Bulgarian CO_2 emissions represent 1.8% and 1.2% out of the total EU-28 carbon dioxide emissions. This proportion can be seen in the Figure 16.

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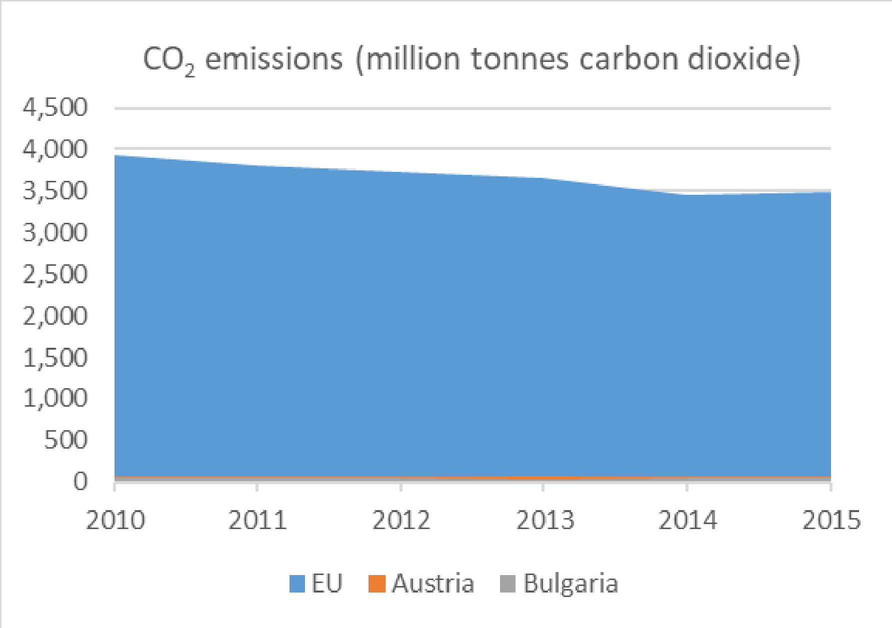

Figure 16. Evolution of CO_2 emissions in the World and the EU-28.

Gross Domestic Product per capita

For the period between 2010 and 2015, the European Union has increased its GDP per capita by 2%. These data are shown in the following table and expressed in 2010 USD.

Table 14. EU-28, Austria and Bulgaria GDP per capita data.

Time	2010	2011	2012	2013	2014	2015	Ratio 2014
EU-28 (billion 2010 USD using exchange rates/capita)	33,645.19	34,161.70	33,918.79	33,921.04	34,295.99	n.a.	1
Austria (billion 2010 USD using exchange rates/capita)	46,675.84	47,815.26	47,948.99	47,819.58	47,651.05	47,893.82	1.39
Bulgaria (billion 2010 USD using exchange rates/capita)	6,748.65	6,902.04	6,956.22	7,083.91	7,243.77	n.a.	0.15

Source: World Bank; n.a.= not available.

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As shown in the table, the GDP per capita in Austria is almost 1.4 times higher than the GDP per capita in the EU-28, and the GDP per capita in Bulgaria is 0.15 times lower than the EU-28 GDP in 2014. This relation is shown in the Figure 17.

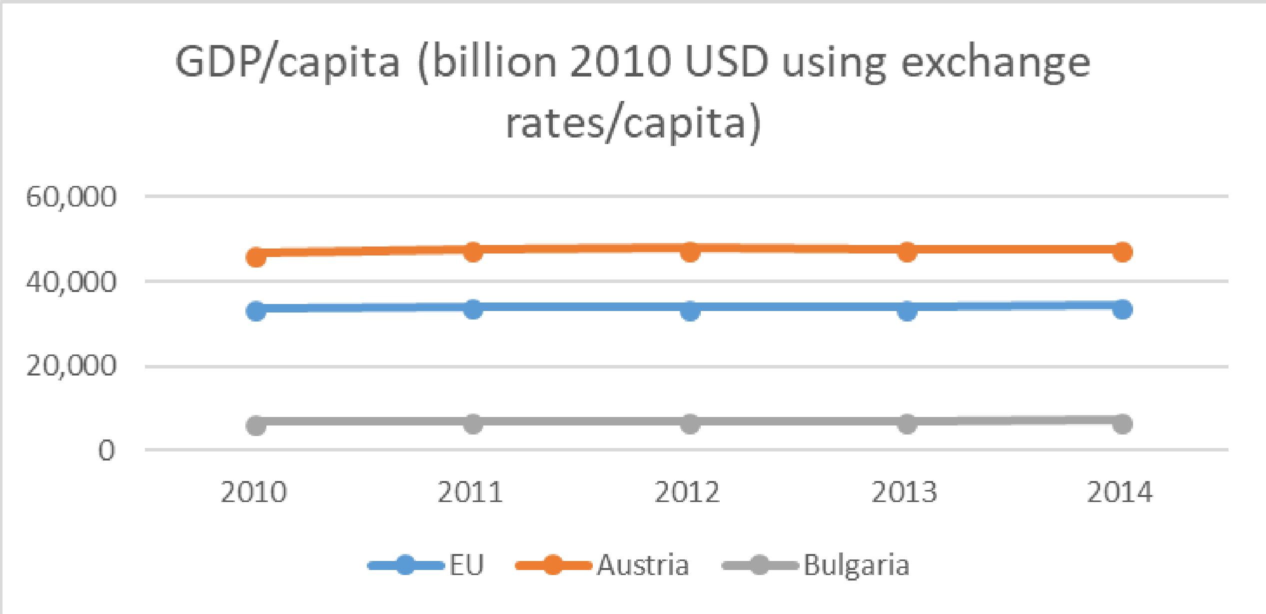

Figure 17. Evolution of GDP per capita in the World and the EU-28.

Primary energy consumption per capita

The data of primary energy consumption per capita represented in the table for the period between 2010 and 2015 is expressed in Million tons of oil equivalent per capita (Mtoe per capita) (Table 15). The primary energy consumption per capita in the European Union has experienced a decrease of 8%, while Austria experienced a decrease of 7.5% and Bulgaria more than 9.5%.

Table 15. EU-28, Austria and Bulgaria primary energy consumption per capita data.

Time	2010	2011	2012	2013	2014	2015	Ratio
EU-28 (Mtoe/capita)	3.49	3.36	3.32	3.29	3.16	3.20	1
Austria (Mtoe/capita)	4.30	4.03	4.19	4.14	3.97	3.97	1.24
Bulgaria (Mtoe/capita)	2.41	2.60	2.47	2.30	2.48	2.64	0.83

Source: Own elaboration with data from BP and OECD iLibrary.

As shown in the Table 15, the primary energy consumption per capita in Austria and Bulgaria is 1.24 times higher than in the EU-28, while the primary energy consumption per capita in Bulgaria is 0.83 times lower than in the EU-28. This proportion can be seen in the Figure 18.

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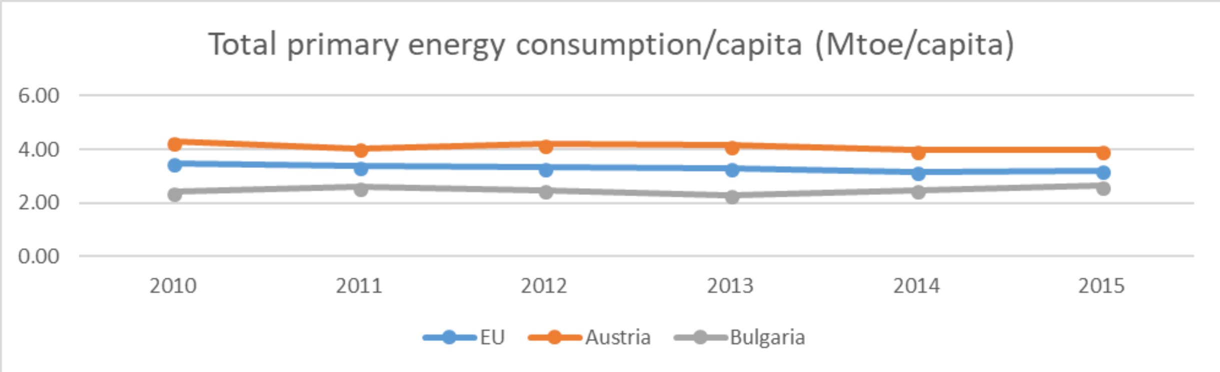

Figure 18. Evolution of Primary Energy consumption per capita in the EU-28, Austria and Bulgaria.

Oil consumption per capita

The average oil consumption per capita in the world has been constant over the last years (from 2010 to 2015). However, the European Union oil consumption per capita has decreased by 10%. Data for this period are represented in the Table 16 and expressed in tons per capita.

Table 16. EU-28, Austria and Bulgaria oil consumption per capita data.

Time	2010	2011	2012	2013	2014	2015	Ratio
EU-28 (Mt/capita)	1.32	1.28	1.22	1.19	1.16	1.18	1
Austria (Mt/capita)	1.60	1.51	1.48	1.50	1.47	1.47	1.25
Bulgaria (Mt/capita)	0.53	0.51	0.53	0.50	0.54	0.58	0.49

Source: Own elaboration with data from BP and OECD iLibrary.

The Austrian oil consumption per capita is 1.25 times higher than the EU-28 oil consumption per capita. Instead, the Bulgarian oil consumption per capita is 0.49 times lower than the average of the EU-28. This can be represented in the Figure 19.

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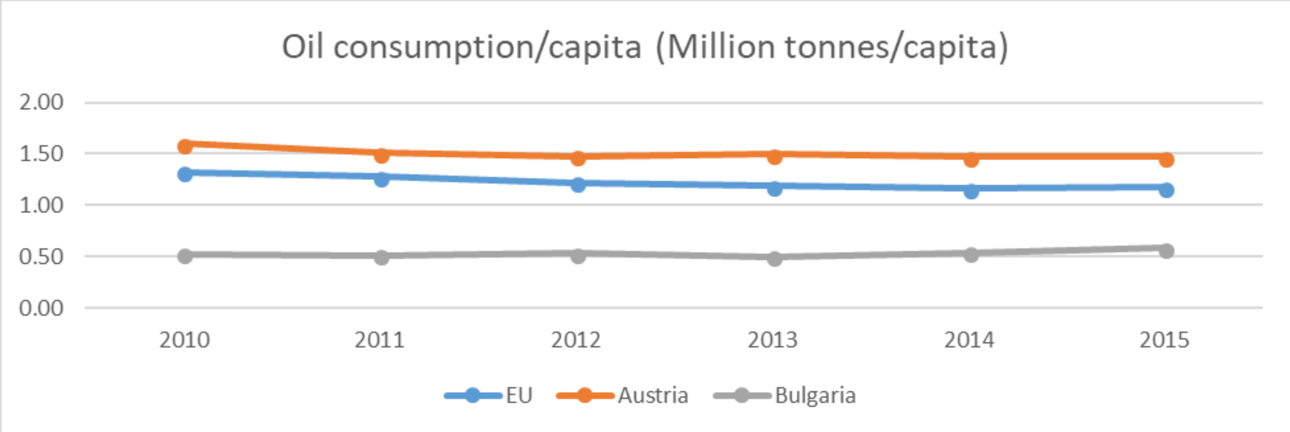

Figure 19. Evolution of Oil consumption per capita in the EU-28, Austria and Bulgaria.

Gas consumption per capita

The EU-28 gas consumption per capita decreased more than 23%. Data are represented in the next table and expressed in tons of oil equivalent per capita (Table 17).

Table 17. EU-28, Austria and Bulgaria gas consumption per capita data.

Time	2010	2011	2012	2013	2014	2015	Ratio
EU-28 (Mtoe/capita)	0.89	0.80	0.78	0.77	0.68	0.71	1
Austria (Mtoe/capita)	1.07	1.01	0.95	0.91	0.83	0.88	1.24
Bulgaria (Mtoe/capita)	0.31	0.36	0.34	0.33	0.33	0.36	0.51

Source: Own elaboration with data from BP and OECD iLibrary.

As presented in the table, the gas consumption per capita in Austria is 1.24 times higher than in the EU-28, while the Bulgarian gas consumption per capita is slightly higher than 0.5 lower than in the EU-28. It is shown in the Figure 20.

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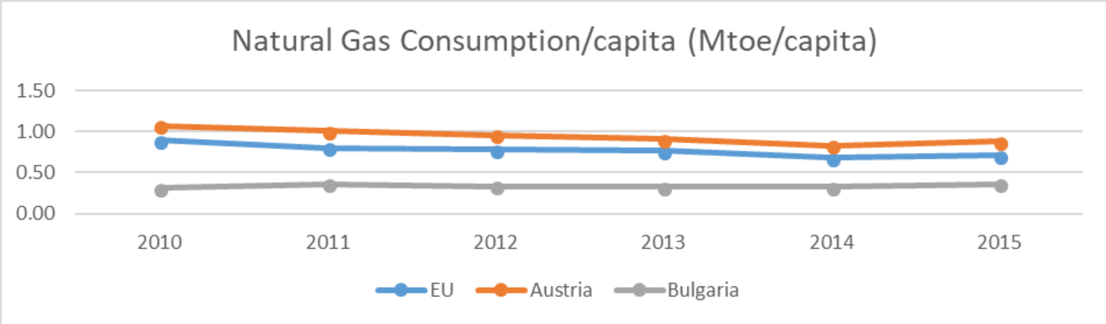

Figure 20. Evolution of the Gas consumption per capita in the EU-28, Austria and Bulgaria.

Coal consumption per capita

Coal consumption per capita in the EU-28 has experienced a small decrease of about 5% for years 2010 to 2015, in Austria about 13% and in Bulgaria 5%. Data, for the period between 2010 and 2015 expressed in tonnes of oil equivalent per capita, are represented in the Table 18.

Table 18. EU-28, Austria and Bulgaria coal consumption per capita data.

Time	2010	2011	2012	2013	2014	2015	Ratio
EU-28 (Mtoe/capita)	0.55	0.57	0.58	0.57	0.53	0.51	1
Austria (Mtoe/capita)	0.41	0.41	0.38	0.39	0.35	0.38	0.75
Bulgaria (Mtoe/capita)	0.93	1.10	0.95	0.82	0.89	0.93	1.82

Source: Own elaboration with data from BP and OECD iLibrary.

As it is represented in the table, the coal consumption per capita in Bulgaria is 1.82 times higher than the EU-28 average, and 0.75 times lower than the EU-28 values in the case of Austria. The pattern of change is presented in the Figure 21.

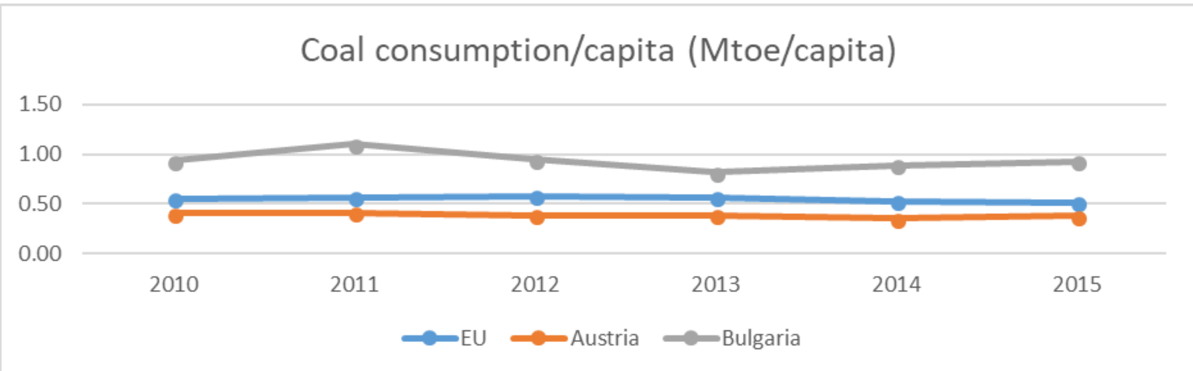

Figure 21. Evolution of the Coal consumption per capita in the EU-28, Austria and Bulgaria.

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Electricity consumption per capita

The European Union consumption of electricity has decreased by 5% during the period between 2010 and 2015, while the Bulgarian consumption has increased 3.4% and Austrian consumption remains at the same level approximately. Data expressed in kWh per capita for the period between 2010 and 2015 can be seen in the following table (Table 19).

Table 19. EU-28, Austria and Bulgaria electricity consumption per capita data.

Time	2010	2011	2012	2013	2014	2015	Ratio 2014
EU-28 (TWh/capita)	6.28	6.14	6.14	6.06	5.91	n.a.	1
Austria (TWh/capita)	8.39	8.43	8.55	8.51	8.36	8.41	1.41
Bulgaria (TWh/capita)	4.56	4.86	4.76	4.64	4.71	n.a.	0.80

Source: Own elaboration with data from OECD iLibrary; n.a. = not available.

As represented in the table, the Austrian electricity consumption per capita is 1.41 times higher than the EU-28 consumption in 2014, while the Bulgarian consumption is 0.8 times lower than in the EU-28. Data are represented in the Figure 22.

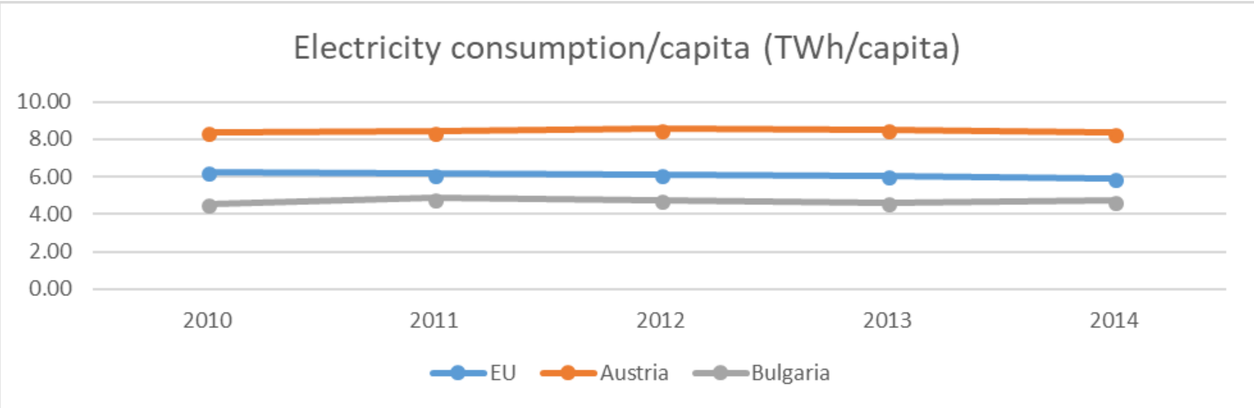

Figure 22. Evolution of Electricity consumption per capita in the World and the EU-28.

Wind energy production per capita

Wind energy production per capita has experienced a significant increase during last years from 2010 to 2015. The production has increased 1.7, 1.8 and 2 times the 2010 values in the EU-28, Austria and Bulgaria, respectively. Data are shown in Table 20 and expressed in kg of oil equivalent per capita.

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Table 20. EU-28, Austria and Bulgaria wind energy production per capita data.

Time	2010	2011	2012	2013	2014	2015	Ratio 2014
EU-28 (ktoe/capita)	25.50	30.61	35.02	40.17	42.85	n.a.	1
Austria (ktoe/capita)	21.23	19.84	25.12	31.97	38.73	48.60	0.90
Bulgaria (ktoe/capita)	7.91	10.07	14.36	16.25	15.85	n.a.	0.37

Source: Own elaboration with data from OECD iLibrary; n.a. = not available.

Taking into account the mean values of each level, the Austrian production is 0.9 times the EU-28 average, and the Bulgarian wind energy production is 0.37 times the EU-28 average production per capita on 2014. This proportion is illustrated in the Figure 23.

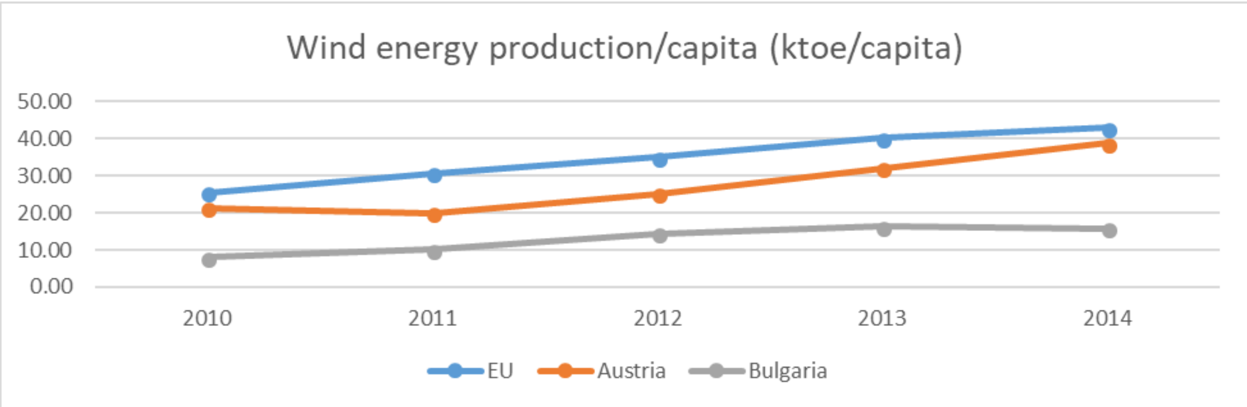

Figure 23. Evolution of the Wind power generation per capita in the EU-28, Austria and Bulgaria.

Solar energy production per capita

The EU-28 solar production has experienced a higher increase as its solar energy production per capita has been multiplied by 3.2 in the period 2010-2014, while Austria increases its production by 1.5 times and Bulgaria by more than 11 times. Data is represented in the table 21.

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Table 21. European Union, Austria and Bulgaria solar energy production per capita data.

Time	2010	2011	2012	2013	2014	Ratio
EU-28 (ktoe/capita)	7.38	11.96	17.81	20.99	23.63	1
Austria (ktoe/capita)	20.04	21.84	24.12	26.87	29.24	1.24
Bulgaria (ktoe/capita)	1.56	3.06	11.68	18.72	17.64	0.75

Source: Own elaboration with data from OECD iLibrary.

Taking into account the mean values of each region, the Austrian solar production per capita is 1.24 times the EU-28 solar energy production per capita, while the Bulgarian solar per capita production in 0.75 times the EU-28 level. This proportion is shown in the Figure 24.

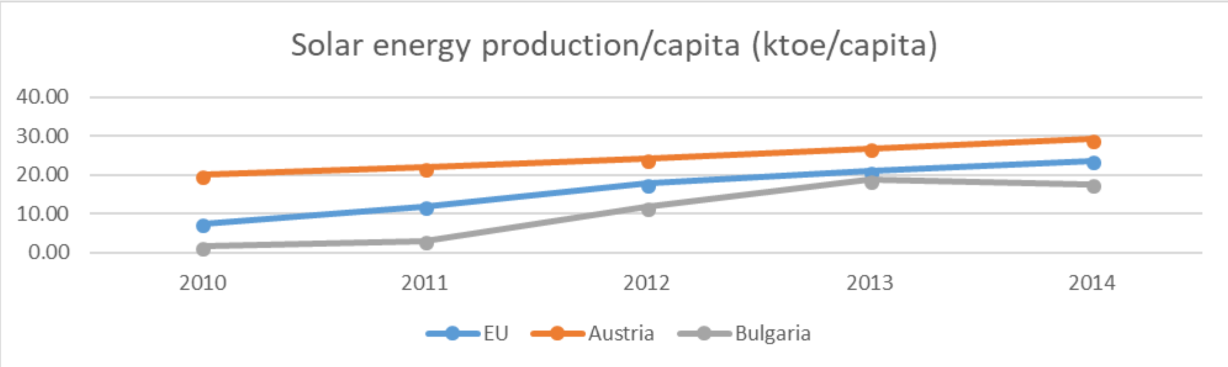

Figure 24. Evolution of Solar power generation per capita in the EU-28, Austria and Bulgaria.

Oil reserves per capita

The European Union oil reserves have experienced a decrease of around 7% during the period 2010-2015. Data, for the three regions, are shown in the Table 22. They are represented in thousand barrels per capita.

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Table 22. European Union, Austria and Bulgaria oil reserves per capita data.

Time	2010	2011	2012	2013	2014	2015	Ratio
EU-28 (thousand million barrels)	0.0119	0.0122	0.0118	0.0115	0.0111	0.0109	1
Austria (thousand million barrels)	0	0	0	0	0	0	-
Bulgaria (thousand million barrels)	0	0	0	0	0	0	-

Source: Own elaboration with data from BP and OECD iLibrary.

As shown in the table, the oil reserves of Austria and Bulgaria are negligible. Data are illustrated in the Figure 25.

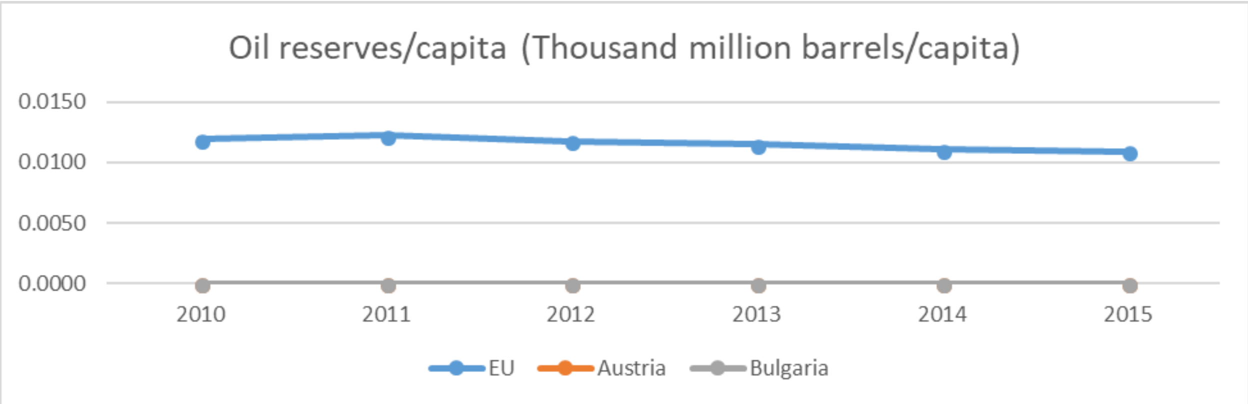

Figure 25. Evolution of the Oil reserves per capita in the World and the EU-28.

Gas reserves per capita

The European Union gas reserves per capita have decreased by 45% during the period 2010-2015. These data are represented in the Table 23.

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Table 23. EU-28, Austria and Bulgaria gas reserves per capita data.

Time	2010	2011	2012	2013	2014	2015	Ratio
EU-28 (trillion cubic meters)	0.0047	0.0035	0.0030	0.0028	0.0026	0.0026	1
Austria (trillion cubic meters)	0	0	0	0	0	0	-
Bulgaria (trillion cubic meters)	0	0	0	0	0	0	-

Source: Own elaboration with data from BP and OECD iLibrary.

Austrian and Bulgarian gas reserves per capita are negligible. According to these data, the pattern is illustrated in the Figure 26.

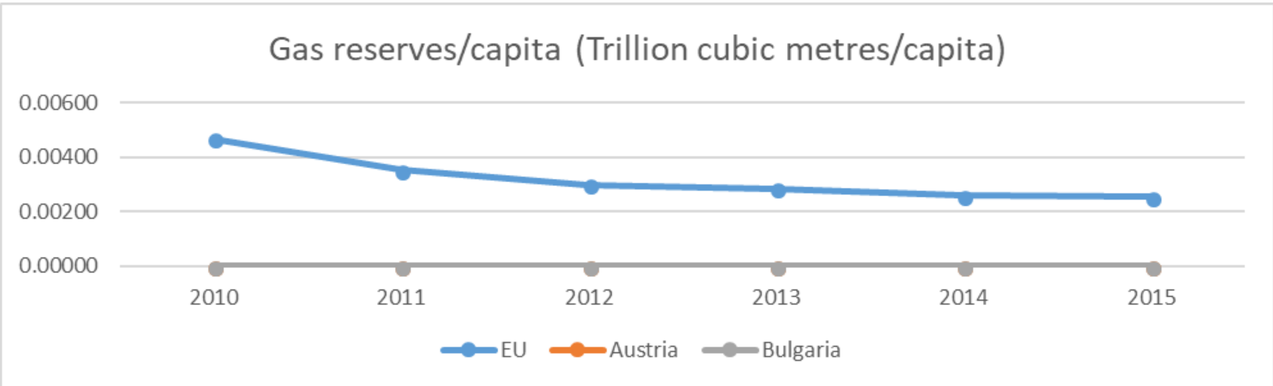

Figure 26. Evolution of Gas reserves per capita in the EU-28, Austria and Bulgaria.

Coal reserves per capita

When it comes to coal reserves per capita, there is data for the end of the year 2015 for the European Union and the countries selected. These data are represented in the Table 24.

Table 24. EU-28, Austria and Bulgaria coal reserves per capita data.

Time	2015	Ratio
EU-28 (Mt/capita)	110.036	1
Austria (Mt/capita)	0	-
Bulgaria (Mt/capita)	329.986	3

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Source: Own elaboration with data from BP and OECD iLibrary.

As shown in the table, the Bulgarian coal reserves per capita are 3 times higher than the EU-28 average level. The temporal pattern of change can be seen in the Figure 27.

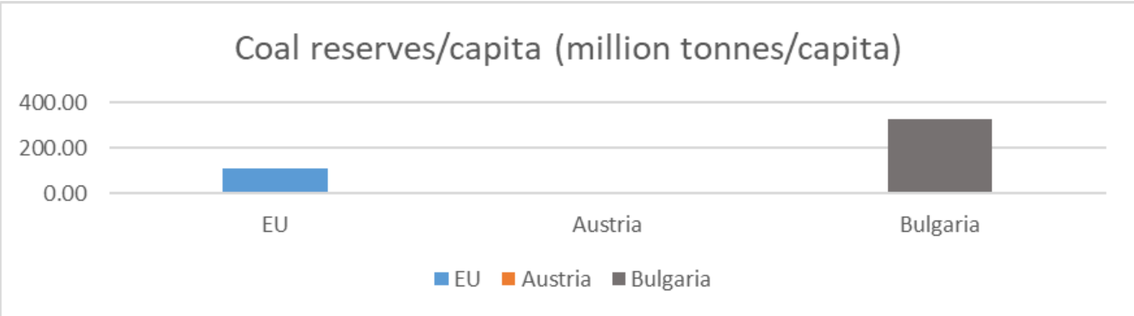

Figure 27. Coal reserves per capita in 2016 for the EU-28, Austria and Bulgaria.

CO_2 emissions per capita

The last indicator is carbon dioxide emissions per capita. These emissions have decreased by 13%, 15 % and 3 % in the EU-28, Austria and Bulgaria, respectively for this period. These data are shown in Table 25.

Table 25. EU-28, Austria and Bulgaria CO_2 emissions per capita data.

Time	2010	2011	2012	2013	2014	2015	Ratio
EU-28 (Mt CO_2/capita)	7.81	7.53	7.38	7.21	6.78	6.85	1
Austria (Mt CO_2/capita)	8.34	7.98	7.62	7.56	7.10	7.33	1.07
Bulgaria (Mt CO_2/capita)	6.08	6.85	6.20	5.49	5.89	6.30	0.92

Source: Own elaboration with data from BP and OECD iLibrary.

As it can be deducted from the table, the Austrian emissions per capita are 1.07 times higher than the average level for the EU-28, while the Bulgarian emissions per capita are 0.92 times lower than the EU-28 average level. This proportion is shown in the Figure 28.

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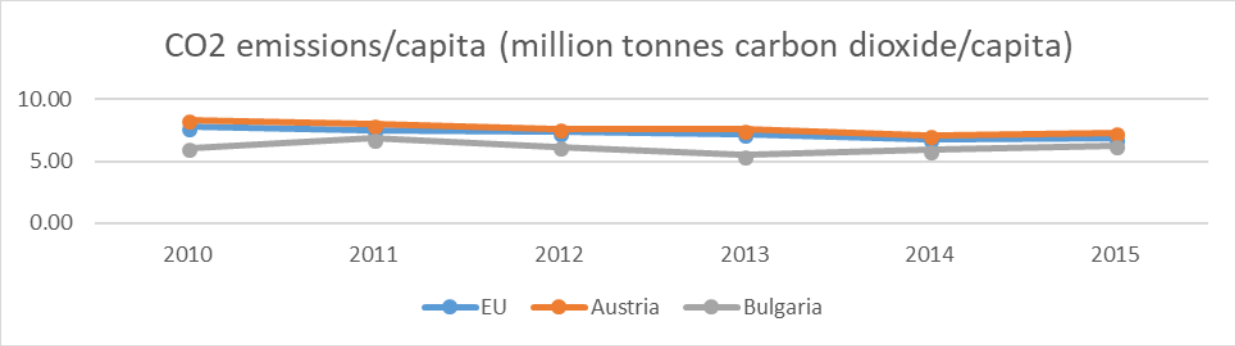

Figure 28. Evolution of the CO_2 emissions per capita in the World and the EU-28.

2.2.1.3. Boundary variables from MEDEAS_eu

As aforementioned, MEDEAS-W and MEDEAS_eu will be used as a ("parent models") which will provide the boundary conditions, within which the MEDEAS country-level models ("child models") will evolve. This paragraph describes which boundary variables from MEDEAS-W and MEDEAS_eu are used (and how) in MEDEAS country-level models. A total of 14 variables are used. The nomenclature from MEDEAS-W 1.1 is used. We describe them in relation to their role in each module of the country-level version of the model:

Economic Module

- "GDP"
- "Real demand by sector"
- "Real total output by sector"
- "Real final energy by sector and fuel"
- "Annual GDP growth rate"

These variables are used in MEDEAS country-level models to estimate the Austrian, Bulgarian, RoEU and RoW final energy intensities, the RoEU and RoW imports and exports and to estimate the final energy footprint.

The "share E-losses CC" refer to the impacts from climate change and are used to estimate the final energy available for society in UE after accounting for these impacts.

Energy Module

- "Real final energy by sector and fuel"
- "Total extraction NRE EJ"
- "PES nat. gas"
- "PES oil EJ"

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- “Extraction coal”
- “Extraction uranium EJ”
- “Share conv vs total gas extraction”
- “Share conv vs total oil extraction”

These variables are used in MEDEAS country-level models to estimate the imports of Austria and Bulgaria from RoEU and RoW of primary non-renewable fuels such as oil, gas, coal and uranium.

Materials module

“Current mineral resources Mt”

“Current mineral reserves Mt”

These variables are used in MEDEAS country-level models to compare the countries’ demand of minerals with the global and European levels of current resources and reserves.

2.2.2. Economy module

2.2.2.1. Literature review

The approach chosen for modelling Economy in MEDEAS country-level has involved a revision of literature in the field to establish the most proper scope.

It is possible to find different approaches which can be encompassed under the general definitions of optimisation/simulation models and top-down/hybrid/bottom-up models (Scrieciu et al., 2013). Optimisation models usually rely on neoclassical –or, more generally, conventional- economics and thus, computable general equilibrium (CGE). They assume clearing markets via price adjustments which, in turn, ensures full employment and productive capacity (Sterman et al., 2012). Furthermore, they consider optimal growth, which is supply-led through the optimisation of a production function dependent on factors capital and labour, and technological progress. In contrast, simulation models describe intertwines between energy-economy-climate, which allows examining the propagation of disturbances into the system and evaluating the different outcomes of policies. The most known contribution to simulation models was the pioneering World3 model of *Limits to Growth* (Meadows, 1972).

Beyond optimisation-simulation, there are different (but related) approaches regarding the main driver of economy. Optimisation models tend to be supply-led, using the availability of productive factors, i.e. capital, labour and, eventually, natural capital as the engine of modelling. Conversely, demand-led models are usually sustained in post-Keynesian economics assuming disequilibrium,

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meaning non-clearing markets, demand-led growth and supply constraints (Lavoie, 2014; Taylor et al., 2016). Demand-led models start modelling demand, i.e. the direct and real expression of the productive factors capacity. In these models, however, supply can act as a constraint for the economic activity. As simulation better fits with dynamic modelling and disequilibrium economics, a number of models have been grounded on these approaches. Some examples are the non-equilibrium E3MG model (Pollit, 2014), ICAM (Dowlatabadi, 1998), GTEM (Kemfert, 2005) AIM (Kainuma, 2003; Masui et al., 2006; Morita et al., 2003) and IMAGE (Alcamo et al., 1998; Bouwman et al., 2006; E. Stehfest et al., 2014).

Other useful categorization distinguishes between top-down, hybrid and bottom-up models. The former one implies a macroeconomic perspective where policies and main macro-magnitudes are the essential drivers of the model outcomes. The latter, conversely, represents a partial equilibrium –throughout technologies competition- in the energy sector. Hybrid models, on the other hand, combine a detailed macroeconomic and energetic view of technologies.

While at the early times, top-down optimisation models where dominant, critical observations have been made to this approach. The assumption of perfect substitutability between factors has been widely criticised from ecological economics, which considers that complementarity better fits reality (Christensen, 1989; Farley and Daly, 2003; Stern, 1997). In addition, there is a lack of economic sectoral disaggregation which does not allow models to capture the relevance of economic structure in energy-environment-economy interactions (De Haan, 2001; James et al., 1978). Moreover, optimisation reveals as an unrealistic approach to model complex, dynamic systems in which feedbacks and time matters (Capellán-Pérez, 2016; Uehara et al., 2013). Nevertheless, the majority of demand-led models account with a sequential structure instead of the feedback-rich structure of SD models.

Regarding this body of literature, MEDEAS-Austria and MEDEAS-Bulgaria economy modules are defined as a simulation and hybrid models (Scrieciu et al., 2013) (Figure 29). Furthermore, MEDEAS country-level economy modules are demand-led, sector-disaggregated and based on a disequilibrium approach and Input-Output Analysis (IOA). The MEDEAS framework considers demand-led approach more realistic than supply-led, since the latter implies non-reasonable assumptions about the productive factors' utilisation capacity. By adopting a demand-led approach, MEDEAS contributes to widen this demand-side body of literature. Moreover, it is a more realistic procedure, as demand represents the actual economic activity deployed by the productive factors, whether they are in equilibrium or not. However, demand-led models tend to underestimate or directly not take into consideration biophysical supply-side constraints, so GDP is

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able to keep growing unhindered. The main contribution of MEDEAS in that way is the inclusion of supply constraints and climate change, which feedback the economy throughout energy availability, and emissions.

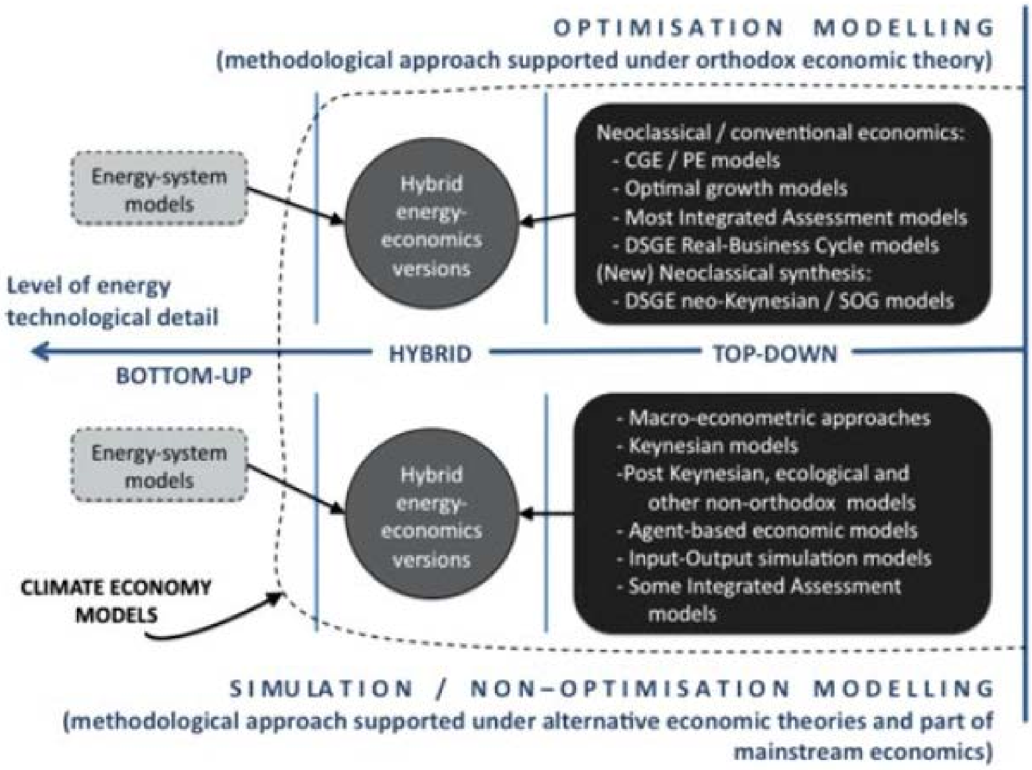

Figure 29. Macro-economic modelling in IAMs.

IOA reveals itself as a powerful tool to assess the direct and indirect effects in sectoral production given an economic structure and the evolution of demand (Leontief, 1970; Miller and Blair, 2009). In addition, IOA allows including environmental hybrid approaches and has been combined with system dynamics in energy-economy-climate modelling (Briens, 2015; Cordier et al., 2017). By using IOA to start the demand modelling, MEDEAS not only can make a sectoral analysis of its results, but it also assumes disequilibrium and it is able to capture structural conditioners in transitions, something that it is often missing from macro-economic modelling. IOT does not make assumptions on equilibrium neither in the goods market nor in the factors market but reveals the actual nature of economic evolution.

Trying to model disequilibrium in factors market necessarily leads to make unrealistic assumptions. For instance, modelling labour supply as a positive function of wages considers implicitly perfect mobility of labour and/or the societal capacity to permanently sustain a significant share of inactive population. MEDEAS, on the contrary, considers disequilibrium in

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factors market as given in the data, reacting each economic variable according to implicit unemployment and under-utilisation of capital. The model overcomes the main limitations of energy-economy-environment modelling that rely on optimisation, sequential structure, neoclassic production function regardless of disequilibrium and economic structure, and lacks biophysical constraints. MEDEAS country-level Economy-module can be seen as a contribution to the now emerging field of ecological macroeconomics (Hardt and O'Neill, 2017; Rezai and Stagl, 2016).

2.2.2.2. Overview of the economy module

Economy module in MEDEAS country-level is regionally broken down into three different regions: the analyzed country (Austria or Bulgaria: AUT or BGR), the rest of Europe (RoEU) and the rest of the world other than Europe (RoW). Although the general structure is quite similar to the economy module of MEDEAS-Europe (see more details in Deliverable 4.2), it is adapted to the 'many regions' IOA features instead of the 'two regions' IOA. For instance, as it is carefully described below, final demand now includes two exports by sector regarding each foreign region. As can be seen in Figure 30, RoW and RoEU final demand by sector influences the expected production in each country. The energy-economy feedback is also taken into account. Nevertheless, energy supply availability considers energy trade since not all energy demand can be supplied by domestic resources.

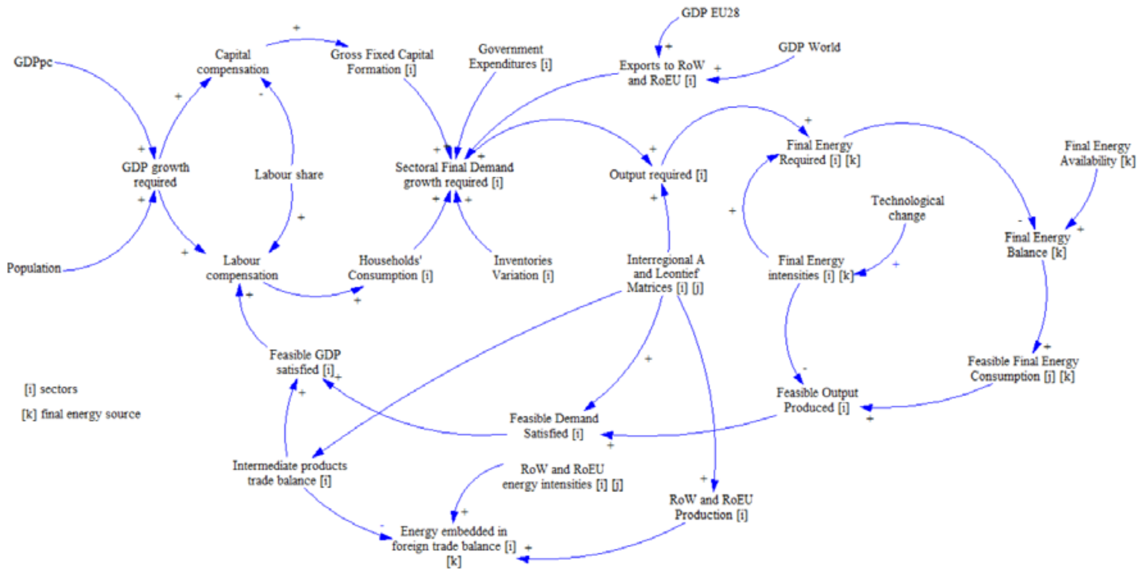

Figure 30. Overview of MEDEAS country-level economy module.

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Through IOA with trade, MEDEAS country-level models are able to estimate the energy embedded in trade balance, by using not only the countries energy intensities, but also RoW's and RoEU's. Since GDP is defined as the total final demand plus the intermediate trade balance, it is necessary to also estimate the latter. Finally, inputs to final demand function come from income (labour and capital compensation), obtained thanks to exogenous income share scenarios. Moreover, there are other exogenous variables, which can be used to determine sectoral final demand. Despite these variables have been disabled after finding no statistical significance for these countries, the model structure allows the user to estimate their own coefficients and feeding the model with them.

Schematically, the economy module follows a structure like shown in Figure 31. The user of MEDEAS-Country can input exogenous scenarios of GDP per capita and population growth, as well as different estimates for income shares (a measure of inequality). Then, demand function comes into motion, providing the IOA with the demand shock that it requires to estimate production. In MEDEAS-Europe, IOA includes trade, meaning that there is not only one interpretation for A and Leontief matrices, but also one interpretation for each of the sub-matrices in which it is divided. Trade and foreign regions' economic structure also matters to determine the production required to satisfy each country's demand. Hereafter, through energy intensities, energy consumption required by the economic system is estimated and faced to the energy availability. That delivers with the feasible energy actually consumed, as well as feasible production and demand under energy constraints. Once feasible demand is estimated, feasible GDP is calculated by summing up the intermediate products trade balance.

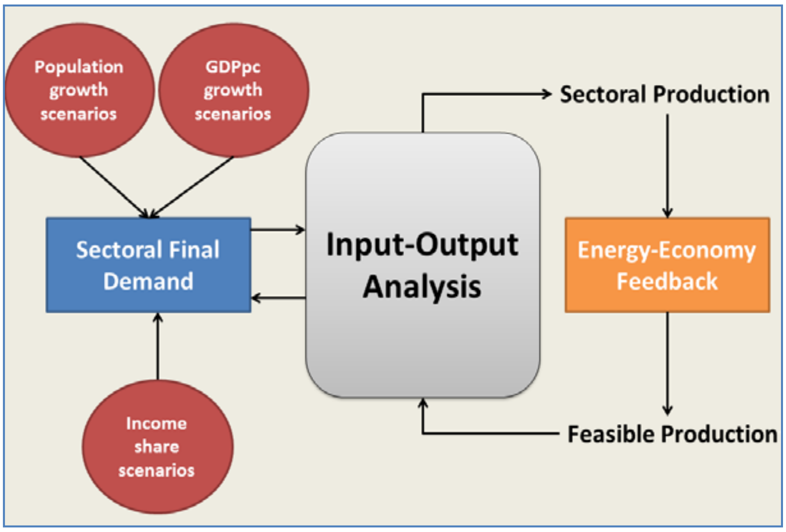

Figure 31. Schematic overview of MEDEAS country-level economy module.

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Thus, this section describes the functioning of each economy module's stage, regarding its main features: i/final demand function; ii/ Input-Output Analysis with trade; iii/ Energy-Economy feedback; iv/ Income.

2.2.2.3. Description of the economy module

2.2.2.3.1. Demand Function

MEDEAS country-level models are demand-led models, as explained before. Exogenous final demand growth provides inputs to the final demand function, whose commitment is distributing this final demand change amongst sectors. Since total GDP growth is exogenously determined by scenarios, final demand function estimates the agents final demand of each industry's products. Whereas MEDEAS_w (Deliverable 4.1.) final demand (FD) does not include trade -since at the world level imports are offset by exports- MEDEAS country-level models do. Input-Output Analysis (IOA) used by the economy module afterwards imposes a particular final demand point of view. Because IOA is oriented to estimate production in the objective region, it is necessary to measure the final demand of this region's products. This way, FD in MEDEAS country-level consists of domestic and foreign demand of each country's products, i.e., domestic demand and exports. It is worth to emphasize that FD is not referred to final demand made by European agents, as this would imply to include final imports. However, although by definition final imports are not domestically produced and thus, are not included in FD, they play a crucial role in MEDEAS country-level models. Therefore, final demand for each industry follows Eq. 1:

$$FD_{it} = HH_{it} + GFCF_{it} + GE_{it} + INVENT_{it} + FD^{EXP}_{it,DOM,RoW} + FD^{EXP}_{it,DOM,RoEU} \qquad i \in 1 \ldots 35 \qquad (1)$$

Being i the subscript for each industry, t the time subscript; HH the households' consumption, GFCF the gross fixed capital formation, GE the government expenditures, INVENT the changes in inventories and $FD^{EXP}_{it,DOM,RoW}$ and $FD^{EXP}_{it,DOM,RoEU}$ final exports (not included intermediate exports) to RoW and RoEU according to their subscripts. Whilst all the categories mentioned are associated with the final consumption of each country's products made by each institutional sector, GFCF does not follow the same approach for Bulgaria. GFCF is the final consumption of investment products made by any agent. For example, people purchasing the primary residence is GFCF in sector 18 (Construction). Likewise, real estate investment made by a corporation or the purchase of a building made by the government are also GFCF in sector 18. In fact, because the special features of this sector and its relative importance -total gross fixed capital formation in construction rises up to 53% of total investment- it is estimated separately from the other sectors in Bulgaria. Although there were no significant differences between the performance of this

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industry and the other, which might justify this separation for Austria, the model structure allows the user to estimate their own coefficients separately. Finally, whilst HH_{it}, $GFCF_{it}$, and EXP_{it} (more than 95% of sectoral final demand except on sectors 26 and 30-34) can be estimated throughout econometric functions, GE_{it} and $INVENT_{it}$ remains as a constant share of total final demand based on the time series values. Thus, regarding the structure of the data used (Dietzenbacher et al., 2013) with 35 industries and 15 years, we have a panel with 525 observations.

As already known, in a highly complex system dynamics model as MEDEAS, the main objective is to capture trends to assess how the system reacts under different conditions. Nonetheless, it has been followed a systematic process to estimate robust panel data regressions, in order to account with the most accurate forecasts as possible. Although not very common in panel data estimation, unit root tests had been used to determine the presence of non-stationarity in the panels. Whether to use random or fixed effects was tested through the Hausman's (Hausman, 1978) specification test. Finally, once detected heterokedasticity, autocorrelation and cross section dependence problems, corrected regressions were estimated. Finally, joint significance tests were used in order to accept the different models. As a result of this correction process, errors were narrowed as lower as possible (errors ≃ 0-2%).

The inputs used in them have been chosen according to the literature and conditioned by the limits imposed by the data source used. Income is the main input to the sectoral final demand functions, being present in all of them. Labour and capital compensation are the main drivers of households' consumption and gross fixed capital formation respectively, whilst the world's final demand plays the same role for exports. All these inputs are calculated by the model or by MEDEAS_w (in the case of the world's GDP). For this reason, despite total GDP (and final demand variation) is determined by scenarios exogenously, sectoral final demand is highly integrated into the endogenous dynamics of the model.

Households' consumption (HH_{it}) stands for the consumption made by domestic households of consumption goods and services produced in each country. For instance, sector 4 (Textiles and Textile products) accounts the purchases made by households of clothes, amongst other products. It has been assumed that HH_{it} is determined by labour compensation, as it is the main source of households' income. Although disposable income would have been a much better indicator to estimate this variable, difficulties to introduce it in the dynamics of the model made it useless. Nevertheless, the econometric model estimated proved to be robust and its error is nearly zero for both countries

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As mentioned before, $GFCF_{it}$ has been split into construction investment ($GFCF_{18t}$) and the other sectors for Bulgaria (not for Austria). General $GFCF_{it}$ collects investment made by all institutional sectors. For instance, optical equipment (sector 14) purchased by a medical enterprise is included here. But it is also included the household purchase of consumer durables such as vehicles, usually acquired through consumer lending. Thus, the main explanatory variable of $GFCF_{it}$ is capital compensation (Cap). In addition, real long-term interest rate (deflated with the GDP deflator for EU28) ($long\_term\_ir_t$) is the interest rate chosen to explain investments. Regarding that a significant share of construction sector gross fixed capital formation ($GFCF_{18t}$) is dedicated to households' house purchases, explanatory variables are labour compensation (Lab_t) and real interest rates for loans for house purchases ($real\_irhh_t$). In addition, for investment made by the other institutional sectors, real effective interest rate for corporations ($real\_irc_t$) remains in the equation. Data for interest rates for EU28 are rather difficult to obtain, according to the diversity of currencies in the Union. Interest rates for both countries were collected from International Monetary Fund (IMF) database and no statistical significance were found.

The case of $FD^{EXP}_{it,DOM,RoEU}$ and $FD^{EXP}_{it,DOM,RoW}$ is rather different. Exports of final consumption goods and services are considered to depend on exchange rates and the income of the trading partners (Hassan et al., 2016; Ho, 2012). In MEDEAS-Country, real effective exchange rate for Austria and Bulgaria (IMF estimates) has been used as explanatory variable for exports.

Exchange rates for Austria's$FD^{EXP}_{it,DOM,RoEU}$ have been dismissed as most of its exports to RoEU are delivered to the Euro Zone. Besides, no statistical significance has been found between any exchange rate indicator and sectoral exports, being the trading partner's income the main explanatory variable. Recent literature points out the disconnection between exchange rates and exports due to global value chains and international financial flows (Ollivaud et al., 2015; Swarnali et al., 2015) as well as quality instead of competitiveness (Feenstra and Romalis, 2014). Furthermore, because the RoW and RoEU gross domestic product (GDP) is calculated each year t as the difference between World and Europe GDP (data loaded directly from MEDEAS-W and MEDEAS-Europe respectively) and each country's GDP, RoW and RoEU GDP in year t cannot be used to estimate exports in year t. Since it would not make economic sense to estimate year t exports as a function of RoW GDP in t-1, it is a more reasonable approach to make it depend on world's and Europe's GDP, given the small share which represent each country over both regions.

Hence, the equations that estimate the three main components of final demand, plus the construction sector regression, in MEDEAS-Europe are the following (Eq. 3-6):

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$$lnHH_{it} = \beta_0 + \beta_{1i}Sec_i + \beta_2 lnLab_t \qquad \text{i} \in 1\ldots35 \qquad (3)$$

$$lnGFCF_{it} = \beta_0 + \beta_{1i}Sec_i + \beta_2 lnCap_{t-1} + \beta_3 real\_irc_t + \beta_4 real\_irchh_t \qquad \text{i} \in 1\ldots34 \qquad (4)$$

$$lnGFCF_{18t} = \beta_0 + \beta_1 lnLab_t + \beta_2 real\_irc_t + \beta_4 real\_irhh_t \qquad (5)$$

$$lnFD^{EXP}_{it,region} = \beta_0 + \beta_1 Sec_i + \beta_2 real\_exch_t + \beta_3 lnRegion\_gdp_t \qquad \text{i} \in 1\ldots35 \qquad (6)$$

Sec_i is a dichotomous variable whose value is 1 when calculating each sector and 0 when it is any other sector. For instance, for sector households' consumption in sector 3, Sec_3 equals 1, so just $\beta_{1,3}$ is applied. Besides, because β_{1i} are estimated as a measure of the incidence of the particulars of each sector in the explanation of the dependent variable, their value is defined in reference to one sector, which here is sector 1. It means that $\beta_{1,0}$is always equal to 0 and β_{1i} has a value different to zero, according to the different effect of each sector on the dependent variable, regarding that of the sector 1. So, there are 34 different β_{1i} as shown in panel data regressions tables for each country (see Annex XX). *Lab* stands for labour compensation for the whole economy. There is no economic justification to assume that wages paid in one sector will be expended in the same sector. We use labour compensation instead of disposable income because it is not possible to estimate it inside the model, while primary income is obtained as described below. Cap stands for capital compensation and, following the definition of gross fixed capital formation given above, it must be used the total capital compensation of the whole economy, not just that of the sector. As mentioned before, sector 18 has only been taken separately (Eq.5) for Bulgaria, whilst this sector performs as in Eq.4 for Austria. Finally, $region\_gdp$ is the World's and Europe's GDP for $FD^{EXP}_{it,DOM,RoW}$and $FD^{EXP}_{it,DOM,RoEU}$, loaded from MEDEAS_w and MEDEAS-Europe respectively. All the variables are provided in logarithms (ln) in order to avoid non-linear relationships between variables. Annex X shows the parameters of the robust panel data regressions ran for the main components of final demand. The approach followed to translate these equations into system dynamics programming relies on considering them as absolute variations. These variations are the fluxes that feed households final demand (HH_{it}), gross fixed capital formation ($GFCF_{it}$) and exports (EXP_{it}) as stocks[1]. Thus, taking equation 2 for households' consumption in sector i, it can be expressed as (Eq. 7-8):

[1] From an economic point of view, final demand is a flow, not a stock. But, the operation of the system dynamics model requires the accumulation of certain variables as a stock feed by its variation as the main flow, regardless of its economic meaning.

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$$HH_{it} = e^{\beta_0} e^{\beta_{1i} Sec_i} Lab_t^{\beta_2} \tag{7}$$

$$\Delta HH_{it} = e^{\beta_0} e^{\beta_{1i} Sec_i} (Lab_t^{\beta_2} - Lab_{t-1}^{\beta_2}) \tag{8}$$

Equivalently, $GFCF_{it}$ and FD_{it}^{EXP} to both regions would be expressed equally but using different explanatory variables. In order to calculate in the model, the new final demand flow to their respective stocks, the variation is taken. Regarding $GFCF_{it}$, lagged capital compensation and real long-term interest rates have been chosen as explanatory variables. Nevertheless, it is income which mostly explains investment, since interest rates have been found non-significant as explanatory variables. In fact, after introducing all kinds of real interest rates to explain investment, what we found is that they have a small or even none significance at all. Moreover, even taking into account the low value obtained for interest rate coefficient, its sign is positive, against the mainstream theory. Firstly, there is an increasing body of literature pointing out that interest rates may have been playing a different role amongst countries or historical contexts. This way, real interest rates influence varies according to different regimes (Hein and Ochsen, 2003) or having indirect effects instead of direct (Lavoie, 2014, 1995) that could even lead to non-significance (Banerjee et al., 2015; Sharpe and Suarez, 2015; Stockhammer et al., 2009). Secondly, the time series sample encompasses a very unusual period for investment, i.e. the economic crisis. Indeed, time effects had to be included in the regression to avoid the disruptive influence of this years. As mentioned before, exchange rates suffer for the circumstances previously explained. As a consequence, interest and exchange rates are included in the model's structure for the user to establish their own estimation but are not included in the panel data regressions of this version (see Annex 1).

Once final demand of each country's products is estimated for year t, Input-Output Analysis (IOA) come into play. As it is explained afterwards, IOA with trade requires not only domestic products final demand variation, but also other regions' change. To sum up, final demand in MEDEAS-Europe relies on inputs provided by an exogenous change in total final demand. Then, income is calculated to provide the inputs for the final demand function, which distributes this change in total final demand amongst the 35 industries. Finally, these sectoral changes activate IOA, which provides the model with the sectoral production required to satisfy the demand. The purpose of the following section is to explain that process.

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2.2.2.3.2. Input-output analysis

MEDEAS-Country relies on a 'Many regions' Input-Output model which is rather different to a one-region Input-Output Table (IOT) and even to a two-region IOT. Not only the accounting balances are different, but also the procedure needed to be carried out for estimating the main aggregates. Figure 32 shows the general structure of both approaches, which consists of as many regions as determined previously regions r, with r ∈ 1,…,n. As usual, it contains as many, industries as displayed by rows (sales) and columns (purchases), i and j respectively.

World IOT

Z_{ij}^{r}	D_i^r	X_i^r
VA_j^r		
X_j^r		

Many region IOT

Z_{ij}^{rr}	$Z_{ij}^{r,\dots}$	$Z_{ij}^{r,n}$	$D_i^{r,r}$	$D_i^{\dots,r}$	$D_i^{n,r}$	X_i^r
$Z_{ij}^{\dots,r}$	$Z_{ij}^{\dots,\dots}$	$Z_{ij}^{\dots,n}$	$D_i^{\dots,r}$	$D_i^{\dots,\dots}$	$D_i^{\dots,n}$	$X_i^{\dots}$
$Z_{ij}^{n,r}$	$Z_{ij}^{n,\dots}$	$Z_{ij}^{n,n}$	$D_i^{n,r}$	$D_i^{n,\dots}$	$D_i^{n,n}$	X_i^n
VA_j^r	$VA_j^{\dots}$	VA_j^n				
X_j^r	$X_j^{\dots}$	X_j^n				

$Z_{ij}^{r,r}$: Intrarregional Intermediate trade in region r; $Z_{ij}^{r,\dots}$: Intermediate exports (r→…).

$Z_{ij}^{\dots,r}$: Intermediate imports (…→r); $D_i^{r,r}$: Intra-regional Final Demand in region r;

$D_i^{r,\dots}$: Final products exports (r→…); $D_i^{\dots,r}$ Final products imports (…→r).

VA_j^r: Value added in region r; X_j^r: Production in region r.

Figure 32. General structure of World and 2-region Input-Output Tables.

In order to provide a more comprehensive picture of the most relevant economic flows from the countries point of view, the Many region IOT has been redesigned (Figure 33). The Country IOT has been compiled on the basis of the deflated interregional IOT, which includes the European Union 27 (EU27) countries, 13 other major economies and a Rest of the World (RoW) region. Thus, a systematic process was implemented to obtain the country IOT, comprising five stages for each year in the time series (1995-2009): i/ rearranging the interregional World IOT (WIOT) to put together the EU27 countries both intermediate consumption and final demand; ii/ balancing intermediate and final products purchases and sales between EU27 countries; iii/ apply the

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previous stage to the other countries to obtain RoW; iv/ add Croatia to EU27 to transform it in EU28 and deduct it in the new RoW region v/ establish the relationships between the country, the rest of Europe (RoEU) and the rest of the world other than Europe (RoW). Once this process is fulfilled, we have a 3 region IOT encompassing different sub-matrices taking into account the bilateral economic flows between these regions (Figure 33).

$IC_{DOM,DOM}$	$IC^{EXP}_{DOM,RoW}$	$IC^{EXP}_{DOM,RoEU}$	$FD_{DOM,DOM}$	$FD^{EXP}_{DOM,RoW}$	$FD^{EXP}_{DOM,RoEU}$	X_i^{DOM}
$IC^{IMP}_{RoW,DOM}$	$IC_{RoW,RoW}$	$IC^{EXP}_{RoW,RoEU}$	$FD^{IMP}_{RoW,DOM}$	$FD_{RoW,RoW}$	$FD^{EXP}_{RoW,RoEU}$	X_i^{RoW}
$IC^{IMP}_{RoEU,DOM}$	$IC^{EXP}_{RoEU,RoW}$	$IC_{RoEU,RoEU}$	$FD^{IMP}_{RoEU,DOM}$	$FD^{EXP}_{RoEU,RoW}$	$FD_{RoEU,RoEU}$	X_i^{RoEU}
VA_j^{DOM}	VA_j^{RoW}	VA_j^{RoEU}				
X_j^{DOM}	X_j^{RoW}	X_j^{RoEU}				

DOMESTIC
TRADE
OTHER REGIONS

IC: Intermediate consumption; FD: Final Demand; VA: Value Added; X: Production;
Superscripts: EXP: Exports from one region to other (IC and FD); IMP: Imports to one region from other (IC and FD);
Subscripts: First term: producing region; Second term: purchasing region. DOM: Domestic; RoW: Rest of the World (other than Europe); RoEU: Rest of Europe.

Figure 33. General structure of EU28-Rest of the World (RoW) Input-Output Matrix.

Since WIOT does not account for commerce, accounting balances are very simple. Gross Domestic Output (GDP) in each IOT is therefore obtained differently. According to the Input-Output methodology, output for each industry can be derived both from supply and demand side. The former is the addition of all intermediate products purchased by the industry plus the value added. The latter can be obtained by adding both intermediate and final products sold by the industry to the other industries and the institutional sectors of the economy respectively. In a 3 region IOT (3RIOT), it implies adding trade to both of them. For each region, output from the supply side requires including intermediate product imports and, from the demand side, intermediate and final product exports (Eq.7-8).

$$X_j^r = Z_{ij}^{r,r} + Z_{ij}^{\dots,r} + VA_j^r \qquad (7)$$

$$X_i^r = Z_{ij}^{r,r} + Z_{ij}^{r,\dots} + D_i^{r,r} + D_i^{r,\dots} \qquad (8)$$

Thus, considering that $X_j^r = X_i^r$, we can establish that:

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$$Z_{ij}^{r,r} + Z_{ij}^{r,\cdots} + D_{i}^{r,r} + D_{i}^{r,\cdots} = Z_{ij}^{r,r} + Z_{ij}^{\cdots,r} + VA_{j}^{r} \qquad (9)$$

And, therefore, rearranging:

$$VA_{j}^{r} = Z_{ij}^{r,\cdots} + D_{i}^{r,r} + D_{i}^{r,\cdots} - Z_{ij}^{\cdots,r} \qquad (10)$$

Finally, we can calculate GDP using Eq.10. through the production approach ($GDP = \sum VA$[2]). Thus, GDP in a 3RIOT can be obtained as the sum of final products, domestic and external (exports) demand and intermediate products trade balance (exports minus imports). It is worth mentioning that imports of final products are included implicitly in the equation. However, since final products imports are included in the demand made by each country's institutional sector, then they have to be subtracted if GDP wants to be calculated. Thus, both values are cancelled. Therefore, for the sake of simplicity, imports are not required to calculate each region's GDP (see Table 26). Nevertheless, it is worth mentioning that in the 3RIOT, final products imports made by the country ($DOM\ IMP\ FD$ for each region in Figure 33) are equal to the final products exports made by RoW and RoEU regions. Consequently, as described below, they are a crucial variable to derive the output variation after a demand shock in the IOA applied to a 2RIOT.

Table 26. GDP measure in different IOTs by approach Source.

Approach	Supply	Income	Demand
World IOT	$X_j^{rr} - Z_{ij}^{rr}$	VA_j^r	D_i^{rr}
Many-region IOT	$X_j^r - Z_{ij}^{rr} - Z_{ij}^{\cdots,r} - Z_{ij}^{n,r}$	VA_j^r	$Z_{ij}^{r,\cdots} + Z_{ij}^{r,n} + D_i^{r,r} + D_i^{r,\cdots} + D_i^{r,n}$ - $Z_{ij}^{\cdots,r} - Z_{ij}^{n,r}$
3RIOT-MEDEAS	$X_j^{DOM} - DOM_{IC} - IMP_{IC}$	VA_j^{DOM}	$EXP_{IC} + DOM_{FD} + EXP_{FD} - IMP_{IC}$

2.2.2.3.2.1. General framework of trade within input-output table

Including trade in the Input-Output framework requires making some changes in the classic equations. What remains unchanged is the demand-led evolution of the economy. In IOA, regardless of the number of regions involved, a demand shock leads to a response in the output necessary to satisfy it. This response shall be different attending to the economy's structure and

[2] Since Value Added is also the sum of labour compensation (LAB), capital compensation (CAP) and taxes less subsidies on products (TAX), we can also define GDP from the income approach as the VA (see Table 26).

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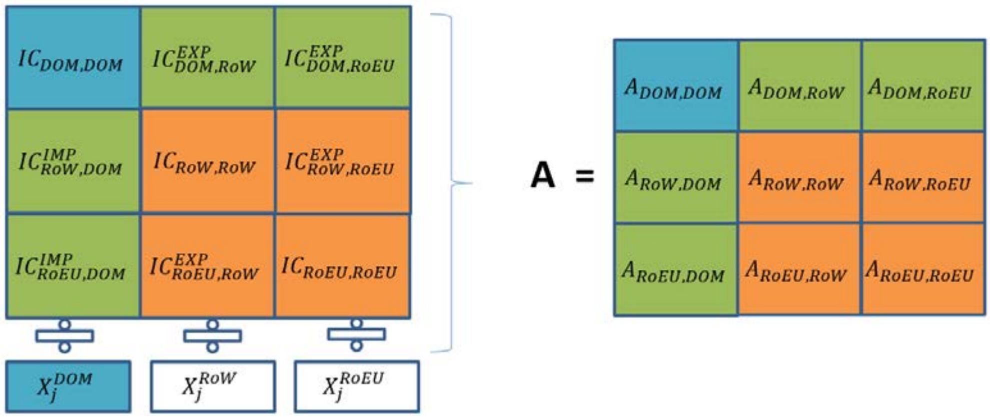
the underlying technological assumption provided by technical coefficients. Technical coefficients measure the amount of inputs (nationally produced or imported) required to produce 1 unit of output. These values are collected in a matrix named A matrix. Meanwhile in a WIOT there is only one technical coefficient's matrix, the number of sub-matrixes increases exponentially with the number of regions included in the multiregional IOA. There is an A matrix for each purchase matrix following this relationship due to the squared shape of IOTs (Eq. 11):

$$N_A = N_r^2 \qquad (11)$$

Being N_A the number of A sub-matrixes and N_r the number of regions. Thus, in a 3RIOT the number of sub-matrixes required is 9, as schematically expressed in Figure 34. Given this definition, technical coefficients must be read in terms of purchases (columns). Hence, the country's technical coefficients are the intermediate products purchases made by the country's industries from the same country's industries (DOM_{IC}) and abroad (IMP_{IC}). The same applies to the RoW and RoEU technical coefficients, because their imports are the country's exports (EXP_{IC}). The dimensions of this squared A matrix with trade are imposed by the number of industries and regions (Eq. 12):

$$D_A = N_r * N_s; \qquad (12)$$

being D_A the dimensions of the A matrix and N_s the number of sectors. In our 3RIOT using WIOD (Dietzenbacher et al., 2013) as explained before, the A matrix is a 70x70 ($D_A = 3 * 35$) matrix encompassing 9 different submatrices.



$\boldsymbol{A_{DOM,DOM}}$: Intermediate inputs produced in the country required for the country's production.
$\boldsymbol{A_{DOM,RoW}}$ *and* $\boldsymbol{A_{DOM,RoEU}}$: Intermediate inputs produced in the country required for the country's exports.
$\boldsymbol{A_{RoW,DOM}}$ *and* $\boldsymbol{A_{RoEU,DOM}}$: Intermediate inputs imported by the country required for the country's production.
$\boldsymbol{A_{...,...}}$: Intermediate inputs produced in each region required for both each and each other region's production.

Figure 34. Schematic framework for A sub-matrices in a 2-region IOT.

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In this way, MEDEAS country-level has 9 A sub-matrixes from whom just are used 5 (apart from Leontief Matrix calculation): one for domestic intermediate consumption without imports ($\boldsymbol{A}_{\boldsymbol{DOM},\boldsymbol{DOM}}$), and 4 of them for the country's imports ($\boldsymbol{A}_{\boldsymbol{RoW},\boldsymbol{DOM}}$ *and* $\boldsymbol{A}_{\boldsymbol{RoEU},\boldsymbol{DOM}}$) and exports ($\boldsymbol{A}_{\boldsymbol{DOM},\boldsymbol{RoW}}$ *and* $\boldsymbol{A}_{\boldsymbol{DOM},\boldsymbol{RoEU}}$:). In this sense, first subscript stands for the region where the product was produced and the second one the region where it was sold to. The rest of them are useful just for estimating Leontief Matrix, which in this version is done outside the model. On the one hand, $\boldsymbol{A}_{\boldsymbol{DOM},\boldsymbol{DOM}}$, $\boldsymbol{A}_{\boldsymbol{RoW},\boldsymbol{DOM}}$ and $\boldsymbol{A}_{\boldsymbol{RoEU},\boldsymbol{DOM}}$ are the inputs intensity required by the country's industries to produce its output, whether they have to purchase their inputs home or abroad. On the other hand, $\boldsymbol{A}_{\boldsymbol{DOM},\boldsymbol{RoW}}$ and $\boldsymbol{A}_{\boldsymbol{DOM},\boldsymbol{RoEU}}$ are the inputs requirements to produce RoW and RoEU output, which they need to purchase in the country (thus, representing the country's intermediate exports). With this in mind, IOA with trade differs from IOA without trade in the number of sub-matrices included in the A matrix. Hence, since trade and economic structure in the other regions matters, obtaining production in each region implies using the interregional sub-matrices as a whole, following the classic IOA equations (13-15):

$$X = Z + D \tag{13}$$

$$A = Z * \hat{x}^{-1} \rightarrow X = AX + D \rightarrow X = (I - A)^{-1} * D \tag{14}$$

$$(I - A)^{-1} = L \rightarrow X = L * D \tag{15}$$

where X is a row vector representing the country's, RoW's and RoEU's production, Z a matrix consisting of the 9 intermediate consumption sub-matrices, and D a column vector with the final demand of each regional product (domestic demand and exports) made by both regions. $\hat{x}^{-1}$ is the inverse diagonal matrix of X, A is the interregional A matrix, I the identity matrix and L the new interregional Leontief Matrix.

As IOA objective is to estimate production in a region, for instance in the country case, it is important to understand that the relevant Final Demand here is the demand of the country's products made by the same country (domestic demand) and by foreign regions (final products exports to RoW and RoEU) agents (Miller and Blair, 2009). This Final Demand is explicitly explained in section 2.2.2.3.1. Therefore, the new interregional Leontief Matrix (L) consists of 9 sub-matrices, analogous to those from the interregional A matrix. Interregional L interpretation differs from that of the one region L. The final step for obtaining production in IOA with trade, requires the interregional L matrix and the vector column formed by each region's final demand, as in Eq. 15 and Figure 35 for the country.

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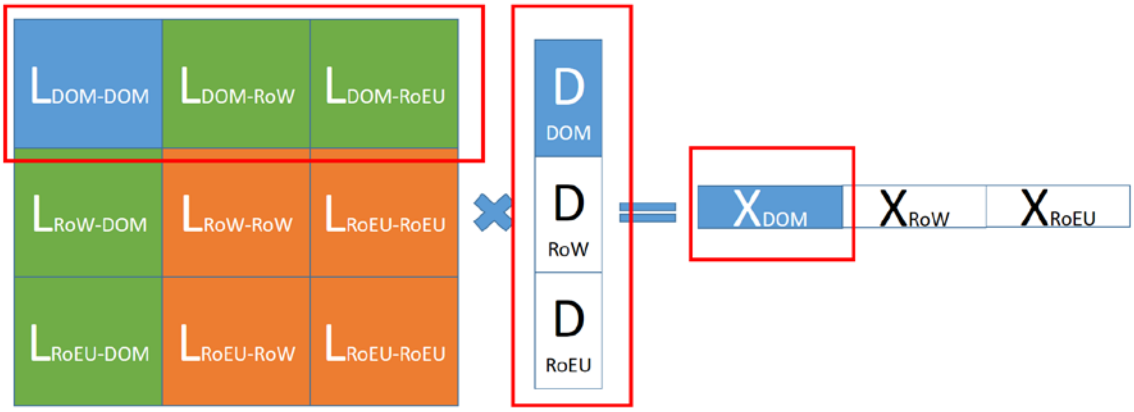

Figure 35. Obtaining EU28 production in the 2-region Input-Output Analysis.

As shown in Figure 35, it only takes three submatrices of the interregional Leontief Matrix, pre-multiplied by the column vector of final demands by region to obtain domestic production. In order to better understand the L matrix interpretation and, therefore, how the IOA with trade works in MEDEAS country-level, we can follow a simplified example with 3 sectors, 3 regions and aggregated final demand (including all institutional sectors and exports). First, we have the complete IOT with its economic flows (Figure 36) and then, the interregional A matrix (Figure 37) is obtained by dividing each submatrix by its industry output (by columns).

		COUN			RoEU			RoW					
		1	2	3	1	2	3	1	2	3	FD		X
COUN	1	15	9	4	8	3	1	3	2	2	51	EU	98
	2	5	12	9	1	9	2	4	3	1	60		106
	3	1	4	7	1	2	10	5	6	3	45		84
RoW	1	6	2	2	120	100	53	3	2	1	135	ROW	424
	2	5	10	1	25	60	52	2	2	3	288		448
	3	3	6	11	12	27	45	4	1	1	230		340
RoEU	1	8	1	1	6	5	3	160	120	70	212	RoEU	586
	2	3	9	2	2	10	6	40	85	76	350		583
	3	1	2	10	2	1	11	21	37	63	280		428
	VA	51	51	37	247	231	157	344	325	208			
	X	98	106	84	424	448	340	586	583	428			

Domestic transactions
Foreign transactions
Transactions between other regions

Figure 36. Input-Output Table (many region example).

Both the A-Matrix and the Leontief Matrix have the same dimensions (9x9) and number of sub-matrixes (9) following Eqs. 11-12. According to this example, producing 1 unit of sector 1's output of the country would take 0.1531 units of input from domestic sector 1, 0.0612 units of imported (from Row) sector 1 intermediate products and 0.0816 units of imported (from RoEU) sector 1 intermediate products. Likewise, RoW's sector 1 requires 0.0189 units of input imported from our

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country in order to produce 1 unit of its output. In the case of RoEU, the figure would be 0.0051. Therefore, the other regions' structure determines the country's exports and thus, the country production (and vice versa). This is the reason why we need external economic structure and demand to estimate the country's production.

		DOMESTIC			RoW			RoEU		
	Sectors	1	2	3	1	2	3	1	2	3
DOM	1	0.1531	0.0849	0.0476	0.0189	0.0067	0.0029	0.0051	0.0034	0.0047
	2	0.0510	0.1132	0.1071	0.0024	0.0201	0.0059	0.0068	0.0051	0.0023
	3	0.0102	0.0377	0.0833	0.0024	0.0045	0.0294	0.0085	0.0103	0.0070
RoW	1	0.0612	0.0189	0.0238	0.2830	0.2232	0.1559	0.0051	0.0034	0.0023
	2	0.0510	0.0943	0.0119	0.0590	0.1339	0.1529	0.0034	0.0034	0.0070
	3	0.0306	0.0566	0.1310	0.0283	0.0603	0.1324	0.0068	0.0017	0.0023
RoEU	1	0.0816	0.0094	0.0119	0.0142	0.0112	0.0088	0.2730	0.2058	0.1636
	2	0.0306	0.0849	0.0238	0.0047	0.0223	0.0176	0.0683	0.1458	0.1776
	3	0.0102	0.0189	0.1190	0.0047	0.0022	0.0324	0.0358	0.0635	0.1472

Figure 37. A matrix (2-region example)

Finally, the Leontief matrix (Figure 38) provides a measure of the production sensitivity to final demand changes, both domestic and external (exports). For instance, in this example, the country's sector 1's production increases 1.1956 for one additional unit of final demand for their products and 0.1523 of imported units from the same sector. Similarly, if RoW's final demand is increased in one unit, exports made by the country to RoW grows by 0.0352 and 1.4465 inside the RoW region.

		DOMESTIC			RoW			RoEU		
	Sectors	1	2	3	1	2	3	1	2	3
DOM	1	1.1956	0.1239	0.0826	0.0352	0.0234	0.0190	0.0127	0.0108	0.0126
	2	0.0765	1.1479	0.1438	0.0103	0.0327	0.0214	0.0152	0.0137	0.0109
	3	0.0221	0.0559	1.1080	0.0077	0.0129	0.0429	0.0168	0.0193	0.0169
RoW	1	0.1523	0.1168	0.1156	1.4465	0.4015	0.3371	0.0213	0.0173	0.0180
	2	0.1020	0.1607	0.0795	0.1125	1.2057	0.2379	0.0139	0.0128	0.0179
	3	0.0642	0.1038	0.1903	0.0585	0.1023	1.1893	0.0174	0.0113	0.0121
RoEU	1	0.1707	0.0891	0.1037	0.0444	0.0483	0.0566	1.4326	0.3746	0.3554
	2	0.0769	0.1455	0.1002	0.0214	0.0478	0.0538	0.1331	1.2266	0.2832
	3	0.0355	0.0543	0.1787	0.0157	0.0177	0.0607	0.0738	0.1107	1.2120

Figure 38. Leontief matrix (2-region example).

Hence, IOA with trade not only shows the direct and indirect effects on production due to final demand and other industries' requirements (economic structure), but also the direct and indirect effects due to other regions' final demand and economic structure. So, the IOA with trade shows that in an interrelated global economy, production in one region depends not only on domestic demand but also on foreign demand. Moreover, it shows that the products that one region demands from the rest of the world have to be produced according to their economic structure, which is rather different from domestic one. Particularly, this characteristic allows estimating the energy footprint of trade, as explained below.

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2.2.2.3.2.2. Input-output analysis with trade in MEDEAS country-level models

The analytical framework described before has to be translated into system dynamics language. The simplified influences diagram for IOA with trade in MEDEAS-Country is shown in Figure 39.

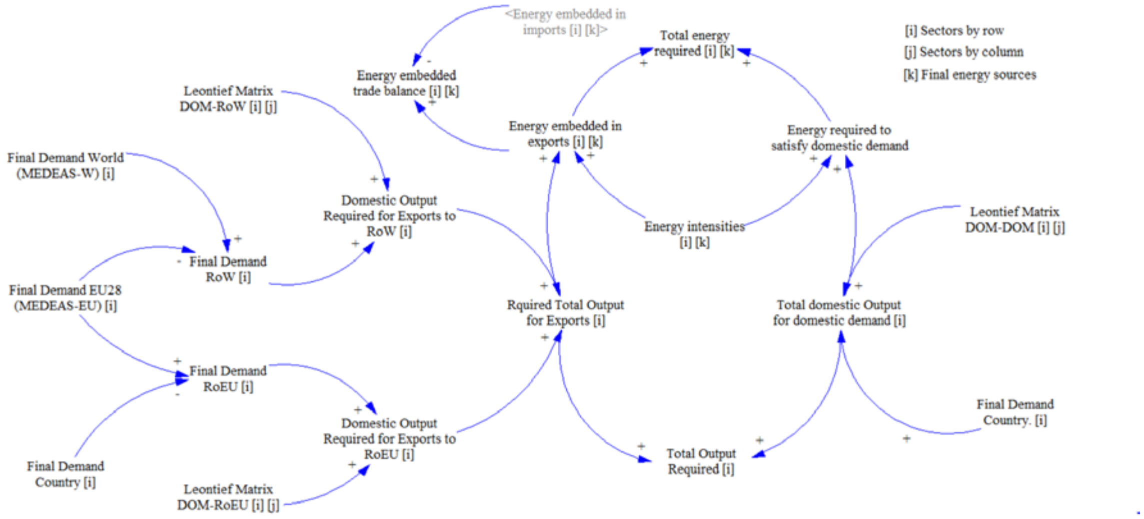

Figure 39. Simplified influences diagram for Input-Output Analysis in MEDEAS country-level models.

Final demand changes exogenously according to the IPCC SSPs (IPCC, 2013) and this variation is distributed amongst sectors in accordance with the final demand function described in section 2.2.2.3.1. Production in each region is committed to satisfy domestic and foreign, both intermediate and final demand, that is, domestic intermediate and final consumption and intermediate and final products exports. So, the country's production depends on domestic and foreign final demand of the country's products and its production sensitivity to changes in them ($L_{DOM,DOM}$). Moreover, we know that final demand of foreign regions' products is satisfied by the foreign regions' production which, in turn, requires to import intermediate inputs from the country (i.e. intermediate exports defined by $IC^{EXP}_{DOM,RoW}$ and $IC^{EXP}_{DOM,RoEU}$ in Fig. 33). Thus, the the country's production is also affected by the final demand of RoW and RoEU products and the RoW's and RoEU's production sensitivity to the country's intermediate demand of imports ($\boldsymbol{L_{DOM,RoW}}$ and $\boldsymbol{L_{DOM,RoEU}}$). The result of the addition of both direct and indirect effects (see Eq.16 and Fig.39) is the production in the country.

$$X^{DOM} = FD^{DOM} * L_{DOM.DOM} + FD^{RoW} * L_{DOM.RoW} + FD^{RoW} * L_{DOM.RoEU} \tag{16}$$

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As can be noticed in Fig.39, RoW and RoEU's final demand are obtained drawing MEDEAS_w and MEDEAS-Europe's results. Thus, RoW's (rest of the world other than Europe) final demand is the difference between World's final demand and Europe's; whilst RoEU's final demand is obtained as the difference between Europe final demand and the country's (with a functional slight lag in order to adjust it dynamically in the same period t). In this way, MEDEAS country-level economy module is nested into the MEDEAS_w and MEDEAS-Europe's models. The first and second terms in Eq.16 are calculated separately, providing the model with the 'Total domestic output for domestic demand' and the 'Total domestic demand for exports', both of them, sectorally disaggregated. Once aggregated, the country's production is collected in variable 'Total output required'. Then, the model continues with the energy-economy feedback, as explained in the following section. Basically, production and demand are forced to adapt to final energy availability, since in MEDEAS the economic system is subject to biophysical constraints. Hence, if energy scarcity appears, production has to be shorten throughout the process explained in section 2.2.2.3.4. Once this adaption is completed (if that is the case) the final demand satisfied by this reduced production has to be necessarily lower. In order to respect the economic structure given by the A Matrix, an inverse process to that showed in Eqs.7-9 has to be followed. In essence, Eq. 13 must be solved for final demand (D) and not for production (X), resulting in Eq.17:

$$D = (I - A) * X \qquad (17)$$

$(I - A)$ matrix follows the same rules as the L and A Matrices for its size and number of sub-matrixes (see Eqs.11-12). By pre-multiplying $(I - A)$ by the column vector of new productions (both the country and RoW and RoEU), the column vector of final demand is obtained.

Once the feasible or 'real final demand' is estimated, we translate this variable into GDP, by adding intermediate exports ($IC_{DOM,RoW}^{EXP}$ and $IC_{DOM,RoEU}^{EXP}$) and subtracting intermediate imports ($IC_{RoW,DOM}^{IMP}$ and $IC_{RoEU,DOM}^{IMP}$) following Eq.4. These figures are calculated multiplying both the country and foreign productions (X_j^{DOM}, X_j^{RoEU} and X_j^{RoW}) by $\boldsymbol{A_{DOM,RoW}}$ and $\boldsymbol{A_{DOM,RoEU}}$ (for intermediate exports) and by $\boldsymbol{A}_{RoW,DOM}$ and $\boldsymbol{A_{RoEU,DOM}}$ (for intermediate imports). We know that the country's total imports (both intermediate and final) are produced in RoW and RoEU, and that all of the country's exports are produced inside its borders. Given that, by multiplying RoW and RoEU energy intensities on the one hand, and the country's on the other hand, by imports and exports respectively, MEDEAS-Country is able to estimate the energy embedded both in imports and exports. Finally, by subtracting energy embedded in imports from energy embedded in exports, the model estimates the energy balance of trade or the energy trade footprint of the country. After that, the EU28 energy footprint can be estimated.

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2.2.2.3.3. Income

Previous section has established the definitions for GDP in an economy with external sector. While at the world level this definition is right: GDP=∑VA=FD; at interregional level, one chain is not: GDP=∑VA≠FD. That implies that exogenous GDPpc growth scenarios are no longer valid to directly initiate the economy module. Since GDP is now defined (demand approach) as in Eq. 10, the only difference with GDP at the world level is the inclusion, in addition to total final demand, of the trade balance for intermediate products. For the sake of simplicity and, after observing that both final demand and value-added growth are highly correlated, it has been assumed that GDP growth is the same as final demand growth rate. Figure 40 shows that the differences between both variables are slight, according to the data from WIOD (Dietzenbacher et al., 2013).

a)

b)

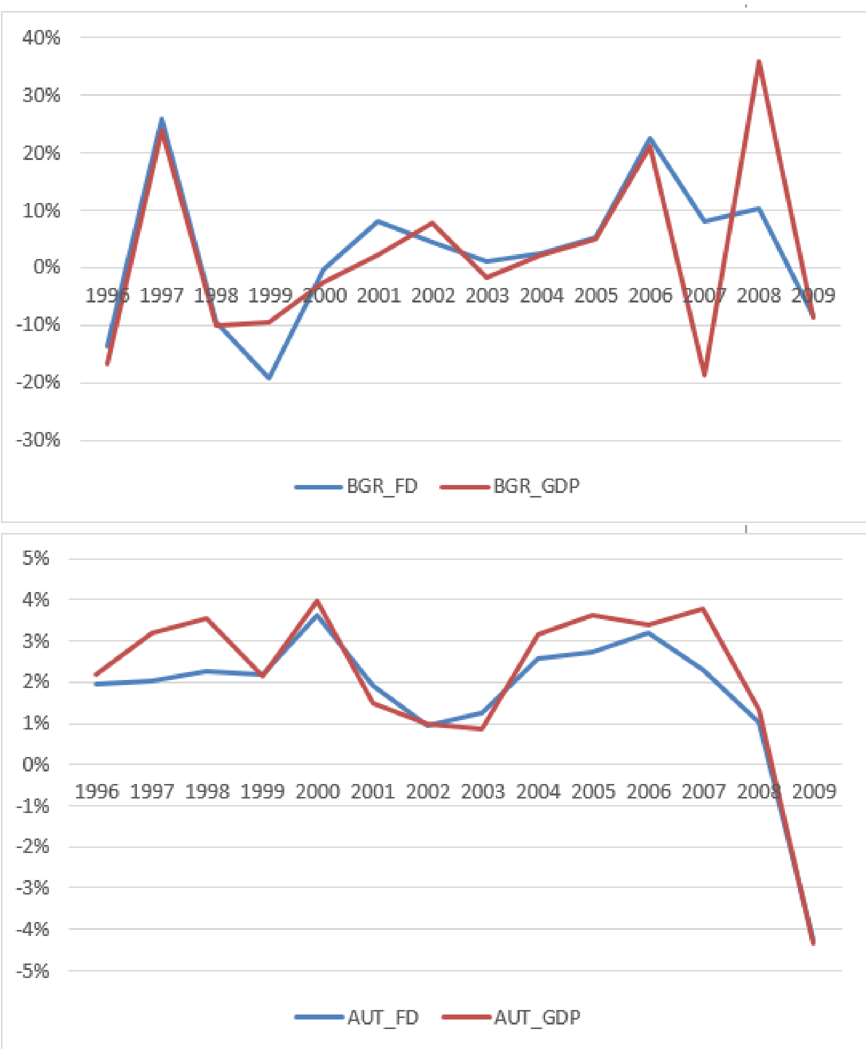

Figure 40. Final demand and value added (GDP) growth for (a) Bulgaria (BGR) and (b) Austria (AUT) (1996-2009).

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While at the world level it was assumed that gross value added was at cost factor –including taxes less subsidies on production-, here it is disaggregated. Income shares have been estimated using Eurostat data. This made possible not only to obtain labour and capital shares, but also the GDP share on production taxes. Taking gross domestic product (income approach) for Bulgaria and Austria (BGR and AUT) labour compensation (LAB), capital compensation, gross operating surplus, mixed income (CAP) and net taxes on production (TAX) can be used to estimate functional distribution for the period, as in Figure 41.

a)

b)

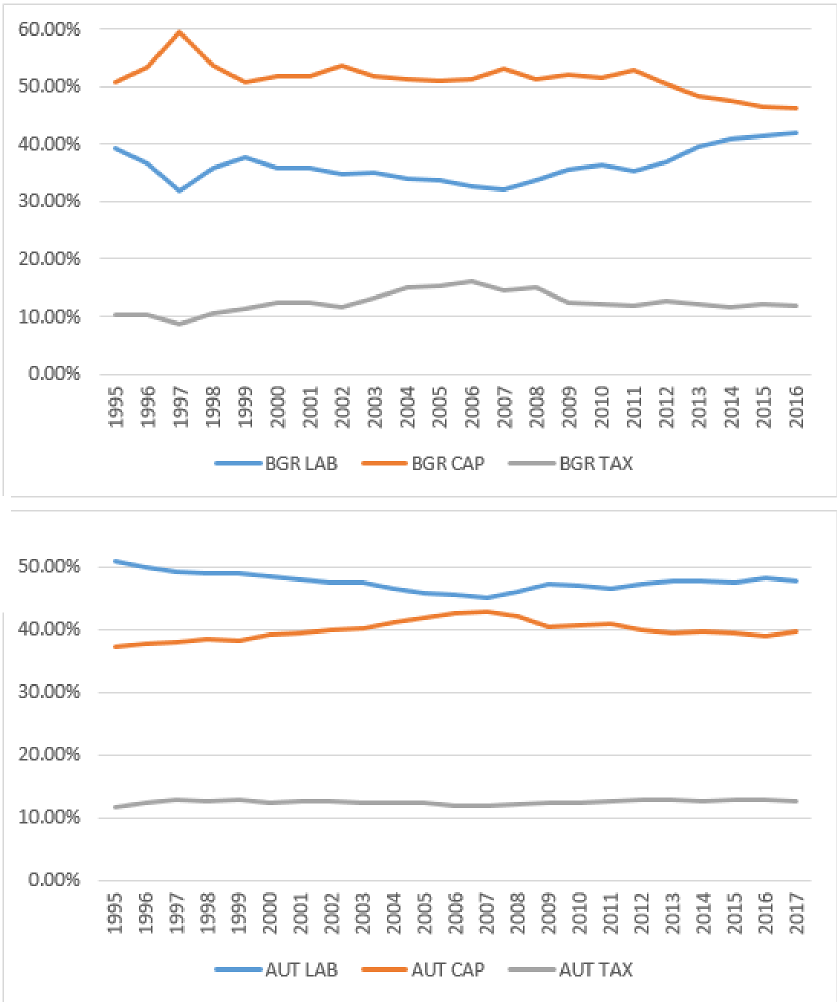

Figure 41. Source: OECD. Functional income distribution in (a) Bulgaria (BGR) and (b) Austria (AUT) (1995-2015).

Given that now TAX is included, we cannot assume that α_{cap}=1-α_{lab}. Because of this, scenarios after 2015 must be estimated for both labour and capital shares.

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2.2.2.3.4. Energy-economy feedback

Most energy-economy-environment models consider economic growth to be independent from biophysical limits. In the MEDEAS framework, economy cannot trespass the boundaries set by nature. The Economy module is subject, at least, to an indirect and a direct feedback from the whole system. The indirect feedback is provided by the impacts of the emissions. As the direct feedback for the economy module comes from the energy module, it is worth to focus here in this relationship, a key point of the model.

Once the production required to satisfy demand by sector is calculated as described in previous sections, the final energy required to satisfy demand is obtained by the Eqs. 18-19.

$$\hat{\mathrm{I}}_e = \hat{\mathrm{E}}\hat{x}^{-1} = \begin{pmatrix} \frac{E_{ij}}{x_i} & 0 \\ 0 & \frac{E_{nn}}{x_n} \end{pmatrix} = \begin{pmatrix} I_{e,ij} & 0 \\ 0 & I_{e,nn} \end{pmatrix}, \qquad \mathrm{i} \in 1 \ldots 35; \mathrm{j} \in 1 \ldots 5 \tag{18}$$

$$E = \hat{\mathrm{I}}_e x = \hat{\mathrm{I}}_e \, * L \, * D \tag{19}$$

Let ê be the diagonal matrix of energy coefficients and Ê the diagonal matrix of total final energy demand (FED) by industrial sector (i) and final energy source (j). The energy coefficients stand for the energy intensities by sector and final energy source. World final energy consumption (FEC) by sector and energy source is collected from WIOD environmental accounts (Genty et al., 2012) and balanced with the International Energy Agency accounts. By pre-multiplying production by the energy coefficients (intensities), the model estimates the final energy required to satisfy demand. At this point, the energy demand of the economic system has to be compared with the energy available to supply it. Thus, FED required satisfying economy demand by sector and final energy source is compared with the final energy supply (FES) by source (Figure 42).

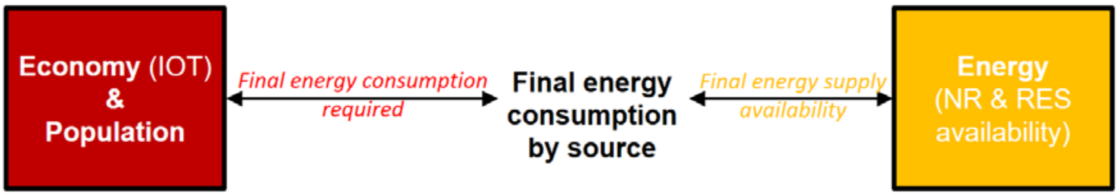

Figure 42. Energy-Economy feedback in MEDEAS.

Then, scarcity on one source can force the industrial sectors relying on this source to demand substitutive final energy types in the proportion established by the supply-demand gap. A shortage coefficient for each final energy source is calculated as a ratio between the FES and FED. In this

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model version, we consider that the scarcest final energy source is the one that conditions the sectorial production process, following the approach of "limitant factor" applied in (Capellán-Pérez et al., 2015; de Castro, 2009). This shortage coefficient equals 1 when final energy consumption (FEC) satisfies demand, i.e. there is no supply restriction. In the case that energy demand is higher than energy supply, energy consumption matches the energy supply and the shortage coefficient is lower than 1, reducing the proportion of energy demanded which is actually consumed by each sector.

For each time period (Eqs. 20-23):

$$shortage\ coefficient_j = \frac{FES_j}{FED_j} \qquad (20)$$

$$\text{If shortage coefficientj} \begin{cases} = 1\text{: no energy constraints} \\ <1\text{: energy constraints of fuel j} \end{cases}$$

$$ShC = MIN(shortage\ coefficient_j) \qquad (22)$$

$$FEC_{i,j} = ShC \cdot FED_{i,j} \qquad (23)$$

Subscript i stands for the usual 35 industrial sectors plus household's final energy consumption and subscript j for the different final energy sources considered in MEDEAS. Finally, the energy limits transfer to the economy throughout an inverse Input-Output Analysis (IOA). Taking the inverse of energy intensity ($\hat{I}_e{}^{-1}{}_{ij}$) and the final energy actually consumed (E'_{ij}), feasible production is obtained (X'_i). Then, a set of feasible productions according to each final energy source is collected (Eqs. 24-25). The model is programmed to choose the minimum feasible production, as the scarcest final energy source is what limits the most, being consistent with the complementarity approach above mentioned.

$$\hat{I}_e{}^{-1}{}_{ij} * E'_{ij} = X'_i \qquad (24)$$

$$X' = Min\ (X'_i) \qquad (25)$$

Finally, the inverse process followed (from FD to X) takes places (from X' to FD') as described in the following equations (Eqs. 26-27):

$$X' = AX + FD' \qquad (26)$$

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$$FD' = X(I - A) \tag{27}$$

In the model, this feedback is present not only at this level, but also for all relevant variables, which include 'not covered' as an addendum. For each variable included, the not-covered variables quantify the gap between the value of that variable with and without the feedback. Hence, when the energy demand is lower than the energy supply, not-covered variables equal 0. Contrarily, when there is energy scarcity, not-covered variables need to gather the quantities that should not be added in the subsequent periods. If they were not included, the feedback would only apply in the year when it appears, not responding dynamically in later years.

In the current version of MEDEAS, economy module is feedbacked by the energy availability (as well as indirectly by climate change impacts and EROI), obtaining a more realistic approach in the energy-economy-environment modelling. Without feedback between energy and economy, energy demand shall grow exogenously not taking into consideration availability of resources (Capellán-Pérez et al., 2016; Höök and Tang, 2013; Wang et al., 2017). The underlying assumption here is that this availability of resources matters, and that the functioning of the real economy depends on it. Thus, these models tend to look for an optimum energy mix regardless its supply availability –even though they usually take into consideration efficiency gains. Conversely, the energy-economy feedback provides a result that is not often taken into consideration in other IAMs.

As highlighted before, economic structure matters in MEDEAS. Each industrial sector has a different sensitiveness to final energy consumption by source. These are collected in the Appendix and, in Interregional Input-Output, for domestic production oriented to satisfy domestic demand are calculated in the model as $\hat{\mathrm{I}}_{ek}\, L_{DOM,DOM}$: diagonal matrix of energy intensities by sources 'k' times Leontief Matrix (upper-left quadrant). This represents the amount of final energy required to satisfy changes in final demand in monetary terms.

Finally, it is worth making a brief comment on the evolution of energy intensities, described in detail in section 2.2.2.4. The historical data observed shows that even though sectoral energy intensities are slightly declining, they have remained more or less stable over time. However, different changes may occur due to energy efficiency gains and change of energy technology in a sector. For the moment, energy intensities evolve following their trends but further developments could estimate the parameters to introduce the mentioned dynamics.

In MEDEAS_w there is no trade, since all the energy consumed was produced at the same regional level. Thus, net energy final consumption could not trespass the biophysical boundary imposed by energy availability in the same region (the entire world). However, for the MEDEAS-Country model

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it is not that simple. Boundaries can be artificially trespassed thanks to international trade, i.e. the country is able to consume more energy than it produces. Actually, this is the current situation for each country and one of the main vulnerabilities in the context of global energy depletion. In this sense, different scenarios could be assumed: no limits in imports, constant imports share, imports driven by global average values, etc. (see Table 27). However, in the model version, for the sake of simplicity no limits to European trade are modelled.

Table 27. Energy-economy feedback under different imports scenarios.

Scenarios	Features
No limits	The country can import energy limitless.
Current shares	The country can import energy at current level share.
Fixed share	The country can import energy with a fixed level.
World scarcity->The country scarcity	MEDEAS_w scenarios impose scarcity to the countries.

Source: own elaboration.

In the 'No limits' scenario, there is no restriction for the country. Thus, the country is allowed to import as much energy as it needs to consume, even if that means consuming 100% of the world's energy for each type.

Regarding exports' regression (EXP_{it}), depicted in the Appendix, real exchange rates suffers from similar issues than interest rates. Although negative, its low value can be more than offset by positive sectoral intercepts in some industries (with everything else constant). In some sectors, inelasticity of exports products could even lead to a positive effect of exchange rates. In addition, even though the model is jointly significant, real exchange rate is not individually significant. The most determinant explanatory variable is global GDP.

2.2.2.4. Modelling of final energy intensities

In the world model, a method for calculating the final energy demanded to avoid double counting was developed. In the European model, due to the available data and trade exchanges, this method cannot be used. Therefore, in the case of Austria and Bulgaria, we will calculate the energy consumption by final source, as it is explained below.

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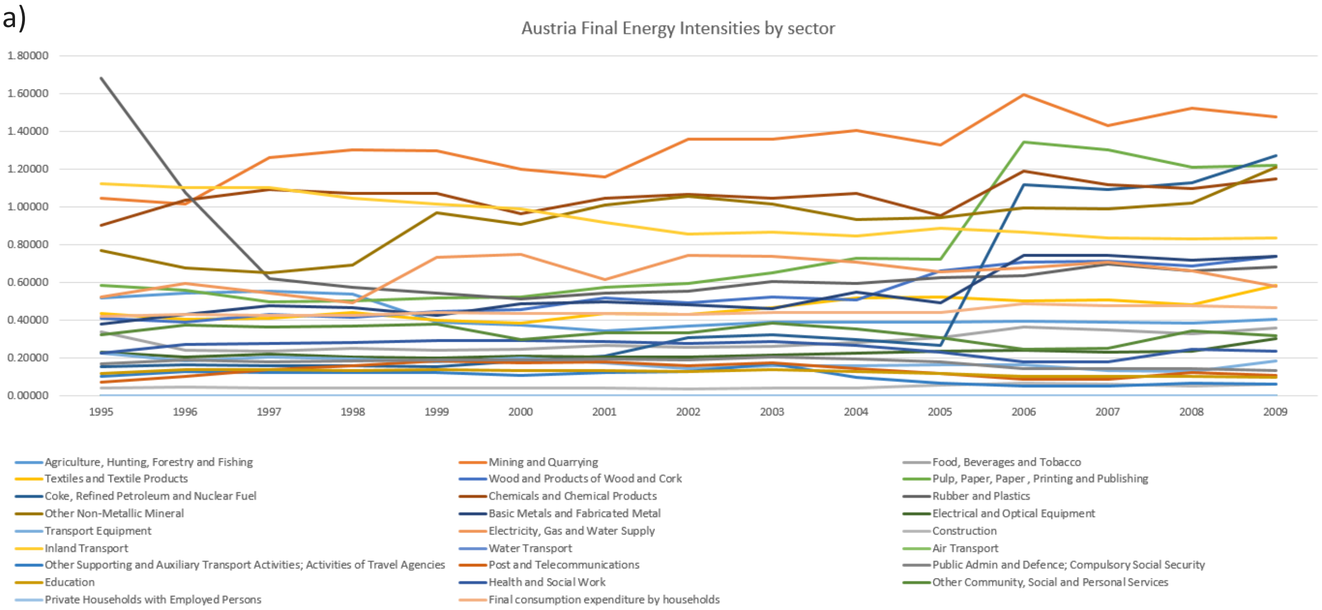
a)



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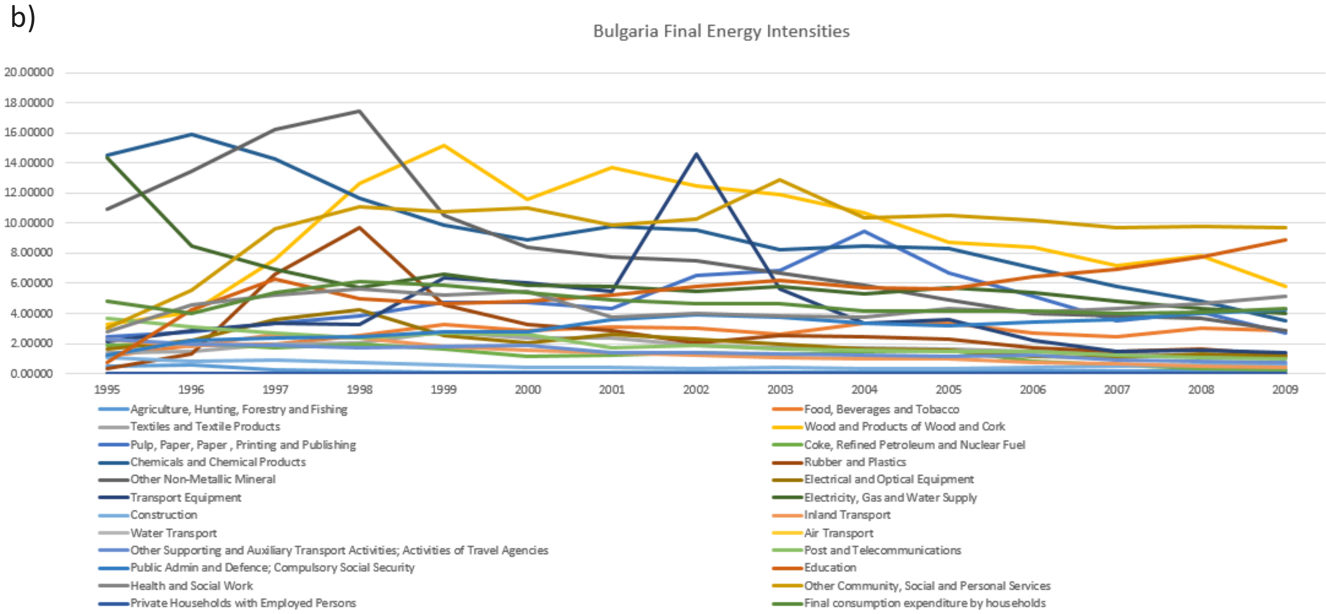

Figure 43. Historical evolution of electricity intensity by sector in (a) Austria and (b) Bulgaria.

1. First, we need to compare the data calculated for the world (without double counting) for liquids, gases and solids with the original data taken from WIOD.
2. Through this sectoral and annual comparison of both values, we calculate a percentage that represents the variation.
3. The next step will be to calculate the average percentage for each sector over time.

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4. Once we have these percentages calculated, we apply them to each sector for liquids, solids and gases, and so we calculate the energies in final source for the European Union without double counting.

After calculating the energy consumption for liquids, gases, solids, heat and electricity for each country, we calculate the energy intensities following the same methodology as we did for the world, taking into account the data calculated previously. The following figure shows an example of final energy intensities in some sectors for electricity in (a) Austria and (b) Bulgaria (Figure 43).

2.2.3. Energy and infrastructures module

This part of the deliverable documents the estimation of energy demand (section 2.2.3.1), the energy supply (section 2.2.3.2), and the energy resources availability in MEDEAS country-level models (non-renewable resources in section 2.2.3.3 and renewable-resources in section 2.2.3.4). Primary energy in the model refers to the direct equivalent method.[3]

In relation to the alternative energy technologies considered in the European model, we consider the same two main criteria as in the global model: (1) focus on those technologies currently available, demonstrated and commercial; and (2) assure that the net energy balance of the considered technologies is positive (see Deliverable 4.1 for more information).

2.2.3.1. Estimation of energy demands

Methodology used for the estimation of energy demands in the MEDEAS country-level models is similar to the one employed for estimations in the MEDEAS_w and MEDEAS-Europe models. Here, we include just a summary of main aspects. Deliverable 4.1. and 4.2. contain more detailed information.

2.2.3.1.1. Historic final demand

The WIOD database at the European level is the main source used to estimate the historic final energy data by fuel in order to match with the economic structure of the country-level models.

[3] There are three alternative methods predominantly used to report primary energy. While the accounting of combustible sources, including all the fossil energy forms and biomass, is unambiguous and identical across the different methods, they feature different conventions on how to calculate primary energy supplied by non-combustible energy sources, i.e., nuclear energy and all renewable energy sources, except biomass. The direct equivalent method counts one unit of secondary energy provided from non-combustible sources as one unit of primary energy, that is, 1 kWh of (useful) electricity or heat is accounted for as 1 kWh = 3.6 MJ of primary energy. For more information see Annex II of (IPCC, 2011).

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MEDEAS-Austria and MEDEAS-Bulgaria aggregate the final energy sources in five categories: solids, liquids, gases, heat and electricity. The aggregation is performed using the WIOD database sources (Dietzenbacher et al., 2013; Timmer et al., 2012), which ultimately was built from the IEA database (IEA, 2016).

For the estimation of the 5 MEDEAS country-level categories of final fuels, the energy variable "Energy use, emission relevant" from WIOD energy data has been used with corrections, i.e., subtraction of energy associated to electricity/heat generation in order to avoid double counting.

2.2.3.1.2. Adjustment of energy demands to account for all non-commercial heat

In Deliverable 4.1 (section 2.3.1.3), the need for adjusting the demands of fuels to account for all non-commercial heat was justified in order to promote policies of substitution of non-renewable fuels by renewables sources in the heat sector.

The approach of MEDEAS_eu and MEDEAS country-level consisted on applying the global and static results from (IEA, 2014) which concluded that for the year 2011:

- More than 40% of primary energy supply of natural gas is used for heat production in industry and buildings.
- Around 20% each of world primary supply of coal and oil are also used for heating.
- Out of the 54 EJ of primary bioenergy supply in 2011, more than 80% were used for heat production in buildings, and a smaller amount (15% of the total) was used in industry.

A sectorial approach was thus not possible given the lack of available data. Thus, the total final energy demands for heat, solids, gas and liquids were modified accordingly assuming that the share of non-commercial heat in relation to the TPES of each source is maintained constant in the future (although this parameter can be modified by the user).

2.2.3.2. Energy supply in MEDEAS country-level models

In MEDEAS country-level primary total energy demand is covered with different primary energy sources (see Table 28).

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Table 28. Sources of energy supply in MEDEAS country-level models.

MEDEAS final energy category	NRE / RES	Energy source modelled in MEDEAS
Solids	NRE	Coal
		Peat
		Charcoal
		Waste
	RES	Primary solid biofuels (modern)
		Primary solid biofuels (traditional biomass)
Liquids	NRE	Conventional oil
		Unconventional oil
	RES	Biofuels (different generations and technologies)
Gases	NRE	Conventional gas
		Unconventional gas
	RES	Biogas
Electricity	NRE	Natural gas
		Oil
		Coal
		Uranium
	RES	Hydro
		Geothermal
		Solid bioenergy
		Oceanic
		Wind onshore
		Wind offshore
		Solar PV
		Solar CSP
Heat	NRE	Coal
		Natural gas
		Oil
		Waste
	RES	Geothermal
		Solar

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		Solid biomass
		Biogas

Natural gas refers to both conventional and unconventional. Oil refers to both conventional and unconventional.

Although in practical terms heat can be demanded at different temperature levels (IEA, 2014),[4] for the sake of simplicity, in this model version all heat demand and supply is aggregated.

2.2.3.3. Non-renewable energy resources availability

MEDEAS country-level considers the following non-renewable primary energy resources:

- Conventional oil: refers to crude oil and NGLs.
- Unconventional oil: includes heavy and extra-heavy oil, natural bitumen (oil sand and tar sands) and oil shales, and biofuels.
- Conventional gas.
- Unconventional gas: includes shale gas, tight gas, coal-bed methane (CBM) and hydrates.
- Coal: includes anthracite, bituminous, sub-bituminous, black, brown and lignite coal.
- Uranium.

As explained with more detail in the section 2.8 of deliverable 4.1. and section 2.3.3 of deliverable 4.2., we assume that the technologies which claim that they could increase the fissile material by 50 to 100 times, like fast breeders and the so-called fourth generation reactors, will not be available in the next decades. Nuclear fusion is not considered since the ITER and DEMO projects estimate that the first commercial fusion power will not be available before 2040 (http://www.iter.org). This would prevent this technology from substantially contributing to the energy mix in the timeline of MEDEAS.

[4] Heat-temperature ranges are typically defined as low (<100 degrees Celsius [°C]), medium (100°C to 400°C) and high (>400°C). Temperature levels are important to define the suitability of different supply technologies to meet specific heat requirements in the various end-use sectors (IEA, 2014).

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2.2.3.3.1. Modelling of primary non-renewable energy resources in MEDEAS country-level models

The availability of non-renewable energy resources in MEDEAS country-level models depends on two constraints:

- Stock (available resource in the ground), i.e., energy (Joules),
- Flow (extraction rate of this resource), i.e., power = energy/time (Watts).

Figure 44. illustrates the depletion over time of a non-renewable resource stock (cumulative extraction, grey dashed line) through flows (depletion curve, black solid line) in the absence of non-geologic restrictions (Kerschner and Capellán-Pérez, 2017). The maximum flow rate is reached much earlier than the full depletion of the stock, at half the time assuming that the extraction rate follows a logistic curve.

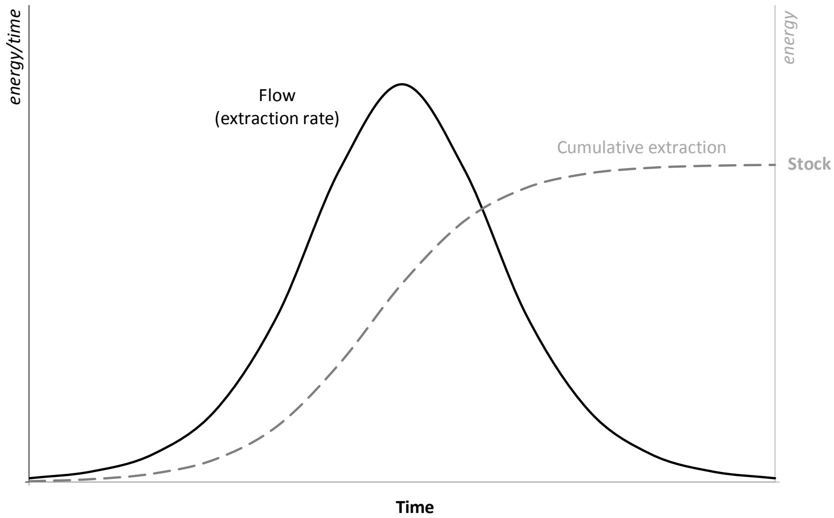

Figure 44. Simplified representation of the depletion of a non-renewable resource in the absence of non-geologic constraints. Stocks and flows of energy relative to time.

The available stock of a resource is usually measured in terms of ultimately recoverable resources (URR), or remaining RURR (RURR) if referenced to a given year. The RURR in a given time t is defined as the difference between the URR and cumulative extraction in time t (Eq. 28).

$$RURR_t = URR - cumulative\_extraction_t \tag{28}$$

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In order to estimate the future availability of fossil fuels, we have reviewed the studies providing depletion curves for non-renewable energy resources taking into account both stocks and flow limits. These studies provide depletion curves as a function of time based by estimating the likely extraction rate of wells and mines. Although at global level there are many studies(e.g. (Aleklett et al., 2010; ASPO, 2009; EWG, 2013, 2008, 2007, 2006; Höök et al., 2010; Laherrère, 2010, 2006; Maggio and Cacciola, 2012; Mohr, 2012; Mohr et al., 2015; Mohr and Evans, 2011, 2009; Patzek and Croft, 2010; Zittel, 2012)), analyses focusing specifically on EU countries are scarce. For this reason, in the standard version of the MEDEAS country-level models the three cases from Mohr et al 2015 were built from the original dataset for Austria and Bulgaria. However, any user can introduce any other curve and run a simulation. These curves should not be interpreted as projections of the extraction of a given fuel, but instead they represent curves of maximum possible extraction given the geological constraints (i.e., assuming no demand or investment constraints).

The depletion curves of non-renewable energies reviewed in the literature represent extraction levels compatible with geological constraints as a function of time. Thus, to be incorporated as inputs in the model, these depletion curves must be transformed, since demand is endogenously modelled for each resource. We assume that, while the maximum extraction rate (as given by the depletion curve) is not reached, the extraction of each resource matches the demand. Actual extraction will therefore be the minimum between the demand and the maximum extraction rate (Figure 45. 45a). To do this, the depletion curves have been converted into maximum production curves as a function of remaining resources (Mediavilla et al., 2013). In these curves, as long as the remaining resources are large, extraction is only constrained by the maximum extraction level. However, with cumulated extraction, there is a level of remaining resources that makes physical limits binding and maximum extraction rates are gradually reduced. The model uses a stock of resources (the RURR) and it studies how this stock is depleted depending on production, which is in turn determined by demand and maximum extraction (Figure 45. 45b).

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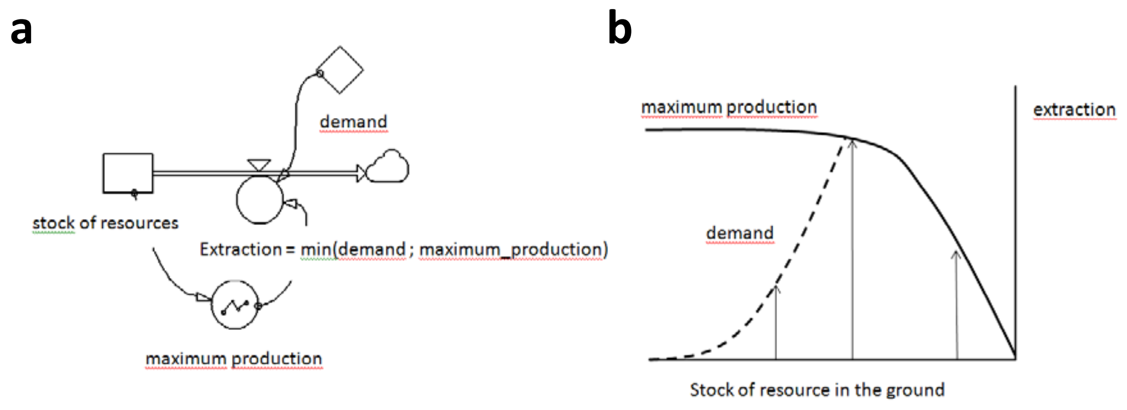

Figure 45. Integration of depletion curves in the model. (a) SD model. (b) A curve of maximum extraction (solid) compared with the demand (dashed).

Each study follows its own assumptions to derive the depletion curves of each fuel, and these should be carefully assessed before applying a depletion curve in the model by the users. The following subsections review the depletion curves of non-renewable energy resources by fuel found in the literature together with a brief discussion: coal, oil, and natural gas. MEDEAS allows selecting a diversity of depletion curves for each fuel (as well as considering a customized one or assuming the unconstrained extraction of the fuel).

The maximum extraction curve does not allow capturing the flow constraints when the peak rate of a fuel has not been reached. For this reason, unconventional oil & gas extraction is subject to an additional constraint that limits the maximum annual growth extraction rate to avoid unrealistic growth extraction rates (see section 2.2.3.3.2).

2.2.3.3.2. Depletion curves by fuel

Studies elaborating depletion curves of non-renewable energy resources focusing on the EU countries are scarce in the literature. MEDEAS country-level models incorporate the 3 availability cases (Low, BG and High) considered by (Mohr et al., 2015), reporting data at country level.

Historic data for the different energy sources are from Mohr et al., (2015). High, BG and Low correspond to the country case and do not necessarily correspond with the global scenarios as named in Mohr et al., (2015)

Coal

Coal production during the 20th century peaked to over 0.057 EJ/yr in the late 1950s for Austria and 0.35 EJ/yr in the late 1980s for Bulgaria. Then, the coal production for Austria has declined

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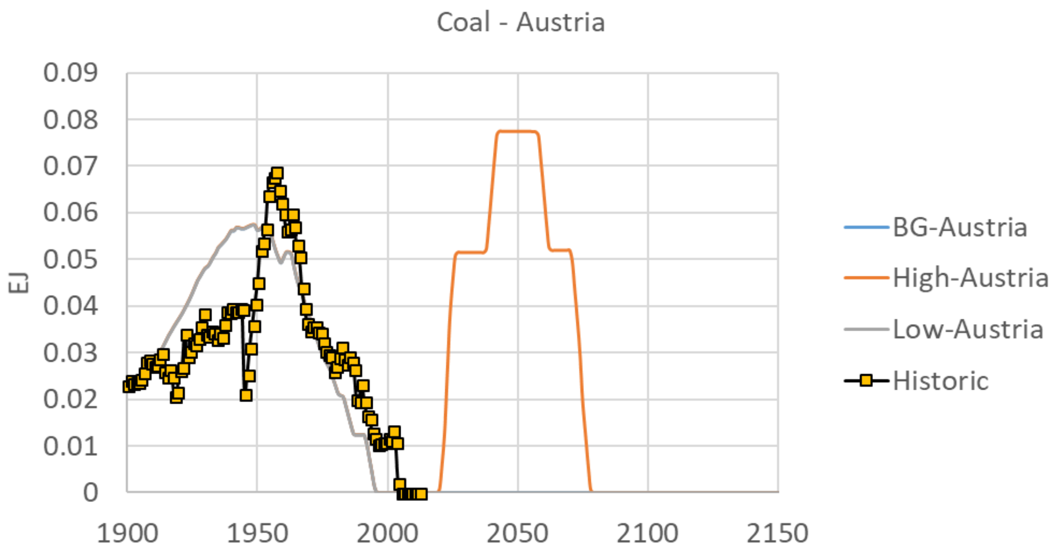
until the complete absence of production, and the production for Bulgaria has declined in the 20th century but increasing later until the same production levels of the 1950s in the last years (see Figure 46).

a)



b)

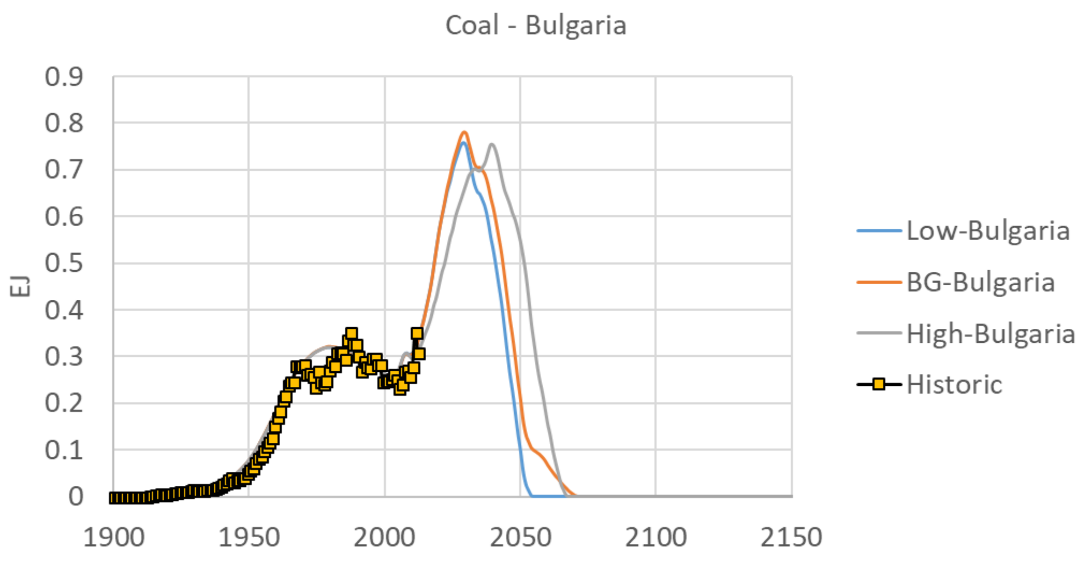


Figure 46. Coal historical extraction in (a) Austria and (b) Bulgaria, and 3 future availability cases (low, BG and high).

Mohr projections consider that the future production might strongly increase until 2050 only for High scenario in the case of Austria, reaching the zero value in 2079. In the case of Bulgaria, the peak for the three scenarios is reached by 2030 (Figure 46).

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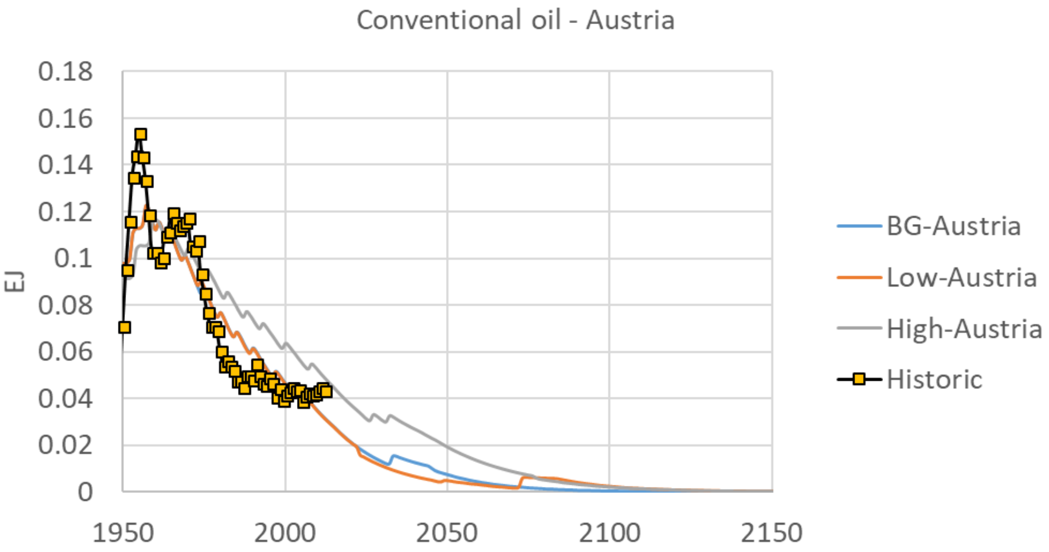
Oil

Conventional oil dominates past extraction of oil in both Austria and Bulgaria, although oil extraction is not very important for these countries in the EU-28 context, reaching 0.16 EJ7yr in Austria and less than 0.03 EJ/yr in Bulgaria. Future extraction is considered only possible for Bulgaria until 2023 reaching levels of the 1960s in the High scenario and declining to reach zero production in the 2060s (Figure 47). Austria present a constant declining pattern reaching zero production in the 2100s.

a)



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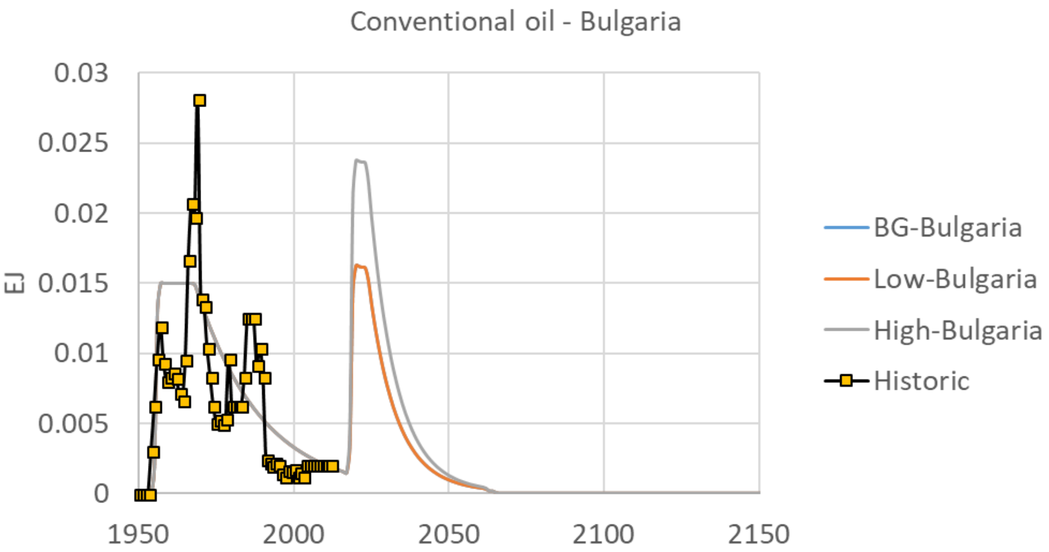

Figure 47. Conventional oil historical extraction in (a) Austria, (b) Bulgaria and 3 future availability cases (low, BG and high).

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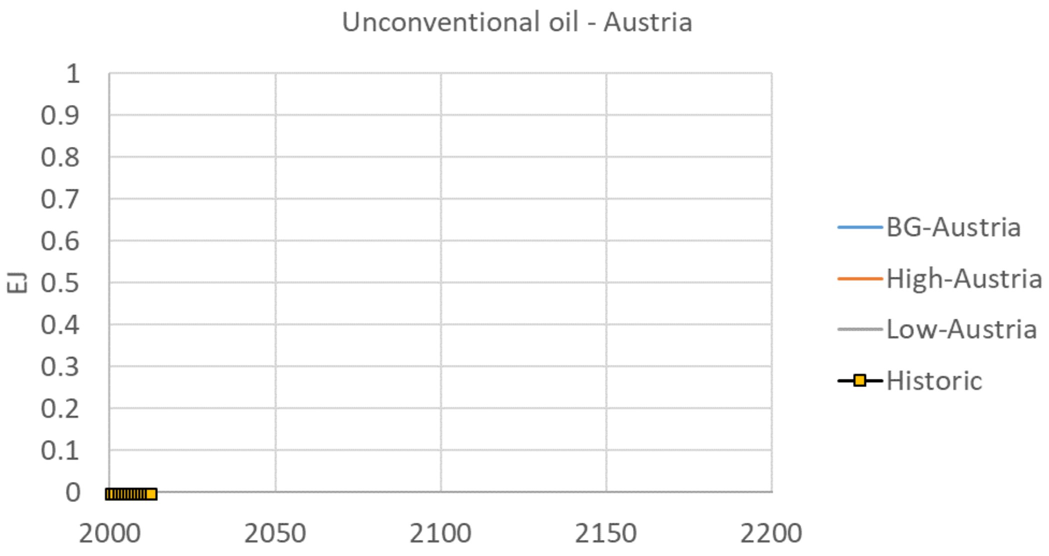
Similarly, unconventional oil could only play a significant role under the "high" scenario and reaching a potential annual output of around 0.08 EJ by 2028 (Figure 48).

a)



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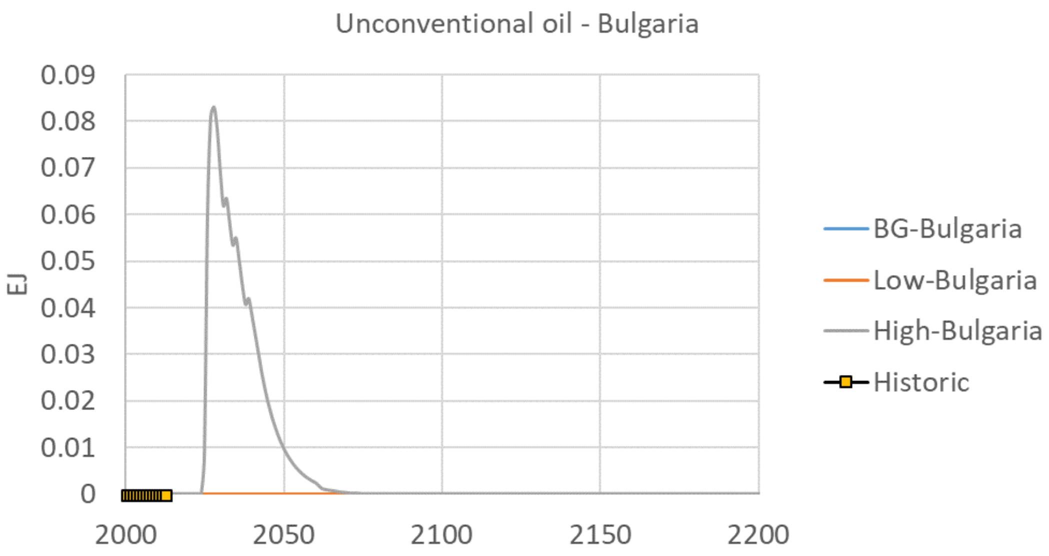

Figure 48. Unconventional oil historical extraction in (a) Austria, (b) Bulgaria and 3 future availability cases (low, BG and high).

Gas

Mohr projections show a great agreement for the future availability of natural gas in both Austria and Bulgaria, finding that in all cases extraction will tend to decrease in the next decades, peaking

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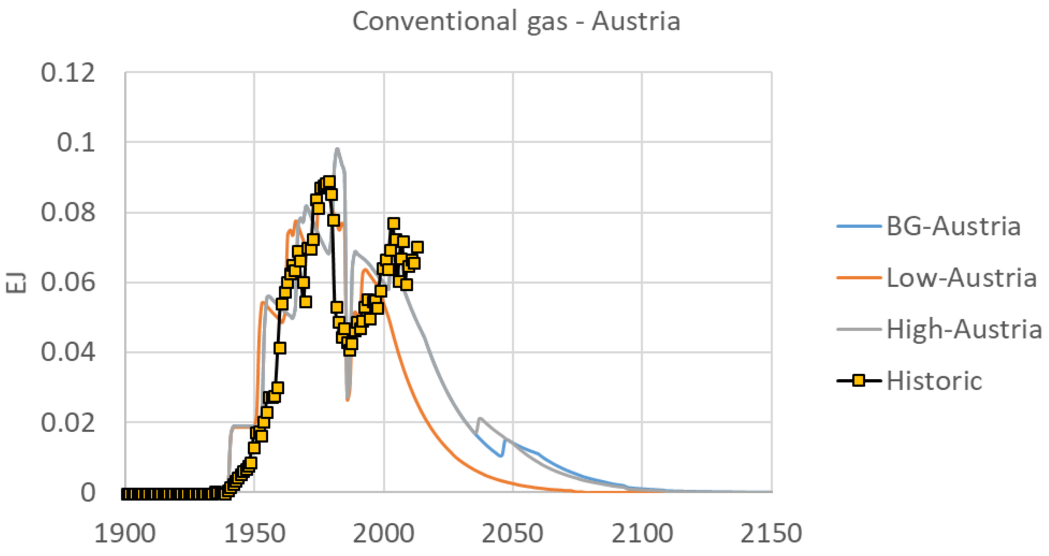
in this decade in Bulgaria, and in the previous decade in Austria, and reaching approximately zero levels close to 2100 for Austria, and around 2075 for Bulgaria (Figure 49).

a)



b)

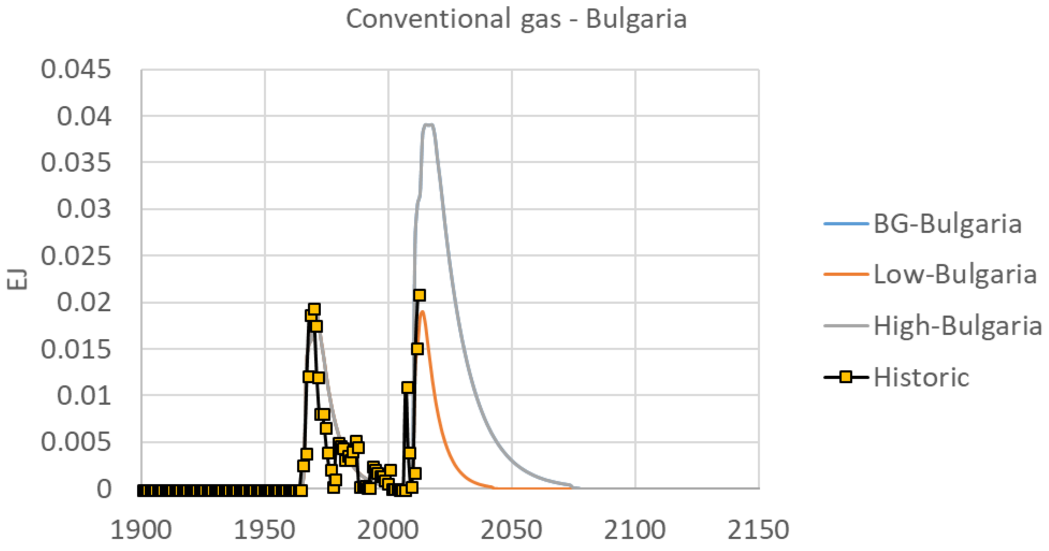


Figure 49. Conventional gas historical extraction in (a) Austria, (b) Bulgaria and 3 future availability cases (low, BG and high).

There is great uncertainty in relation to the future geological availability of unconventional gas resources in the EU, maximum projections ranging from around 0.05 EJ/year for the low scenario and 0.4-0.5 EJ for the BG and High scenarios (Figure 50).

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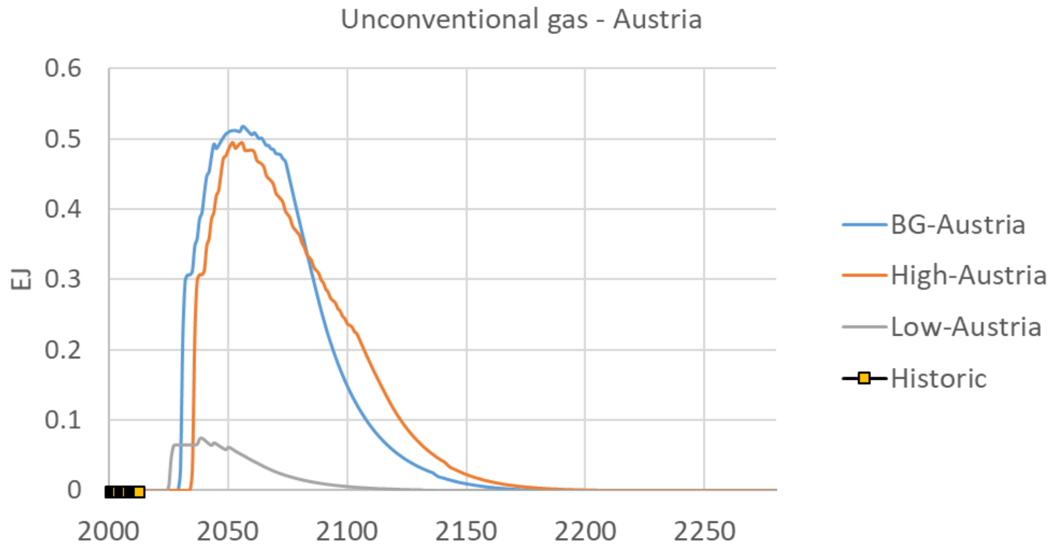
a)



b)

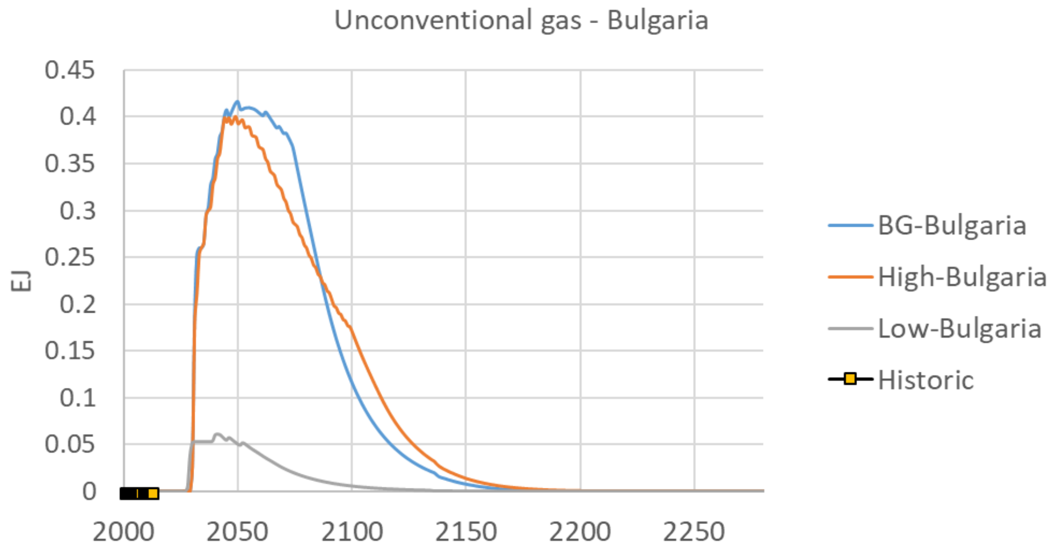


Figure 50. Unconventional oil historical extraction in (a) Austria, (b) Bulgaria and 3 future availability cases (low, BG and high).

Depletion curves available in MEDEAS country-level models

All the afore-mentioned curves are available as maximum extraction curves in MEDEAS country-level models. Table 29 summarizes them.

However, we recall that these curves represent maximum extraction levels due to geological constraints, and “above-ground” factors (i.e. social, political, economic, cultural, etc.) might limit their actual constraints. In particular, the expansion of the extraction of unconventional oil from USA to other regions of the globe is highly disputable (Murray, 2016). Also, the extraction of unconventional gas implies a number environmental impacts (e.g. (Darrah et al., 2014; Howarth,

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2015)). For these reasons, the by-default cases considered in MEDEAS country-level models are "BG" for conventional fuels (coal, conventional oil and conventional gas) and "Low" for unconventional fuels (unconv gas and unconv oil). The by-default cases considered for Austria and Bulgaria are highlighted in grey in the Table 29.

Table 29. URR for each fossil fuel resource and case (low, best guess and high) for Austria and Bulgaria from (Mohr et al., 2015). The by-default cases considered in MEDEAS country-level are highlighted in grey.

Fossil fuels (EJ)	BG-EU	Low-EU	High-EU
Austria			
Coal	3.863	3.863	7.026
Conv oil	5.860	7.240	5.860
Unconv oil	0.000	0.000	0.000
Conv gas	5.300	5.300	4.230
Unconv gas	30.410	3.000	30.410
Bulgaria			
Coal	36.828	42.828	39.968
Conv oil	0.700	0.800	0.700
Unconv oil	0.000	1.146	0.000
Conv gas	1.000	1.000	0.410
Unconv gas	24.290	2.430	24.290

Source: own work from (Mohr et al., 2015)

These depletion curves are subsequently transformed to curves of maximum extraction following the methodology afore-mentioned. Below we show the example of the curves built for unconventional gas (Figure 51).

In Figura 51b and d, the y-axis represents the maximum achievable extraction rate (EJ/year) in function of the RURR (EJ). As extraction increases and the RURR fall below the point where the maximum extraction can be achieved, the extraction is forced to decline following the estimations of the studies selected.

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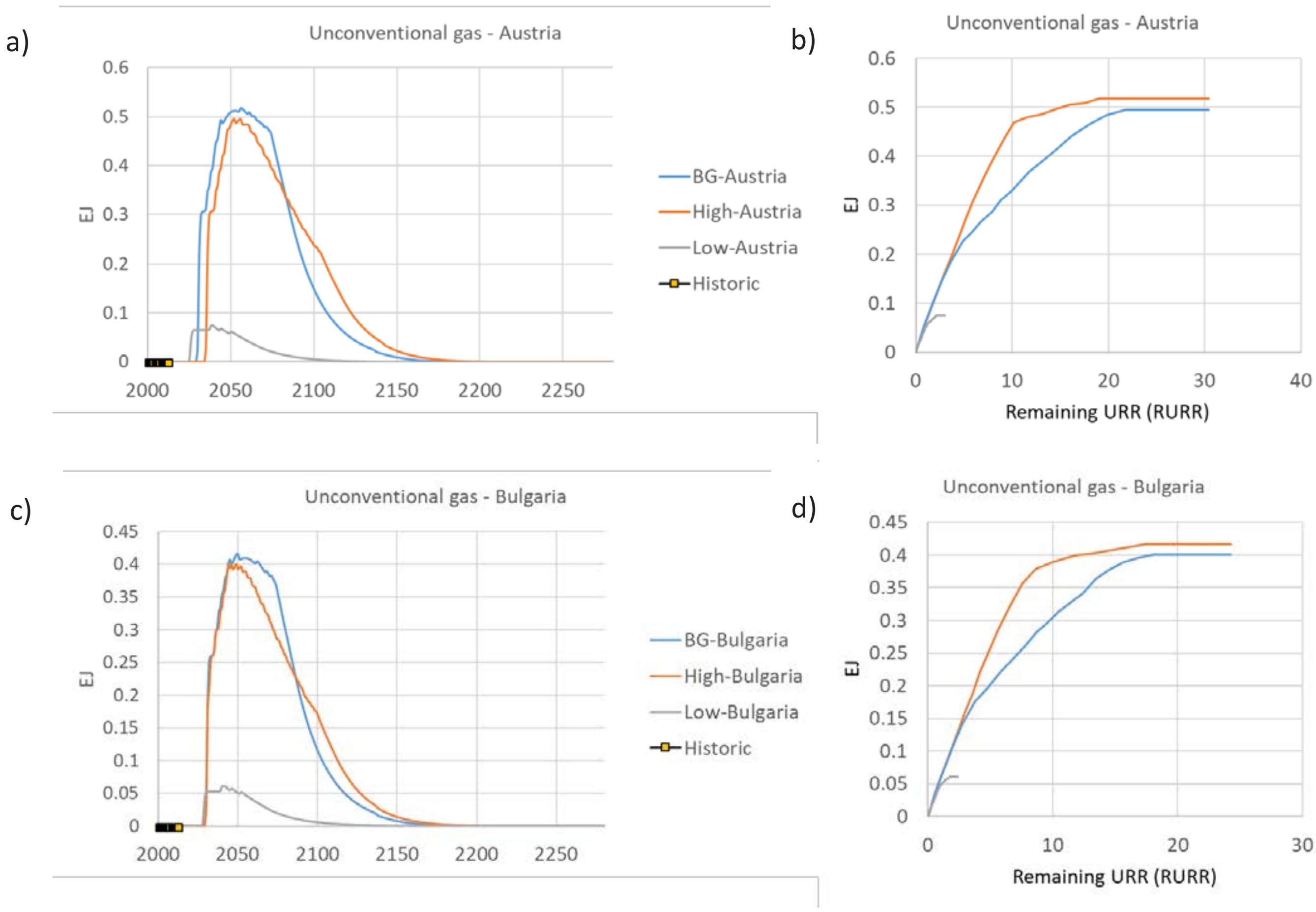

Figure 51. Domestic unconventional gas availability for Austria (a and b) and Bulgaria (c and d): (a and c) depletion curve as a function of time from the original reference; (b and d) curves of maximum extraction in function of the RURR as implemented in the model.

The same constraints to the (growth) extraction of unconventional fuels applied in D4.1 and D4.2. are also considered for the country-level cases.

2.2.3.3.3. Waste to energy

Industry and municipal waste (renewable and non-renewable) are aggregated in the same category. However, from a sustainable and social point of view, waste-to-energy is the worse option in terms of residues management. This issue has been recognized by the EU legislation which establishes a hierarchy of waste management options where the priority is given to prevention and reduction, and once the residues are generated, to its reuse and recycling (Koroneos and Nanaki, 2012). Thus, the application of sustainability policies in MEDEAS country-level translates into the reduction of the potential of waste. Current final use share and efficiencies of waste-to-energy are assumed constant given its past evolution (IEA, 2016).

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2.2.3.4. Renewable energy sources (RES) availability

Renewable energy is usually considered as a huge abundant source of energy; therefore, the technological limits are assumed to be unreachable for decades, and the alarm is supposed to be on the economic, political or ecological constraints (de Castro et al., 2011; IPCC, 2011; Kerschner and O'Neill, 2016). However, the large-scale deployment of renewable alternatives faces serious challenges in their integration within the electricity mix as a consequence of certain particular characteristics of these energy sources. In particular, their intermittency, seasonality and uneven spatial distribution, requiring storage (Lenzen, 2010; Smil, 2008, p. 362; Trainer, 2007); also, their lower energy density (de Castro et al., 2014, 2013, 2011; Smil, 2008); in many cases, their lower EROI than fossil resources (Prieto and Hall, 2013); their dependence on more or less scarce minerals and materials for the construction of power plants and related infrastructures (de Castro et al., 2013; García-Olivares et al., 2012); and finally, their associated environmental impacts (Abbasi and Abbasi, 2012; Danielsen et al., 2009; Keith et al., 2004; Miller et al., 2011). All together, these issues significantly reduce their sustainable potential (Capellán-Pérez et al., 2014; de Castro et al., 2014, 2013, 2011; Smil, 2008; Trainer, 2007).

Given that the potential of renewable technologies for the different uses (electricity, heat and biofuels) is a parameter dependent on each scenario, a straightforward assumption has been taken to consider the techno-sustainable potentials of renewable energies in Austria and Bulgaria. By default, the potentials have been estimated as being proportional to the ratio of the terrestrial surface of each country (excluding permanent ice) in relation to EU-28 (see D4.2). Austria represents 2% of the EU-28 total and Bulgaria represents the 2.5%. In those cases where the potential obtained by this method was inconsistent with current data, a correction taking into account current generation was applied.

2.2.4. Transport module

The Transport module in MEDEAS country-level is very similar to the transport module of MEDEAS-Europe (see more details in Deliverable 4.2). It is based on five views that treat *Energy demand for transportation*, *Households transportation*, *Inland commercial transportation*, *Total number of vehicles* and *Batteries for alternative transportation*.

As in MEDEAS_w, modelling of the transport sectors is based on two main dynamics: a general enhancement of liquid-based vehicles due to improvements in motor efficiency (which is relatively low since vehicle market is already covered by fuel economy standards (IEA/OECD, 2014)) and a shift from one type of vehicle to another with a different energy source. The model separates

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commercial transportation (Inland, Air and Water Transport sectors) and households transport activity. For Inland Transport and Households transportation, the vehicle shift is considered as well as the general efficiency improvement, in Air and Water transportation only the general improvement is studied.

The changes of vehicles considered are from conventional liquids-based vehicles to battery electric, plug and non-plug-in hybrids and natural gas vehicles for all types of vehicles. Biofuels and LPG are considered liquid fuels and are not included for vehicle change. One of the policies that might lead to important energy saving and has been introduced in the model, is the shift from four wheelers to two and three wheels vehicles, which is combined with the electrification of two wheelers. Changes in mobility patterns that require profound social transformations, such as shift to public transportation, non-motorized transport or very light electric vehicles (electric bikes and three wheelers) for the moment, are not included in the model. Cars using hydrogen, synthetic fuel and similar alternatives are not introduced in the model as they are still in a developmental stage.

Household vehicles are organized into six types: liquid, electric, hybrid and gas four wheelers and liquid and electric two wheelers. Inland Transport vehicles are classified into the following types: liquid, hybrid and gas heavy vehicles (trucks); liquid, hybrid, electric and gas light cargo vehicles; liquid, electric, hybrid and gas buses; electric and liquids trains. Classification and the data came from Pocketbook 2017 https://ec.europa.eu/transport/sites/transport/files/pocketbook2017.pdf

Statistical data about alternative vehicles has been obtained from the European average values in the case of Austria (IEA/OECD, 2017 , TERM2016 (EEA, 2016)), and Bulgarian government datasets https://opendata.government.bg/dataset for Bulgaria. Energy statistics for conventional vehicles are obtained from the EU-Transport Statistical Pocketbook 2017 https://ec.europa.eu/transport/sites/transport/files/pocketbook2017.pdf

2.2.4.1. Households intensity variation

The methodology used to calculate energy savings due to vehicle change is the same used in MEDEAS_w model. Households intensities are the relation between their economic demand and the energy of each type consumed. The change of these intensities is related to the changes of types of vehicles using the following equations (Eqs. 33-35):

$$\frac{dIH_{liq}}{dt} = A_1 \frac{d}{dt}\%H_{liq4w} + A_1 \cdot sr_{hyb} \cdot \frac{d}{dt}\%H_{hyb4w} + A_2 \cdot \frac{d}{dt}\%H_{liq2w} \quad (33)$$

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$$\frac{dIH_{elec}}{dt} = A_1 \cdot sr_{elec4w} \frac{d}{dt} \%H_{elec4w} + A_2 \cdot sr_{elec2w} \cdot \frac{d}{dt} \%H_{liq2w} \quad (34)$$

$$\frac{dIH_{gas}}{dt} = A_1 \cdot sr_{gas4w} \frac{d}{dt} \%H_{gas4w} \quad (35)$$

Being $\%H_{liq4w}, \%H_{hyb4w}, \%H_{liq2w}$ the percentages of liquid four wheelers, hybrid four wheelers and liquid two wheelers, $\frac{dIH_{liq}}{dt}, \frac{dIH_{elec}}{dt}, \frac{dIH_{gas}}{dt}$,the derivatives of the intensities of Households Transportation to each type of fuel and $rs_{hyb,} sr_{elec2w}, sr_{elec4w}, \; rs_{gas4w,}$ the ratios between the efficiencies of each vehicle compared to the one of average four wheelers of liquid fuels. Parameters A_1 and A_2 are estimated using the values of the initial calibrating year (2015 by default for Austria and 2017 for Bulgaria).

For the intensity of Inland Transportation sector, a similar approach is used, and changes in the intensities are related to the changes in percent of vehicles using the following equations (Eqs. 36-38):

$$\frac{dI_{liq\ inland\ t}}{dt} = CX_{HV} \cdot \frac{d}{dt} \%HV_{liq} + CX_{LV} \cdot \frac{d}{dt} \%LV_{liq} + CX_{bus} \cdot \frac{d}{dt} \%bus_{liq} + CX_{train} \cdot \frac{d}{dt} \%train_{liq} \quad (36)$$

$$\frac{dI_{elec\ inland\ t}}{dt} = CX_{LV} \cdot sr_{elec\ LV} \cdot \frac{d}{dt} \%LV_{elec} + CX_{bus} \cdot sr_{elec\ bus} \cdot \frac{d}{dt} \%bus_{elec} + CX_{train} \cdot sr_{elec\ train} \cdot \frac{d}{dt} \%train_{elec} \quad (37)$$

$$\frac{dI_{gas\ inland\ t}}{dt} = CX_{HV} \cdot sr_{gas\ HV} \cdot \frac{d}{dt} \%HV_{gas} + CX_{LV} \cdot sr_{gas\ LV} \cdot \frac{d}{dt} \%LV_{gas} + + CX_{bus} \cdot sr_{gas\ bus} \cdot \frac{d}{dt} \%bus_{gas} \quad (38)$$

Where $\%HV_{liq}, \%HV_{hyb}, \%HV_{gas}$ stand for the percent of heavy vehicles of different fuels, $\%LV_{liq}$ $\%LV_{elec}, \%LV_{hyb,} \%LV_{gas}$ for light cargo vehicles, $\%bus_{liq}$, $\%bus_{elec}, \%\ bus_{hyb}, \%bus_{gas}$ for buses of different types $\%train_{liq}, \%train_{elec}$ of and trains all relative to each group of vehicle. Constants $CX_{\ vehicle}$ are calculated using the initial values of vehicles, for each vehicle.

Similar saving ratios as the ones described for Households Transportation are used. A summary is shown in Table 30.

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Table 30. Saving ratios estimated for different vehicles and fuels compared to liquid-based equivalent vehicles.

	Electric	Hybrid	Gas
Light four wheelers	0.33	0.6	1
Heavy vehicles and buses	0.50	0.6	1
Two wheelers	0.21	-	-
Trains	0.60	-	-

2.2.4.2. Transport Policies

The implementation of transport policies in MEDEAS country-level models is based on the growth of the share of certain types of vehicles in the vehicle fleet (Table 31). The value of the variables *P percent elec Hveh, P percent hyb Hveh, P percent gas Hveh, P percent 2w elec* determines the value of each percentage in the final year of the policy (*T fin Hveh*). The figures are associated with each type of vehicle (two or four wheelers). Additionally, the variable *P share 2wheelers*, determines the percent of two wheelers. For the vehicles of Inland Transport sector similar variables are used: *P percent HV hyb, P percent HV gas, P percent LV elec,* etc.

The stock of electric, plug-in hybrids and natural gas-powered vehicles is still very low compared to the global number of vehicles. The 200.000 electric vehicles sold in Europe in 2016 are an important achievement (helped by the estate incentives of France, Germany and Norway), but this number still pales compared to the 14.6 million new registrations of all cars. MEDEAS-Austria and MEDEAS-Bulgaria consider an BAU scenario for the growth of alternative vehicles with the same percent of vehicles in the final year of the policy as those considered for the World and full described in Deliverable 4.1. The BAU scenario is based on a linear growth that continues the observed increment of these vehicles in last years. The only difference is stablished in the electric 2 wheelers, which are very common in Asia but are almost non-existent in Europe, and in electric railways, more common in Europe than the average Worlds number.

The prospects for alternative vehicles are highly uncertain, as the breakthrough to fully commercial models has yet to come and consumers would have to adjust to the characteristics of the new vehicles. Therefore, a more optimistic scenario about the growth of alternative vehicles must have a high component of speculative thinking. Scenario 2 has been defined multiplying the objectives of BAU scenario, in some cases one order of magnitude. Still the final percentage of alternative vehicles is small due to the delays of the stock of vehicles. For a detailed description of the choice of the parameters of the BAU scenario, see Deliverable 4.1.

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The batteries needed for the electric and hybrid vehicles of all types have been calculated using the ratios described in section 2.14.7.4. of Deliverable 4.1.

Table 311. Objectives of stocks of alternative vehicles in the final year of the policy expressed in terms of the percent of vehicles relative to each class for BAU and Scenario 2.

Type of vehicle	Percent in year T fin (2050 default) BAU	Percent in year T fin (2050 default) Scenario 2
Electric households 4 wheeler	0.64	6.4
Hybrid households 4 wheeler	1.08	10.8
Gas household vehicle 4 wheeler	14.89	30
Electric 2 wheeler	0	10
Percent 2 wheelers	33.25	33.25
Hybrid heavy vehicles	0.045	0.45
Gas heavy vehicles	0.045	0.45
Electric light cargo vehicles	0.074	0.74
Hybrid light cargbo vehicles	0.036	0.36
Natural gas light cargo vehicles	1.597	15.97
Electric bus	0	6
Hybrid bus	0	10
Natural gas bus	0	30
Electric train	90	90

2.2.5. Materials module

In the materials module, MEDEAS country-level models follow a similar structure to MEDEAS-W and MEDEAS_eu (deliverables 4.1. and 4.2.). Thus, the same set of minerals is considered: Aluminium (Al), Cadmium (Cd), Chromium (Cr), Copper (Cu), Gallium (Ga), Indium (In), Iron (Fe), Lithium (Li), Magnesium (Mg), Manganese (Mn), Molybdenum (Mo), Nickel (Ni), Lead (Pb), Silver (Ag), Tin (Sn), Tellurium (Te), Titanium (Ti), Vanadium (V), and Zinc (Zn).

However, the difficulty to find consistent and homogenous data at country-level, and other additional variables required to model trade (e.g. past production and consumption, reserves and

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resources, recycling rates, etc.) compelled to adapt the modelling. In particular, the databases shown in table 32 have been reviewed.

Table 32. Mineral databases reviewed for the MEDEAS country-level models.

Database	Data provided	Area/Countries	Minerals	Data period
USGS. USA Geological Survey	There are only data available for **mineral production.** They can be downloaded in MSExcel format. Data files are released each year, so, in order to have a long historical data series files must be grouped together.	Data for all the EU-28 countries, including Austria and Bulgaria.	We have data for the following minerals: aluminium, copper, iron and steel, lead, manganese ore, nickel, silver, tin, titanium and zinc.	1995-2013 Different years in each file
BGS. British Geological Survey	There are data available for **mineral production, exports and imports**. They can be downloaded in an MSExcel file, but also in PDF.	We do not have data for every country in EU-28. It could be because not in every country exists production of every mineral.	We have data for all minerals needed, but we can only download data for one mineral each time.	1970-2015 Disadvantage: data can be downloaded for a maximum of ten years each time.
Euromines. European Association of Mining Industries, Metal Ores & Industrial Minerals	There is only data available for **mineral production**. Data is not available in MSExcel format; they are only displayed in the screen.	We do not have data for every country in EU-28.	We have data for the following minerals: Aluminium, Antimony, Bauxite, Copper, Gold, Iron, Lead, Manganese, Nickel, Platinum, Silver, Titanium, Tungsten and Zinc.	1999-2015
Minerals4EU	We have data for **mineral production, imports and exports, resources and reserves**. Data are not available in Excel format. They are displayed in the screen.	We have data for all the countries in the EU-28.	We have data for all minerals except aluminium, gallium and titanium.	2004-2013

The review of databases revealed that there is no database that includes all the dimensions required for modelling minerals in MEDEAS. For example, just 1 out of 4 databases include information for the whole dataset of minerals included in MEDEAS (BGS), but this database lacks

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information related to the level of reserves and resources at EU-level. In fact, as reported by Minerals4EU, the reserve and resource available data at EU member state level belong to different reporting systems (e.g. JORC, PERC or NI 43-101, or to a national system restricted to an individual country or group of countries). Because of these variations in reporting methodology, it is inappropriate to aggregate the resource and reserve data presented to determine national or European totals because the figures are not directly comparable.

Thus, the modelling of materials in MEDEAS country-level models has to be adapted to data availability, and consists mainly of:

- Modelling of future demand of minerals for the main RES technologies for the generation of electricity (CSP, PV, wind), grids (high power, HVDCs) and EV batteries, with the method already explained within the section 2.4.1.1 of deliverable 4.1.,
- Recycling levels of minerals in EU countries correspond with the World average (section 2.4.3 of deliverable 4.1)
- Comparison of the cumulated demand of each mineral in EU and EU countries with the world level of current reserves and resources (information coming from MEDEAS-W boundary simulation).
- Comparison of the annual demand of each mineral in EU countries with the current production level.

EROI levels per technology as well as the EROI of the energy system are calculated exactly the same as in the case of MEDEAS-W and MEDEAS_eu.

Table 33 shows the current (2015) level of production of each mineral in Austria and Bulgaria in tonnes (BGS, 2017).

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Table 33. Austrian and Bulgarian domestic current production level for each mineral considered in MEDEAS (2015).

	Production in Austria 2015 (t)	Production in Bulgaria 2015 (t)
Aluminium	0	0
Cadmium	0	0.00038
Chromium	0	0
Copper	0	0.11175
Gallium	0	0
Indium	0	0
Iron	2.783	0
Lithium	0	0
Magnesium	0	0
Manganese	0	0.04650
Molybdenum	0	0
Nickel	0	0
Lead	0	0.01676
Silver	0	0.05500
Tin	0	0
Tellurium	0	0
Titanium	0	0
Vanadium	0	0
Zinc	0	0.01562
Uranium	0	0

Source : own elaboration from (BGS, 2017).

2.2.6. GHG emissions module

As a first approximation, in MEDEAS-W (Deliverable 4.1) all the GHG emissions were calculated as the sum of CO_2 and CH_4 (in terms of CO_2 equivalents). In the European model, the emissions due to the six main greenhouse gases included in the RCPs and SSPs (i.e., CO_2, CH_4, N_2O, SF_6, PFC, HFC) were calculated. This method has been also employed for country-level models in Austria and Bulgaria.

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To transform the effects of different emissions to a common scale — often called 'CO_2 equivalent emissions'—the emissions (E_i) associated to a certain i component can be multiplied to the adopted normalized metric (M_i), as follows (Eq. 39):

$$CO_2 - eq_i = M_i \cdot E_i \qquad (39)$$

One well-known M_i is the Global Warming Potential (GWP), defined as the time-integrated Radiative Forcing (RF) due to a pulse emission of a given component, relative to a pulse emission of an equal mass of CO_2. The GWP was presented in the First IPCC Assessment (IPCC, 1990), and the GWP value of each gas depends on the chosen time horizon, usually 20 years and 100 years are the most used values.

A time horizon of 100 years was later adopted as a metric to implement the multi-gas approach embedded in the United Nations Framework Convention on Climate Change (UNFCCC) and made operational in the 1997 Kyoto Protocol. In this module we have used both the 20-year time horizon and the 100-year time horizon, so using the variable "GWP time frame" we can choose which of the 2 different time intervals will be used for the calculation.

Total emission, expressed on CO_2-equivalent, are the sum of the contribution of each gas, so the GWP data of each gas and for each time horizon are necessary (Eq. 40).

$$Total\ CO_2 - eq\ emissions = CO_2\ emissions + GWP_{CH_4} \cdot CH_4\ emissions + GWP_{N_2O} \cdot N_2O emissions + GWP_{SF_6} \cdot SF_6\ emissions + GWP_{PFCs} \cdot PFCs\ emissions + GWP_{HFCs} \cdot HFCs\ emissions \qquad (40)$$

According to the data of the IPCC fifth assessment report (IPCC, 2013), the GWP data for the gases studied and for the different time horizons chosen are shown in the Table 34.

CO_2 emissions

CO_2 emissions are those calculated endogenously as the sum of those due to the combustion of fossil fuels, soil management, the land use change and the combustion of biofuels.

CH_4 emissions

In the case of CH_4 emissions, the same methodology used in MEDEAS-W has been used. Thus, total CH_4 emissions is the sum of the RCPs data (Representative Concentration Pathways; RCP 2.6, RCP 4.5, RCP 6.0 and RCP 8.5) (Clarke et al., 2007; Fujino et al., 2006; Grübler, 2007; Hijioka et al., 2008; Smith and Wigley, 2006; van Vuuren et al., 2007; Wise et al., 2009), excepting the corresponding

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part of the emissions generated by power plants, energy conversion, extraction and distribution, with the data obtained endogenously due to the emissions generated in the extraction of the different fossil fuels.

Table 34. Global warming potentials (GWP) for the 20 years and the 100 years horizons (without carbon feedback factors). Source: (IPCC, 2013).

GAS	GWP 20 years	GWP 100 years
CH_4	84	28
N_2O	264	265
PFCs	4,880	6,630
SF6	17,500	23,500
HFC-134a	3,710	1,300
HFC-23	10,800	12,400
HFC-32	2,430	677
HFC-125	6,090	3170
HFC-143a	6,940	4,800
HFC-152a	506	138
HFC-227ea	5,360	3,350
HFC-245ca	2,510	716
HFC-4310mee	4,310	1,650

Rest of GHGs emissions (N_2O, SF_6, PFCs (CF_4), HFCs)

For the historical data on gas emissions in the countries, the World Bank data base for the years 2000, 2005 and 2010 has been used.

Whereas, the country/EU-28 emission ratios of historical emissions have been used and have been maintained constant for the different RCPs up to the year 2100 for the evolution of the data since 2015, according to the IIASA RCP database (http: //www.iiasa. ac.at/web-apps/tnt/RcpDb) (Clarke et al., 2007; Fujino et al., 2006; Grübler, 2007; Hijioka et al., 2008; Smith and Wigley, 2006; van Vuuren et al., 2007; Wise et al., 2009). For the sake of simplicity, these ratios have been considered only for CH_4 and N_2O, and the ratio for the rest of the gases has been considered zero.

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2.2.7. Land-use module

The representation of land use and land cover dynamics is highly complex given that they depend on a diversity of natural and human factors. Forthcoming climate change increases the challenge. In this sense, relatively few integrated assessment models include this dimensions, such as GCAM (Kyle et al., 2011) or IMAGE (Elke Stehfest et al., 2014).

Given the scope of the project, a stylized representation of land-use in Austria and Bulgaria has been included in the model. It does not attempt to comprehensively model the biophysical-human interrelations and represent all the land use and land cover types. Instead, its main objective is to allow to endogenize some variables which in previous versions of the model had to be assumed exogenous although they are ultimately land-dependent. These variables are:

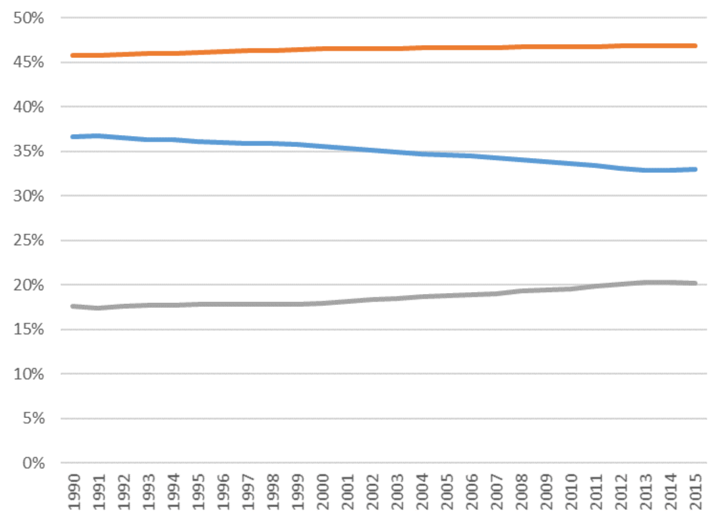
- Built-up land,
- Potential for biomass (including the explicit consideration of the demand of biomass for non-energy uses),
- Potential for solar energy (both on land –PV and CSP) and rooftop –PV and solar thermal-).

This approach has the advantage that it takes into account that most land uses are mutually exclusive. Most data for the construction of this module has been taken from FAOSTAT (http://www.fao.org/faostat/en/).

2.2.7.1. Current situation

In terms of land-use, the land dedicated to agriculture (including arable land, permanent crops and permanent pastures, FAOSTAT definitions) has been decreasing in the last 25 years at an annual average rate of -0.4% and -0.7% in Austria and Bulgaria, respectively. The forest area (including primary, planted and other naturally regenerated) has increased at +0.1% and 0.6% in Austria and Bulgaria per year, respectively. Other land, which accounts for the rest of land (i.e. built-up and related land, barren land, other wood land, etc.) has increased at 0.1% and 1 % in Austria and Bulgaria, respectively (FAOSTAT, 2017) (Figure 52).

a)



b)

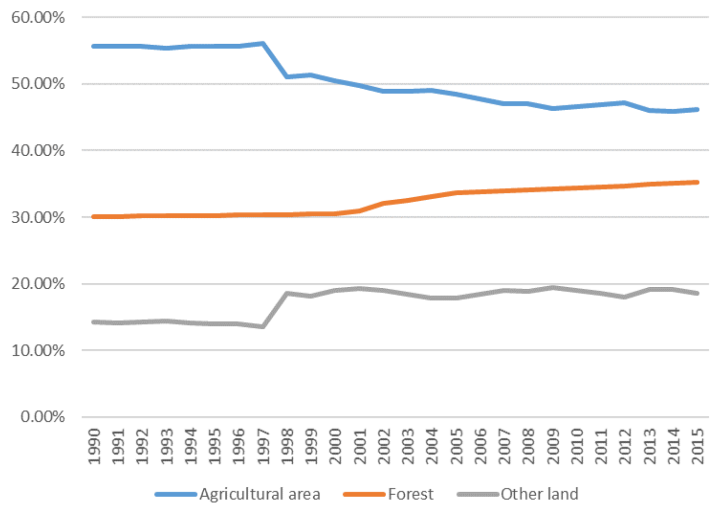


Figure 52. Historical evolution of land-use shares (1990-2015) for agricultural area, forest and other land in Austria (a) and Bulgaria (b).

In relation to domestic forests and plantations in Austria and Bulgaria, most of the forest area corresponds to naturally regenerated forest, increasing more than 6% in Austria, and decreasing almost 2% in Bulgaria during the period 1990-2015. Plantations have decreased 6.5% and 3.1% during the period in Austria and Bulgaria, respectively. Primary forests represent a mere 3% of forest area in Austria while Bulgaria primary forests still represent about 15.6 % of total forest area (Figure 53). It is remarkable that the surface occupied by primary forests (0.11 Mha) is smaller than the artificial surfaces (including urban and associated areas) in Austria (0.17 Mha) but not in Bulgaria (0.60 Mha vs 0.17 Mha).

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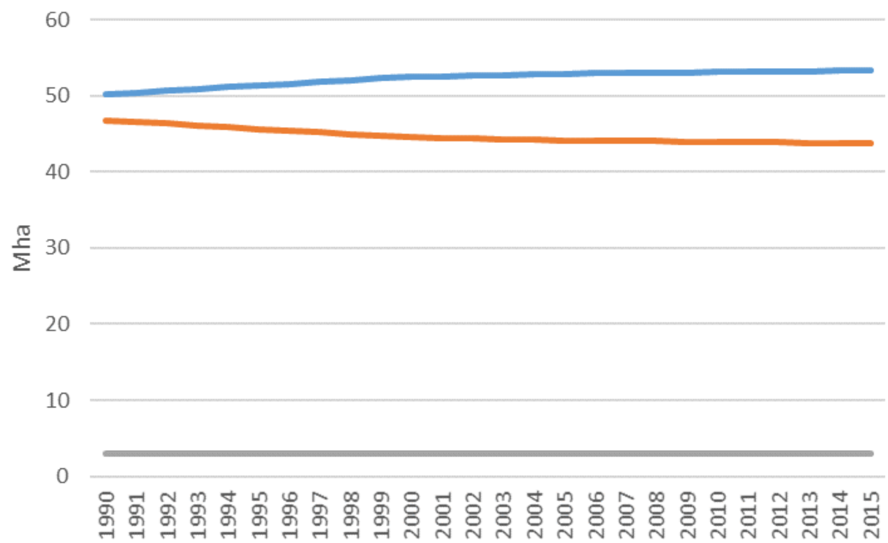
a)



b)

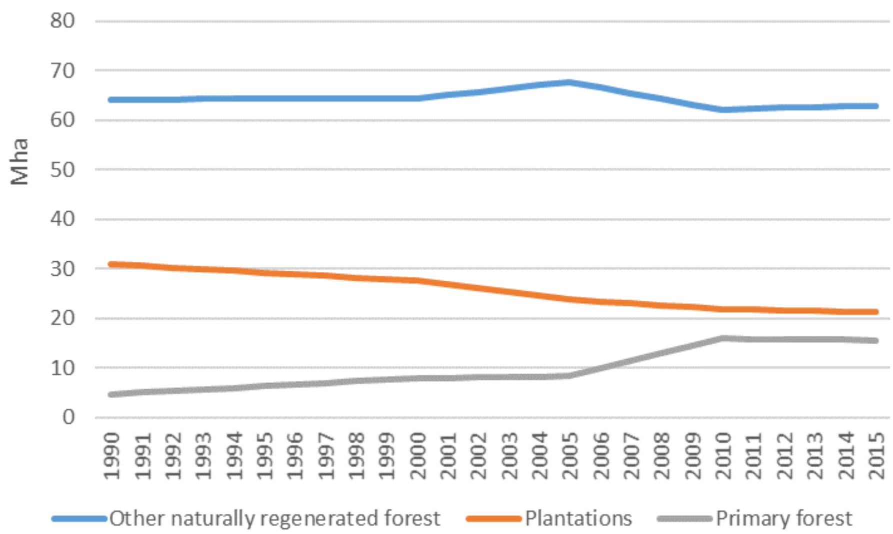


Figure 53. Historical evolution of area covered of forest by type in (a) Austria and (b) Bulgaria (1990-2015).

2.2.7.2. Overview of the modelling approach to build the Land Module in MEDEAS country-level

Figure 54 shows a simplified representation of the Land Module in MEDEAS country-level models. The boxes represent the stocks modelled, depicting different types of land-use and cover (most categories correspond with FAO nomenclature given that this database has been the main source of data for the construction of the module):

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- Primary forest: naturally regenerated forest of native species, where there are no clearly visible indications of human activities and the ecological processes are not significantly disturbed (FAO, 2014).

- Forest available: represents the rest of forests in FAO database, i.e. "Plantations" (forest predominantly composed of trees established through planting and/or deliberate seeding) and "Other naturally regenerated forest" (forest predominantly composed of trees established through natural regeneration where there are clearly visible indications of human activities) (FAO, 2014).

- Agricultural land: includes both categories "Arable land and Permanent crops" and "Permanent pastures":
    - Arable land represents the land under temporary agricultural crops (multiple-cropped areas are counted only once), temporary meadows for mowing or pasture, land under market and kitchen gardens and land temporarily fallow (less than five years). The abandoned land resulting from shifting cultivation is not included in this category. Data for "Arable land" are not meant to indicate the amount of land that is potentially cultivable.
    - Permanent crops is the land cultivated with long-term crops which do not have to be replanted for several years (such as cocoa and coffee); land under trees and shrubs producing flowers, such as roses and jasmine; and nurseries (except those for forest trees, which should be classified under "forest"). Permanent meadows and pastures are excluded from land under permanent crops.
    - Permanent meadows and pastures is the land used permanently (five years or more) to grow herbaceous forage crops, either cultivated or growing wild (wild prairie or grazing land).

- Urban land: corresponds with FAO's "Artificial surfaces (including urban and associated areas)", including areas that have an artificial cover as a result of human activities such as construction (cities, towns, transportation), extraction (open mines and quarries) or waste disposal.

- Available land: this category has been built specifically for the Land Module of MEDEAS framework following the approach used in (Capellán-Pérez et al., 2017), and represents the terrestrial land that is currently neither being used by the primary sector (arable land,

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permanent crops, permanent meadows and pastures and productive forest area) nor built-up.

- Land for solar and hydro RES: represents the land occupied by solar facilities and hydropower plants
- Marginal land occupied by biofuels: represents the marginal lands occupied by biofuels,
- Agricultural land for BioE: represents the agricultural land used to grow biofuels.

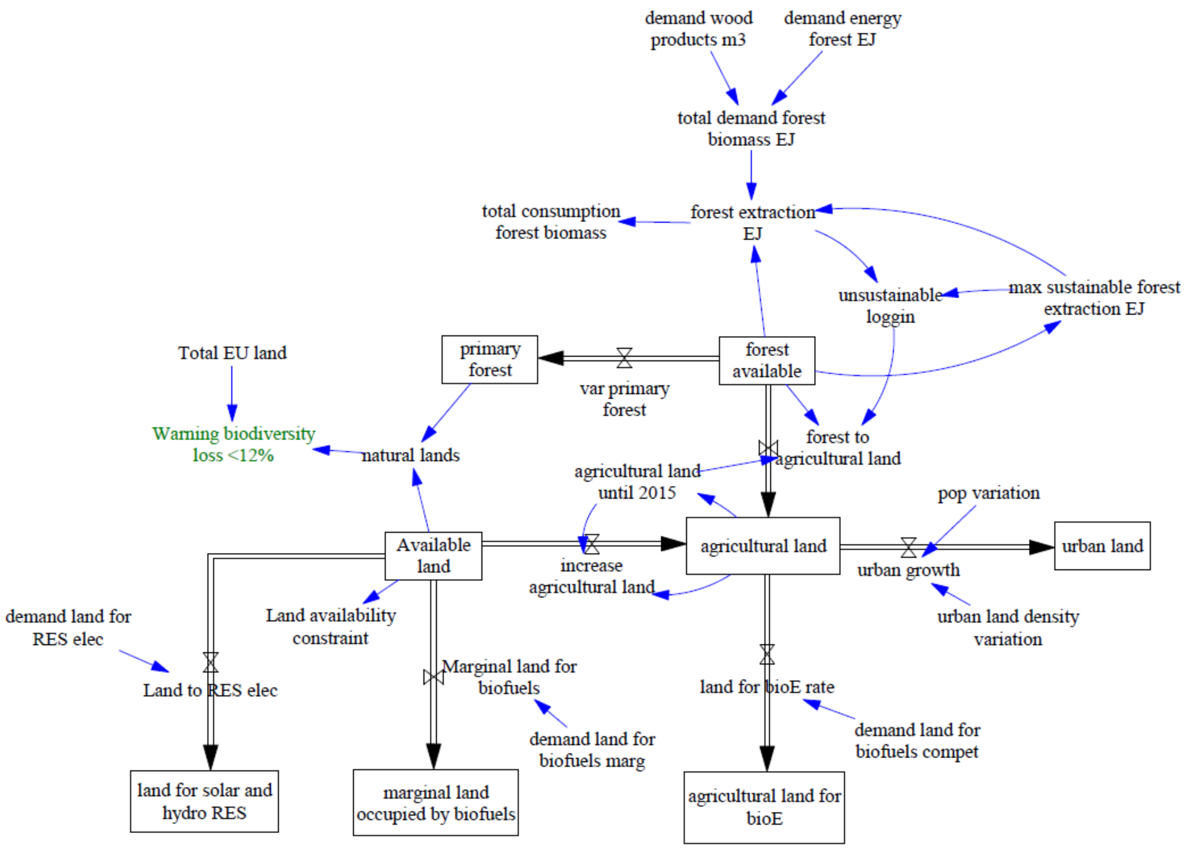

Figure 54. Overview of the Land Module in MEDEAS country-level models.

The Land Module functions as follows: It takes the demand of different types of final energy (e.g. electricity, liquids, heat) generated by the Economy module (see section 2.2.2.3.1.) as inputs. Depending on the assumptions and policy targets of each scenario, there will be a demand for renewable energy resources which are dependent on land: bioenergy (from forests and grown as crops) and renewable energies for the generation of electricity, such as PV, CSP and Hydro. Solar thermal and rooftop PV are related to the urban surface and policy targets in terms of urban land density variation. Non-energetic uses of wood are also taken into account. These demands are confronted with the land availability (forest, agricultural land, available land), which may

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ultimately constrain the actual extraction of bioenergy resource/installation of power centrals. A "warning" indicator of "Biodiversity loss" is formulated, considering the ratio of natural areas vs the total land, which gives a qualitative idea of the potential danger of biodiversity loss of the scenario simulated.

2.2.7.3. Methodology

In this subsection the rationale and assumptions considered for the modelling of Land in MEDEAS country-level are described.

2.2.7.3.1. Primary forests

Given past trends (slow annual growth in the period 1992-2015) and for the sake of simplicity, primary forest area is considered to remain constant in the standard version of MEDEAS. However, the user can consider the continuation of past trends or introduce a customized value.

2.2.7.3.2. Forest available

Solid bioenergy to be extracted from forests in the model is dependent on the area of forest available, as well as from a scenario-dependent parameter of "unsustainable logging". This parameter allows for a higher extraction of wood but at the cost of degrading the stock of forests which ultimately causes deforestation. This degradation process is assumed to increase the availability of land for agriculture, which is an optimistic assumption given that in some cases degraded forests may also end up being marginal or barren lands.

However, in the standard version of the model the total area for forest is assumed to remain constant, assuming unlikely that the area dedicated to forest in the UE countries will decrease in future decades since it goes against historical trends and allows to capture CO_2, preserve biodiversity, etc. (excepting in the cases of potential collapse/rapid degradation scenarios).

2.2.7.3.3. Agriculture land

This is a key stock of the country-level models given that in recent decades land for agriculture has been the main use of land at EU-level (although with a decreasing trend: 49% in 1992 vs 44% in 2015 FAOSTAT). In Austria, the agricultural land has slightly decreased from 36.6 % to 32.9%; meanwhile, in Bulgaria, the agricultural land use has decreased from 55.7% to 46.2%.

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The requirements of land for agriculture depend on many parameters, some technical such as productivity yields, and other socio-cultural such as diets. In this context, 2 key factors must be taken into account:

(1) Most of the EU28 countries are net food importer, and net imports have gone up significantly in the past years (Von Witzke and Noleppa, 2010).
(2) It seems unlikely that this deficit may be covered by yields increases. Recent studies have found strong evidence of yield plateaus in some of the world's most intensive cropping systems, among them some of the most important EU producers. A hypothesis that can explain the occurrence of yield plateaus is that average farm yields approach a biophysical yield ceiling for the crop in question, which is determined by its yield potential in the regions where the crop is produced (Grassini et al., 2013). Moreover, yield increases are critically dependent on the use of inputs such as fertilizers (natural gas) and water, which may be scarcer in the future.

Hence, given that a substantial amount of food consumption in EU countries depends on imports and the adverse impacts on biodiversity on virtual land imports of UE in the rest of the world, we assume as a reasonable future target that the EU countries will roughly maintain the current area dedicated to agriculture. Moreover, this is also consistent with the fact that demand for food in next decades is assumed to increase substantially at a global level (together with population increase). This implies a global increase in the competition for land. This target might even be seen as conservative given that future climate impacts affecting current yields are not considered in the Land module of MEDEAS_eu.

2.2.7.3.4. Urban land

The future evolution of urban land is commonly related with the evolution of population and economic growth. For example, in IMAGE, urban built-up areas increase per grid cell in the scenario period as a function of GDP and population and depend on a country- and scenario-specific urban density curve (Elke Stehfest et al., 2014). In the AIM model, a similar approach is taken: the spatial distribution is created by assuming that urban grid cells are increased in proportion to the increase in population and GDP in each country; the urbanization rate is also used as explanatory variable (Masui et al., 2011). However, these approaches lack to capture the fact that different types of urbanization exist, although operational indicators of urban sprawl are complex to be set e.g. (Hasse and Lathrop, 2003).

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In MEDEAS country-level, given that resolution at grid level is not available, a simpler approach had to be taken. Firstly, given that built-up areas mostly expand into very productive agricultural areas (Elke Stehfest et al., 2014), we assume that built-up surface is subtracted from the agricultural area, thus, leading to additional demand for agricultural area in the "available land" stock. Secondly, a lineal model was built to estimate the urban land surface considering the variation of population and the variation of urban land density (i.e. urban m^2/population of the country) considering data from 1992 to 2015 for Austria and Bulgaria at aggregated level from FAOSTAT and (World Bank database, 2018):

$$Urban\ land = a \cdot Pop + b \cdot Urban\ land\ density + c \qquad (41)$$

Table 35 reports the main outputs and validation tests of the regression performed for Austria ($R^2 = 0.999922$; $F(2,21) = 134867.1$; $p < 0.1$) and Bulgaria ($R^2 = 0.996377$; $F(2,21) = 2887.694$; $p < 0.1$), which show that the models are significant.

Table 35. Regression model for urban land in MEDEAS country-level models in Austria and Bulgaria.

	Coefficient	Standard deviation	t	p-value
Austrian model				
c	-0.161568	0.00561239	-28.79	2.33E-18***
b	0.000795116	3.79777E-6	209.4	2.39E-36***
a	2.03205E-8	7.53887E-10	26.95	8.94E-18***
Bulgarian Model				
c	-0.0618610	0.0305938	-2.022	0.0561*
b	0.000682185	4.14979E-5	16.45	1.80E-13***
a	9.95954E-9	2.99496E-9	3.325	0.0032***

*p-value ≤0.05 *** p-value < 0.1

The evolution of population is scenario dependent, while the future urban land density is a parameter, which can be selected by the user and is considered also scenario-dependent, since it is a parameter highly dependent on urbanism legislation, cultural practices, etc. A graph with the pattern of change in the ratio of urban land per capita for Austria and Bulgaria (data from FAOSTAT and World Bank) was performed (see Figure 55). This way, the user can select for each scenario the assumed urban land per capita in the year 2050.

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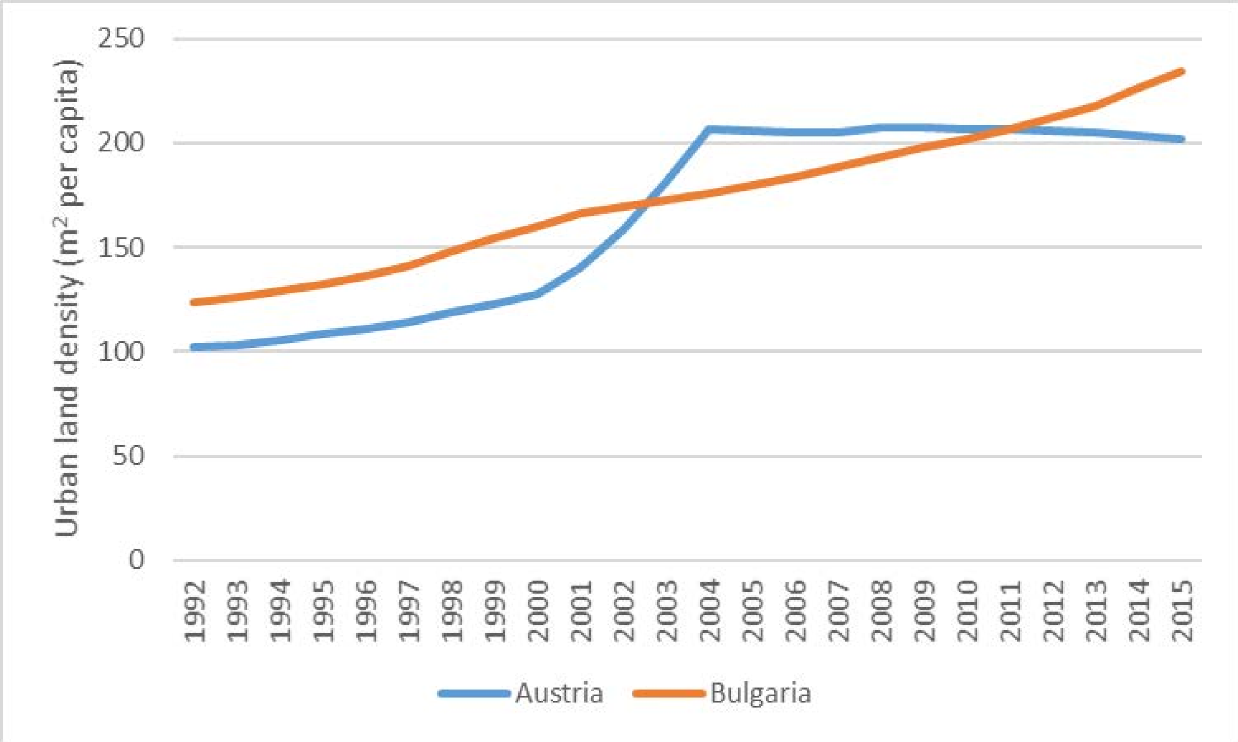

Figure 55. Urban land per capita.

2.2.7.3.5. Available land for human uses

The "land availability" at country-level is defined adapting the methodology applied in (Capellán-Pérez et al., 2017) and includes the terrestrial land that is currently neither being used by the primary sector (arable land, permanent crops, permanent meadows and pastures and productive forest), land nor built-up and permanent snow and glaciers. This stock includes the land required for additional human uses (i.e. balance of agricultural land, installation of plants for generation of electricity from renewable energy sources, biofuel plantations, etc.).

Figure 56 shows the historical evolution of the main land categories in EU, based on (FAO, 2017).

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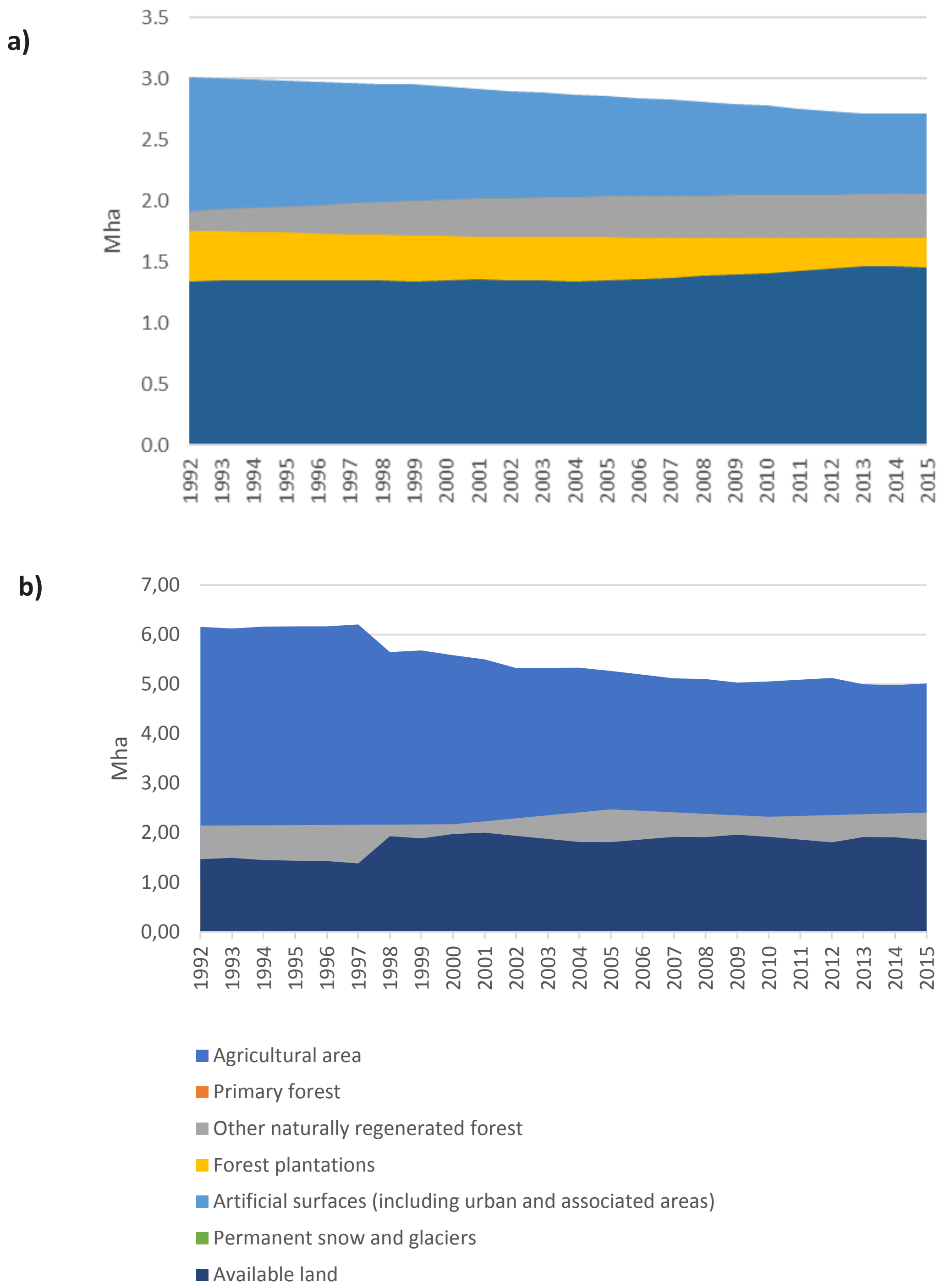

Figure 56. Historical evolution of the main stocks of land considered in the Land Module of MEDEAS_eu (1992-2015) for Austria (a) and Bulgaria (b).

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This definition of land availability must be taken as a first conservative approximation. Many other factors would reduce the land availability: orography (e.g. mountains), yield productivity (e.g. barren lands for biofuels), protected areas (e.g. the EU-27 has an average of around 27% of its surface protected; 34 % and 15 % of total area in Bulgaria and Austria were under the Habitats Directive protection in 2016, according to EUROSTAT), locations with suboptimal resource, etc. (see also (Deng et al., 2015)).

2.2.7.3.6. Natural land and biodiversity warning

Natural lands in MEDEAS are defined as the primary forests and the "available land". We interpret the ratio of natural lands vs the total land as an indicator of biodiversity loss, given that natural lands can be understood as an insurance that ensures the resilience and stability generated by biodiversity. We apply here the value of 12% of the territory as considered in the Brundtland Report and for the calculation of the standard ecological footprint (Wackernagel et al., 2002; WCED, 1987). This value is a conservative lower bound, which has been strongly criticized as being unable to a assure an effective protection of biodiversity (Vačkář, 2012). For example, the UNEP and IUCN give 17% as a reference value (Juffe-Bignoli et al., 2014), while Soulé and Sanjayan (Soulé and Sanjayan, 1998) argued for a minimum share of 25-50%.

2.2.8. Social and environmental impacts

2.2.8.1. Context and MEDEAS approach

The main aim of this module in MEDEAS framework is to translate the behavior of each model scenario into a set of variables that provide information about its social dimension. This is a complex and delicate task, since, in fact, social dimensions such as education, health, culture, life expectancy, etc. depend on more dimensions that the ones modelled in MEDEAS, which mainly evolves through energetic and monetary variables. Thus, the computation of indicators such as HDI is in principle further the scope of the project.

The followed approach consists on reporting outputs which can be obtained from the current version of the model. MEDEAS does not report "a" variable to measure well-being. We consider that well-being is a multidimensional feature which cannot be reduced to a single variable (UN, 1990). Instead, we illustrate the social evolution of each scenario assessing a set of variables. We complete the information with the reporting of key environmental impacts indicators given that well-being is intrinsically linked to a healthy environment (Daily, 1997; Levin et al., 2009; Schneider and Morton, 1981). How energy forces and infrastructures interrelate with institutions and

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ideations of political power are beyond the scope of the project (Boyer, 2014). The construction of this set of indicators was assisted by the D2.2 Task e (MEDEAS, 2016).

2.2.8.2. Social and environmental indicators

As explained with more detail in Deliverable 4.1., in the MEDEAS framework we identify as social and environmental indicators the following variables, also included in MEDEAS country-level models:

- Total Final and by final fuel Consumption per capita
- Total Primary and by fuel Consumption per capita
- Electricity consumption per capita
- Total water use per capita
- Potential HDI level given energy use
- Consumption of RES per capita
- Share of RES in total final consumption
- Annual penetration of RES in the total final and primary energy consumption
- GDP per capita
- Jobs associated to RES technologies
- EROIst of the system
- GHG emissions per capita
- Atmospheric GHG concentration levels
- Temperature increase over pre-industrial levels

The following indicators from the Sustainable Development Goal Indicators (UN, 2015) are available in MEDEAS:

- 7.3.1 Energy intensity measured in terms of primary energy and gross domestic product (GDP)
- 8.1.1 Annual growth rate of real GDP per capita
- 9.4.1. CO_2 emission per unit of value added

Two variables added with MEDEAS_eu are also included in the MEDEAS country-level models, therefore, biodiversity and energy footprint, and methodology for water uses have slightly

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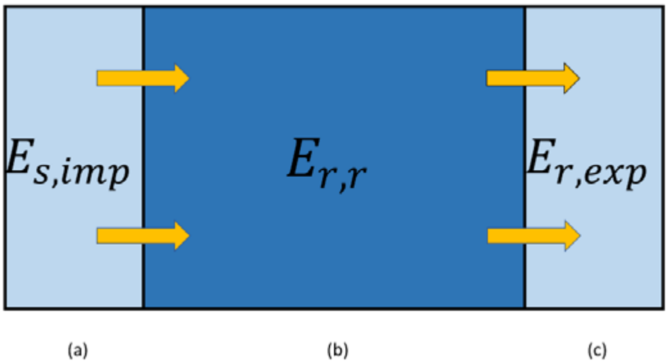
changed. In the next sections, we will explain the methodology used for energy footprint and water uses in the MEDEAS country-level models.

2.2.8.3. Energy footprint

Energy footprint is an indicator which measures the energy used in a territory to produce the output required to satisfy its demand. Because part of one country's demand is produced outside its borders, trade is a fundamental variable. This way, the energy required to produce abroad the products that Europe imports must be incorporated to the European energy footprint. Conversely, the energy consumed during the production process of exports to the rest of the world, do not have to be incorporated following the abovementioned definition. Thus, we can define energy footprint in a certain region 'r' and taking foreign countries as 's' as (Eq.42):

$$EF_r = E_{r,r} + E_{s,imp} - E_{r,exp} \tag{42}$$

Being EF_r the energy footprint in region 'r', first subscript in the other variables represents region where output is produced and the second what demand it is destined to satisfy: domestic demand ('r'), imports ('imp') and exports ('exp'). Energy flows in this framework can be expressed as in Figure 57. Energy required to produce exports is 'exported' within the products exported and energy required to produce (abroad) imports is 'imported' within the products imported.



$E_{r,r}$= Energy consumed in region r to produce output required to satisfy domestic products demand.

$E_{s,imp}$= Energy embedded in imports required to satisfy domestic demand.

$E_{r,exp}$= Energy embedded in exports required to satisfy foreign demand.

Figure 57. Energy flows in MEDEAS-Europe from the Energy Footprint point of view.

Energy footprint can be a measure of environmental load displacement (Cole, 2004; Peng et al., 2016), the process through which developed countries 'displace' dirtier production to the least developed countries. The main methodologies found in the literature to estimate energy footprint

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are life-cycle analysis (Castellani et al., 2018; Kaldellis and Apostolou, 2017) and structural decomposition analysis, or SDA, based on Input-Output Analysis (Kaltenegger et al., 2018; Lan et al., 2016). Even though most of the SDA studies include international trade, only a few do it employing a multi-regional input-output (MRIO) framework (Kagawa and Inamura, 2004; Lan et al., 2016). In MEDEAS-Europe, it has been integrated System Dynamics and Input-Output Analysis employing a MRIO approach.

The methodology applied in MEDEAS country-level models consists on the decomposition of multi-regional Leontief Matrix into four - as explained in section 2.2.2.3.2. Following this approach, Leontief Matrix is divided in different figures: $L_{DOM,DOM}$ is the region r's production sensitivity to final demand of region r products (upper-left quadrant); $L_{DOM,RoW}$ $L_{DOM,RoEU}$ are the country's (DOM) production sensitivity to final demand made by RoW's and RoEU's agents (upper-right quadrants); $L_{RoW,DOM}$ and $L_{RoEU,DOM}$ are the RoW's and RoEU's production sensitivity to the country's imports requirements (lower-left quadrants). Taking these definitions into account, we can express the variables in Eq.42 as (Eq. 43-45):

$$E_{r,r} = L_{DOM,DOM} * I_{DOM} \tag{43}$$

$$E_{s,imp} = L_{RoW,DOM} * I_{RoW} + L_{RoEU,DOM} * I_{RoEU} \tag{44}$$

$$E_{r,exp} = L_{DOM,RoW} * I_{DOM} + L_{DOM,RoEU} * I_{DOM} \tag{45}$$

Being I the diagonal matrix of sectoral energy intensities by energy sources for each region depending on its subscript. And thus the energy footprint is obtained as follows (Eq. 46):

$$EF_r = E_{r,r} + E_{s,imp} - E_{r,exp} \tag{46}$$

In this way, MEDEAS country-level models estimate for each year the net energy carriers of the country's economy, by incorporating energy embedded in imports ($E_{s,imp}$) and subtracting energy embedded in exports ($E_{r,exp}$).

Finally, we can estimate the energy coverage rate as the proportion of the energy actually 'enjoyed' by the country's economy (domestic plus embedded in imports less embedded in exports) over total energy consumed in the country. In terms of Figure 1, (a)+(b) is the total energy 'enjoyed' by the country's economy, (b)+(c) the total energy consumed in the country and (a)-(c)

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the energy balance of trade. Hence, the energy coverage rate is the proportion between them or, more formally (Eq. 47):

$$ECR_r = \frac{E_{r,r}}{EC_r} + \frac{E_{s,imp} - E_{r,exp}}{EC_r} - 1 \qquad (47)$$

where ECR_r is the energy coverage rate in region r, and EC_r the total energy consumed in the same region. That is, ECR_r is a representation of the amount of energy available for the country's consumption over the amount of energy consumed in the region. In other words, a positive ECR_r reflects the proportion of energy enjoyed over energy consumed (because it is being imported embedded in products demanded from abroad). Conversely, if it is negative, it means that the region is enjoying a proportion under its energy consumed (because it is being exported embedded in products demanded abroad). Given the description of energy footprint in Eq.42 we can rearrange Eq. 47 as:

$$ECR_r = \frac{EF_r}{EC_r} - 1 \qquad (48)$$

2.2.8.4. Water use

This part of the module allows calculating water consumption in MEDEAS country-level model by type (blue, green and grey) by economic sector and for households. The aggregated values allow calculating the total water consumption and social indicators such as the total water consumption per capita.

2.2.8.4.1. Water data

Data used in this module is taken from the environmental accounts within the WIOD database (Genty et al., 2012) (Release 2013, http://www.wiod.org/database/eas13 see also (Arto et al., 2016)). This database compiles data of water consumption for each sector, and also for households, disaggregated by country and type of water. Data is available for years 1995 to 2009.

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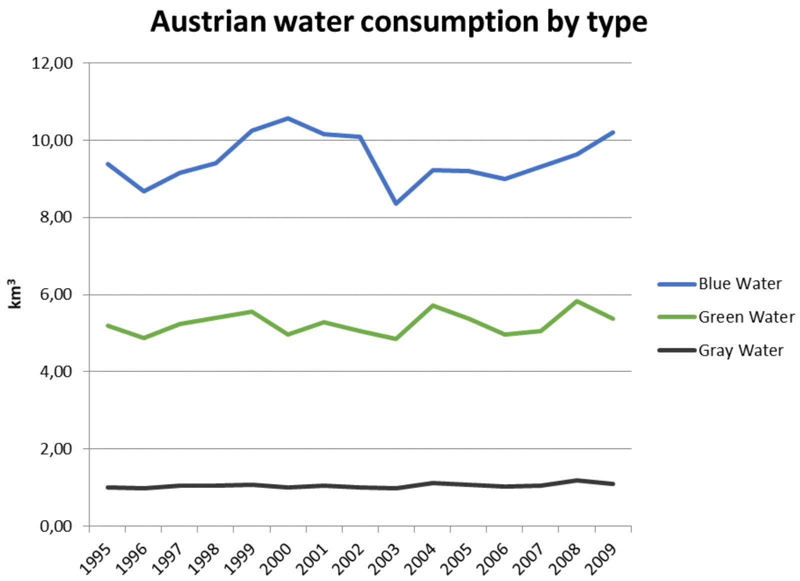

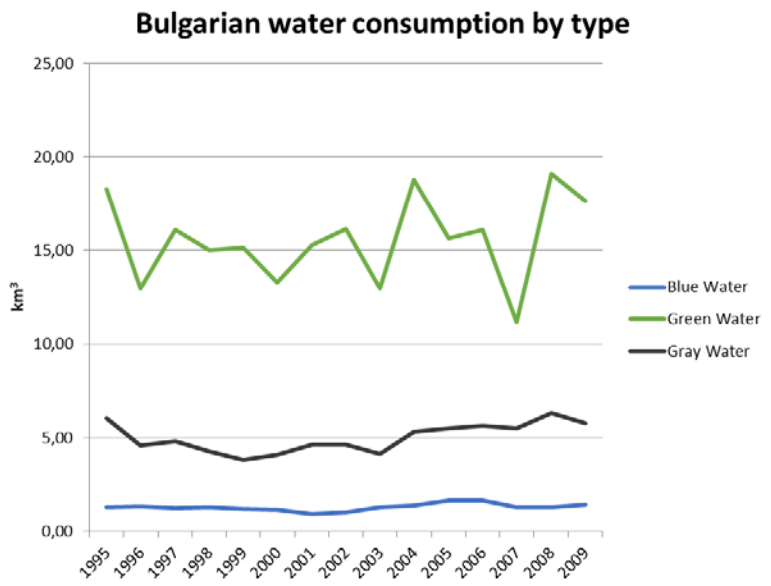

Figure 58. Austrian (a) and Bulgarian (b) water consumption (1995-2009) by type.

According to these data, the Figure 58 represents the Austrian and Bulgarian consumption of water by type for the 1995-2009 period.

2.2.8.4.2. Water potential

Two water potentials at country level are considered: the total water resource and the share of it which is accessible for human use. First, we have used the Internal Renewable Water Resources

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(IRWR) from AQUASTAT,[5] which is a metric of the long-term average annual flow of rivers and recharge of aquifers generated from endogenous precipitation (double counting of surface water and groundwater resources is avoided by deducting the overlap from the sum of the surface water and groundwater resources): 55 km^3 (Austria) and 21 km^3 (Bulgaria).

The share available for human use was obtained combining the IRWR for UE-28 with the share of total renewable (blue) water supply accessible to humans from the OECD (75%) from Table 10.1 from (UNESCO, 2009): 41.25 km^3 (Austria) and 15.75 km^3 (Bulgaria).

2.3. Tested scenarios and results

2.3.1. Scenarios

The objective of this section is to present the country-level version of the MEDEAS model. In order to illustrate some of the capabilities and diversity of features included in the model, this section reports the outputs from two experimental simulations. It is important to recall that the model includes thousands of variables and it is very flexible in the design of its scenarios. This section does not pretend to be comprehensive and exhaustive, but only to illustrate some experimental results. Section 2.3.1.1. describes the tested scenarios, section 2.3.1.2. the implementation in the model and, finally, section 2.3.2 reports some of the results.

2.3.1.1. Tested scenarios

MEDEAS country-level models, as any simulation tool, needs assumptions about the socio-economic context evolution of both the EU and the rest of the World as external inputs, such as expected economic growth, population evolution or technological progress.

Running models can be a cumbersome task when the models have several parameters, assumptions and policies that can be varied at the same time. In order to establish those inputs in a coherent and sensible way, scenario methodology is usually applied. The current standard set of scenarios in climate change research is the Shared Socioeconomic Pathways (SSPs). The SSPs are a set of five qualitative descriptions of future changes in demographics, human development, economy and lifestyle, policies and institutions, technology, and environment and natural resources. The narratives are intended as a description of plausible future conditions at the level of large world regions that can serve as a basis for integrated scenarios of emissions and land use,

[5] http://www.fao.org/nr/water/aquastat/water_res/index.stm

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as well as climate impact, adaptation and vulnerability analyses (MEDEAS, 2017a; O'Neill et al., 2017).

In this report, we apply the SSP2 scenario from the climate change modelling community in the MEDEAS country-level framework, which constitutes a scenario similar to a BAU (continuation of current trends). We follow the approach of "adaptive scenarios" presented in Task 3.3.c (MEDEAS, 2017b); i.e. the inclusion of biophysical feedbacks and constraints modifies the exogenous assumptions of the scenario. We call that scenario SSP2-baseline.

Subsequently, we apply a set of policies to try to mitigate GHG emissions to safe levels. We refer to this scenario as SSP2-OLT (optimum level transition, D3.3 (MEDEAS, 2017a)).

2.3.1.2. Implementation of the scenarios in MEDEAS country-level

For the implementation of SSP2-Baseline and SSP2-OLT in MEDEAS country-level models, the exogenous drivers of population evolution (Figure 59) and expected GDP change (see Figure 60) for Austria and Bulgaria have been used.

As shown in Figure 59, emigration is being a key factor for evolution in Bulgarian population.

Taking account climate change consequences and using that as a constraint, GDP presents a declining pattern in both countries (Figure 60), although the decreased expected for Austria starts in the middle 2020s and the decreased pattern expected for Bulgaria starts in the early 2030s.

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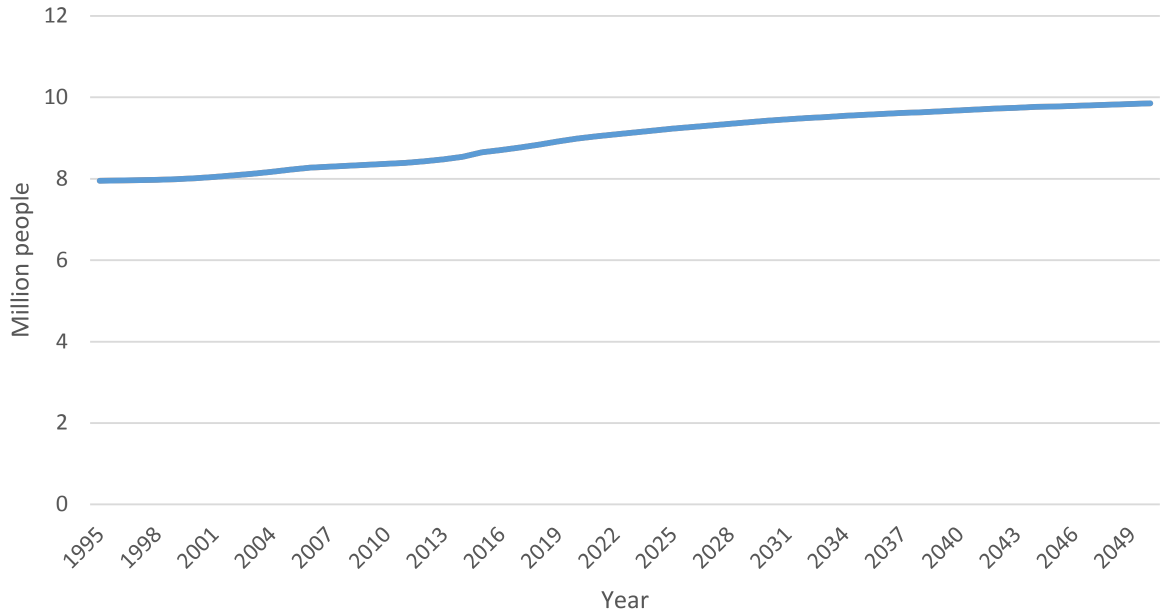
a)



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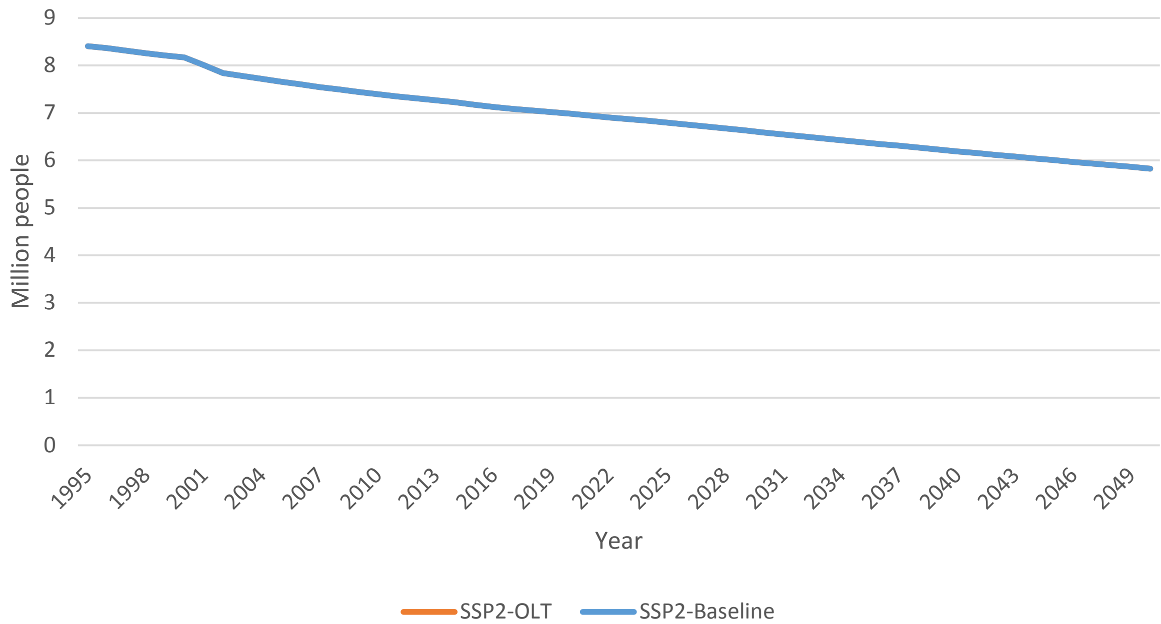

Figure 59. Evolution of population for the SSP2-Baseline and SSP2-OTL scenarios in (a) Austria and (b) Bulgaria.

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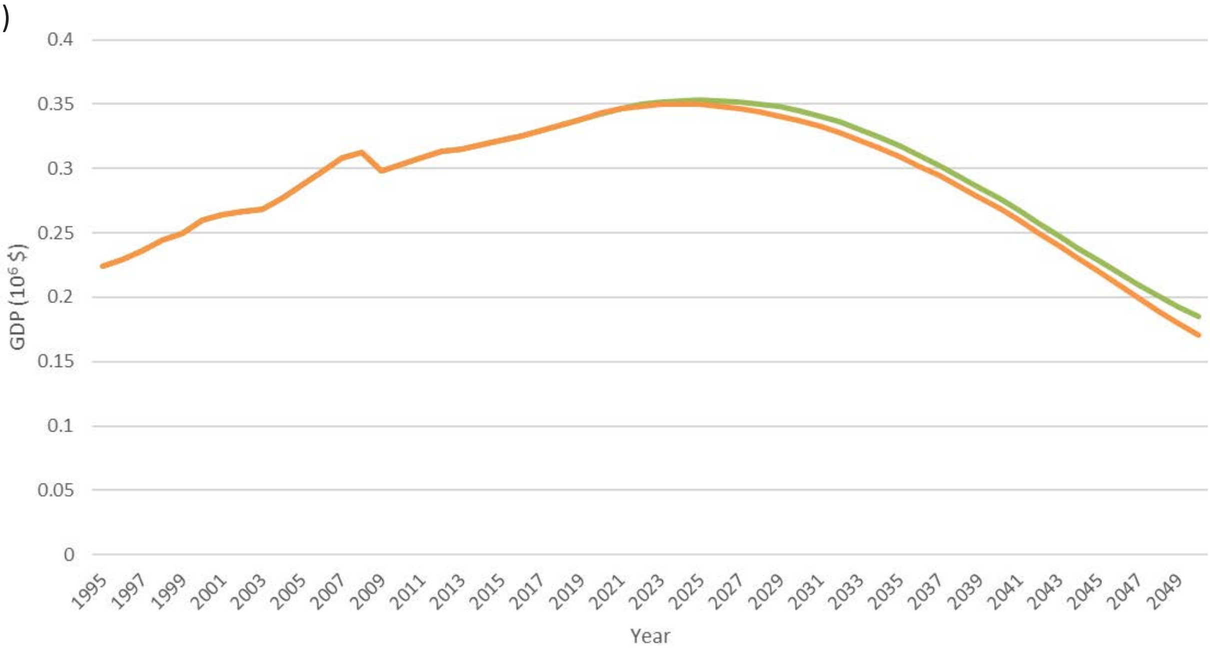
a)



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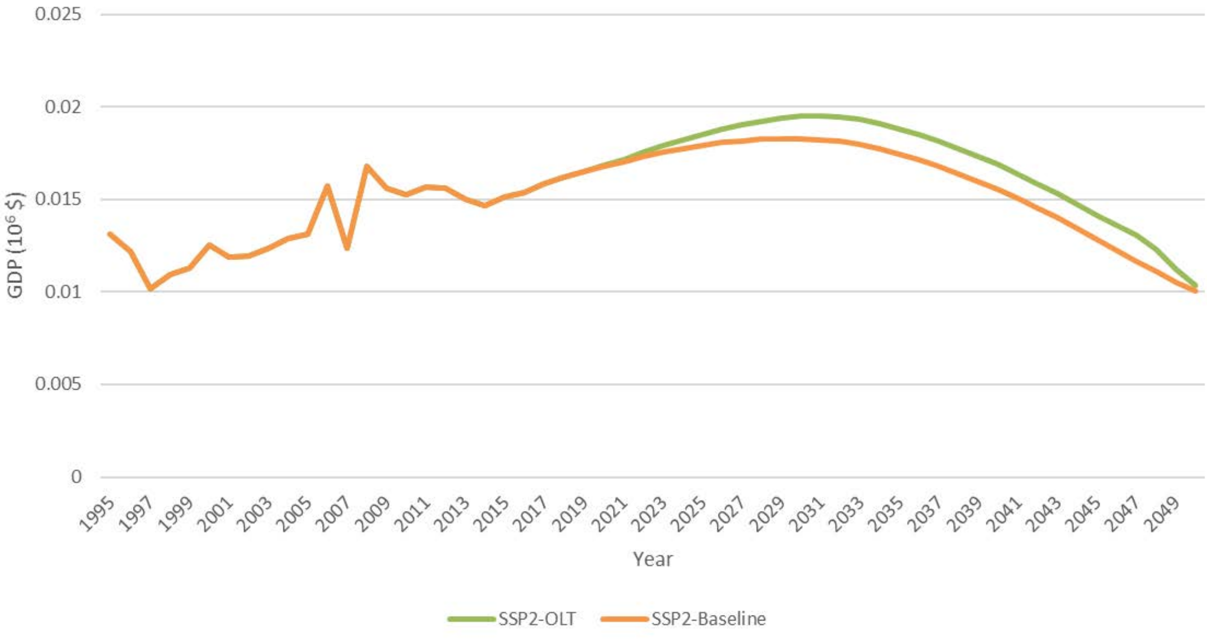

Figure 60. Quantification of the GDP evolution in the SSP2-Baseline and SSP2-OTL scenarios for (a) Austria and (b) Bulgaria.

We shall recall that in MEDEAS, GDP is an endogenous variable, so in the spirit of “Adaptive scenarios” Task 3.3.c (MEDEAS, 2017b), the exogenous GDP trend will be achieved only in the case that there are not constraints that limit it.

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For the rest of assumptions to run the SSP2-Baseline, we have interpreted the narrative and adjusted the parameters of the model to it. We recall that this narrative is basically a BAU, i.e. an extrapolation of current trends.

For the SSP2-OLT, after literature review, we have implemented a set of policies starting in 2020 with the aim of directing the energy system towards a low carbon and sustainable future, which includes:

- Higher deployment of RES for electricity, biofuels and heat,
- Preference to technologies which save land (e.g. rooftop PV),
- (Slight) increase in nuclear power,
- Higher electrification (and shift to hybrid modes) of transport,
- Higher recycling rates of minerals,
- Reducing the share of oil in electricity and heat consumption,
- Increase the final energy efficiencies at both economic sector and technology-levels.

Thus, the SSP2-OLT could be classified as a "Green Growth" scenario.

Both scenarios share the same characteristics in terms of required GDPpc required, population evolution and fossil fuel and uranium endowments, among others. As explained before, the simulation of a scenario within MEDEAS country-level models requires the global and EU contexts to be taken into account, i.e. the SSP2-Baseline for Austria or Bulgaria is affected by the evolution of some key variables of this same scenario at global and EU levels (the same applies for SSP2-OLT); see D4.1 and D4.2 for more details on these results.

2.3.2. Experimental results

This section reports some of the main results of MEDEAS country-level models up to 2050 with the scenarios described in the previous section (SSP2-Baseline and SSP2-OLT). Population changes following the exogenous path imposed.

The generation of energy from RES increases steadily until 2040s (Figure 61) in Austria for both scenarios, although the BAU scenario is higher 0.1 EJ; in the case of Bulgaria, both scenarios increases the generation of energy from RES multiplying by 2 previous values, although the OLT scenario present higher generation since Bulgaria starts from previous low renewables production values.

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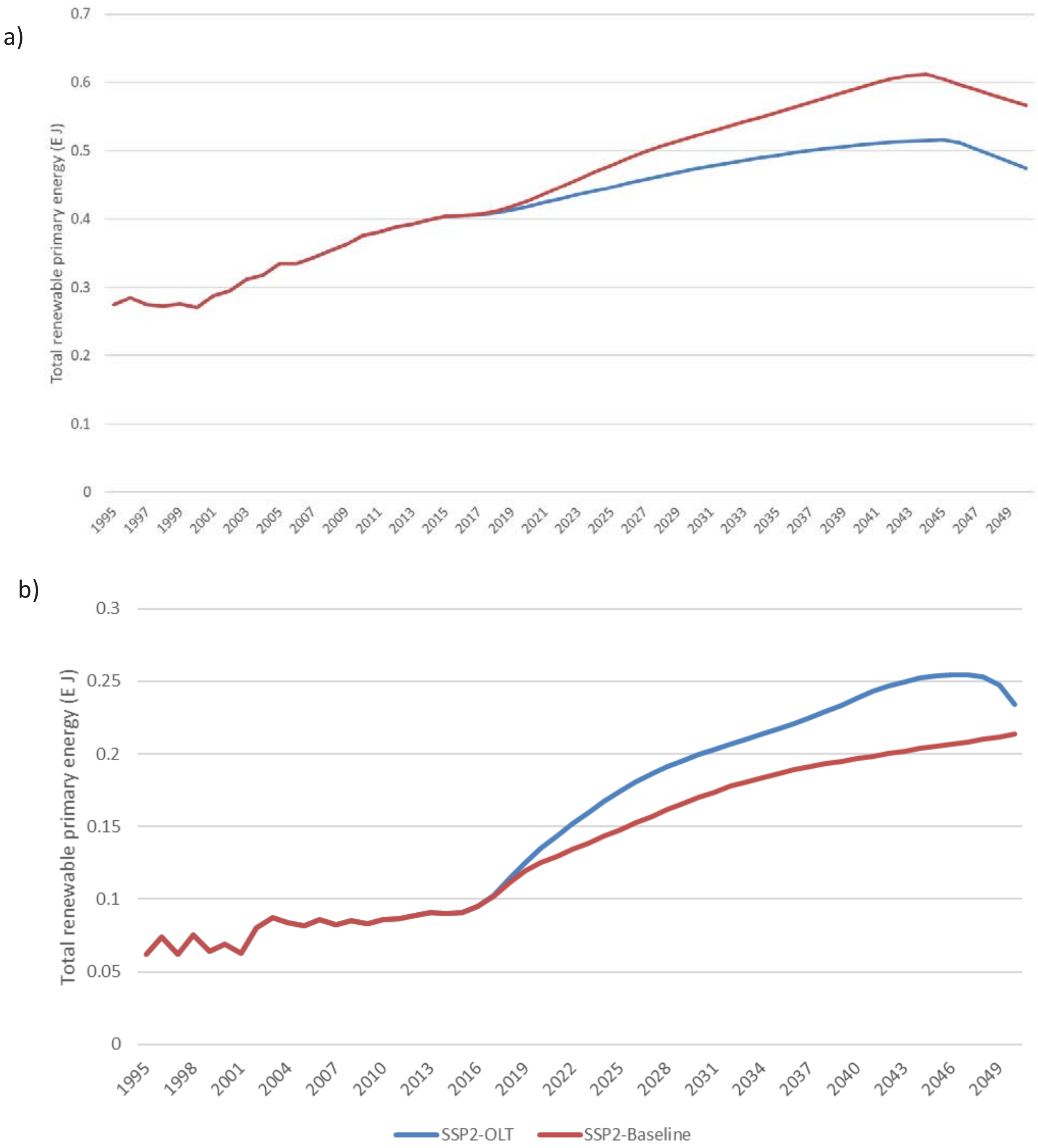

Figure 61. Total primary renewable energy in (a) Austria and (b) Bulgaria for OLT and BAU scenarios.

The consumption of non-renewable energies (oil, coal, gas and uranium) declines in the early 2020s in Austria, with an OLT scenario slightly more intensive in non-renewable primary energy. In the case of Bulgaria, the decrease starts in the late 2020s or the early 2030s, reaching similar values to those of Austria, although the BAU scenario presents higher levels of non-renewables due to the starting point of Bulgaria (Figure 62).

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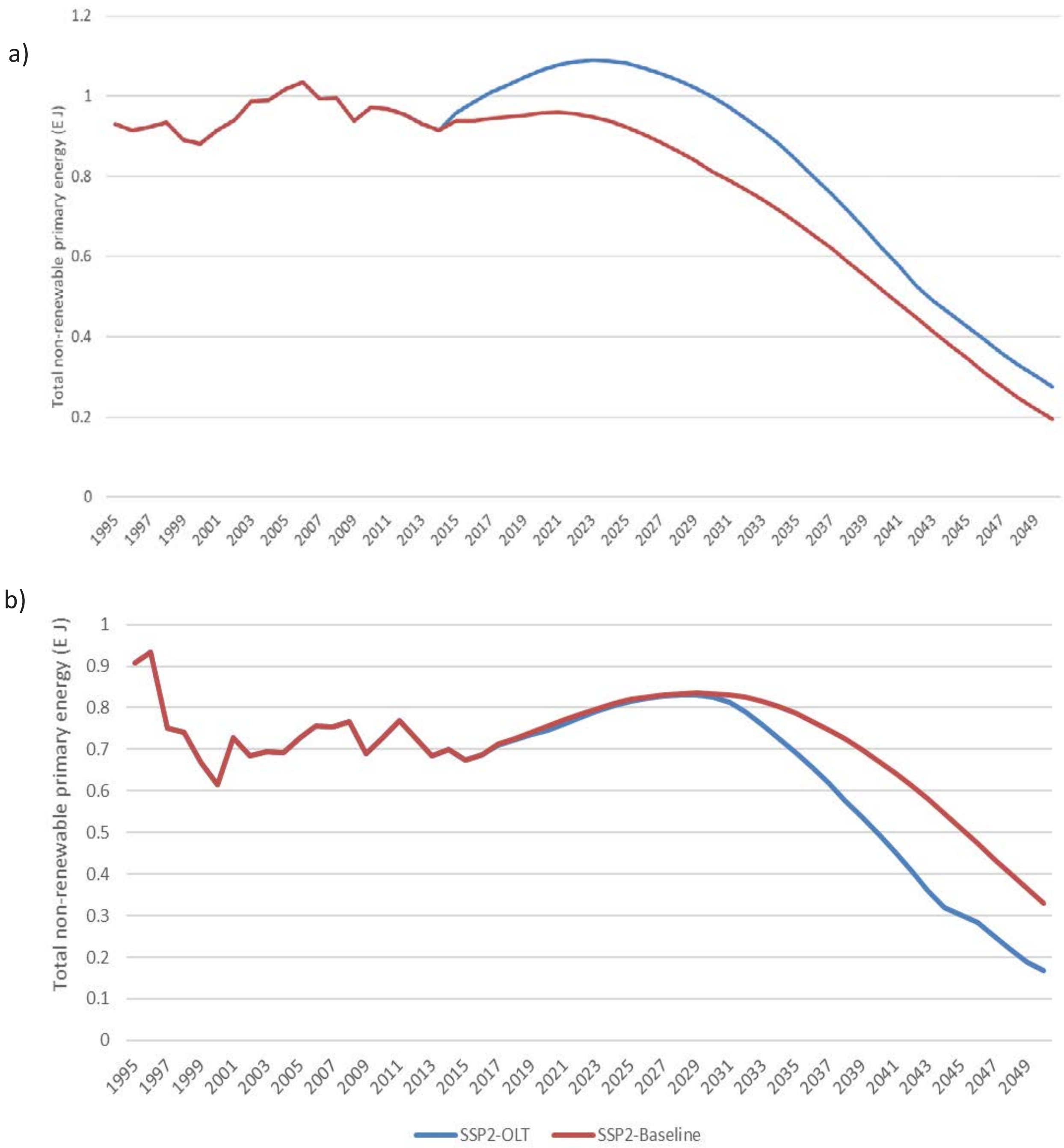

Figure 62. Total non-renewable primary energy in (a) Austria and (b) Bulgaria for OLT and BAU scenarios.

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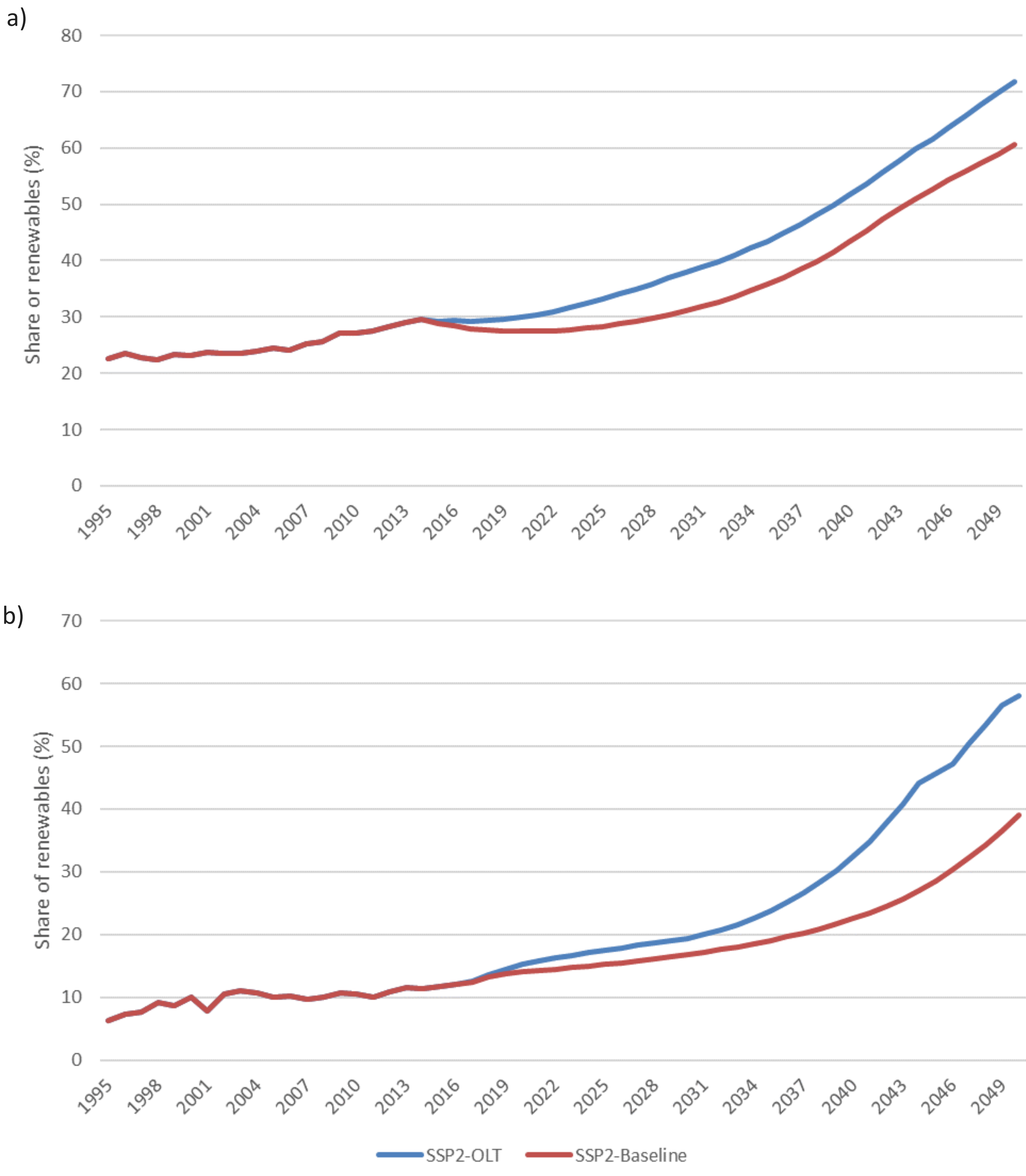

Figure 63. Share of renewables in the energy mix in (a) Austria and (b) Bulgaria for OLT and BAU scenarios.

As a result, the share of renewables in the energy mix increases to almost reach 60%-70% in the Austrian BAU and OLT scenarios, respectively; also, reaches 40%-60% in the case of Bulgarian BAU and OLT scenarios, respectively (Figure 63).

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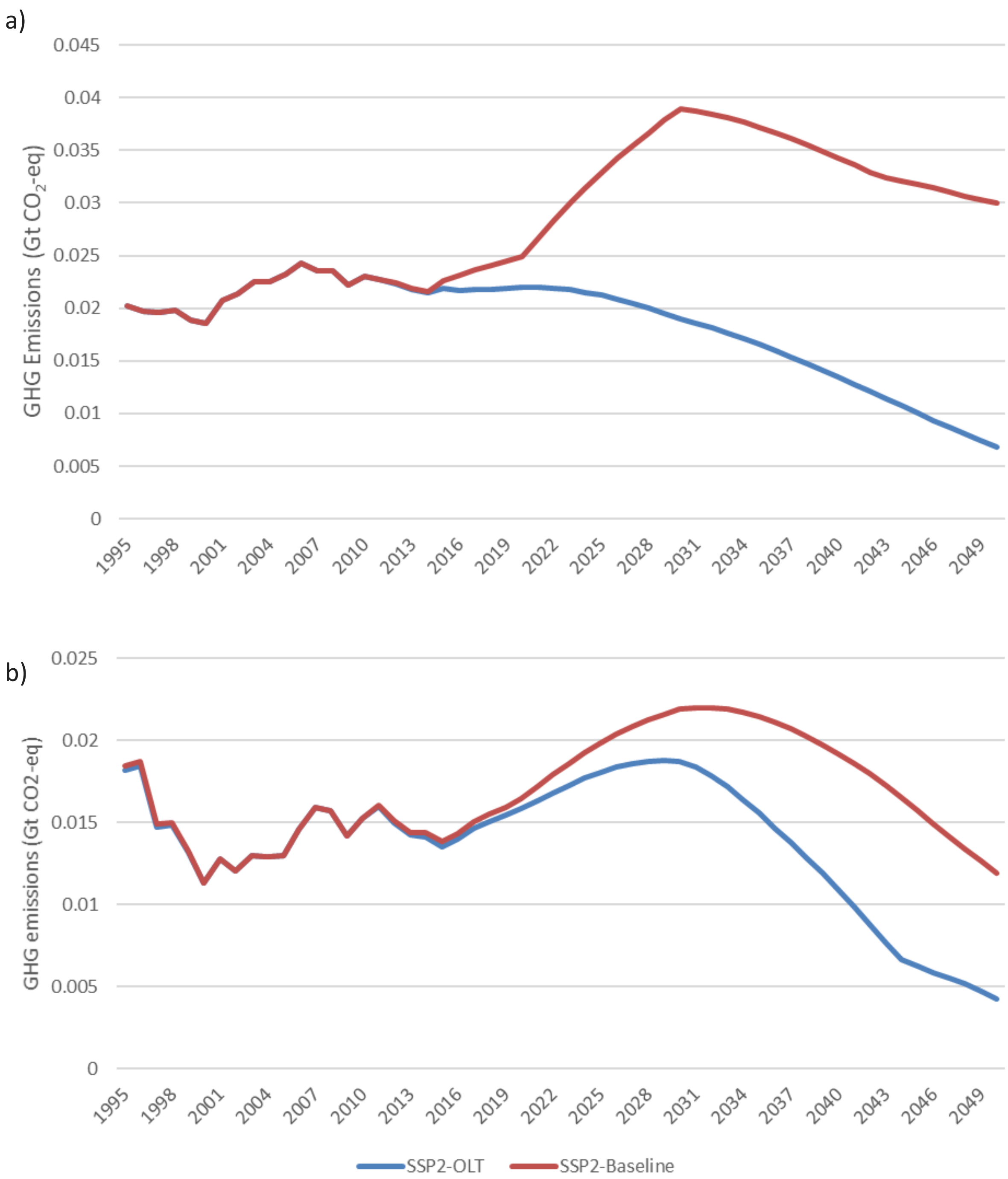

Figure 64. GHG emissions in (a) Austria and (b) Bulgaria for OLT and BAU scenarios.

GHG emission present similar patters to the non-renewables consumption. GHG emissions in the baseline scenario present higher levels of emissions in both countries. In Austria BAU emissions multiply by 6 OLT values; in Bulgaria, it multiplies by 2 OLT values (Figure 64).

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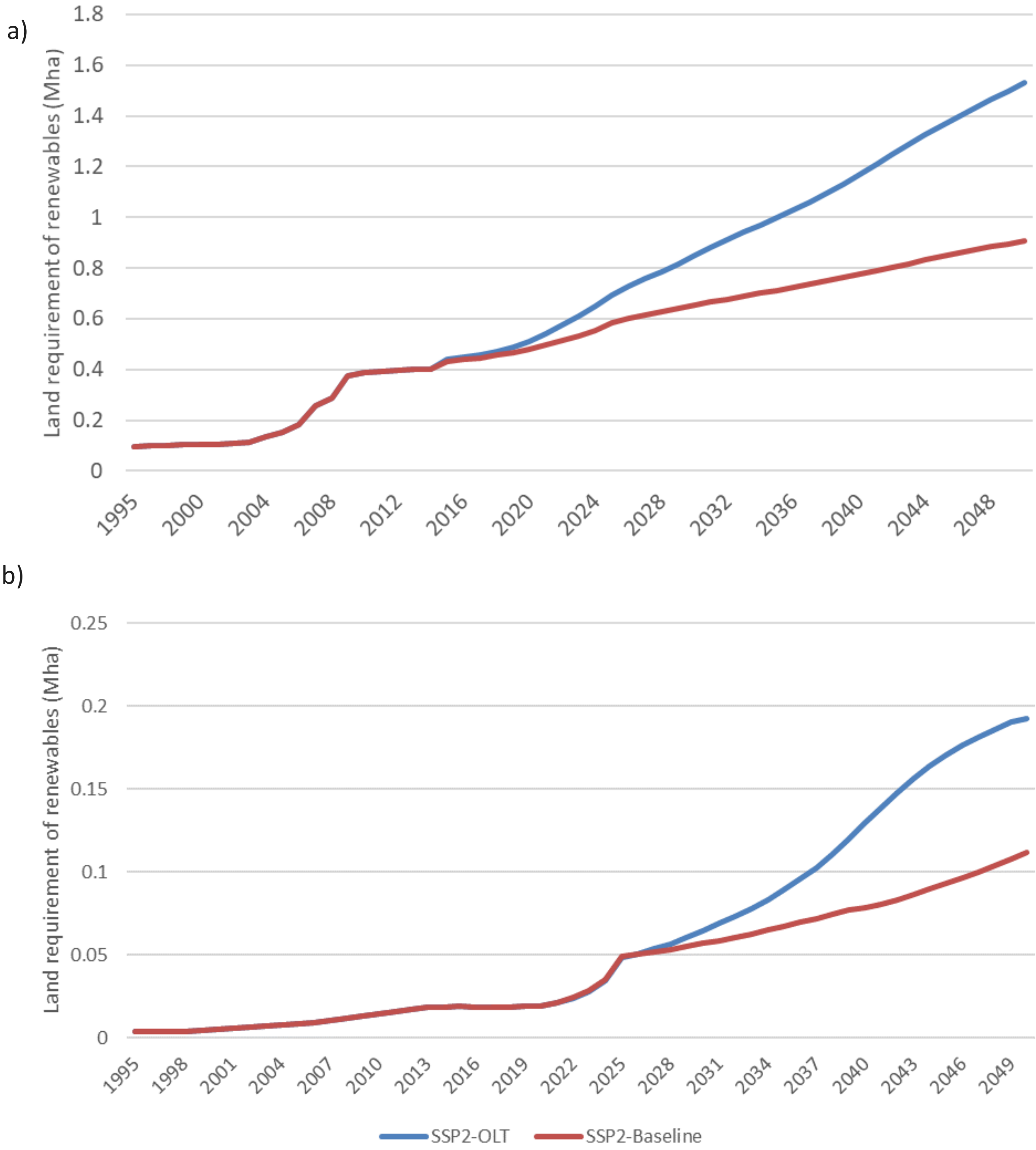

Figure 65. Land requirement for renewables in (a) Austria and (b) Bulgaria for OLT and BAU scenarios.

The expansion of renewables in both scenarios drive the increase in the use of land for energy purposes, reaching 0.9 and 1.5 Mha in Austrian BAU and OLT scenarios, respectively, and 0.1 and 0.2 in Bulgarian BAU and OLT scenarios (Figure 65). It can be compared to the 0.174 Mha and 0.168 Mha of built-up surfaces in 2015 for Austria and Bulgaria, respectively.

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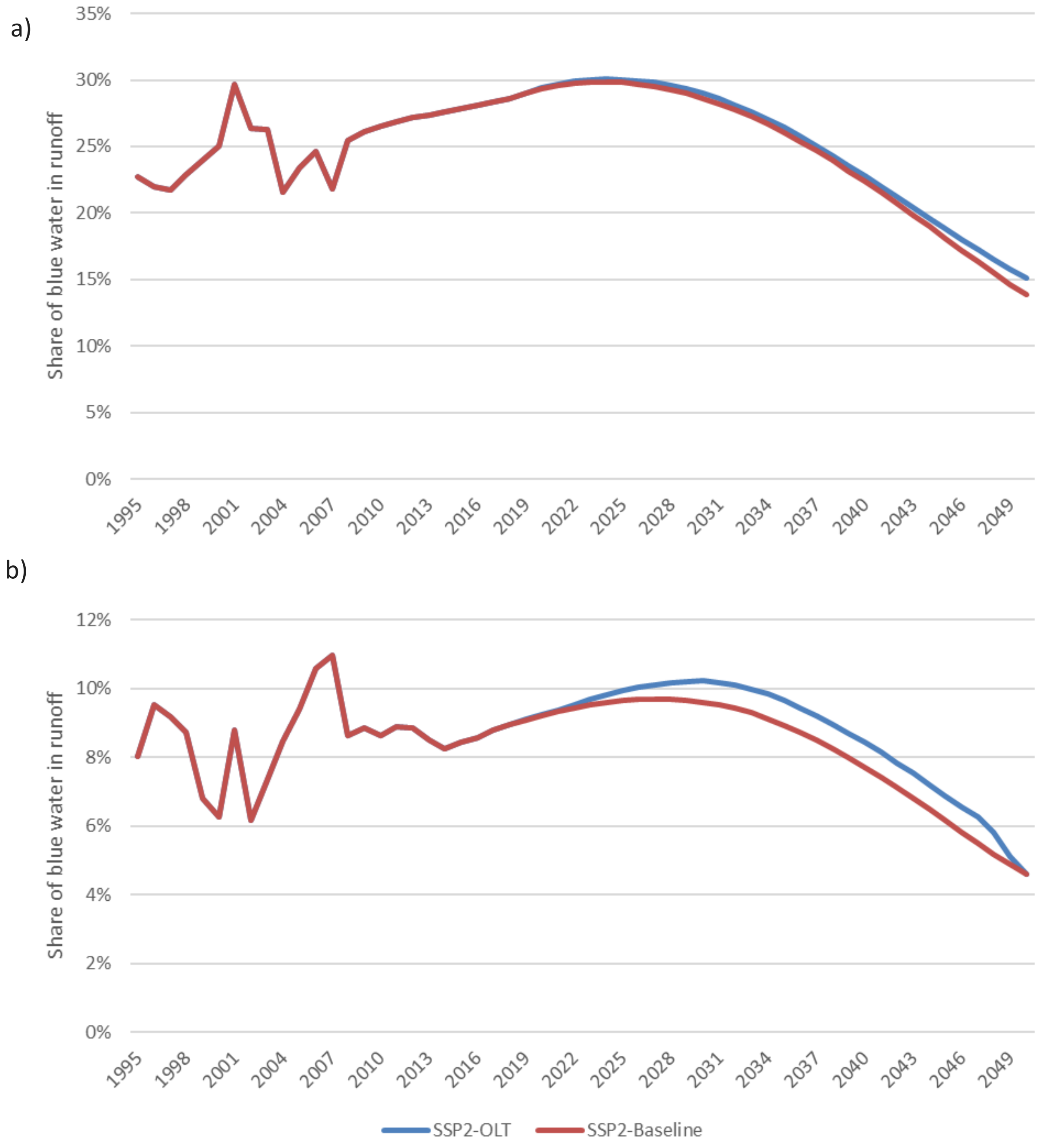

Figure 66. Share of blue water use vs. accessible runoff in (a) Austria and (b) Bulgaria for OLT and BAU scenarios.

In addition, water consumption increases until middle 2020s in Austria reaching values around 30%, decreasing up to 15% in 2050 for both scenarios. In Bulgaria, the patterns is similar, reaching the top in the 2030s (10%) and decreasing below 5% in 2050 (Figure 66).

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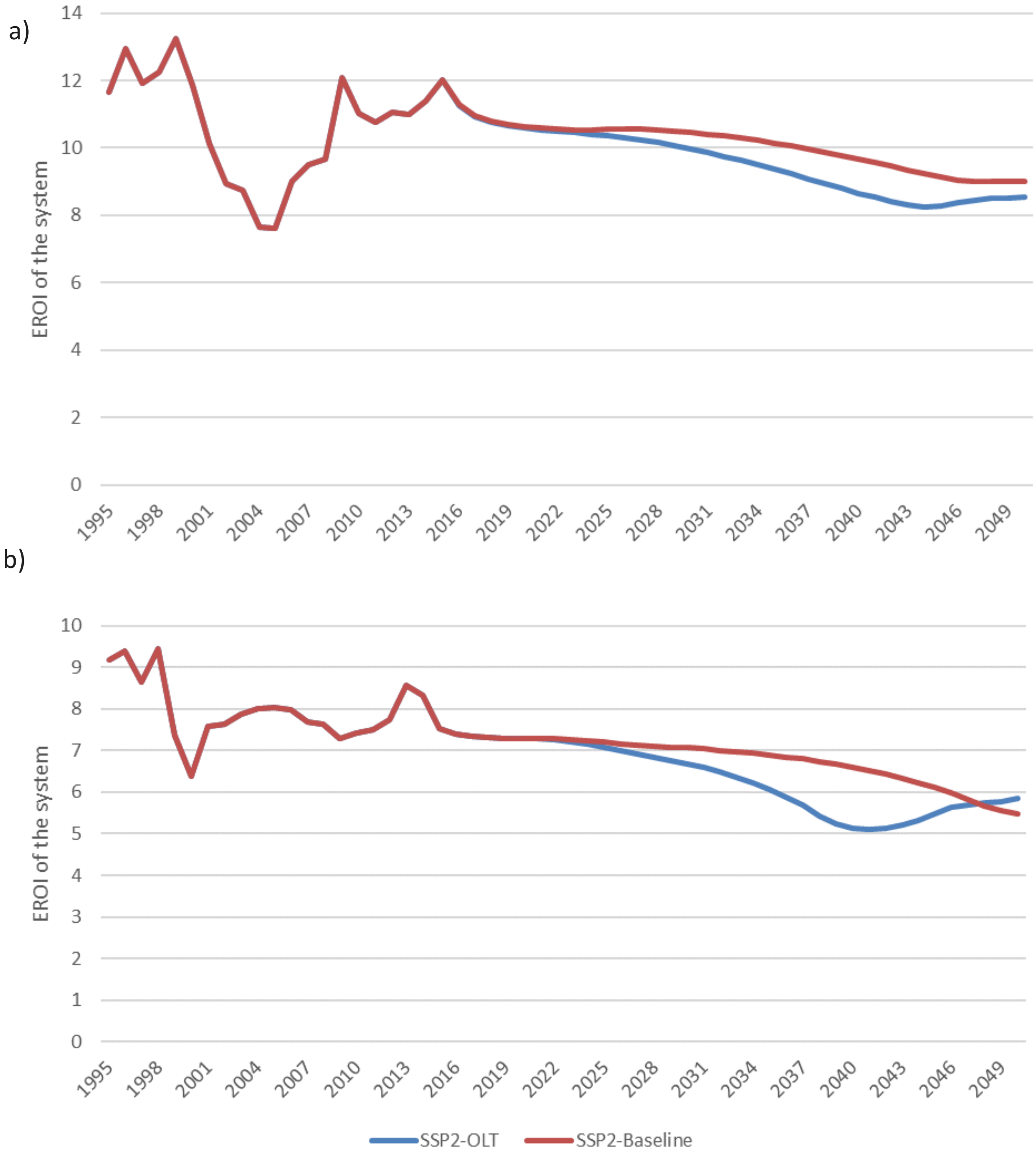

Figure 67. EROI of the system in (a) Austria and (b) Bulgaria for OLT and BAU scenarios.

In terms of the efficiency of the system, Figure 67 shows that the EROI of the system declines for both scenarios of each country. In the case of Austria, values oscillate around 9:1, and in Bulgaria EROI values are under 6:1 in 2050. These levels represent a mid-way between the minimum EROI levels identified in the literature to sustain a complex society typical from the advanced industrial

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economies of the North hemisphere (Brandt, 2017; Hall et al., 2009). The decline in the OLT scenario is higher due to the larger penetration of renewables in the energy mix of this scenario.

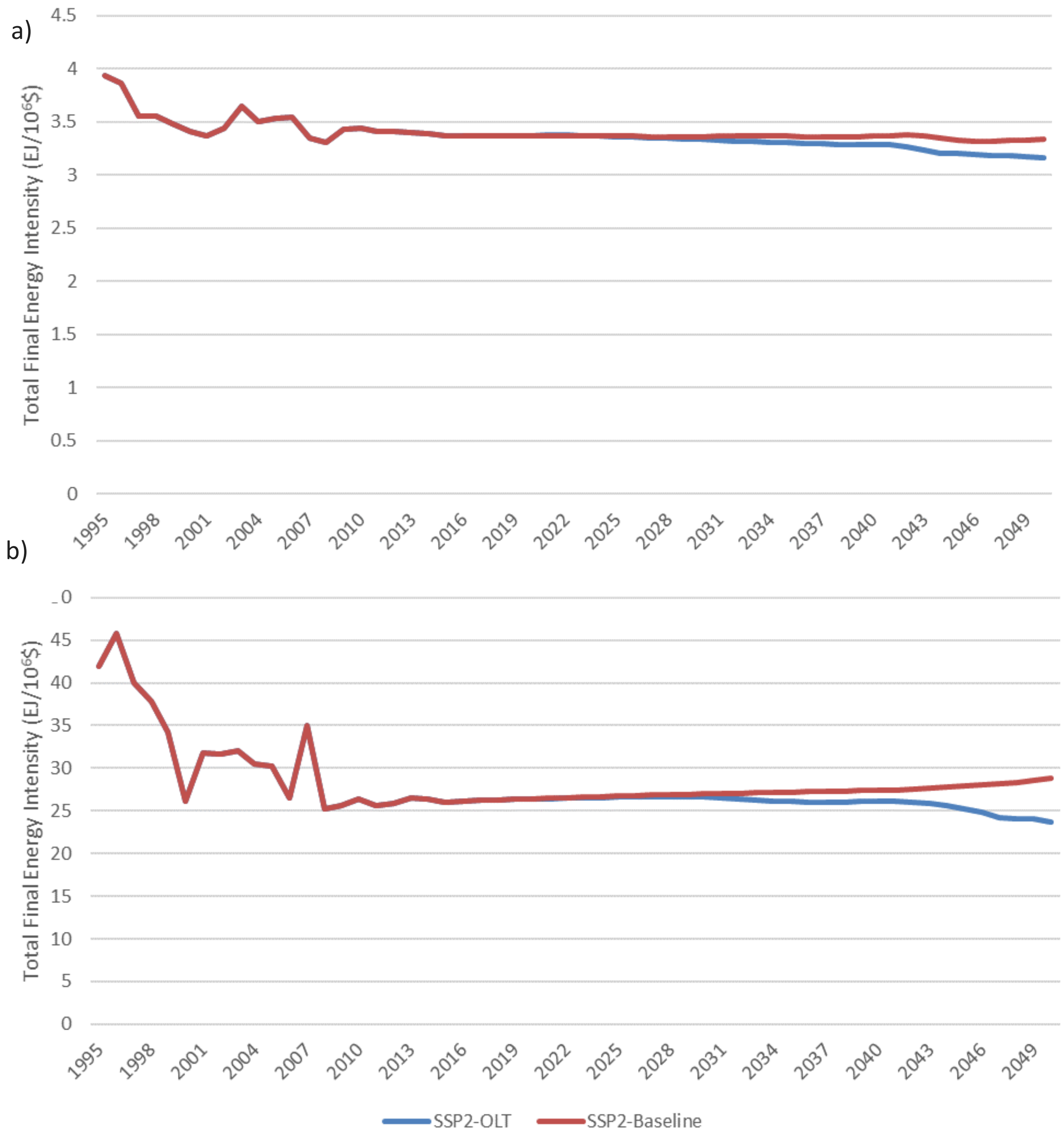

Figure 68. Total Final Energy Intensity (TFEI) in (a) Austria and (b) Bulgaria for OLT and BAU scenarios.

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Figure 68 shows the evolution of the total final energy intensity (all sectors and households aggregated). Scenario OLT achieves higher efficiency levels by 2050 in both countries from very different starting points. Bulgaria presents values 6 to 10 times intensity values of Austria.

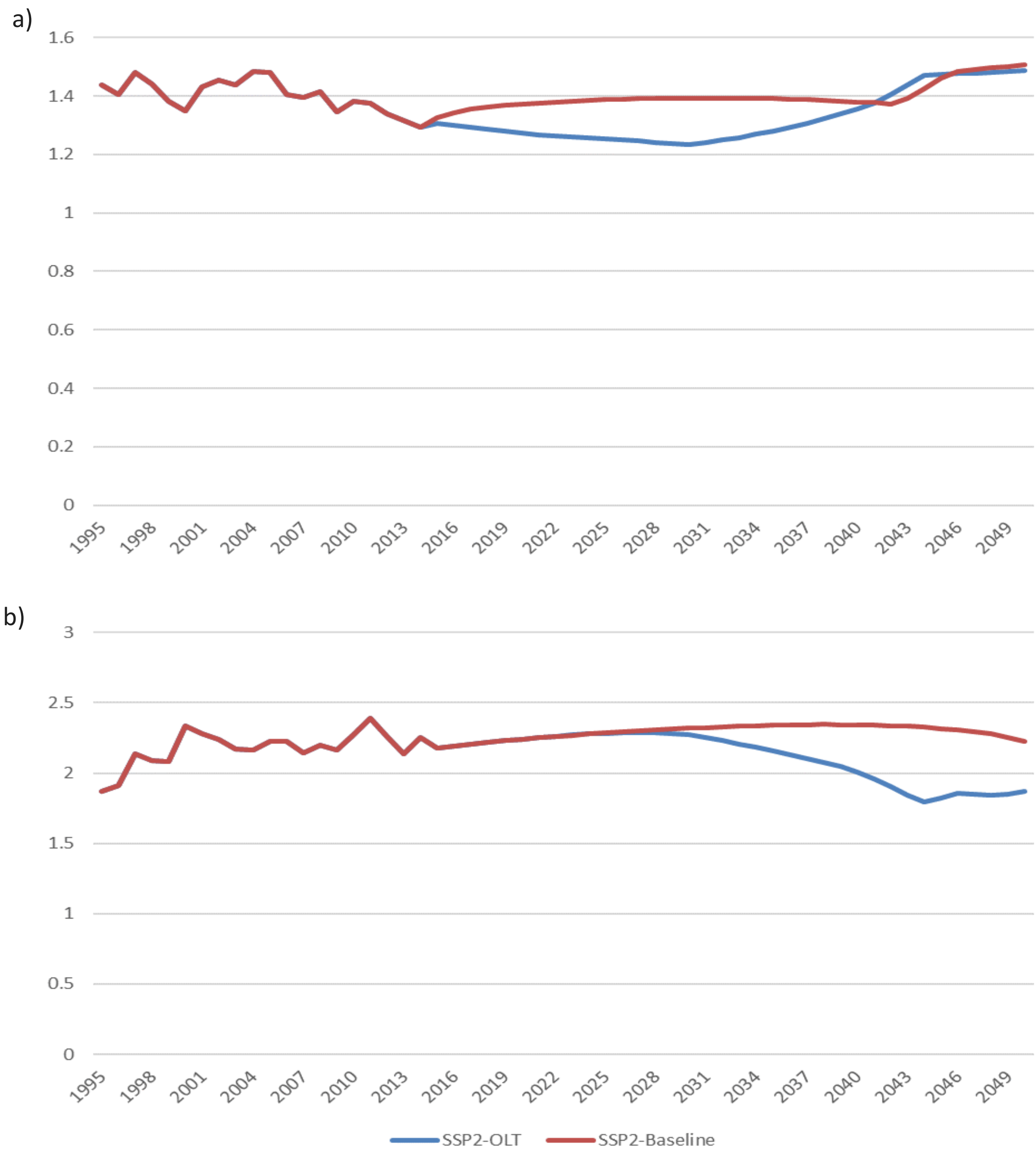

Figure 69. Physical energy intensity TPES vs net in (a) Austria and (b) Bulgaria for OLT and BAU scenarios.

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However, Figure 69 shows that in terms of physical energy intensity, i.e. taking into account the ratio between the primary energy actually consumed and the net energy used by the society, the efficiency of the system does not improve for any of the simulated scenarios and countries.

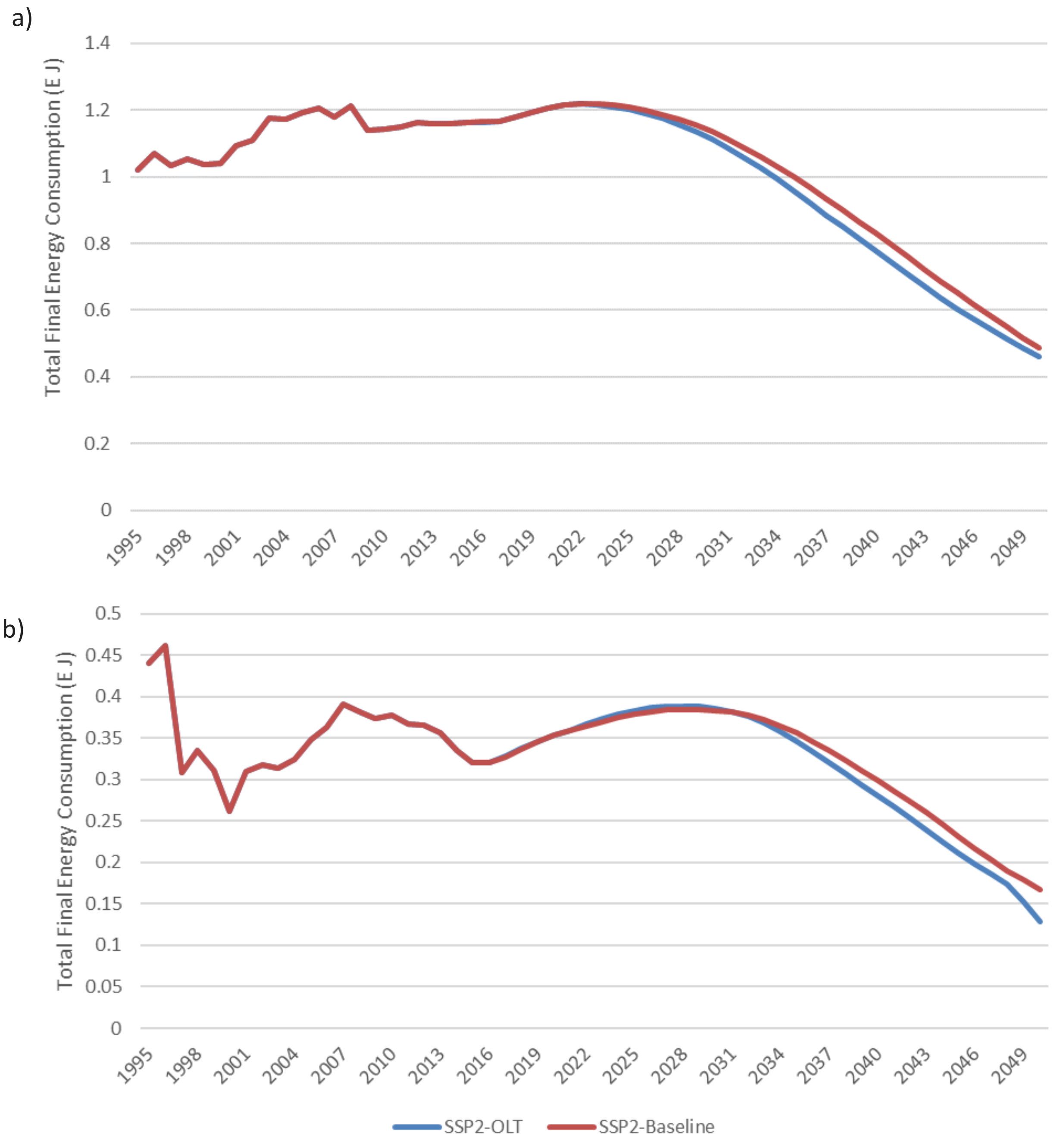

Figure 70. Total Final Energy Consumption in (a) Austria and (b) Bulgaria for OLT and BAU scenarios.

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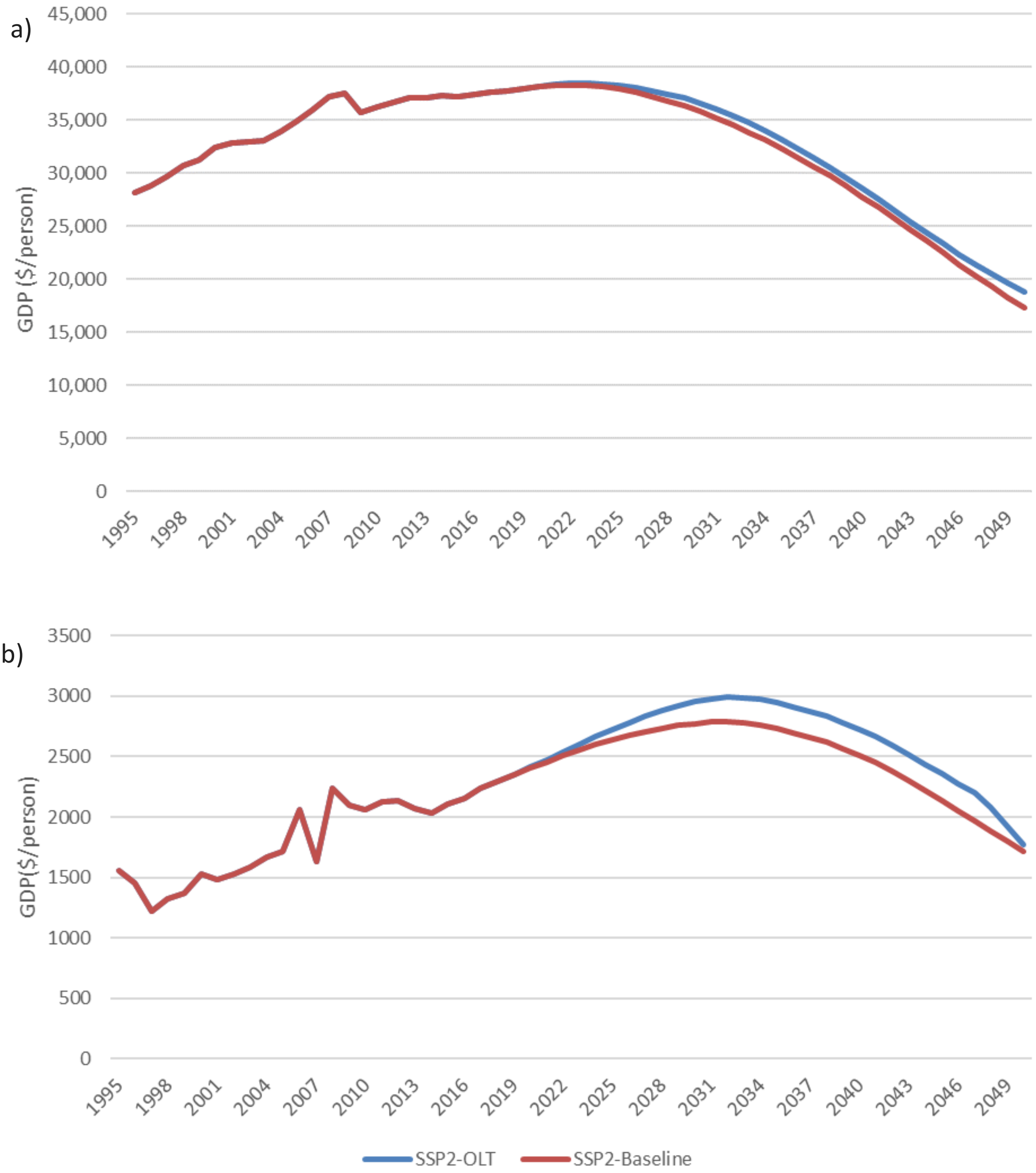

Figure 71. GDP per capita in (a) Austria and (b) Bulgaria for OLT and BAU scenarios.

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In terms of aggregated energy and monetary variables, both the Total Final Energy Consumption (TFEC) and Gross Domestic Product (GDP) show a similar trend for both scenarios and countries (Figure 60, 70 and 71) roughly maintaining current levels up to 2025-2030, and a declining thereafter. This is mainly due to the strong climate change impacts coming from the MEDEAS-W and MEDEAS_eu in both scenarios, reaching 5-6% by 2050.

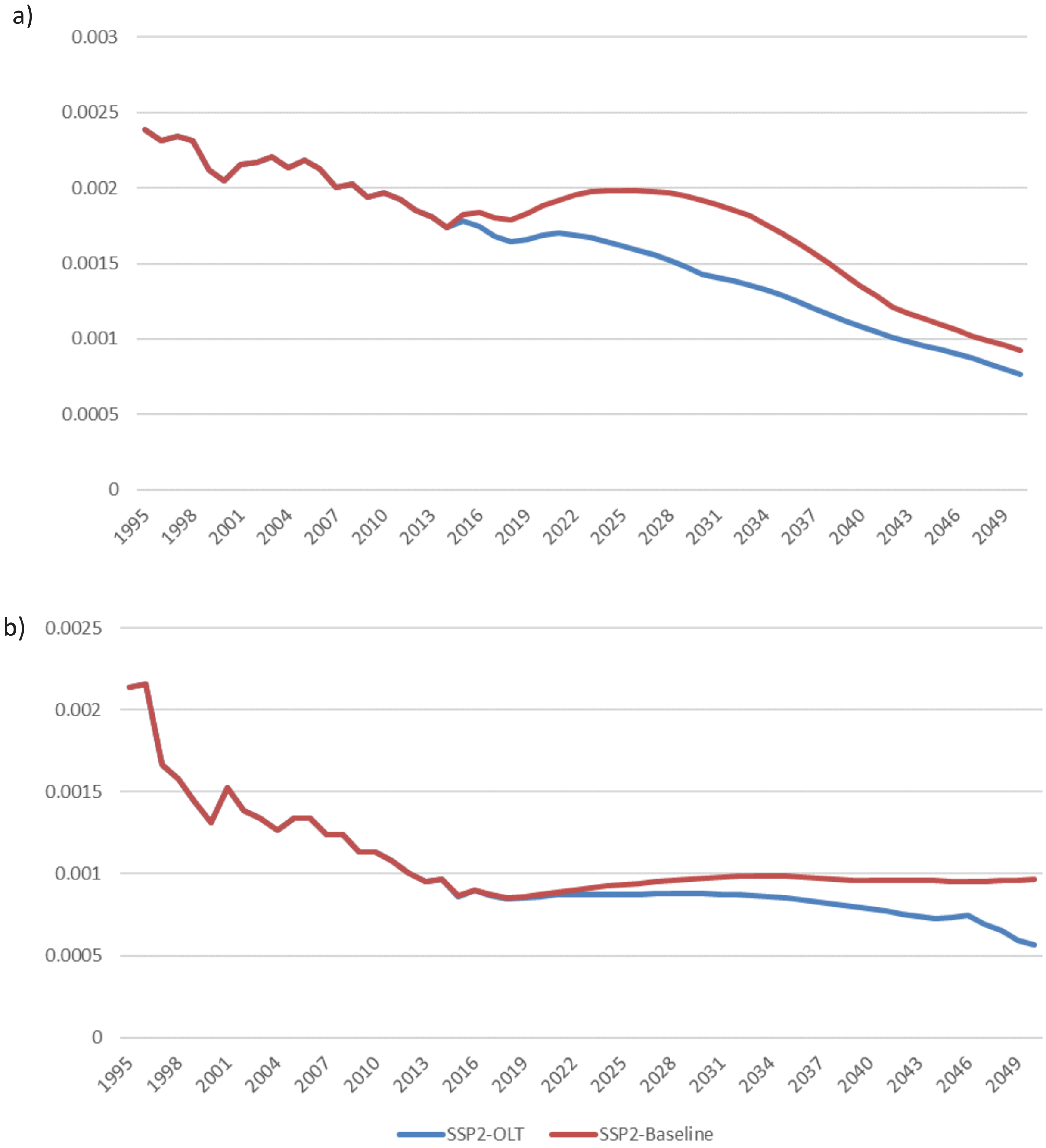

Figure 72. Share of non-renewable energy imports from RoW as a share of the global non-renewable energy extraction in (a) Austria and (b) Bulgaria for both OLT and BAU scenarios.

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In the performed simulations, trade of Bulgaria and Austria from RoW has not been constrained. However, as shown in Figure 72, the share of imports of non-renewable energies of EU from the RoW as a share of the global non-renewable energy extraction decreases to values below 0.1 % in Austria and maintains levels between 0.05 and 0.1 % in the case of Bulgarian OLT and BAU scenarios, respectively.

2.4. Limitations and further developments in the MEDEAS country-level models

As any model, MEDEAS country-level models present a number of limitations. Most of them are shared with MEDEAS_w and MEDEAS_eu models.

2.4.1. Structure of the model

By submodules, we identify the most significant potential developments:

Economy module

- The main data source (WIOD database) provides a limited number of observations (15 years from 1995 to 2008). For the update of the global version as well as development of MEDEAS_eu and country level new data sources may be used instead,
- Consistent endogenous integration of technological change in the economic submodule (dynamic evolution of technical coefficients of A matrix, energy intensities evolution, etc.),
- Dynamic evolution of technical coefficients of A matrix: in the current version the A matrix remains constant with the 2009 values while the pathways simulated by the model imply in fact structural changes in the economic structure.
- Consideration of rebound effect,
- Consideration of employment,
- Consideration of taxes. The current modelling structure may allow to separately taxing (1) households and (2) firms (Gross Operating Surplus), which would subsequently affect public investment,

Energy and infrastructures module

- Expand the modelling of energy infrastructures to all energy generation and distribution technologies,
- Computation of the EROIst (and allocation mechanism) to all energy sources,

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- Estimation of EROIst, EROIpou and EROIext of the whole system

Interaction of Energy and Economy

- Integration of primary energy intensities,
- More realistic allocation of energy scarcity between economic sectors (investigate different allocation rules beyond the proportional method implemented in this model version),
- Improve the modelling of the interaction between energy supply and demand in cases of energy scarcity for a more realistic, dynamic approach (e.g. replacement of final fuels),
- Improve the method to feed-back the EROI of the energy system to the economic submodule.

The improvement of the representation of the energy and economic interaction may allow to explore the possibility to reach a steady-state economic level based on a constant level of RES sustainable exploitation.

Materials

- Consider estimates at country levels of the future availability of minerals in the EU-28 context.
- Improve the representation of minerals supply constraints, and eventually feed-back to the energy and infrastructure submodule.
- Include the dependence of energy requirements as a function of decreasing ore for those minerals where this is a relevant fraction of the full LCA.

GHG module

- Pursue the investigation related to the design and implementation of the damage function, given the high uncertainties related to the climate change impacts,
- Implications of different levels of adaptation (Füssel, 2010; Watkiss et al., 2015),
- Explore integration of climate change feedbacks through the economy module of MEDEAS (e.g. climate impacts as loss of productive capacity),

Social and environmental impacts indicators

- Estimate jobs of NRE to be able to compare the net gain/loss of jobs after the energy transition.

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- Implement a relationship between inequality indicators (e.g. ratio labour vs capital share) and other inequality indicators such as Gini. The relationship between inequality and climate change impacts might also be investigated (Neher and Miola, 2015).

The current version of MEDEAS focus on solely 1 of the 9 planetary boundaries identified in the literature: climate change. Further versions of the model would substantially benefit through the implementation of aspects of the other dimensions: novel entities, stratospheric ozone depletion, atmospheric aerosol loading, ocean acidification, biogeochemical flows (phosphorus and nitrogen), freshwater use and land-system change (Rockström et al., 2009; Steffen et al., 2015). However, the limitations to include these dimensions are considerable given the uncertainties and complexities involved.

Given that neither climate change impacts nor potential energy scarcities play a role in most energy-economy-environment models in the literature, most models operate within a "growth paradigm". However, this is not the case in MEDEAS framework, where biophysical constraints have the potential to restrain economic production significantly. Thus, further work must be focus on the consistent integration of feedbacks that may start to operate in situations of continued GDP reductions (e.g. affecting investments, demand, etc.). These feedbacks will likely be very different depending on the societal approach to deal with this situation, e.g. maintain of the "growth paradigm" or shift to alternative "no-growth" approaches (Capellán-Pérez et al., 2015). Non-linear effects such as the so-called "Seneca effect" (i.e. when the decline is faster than growth) might also be expected.[6]

2.4.2. Policies

The current MEDEAS model has a set of policies to explore alternative scenarios. However, most of these are technological options, and non-technological alternatives focusing on the shift of individual and collective preferences and lifestyle changes are scarce (as most models in the literature (van Sluisveld et al., 2016)). Hence, further versions of MEDEAS may include:

- Alternative diets with lower carbon and energy footprint –and potentially healthier- (Green et al., 2015),
- Higher education, which could lead to reduced energy intensity in production (MEDEAS, 2016, p. 2),
- Reduction in working hours per person (MEDEAS, 2016),

[6] http://cassandralegacy.blogspot.rs/2011/08/seneca-effect-origins-of-collapse.html.

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- Demand management policies (mobility, etc.),
- Agroecological farming (reduce fossil fuel inputs, peak potassium, peak phosphorus) (García-Olivares, 2015).
- A more sophisticated modelling of the non-energy use demand would allow to implement more targeted substitution policies (Daioglou et al., 2014; García-Olivares, 2015).

2.5. Conclusions

MEDEAS country-level simulation models for Austria and Bulgaria are the main result of the deliverable 4.3 of the MEDEAS project. It is an integrated energy-economy-environment assessment model that has been developed with the systems dynamics methodology and initially programmed with the Vensim software. However, it will be later translated to Python, in order to provide a model in open-source software. This model requires as input some of the results of the simulation of the MEDEAS_w and MEDEAS_eu models. Thus, it is required to design and run in parallel two compatible storylines at global and European levels in order to obtain consistent results in MEDEAS country-level models. MEDEAS country-level models are based on the global and EU28 versions of MEDEAS and consists of 7 modules: Economy, Energy, Infrastructures, Materials, Land Use, Social and Environmental Impacts Indicators and GHG Emissions. Among the main novelties of the MEDEAS framework with respect to other IAMs are the integration of input-output matrices, feedback between vaiables of the environmental, economic and energy modules and the estimation and feedback of the EROI. In particular, the adaptation the country level includes the representation of trade (at both final goods/services and primary energy level) with the rest of the world and the rest of European countries, as well as a simplified representation of the land-use system.

By default, the simulation models of MEDEAS country-level are designed to be run in the 1995-2050 time window, being the year the unit of time, although internally the simulation has a lower sampling period. Conceptually, the MEDEAS country-level models are structured in 7 modules:

- Economy and population: the economy of MEDEAS is modelled following a post-Keynesian approach assuming disequilibrium (i.e. non-clearing markets), demand-led growth and supply constraints. The economic structure is captured by the integration of IOA (35 industrial sectors and households).
- Energy: this module includes the renewable and non-renewable energy resources potentials and availability, taking into account biophysical and temporal constraints. In

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total, 5 final fuels are considered (electricity, heat, solids, gases and liquids) and a diversity of energy technologies are modelled. A net energy approach has been followed.

- Energy infrastructures represent the infrastructures of power plants to generate electricity and heat.
- GHG Emissions: this module projects the GHG emissions for Austria and Bulgaria generated by human activities.
- Materials: estimation of the materials required for the construction and O&M of the alternative energy infrastructures.
- Land-use: it is a simple model oriented to obtain information to estimate the potential for biomass and the potential for solar energy.
- Social and environmental impacts: this module translates the “biophysical” results of the simulations into metrics related with social and environmental impacts. The objective of this module is to contextualize the implications for human societies in terms of well-being for each simulation.

These modules have been programmed in approximately 100 simulation windows and using more than 5,000 variables. The modules of economy and energy are the most extensive and reach the highest degree of disaggregation. The model consists of a modular and flexible structure, where each module can be expanded/simplified/replaced by another version or submodel, new modules can be added, etc.

The scope of the model covers all the challenges that were proposed in the project. Some of these relevant challenges are:

i) Use of information generated by the MEDEAS_w and MEDEAS_eu simulation models.
j) Integration of Input-Output Matrices (IOT) in the Economy module.
k) Modeling the commercial relations with the rest of the World and the rest of the European countries through the IOT.
l) EROI estimation and its feedback.
m) Socio-economic indicators model implementation.
n) Supply-demand closures model implementation. The energy shortage determines the feedback between the energy and the economic module.
o) The effects of climate change are feedback into energy consumption.
p) Two standard scenarios have been modelled and implemented. Three other scenarios have been programmed.

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The experimental results presented in this report illustrate the potentiality of MEDEAS country-level models by using the cases of two countries: Austria and Bulgaria. The flexible modelling approach allows to model different assumptions and hypothesis. The preliminary results show the great importance of global and EU evolution for the countries future: without a global coordinated and fast action to mitigate GHG emissions, the European countries may have too little leeway to adapt to climate change impacts.

Despite the challenges encountered with the model, there are still many limitations and uncertainties. In particular, further developments should address the inclusion of more dynamics in the economy module. Concretely, it is important to make A matrix evolving under different scenarios, but endogenously as well. More dynamization would help to improve the model's allocation between different energy fuels and technologies. Moreover, the modelling of the interaction between energy supply and demand in cases of energy scarcity should be improved. The portfolio of policies should be expanded to include more non-technological options. For these and other reasons detailed in the previous section, the interpretation of the results must be done with caution.

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3. Case study with TIMES-Austria

3.1. Introduction

This section describes the development of scenarios for Austria for the comparison and benchmarking of the MEDEAS country level models. Three different scenarios for Austria up to 2050 were developed, using the Austrian TIMES energy system model.

The goal of these scenarios was to explore the structure and requirements of an energy system that keeps the GHG emissions within the given carbon budgets. The economic or political feasibility of the changes and measures necessary to enable such a transition has not been assessed.

In this section, first the methodology, a short description of the scenarios and the main assumptions of the different scenarios are presented. Next, the detailed results for the different scenarios are shown and shortly described.

Finally, the results of the scenarios are compared, and the major conclusions are drawn.

3.2. Methodology and assumptions

3.2.1. The Austrian TIMES Energy System Model

The energy system model of the Austrian Energy Agency is a tool for the comprehensive analysis of the Austrian energy system, the assessment of the impact of policies and measures, and the development of quantified scenarios of energy demand and consumption. It is driven by the demand for energy services and useful energy demand (like living area, transport or economic activity) and covers the energy flows resulting from this demand, taking into account the various conversion cascades to the point of primary energy supply.

Its general structure and the represented set of fuels follow the structure of the energy balances and useful energy analysis of Austrian Statistical Office, which ensures comparability of results with base data for national energy policy processes and targets and for international reporting. Furthermore, this approach avoids the necessity of the development of definitions for sectors, fuels, etc. Figure 73 gives an overview on the structure of the model.

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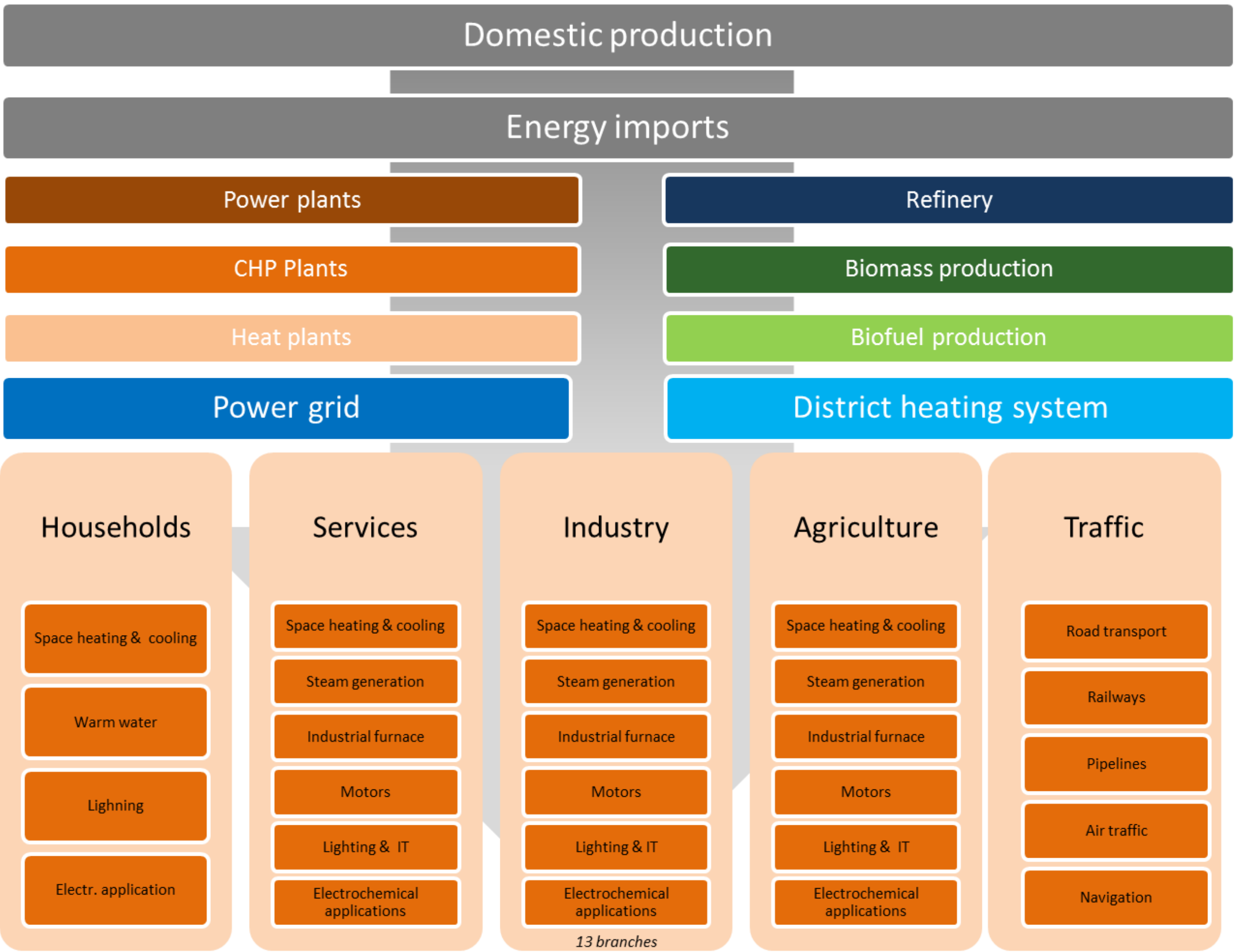

Figure 73. Structure of the Austrian TIMES energy system model.

It covers the time horizon until 2050 in an annual resolution, and takes into account different seasonal and day-night patterns for electricity and district heat generation and consumption.

Key sectors of the energy system like the generation of power and heat, the transport and the building sector are modelled using a bottom-up approach. It takes into account the technical and economic properties of the technologies used for the conversion of energy and the fulfilment of the end-use demand, like conversion efficiencies, annual load hours and technology stock development, but also investment and operational costs. All major GHG emissions related to the consumption of fuels are accounted for.

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The Austrian energy system model is a linear optimisation model that has been implemented using the TIMES model generator of the IEA-ETSAP Implementing Agreement[7].

3.2.2. Scenarios

The comparison of the MEDEAS model on the Austrian level is based on the development of three different scenarios.

The first scenario serves (Business-as-Usual, BAU) as a reference and shows the development of energy supply and consumption under the currently known boundary conditions. It takes into account the current trends and projections for population and economic growth, and assumes the implementation of the currently known policies.

Based on this BAU scenario, two more ambitious scenarios have been developed. These scenarios show a development of the energy system given a carbon budget that restricts the cumulative GHG emissions for a specified period. This budget is the same in both transition scenarios; they only differ in the year in which the deviation from the BAU scenario is being made. In the Optimal Level Transition (OLT) scenario, the transition starts in 2021, whereas in the Midterm Level Transition (MLT) scenario, the transition is delayed to 2030.

The development of the OLT and MLT scenario follows the following steps:

- The scenario results are fixed to the BAU scenario up to 2020 (OLT) and 2030 (MLT)
- An upper bound on the cumulative carbon emissions for the remaining period from 2020 resp. 2030 until 2050 is being set.
- Constraining technical scenario assumptions (e.g. retrofit rate, fuel shift limits, vehicle choice etc.) are being relaxed.
- The demand for useful energy is adjusted to meet supply restrictions (with focus on the transport demand, the modal split for person transport and the steel production).

3.2.3. Carbon Budgets

The carbon budget for Austria has been derived by INSTM. This amounts to 1.4 Gt CO_2eq for the period 2011 to 2050. In the BAU scenario, the emissions from 2011 to 2060 amount to 2.4 Gt CO_2eq.

[7] https://iea-etsap.org/index.php/etsap-tools/model-generators/times

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The carbon budget includes both energy and non-energy related emissions, and represents also statistical, modelled and projected data. The sources for these numbers are:

- Austria's Annual Greenhouse Gas Inventory
- Transition-scenario of the report "Energie- und Treibhausgas-Szenarien im Hinblick auf 2030 und 2050", Vienna, May 2018.
- Model results.

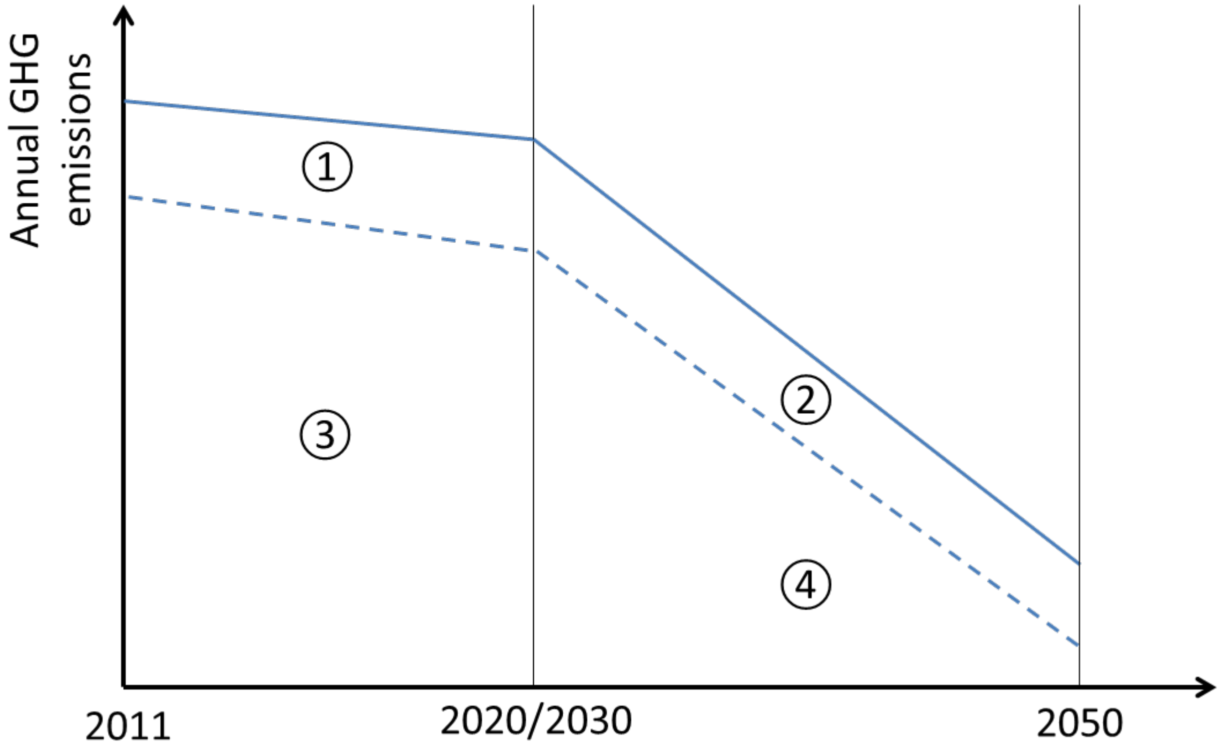

Figure 74 Decomposition of the carbon budget in four different areas to inform the model's scenarios.

Figure 74 shows the decomposition of the carbon budget into these different contributions:

- Area 1 represents the non-energetic emissions from 2011 until 2020 resp. 2030. This value is taken from the national emission report until 2015, and from 2015 to 2020/2030 from the transition scenario of the report on the national emission scenarios
- Area 2 contains the non-energy emissions from 2021/2031 to 2050. The value stems from the transition scenario of the report on the national emission scenarios

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- Area 3 corresponds to the energy-related emissions from 2011 to 2020/2030[8]. This value has been calculated from the results of the BAU scenario
- Area 4 shows the energy related emissions from 2021/2031 to 2050. These emissions are subject to a cumulative constraint.

As for the OLT scenario, the non-energy related GHG amount 41 $MtCO_2e$ for 2011-2020 and 99 $MtCO_2e$ for 2021-2050 whereas the energy related GHG amount 695 $MtCO_2e$ for 2011-2020 and 565 $MtCO_2e$ for a four times longer period 2021-2050.

The results for the carbon budget for the OLT scenario are presented in Table 36 below.

Table 36. carbon budget divided by sectors for the OLT scenario.

Area	Description	Emissions (Mt CO_2eq)
1	Non-Energy GHG emissions 2011-2020	41
2	Non-Energy GHG emissions 2021-2050	99
3	Energy GHG emissions 2011-2020	688
4	Energy GHG emissions 2021-2050	572
Total	Total GHG emissions 2011-2050	1,400

As for the MLT scenario, the non-energy related GHG amount 80 $MtCO_2e$ for 2011-2030 and 60 $MtCO_2e$ for 2031-2050 whereas the energy related GHG amount 1328 $MtCO_2e$ for 2011-2030. Although the annual emissions for Austria are declining from 2021 to 2050, the sum of the energy related GHG emissions from 2011 to 2030 and the non-energy GHG emissions from 2011 to 2050 is higher than the carbon budget of 1.4 Gt CO_2eq. The results for the carbon budget for the MLT scenario are presented in Table 37 below.

[8] Until 2016 the GHG-emission of the energy related component is compliant with Austria's Annual Greenhouse Gas Inventory.

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Table 37. Carbon budget divided by sectors for the MLT scenario.

Area	Description	Emissions (Mt CO_2eq)
1	Non-Energy GHG emissions 2011-2030	80
2	Non-Energy GHG emissions 2031-2050	60
3	Energy GHG emissions 2011-2030	1,328
4	Energy GHG emissions 2031-2050	-
Total	Total GHG emissions 2011-2050	1,468

3.2.4. Implementation of the scenarios

3.2.4.1. BAU scenario assumptions

The key drivers of the scenarios are population and economic activity. As shown in Table 38 and Figure 75, Population and the associated number of households grow from 2020 to 2050 (on average) by 0.4 % p.a. The economic activity is further disaggregated into 3 sectors, with the industry sector being again split into 13 industrial branches. The average annual growth rate of the overall economy is 1.5 % p.a., the industry grows with 1.4 % p.a.

Table 38. Population and households.

	2010	2020	2030	2040	2050	*Annual growth*	
						2010 - 2030	***2030 - 2050***
Population	8,361,069	8,941,643	9,331,401	9,561,947	9,702,682	*0.6%*	*0.2%*
Households	3,533,610	3,907,044	4,139,640	4,307,680	4,420,584	*0.8%*	*0.3%*

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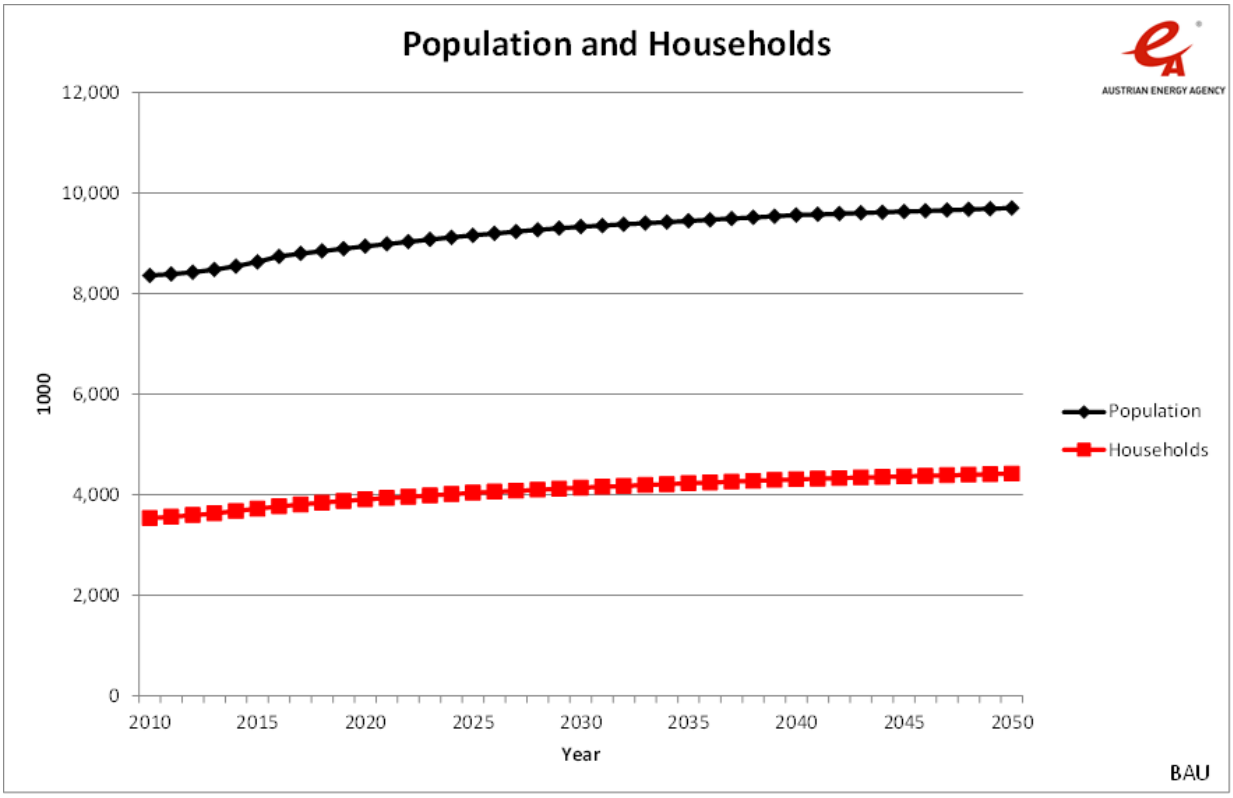

Figure 75 Population and households.

The road transport demand is driven by the population and the economic activity (Table 39 and Figures 76-78), and grows slightly faster than the respective driver, by 0.5 % p.a. (person transport demand) and 1.5 % p.a. (freight transport demand) (Table 40 and Figure 79).

Table 39 Gross Production Value by Sector.

	2010	2020	2030	2040	2050	*Annual growth*	
						2010 - 2030	*2030 - 2050*
Total	516,450	615,426	714,924	838,150	969,513	*1.6%*	*1.5%*
Services	320,660	379,425	444,514	525,521	612,962	*1.6%*	*1.6%*
Agriculture	8,680	9,430	9,796	10,128	10,147	*0.6%*	*0.2%*
Industry	187,110	226,571	260,614	302,501	346,404	*1.7%*	*1.4%*
Iron and Steel Industry	2,339	3,441	4,277	5,336	6,546	*3.1%*	*2.2%*
Chemical Industry (incl. Petrochemical)	15,930	19,535	24,134	29,986	36,643	*2.1%*	*2.1%*
Non-Ferrous Metals	10,821	14,192	16,614	19,613	22,843	*2.2%*	*1.6%*

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	2010	2020	2030	2040	2050	*Annual growth*	
						2010 - 2030	*2030 - 2050*
Stone, Pottery & Building Material Industry	6,190	6,693	7,226	7,827	8,309	*0.8%*	*0.7%*
Transport Equipment	13,970	19,404	23,769	29,319	35,594	*2.7%*	*2.0%*
Machinery	43,220	57,420	66,725	78,285	90,622	*2.2%*	*1.5%*
Ore Extraction Industry	6,880	8,591	9,589	10,791	11,961	*1.7%*	*1.1%*
Food, Drinks & Tabacco	12,490	16,059	20,513	26,221	32,844	*2.5%*	*2.4%*
Paper and Pulp & Printing	8,870	9,024	9,216	9,310	9,041	*0.2%*	*-0.1%*
Wood and Wood Products	7,370	8,819	9,775	10,916	11,997	*1.4%*	*1.0%*
Construction	43,650	47,674	52,690	58,609	64,136	*0.9%*	*1.0%*
Textile, Leather & Clothing	2,980	2,877	3,033	3,184	3,254	*0.1%*	*0.4%*
Other Industries	12,400	12,842	13,053	13,104	12,613	*0.3%*	*-0.2%*

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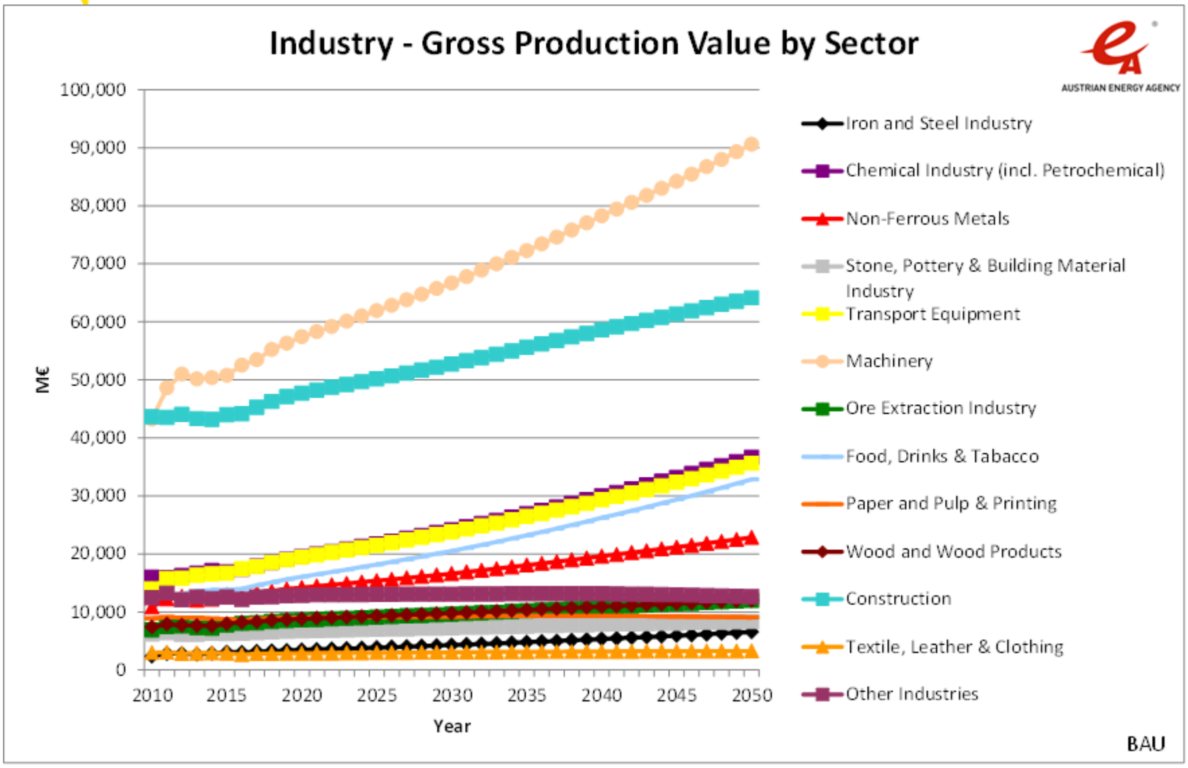

Figure 76. Industry - Gross Production Value by Sector.

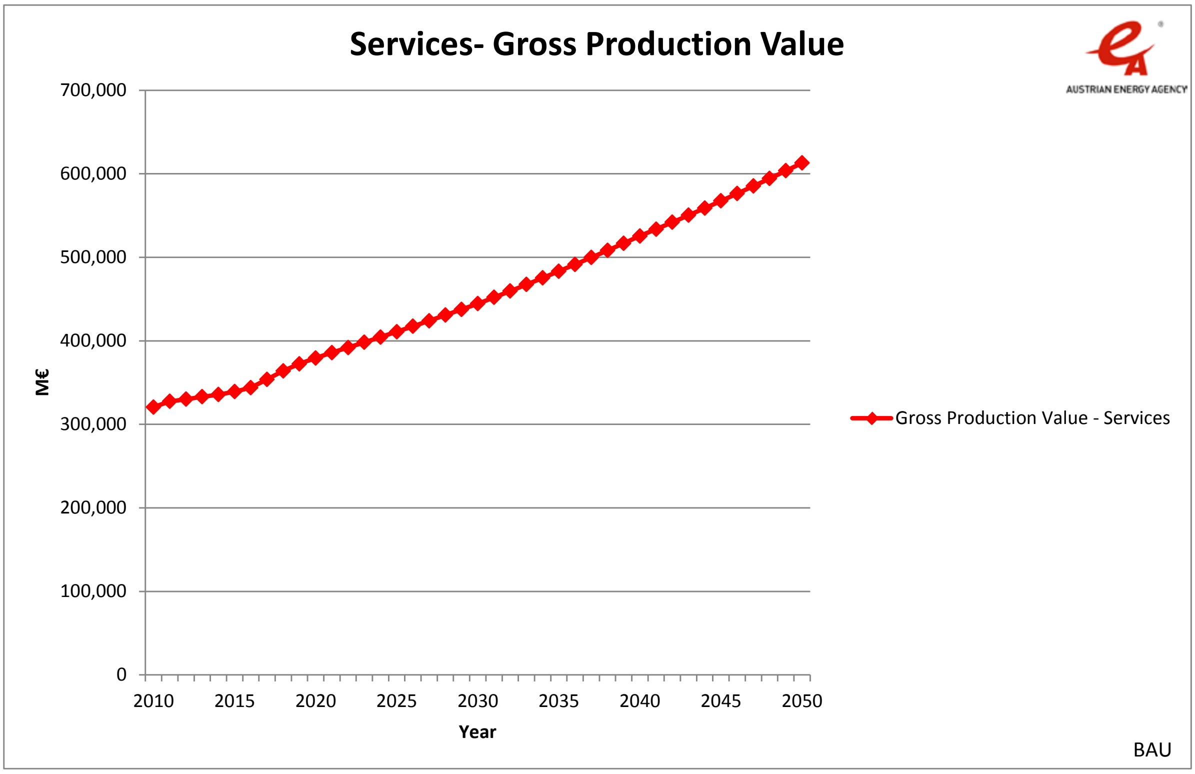

Figure 77. Services – Gross Production Value.

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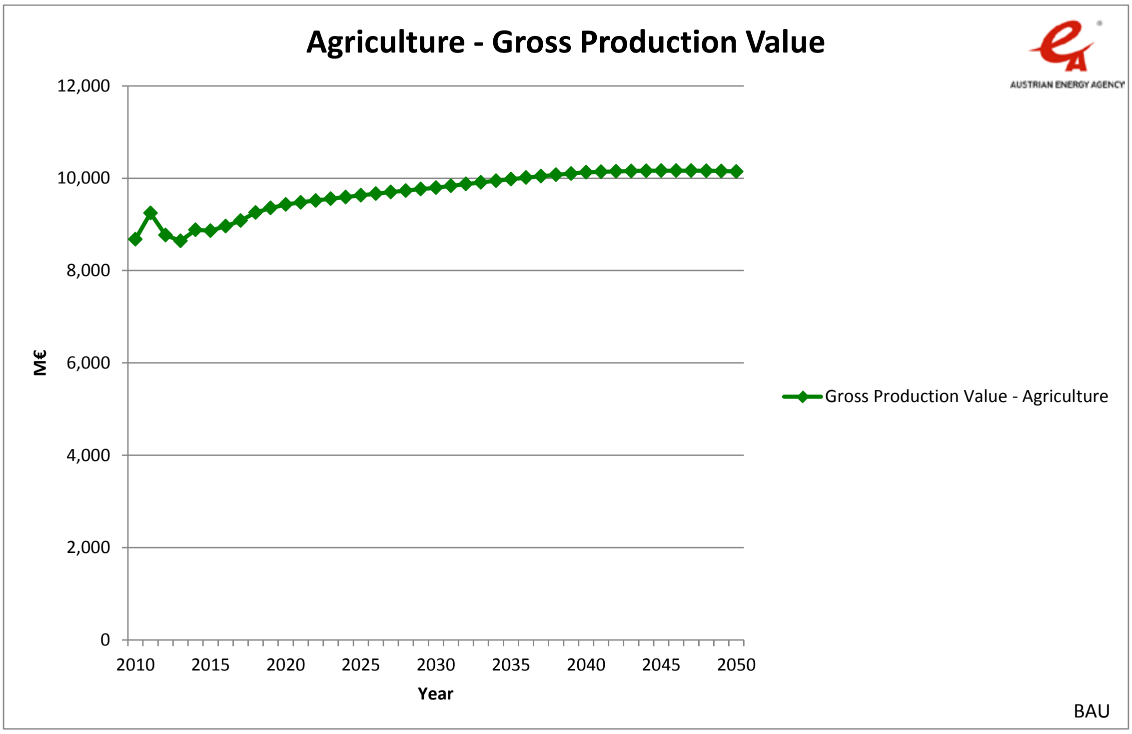

Figure 78. Agriculture - Gross Production Value.

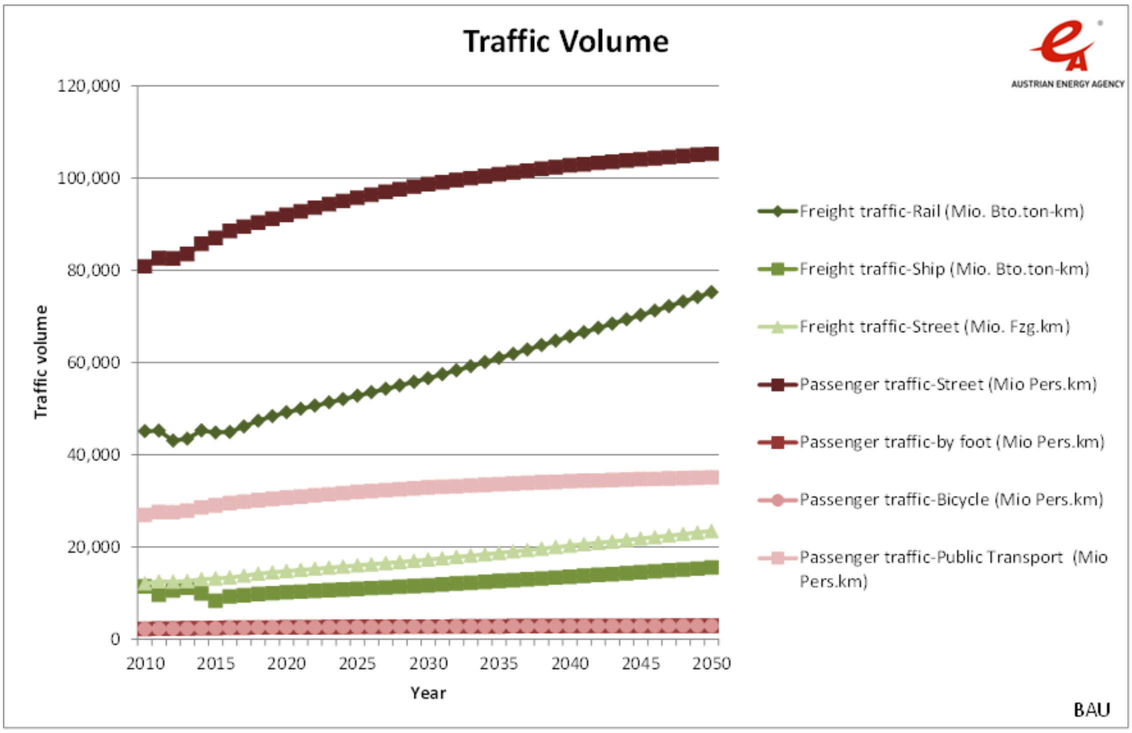

Figure 79. Traffic Volume – Scenario BAU

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Table 40. Traffic Volume.

	2010	2020	2030	2040	2050	*Annual growth*	
						2010 - 2030	***2030 - 2050***
Freight traffic-Rail (Mio. Bto.ton-km)	45,120	49,210	56,603	65,701	75,236	*1.1%*	*1.4%*
Freight traffic-Ship (Mio. Bto.ton-km)	11,451	10,156	11,682	13,560	15,528	*0.1%*	*1.4%*
Freight traffic-Street (Mio. Fzg.km)	12,089	14,790	17,276	20,293	23,489	*1.8%*	*1.5%*
Passenger traffic-Street (Mio Pers.km)	80,829	92,004	98,675	102,745	105,249	*1.0%*	*0.3%*
Passenger traffic-by foot (Mio Pers.km)	2,245	2,556	2,741	2,854	2,924	*1.0%*	*0.3%*
Passenger traffic-Bicycle (Mio Pers.km)	2,245	2,556	2,741	2,854	2,924	*1.0%*	*0.3%*
Passenger traffic-Public Transport (Mio Pers.km)	26,943	30,668	32,892	34,248	35,083	*1.0%*	*0.3%*

3.2.4.2. OLT scenario assumptions

The OLT scenario has been developed based on the BAU scenario results (Figure 80). Two types of adjustments have been implemented to keep the emissions between 2021 and 2050 within the given carbon budget, affecting the technology choice and demand changes The technologies and demands have been chosen based on their impact on meeting the given carbon budget.

In the most important sectors, technical flexibilities have been implemented (Table 41).

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Table 41. Flexibilities implemented in the OLT scenario for TIMES-Austria.

Sector	Flexibilities
Buildings	The limit for the retrofit rates has been removed, to allow the amount of retrofitting necessary to reduce the carbon emissions from this sector. The choice of the type of boiler has been relaxed to allow the switch to carbon-free heating systems (mainly heat pump and district heat).
Industry	Energy efficiency can be improved, with the savings and the associated costs based on the branch and useful energy category. Additionally, the switch from fossil to non-fossil fuels based on the branch and useful energy category has been made possible.
Steel production	The production of raw iron and steel using conventional blast furnaces and coke oven plants is changed to electric arc furnaces and hydrogen reduction methods.
Transport	The distribution of the engine types that enter the fleet each year has been relaxed to allow a switch to low carbon technologies like electric motors, batteries and hydrogen fuel cells. All diesel trains are replaced by electric trains. The efficiency of planes is improved annually by 2% (instead of 0.5% p.a. in BAU)
Energy production	The maximum potential for carbon-free technologies like wind and solar power has been increased to the highest numbers available (in 2050: PV - 25.7 GW instead of 10 GW, Wind - 17.5 GW instead of 10 GW). Autoproducers based on fossil fuels are being phased-out between 2021 and 2030.

In a second step, the growth of selected useful energy demands has been changed (Table 42).

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Table 42. Demand changes implemented in the OLT scenario for TIMES-Austria.

Sector	Flexibilities
Steel production	The change of the production technologies leads to a reduction of the annual steel production to 75% in 2030, and a slight decrease to 55% in 2050.
Transport	The specific person and freight transport demand is decreasing. The share of public and bicycle transport in the modal split of person transport is increasing. Air transport demand is growing by 0.5 % slower.

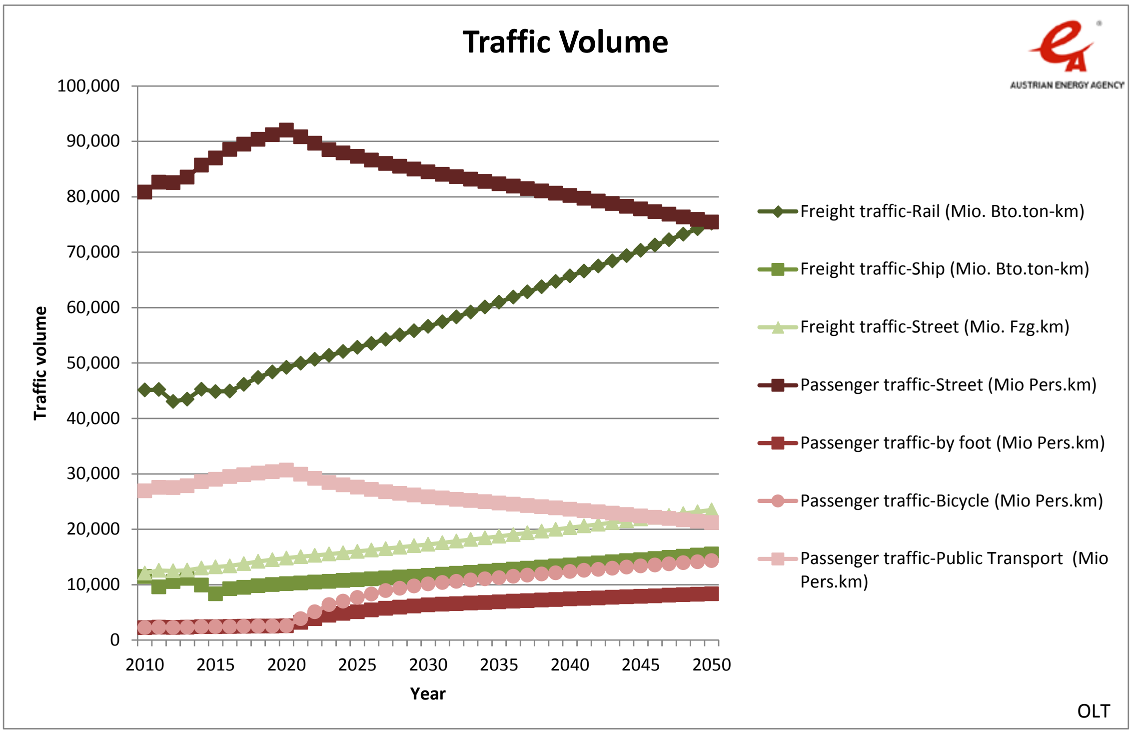

Figure 80. Traffic Volume – Scenario BAU.

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3.2.4.3. MLT scenario assumptions

As the calculations required for the implementation of the MLT carbon budget showed (see Table 37), literally the whole carbon budget until 2050 was used until 2030. Therefore, it was not possible to develop measures and assumptions for a MLT scenario that meets the given carbon budget.

3.3. Results

Below, the results for the BAU and OLT scenarios for Austria are shown. The structure of the representation of the results of each scenario follows a simple structure:

- Results for the total energy system (Final Energy, Gross domestic consumption (i.e. the primary energy consumption), and GHG-emissions;
- Sectoral results of the final energy consumption (Residential (i.e. households), Industry, Services, Agriculture, Transport (incl. road transport), and Road transport;
- Consumption and production of electricity and heat, by sector resp. by technology;
- Selected indicators (FEC per GPV, FEC per capita, GDC per GPV and per capita, GHG per capita, Share of renewable energy in gross final energy consumption)

3.3.1. BAU scenario

The total final energy consumption (Figure 81) stays constant until 2050, but a shift of the share of the fuels can be observed. The share of liquid fossil fuels – the most important group of fuels now - declines, and electricity takes over. The share of all other fuels remains stable. Also, a shift between the sectors (Figure 82) can be observed. Whereas households and transport consumption declines, the industrial consumption grows.

The gross domestic consumption (Figure 84) – which is essentially the primary energy consumption including the non-energetic use – increases slightly. Two thirds of the gross domestic consumption in 2050 is still based on fossil fuels, but here natural gas is taking over from coal and oil, and the share of fossil fuels declines slightly. The results of this development can also be seen in the very moderate decrease of GHG emissions (Figure 85).

In the household sector (Figure 86) and the service sector (Figure 88), development is dominated from the improved insulation of buildings and the switch to other heating systems. In both sectors, the share of the fossil fuel consumption decreases significantly, mainly due to the switch of the

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heating systems towards biomass, heat pumps and district heat. In the industry sector (Figure 87), the consumption grows with the economic growth, slightly dampened by efficiency developments. In the transport sector (Figures 90 and 91), the reduction of the consumption due to the shift towards more efficient vehicle technologies (i.e. more hybrid and battery electric vehicles) outweighs the transport demand growth.

The electricity production (Figure 93) grows slower than the electricity consumption (Figure 92), which leads to a doubling of the imports, although significant capacities of wind power and PV are being added. The consumption of district heat (Figure 94) stems from the household and the service sector, with a rising share from industry. The production (Figure 95) is dominated by biomass CHP and natural gas CHP, but the contribution of Power2Heat is growing.

The specific final energy (Figure 96, Figure 97) and the specific gross domestic consumption (Figure 98) both are decreasing. The demand per gross production value decreases faster because the economic growth rate outweighs the population growth rate. The shift to more renewable energy leads to a decrease of the GHG emissions per capita of about 30% (Figure 99), and an increase of the share of renewable energy of about 45% (Figure 100).

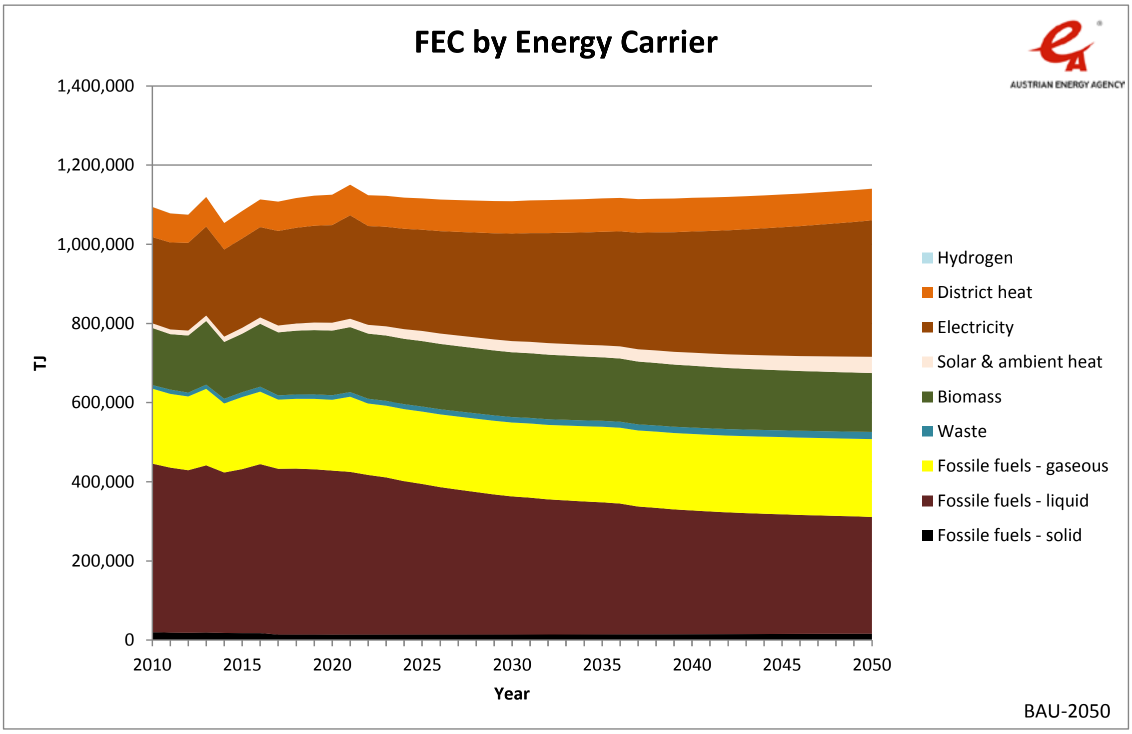

Figure 81. FEC by Energy Carrier – Scenario BAU

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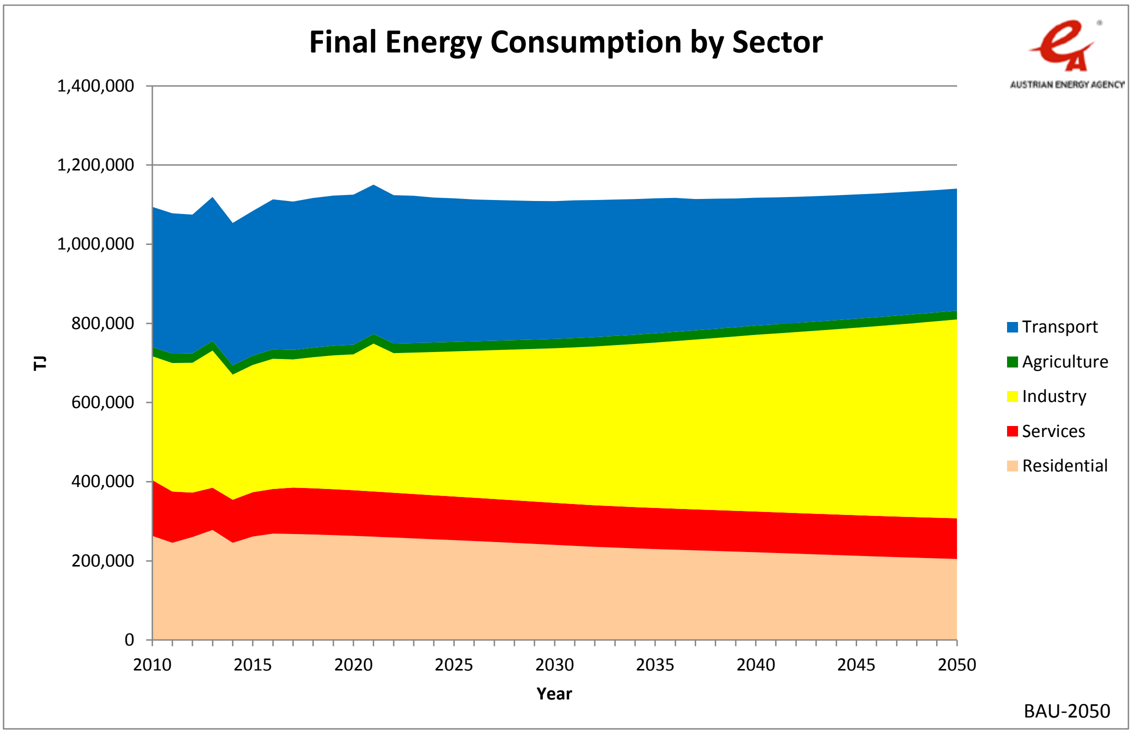

Figure 82. FEC by Sector – Scenario BAU

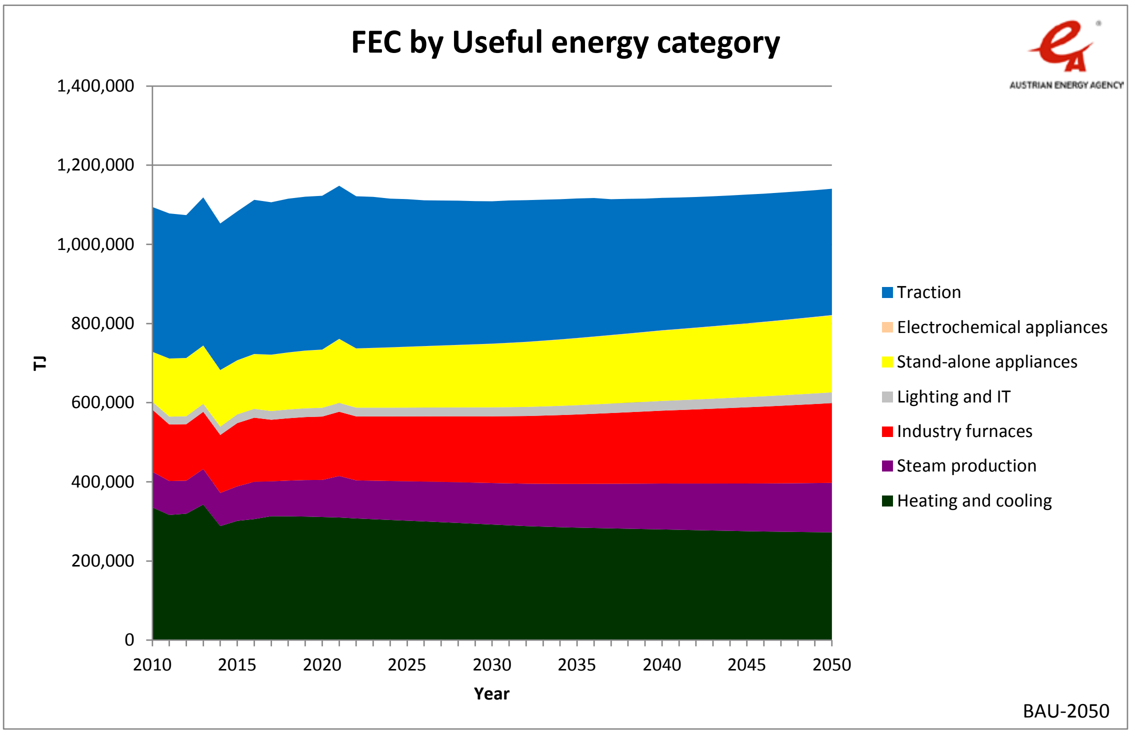

Figure 83. FEC by Useful energy category – Scenario BAU

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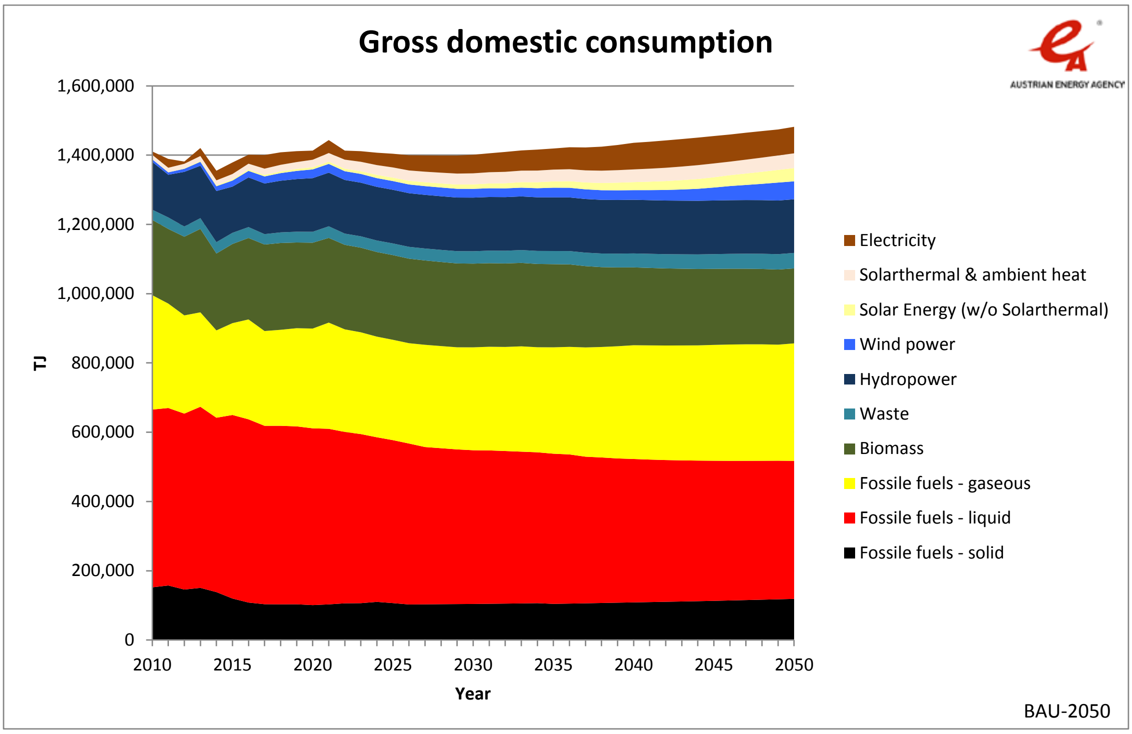

Figure 84. Gross domestic consumption – Scenario BAU.

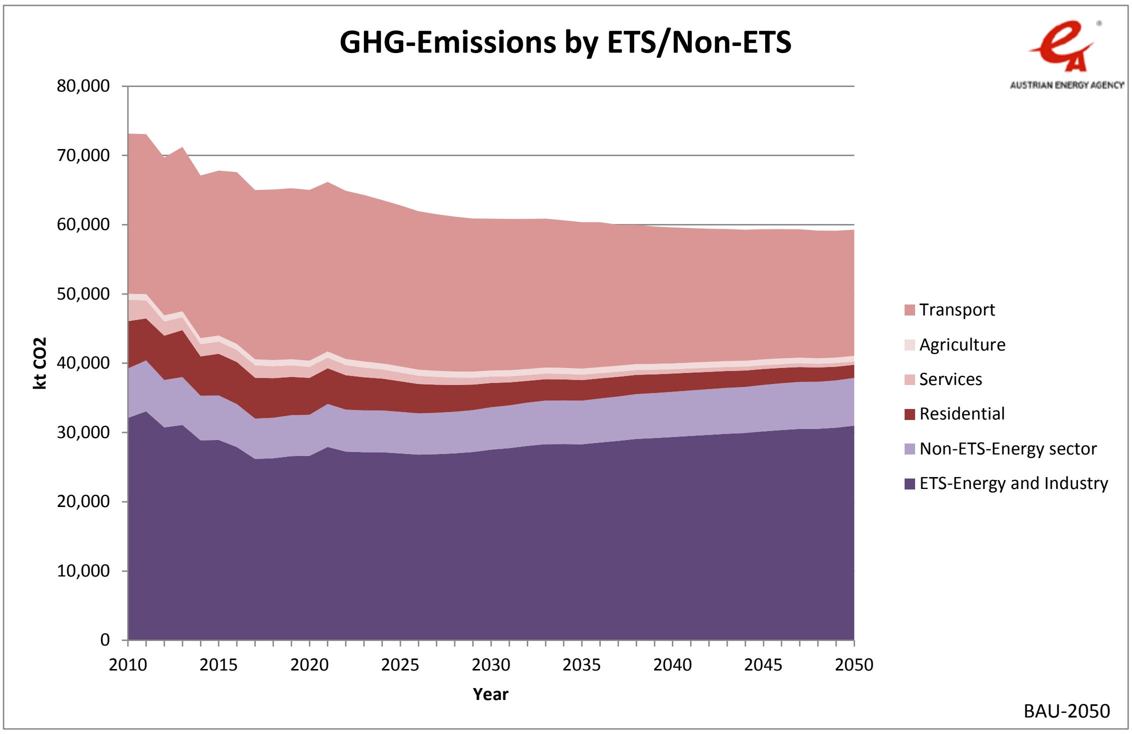

Figure 85. GHG-Emissions by ETS/Non-ETS – Scenario BAU.

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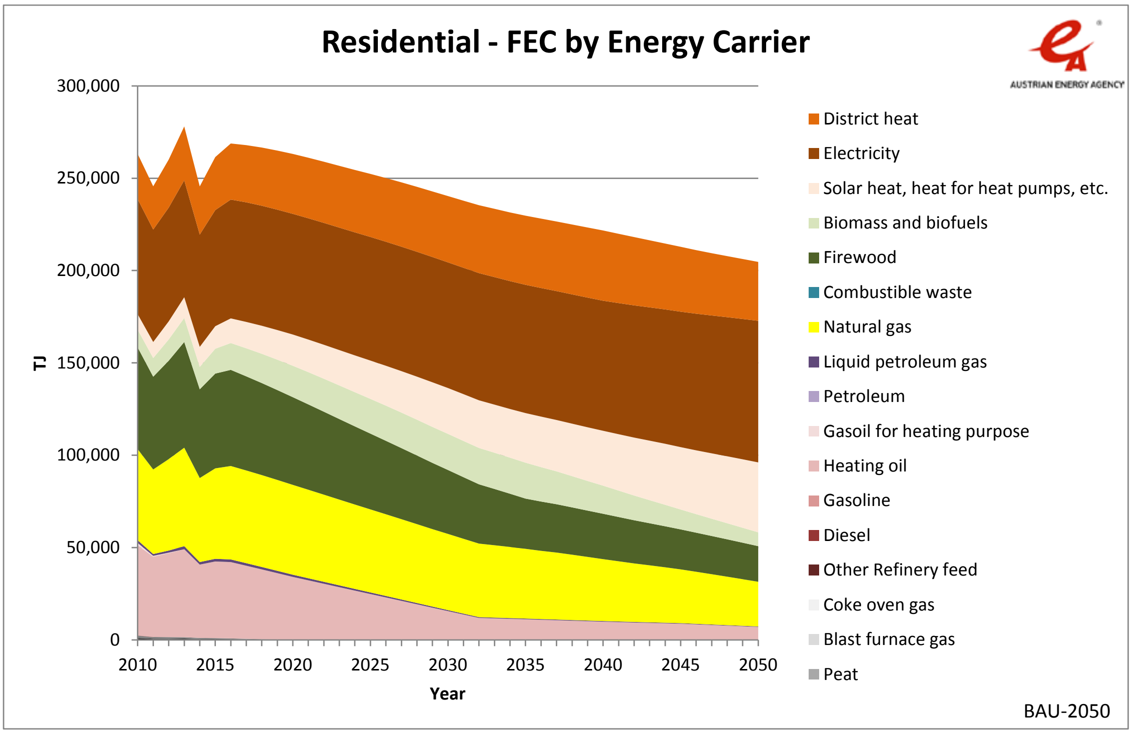

Figure 86. Residential - FEC by Energy Carrier – Scenario BAU.

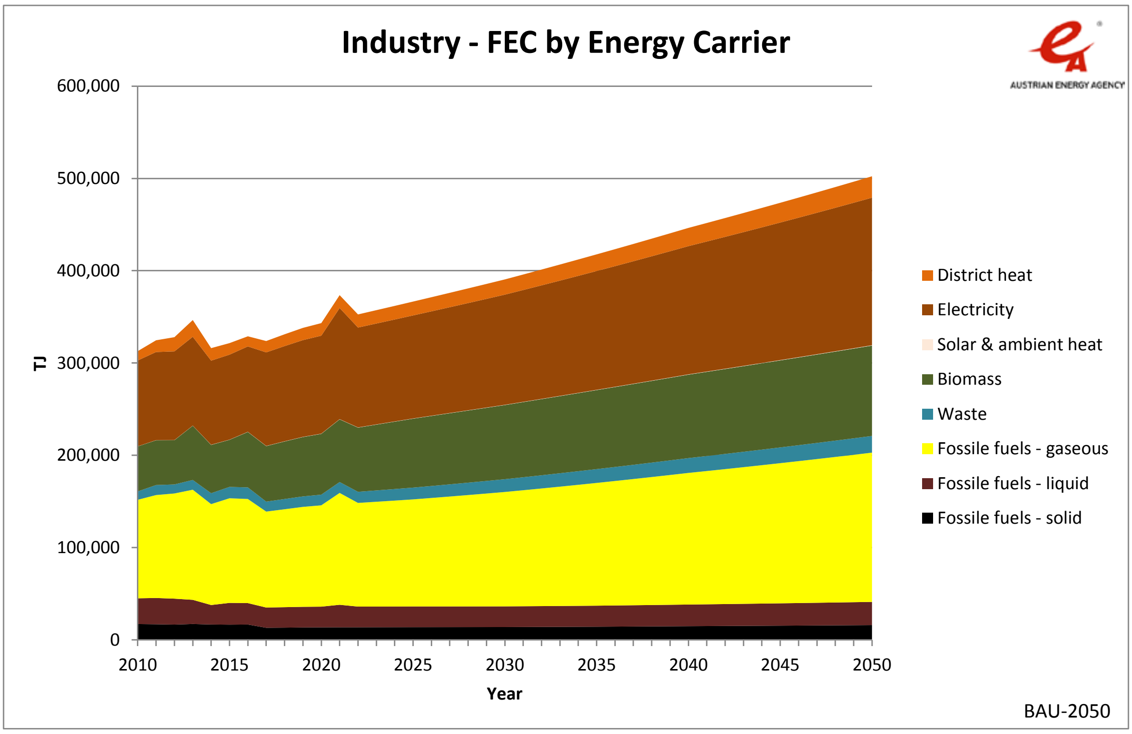

Figure 87. Industry - FEC by Energy Carrier – Scenario BAU.

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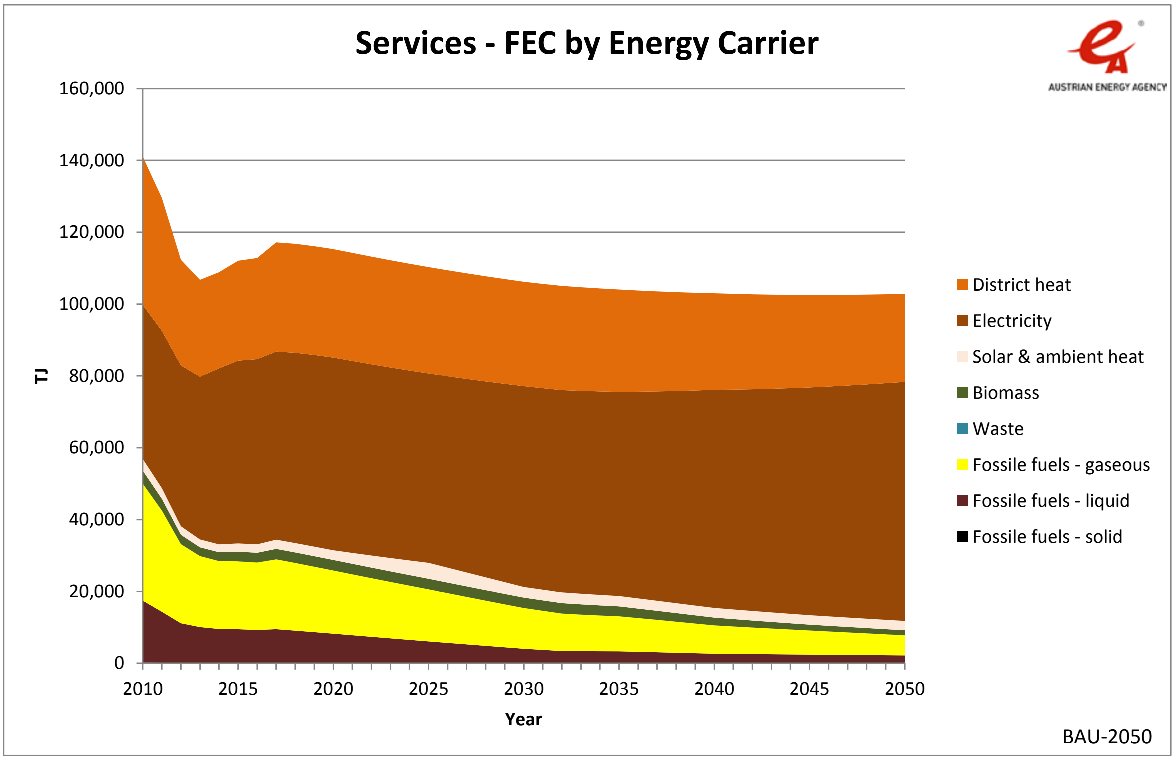

Figure 88. Services - FEC by Energy Carrier – Scenario BAU.

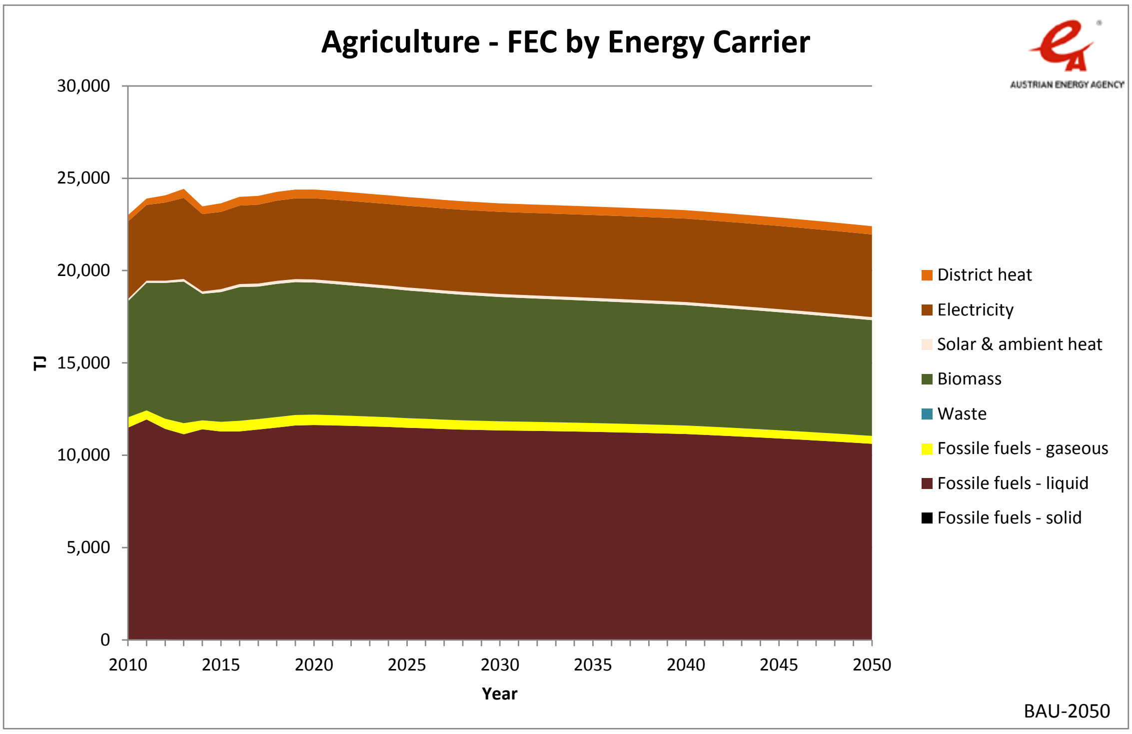

Figure 89. Agriculture - FEC by Energy Carrier – Scenario BAU.

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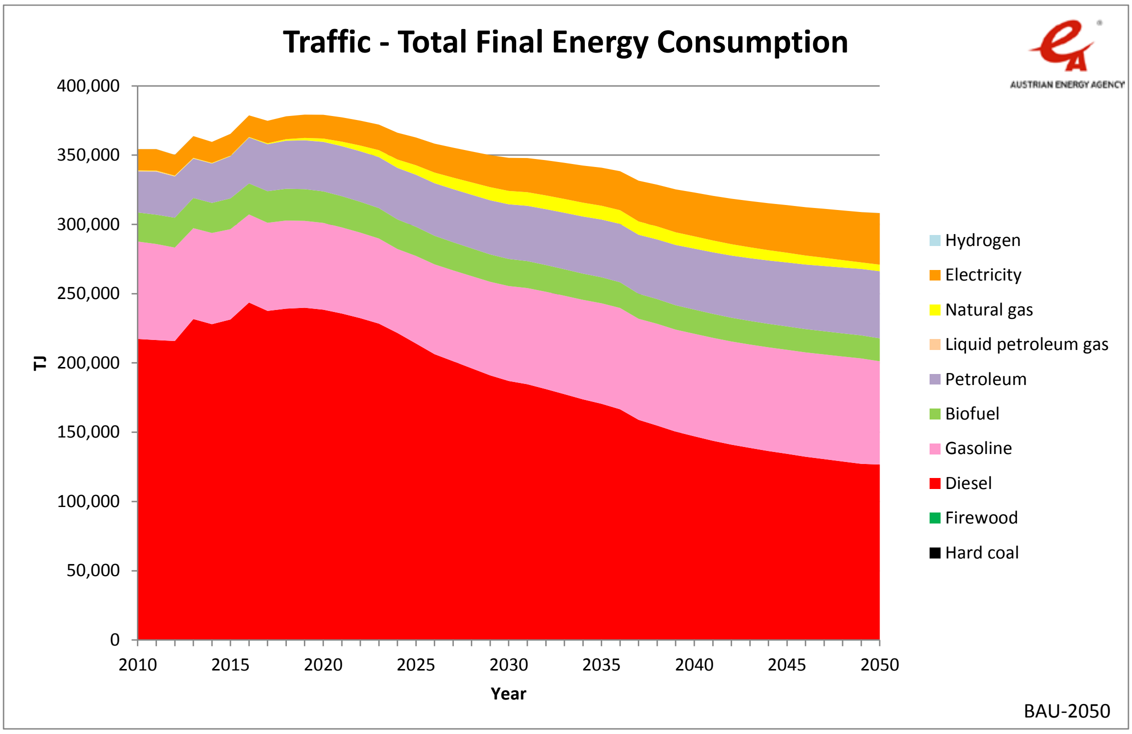

Figure 90. Traffic - Total Final Energy Consumption – Scenario BAU.

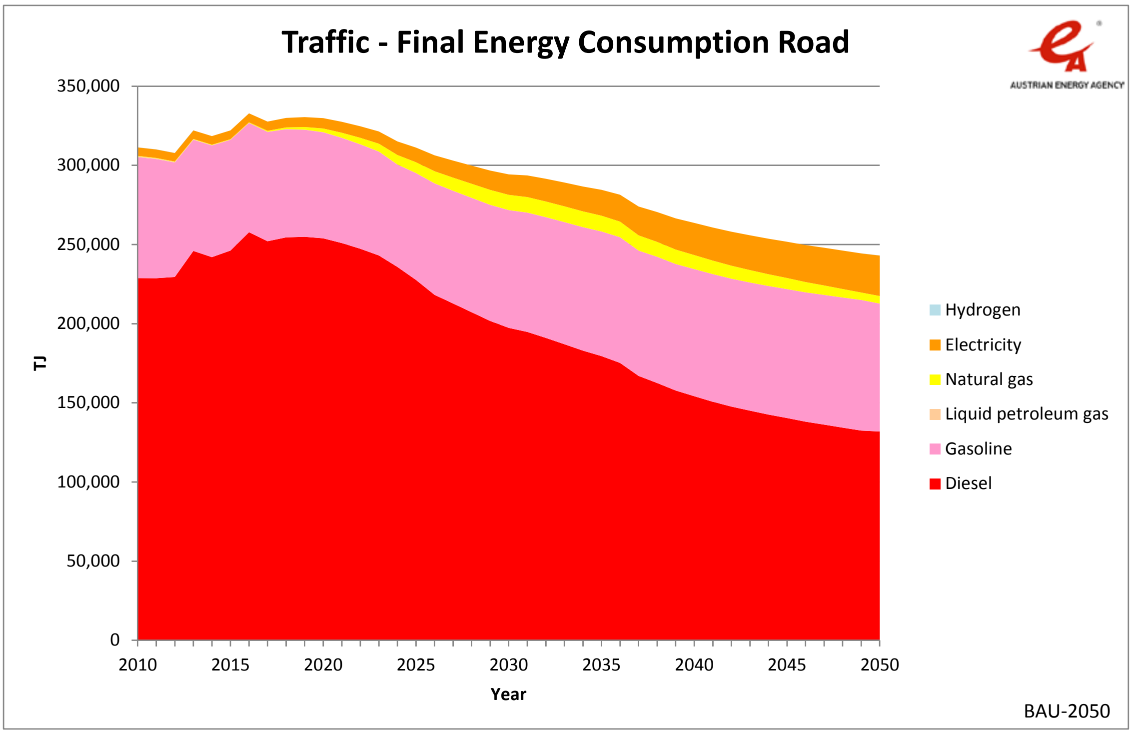

Figure 91. Traffic - Final Energy Consumption Road – Scenario BAU.

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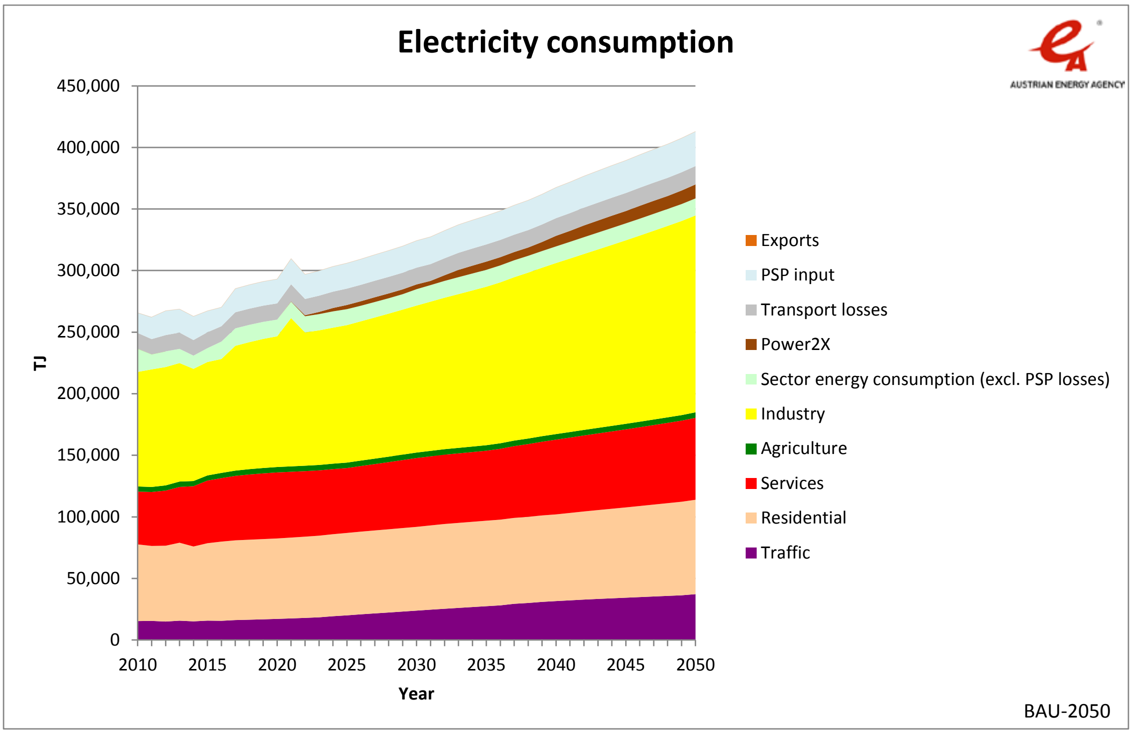

Figure 92. Electricity consumption – Scenario BAU.

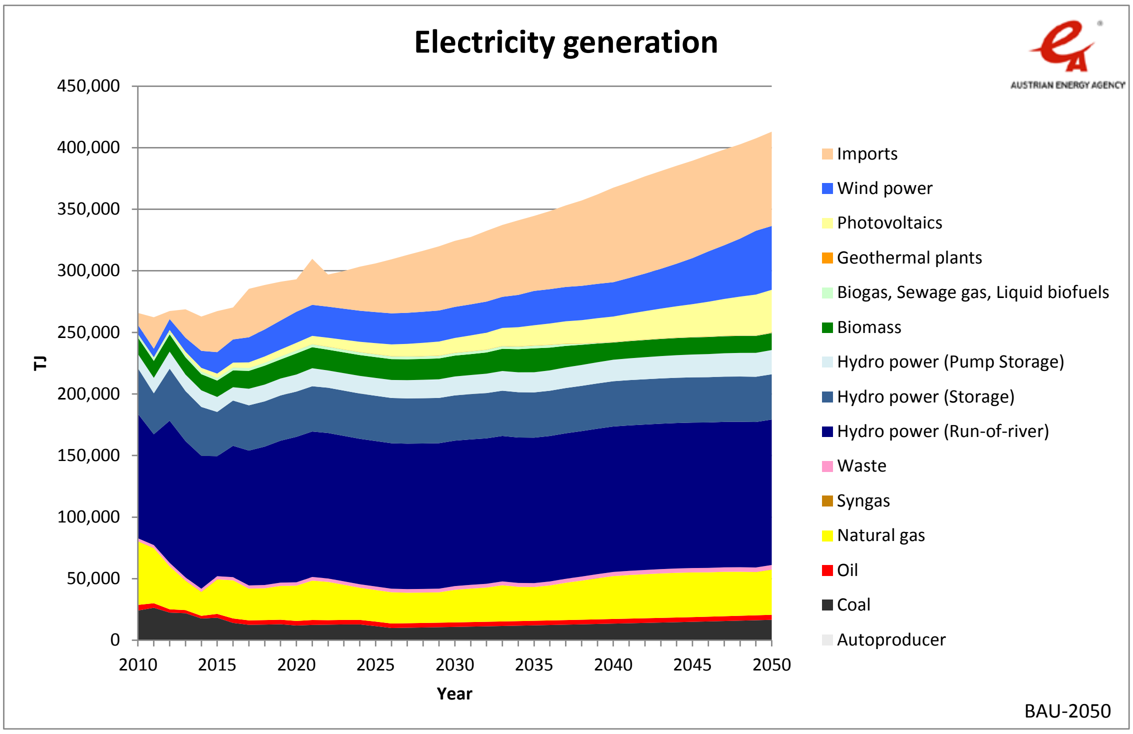

Figure 93 Electricity generation – Scenario BAU.

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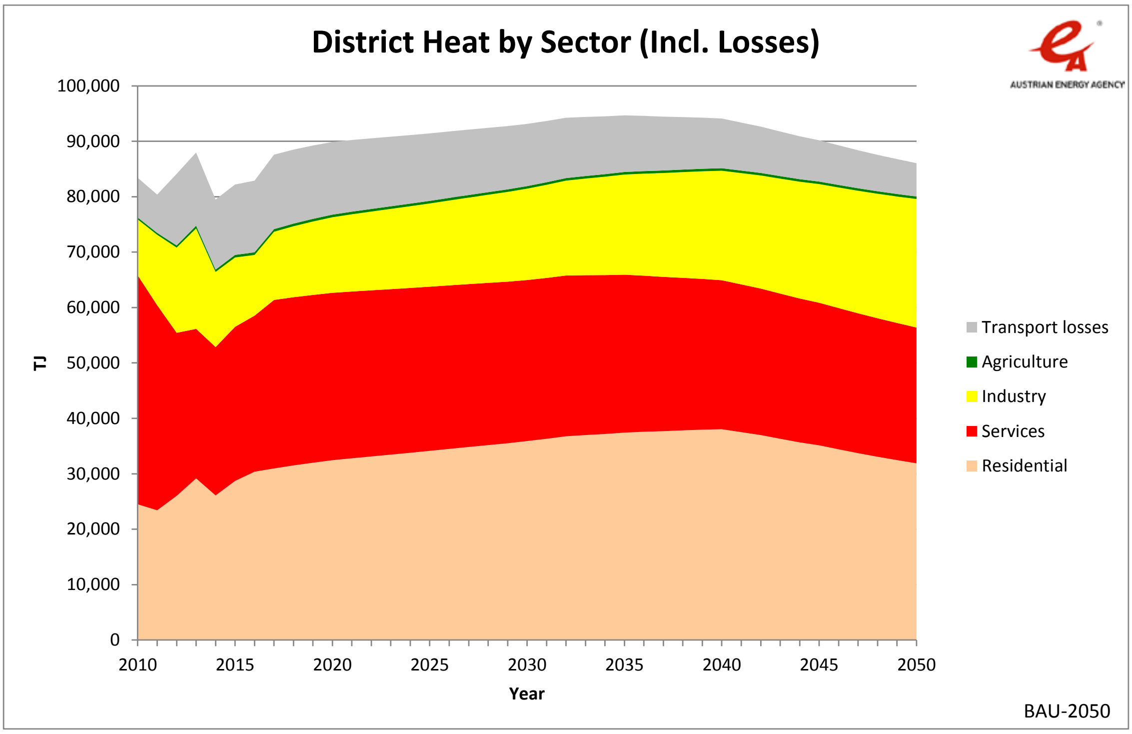

Figure 94. District Heat by Sector (Incl. Losses) – Scenario BAU.

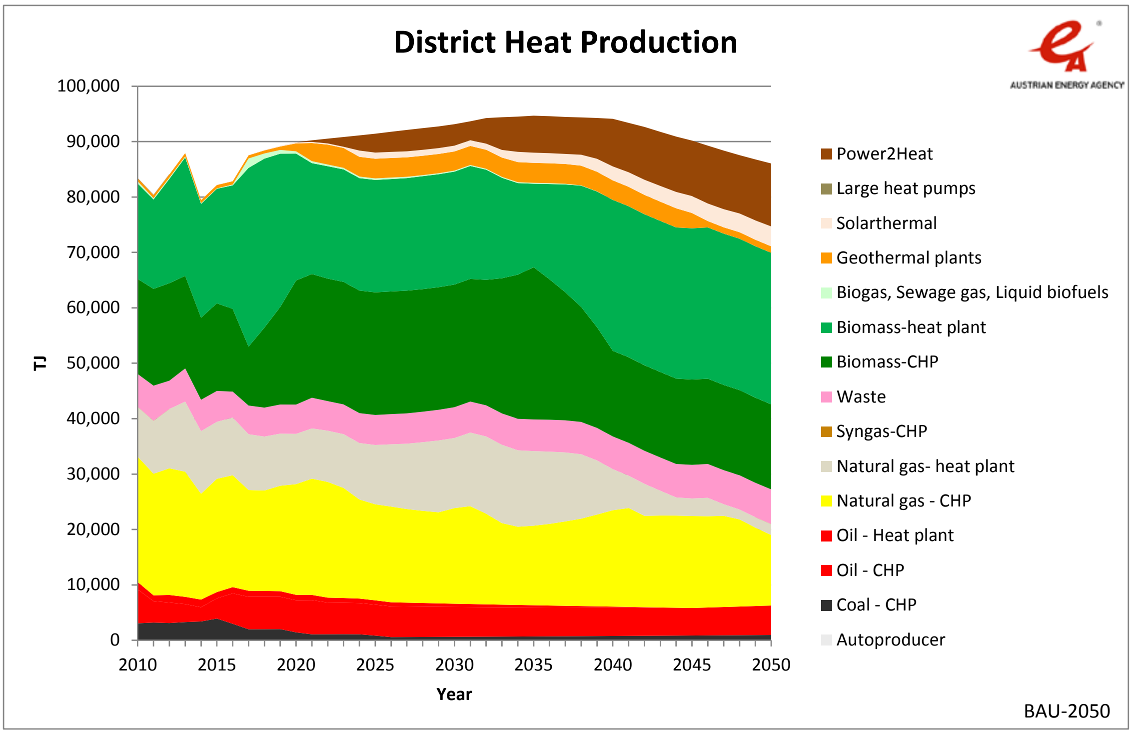

Figure 95. District Heat Production – Scenario BAU.

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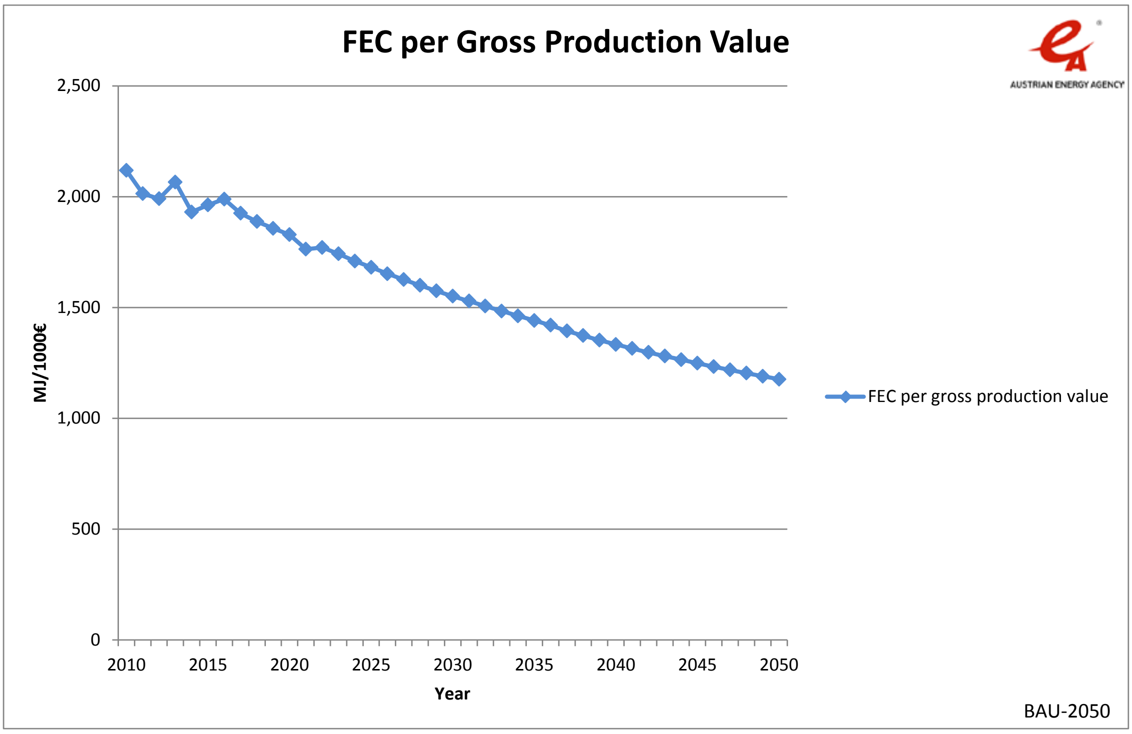

Figure 96. FEC per Gross Production Value – Scenario BAU.

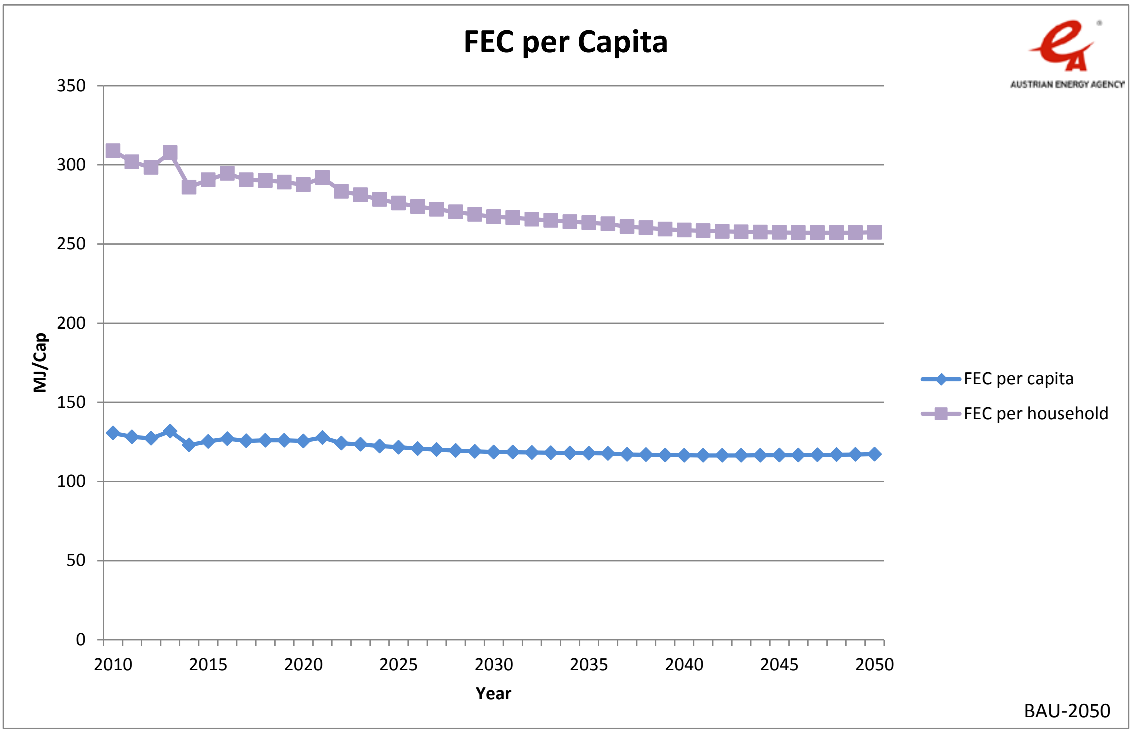

Figure 97. FEC per Capita – Scenario BAU.

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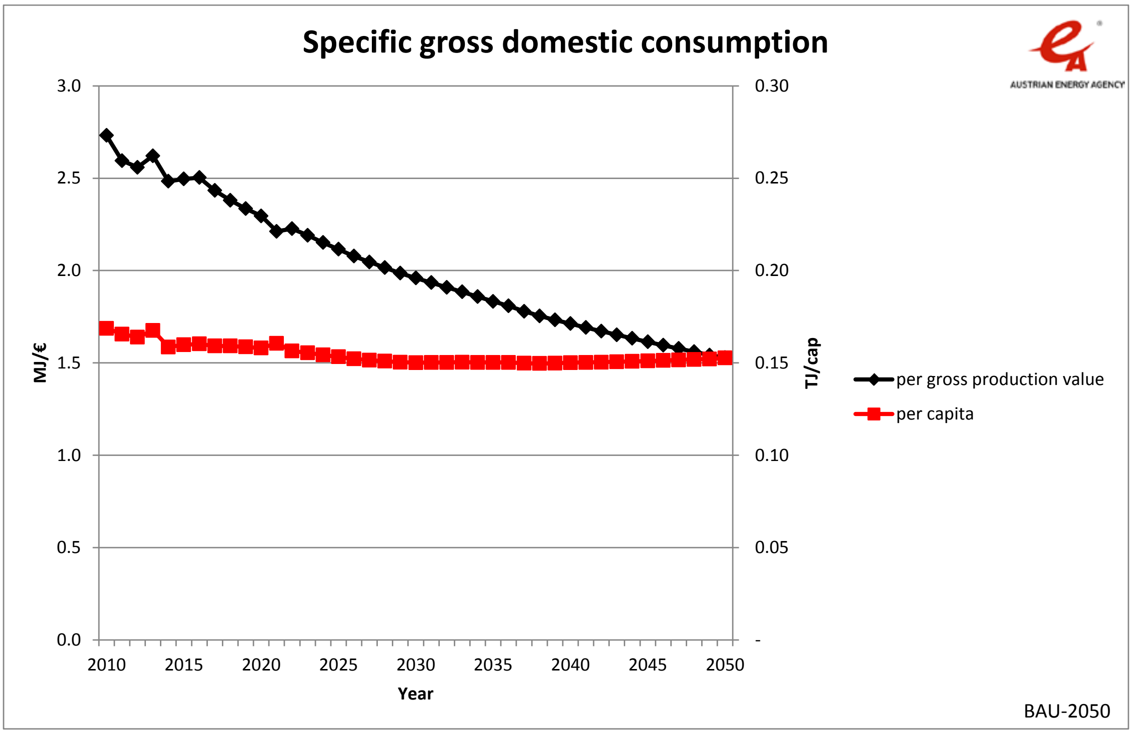

Figure 98. Gross domestic consumption per gross domestic value and capita – Scenario BAU.

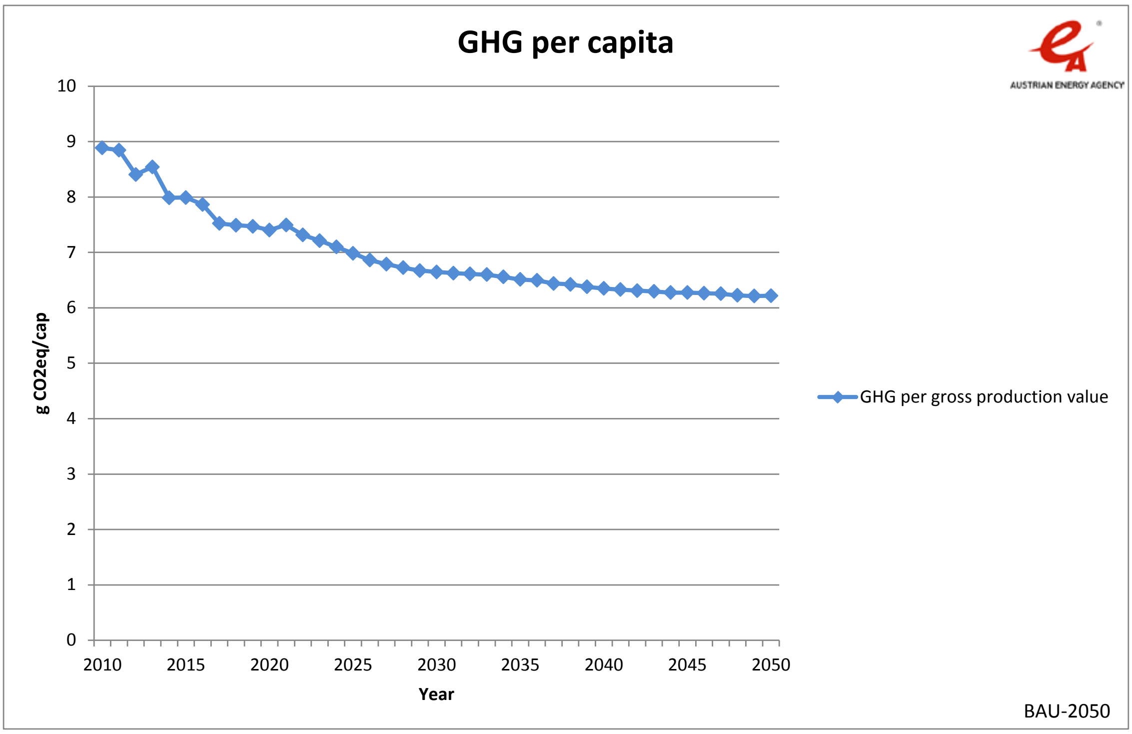

Figure 99. GHG per capita – Scenario BAU.

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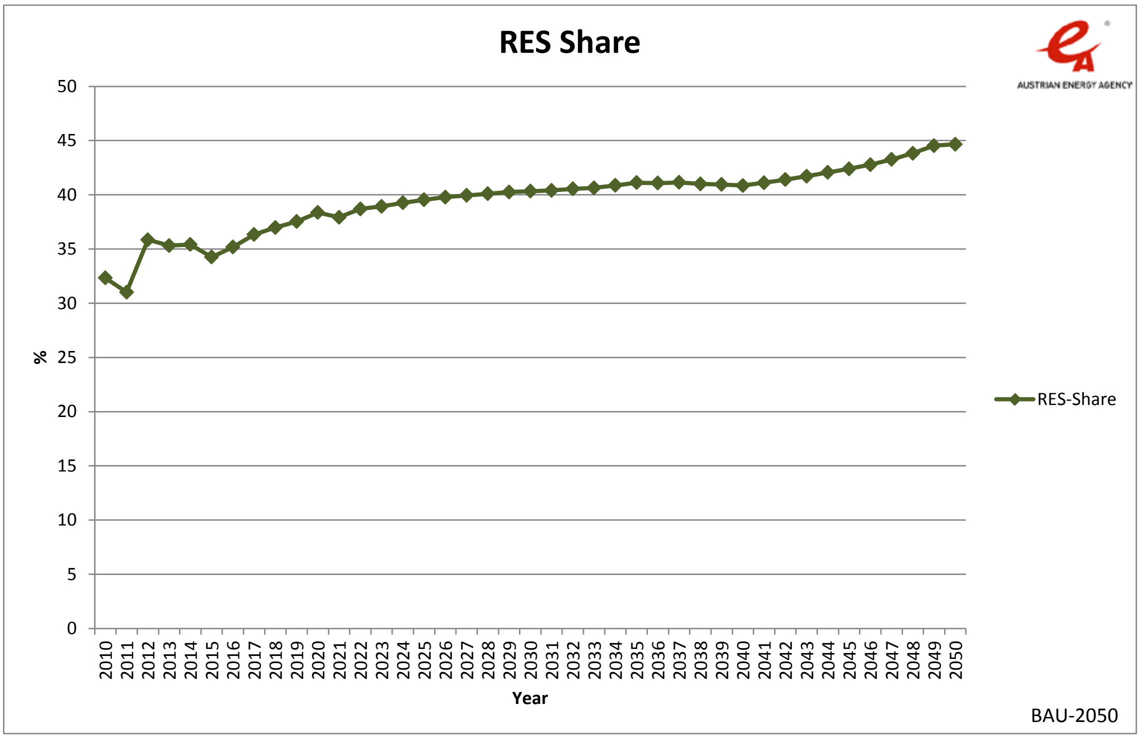

Figure 100. RES Share – Scenario BAU.

3.3.2. OLT scenario

In the OLT scenario, the total final energy consumption (Figure 101) decreases sharply between 2030 and 2030. Electricity becomes the most important fuel with a share of about 50% in 2050, followed by ambient heat and biomass. The share of fossil fuels almost vanishes and contributes only 10% to the final energy consumption in 2050. Industry becomes the biggest sector in 2050, making up about 50% of the total final energy consumption (Figure 102). Households and services decline until 2025, afterwards they stay constant until 2050. The transport consumption declines by 65%.

The gross domestic consumption (Figure 104) decreases by 20%. Only 20% is still based on fossil fuels, the rest is based on renewable energy sources equally distributed over all types. As a results, the GHG emissions decrease drastically by 80% until 2030 and 90% until 2050 (Figure 105).

In the household sector (Figure 106) and the service sector (Figure 108), the massive refurbishment of buildings and the switch to other heating systems leads to a steep decline in the final energy consumption until 2025. In both sectors, the consumption of fossil fuels almost completely vanishes, with ambient heat having a higher share in the household sector. In the industry sector (Figure 107), energy efficiency and fuel shift measures are being implemented,

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leading to an increase of about 50% of the total consumption until 2050. The fuel shift reduces the share of fossil fuels to less than 10%, and electricity becomes the most important fuel (50% of the total consumption). In the transport sector (Figure 110, Figure 111), the consumption halves by 2030, and stays at one third of pre-2020 consumption in 2050, due to an immediate shift to efficient vehicle technologies. Kerosene for air transport remains the most important fossil fuel, outweighed by electricity and biofuels.

The electricity production (Figure 113) grows slower than the electricity consumption (Figure 112), leads to a maximum of an import dependence of more than 30% in 2030, and still 20% in 2050. The main consumption of district heat (Figure 114) stems from the household and the service sector, with a rising share from industry. Between 2025 and 2040, the production (Figure 115) is dominated by biomass CHP, whereas in 2050 it is evenly distributed between biomass CHP, synthetic natural gas CHP, geothermal plants and Power2Heat.

The specific final energy (Figure 116, Figure 117) and the specific gross domestic consumption (Figure 118) both are decreasing. The shift to more renewable energy leads to a decrease of the GHG emissions per capita of about 90% (Figure 119), and an increase of the share of renewable energy of about 85% in 2050 (Figure 120).

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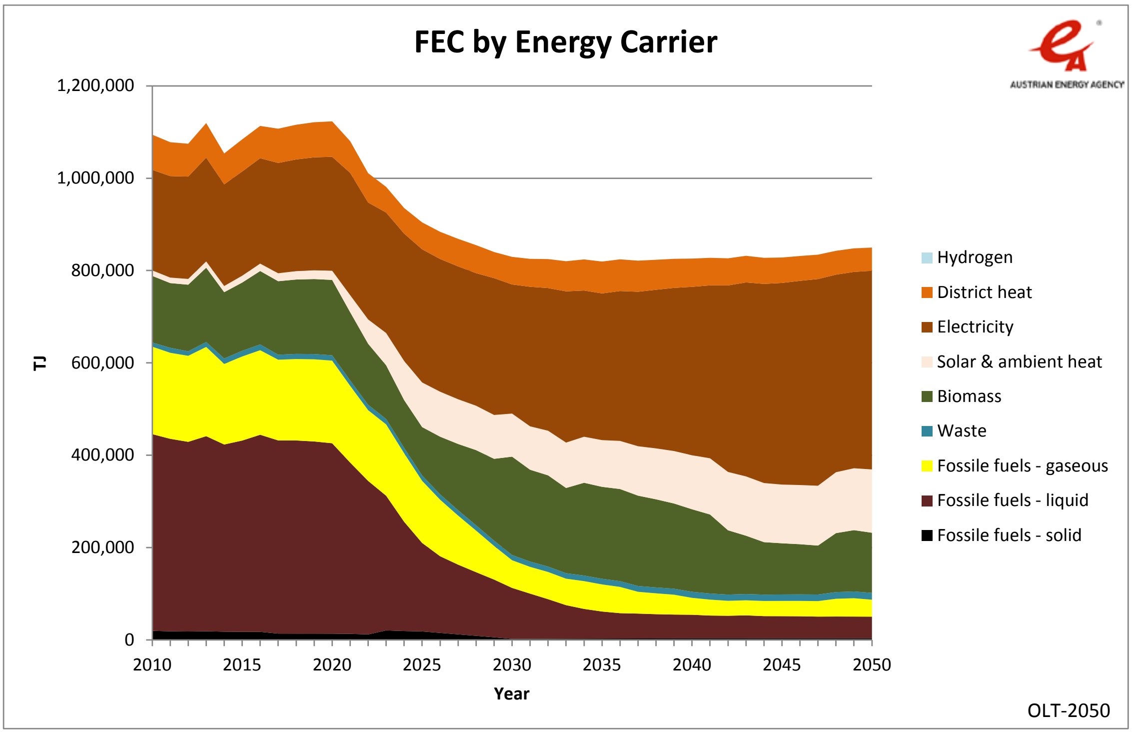

Figure 101. FEC by Energy Carrier – Scenario OLT.

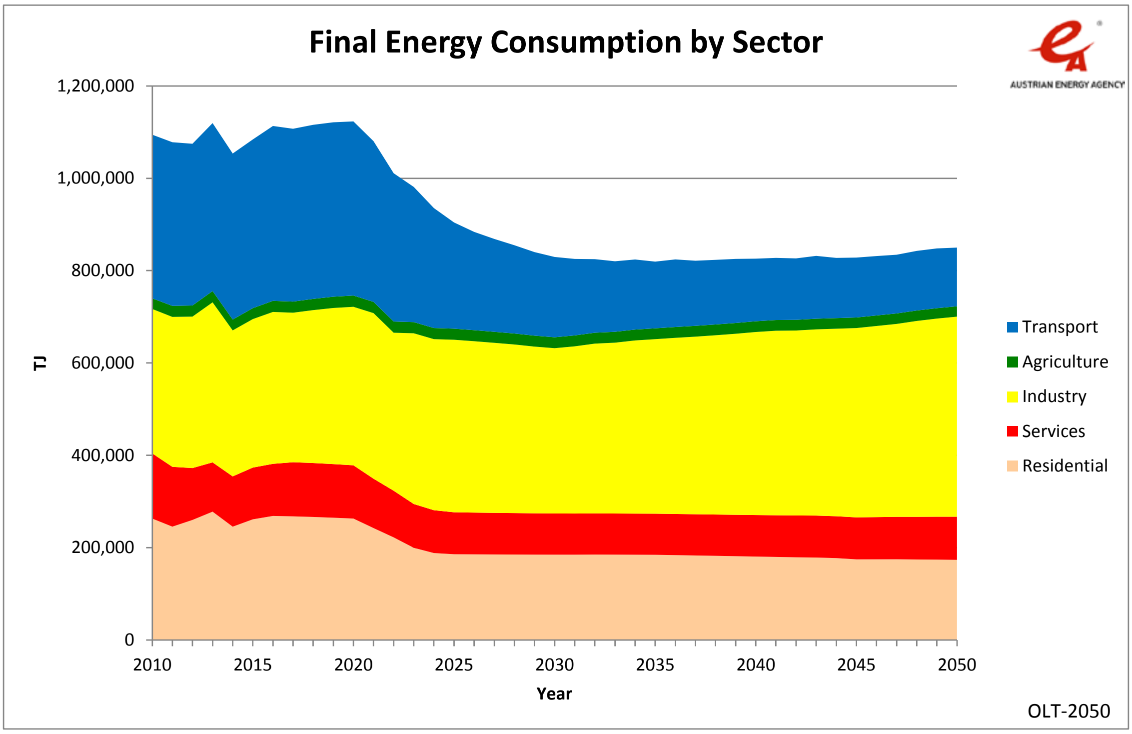

Figure 102. Final Energy Consumption by Sector – Scenario OLT.

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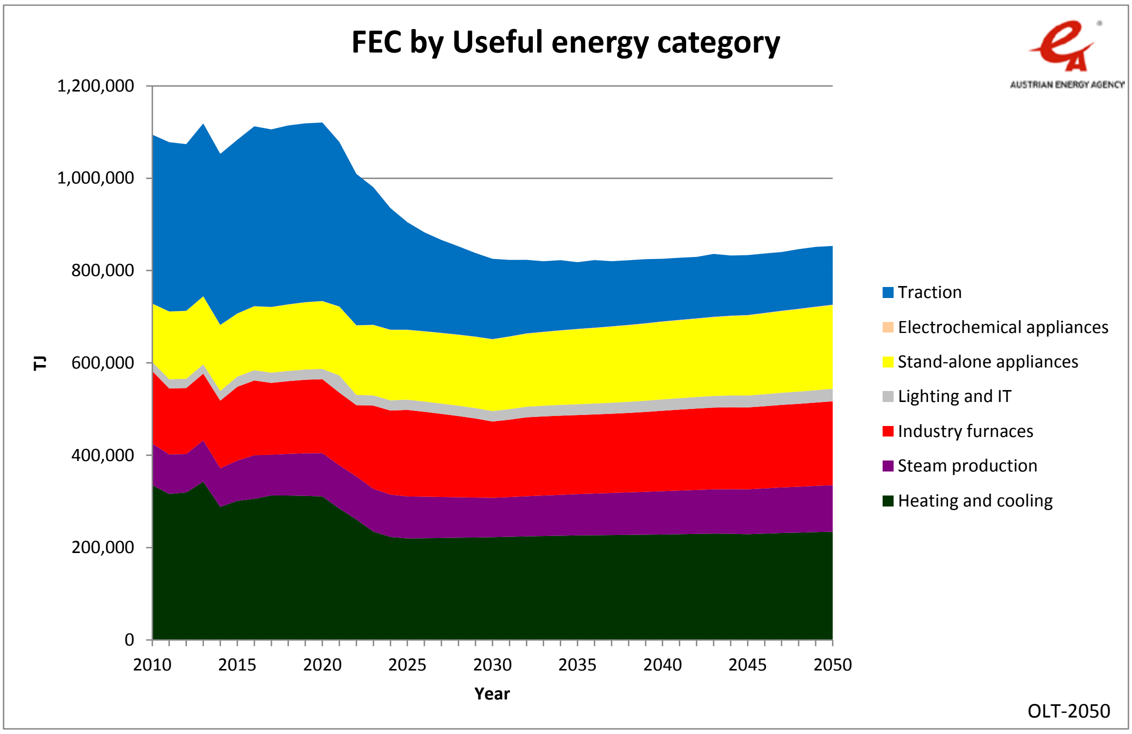

Figure 103. FEC by Useful energy category – Scenario OLT.

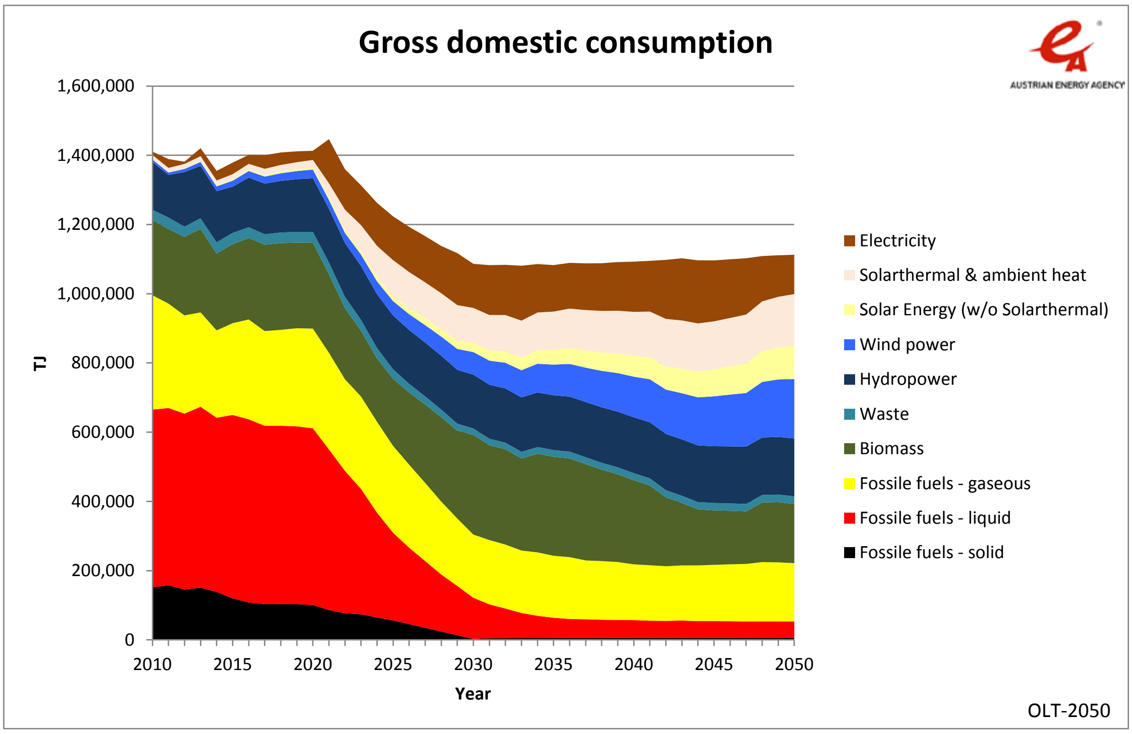

Figure 104. Gross domestic consumption – Scenario OLT.

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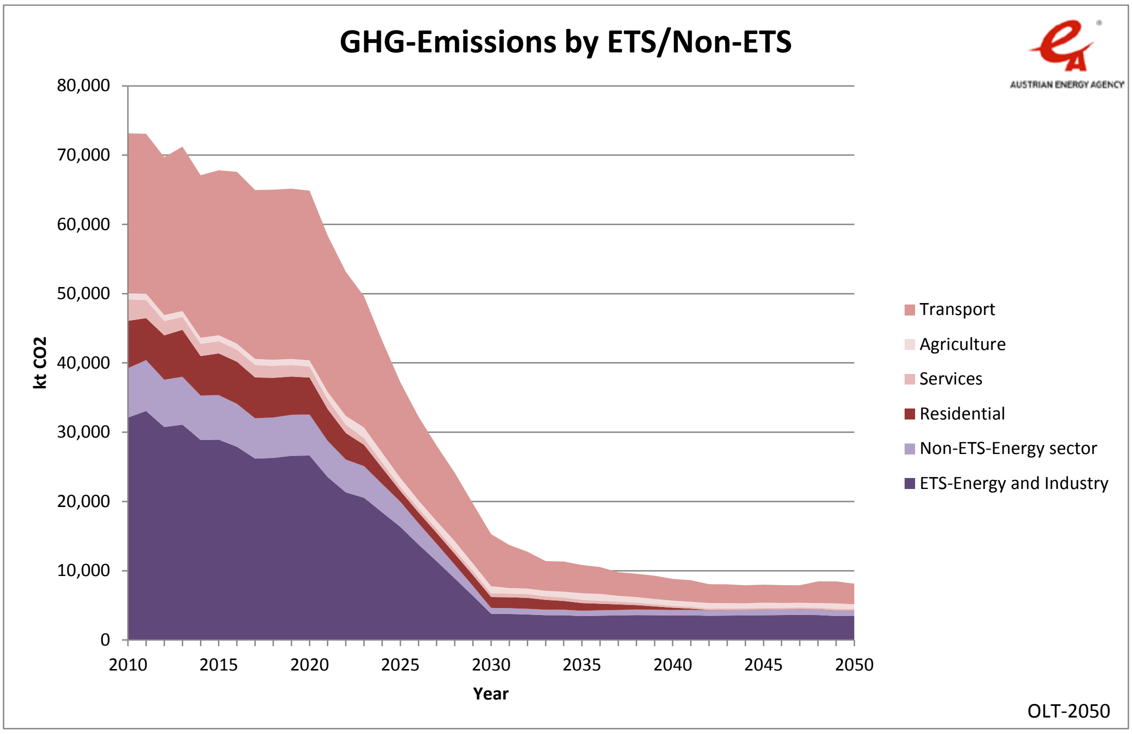

Figure 105. GHG-Emissions by ETS/Non-ETS – Scenario OLT.

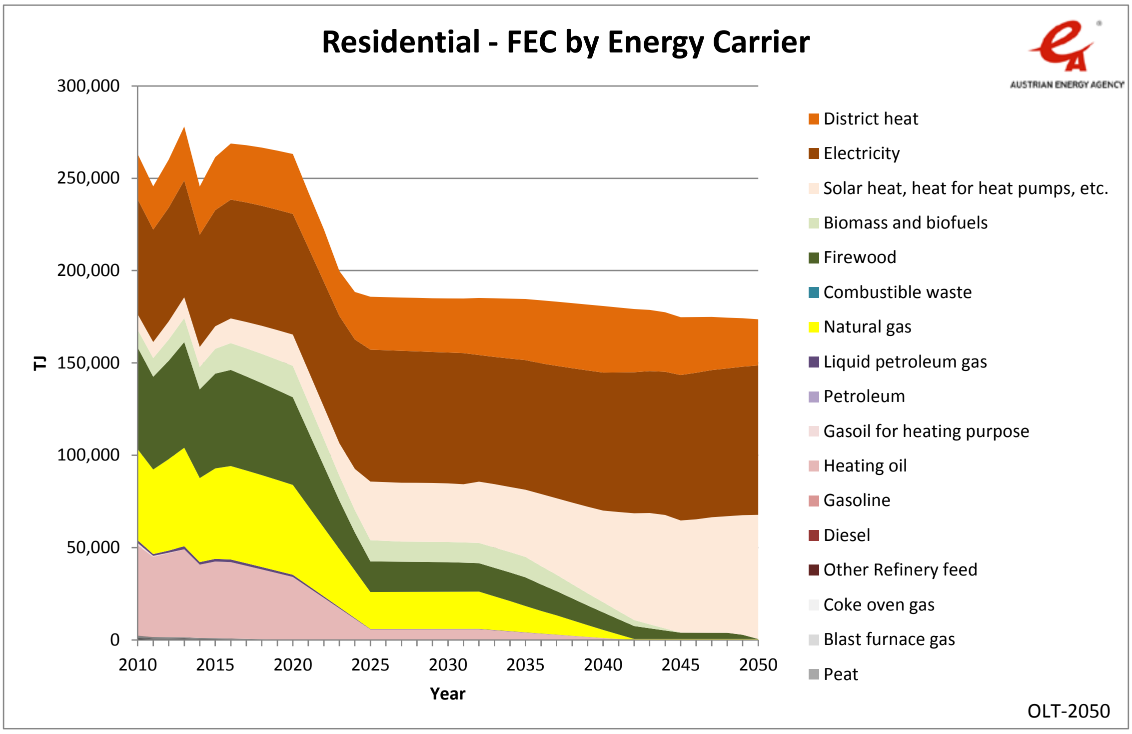

Figure 106. Residential - FEC by Energy Carrier – Scenario OLT.

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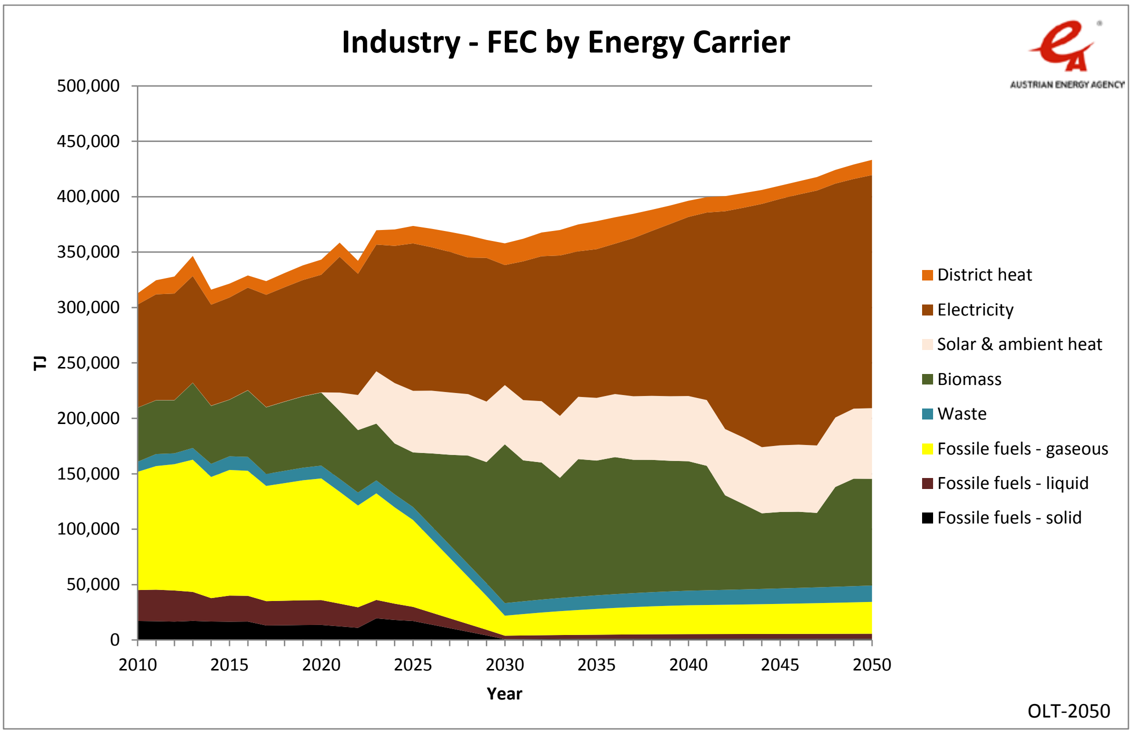

Figure 107. Industry - FEC by Energy Carrier – Scenario OLT.

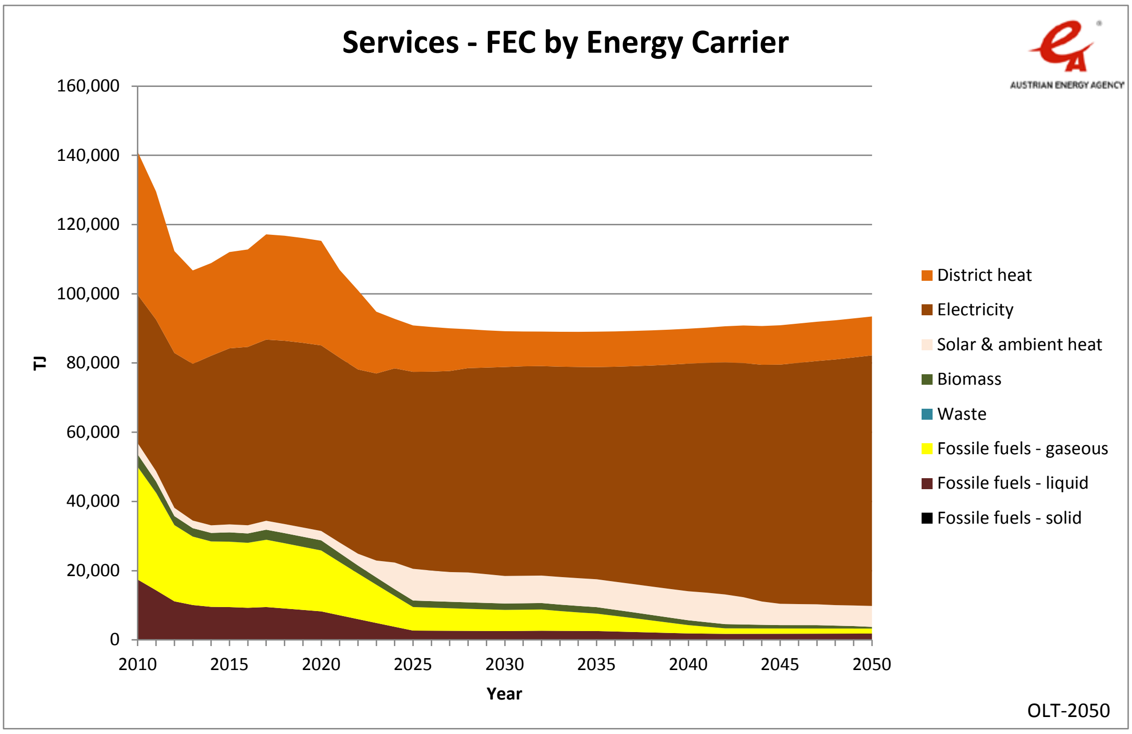

Figure 108. Services - FEC by Energy Carrier – Scenario OLT.

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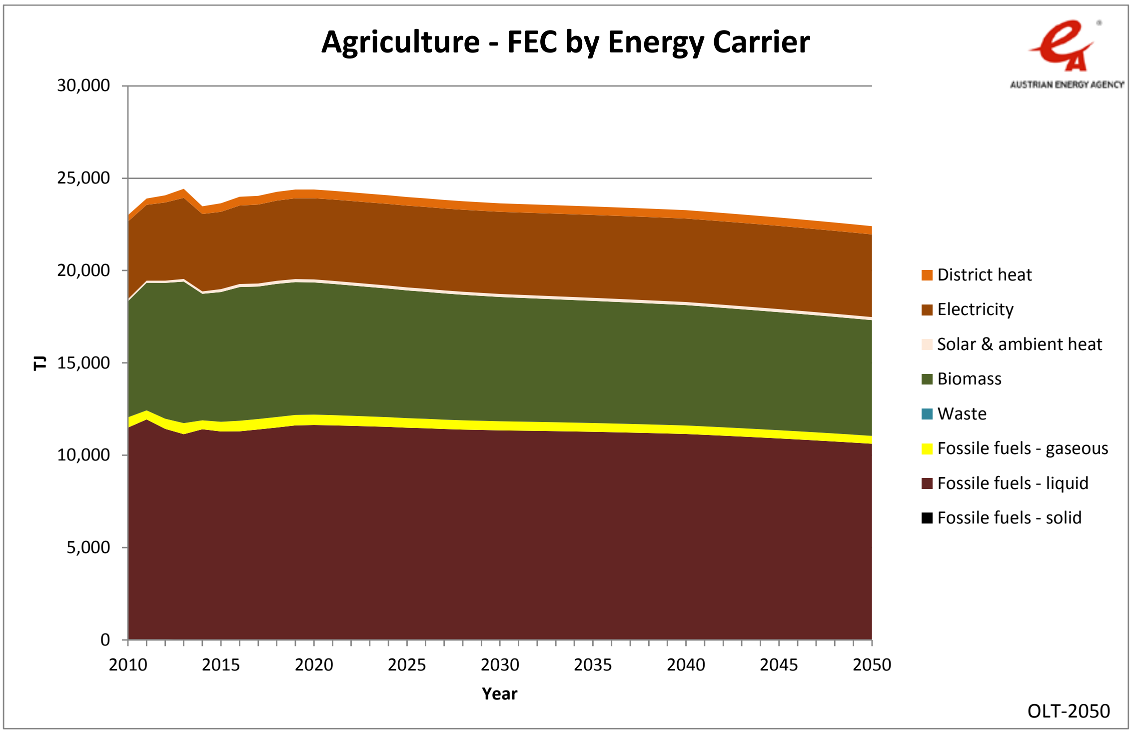

Figure 109. Agriculture - FEC by Energy Carrier – Scenario OLT.

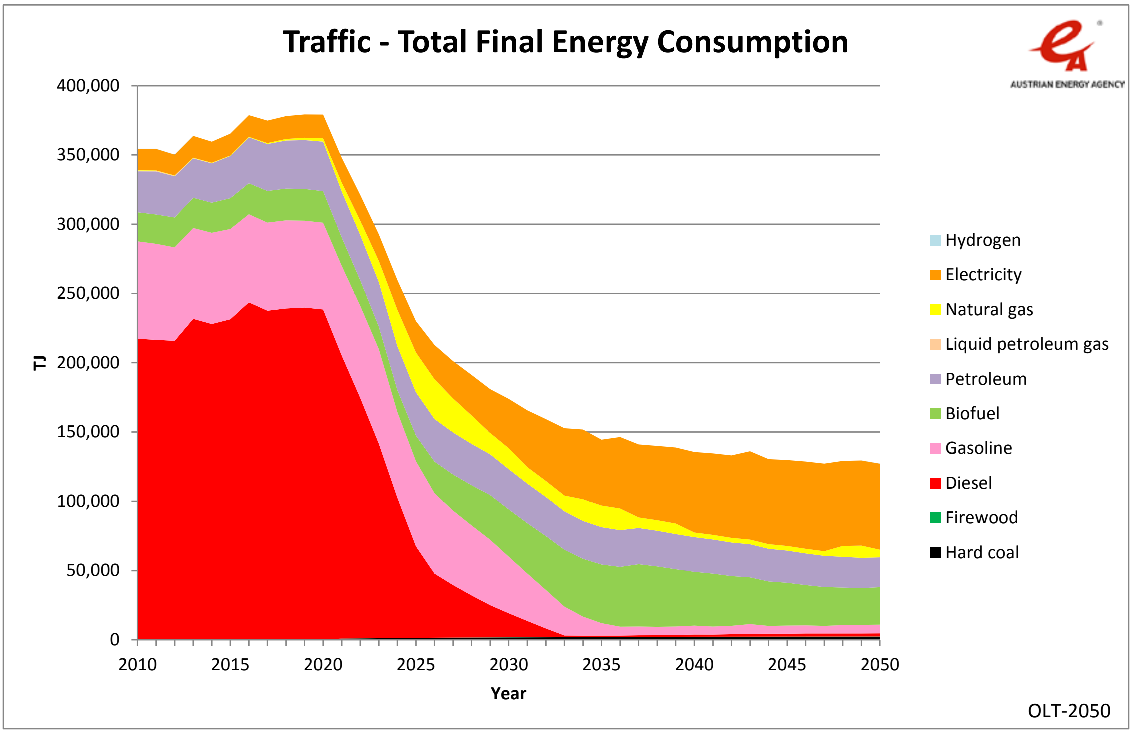

Figure 110. Traffic - Total Final Energy Consumption – Scenario OLT.

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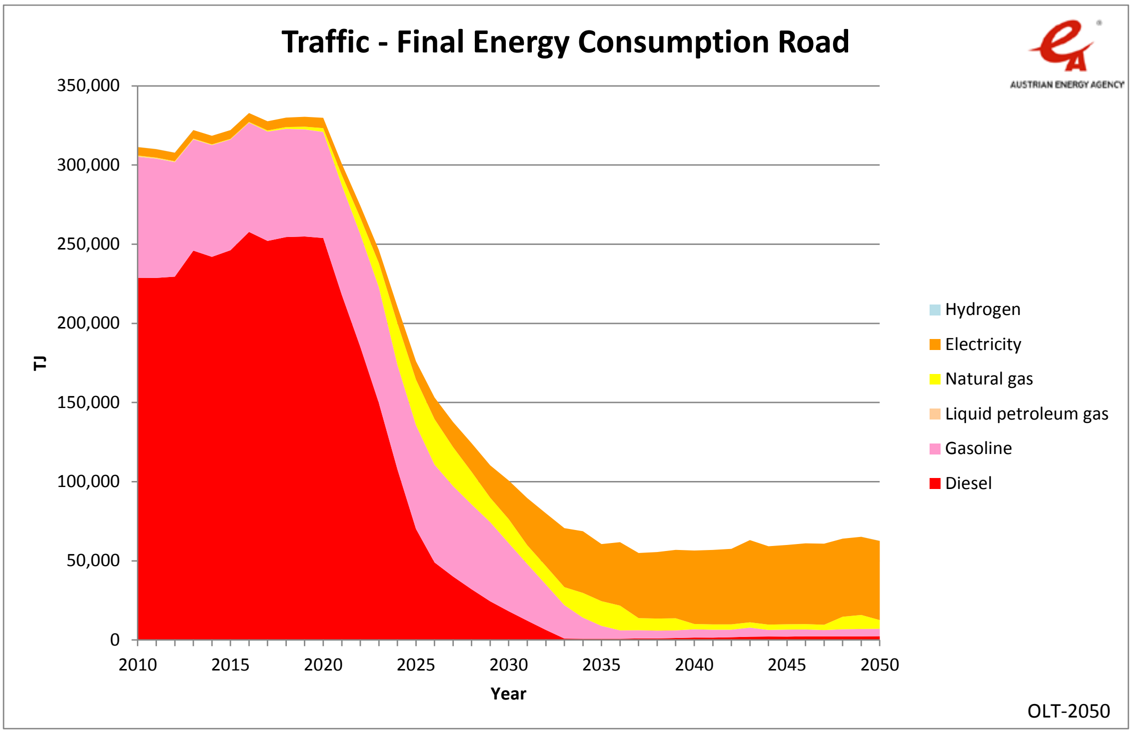

Figure 111. Traffic - Final Energy Consumption Road – Scenario OLT.

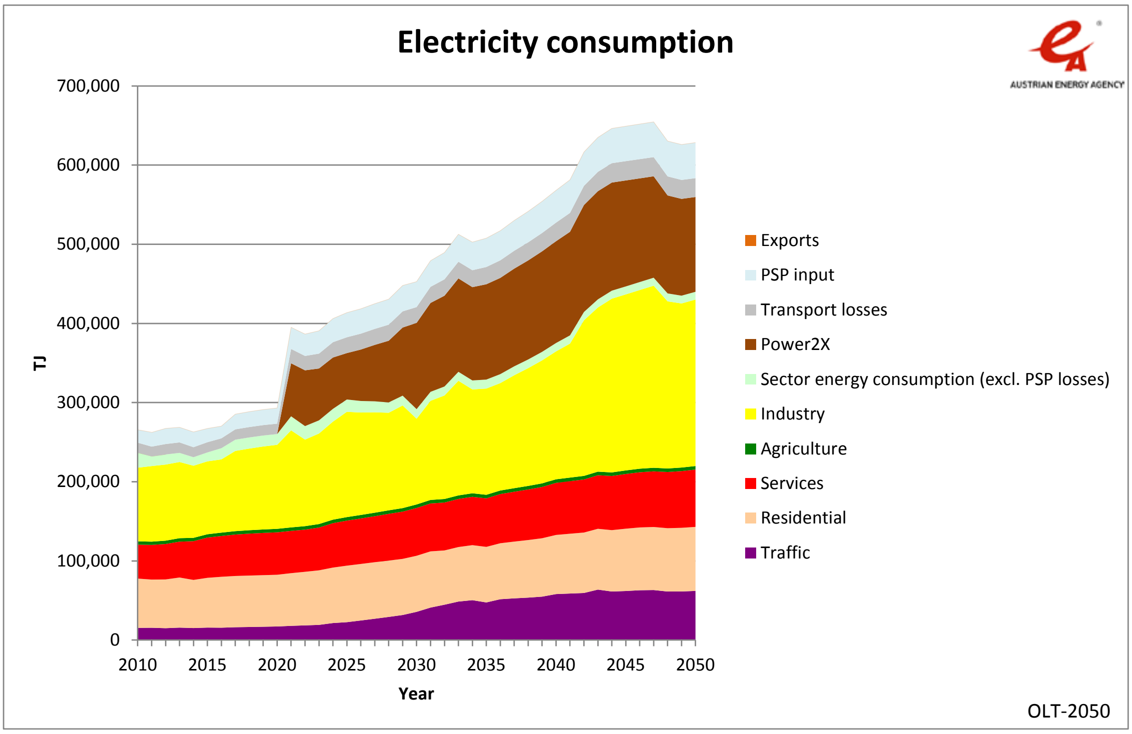

Figure 112. Electricity consumption – Scenario OLT.

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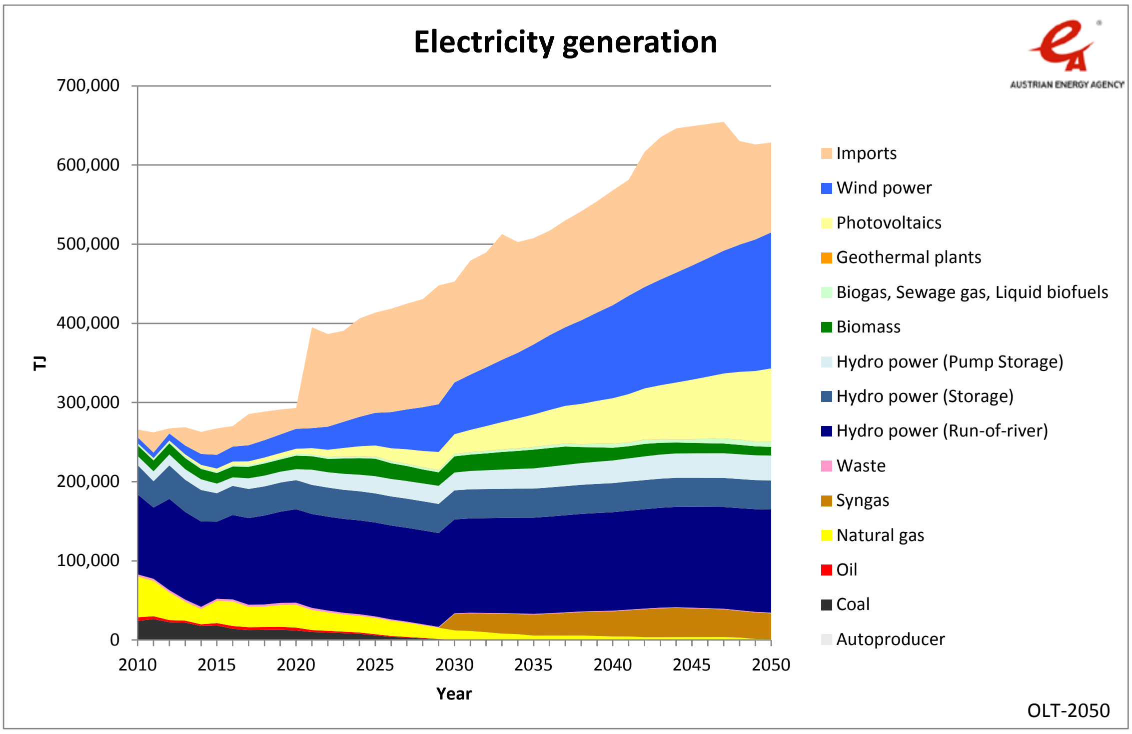

Figure 113. Electricity generation – Scenario OLT.

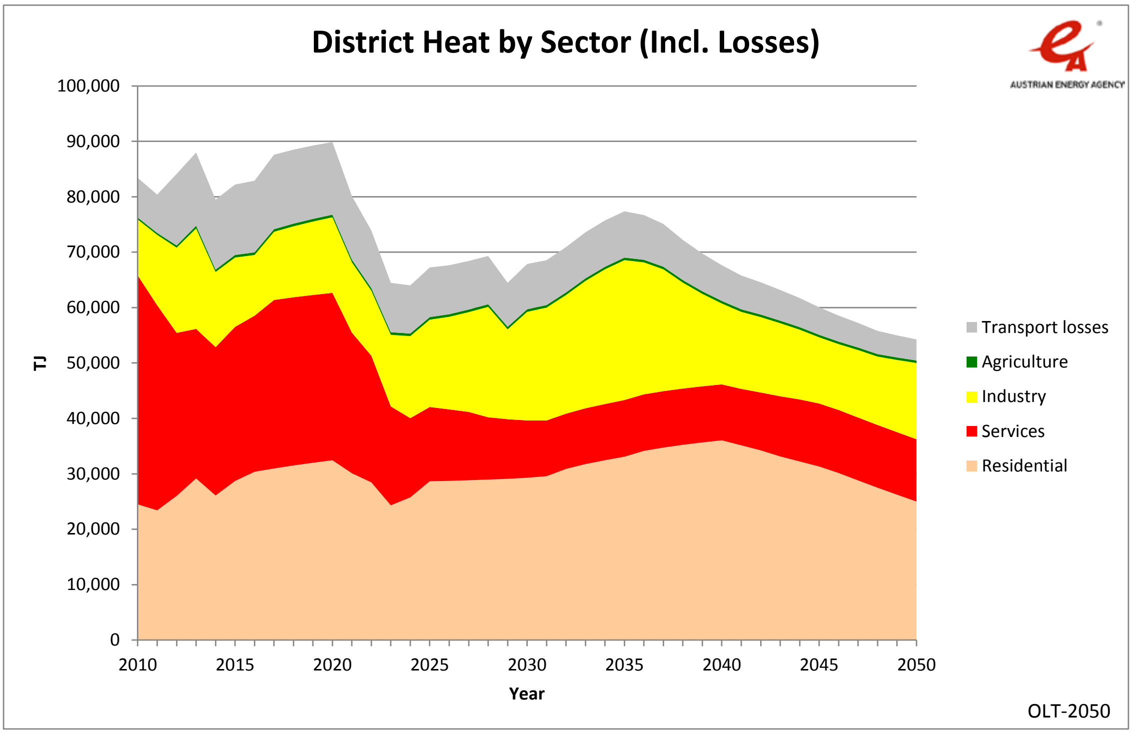

Figure 114. District Heat by Sector (Incl. Losses) – Scenario OLT.

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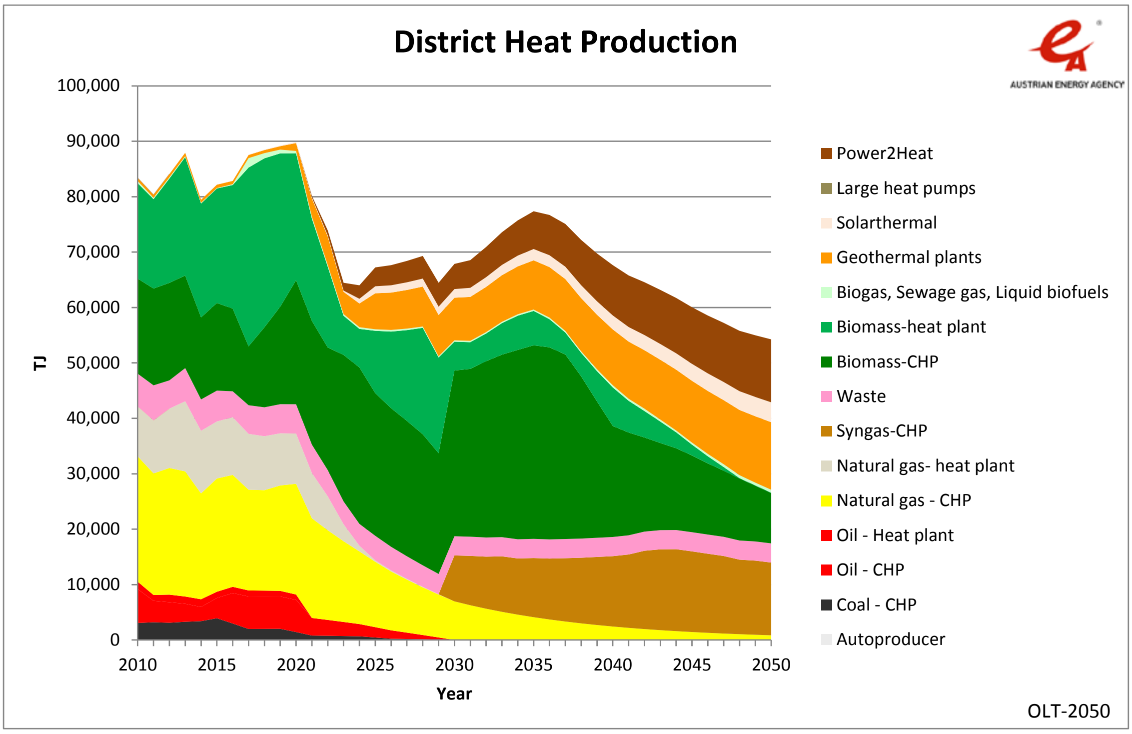

Figure 115. District Heat Production – Scenario OLT.

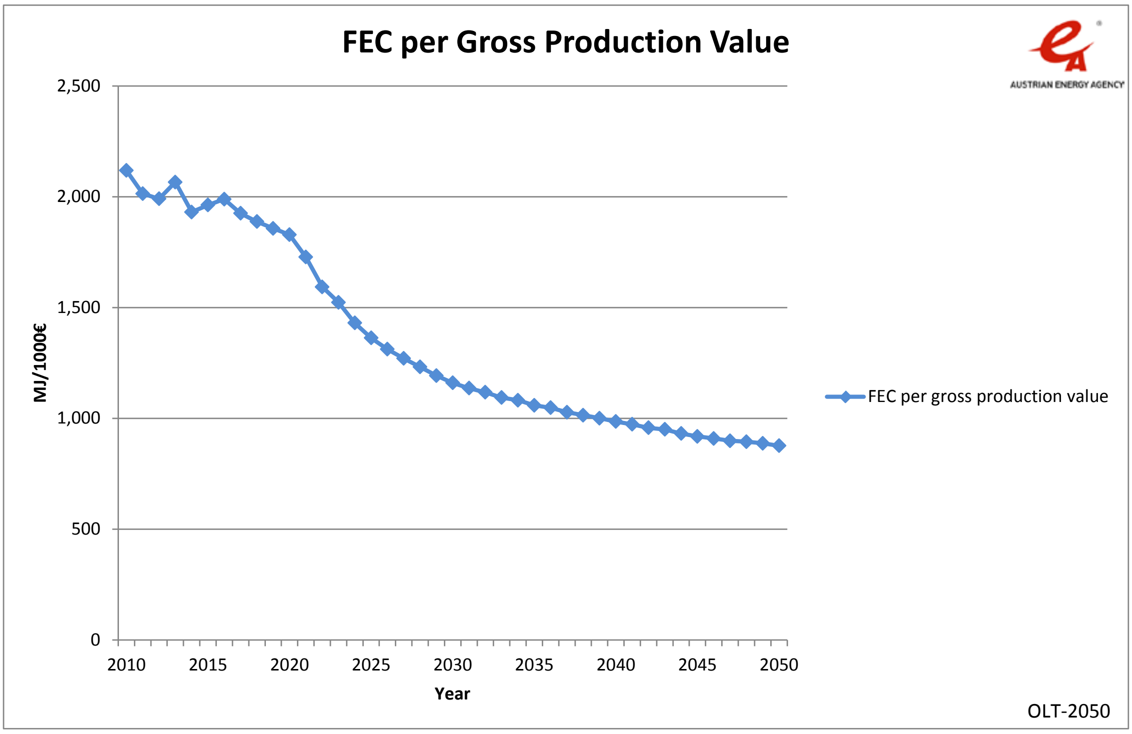

Figure 116. FEC per Gross Production Value – Scenario OLT.

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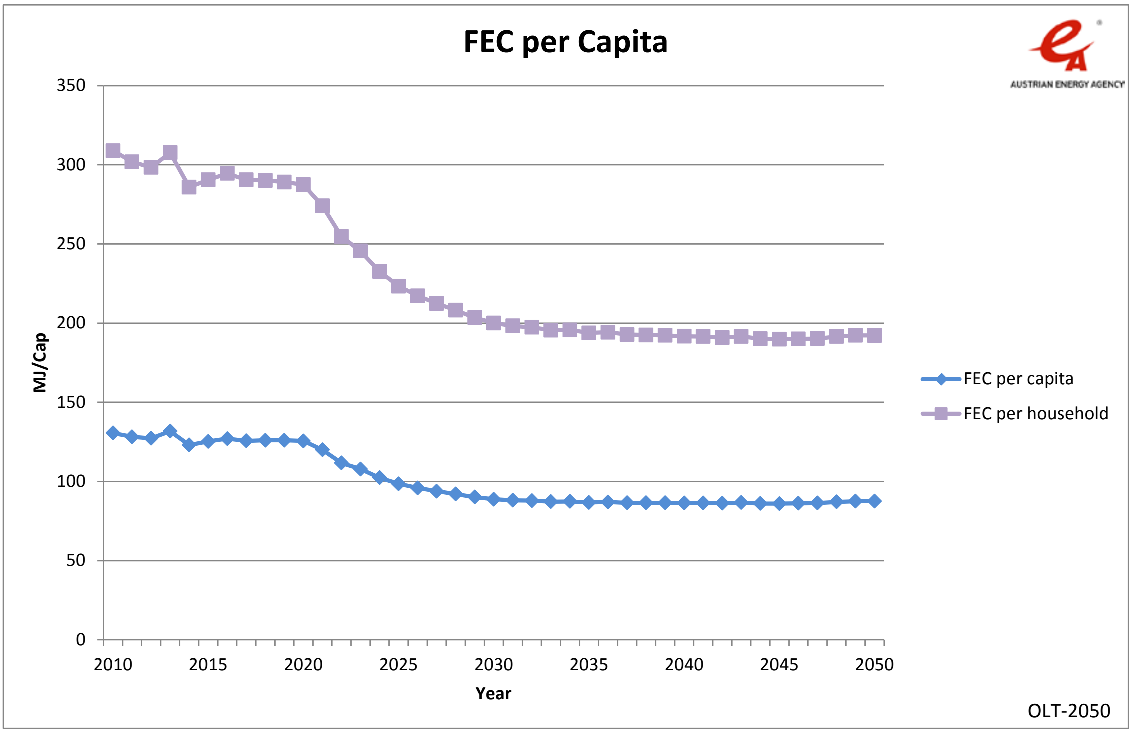

Figure 117. FEC per Capita – Scenario OLT.

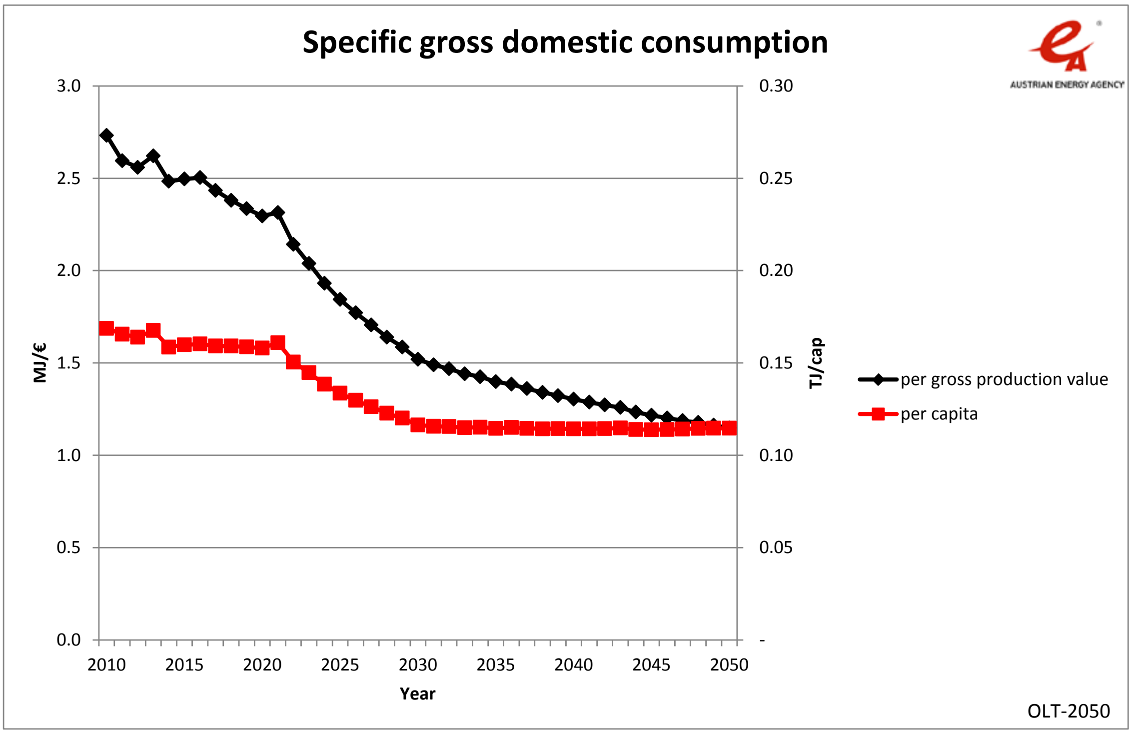

Figure 118. Gross domestic consumption per gross domestic value and capita – Scenario OLT.

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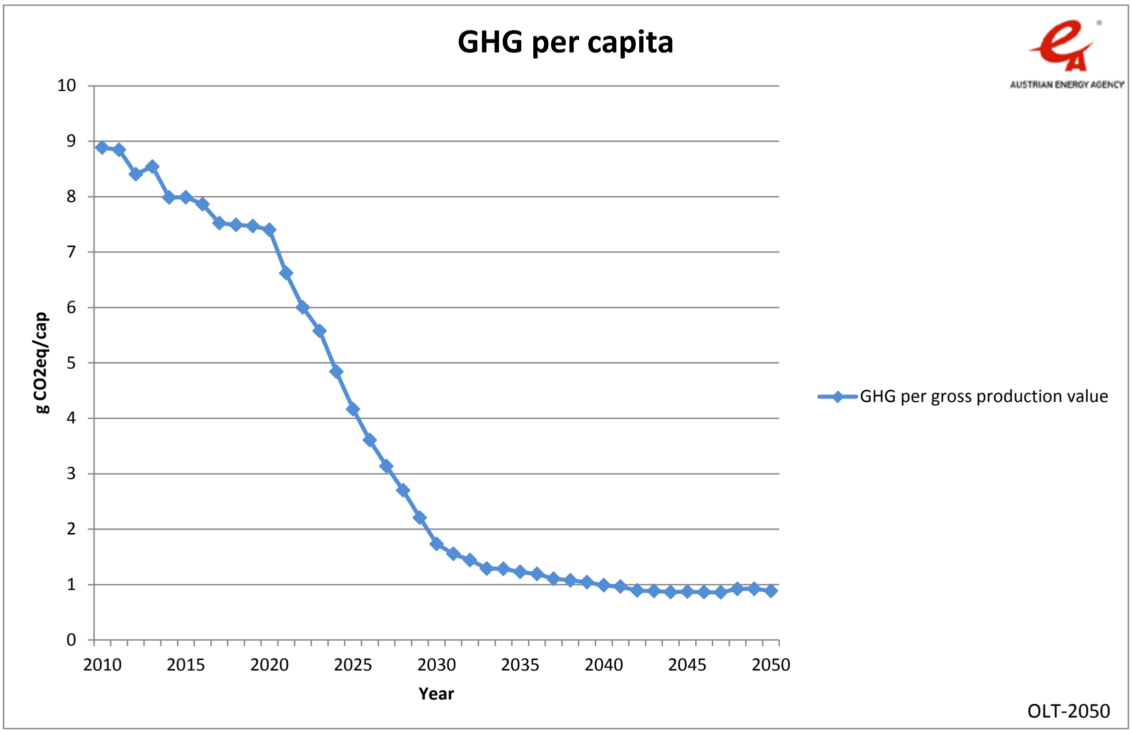

Figure 119. GHG per capita – Scenario OLT.

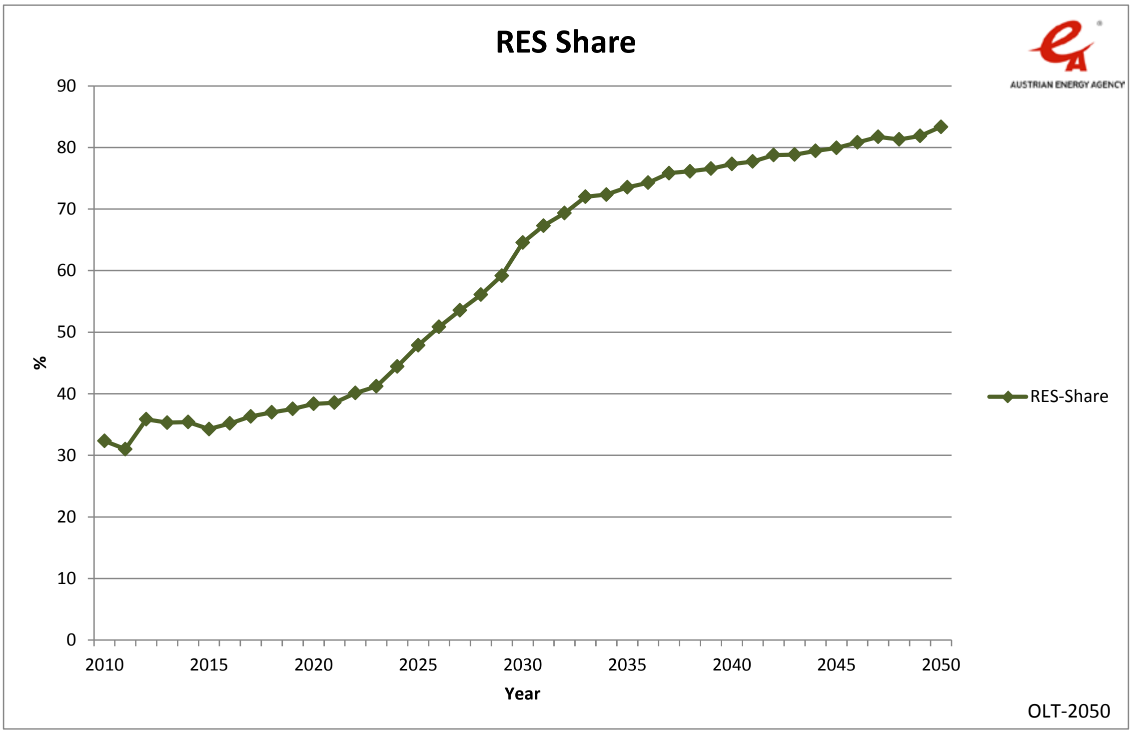

Figure 120. RES Share – Scenario OLT.

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3.3.3. Comparison of BAU and OLT scenario

Figures 121 to 127 compare BAU and OLT scenario for the different variables. In the BAU scenario, the total FEC and GDC are increasing, but the GHG emissions as well as the specific consumption and emissions indicators are already decreasing.

In the OLT scenario, a major deviation from the development of the BAU can be seen between 2020 and 2030. Although some development can also be observed (in all indicators) after 2030, the main changes take place in the first decade of the implementation of new policies.

By comparing the specific GHG reductions with the specific energy consumption it can be seen that the emissions decrease faster than the energy consumption. That means that the fuel shift towards renewable and low carbon fuels) is having a higher impact on the emission reductions than energy efficiency measures. This is also shown in the development of the RES share.

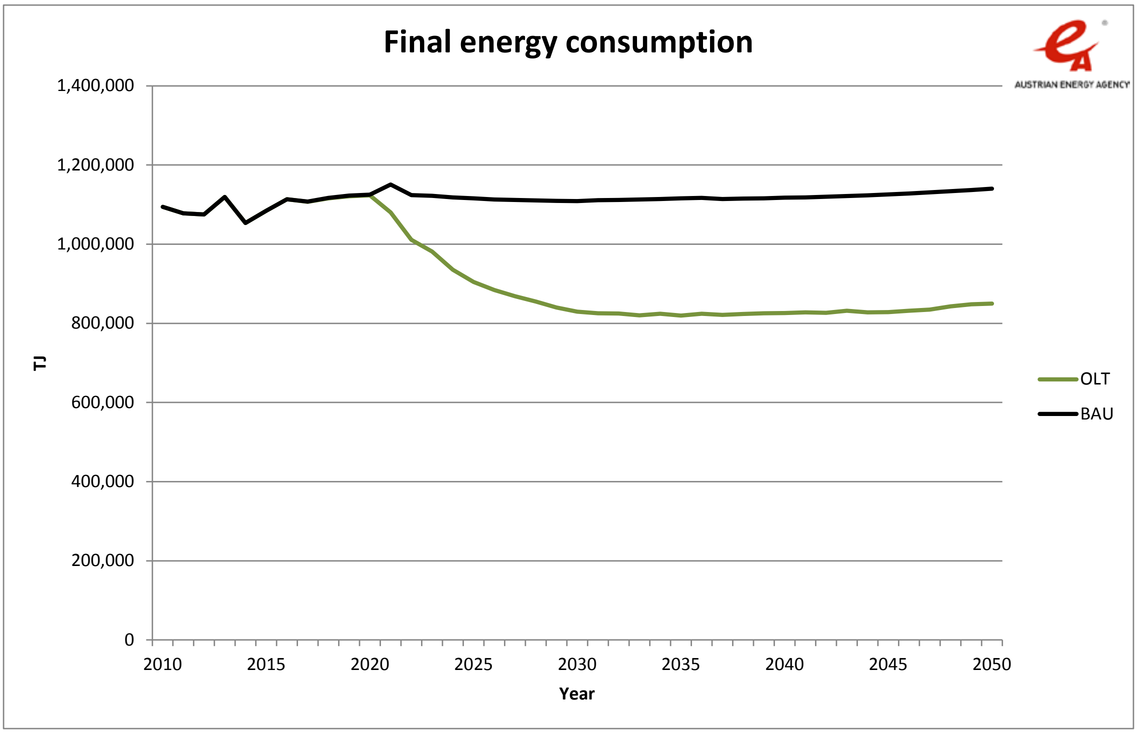

Figure 121. Final energy consumption.

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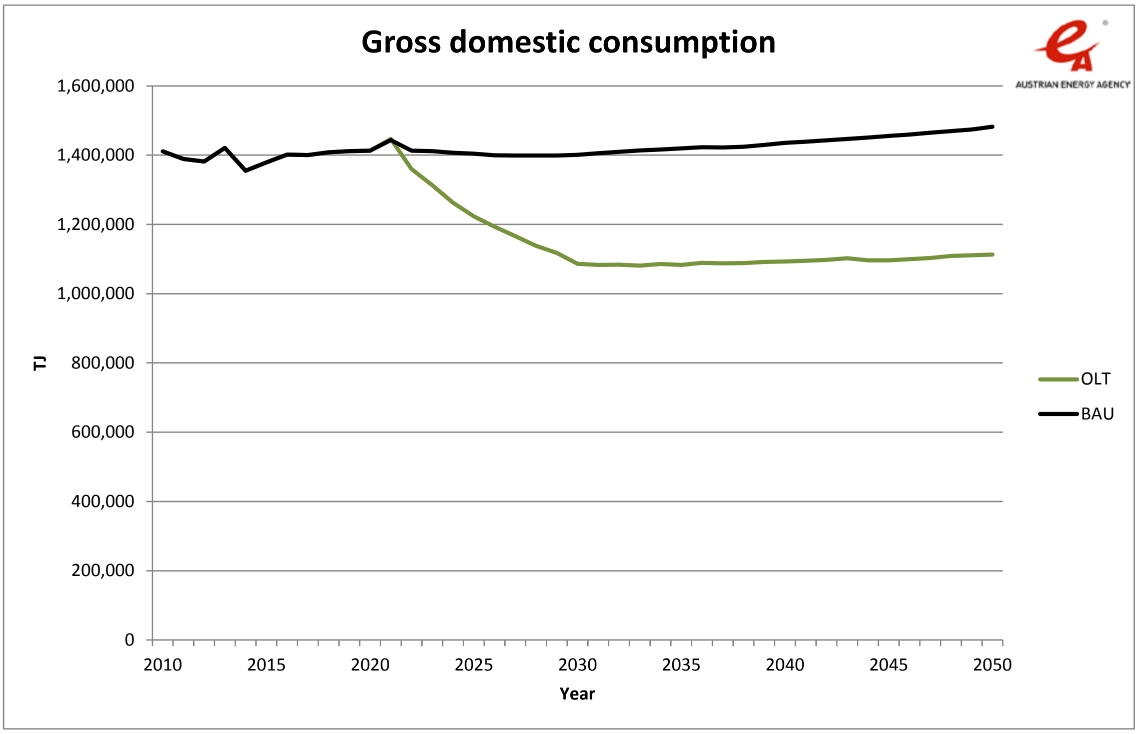

Figure 122. Gross domestic consumption.

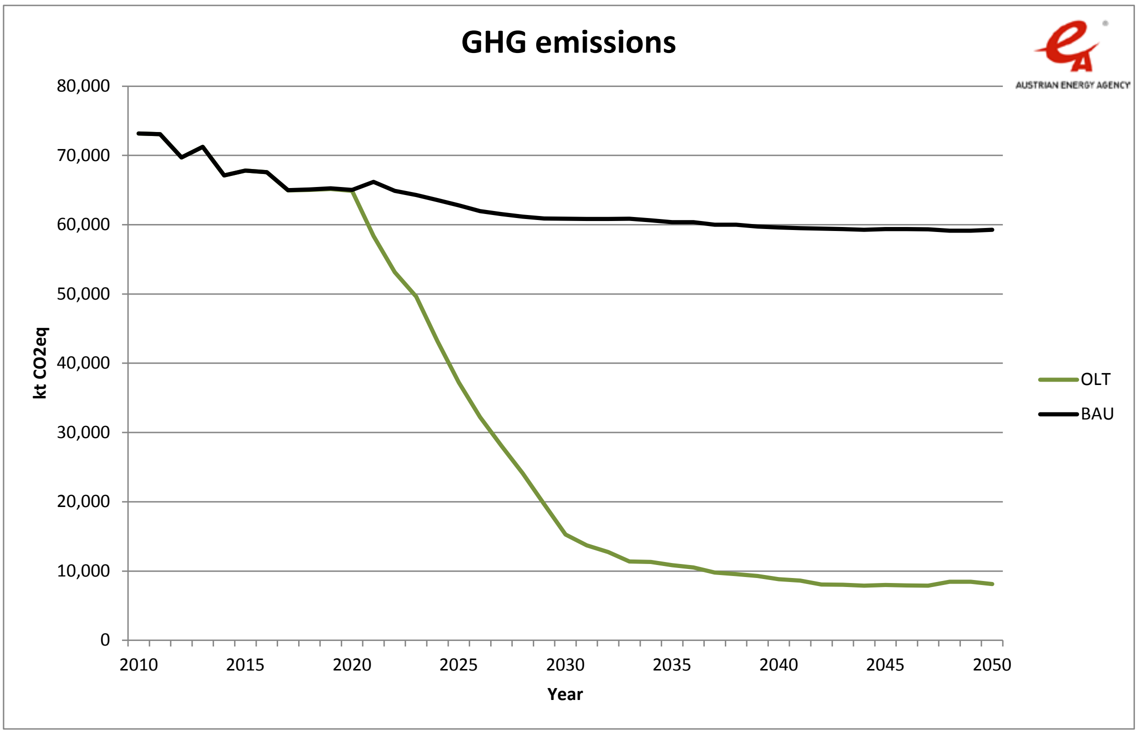

Figure 123. GHG emissions.

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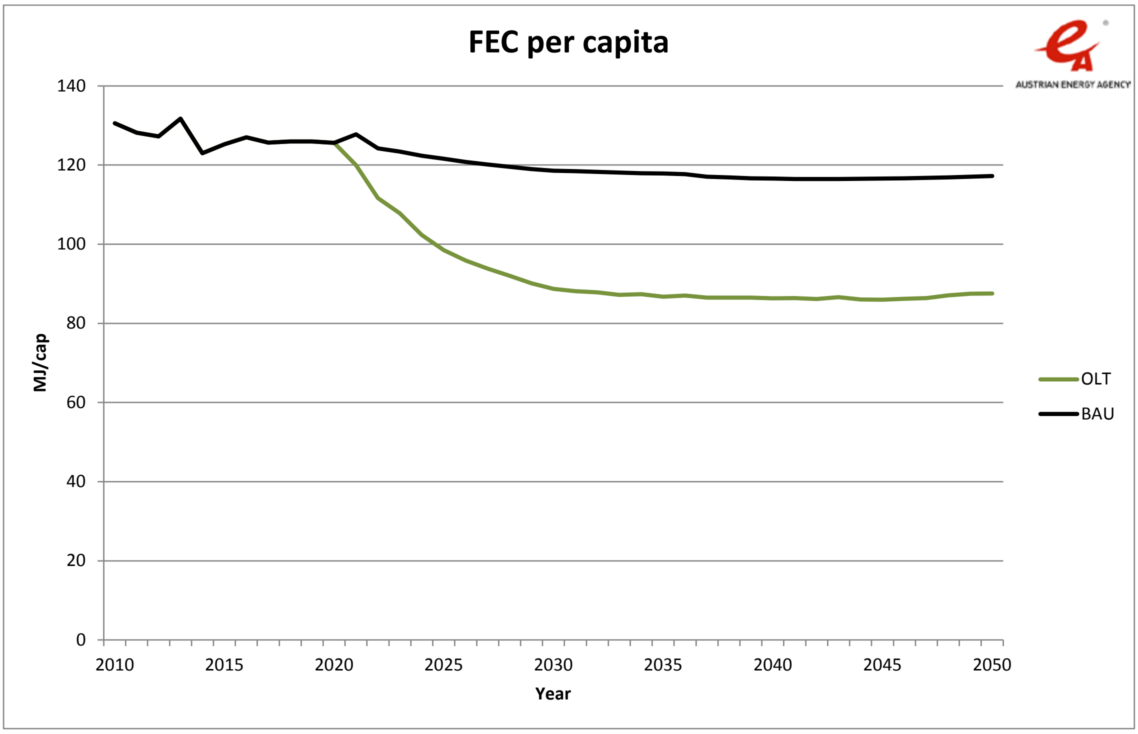

Figure 124. FEC per capita.

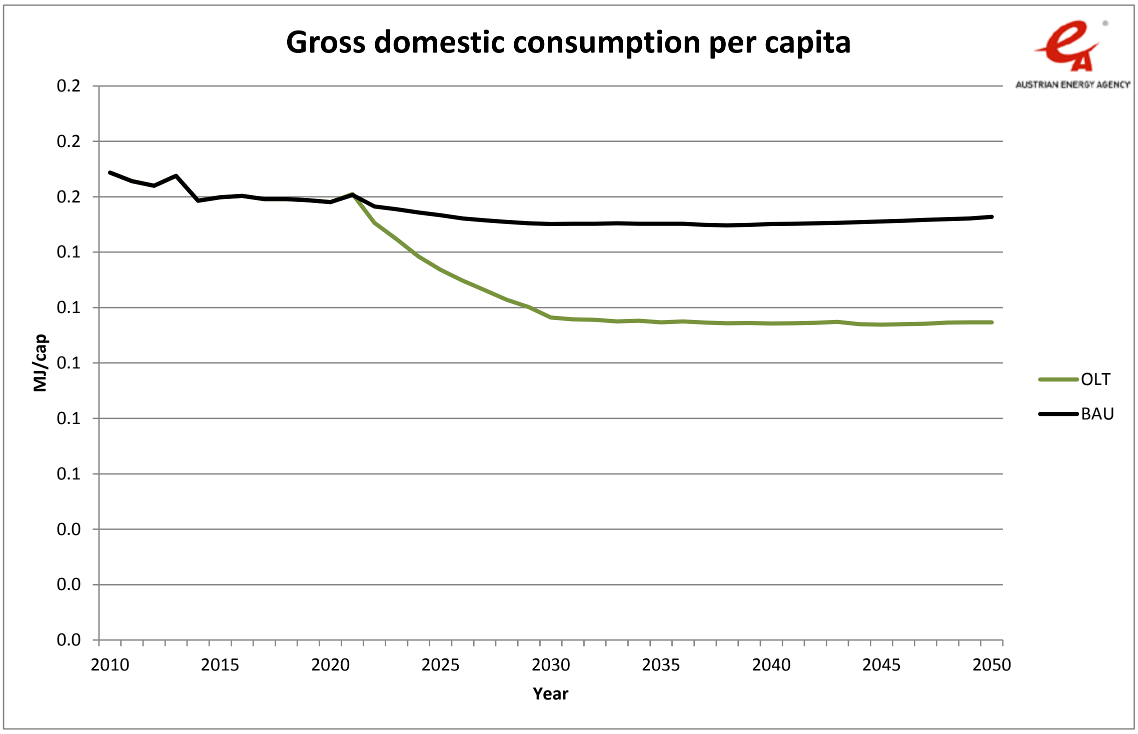

Figure 125. Gross domestic consumption per capita.

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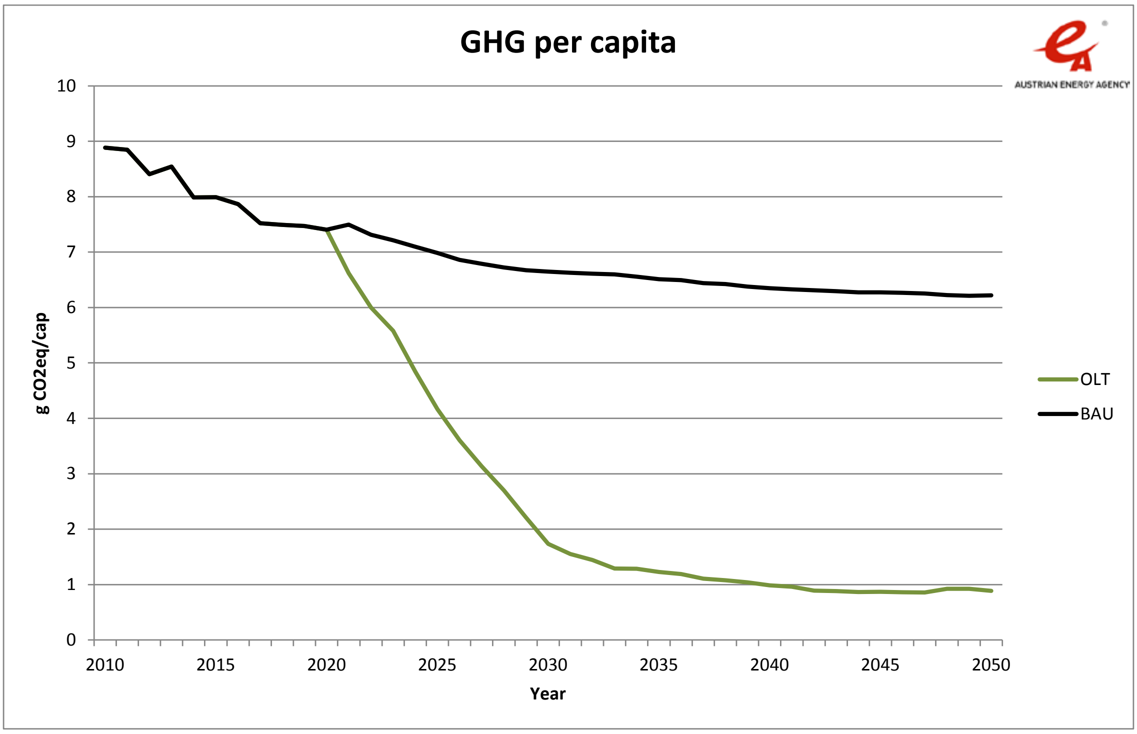

Figure 126. GHG per capita

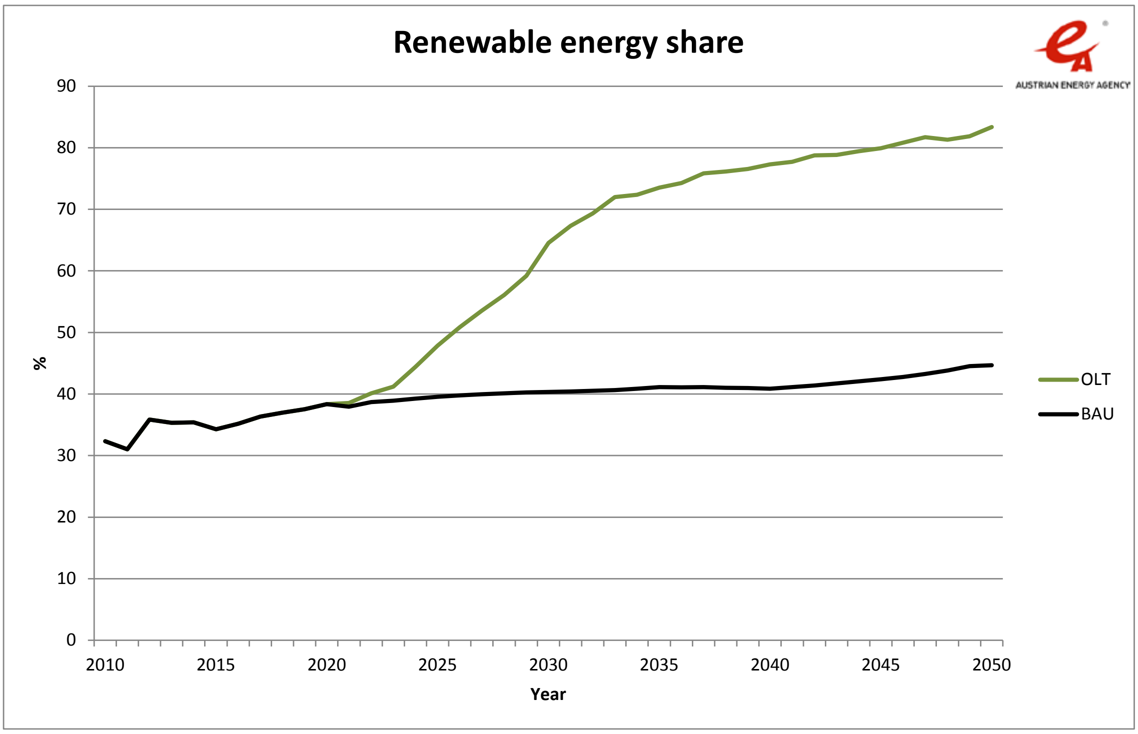

Figure 127. Renewable energy share.

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3.4. Conclusions

In the BAU scenario, it can be seen that GHG missions are slightly decreasing, although final energy and gross domestic consumption are slightly increasing until 2050. Already in this scenario, the trend towards energy efficiency and renewable energy continues, but energy efficiency cannot keep pace with economic growth. The sectorial results show the industrial energy consumption outweighs energy savings in transport and buildings. Thus, the share of renewable energy is also only slightly increasing.

The OLT scenario assumes that after 2020, policies leading to a renewable and low carbon energy transition come into effect. The main impact of these policies that intent to stay within a carbon budget of 1.4 Gt CO2eq is that electricity becomes the main fuel in all energy sectors. This starts from households and services (for appliances and heat pumps), goes over to transport (battery electric vehicles) and industry (where a lot of appliances are switched to electricity) and finally also to the iron and steel production (using electricity for electric arc furnaces and for hydrogen production for the new steel production processes).

As electricity production more than doubles until 2050 and exceed the growth of the production capacities, huge electricity imports will be necessary to satisfy the demand. As the production capacity nearly triples, huge challenges for storage and the grid have to be tackled.

In general the development can be described as a massive switch towards renewable and low carbon fuels, supported by energy efficiency measures and demand reduction.

The analysis of the GHG emissions in the case of the MLT scenario shows that due to the slow decrease of the annual emissions from today until 2030, the remaining carbon budget is actually less than zero. This shows that a feasible MLT scenario requires

- a significantly higher carbon budget, and
- an earlier deviation from the baseline scenario; or
- a baseline scenario with significant emissions reduction from as early on as possible.

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4. Case study with LEAP-Bulgaria

4.1. Introduction

This section describes LEAP-Bulgaria model implementation, developed specifically to reflect all requirements of MEDEAS project. The report presents the applied methodology, scenarios concept, assumptions (dynamics of the partially aggregated variables - PAVs), and results related to the following 3 decarbonisation scenarios for Bulgaria by 2050:

- business-as-usual (BAU) scenario, assuming development based only on the current energy policy;
- optimum level transition (OLT) scenario, based on ambitious decarbonization policy starting in 2020;
- medium level transition (MLT) scenario, which follows BAU until 2029 and considers extremely demanding decarbonisation policy starting in 2030.

The objective of the development of OLT and MLT scenarios is to identify a feasible or at least a possible projection to achieve the carbon budget (accumulated GHG emissions until 2050) for Bulgaria for each of the two scenarios.

The report starts with the presentation of the scenario development methodology, describing the approach to design the scenarios (scenarios concept), the modelling methodology, and the methodology for consideration of the carbon budget in each scenario.

Next, the national energy and climate targets affecting the scenarios are briefly summarized.

Furthermore, the report looks into the assumptions that are common for all scenarios and the scenario-specific assumptions for the energy demand (residential, transport, etc.) and energy supply (electricity and heat) sectors.

Finally, emissions and energy results are presented and conclusions are drawn.

4.2. Methodology

4.2.1. Scenarios

Three energy scenarios, based on different decarbonisation policies, have been developed for Bulgaria. The scenarios are based on historical data up to 2015 and scenario years from 2016 to 2050.

To ensure comparability of the scenario results, and therefore of the policy portfolios, on which these are based, the parameters (almost) unaffected by the decarbonization policies are considered to be common for the three scenarios.

All scenarios build on the existing legislation and the available national plans, with minor exceptions when these plans are not binding and incompatible with the feasible achievement of the respective carbon budget (these exceptions are described in the relevant scenario section). Most published national plans have time horizon only until 2020, but additional information with longer time horizon, based either on draft policy documents or intentions, has been collected by relevant Government authorities, electricity, heating, and gas companies. Where the above are not available, relevant (for the particular scenario) assumptions have been made based on either literature review or expert estimation.

Business as usual scenario (BAU), also referred to as SSP2, is based only on the policy (Laws, Strategies, Plans, etc.) adopted until the last historical year (2015). This scenario takes into account the expected demographic, macroeconomic, and technology developments until 2050.

In BAU, where no literature is available about a given parameter, two approaches have been taken, depending on the drivers of the particular parameter. The first approach is to extrapolate the historical trends. The second one is to assume that the historical numbers, either based on the last historical year or on the average of the whole historical period, remain constant until 2050. The second approach has been used in the majority of the cases.

In BAU no carbon budget has been considered. Instead, the emissions until 2050 result from the business-as-usual development of the country.

Optimal level transition (OLT) scenario is based on an ambitious decarbonisation policy, starting in 2020, while 2016-2019 development follows BAU. This scenario aims to achieve in a feasible way GHG emissions that do not exceed the carbon budget of Bulgaria for this particular scenario

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(see section “Carbon Budget” for details). OLT assumes a number of measures, resulting in improvement of energy efficiency at the supply and demand sides, fuel switch at the supply and demand sides, transport modal shift, behavioural change, and others.

OLT is based on assumptions from the literature review and feasible (according to the Government or experts) policies. The methodology for the design of this scenario used the following cycle:

1) development of a set of assumptions
2) simulation of the scenario, using LEAP software tool
3) if the carbon budget is not achieved, modify the assumptions and start again from 1).

The initial simulation of OLT exceeded the carbon budget by about 10%, so introduction of additional/stronger measures was needed. Next, the scenarios were iteratively adapted by changing the assumptions whose change is the most feasible, until the GHG emissions correspond to the carbon budget.

Mid-level transition (MLT) scenario is based on a very ambitious decarbonisation policy, starting in 2030, while 2016-2029 development follows BAU. The scenario aims to achieve GHG emissions that are within the MLT carbon budget of Bulgaria. Due to the delayed start of the decarbonization policy, this scenario has to achieve sharp reduction of GHG emissions immediately after 2030. The approach applied in MLT is similar to the one in OLT, but the feasibility of the decarbonisation policies is apparently lower.

4.2.2. Modelling approach

The modelling approach, i.e. the applied modelling tool, is very important for the development of the scenarios and pathways, as it determines the input variables, on which the assumptions should focus, and the outputs. The tool applied is Long-range Energy Alternatives Planning (LEAP) system. LEAP is an integrated, scenario-based modelling tool that can be used to track energy consumption, production and resource extraction in all sectors of an economy. It is used to account for both energy sector and non-energy sector greenhouse gas (GHG) emission sources and sinks (Heaps, 2016).

The LEAP modelling procedure is as follows:

- Specification of key non-energy assumptions (demographic, macroeconomic, etc.)
- Specification of energy demand – sectors, applications, technologies, fuels, costs

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- Specification of energy supply - energy losses, own needs, exogenous and endogenous production capacities, import/export
- LEAP calculates the necessary energy production (to cover the demand, losses, etc.), additional capacities needed, primary energy requirements, emissions, and costs.

The LEAP structure is presented below (Figure 128)

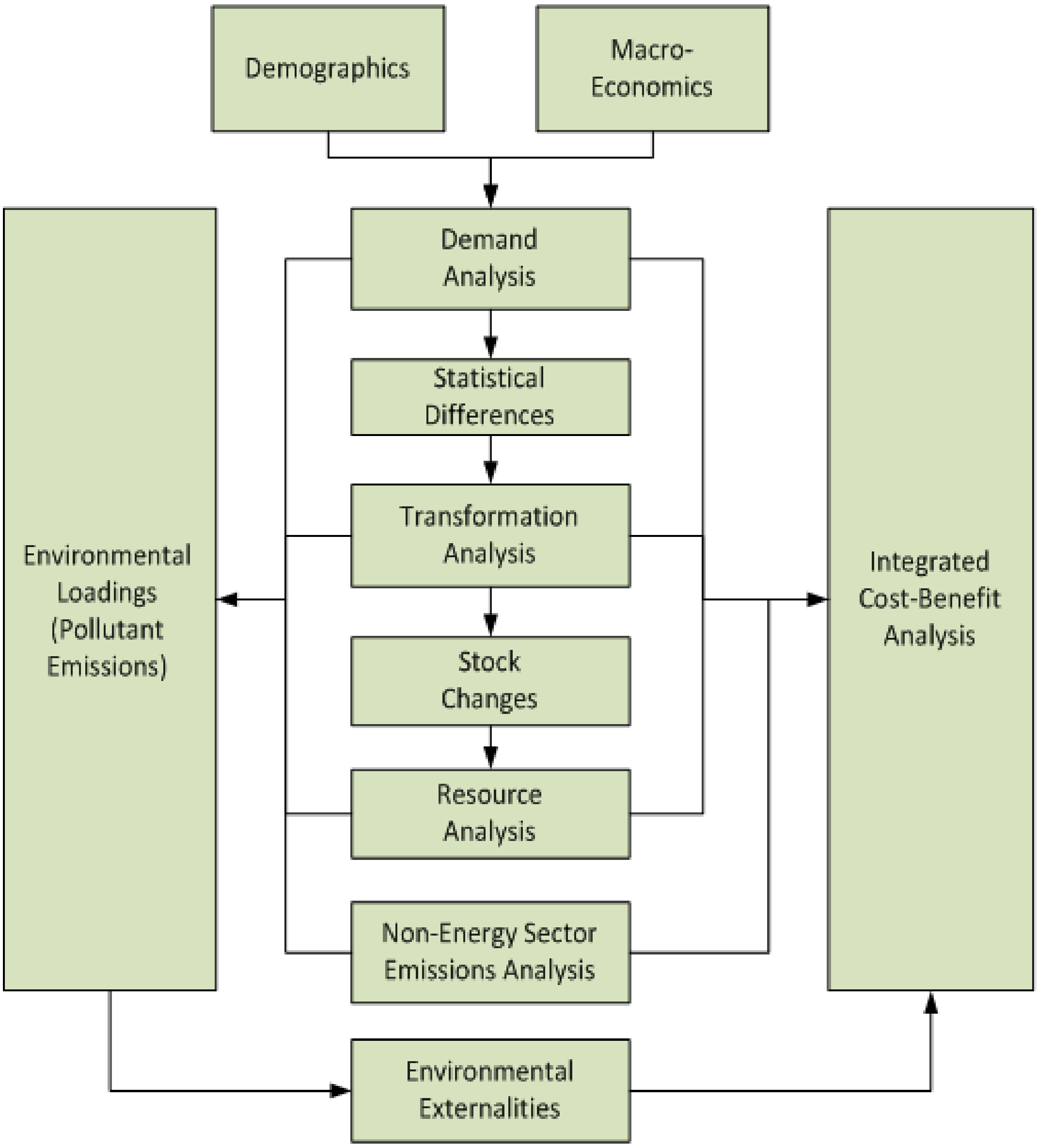

Figure 128. Simplified LEAP structure

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4.2.3. Carbon budget

The carbon budgets for OLT and MLT for Bulgaria have been elaborated by the MEDEAS project partner - the National Interuniversity Consortium of Materials Science and Technology (Perissi et al., 2018) with minor support from BSERC. The carbon budgets cover the period 2010-2100. They contain annual values for 5 sectors:

- Energy
- Industry processes and product use
- Waste
- Land Use, Land Use Change, and Forestry (LULUCF)
- Agriculture

Given that the Bulgarian model covers the period up to 2050, only the years until 2050 are considered. The carbon budgets in OLT and MLT are equal when considering the period up to 2100. However, they slightly differ for the period until 2050, due to the different emission reduction curves.

The annual emission values for all sectors, except for energy, are exogenous inputs in LEAP, as LEAP has no specific modelling methodologies for these sectors. On the other hand, LEAP calculates endogenously the GHG emissions of the energy sector.

The annual emission values (carbon budget) for OLT and MLT for the period 2015-2050 are presented respectively in 43 and Table 44 below.

Table 43. Carbon budget for OLT, $MtCO_2$

	energy	Industry processes	waste	land use	agriculture	TOTAL
2015	45.65	5.70	4.20	1.18	5.94	62.67
2016	45.27	5.42	4.05	1.19	5.95	61.88
2017	44.89	5.14	3.91	1.19	5.96	61.08
2018	44.52	4.86	3.76	1.19	5.97	60.29
2019	44.14	4.58	3.61	1.19	5.98	59.50
2020	43.76	4.30	3.47	1.19	5.99	58.71
2021	42.14	4.14	3.34	1.15	5.77	56.54
2022	40.56	3.99	3.21	1.10	5.55	54.42
2023	39.02	3.83	3.09	1.06	5.34	52.35
2024	37.52	3.69	2.97	1.02	5.14	50.34
2025	36.06	3.54	2.86	0.98	4.94	48.38
2026	34.64	3.40	2.74	0.94	4.74	46.47
2027	33.25	3.27	2.63	0.90	4.55	44.61

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2028	31.90	3.13	2.53	0.87	4.37	42.80
2029	30.59	3.01	2.42	0.83	4.19	41.04
2030	29.32	2.88	2.32	0.80	4.01	39.33
2031	28.08	2.76	2.22	0.76	3.84	37.67
2032	26.88	2.64	2.13	0.73	3.68	36.06
2033	25.71	2.53	2.04	0.70	3.52	34.49
2034	24.57	2.41	1.95	0.67	3.36	32.97
2035	23.47	2.31	1.86	0.64	3.21	31.49
2036	22.41	2.20	1.77	0.61	3.07	30.06
2037	21.37	2.10	1.69	0.58	2.93	28.67
2038	20.37	2.00	1.61	0.55	2.79	27.33
2039	19.40	1.91	1.54	0.53	2.66	26.03
2040	18.46	1.81	1.46	0.50	2.53	24.77
2041	17.56	1.72	1.39	0.48	2.40	23.55
2042	16.68	1.64	1.32	0.45	2.28	22.37
2043	15,83	1,56	1,25	0,43	2,17	21,24
2044	15,01	1,47	1,19	0,41	2,06	20,14
2045	14,22	1,40	1,13	0,39	1,95	19,08
2046	13,46	1,32	1,07	0,37	1,84	18,06
2047	12,73	1,25	1,01	0,35	1,74	17,07
2048	12,02	1,18	0,95	0,33	1,65	16,12
2049	11,34	1,11	0,90	0,31	1,55	15,21
2050	10,68	1,05	0,85	0,29	1,46	14,33
Total	**993,5**	**101,2**	**80,4**	**26,8**	**135,1**	**1,337,1**

Table 44. Carbon budget for MLT, $MtCO_2$

	energy	Industry processes	waste	land use	agriculture	TOTAL
2015	45.65	5.70	4.20	1.18	5.94	62.67
2016	45.27	5.42	4.05	1.19	5.95	61.88
2017	44.89	5.14	3.91	1.19	5.96	61.08
2018	44.52	4.86	3.76	1.19	5.97	60.29
2019	44.14	4.58	3.61	1.19	5.98	59.50
2020	43.76	4.30	3.47	1.19	5.99	58.71
2021	43.39	4.02	3.32	1.19	6.00	57.92
2022	43.01	3.74	3.17	1.19	6.01	57.13
2023	42.63	3.46	3.03	1.19	6.02	56.34
2024	42.26	3.18	2.88	1.19	6.04	55.55
2025	41.88	2.90	2.73	1.19	6.05	54.76
2026	41.51	2.62	2.59	1.20	6.06	53.96
2027	41.13	2.34	2.44	1.20	6.07	53.17
2028	40.75	2.06	2.29	1.20	6.08	52.38
2029	40.38	1.78	2.15	1.20	6.09	51.59
2030	40.00	1.50	2.00	1.20	6.10	50.80
2031	37.22	1.40	1.86	1.12	5.68	47.27

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2032	34.60	1.30	1.73	1.04	5.28	43.95
2033	32.13	1.20	1.61	0.96	4.90	40.81
2034	29.81	1.12	1.49	0.89	4.55	37.85
2035	27.61	1.04	1.38	0.83	4.21	35.07
2036	25.55	0.96	1.28	0.77	3.90	32.45
2037	23.62	0.89	1.18	0.71	3.60	30.00
2038	21.80	0.82	1.09	0.65	3.33	27.69
2039	20.10	0.75	1.01	0.60	3.07	25.53
2040	18.51	0.69	0.93	0.56	2.82	23.50
2041	17.01	0.64	0.85	0.51	2.59	21.61
2042	15.62	0.59	0.78	0.47	2.38	19.84
2043	14.32	0.54	0.72	0.43	2.18	18.19
2044	13.11	0.49	0.66	0.39	2.00	16.65
2045	11.98	0.45	0.60	0.36	1.83	15.21
2046	10.93	0.41	0.55	0.33	1.67	13.88
2047	9.95	0.37	0.50	0.30	1.52	12.64
2048	9.05	0.34	0.45	0.27	1.38	11.49
2049	8.21	0.31	0.41	0.25	1.25	10.43
2050	7.44	0.28	0.37	0.22	1.13	9.45
Total	**1,073.8**	**72.2**	**69.0**	**30.7**	**155.6**	**1,401.2**

LEAP results for the energy-related GHG emissions in 2015 (last historical year in the scenarios) have been calibrated to become identical to the official statistical number for that year – 45,646 $MtCO_2eq$. There was no need to calibrate the previous historical years and the years before 2015 are ignored.

The main objective of the scenario simulation is that LEAP results for the energy sector are aligned the carbon budget for this sector. It is inappropriate to try to match the emission values between the carbon budget (the above tables) and LEAP year by year, although LEAP has such capabilities. The reason is that such an "artificial" matching cannot consider the numerous factors affecting the national energy sector development and would require inefficient policies. Instead, only the total energy-related carbon budget for 2015-2050 was considered for OLT (993.5 Mt CO_2) and MLT (1,073.8 Mt CO_2), while the shape of the emission curves differs between LEAP and the values in the above two tables.

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4.2.4. National energy and climate targets

The three scenarios developed for Bulgaria take into account as a starting point:

- the policies that are currently in place - Energy Act, Energy Efficiency Act, Renewable Energy Act, etc.; and
- the planned policies - Energy Strategy, National Energy Efficiency Action Plan (NEEAP), National Renewable Energy Action Plan (NREAP), National Plan for Nearly Zero Energy Buildings (NP NZEB), national transport strategy, the 10-year plan of the Electricity System Operator and others.

Additionally, the energy and emission targets are considered. These are reviewed below.

The primary energy saving target was established in Bulgaria's Energy Strategy up to 2020 (MEET, 2011a). It foresees a reduction of 50 % of primary energy intensity (PEI) by 2020 compared to 2005. The achievement of this target is estimated to bring about 5.8 Mtoe of primary energy savings compared to the set up in the 2020 reference scenario's Gross national consumption of 21.6 Mtoe (SEDA, 2011).

Bulgaria has set indicative national energy-saving targets for 2020 in the National Energy Efficiency Action Plan (NEEAP): 716 ktoe/y energy savings at final energy consumption and 1,590 ktoe/y - at primary energy consumption. According to this document, the achievement of these targets by 2020 will reduce the final energy consumption in 2020 from 18,460 ktoe, as per the reference scenario, to 16,870 ktoe, which corresponds to a 41 % reduction of the primary energy intensity in 2020 compared to 2005.

The 2020 national target for 16 % renewable energy share in the gross final energy consumption (MEET, 2011b) has been exceeded in the last years, e.g. the actual share was 18.4 % in 2016 (NSI, 2018a), so it does not need to be considered in the three scenarios. Only one specific target for renewable energy needs to be taken into account - according to the Energy from Renewable Sources Act (ERSA, 2018), as of 1st March 2019, the fuels for petrol engines must contain at least 9 % biofuels.

Bulgaria has set targets for reduction of greenhouse gas (GHG) emissions in non-ETS sectors, such as transport (except for aviation and international maritime shipping), buildings, agriculture and waste. For 2020 the target is to keep GHG emissions within 120 % of the 2005 levels (EC, 2009), while for 2030 – they should not exceed the amounts from 2005 (EC, 2018).

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4.2.5. Common assumptions for BAU, OLT and MLT

The three scenarios are based on different decarbonisation policy portfolios. To ensure comparability of the policy portfolios, there have been set common parameters unaffected by these portfolios. This section describes the parameters that are assumed to be common for BAU, OLT and MLT.

4.2.5.1. Demographics

Population dynamics is an important driver of the energy consumption, mostly in the residential and transport sectors. There are several available forecasts for the Bulgarian population, the most recent being the three (low, medium, and high) forecasts of (NSI, 2017) and the 3 forecasts (low, medium, and high) of (BAS, 2017). For the aims of the MEDEAS study, the medium forecast of the Bulgarian National Statistical Institute (NSI, 2017) was used - see Table 45[9].

Table 45. Bulgaria's population forecast - medium

Year	Population (persons)	Year	Population (persons)	Year	Population (persons)
2010	7,504,868	2024	6,801,832	2038	6,244,032
2011	7,327,224	2025	6,760,045	2039	6,205,903
2012	7,284,552	2026	6,718,993	2040	6,167,774
2013	7,245,677	2027	6,678,197	2041	6,131,841
2014	7,202,198	2028	6,637,692	2042	6,096,113
2015	7,153,784	2029	6,597,502	2043	6,059,976
2016	7,101,859	2030	6,554,784	2044	6,024,043
2017	7,068,046	2031	6,515,015	2045	5,988,110
2018	7,034,233	2032	6,475,673	2046	5,953,198
2019	7,000,420	2033	6,436,741	2047	5,918,286
2020	6,966,607	2034	6,398,199	2048	5,883,374
2021	6,925,295	2035	6,355,938	2049	5,848,462
2022	6,884,034	2036	6,318,305	2050	5,813,550
2023	6,842,867	2037	6,281,012		

[9] 2010-2015 data are historical

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4.2.5.2. Economic activity

Economic activity is another important factor that affects the energy consumption. Although most GDP forecasts for Bulgaria are a short-term ones, there are a couple of recent long-term forecasts (BAS, 2017; OECD, 2017). Among them the OECD forecast (OECD, 2017) for GDP growth rates has been selected. The result is presented in Table 46[10].

Table 46. Bulgaria's GDP forecast

Year	GDP (2010 prices), mln BGN	Year	GDP (2010 prices), mln BGN	Year	GDP (2010 prices), mln BGN
2010	74,771	2024	108,005	2038	158,971
2011	76,203	2025	111,650	2039	162,739
2012	76,227	2026	115,418	2040	166,596
2013	76,884	2027	119,314	2041	169,342
2014	77,906	2028	123,340	2042	172,133
2015	80,724	2029	127,503	2043	174,971
2016	83,503	2030	131,806	2044	177,855
2017	86,143	2031	134,930	2045	180,787
2018	88,867	2032	138,128	2046	183,767
2019	91,677	2033	141,402	2047	186,796
2020	94,576	2034	144,753	2048	189,875
2021	97,768	2035	148,183	2049	193,005
2022	101,068	2036	151,695	2050	196,186
2023	104,479	2037	155,291		

Additionally, the economic activity of specific economy sectors takes into consideration the sectoral value added. The annual growth rates considered for Bulgaria in the EU Reference Scenario (Capros et al., 2016) have been applied (Figure 47)[11].

[10] 2010-2016 data are historical data from NSI
[11] The absolute values provided in this source are ignored, because more recent statistical data are used.

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Table 47. Sectoral annual growth rate forecast

Sector	Annual growth rate, %			
	2016-2020	2020-2030	2030-2040	2040-2050
Iron and steel industry	1.1	2.8	1.9	1.4
Non-ferrous metals industry	1.6	1.9	0.9	0.8
Chemicals industry	1.5	0.8	0.3	0.2
Non-metallic mineral industry	0.6	2.0	1.5	1.3
Paper pulp industry	1.7	2.5	1.5	1.3
Food, drink, tobacco industry	0.6	1.1	0.7	0.7
Engineering industry	2.9	3.0	2.0	1.7
Textiles industry	-0.6	-1.0	-0.9	-0.7
Other industries	1.8	2.0	1.3	1.2
Construction	0.5	1.6	0.9	0.9
Tertiary – market services	2.7	1.8	1.4	0.9
Tertiary – non-marker services	0.7	1.4	2.4	1.9
Tertiary – trade	2.1	2.5	2.2	2.1
Tertiary - agriculture	0.4	0.6	0.0	0.0

4.2.5.3. Transport activity

The transport activity, measured in passenger-kilometers (pkm) for the passenger transport and ton-kilometers (tkm) for the freight transport is based on the assumptions for Bulgaria in the EU Reference scenario (Capros et al., 2016), as shown on Table 48.

Table 48. Transport activity forecast

Sector	Annual growth rate, %		
	2016-2020	2020-2030	2030-2050
Passenger transport activity (Gpkm)	1.4	1.1	0.7
Freight transport activity (Gpkm)	2.0	1.6	1.1

While these figures are common for all scenarios, the shares of each mode of transport (road, rail, air) are specific for each scenario, as they could be affected by decarbonization policies.

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4.2.5.4. Residential sector

The construction of new dwellings is assumed to follow the historical trends. During the period 2010 – 2016, the average annual number of new dwellings was 10,869 (NSI, 2018b). Although this number represents only 0.41 % of the dwelling stock in 2015 (NSI, 2018b), it may be reasonable considering the expected serious population decrease, shown in Table 3. Additionally, following the historical trends, it is assumed that 25 % of the dwellings (2,717) are located in single-family houses (1-3 families) and 75 % (8,152) - in multifamily buildings (4+ families).

The assumed share of dwellings is displayed in the figure below (Figure 129)[12].

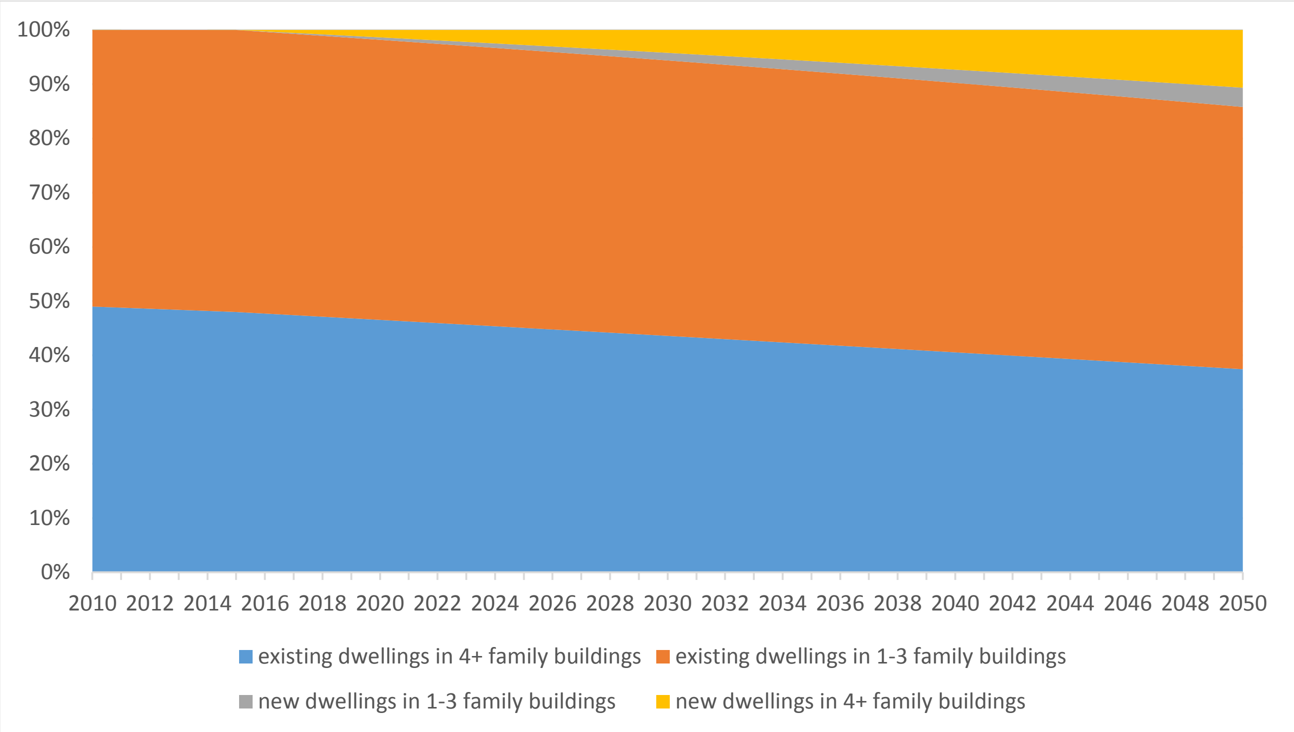

Figure 129. Assumed dwelling structure

All new residential buildings constructed by 2020 are assumed to comply with the current energy performance requirements for new buildings, while those constructed after 2020 –with the national requirements for nearly-zero energy buildings (NP NZEB, 2015).

The net average floor area of the dwellings is assumed to remain unchanged compared to the last historical year (63.8 m^2/dwelling).

[12] Existing dwellings are considered as of 2015; new dwellings are those constructed after 2015.

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The number of persons per household is considered to follow a linear decrease from 2.35 in 2015 to 2.17 in 2050, following the projected rates of change for Bulgaria in the EU Reference Scenario (Capros et al., 2016)[13].

The useful energy services, such as illumination levels, heating/cooling comfort, etc., are considered to be identical in all scenarios. This does not mean, however, that the final energy consumption is identical, e.g. in the case of heating, the efficiency of the heating devices and the heating needs (due to the different level of energy performance of buildings) are different. The energy services, related to illumination, cooking, cooling, hot water preparation, and appliances, are considered to change in relation to GDP per capita, but the exact relation depends on the nature of the given service.

In 2016, according with EUROSTAT, 39.2 % of the Bulgarian population were unable to maintain heating comfort, due to material deprivation status. It is reasonable to assume that (the vast majority of) this population resides in dwellings with low energy performance. It is therefore expected that the heat consumption in these under-heated dwellings will change (increase) proportionally to GDP per capita change (increase), but no more than 50 %[14].

4.2.5.5. Costs

All costs of primary and secondary energy resources and technologies are considered to be identical in all scenarios (they change in time, but in a given year have the same value in all scenarios). Additionally, the unit costs are considered to remain unaffected from the amount of supply and demand. This assumption is made for simplicity, although the actual costs could depend on these factors, for example, due to the increasing marginal cost of RES utilization a higher RES penetration would increase the cost per unit of energy.

The following costs were considered:

- Capital costs, variable and fixed operational and maintenance (O&M) costs of electricity and heat transformation processes;
- Costs of primary (coal, biomass, etc.) and secondary (electricity, heat, biofuels, etc.) energy carriers;

[13] The absolute numbers specified in the quoted source are based on old statistical data, so only the change rates are considered and applied to the actual 2015 statistical data.
[14] This percentage is based on the estimated difference between the average consumption of comfortably heated and under-heated dwellings.

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- Costs of demand-side energy technologies.

The costs data were drawn from NSI (NSI, 2018a), EWRC documents (EWRC, 2018), World Energy Outlook 2017 (IEA/OECD, 2017b), IPCC Assessment reports (IPCC, 2014), and US EIA (US EIA, 2017). The externality costs were not considered.

4.2.5.6. Technical parameters of energy production plants

The main technical parameters of energy (electricity and heat) production plants, such as Process Efficiency, Co-product Efficiency, and Maximum Availability, are considered to be identical in all scenarios. Depending on the particular plant, the figures either remain as of 2015, e.g. if the existing plant is assumed to remain unchanged, or improve, e.g. when a modernization/replacement is expected. An example of the average electric efficiency of power capacities is presented in the figure below (Figure 130).

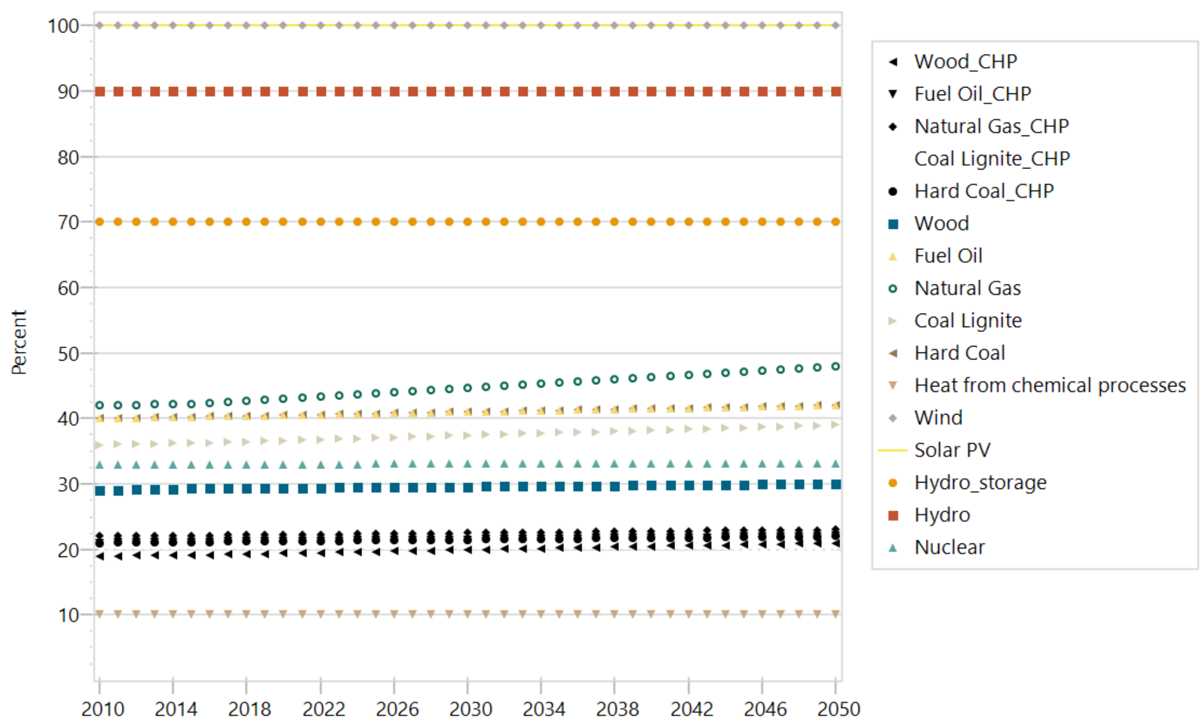

Figure 130. Expected average electric efficiency of power capacities by fuel type

While the technical parameters of the supply-side technologies are identical in all scenarios, this is not the case for the demand-side technologies, whose technical parameters depend to a large extent on the particular decarbonisation policy and are therefore scenario-specific.

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4.2.6. BAU scenario assumptions

In addition to the abovementioned assumptions that are common for all scenarios, in this section the main BAU-specific assumptions are summarized.

4.2.6.1. Residential energy demand

In BAU, the existing buildings would follow the historical energy refurbishment rates of 0.75 %/yr for single family and 0.90 %/yr for multi-family buildings. These percentages are based on the total building stock of the respective type of buildings, not only on the non-refurbished ones. The result is illustrated in Figure 131.

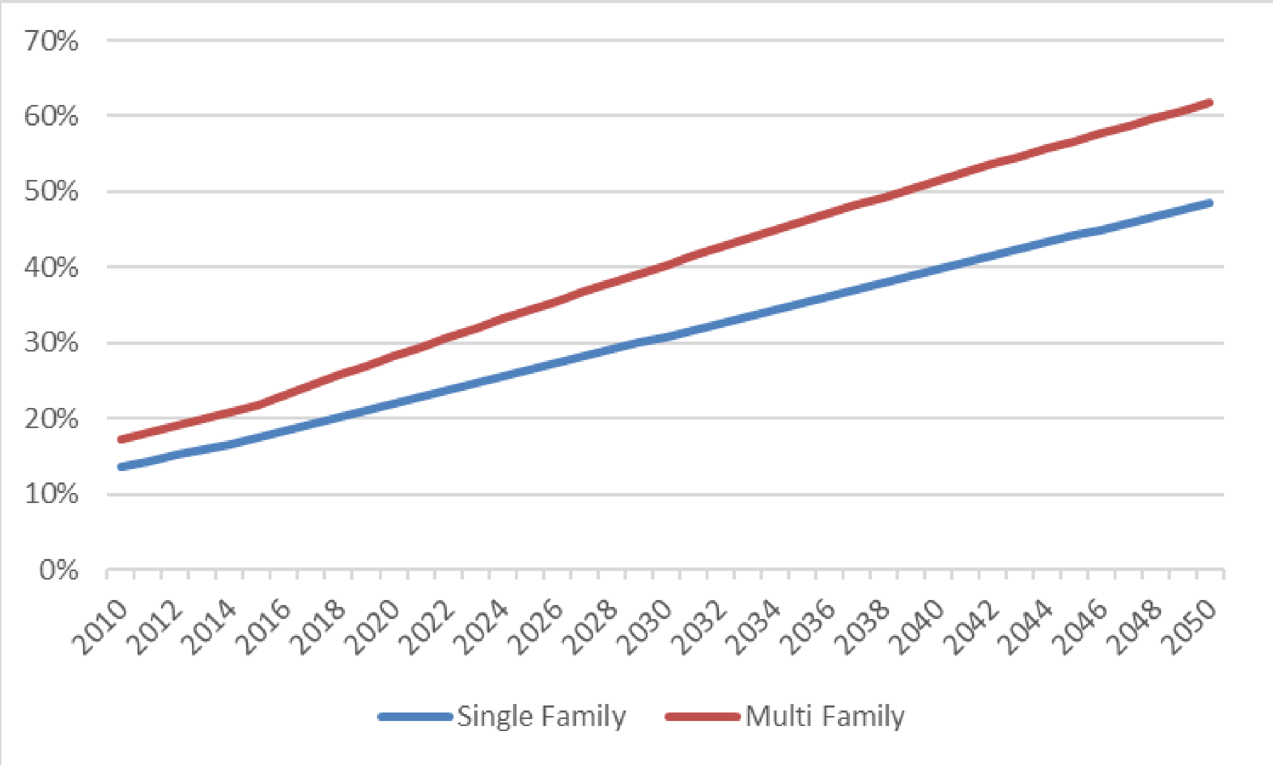

Figure 131. Share of high energy performance residential buildings in BAU

The current energy-related requirements for new (incl. NZEB) and refurbished buildings are considered to be in force until 2050.

The fuel shares in each type of buildings are assumed to remain unchanged until 2050, due to the lack of relevant policies for the period after 2020. This concerns all energy applications – heating, cooling, cooking, hot water preparation, lighting, and appliances.

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The efficiency of the majority of the demand-side conversion technologies is expected to improve slightly in relation to the projections in EU reference scenario (Capros et al., 2016). For the natural gas boilers no improvement has been considered, because the actual 2015 efficiency in Bulgaria was higher than the expected 2050 value (probably due to the recent gasification and the use of advanced boilers). All efficiency improvements are considered to change linearly until 2050.

The above assumptions result in energy demand, shown on *Figure* 132 and *Figure* 133.

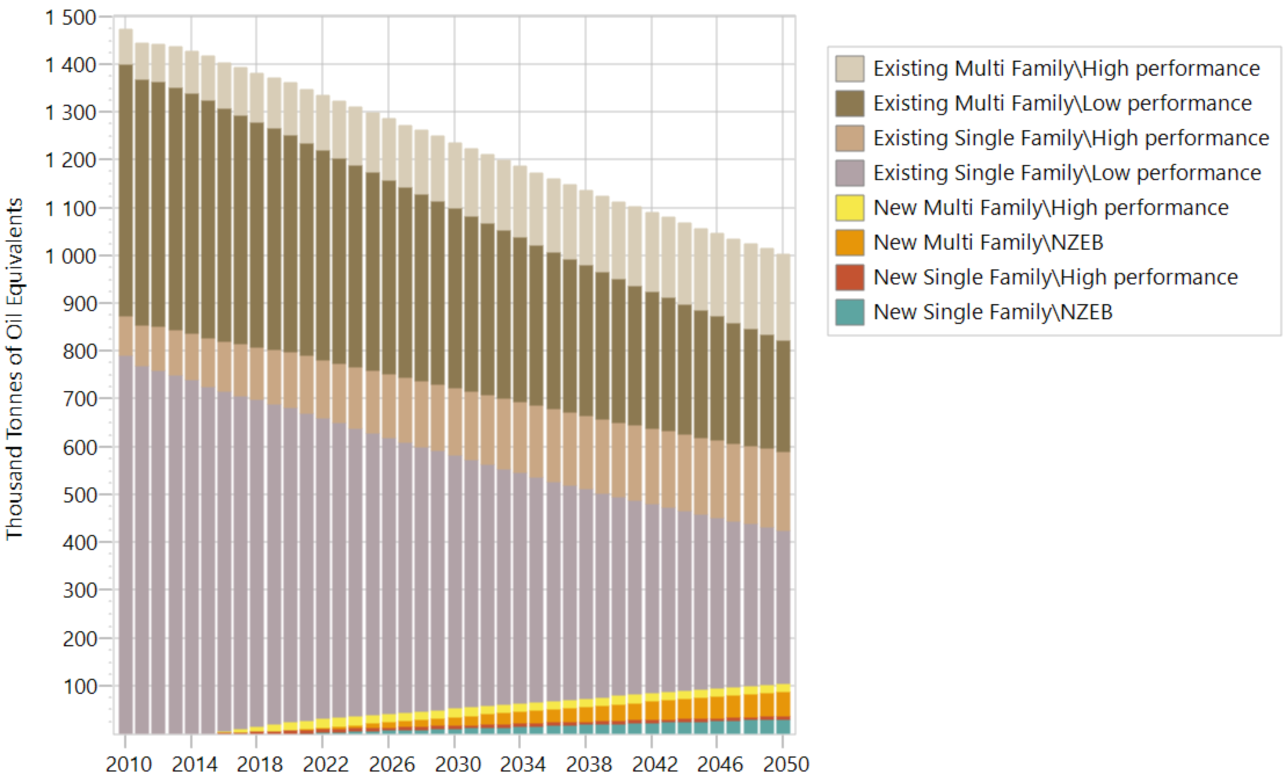

Figure 132. Residential space heating final energy demand by type of building, BAU

The figure shows substantial decrease of the energy space heating demand – from 1,417 ktoe in 2015 to 1,002 ktoe in 2050.

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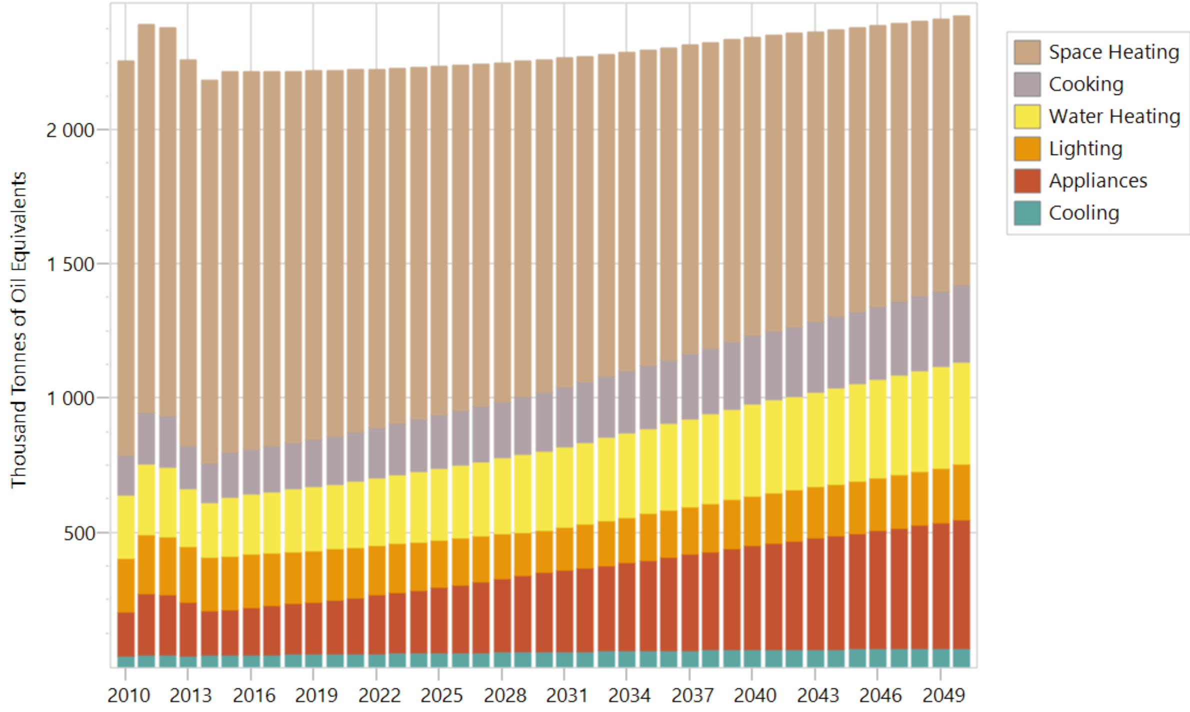

Figure 133. Residential total final energy demand by application, BAU

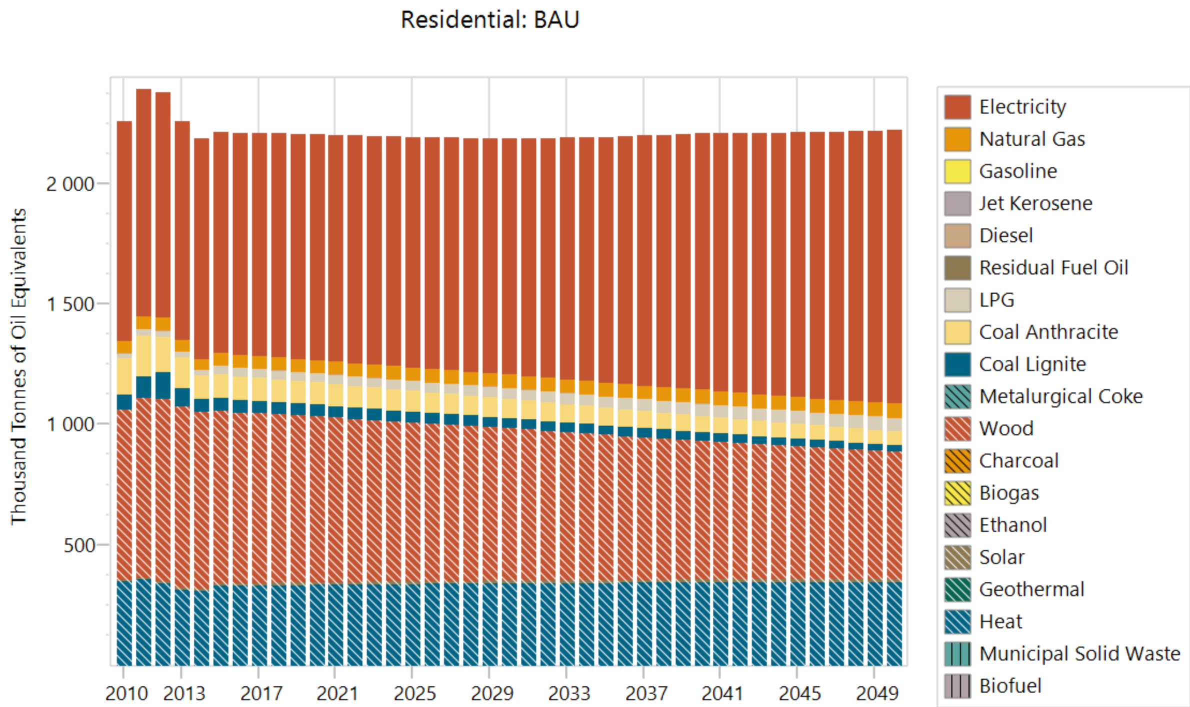

Figure 134. Residential total final energy demand by fuel, BAU

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The changes in the fuel shares in the above figure, e.g. increase of electricity share and decrease of biomass share, are driven by the changes of the shares of the different energy applications (cooking, lighting, etc.) and structure of the building stock, but not by the changes of the fuel mix within a particular application or building type (Figure 134).

4.2.6.2. Transport energy demand

The growth rates of all modes of transport are based on the EU reference scenario for Bulgaria – see Table 49.

Table 49. Transport activity per type of transport, BAU

Sector	Annual growth rate, %		
	2016-2020	2020-2030	2030-2050
Public road transport (Gpkm)	0.6	0.4	0.4
Private cars and motorcycles (Gpkm)	1.3	0.7	0.4
Rail (Gpkm)	1.6	1.6	0.9
Aviation (Gpkm)	4.9	4.5	2.4
Heavy goods & light commercial vehicles (Gtkm)	2.0	1.3	0.9
Rail (Gtkm)	1.9	2.2	1.5

The fuel shares within each mode of transport remain unchanged compared to 2015, except for the planned slight increase of the bio-gasoline share in the road transport by 2019.

The considered energy intensities in the transport sector, shown in Table 50, are also based on the EU Reference Scenario for Bulgaria:

Table 50. Transport energy intensity, BAU

Sector	Annual growth rate, %		
	2016-2020	2020-2030	2030-2050
Transport energy intensity	-0.80	-1.05	-0.55

The above assumptions result in the final energy demand, presented in *Figure* 135.

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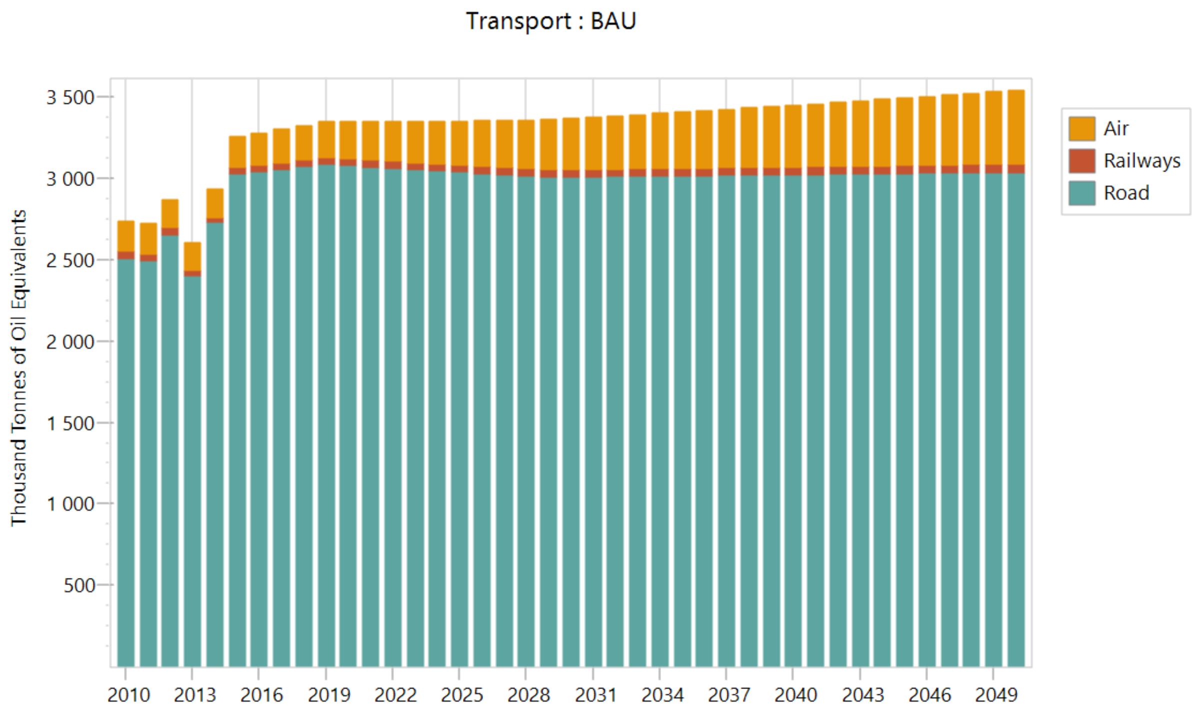

Figure 135. Transport final energy demand, BAU

The figure displays that the road transport has nearly constant energy demand and keeps its dominant position, despite the decrease from 93 % in 2015 to 86 % in 2050. The high growth rates of the activity levels in the aviation and partly in the rail transport outweigh the reduction of the energy intensity, so their energy demand grows.

4.2.6.3. Energy demand by industry

In all industry sub-sectors, the fuel mix (% of each fuel) is expected to remain as in 2015.

The dynamics of the energy intensity of each industrial sub-sector is considered to follow the assumptions for Bulgaria in the EU reference scenario – see Table 51.

Table 51. Industrial energy intensity, BAU

	Annual growth rate, %		
Sector	2016-2020	2020-2030	2030-2050
Energy intensity in industry	-0.5	-1.8	-1.4

This assumption, combined with the economic change of each industrial sub-sector (see Table 5), results in the final energy demand, shown in *Figure 136*.

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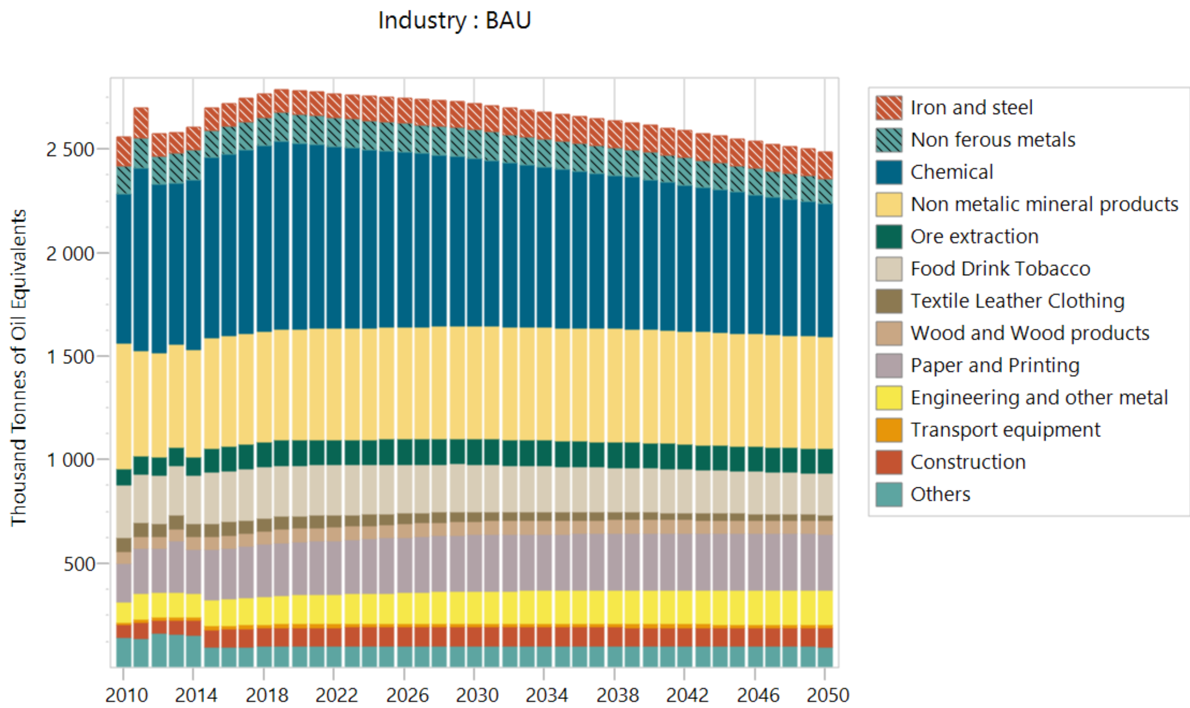

Figure 136. Industry final energy demand, BAU

The figure shows that after 2019, there is a gradual decrease of the energy demand, attributed mainly to the dynamics in the chemical industry.

4.2.6.4. Services, agriculture, and fisheries energy demand

In services, agriculture, and fisheries, the fuel mix is considered to remain the same as in 2015. The energy intensity is based on the EU reference scenario, as shown in Table 52.

Table 52. Services, agriculture, and fisheries energy intensity, BAU

Sector	Annual growth rate, %		
	2016-2020	2020-2030	2030-2050
Tertiary energy intensity	-1.3	-1.5	-1.0

The energy intensity and the economic development of these sectors (see Table 5) determine the dynamics of the final energy consumption, displayed in Figure 137.

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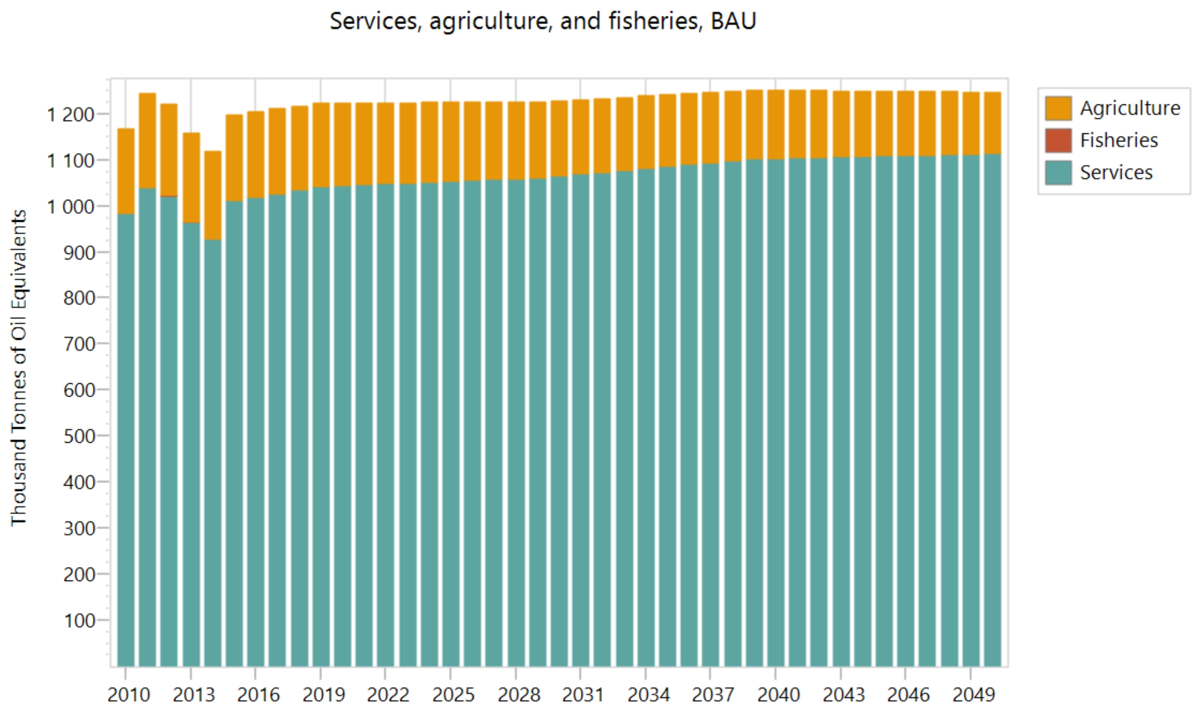

Figure 137. Services, agriculture, and fisheries final energy demand, BAU

4.2.6.5. Energy supply

The transmission and distribution losses are expected to follow the historical trends. The electricity losses would decrease linearly from 11.1 % in 2015 to 10.8 % in 2030 and after that would remain unchanged. The heating losses would decrease linearly from 19.3 % in 2015 to 18,5 % in 2030, as a result of the planned replacement of old poorly insulated pipes, and would be constant after 2030.

Own use share (energy used in energy production plants divided into the total produced energy) in all energy supply sectors is expected to remain unchanged, compared to 2015.

Electricity generation capacities in BAU follow the 2017-2026 plan of the Bulgarian Electricity System Operator and after that period the capacities are expected to remain unchanged – their life will either be prolonged or they would be replaced by new capacities of the same type (BSERC, 2018; ME, 2018). The electricity capacities are shown in the figures below (Figure 138, Figure 139).

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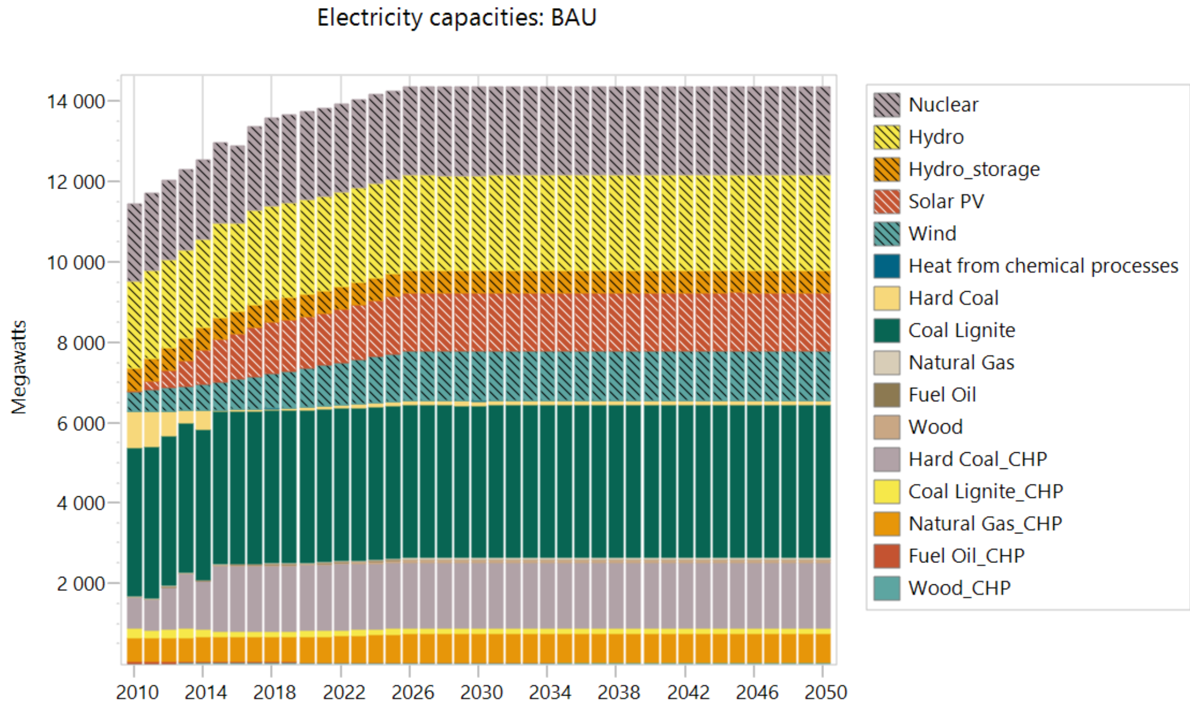

Figure 138. Electricity capacities, BAU

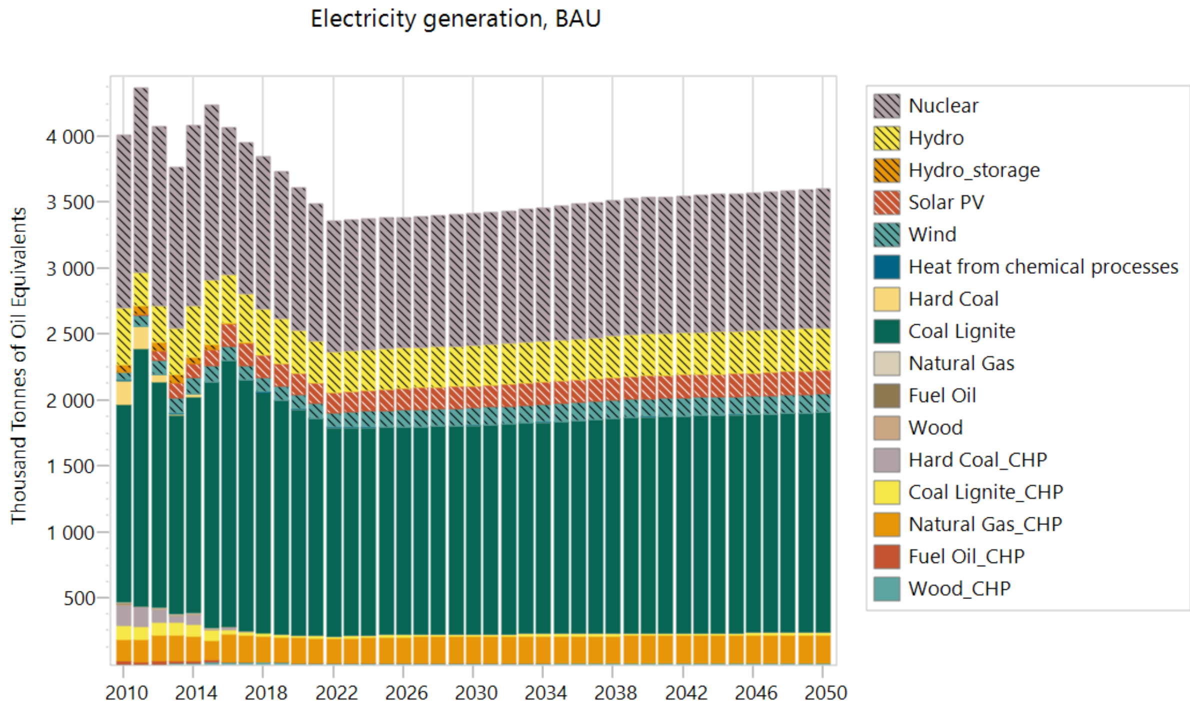

Figure 139. Electricity generation, BAU

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The fuel mix of the district heating plants is assumed to change only slightly in BAU in line with the historical trend and the expectations of the business (BDHA, 2018) for an increase of the share of renewable energy and respectively the decrease of the coal share – see Table 53.

Table 53. Expected change of fuel shares, BAU

Sector	Change for the whole period, percentage points 2016-2030	2030-2050
Biomass share	+1.5 %	+2.0 %
Other RES (solar, waste, etc.) share	+0.5 %	+2.5 %
Natural gas share	-	-
Coal share	-2.0 %	-4.5 %

The heat production from both the district heating plants and CHP is shown in Figure 140.

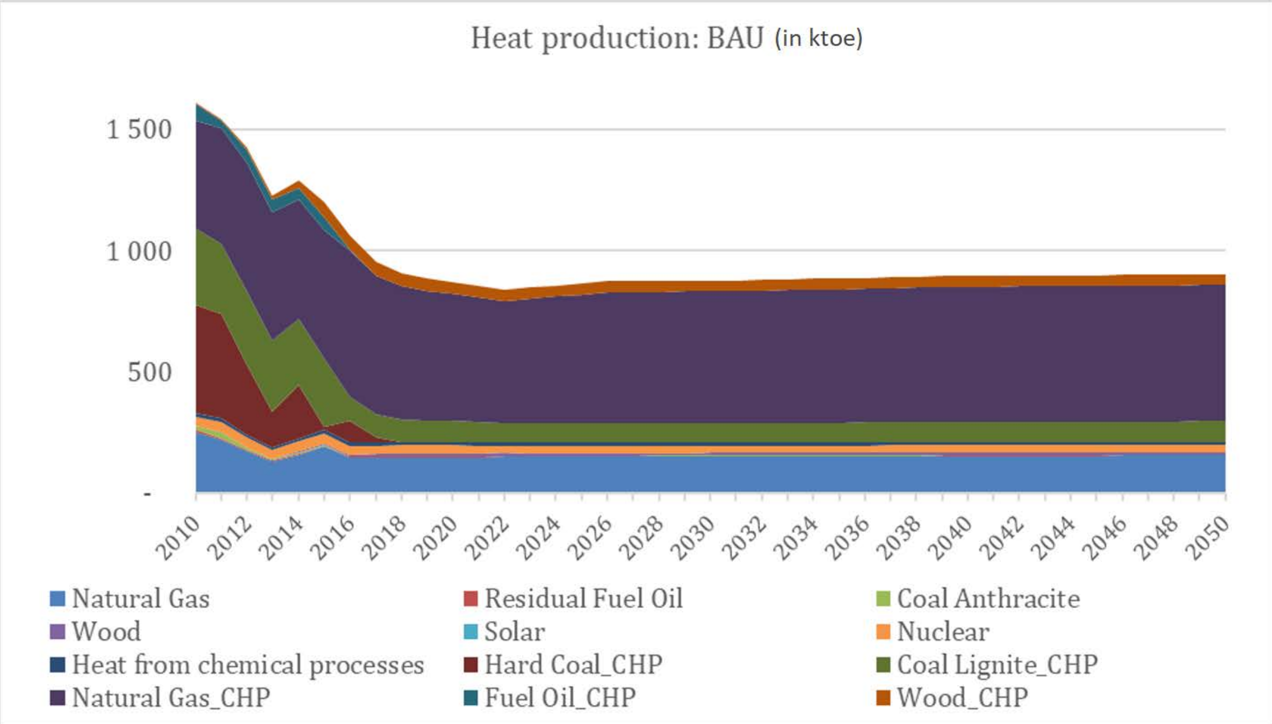

Figure 140. Heat production, BAU (in ktoe)

4.2.7. OLT scenario assumptions

This scenario considers the Common Assumptions. In 2016-2019 it follows BAU, but after that considers ambitious decarbonization policies, which would make its GHG emissions fit in the carbon budget.

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4.2.7.1. Residential energy demand

In OLT, the refurbishment rates from 2020 onward are 2.25 %/yr for the single family (1-3 families) buildings and 2.4 %/yr for multi-family (4+ families) buildings, based on the total building stock of the respective type of buildings. The result is illustrated in Figure 141.

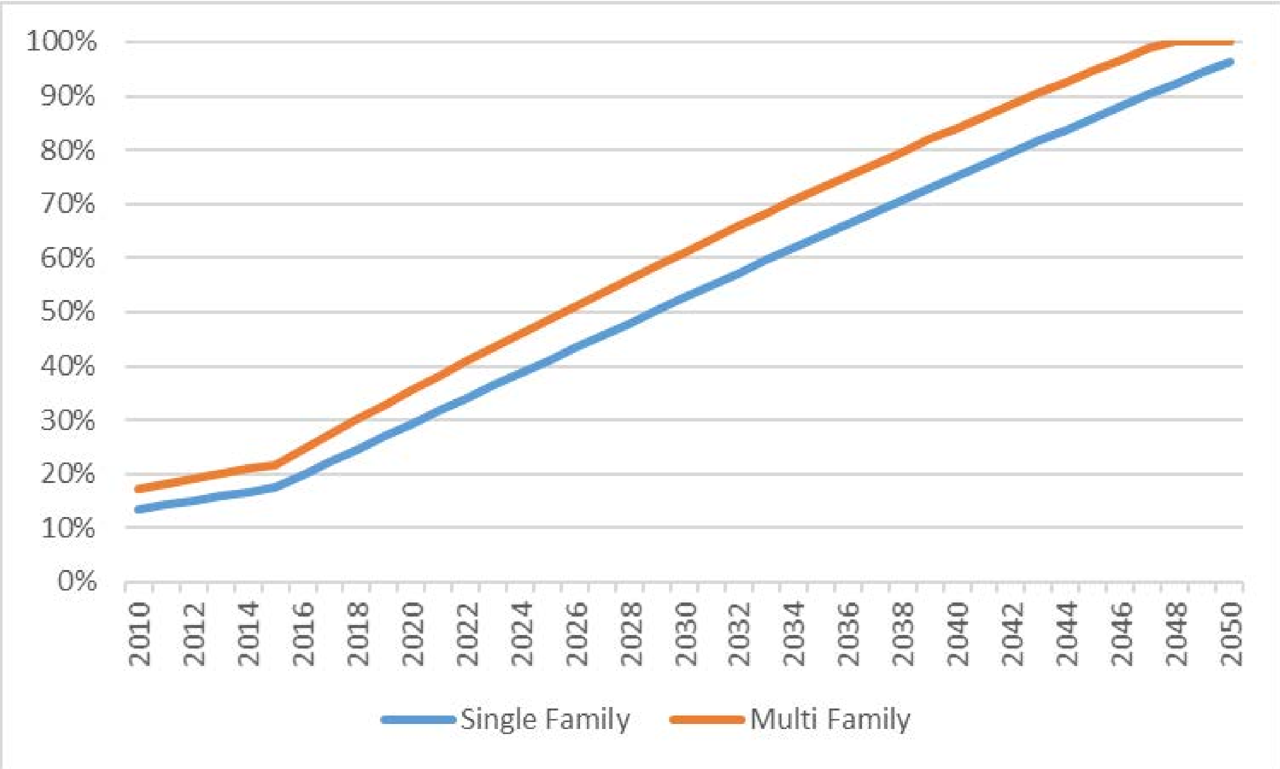

Figure 141. Share of high energy performance residential buildings in OLT

These high rates are backed-up by comprehensive policies involving incentives (gradually reduced grants and soft loans), obligations for energy audits and mandatory implementation of the audit recommendations and information measures.

After 2020 and by 2050, the energy-related requirements for refurbished buildings are considered to become gradually much more demanding (40 % lower energy consumption per square meter), although being still lower than the current NZEB requirements (NP NZEB, 2015).

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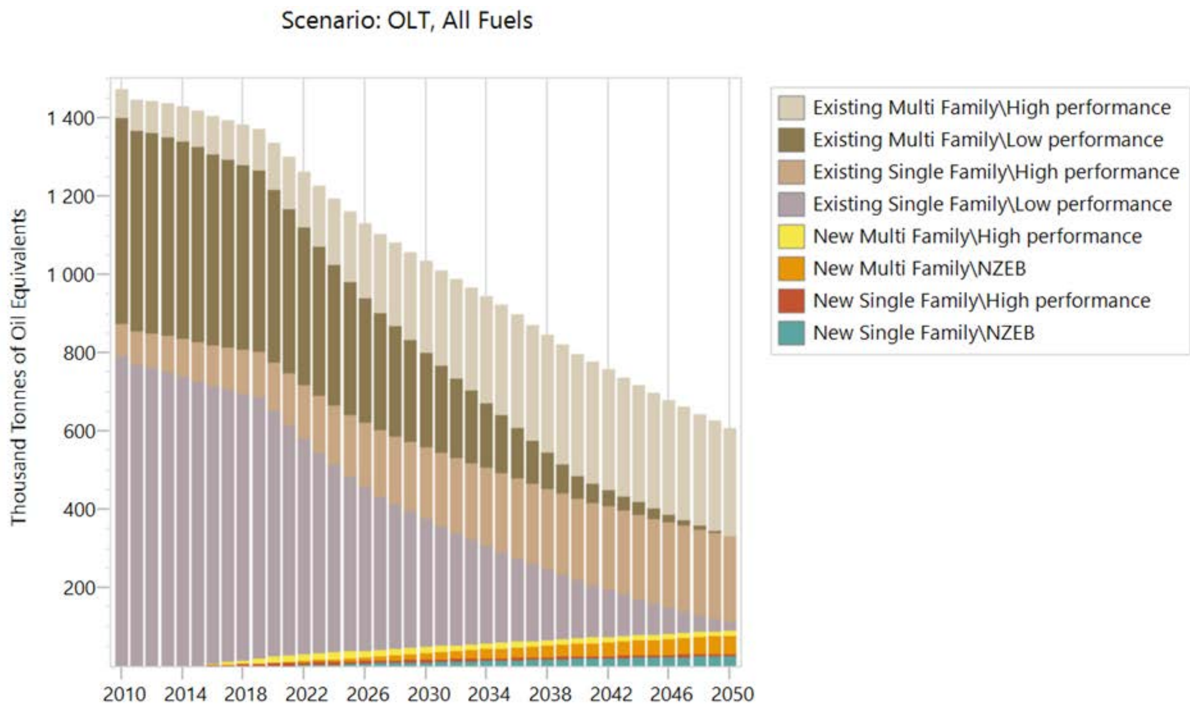

Figure 142. Residential space heating final energy demand by type of building, OLT

The Figure 142 shows a sharp decrease of the energy space heating demand – from 1,417 ktoe in 2015 to only 606 ktoe in 2050.

In space heating demand, by 2030 it is assumed fuel switch from coal and oil to gas and solar thermal energy, and after that - from gas to electricity, district heating, and solar thermal. In cooking and hot water preparation, there is minor fuel switch from biomass and gas to electricity. These changes are in line with the conclusions of a recent national workshop (BSERC, 2018), Deliverable 3.3 of MEDEAS (MEDEAS, 2017a), and the sustainable energy scenario for EC by 2040 in the World Energy Outlook 2017 (IEA/OECD, 2017b). The changes would be driven by pricing policies, building codes, and other measures (Nikolaev and Radulov, 2016).

The efficiency of all demand-side conversion technologies is expected to increase considerably by 2050, following the "Advanced" projection in the EU reference scenario (Capros et al., 2016). The improvement in the period 2020-2030 is steeper, compared to the period after 2030. For example, it is assumed that a stringent regulation on lighting products would prohibit the sale of inefficient bulbs and all residential lighting by 2030 will be LED-based, while after 2030 there will be a limited efficiency improvement, driven mainly by the technology development. The efficiency of the appliances will also improve sharply by 2030 – their consumption may decrease on average from 23.5 % (EC, 2015) up to 25-30 % (Toulouse et al., 2015), compared to the 2010 efficiency levels.

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The above assumptions result in energy demand, displayed in Figure 143 and Figure 144.

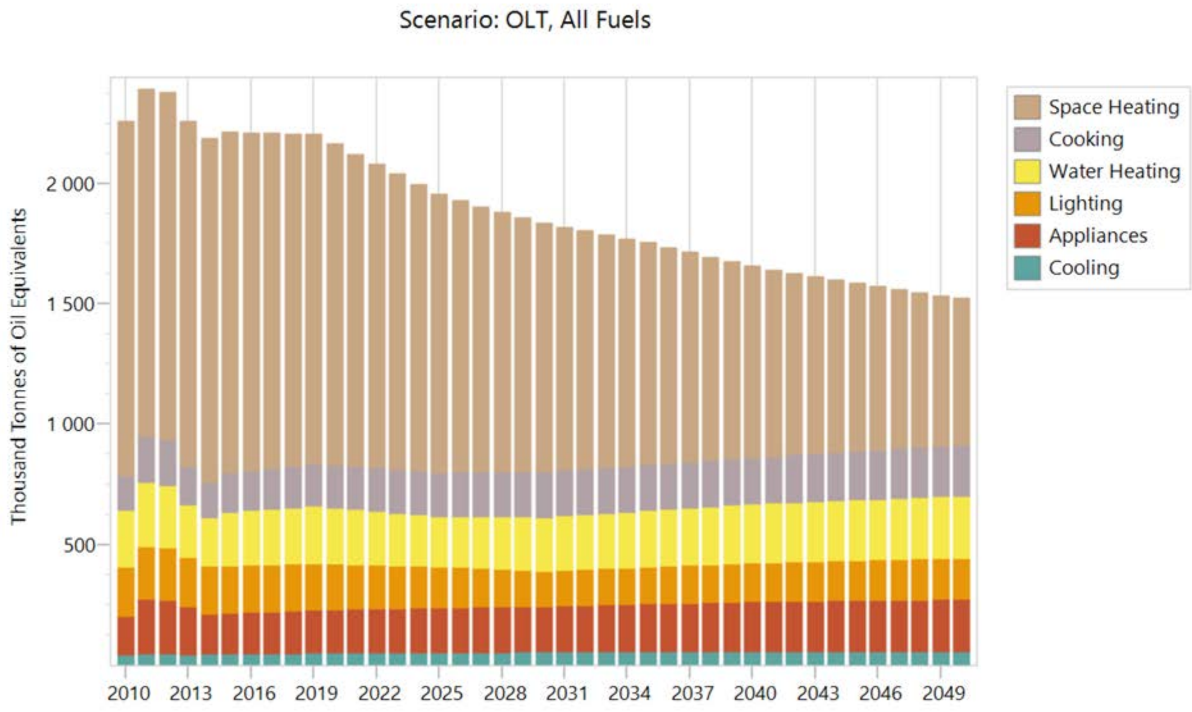

Figure 143. Residential final energy demand by application, OLT

As it could be seen in the figure, while the heating demand decreases, the energy demand for other applications remains relatively constant until 2030 and increases in the period 2031 - 2050. The total residential final energy demand decreases from 2.21 Mtoe (2015) to 1.52 Mtoe (2050).

Figure 144 displays the gradual decrease of all fuels. Only solar thermal energy consumption increases (from 7 ktoe in 2015 to 108 ktoe in 2050). Biomass reduction is the highest (from 716 ktoe in 2015 to 316 ktoe in 2050) - this can be attributed to the diminishing role of the heating in all residential applications and to the urbanization process.

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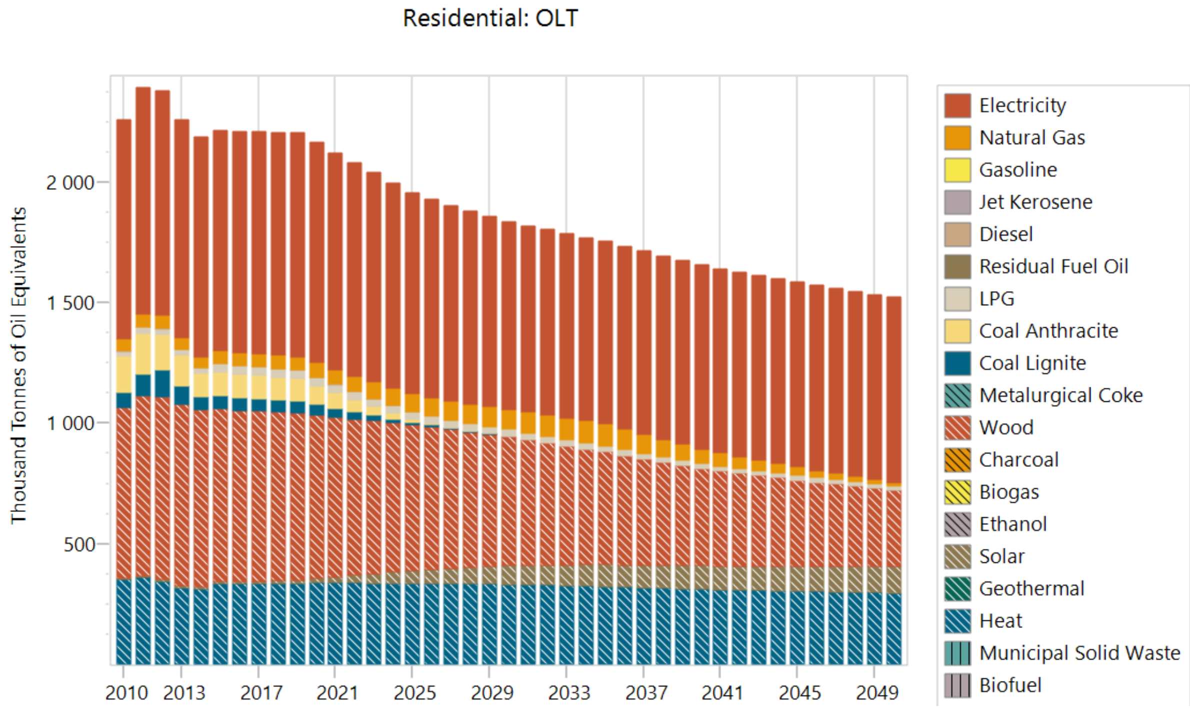

Figure 144. Residential final energy demand by fuel, OLT

4.2.7.2. Transport energy demand

In the transport sector, a number of measures and technology changes are considered:

- Fuel switch, including: penetration of electric and hybrid vehicles in passenger and freight road transport, up to 8 % in 2030 (Nikolaev and Radulov, 2016), and up to 28 % in 2050; increased biofuel share; and respectively lower share of traditional gasoline (from 14 % in 2015 to 4 % in 2050) and diesel (from 65 % in 2015 to 10 % in 2010), rail transport switch to 100 % electricity by 2040 (compared to 82,4 % in 2015).
- Eco-driving in passenger and freight road transport, resulting in up to 7 % fuel economy in this transport, compared to 2015 (Nikolaev and Radulov, 2016).
- Modal shift, including substantial shift from road to rail transport (about 1.5 % annually, compared to BAU) – the road transport activity reaches only about 40 % of the one in BAU by 2050. Rail transport activity increases sharply and its value in 2050 is about 12 times higher compared to 2015. Air transport activity increases by 23 % by 2050, which is notably below the 209 % increase in BAU, due to transfer from air to rail. Minor (about 1 %) shift to cycling/walking is considered.
- More efficient vehicles in passenger and freight rail and road transport: 0.2 %/yr reduction of the consumption per km.

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These changes would be based on the adoption of the following policies (Nikolaev and Radulov, 2016):

- Tax levy for electric and hybrid vehicles, combined with tax burden for non-electric vehicles, especially for highly polluting ones;
- Development of infrastructure for electric charging, rail, cycling, and walking;
- Information campaigns;
- Training on economical driving and mandatory feedback equipment in freight road transport;
- Information campaigns (cycling, walking, car-pooling, rail advantages);
- Biofuel blending obligations for fuel suppliers;
- Rules for public tendering.

The above assumptions result in the final energy demand, presented in Figure 145 (by transport mode) and Figure 146 (by fuel).

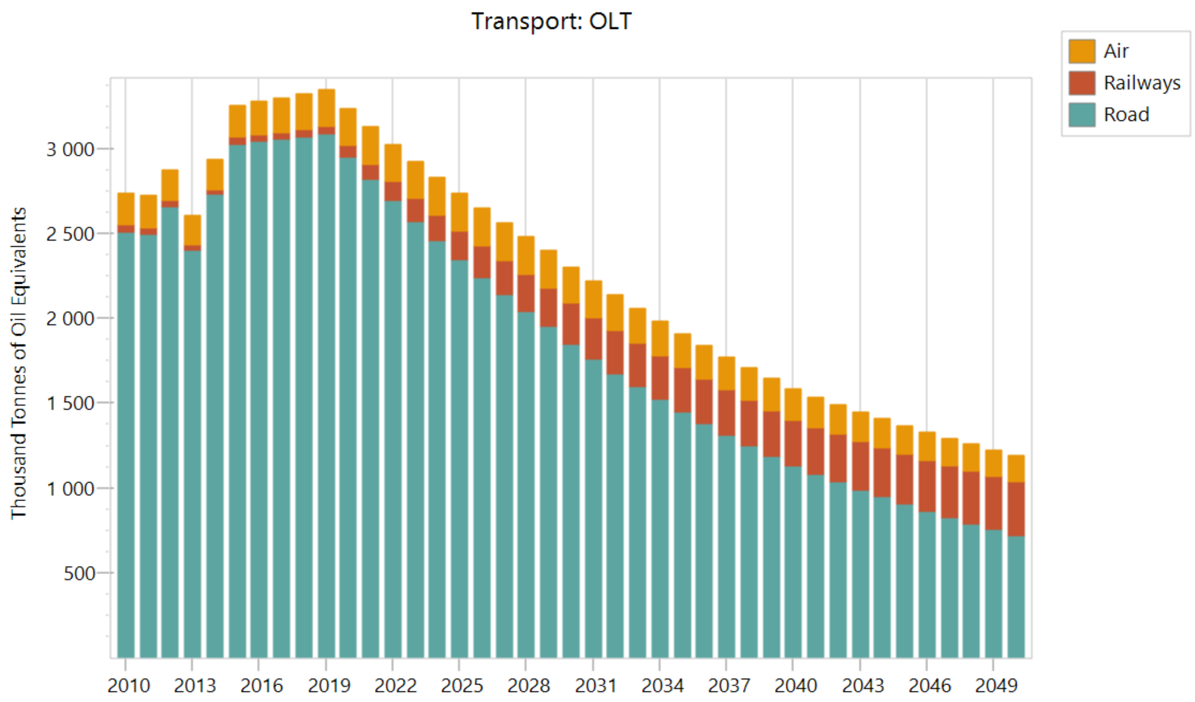

Figure 145. Transport final energy demand by transport mode, OLT

The figure shows serious decrease of the final energy demand in the road transport, while the share of the rail transport becomes significant by 2050.

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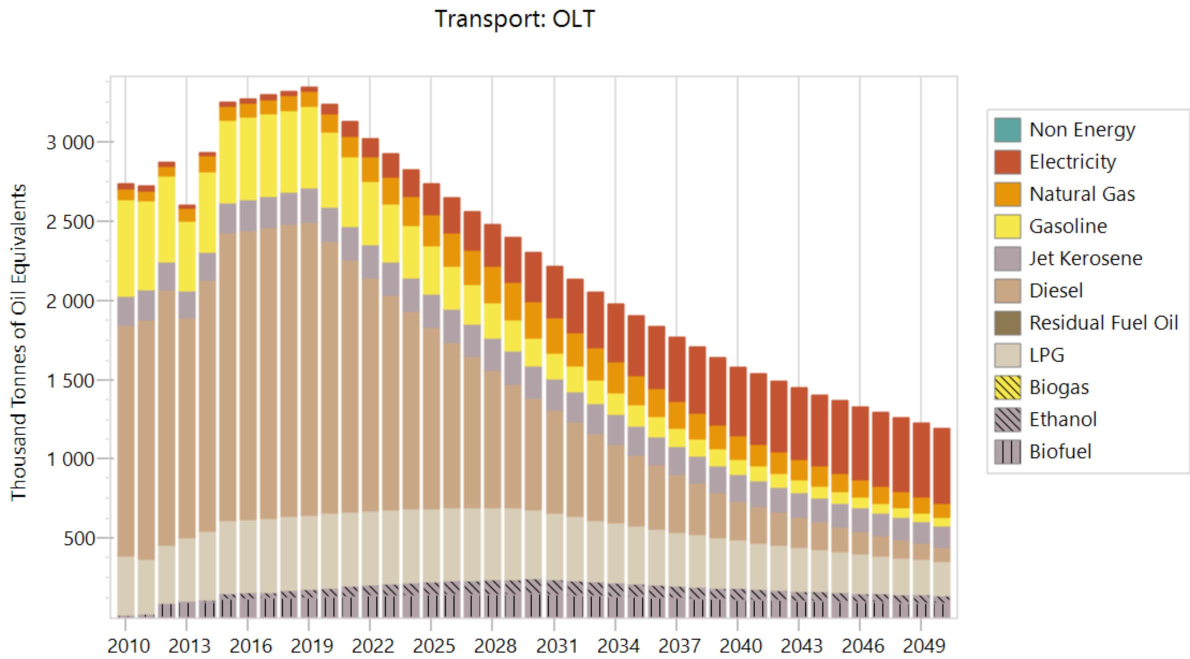

Figure 146. Transport final energy demand by fuel, OLT

The above figure demonstrates the abrupt fuel switch from gasoline and diesel to electricity. Gasoline declines from 522 ktoe in 2015 to 52 ktoe in 2050, while diesel – from 1,814 ktoe to 90 ktoe. Electricity increases from 28 ktoe in 2015 to 470 ktoe in 2050.

4.2.7.3. Industry energy demand

In most industrial sub-sectors, a switch is considered from coal and fuel oil to biomass and solar thermal by 2030. Additionally, there is a switch from coal and fuel oil to natural gas by 2035 and subsequent slight transition from natural gas to electricity by 2050. This delayed switch to electricity is justified by the time necessary to reduce its carbon intensity, by measures taken at the generation side. The particular percentages are industry specific, due to the different possibilities in each sub-sector. The dynamics of the fuel shares suggested in Deliverable 3.3 of MEDEAS (MEDEAS, 2017a), the sustainable energy scenario for EC by 2040 in the World Energy Outlook 2017 (IEA/OECD, 2017b), and considerations of the Ministry of Energy (ME, 2018) have been taken into account.

The energy intensity is assumed to decrease by additional 0.5 % or 1 % per year (depending on the sector and the year), compared to BAU.

The policies considered to drive these changes include:

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- Further GHG emission restrictions for large industries, fees for pollutants;
- Obligatory energy audits combined with obligatory implementation of measures;
- Coal taxation starting in 2020, and gas taxation starting in 2030;
- Support schemes (soft loans and guarantees) for renewable energy utilization and for energy services in industry.

The above assumptions, combined with the economic change of each industrial sub-sector (see Table 47), result in the final energy demand, displayed in Figure 147 (by fuel) and Figure 148 (by industrial sub-sector):

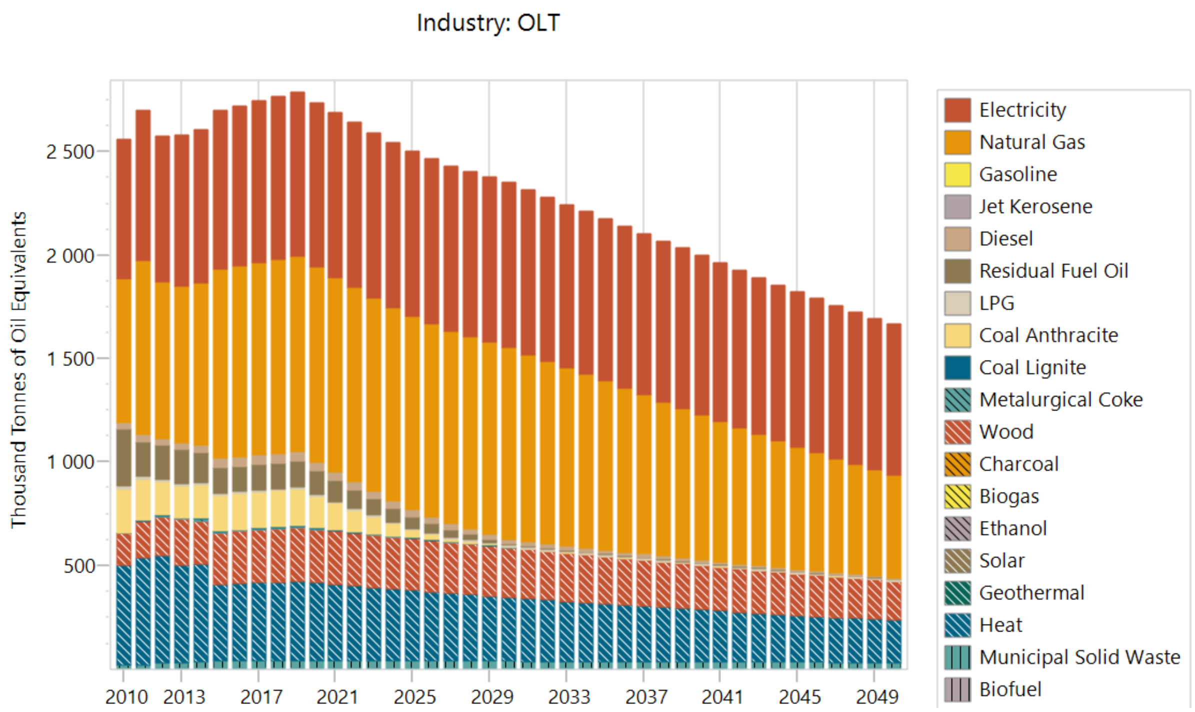

Figure 147. Industry final energy demand by fuel, OLT

The figure shows the quickly diminishing role of the fossil fuels until 2030 and of natural gas after 2030. The heating demand decreases too. Wood and electricity demand remains nearly constant during the whole period.

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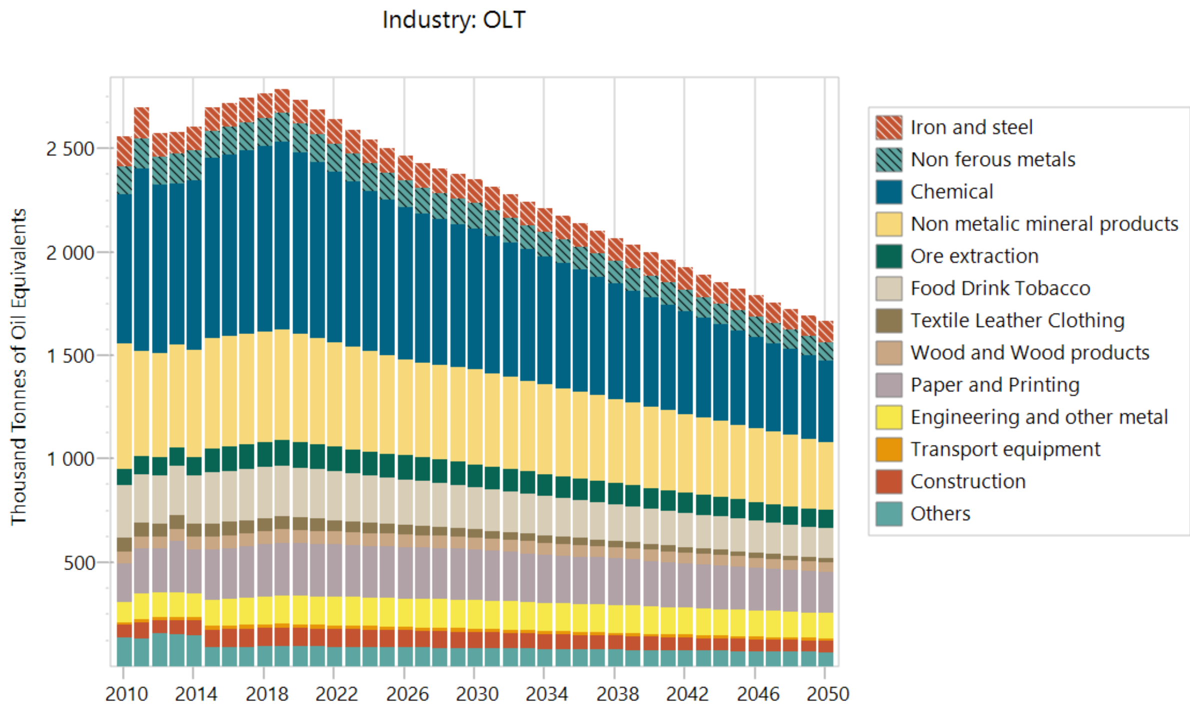

Figure 148. Industry final energy demand by sub-sector, OLT

The figure shows that after 2019, there is a substantial decrease of the energy demand, attributed mainly to two major industries – chemical and non-metallic mineral products.

4.2.7.4. Services, agriculture, and fisheries energy demand

In services, agriculture, and fisheries, fuel switch from liquid and gaseous fossil fuels to electricity, wood, and heat is assumed. Most of this transition takes place before 2035. The dynamics of the fuel shares in Deliverable 3.3 of MEDEAS (MEDEAS, 2017a), the sustainable energy scenario for EC by 2040 in the World Energy Outlook 2017 (IEA/OECD, 2017b), and considerations of the Ministry of Energy (ME, 2018) have been taken into account.

The energy intensity is assumed to decrease by additional 1 % per year, compared to BAU.

The policies considered to drive these changes include:

- Energy taxes;
- Obligatory energy audits combined with obligatory implementation of measures;
- Support schemes (soft loans and guarantees) for renewable energy utilization and for energy services.

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The above assumptions, combined with the economic change of each sector (see Table 47), result in the final energy demand, shown in Figure 149.

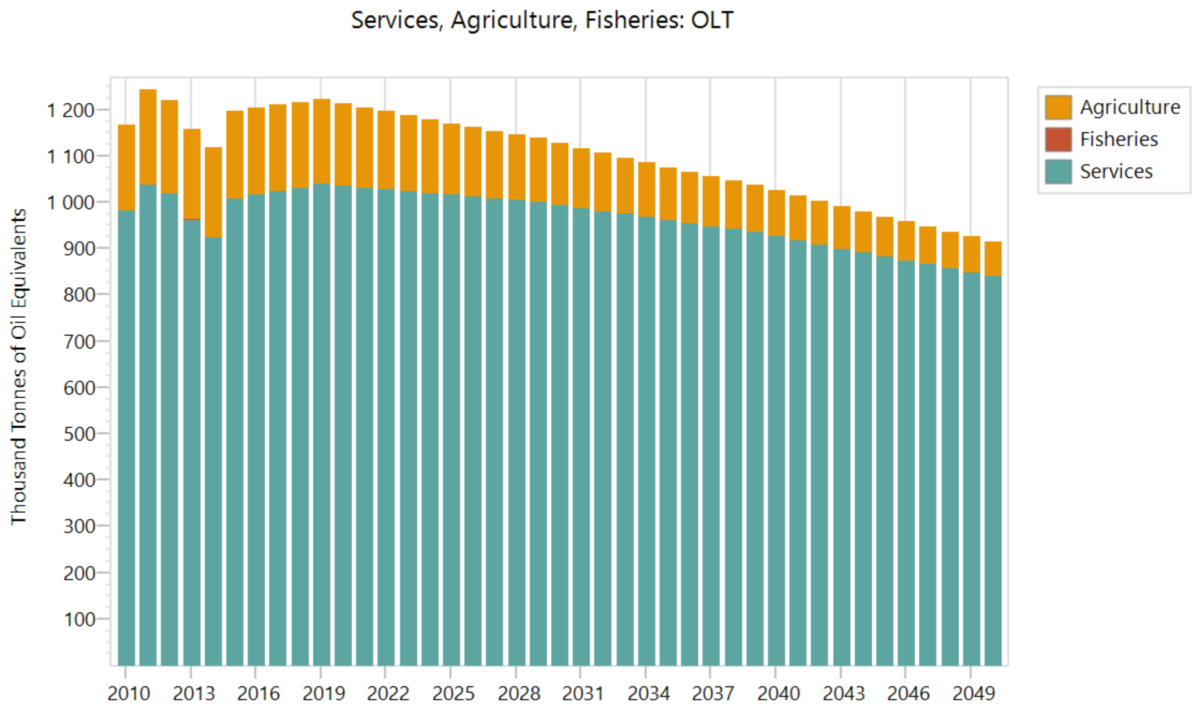

Figure 149. Services, agriculture, and fisheries final energy demand by sector, OLT

The figure shows a serious decrease of the energy consumption in the agriculture sector - from 188 ktoe in 2015 to 73 ktoe in 2050, and a moderate decrease in the services sector - from 1,010 ktoe to 842 ktoe for the same period. The fisheries sector has no energy consumption.

The fuel mix in services and agriculture is shown in Figure 150 and Figure 151.

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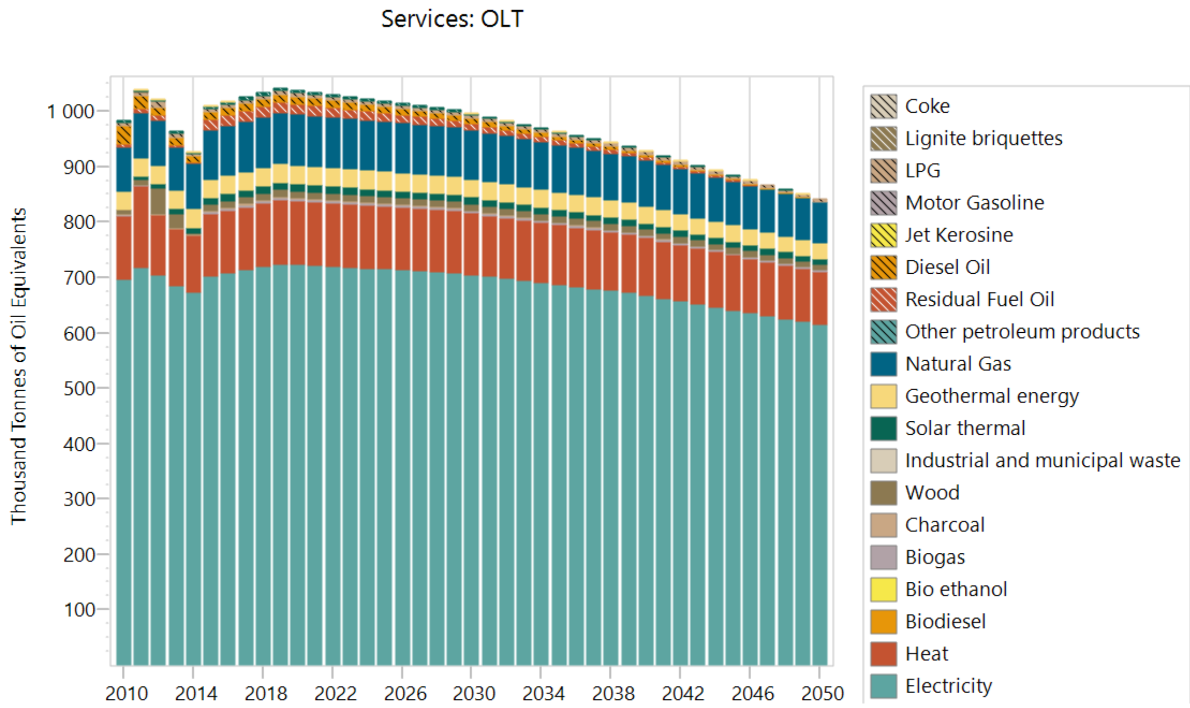

Figure 150. Services final energy demand by fuel, OLT

The above figure indicates that in the services sector, there are no drastic changes in the fuel mix during the projection period.

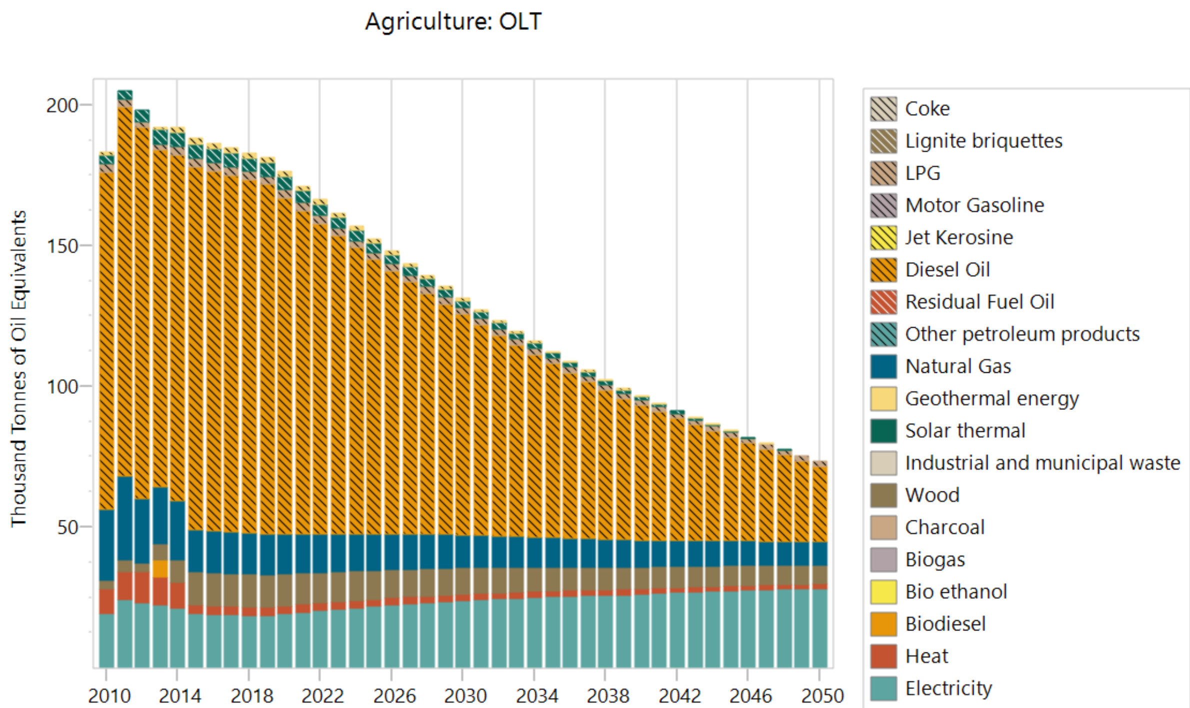

Figure 151. Agriculture final energy demand by fuel, OLT

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In the agriculture, as the figure shows, the most serious change is the reduction of diesel oil consumption – from 129 ktoe in 2015 to 36 ktoe in 2050.

4.2.7.5. Energy supply

The transmission and distribution losses are expected to continue their decrease trend, due to additional grid measures and the introduction of increasing share of distributed generation (DG) close to the consumer. The electricity losses would decrease linearly from 11.1 % in 2015 to 9.0 % in 2050. The heating losses would decrease linearly from 19.3 % in 2015 to 10.0 % in 2050, as a result of the overall replacement of the heating network with advanced pre-insulated pipes.

Own use share (energy used in energy production plants divided to the total produced energy) in all energy supply sectors is expected to decrease slightly, compared to 2015, due to the reduction of the electricity consumption in these sectors.

Electricity generation capacities follow the 2017-2026 plan of the Bulgarian Electricity System Operator 2017 only until 2020, because this plan is incompatible with the feasible carbon budget for OLT. The capacity development takes into consideration several documents - South East Europe Electricity Roadmap for Bulgaria (Szabó et al., 2017), the considerations of the Ministry of Energy (ME, 2018) and the outcomes of a recent workshop (BSERC, 2018).

In comparison to BAU, the main differences with OLT are as follows:

- Constant increase of wind and solar PV capacities – each reaching about 4.4 GW by 2050. This number is within the national technical potential, estimated to about 5 GW for each of the two sources;
- Construction of an additional nuclear unit of 1.2 GW in 2035;
- Complete phase-out of lignite capacities from 2020 (3.8 GW) to 2034 and of hard coal CHP capacities from 2030 to 2040;
- Gradual reduction of natural gas (both electricity only and CHP ones) capacities after 2026;
- Minor increase of wood capacities for electricity and CHP, construction of a small anthracite TPP with CCS (no GHG emissions).

The electricity capacities are shown in the figure below (Figure 152).

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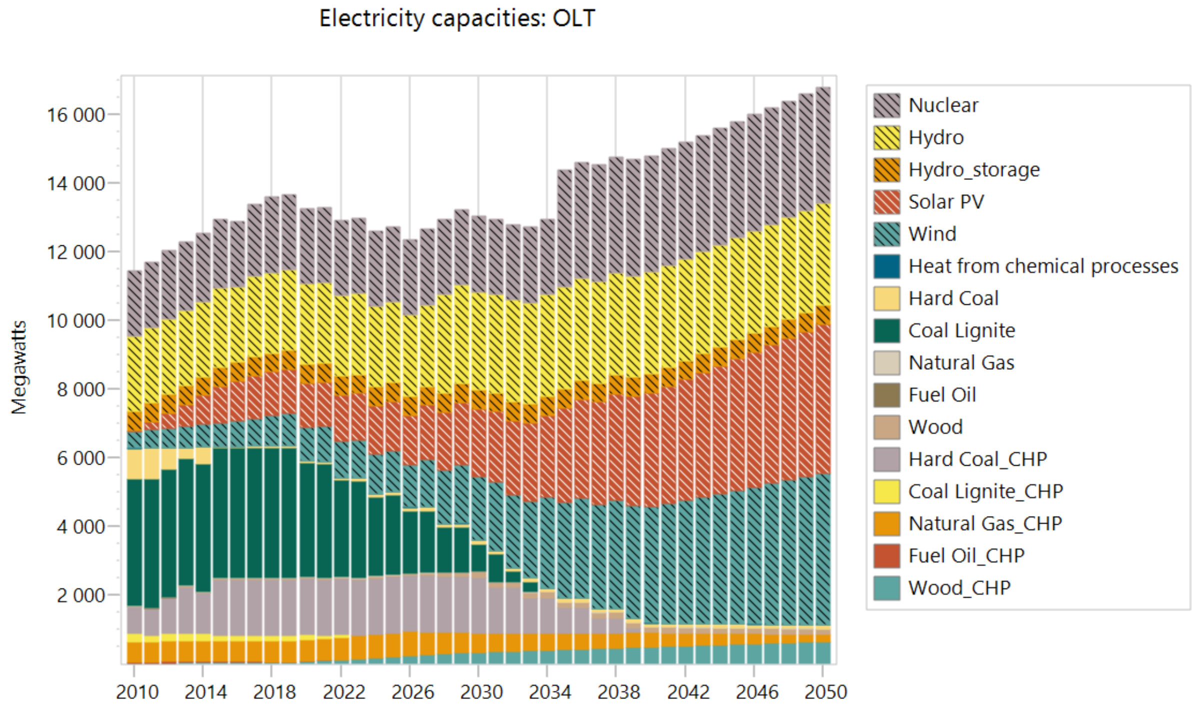

Figure 152. Electricity capacities, OLT

The generation results from the model optimizations (least cost dispatch of capacities) and it is presented in the Figure 153 below.

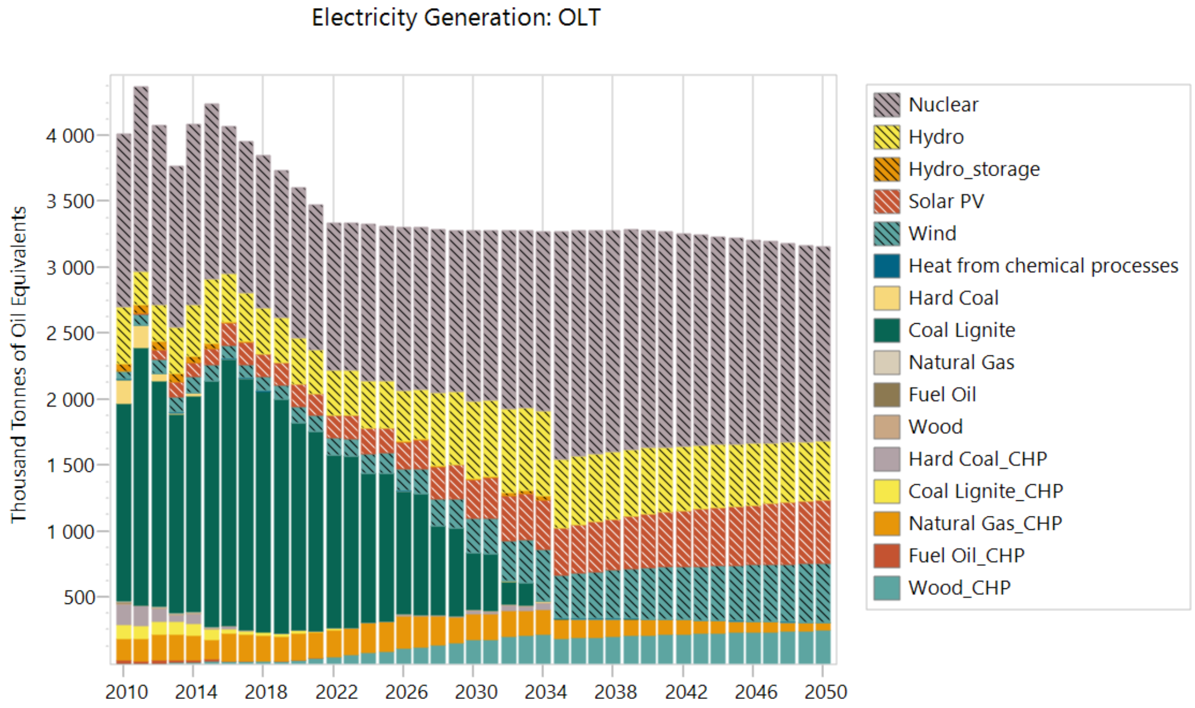

Figure 153. Electricity generation by feedstock fuel in OLT

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The next energy supply branch is the heat supply. The following changes of heat capacities are considered:

- Substantial increase of biomass CHP capacities by 2050;
- Substantial decrease of natural gas CHP capacities by 2050;
- Substantial decrease of dedicated heating natural gas capacities.

The heat production includes two technology types – CHP and dedicated district heating plants. The total heat production is presented in Figure 154.

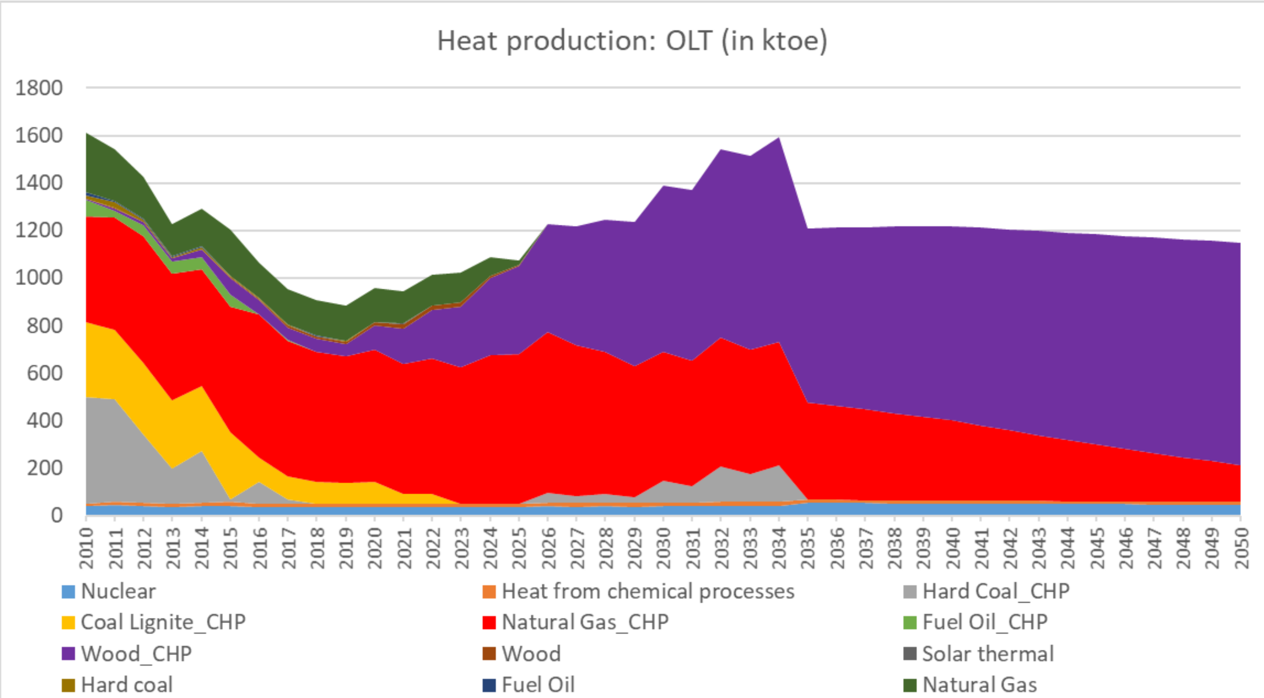

Figure 154. Heat production, OLT

4.2.8. MLT scenario assumptions

The measures introduced in the MLT scenario start in 2030. Due to the necessity to achieve sharp decarbonisation, almost all measures have higher effect during the first years after 2030, compared to the last years.

All policies and measures assumed to bring to the necessary changes (in technology, behaviour, etc.) are the same as in the OLT scenario, but they are much more demanding. For that reason, no policies will be described in this chapter.

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4.2.8.1. Residential energy demand

In MLT, the high refurbishment rates start in 2030. By 2040 all existing multi-family buildings and by 2045 – all existing single-family buildings are refurbished.

After 2030, the energy-related requirements for refurbished buildings are considered to become gradually much more demanding (50 % lower energy consumption per square meter), and by 2045 – at levels similar to the current NZEB requirements (NP NZEB, 2015).

These assumptions result in the following residential space heating demand (Figure 155):

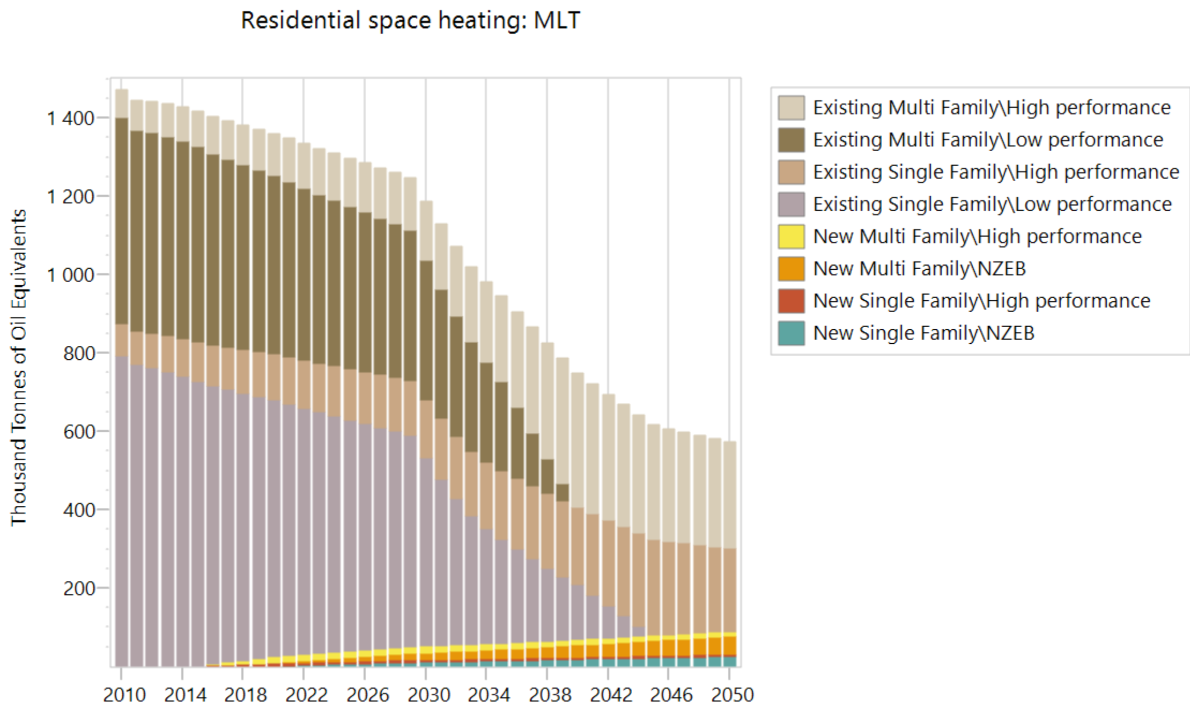

Figure 155. Residential Space Heating final energy demand, MLT

The efficiency of all demand-side conversion technologies is expected to increase substantially; the change rates are particularly high in the period 2030-2035. The efficiency of biomass space heating is considered to reach 69 % (compared to 66 % in OLT) by 2050. Both the specific (per lumen) lighting energy intensity and specific cooling intensity are considered to reach 4 % below OLT levels, while the appliances specific energy intensity – 6.7 % below OLT levels by 2050.

In space heating demand, fuel switch from coal, oil, and gas to solar thermal, district heating, and electricity is assumed. In cooking and hot water preparation, there is minor fuel switch from biomass and gas to electricity.

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The above assumptions result in energy demand, shown on Figure 156 and Figure 157.

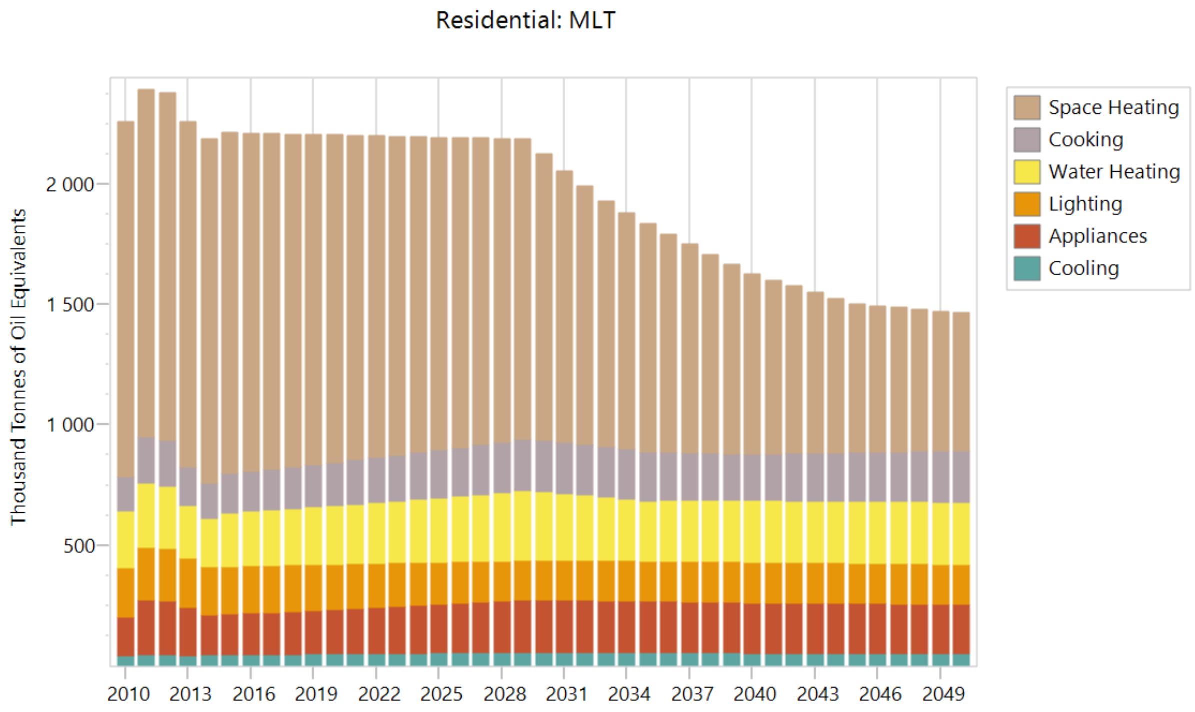

Figure 156. Residential total final energy demand by application, MLT

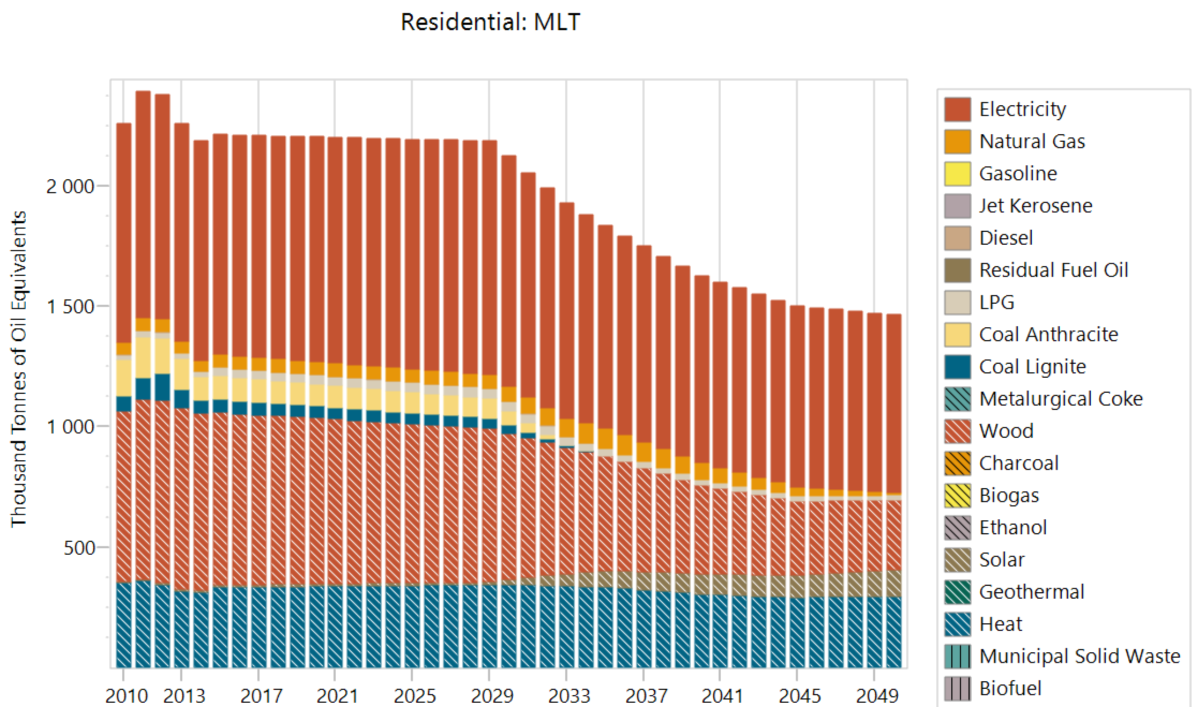

Figure 157. Residential total final energy demand by fuel, MLT

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Figure 157 displays the abrupt decline of space heating consumption after 2029, while the other energy applications remain relatively constant.

The figure demonstrates the reduction of all fuels, except for solar thermal.

4.2.8.2. Transport energy demand

In the transport sector, the following changes are assumed:

- Fuel switch, including: penetration of electric and hybrid vehicles in passenger and freight road transport, up to 40 % in 2050; increased biofuel share, up to 9.5 % biodiesel and 7 % biogasoline in 2050; and respectively lower share of traditional gasoline (reaching only 2 % by 2050) and diesel (reaching only 2 % by 2050), rail transport switch to 100 % electricity by 2040.
- Eco-driving in passenger and freight road transport, resulting in up to 7 % fuel economy in this transport, compared to 2015 (Nikolaev and Radulov, 2016).
- Modal shift, including substantial shift from road to rail transport (about 1.8 % annually, compared to BAU) – the road transport activity reaches only 27.5 % of the one in BAU by 2050. Rail transport activity increases sharply and its value in 2050 is about 16 times higher compared to BAU. Air transport activity declines by 13 % by 2050 and is notably below the 24 % increase in OLT, due to abrupt transfer from air to rail. Minor (about 1 %) shift to cycling/walking is considered.
- More efficient vehicles in rail transport: 0.4 %/yr reduction of the consumption per km, compared to 0.2 %/yr in OLT.

The above assumptions result in the final energy demand, presented in Figure 158 (by transport mode) and Figure 159 (by fuel).

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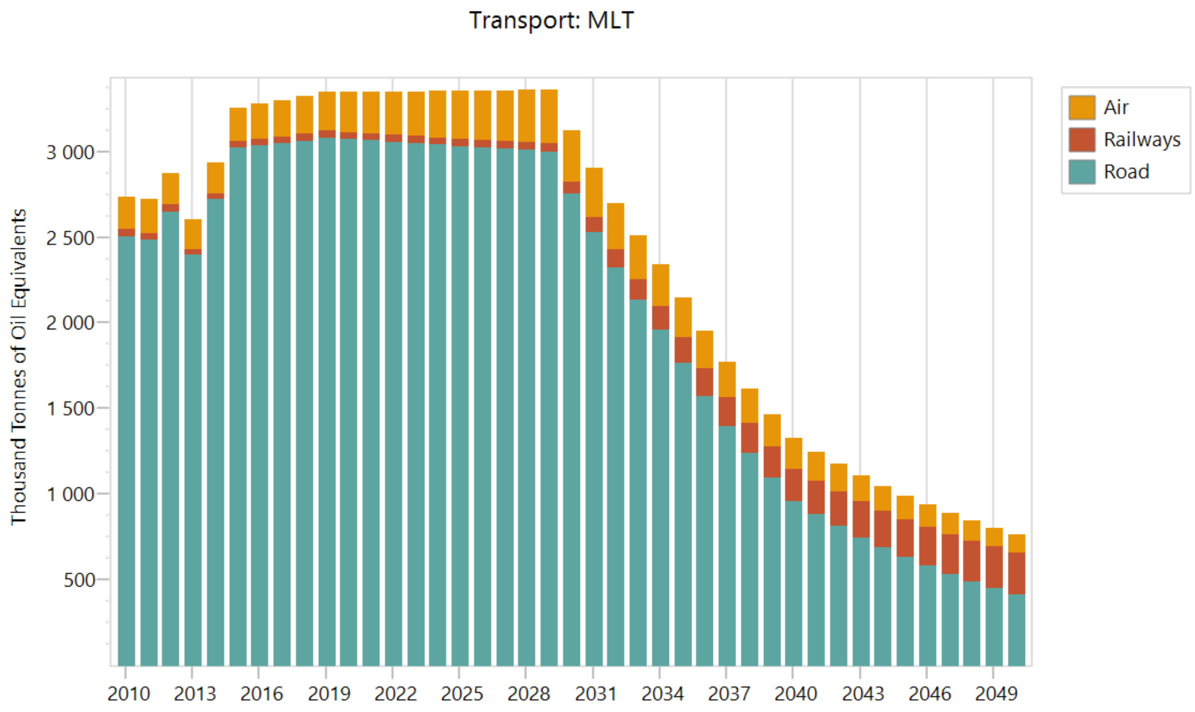

Figure 158. Transport final energy demand by transport mode, MLT

The figure shows a serious decrease of the final energy demand in the road and air transport, while the share of the rail transport becomes significant by 2050.

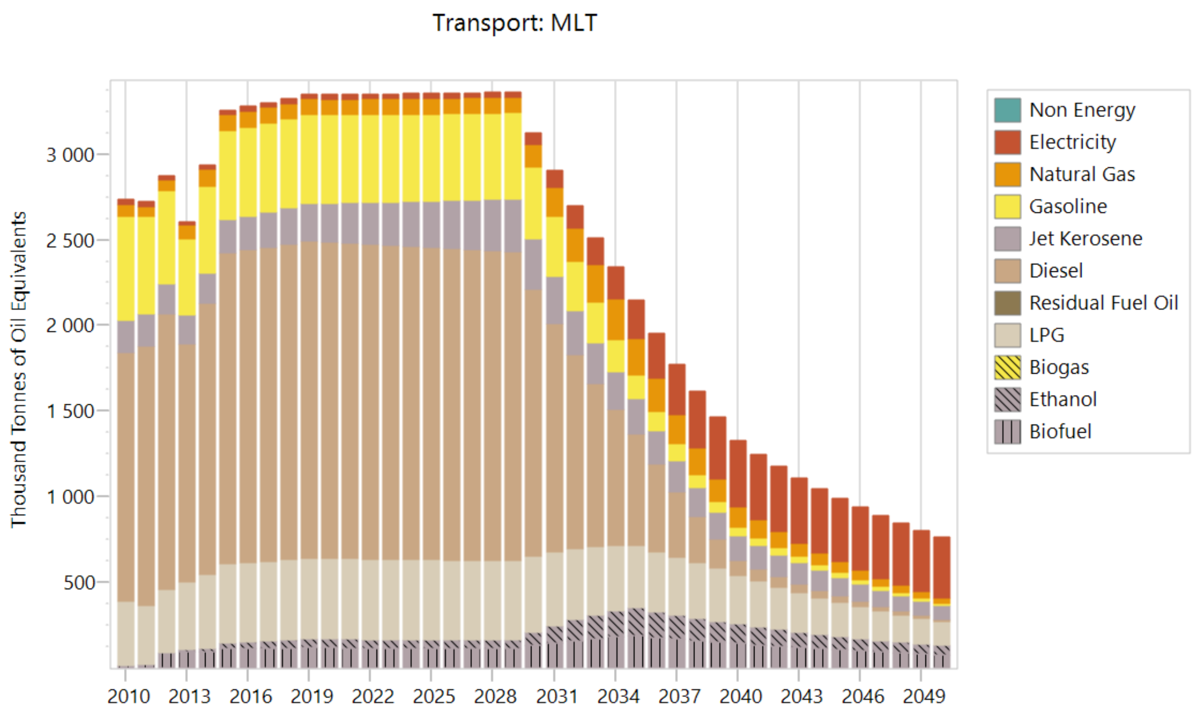

Figure 159. Transport final energy demand by fuel, MLT

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The above figure demonstrates the high fuel switch from gasoline and diesel to electricity. Gasoline declines from 522 ktoe in 2015 to 17 ktoe in 2050, while diesel – from 1,814 ktoe to 13 ktoe. Electricity increases from 28 ktoe in 2015 to 360 ktoe in 2050.

4.2.8.3. Industry energy demand

In most industrial sub-sectors, a switch is assumed from natural gas, coal and fuel oil to biomass, solar thermal, and electricity. The shift is very sharp by 2035. The particular percentages are industry-specific, due to the different possibilities in each sub-sector. The changes are generally similar to OLT, but the transition period is much shorter in order to comply with the carbon budget.

The energy intensity is assumed to decrease by additional 1 % per year, compared to OLT.

The above assumptions, combined with the economic change of each industrial sub-sector (see Table 47), result in the final energy demand, shown in Figure 160 (by fuel) and Figure 161 (by industrial sub-sector):

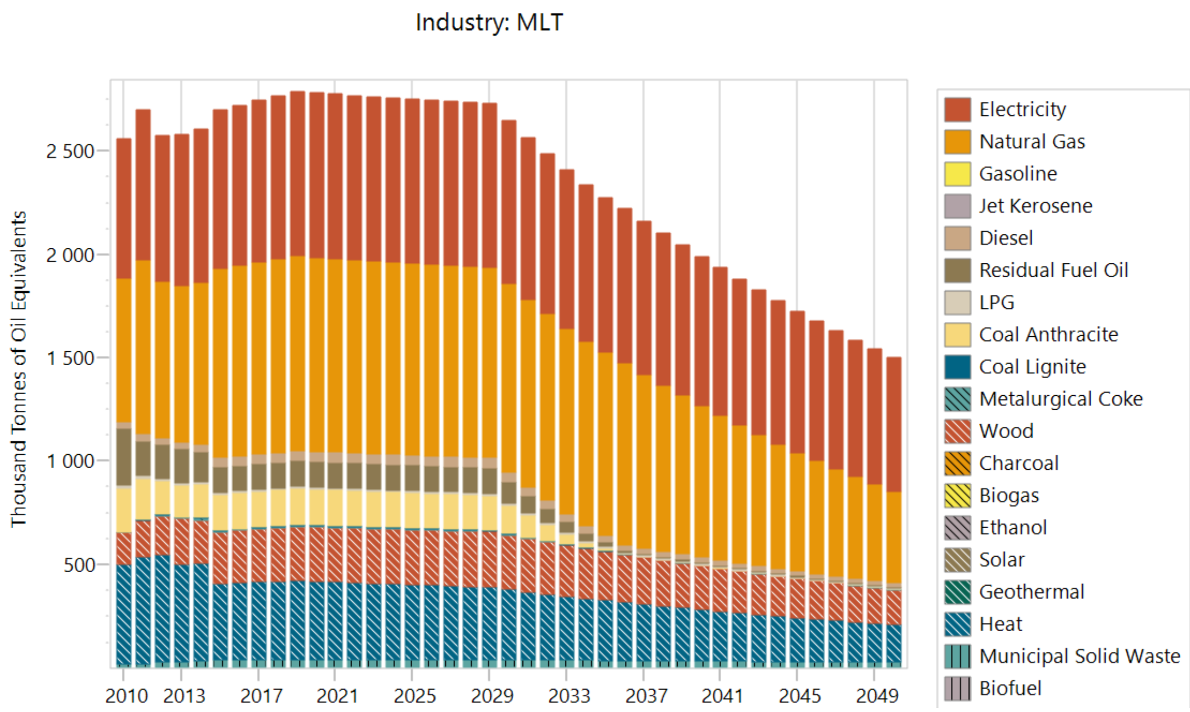

Figure 160. Industry final energy demand by fuel, MLT

The figure shows the quickly diminishing role of the fossil fuels in the period 2030-2035 and of natural gas by 2050. The heating demand decreases too. Wood and electricity demand decrease only slightly.

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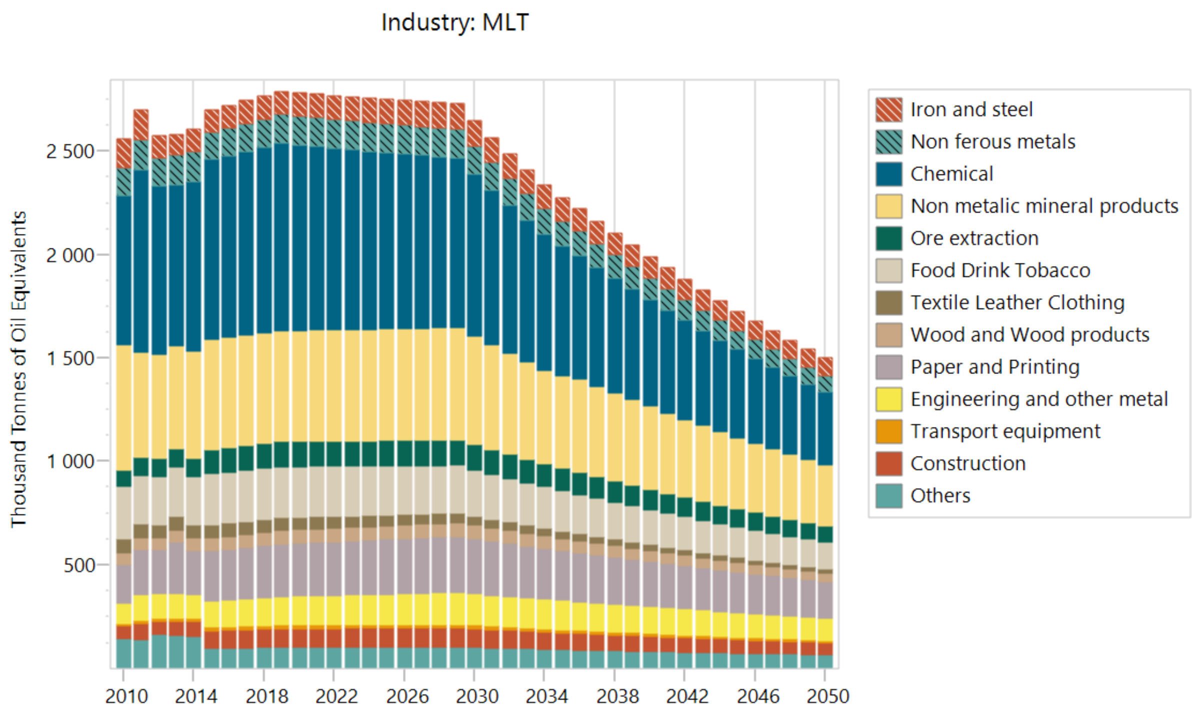

Figure 161. Industry final energy demand by sub-sector, <LT

The figure shows that after 2029, there is a substantial decrease of the energy demand, attributed mainly to the two major industries – chemical and non-metallic mineral products.

4.2.8.4. Services, agriculture, and fisheries energy demand

In services, agriculture, and fisheries, fuel switch from liquid and gaseous fossil fuels to electricity, wood, and heat is assumed. A large part of this transition takes place before 2035.

The energy intensity is assumed to decrease by additional 1 % per year, compared to OLT.

The above assumptions, combined with the economic change of each sector (see Table 47), result in the final energy demand, shown in Figure 162.

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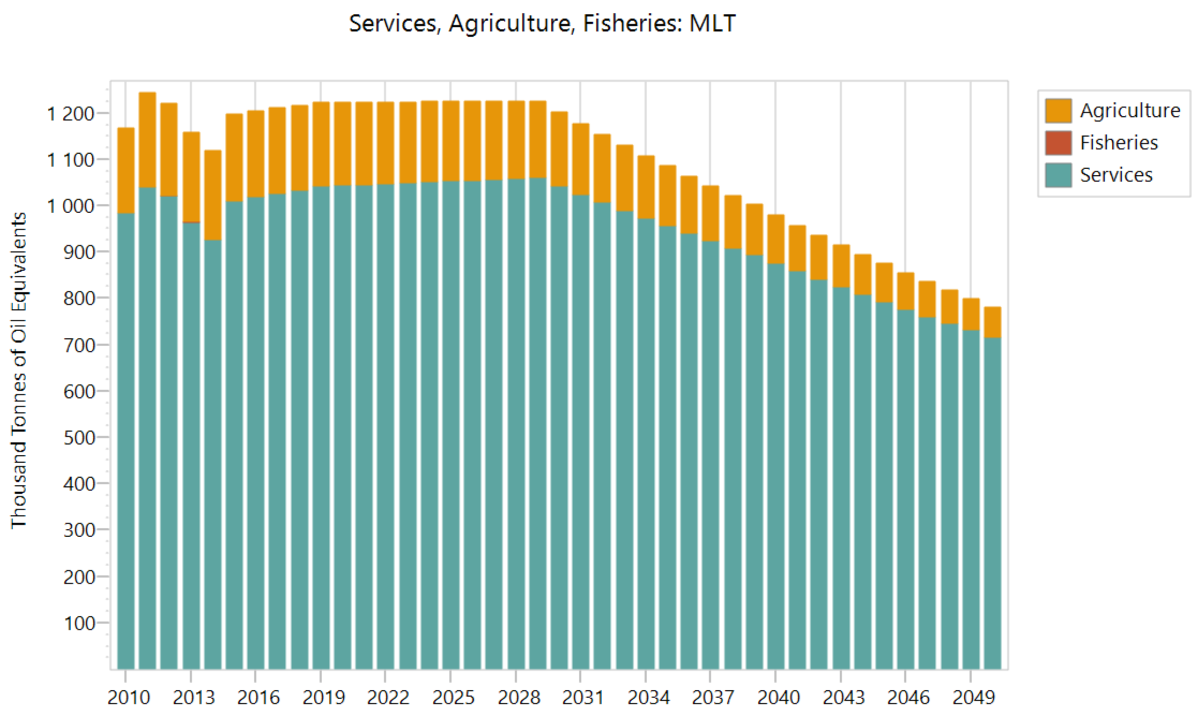

Figure 162. Services, agriculture, and fisheries final energy demand by sector, OLT

The figure shows a serious decrease of the energy consumption in both the agriculture sector - from 188 ktoe in 2015 to 65 ktoe in 2050, and the services sector - from 1,010 ktoe to 716 ktoe for the same period.

The fuel mix in services and agriculture is shown in Figure 163 and Figure 164.

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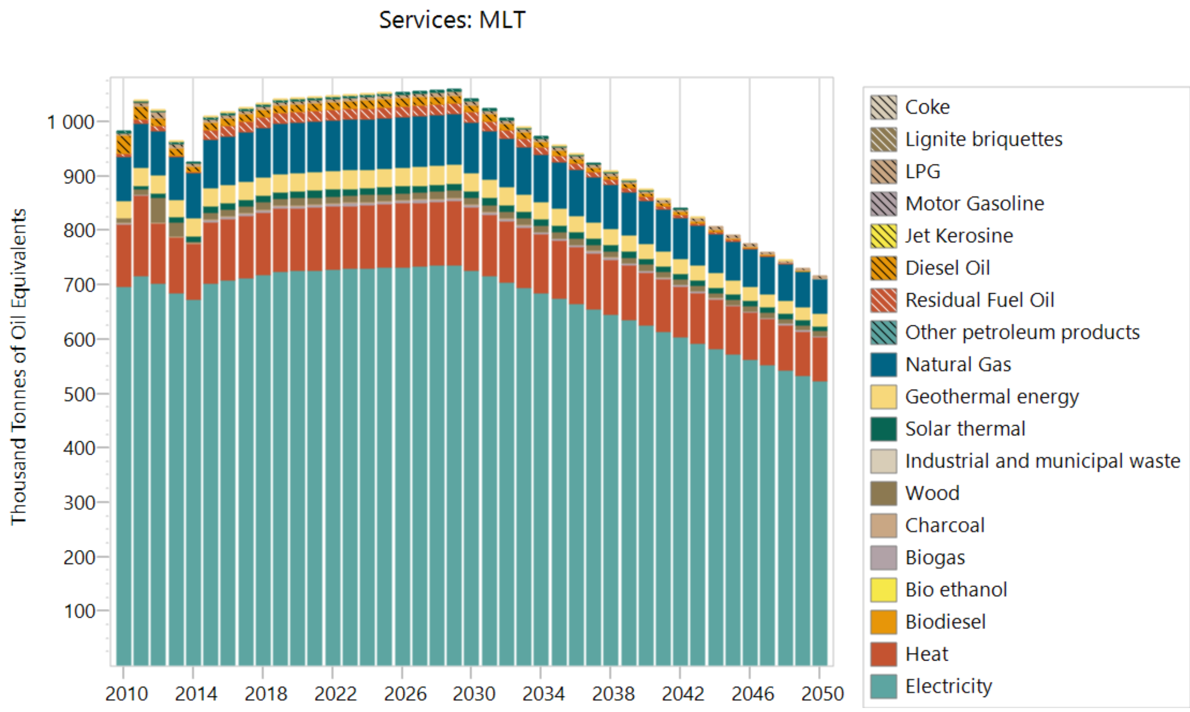

Figure 163. Services final energy demand by fuel, MLT

The above figure indicates that in the services sector, there are no drastic changes in the fuel mix during the projection period.

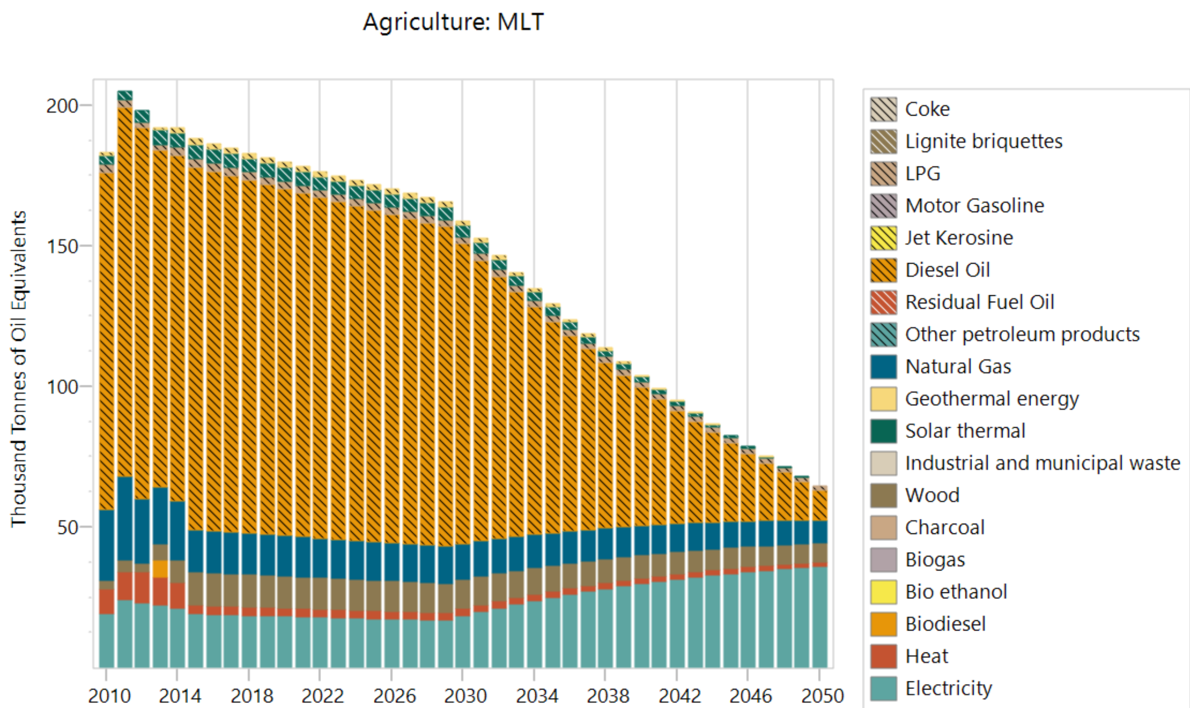

Figure 164. Agriculture final energy demand by fuel, MLT

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In the agriculture, as the figure shows, the most serious change is the reduction of diesel oil consumption – from 129 ktoe in 2015 to 10 ktoe in 2050.

4.2.8.5. Energy supply

The transmission and distribution losses are expected to decrease. The electricity losses would reach 9.0 % in 2050, while the heating losses – 10.0 % in 2050. Both values are identical to OLT, but apparently the change in MLT starts later (in 2030).

Own use share (energy used in energy production plants divided to the total produced energy) in all energy supply sectors is expected to decrease slightly, compared to 2015, due to the reduction of the electricity consumption in these sectors. The 2050 values are identical to OLT.

Electricity generation capacities follow the 2017-2026 plan of the Bulgarian Electricity System Operator 2017. Later, the capacity development takes into consideration several documents - South East Europe Electricity Roadmap for Bulgaria (Szabó et al., 2017), the considerations of the Ministry of Energy (ME, 2018) and the outcomes of the recent workshop (BSERC, 2018).

In comparison to OLT, the main differences in MLT are as follows:

- Increase of wind capacities to 4.7 GW by 2050 (compared to 4.4 GW in OLT) and of solar PV capacities to 4.6 GW (compared to 4.4 GW in OLT) by 2050. These numbers are within the national technical potential, estimated to about 5 GW for each of the two sources;
- No need of construction of an additional nuclear unit;
- Complete phase-out of lignite capacities from 2030 (3.8 GW) to 2034 and of hard coal CHP capacities from 2030 to 2040;
- Sharp reduction of natural gas (both electricity only and CHP ones) capacities in the period 2030-2035.

The electricity capacities are shown in the figures below (Figure 165, Figure 166).

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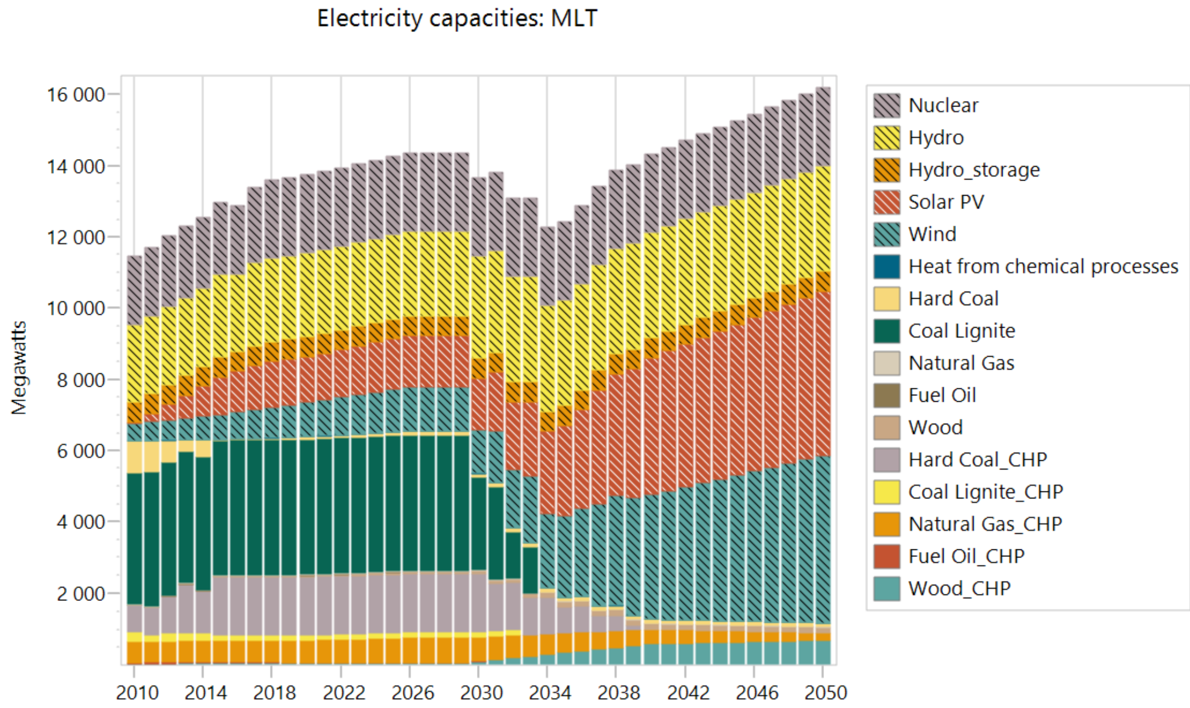

Figure 165. Electricity capacities, MLT

The generation results from the model optimizations (least cost dispatch of capacities) and it is presented in the figure below.

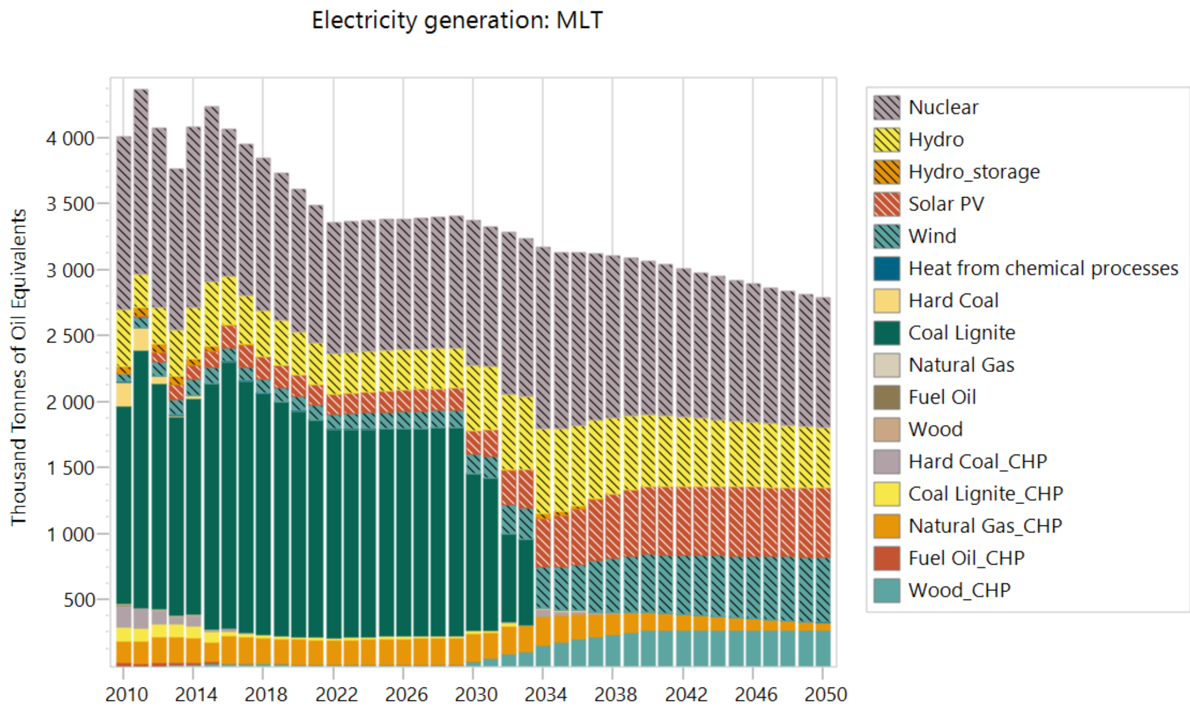

Figure 166. Electricity generation by feedstock fuel in MLT

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In the heat supply, the following changes of heat capacities are considered:

- Substantial increase of biomass CHP capacities by 2050;
- Substantial decrease of natural gas CHP capacities by 2050;
- Substantial decrease of dedicated heating natural gas capacities.

The heat production includes two technology types – CHP and dedicated heat plants. The respective heat production is presented below (Figure 167).

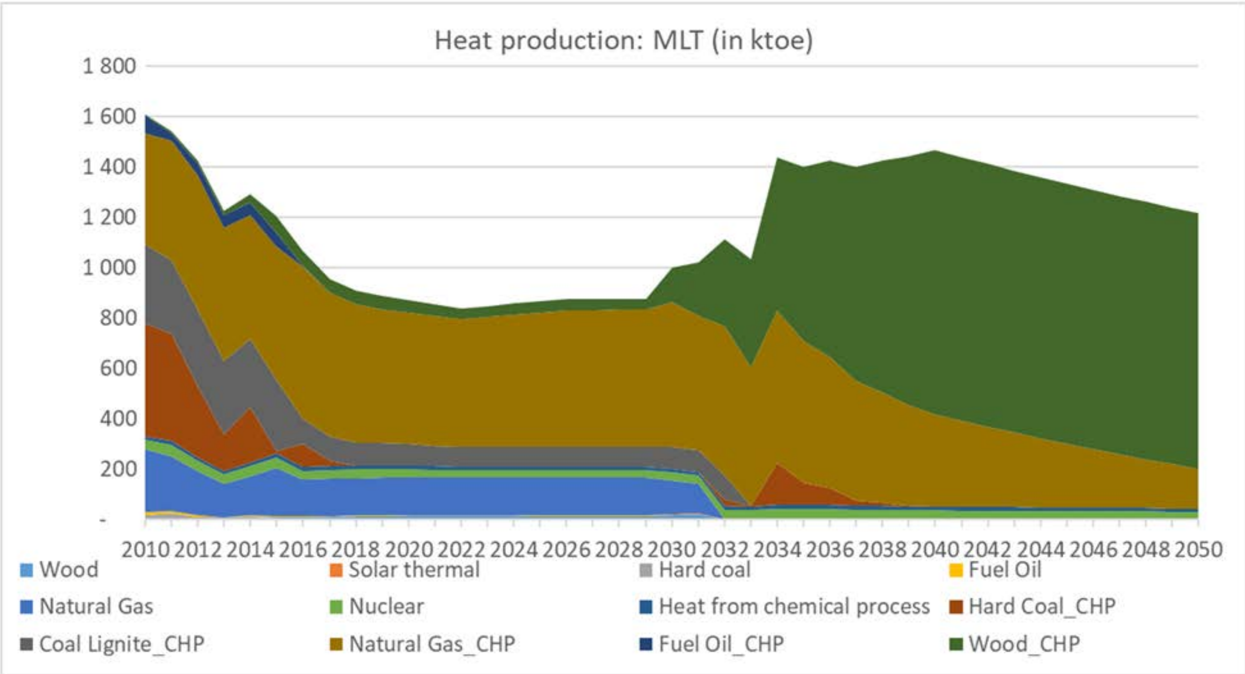

Figure 167. Heat production, MLT

The figure demonstrates a sharp growth of wood CHP capacities after 2030. These become dominant by 2050.

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4.3. Results

4.3.1. Emissions

The GHG emissions in the 3 scenarios are presented in the Figure 168.

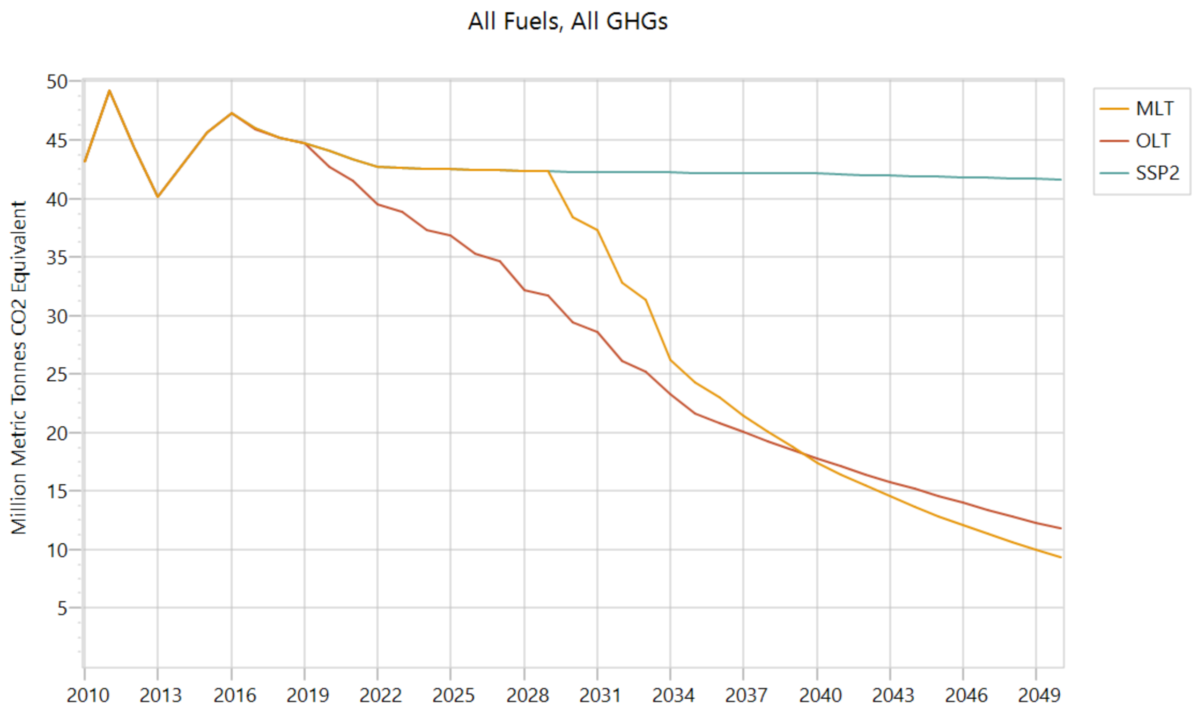

Figure 168. GHG emissions in SSP2(BAU), OLT, MLT

The values of the annual emissions can be seen in detail in the Table 54.

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Table 54. Energy-related GHG emissions for BAU, OLT, and MLT from LEAP, $MtCO_2$

Scenarios	MLT	OLT	BAU
2015	45.6	45.6	45.6
2016	47.3	47.3	47.3
2017	46.0	46.0	46.0
2018	45.2	45.2	45.2
2019	44.8	44.7	44.8
2020	44.1	42.7	44.1
2021	43.4	41.6	43.4
2022	42.7	39.5	42.7
2023	42.6	38.9	42.6
2024	42.6	37.3	42.6
2025	42.5	36.8	42.5
2026	42.4	35.2	42.4
2027	42.4	34.7	42.4
2028	42.4	32.2	42.4
2029	42.3	31.7	42.3
2030	38.4	29.4	42.3
2031	37.3	28.5	42.3
2032	32.8	26.1	42.2
2033	31.4	25.2	42.2
2034	26.2	23.3	42.2
2035	24.2	21.6	42.2
2036	23.0	20.8	42.2
2037	21.5	20.0	42.2
2038	20.1	19.3	42.2
2039	18.7	18.5	42.2
2040	17.5	17.8	42.1
2041	16.4	17.1	42.1
2042	15.5	16.4	42.0
2043	14.6	15.8	42.0
2044	13.7	15.2	41.9
2045	12.9	14.6	41.9
2046	12.1	14.0	41.8
2047	11.4	13.4	41.8
2048	10.7	12.9	41.7
2049	10.0	12.3	41.7
2050	9.4	11.8	41.6
Total	**1,073.8**	**993.5**	**1,538.8**

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As shown in the above table, the energy–related carbon budgets for OLT, as presented in Table 43, and MLT, as presented in Table 44, are fully aligned.

All emission curves from the individual sectors have similar shapes. Below the GHG emissions from the Industry sector are presented as an example (Figure 169).

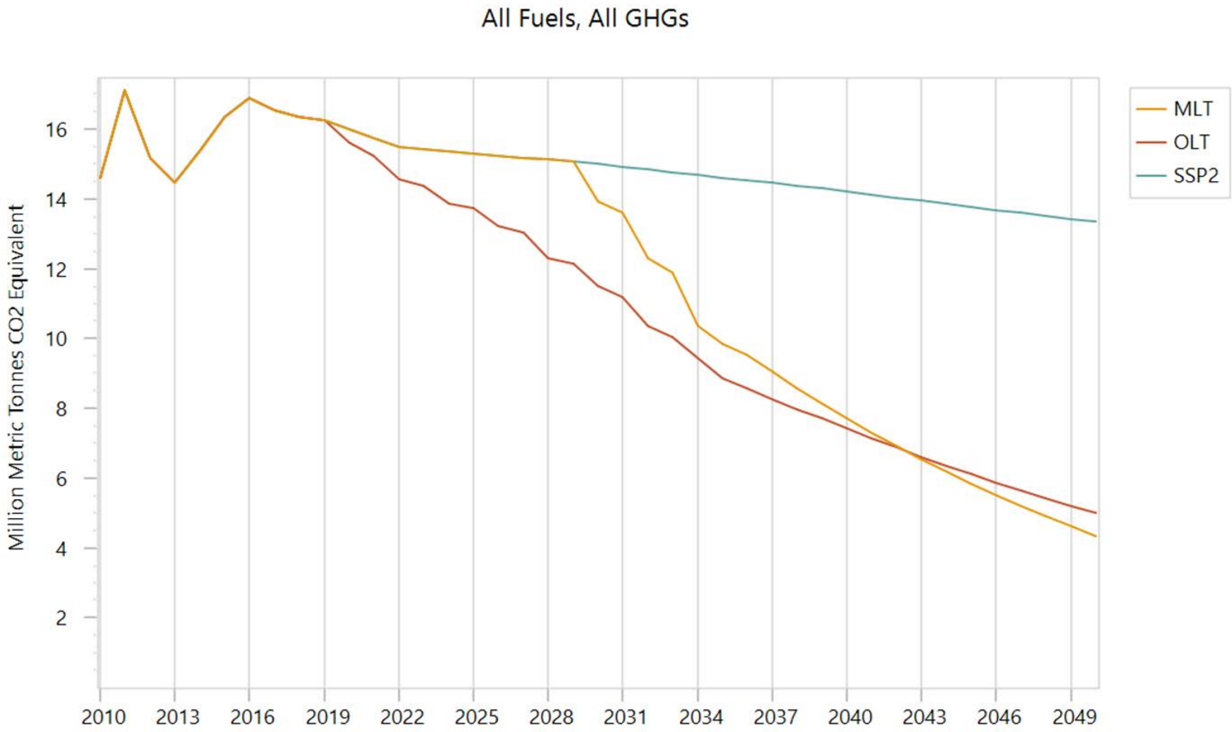

Figure 169. GHG emissions from Industry in SSP2(BAU), OLT, MLT

4.3.2. Energy Demand

The total final energy demand in the 3 scenarios is presented in Figure 170.

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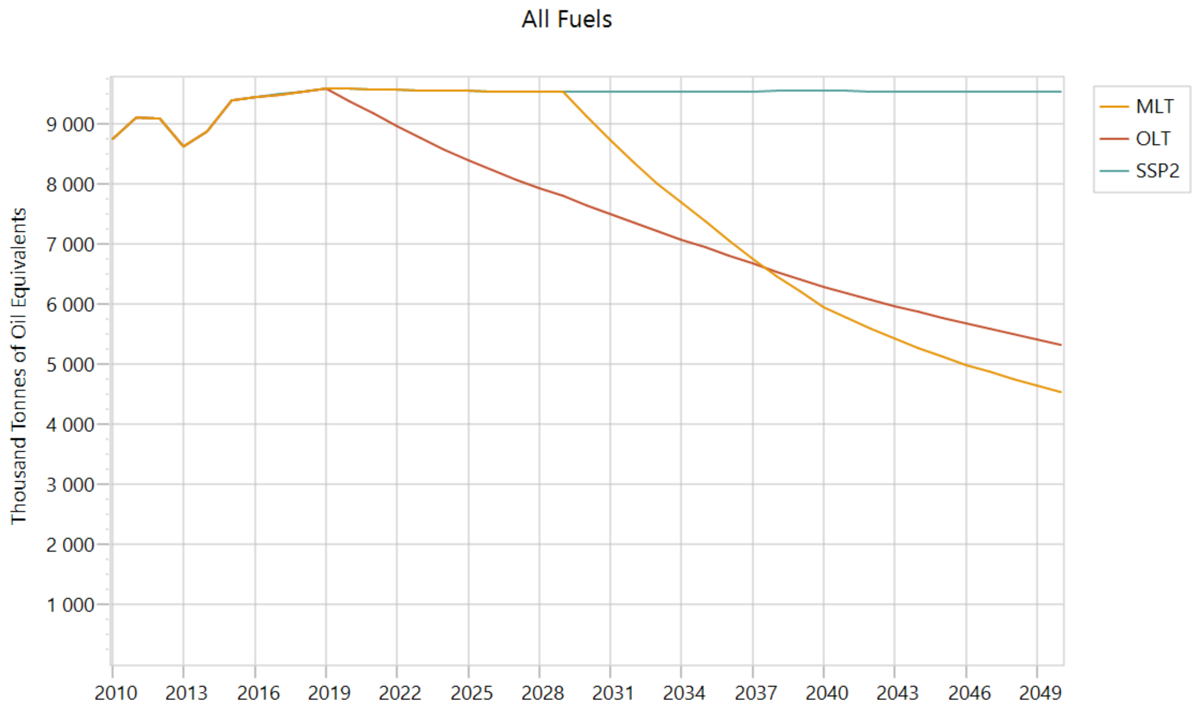

Figure 170. Total final energy demand in SSP2 (BAU), OLT, MLT

The Figure 171 displays the total primary energy consumption in the 3 scenarios:

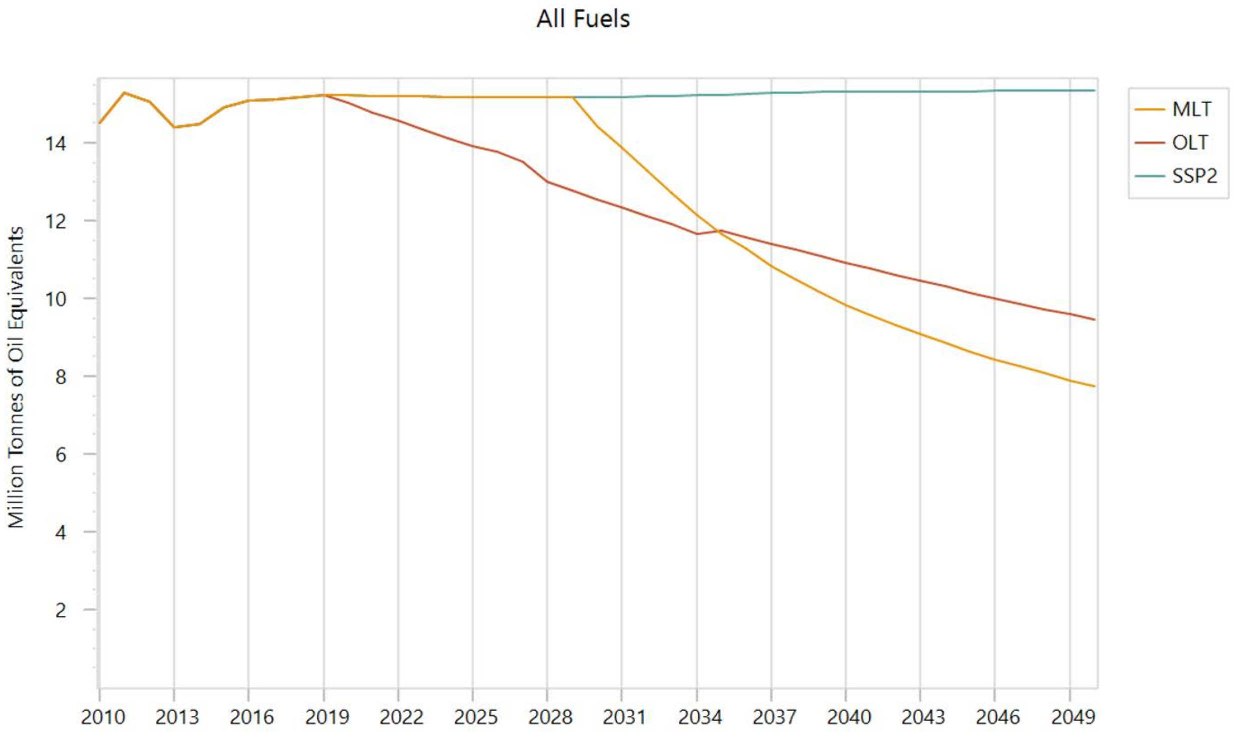

Figure 171. Total primary energy consumption in SSP2(BAU), OLT, MLT

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4.4. Conclusions

This section presented the methodology, main assumptions and results for the three developed scenarios for Bulgaria – BAU, OLT, and MLT, using LEAP tool.

The main objective of OLT and MLT was to align these scenarios with Bulgaria's carbon budget by 2050 in the most feasible way. The scenario results demonstrate that the carbon budget has been aligned. It appeared, however, that the compliance with the limited carbon budget for Bulgaria is a very difficult task, mainly due to the projected high economy growth (the GDP in 2050 is 2.5 times the one in 2015), combined with limited resources to undertake ambitious (and expensive) policies.

In both OLT and MLT, the only feasible solution to comply with the carbon budget is to implement comprehensive measures in all demand and supply sectors. These involve mainly serious energy efficiency improvement combined with abrupt fuel switch to less carbon intensive fuels.

As expected, the most feasible approach to comply with the carbon budget is to implement the decarbonization measures as soon as possible, i.e. to achieve most of the energy savings and fuel switch shortly after 2020 in OLT and shortly after 2030 in MLT.

In this sense, it is obvious that it is much more difficult and expensive to achieve the carbon budget in MLT, compared to OLT. In MLT, the sharp technological changes in 2030 - 2035, such as replacement of energy plants and energy demand equipment (transport vehicles, heating and electricity appliances, etc.) would require discarding operating technologies and massive investment in new equipment and infrastructure, causing economic shock.

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5. General conclusions

This deliverable presents the main methodological basis used to produce the MEDEAS_at and MEDEAS_bg as case studies of the MEDEAS country-level IAM. The MEDEAS-country level models are integrated energy-economy-environment assessment models that have been developed with the systems dynamics methodology. These models, which have been programmed with the Vensim software, use as input the results of the simulation of the MEDEAS_w and MEDEAS_eu models, with which they are linked. The structure of these models are similar and consists of 7 modules: Economy, Energy, Infrastructures, Materials, Land Use, Social and Environmental Impacts Indicators and GHG Emissions. Among the main novelties of this model with respect to other IAMs are the integration of input-output matrices, feedback between vaiables of the environmental, economic and energy modules and the estimation and feedback of the EROI. As well as the EU case, the adaptation to the country level includes the representation of trade (at both final goods/services and primary energy level) with the rest of the world and the other countries from Europe, as well as a simplified representation of the land-use system.

Different scenarios established in WP3 have been developed for Austria and Bulgaria 2050 using MEDEAS country-level models. Also, the same scenarios have been developed with TIMES-Austria and LEAP-Bulgaria for comparison purposes (Deliverable 4.4).

For MEDEAS, the tested scenarios show that the generation of energy from RES increases steadily until 2040s in Austria for both scenarios, although the BAU scenario is higher; in the case of Bulgaria, both scenarios increases the generation of energy from RES, although the OLT scenario present higher generation since Bulgaria starts from previous low renewables production values. The consumption of non-renewable energies declines in the early 2020s in Austria, with an OLT scenario slightly more intensive in non-renewable primary energy. In the case of Bulgaria, the decrease starts in the late 2020s or the early 2030s, reaching similar values to those of Austria, although the BAU scenario presents higher levels of non-renewables due to the starting point of Bulgaria. The share of renewables in the energy mix increases to almost reach 60%-70% in the Austrian BAU and OLT scenarios, respectively; also, reaches 40%-60% in the case of Bulgarian BAU and OLT scenarios, respectively. GHG emission present similar patters to the non-renewables consumption. Lastly, both the Total Final Energy Consumption (TFEC) and Gross Domestic Product (GDP) show a similar trend for both scenarios and countries roughly maintaining current levels up to 2025-2030, and a declining thereafter due to the strong climate change impacts coming from the MEDEAS-W and MEDEAS_eu in both scenarios.

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For TIMES-Austria, in the BAU scenario, it can be seen that GHG missions are slightly decreasing, although final energy and gross domestic consumption are slightly increasing until 2050. Already in this scenario, the trend towards energy efficiency and renewable energy continues, but energy efficiency cannot keep pace with economic growth. The sectorial results show the industrial energy consumption outweighs energy savings in transport and buildings. Thus, the share of renewable energy is also only slightly increasing.

The OLT scenario assumes that after 2020, policies leading to a renewable and low carbon energy transition come into effect. The main impact of these policies that intent to stay within a carbon budget of 1.4 Gt CO2eq is that electricity becomes the main fuel in all energy sectors. This starts from households and services (for appliances and heat pumps), goes over to transport (battery electric vehicles) and industry (where a lot of appliances are switched to electricity) and finally also to the iron and steel production (using electricity for electric arc furnaces and for hydrogen production for the new steel production processes). As electricity production more than doubles until 2050 and exceed the growth of the production capacities, huge electricity imports will be necessary to satisfy the demand. As the production capacity nearly triples, huge challenges for storage and the grid have to be tackled. In general the development can be described as a massive switch towards renewable and low carbon fuels, supported by energy efficiency measures and demand reduction. The analysis of the GHG emissions in the case of the MLT scenario shows that due to the slow decrease of the annual emissions from today until 2030, the remaining carbon budget is actually less than zero. This shows that a feasible MLT scenario requires a significantly higher carbon budget, and an earlier deviation from the baseline scenario or a baseline scenario with significant emissions reduction from as early on as possible.

Finally, regarding LEAP-Bulgaria. The scenario results demonstrate that the carbon budget has been aligned. It appeared, however, that the compliance with the limited carbon budget for Bulgaria is a very difficult task, mainly due to the projected high economy growth (the GDP in 2050 is 2.5 times the one in 2015), combined with limited resources to undertake ambitious (and expensive) policies. In both OLT and MLT, the only feasible solution to comply with the carbon budget is to implement comprehensive measures in all demand and supply sectors. These involve mainly serious energy efficiency improvement combined with abrupt fuel switch to less carbon intensive fuels. As expected, the most feasible approach to comply with the carbon budget is to implement the decarbonization measures as soon as possible, i.e. to achieve most of the energy savings and fuel switch shortly after 2020 in OLT and shortly after 2030 in MLT. In this sense, it is obvious that it is much more difficult and expensive to achieve the carbon budget in MLT, compared to OLT. In MLT, the sharp technological changes in 2030 - 2035, such as replacement of

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energy plants and energy demand equipment (transport vehicles, heating and electricity appliances, etc.) would require discarding operating technologies and massive investment in new equipment and infrastructure, causing economic shock.

Acknowledgements

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Annex. Parameters calculation for the main components of demand function

β_0 value is that in the first column (Coef.) and the last row (_cons). β_{1i}values are given in the first column (Coef.) from sector 2 to 35. For sector 1, β_1 is always equal to 0 because all of them are in reference to it. β_i for explanatory variables is provided by the value in the first column and first row before the sector disaggregation. All panel regressions are heterokedasticity, autocorrelation and contemporary-correlation corrected. Sector 35 has been kept aside from estimation yet it is equal to zero for all the sample.

Variables labels stand for these meanings:

logEXP_EU: logarithm of exports to RoEU (Rest of Europe)

logEU_GDP: logarithm of EU28 GDP.

logEXP_ROW: logarithm of exports to RoW (Rest of the World other than Europe).

logWORLD_GDP: logarithm of Wold GDP

logGFCF: logarithm of Gross Fixed Capital Formation.

logCAP: logarithm of capital compensation.

logLAB: logarithm of labour compensation.

logHH: logarithm of households' demand.

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Household demand

AUSTRIA

Prais-Winsten regression, correlated panels corrected standard errors (PCSEs)

```
Group variable:    sector                          Number of obs      =       525
Time variable:     year                            Number of groups   =        35
Panels:            correlated (balanced)           Obs per group: min =        15
Autocorrelation:   common AR(1)                                   avg =        15
                                                                  max =        15
Estimated covariances      =       630             R-squared          =    0.9559
Estimated autocorrelations =         1             Wald chi2(16)      =  2.56e+16
Estimated coefficients     =        49             Prob > chi2        =    0.0000
```

logHH	Coef.	Panel-corrected Std. Err.	z	P>|z|	[95% Conf.	Interval]
logLAB	.6859897	.0036472	188.09	0.000	.6788414	.6931381
sector						
2	-3.003863	.0747412	-40.19	0.000	-3.150353	-2.857373
3	1.114121	.050073	22.25	0.000	1.015979	1.212262
4	-1.671373	.2050757	-8.15	0.000	-2.073314	-1.269432
5	-5.007545	.5276469	-9.49	0.000	-6.041714	-3.973376
6	-1.637397	.0452737	-36.17	0.000	-1.726132	-1.548662
7	-.7232365	.1026766	-7.04	0.000	-.9244789	-.5219941
8	-.9614648	.1625084	-5.92	0.000	-1.279975	-.6429542
9	-1.961469	.1236022	-15.87	0.000	-2.203725	-1.719213
10	-2.607392	.2996313	-8.70	0.000	-3.194659	-2.020125
11	-2.247564	.070784	-31.75	0.000	-2.386298	-2.10883
12	-1.263766	.0565339	-22.35	0.000	-1.37457	-1.152961
13	-1.13299	.157309	-7.20	0.000	-1.44131	-.8246705
14	-1.341228	.1505662	-8.91	0.000	-1.636333	-1.046124
15	-2.193832	.245845	-8.92	0.000	-2.67568	-1.711985
16	-.5325639	.122307	-4.35	0.000	-.7722813	-.2928465
17	.4760116	.0721506	6.60	0.000	.334599	.6174242
18	-.7392555	.0741942	-9.96	0.000	-.8846735	-.5938375
19	.464856	.0368151	12.63	0.000	.3926997	.5370124
20	1.157277	.0611084	18.94	0.000	1.037507	1.277048
21	.9694171	.0507685	19.09	0.000	.8699127	1.068922
22	1.666287	.0607827	27.41	0.000	1.547155	1.785419
23	.3066816	.045319	6.77	0.000	.2178581	.3955051
24	-5.88747	.2633082	-22.36	0.000	-6.403545	-5.371396
25	-.9462524	.1217649	-7.77	0.000	-1.184907	-.7075976
26	.2379874	.0854439	2.79	0.005	.0705204	.4054543
27	.4837193	.1063371	4.55	0.000	.2753024	.6921361
28	.9214128	.1483268	6.21	0.000	.6306977	1.212128
29	1.97311	.0453474	43.51	0.000	1.884231	2.061989
30	-.6294351	.1515499	-4.15	0.000	-.9264675	-.3324028
31	-1.986765	.0877887	-22.63	0.000	-2.158827	-1.814702
32	-.4590438	.0477664	-9.61	0.000	-.5526642	-.3654234
33	.9723933	.0688853	14.12	0.000	.8373807	1.107406
34	.9611746	.0390347	24.62	0.000	.8846681	1.037681
35	-3.417987	.0506601	-67.47	0.000	-3.517279	-3.318695
year						
1996	-.0126349	4.38e-06	-2883.00	0.000	-.0126435	-.0126263
1997	-.1154125	.0000616	-1874.03	0.000	-.1155332	-.1152918
1998	-.1843108	.0001784	-1033.39	0.000	-.1846604	-.1839612
1999	-.2068323	.0002515	-822.35	0.000	-.2073252	-.2063393
2000	-.2132694	.0003494	-610.45	0.000	-.2139541	-.2125846
2001	-.2085507	.0003648	-571.70	0.000	-.2092656	-.2078357
2002	-.2464246	.0003665	-672.42	0.000	-.2471429	-.2457063
2003	-.2637267	.0003976	-663.25	0.000	-.264506	-.2629473
2004	-.2376291	.0004411	-538.74	0.000	-.2384936	-.2367646
2005	-.2270183	.0005149	-440.91	0.000	-.2280275	-.2260092
2006	-.2453799	.0006168	-397.83	0.000	-.2465888	-.244171
2007	-.3089056	.0007177	-430.44	0.000	-.3103122	-.3074991
2008	-.2931882	.0008293	-353.55	0.000	-.2948135	-.2915628
2009	-.2797511	.0007733	-361.75	0.000	-.2812668	-.2782354
_cons	0	(omitted)				
rho	.6517898					

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BULGARIA

```
Linear regression, correlated panels corrected standard errors (PCSEs)

Group variable:    sector                   Number of obs      =       510
Time variable:     year                     Number of groups   =        34
Panels:            correlated (balanced)    Obs per group: min =        15
Autocorrelation:   no autocorrelation                      avg =        15
                                                           max =        15
Estimated covariances      =       595      R-squared          =    0.9752
Estimated autocorrelations =         0      Wald chi2(15)      =  67124.36
Estimated coefficients     =        34      Prob > chi2        =    0.0000
```

logHH	Coef.	Panel-corrected Std. Err.	z	P>|z|	[95% Conf.	Interval]
logLAB	.8537016	.0121853	70.06	0.000	.8298189	.8775842
sector						
2	-3.291432	.1577976	-20.86	0.000	-3.600709	-2.982154
3	-.5169541	.1020934	-5.06	0.000	-.7170535	-.3168547
4	-2.137336	.2316387	-9.23	0.000	-2.59134	-1.683333
5	-3.164199	.2370359	-13.35	0.000	-3.628781	-2.699617
6	-6.025038	.2450861	-24.58	0.000	-6.505398	-5.544678
7	-3.02999	.1163404	-26.04	0.000	-3.258013	-2.801967
8	-1.90599	.2400745	-7.94	0.000	-2.376527	-1.435452
9	-3.780965	.2503106	-15.11	0.000	-4.271564	-3.290365
10	-4.862484	.2096054	-23.20	0.000	-5.273303	-4.451665
11	-4.318867	.1567442	-27.55	0.000	-4.62608	-4.011654
12	-3.946506	.1558443	-25.32	0.000	-4.251955	-3.641057
13	-4.033895	.1572682	-25.65	0.000	-4.342135	-3.725655
14	-4.690882	.1682366	-27.88	0.000	-5.020619	-4.361144
15	-6.533325	.2558835	-25.53	0.000	-7.034847	-6.031803
16	-4.387934	.2192094	-20.02	0.000	-4.817577	-3.958292
17	-.7564885	.1108617	-6.82	0.000	-.9737734	-.5392036
18	-3.666854	.1305638	-28.08	0.000	-3.922754	-3.410953
19	-2.95707	.1620141	-18.25	0.000	-3.274612	-2.639528
20	-1.69858	.1493078	-11.38	0.000	-1.991218	-1.405942
21	-2.264013	.1566441	-14.45	0.000	-2.571029	-1.956996
22	-.8633566	.1555212	-5.55	0.000	-1.168172	-.5585407
23	-1.386324	.1710693	-8.10	0.000	-1.721614	-1.051034
24	-8.521202	.5525912	-15.42	0.000	-9.604261	-7.438143
25	-7.829647	.3440945	-22.75	0.000	-8.504059	-7.155234
26	-3.46663	.1941333	-17.86	0.000	-3.847125	-3.086136
27	-1.106292	.1668672	-6.63	0.000	-1.433346	-.7792381
28	-3.091518	.262871	-11.76	0.000	-3.606736	-2.5763
29	.4105406	.1089653	3.77	0.000	.1969726	.6241086
30	-4.434155	.0706877	-62.73	0.000	-4.5727	-4.29561
31	-5.145556	.101756	-50.57	0.000	-5.344994	-4.946118
32	-4.005931	.0658363	-60.85	0.000	-4.134967	-3.876894
33	-4.595789	.0869746	-52.84	0.000	-4.766256	-4.425322
34	-2.938407	.1511664	-19.44	0.000	-3.234688	-2.642126

Controlling by the time component was required to estimate a robust regression for Austria, but not in Bulgaria.

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Gross Fixed Capital Formation (GFCF)

AUSTRIA

```
Prais-Winsten regression, heteroskedastic panels corrected standard errors

Group variable:   sector                      Number of obs      =       510
Time variable:    year                        Number of groups   =        34
Panels:           heteroskedastic (balanced)  Obs per group: min =        15
Autocorrelation:  common AR(1)                               avg =        15
                                                             max =        15
Estimated covariances      =        34        R-squared          =    0.9048
Estimated autocorrelations =         1        Wald chi2(48)      = 364732.09
Estimated coefficients     =        48        Prob > chi2        =    0.0000
```

logGFCF	Coef.	Het-corrected Std. Err.	z	P>|z|	[95% Conf.	Interval]
logCAP	.4962294	.0114124	43.48	0.000	.4738615	.5185974
sector						
2	-.9597867	.1291767	-7.43	0.000	-1.212968	-.706605
3	-1.154591	.1266412	-9.12	0.000	-1.402803	-.9063787
4	-1.59285	.1941077	-8.21	0.000	-1.973294	-1.212406
5	-4.351563	.2938204	-14.81	0.000	-4.92744	-3.775685
6	1.276192	.1183122	10.79	0.000	1.044304	1.508079
7	-2.110597	.131765	-16.02	0.000	-2.368851	-1.852342
8	-2.212034	.2543117	-8.70	0.000	-2.710476	-1.713592
9	-.6212839	.1786159	-3.48	0.001	-.9713648	-.2712031
10	-.2402717	.2074883	-1.16	0.247	-.6469414	.1663979
11	1.3323	.166166	8.02	0.000	1.006621	1.65798
12	1.924174	.1334092	14.42	0.000	1.662697	2.185651
13	1.309169	.4095168	3.20	0.001	.5065308	2.111807
14	1.272664	.2129301	5.98	0.000	.8553283	1.689999
15	-.4393468	.4398867	-1.00	0.318	-1.301509	.4228152
16	1.267897	.1246379	10.17	0.000	1.023612	1.512183
17	.2370401	.13256	1.79	0.074	-.0227726	.4968529
18	4.448658	.1157755	38.42	0.000	4.221742	4.675574
19	.5879031	.1195558	4.92	0.000	.3535781	.8222282
20	2.41065	.1176787	20.49	0.000	2.180004	2.641296
21	2.068996	.1165918	17.75	0.000	1.84048	2.297512
22	-2.158319	.1473573	-14.65	0.000	-2.447134	-1.869504
23	.4501715	.177694	2.53	0.011	.1018976	.7984454
24	-5.820348	.5954183	-9.78	0.000	-6.987346	-4.653349
25	-3.613616	.4488756	-8.05	0.000	-4.493396	-2.733836
26	-.9789559	.3719724	-2.63	0.008	-1.708008	-.2499034
27	-2.625355	.2311222	-11.36	0.000	-3.078346	-2.172363
28	-1.183917	.2094635	-5.65	0.000	-1.594458	-.7733758
29	.3189168	.3641842	0.88	0.381	-.3948711	1.032705
30	2.803391	.1317451	21.28	0.000	2.545175	3.061606
31	-1.156156	.1452768	-7.96	0.000	-1.440893	-.8714188
32	-4.944277	.3163399	-15.63	0.000	-5.564292	-4.324262
33	-3.074099	.1806289	-17.02	0.000	-3.428125	-2.720073
34	-.0740134	.1306265	-0.57	0.571	-.3300367	.1820098
year						
1996	-.0318294	.0626347	-0.51	0.611	-.1545913	.0909324
1997	-.1380948	.0806154	-1.71	0.087	-.296098	.0199084
1998	-.1733176	.0905481	-1.91	0.056	-.3507887	.0041535
1999	-.1925578	.0964374	-2.00	0.046	-.3815717	-.003544
2000	-.12564	.1003312	-1.25	0.210	-.3222856	.0710055
2001	-.1186024	.1027344	-1.15	0.248	-.3199581	.0827534
2002	-.1530521	.1042797	-1.47	0.142	-.3574367	.0513324
2003	-.1397555	.1053038	-1.33	0.184	-.3461472	.0666362
2004	-.114063	.1061825	-1.07	0.283	-.3221769	.0940509
2005	-.14583	.1068424	-1.36	0.172	-.3552374	.0635773
2006	-.1430614	.1073383	-1.33	0.183	-.3534407	.0673179
2007	-.1488547	.1077377	-1.38	0.167	-.3600167	.0623072
2008	-.1482076	.1078106	-1.37	0.169	-.3595125	.0630972
2009	-.2037522	.1074551	-1.90	0.058	-.4143602	.0068559
_cons	0	(omitted)				
rho	.6505132					

BULGARIA

```
Prais-Winsten regression, correlated panels corrected standard errors (PCSEs)

Group variable:   sector                        Number of obs      =       480
Time variable:    year                          Number of groups   =        32
Panels:           correlated (balanced)         Obs per group: min =        15
Autocorrelation:  common AR(1)                                 avg =        15
                                                               max =        15
Estimated covariances      =       528          R-squared          =    0.6620
Estimated autocorrelations =         1          Wald chi2(15)      =  2.30e+12
Estimated coefficients     =        46          Prob > chi2        =    0.0000
```

logGFCF	Coef.	Panel-corrected Std. Err.	z	P>|z|	[95% Conf.	Interval]
logCAP	.5299362	.0243291	21.78	0.000	.4822521	.5776204
sector						
2	-2.995871	.3127394	-9.58	0.000	-3.608829	-2.382913
3	-2.20914	.2315485	-9.54	0.000	-2.662967	-1.755313
4	-3.014255	.3437979	-8.77	0.000	-3.688086	-2.340424
5	-4.404602	.4388476	-10.04	0.000	-5.264727	-3.544476
6	-4.790824	.4251189	-11.27	0.000	-5.624042	-3.957606
7	-4.280829	.287824	-14.87	0.000	-4.844953	-3.716704
8	-3.264192	.4649515	-7.02	0.000	-4.17548	-2.352903
9	-3.398362	.2589108	-13.13	0.000	-3.905818	-2.890906
10	-4.005006	.3209322	-12.48	0.000	-4.634022	-3.375991
11	-2.33283	.2997919	-7.78	0.000	-2.920411	-1.745248
12	-1.47523	.3810509	-3.87	0.000	-2.222076	-.7283842
13	.0549341	.5068988	0.11	0.914	-.9385693	1.048438
14	-1.309996	.3310868	-3.96	0.000	-1.958914	-.6610776
15	-2.577468	1.064956	-2.42	0.016	-4.664743	-.4901927
16	-2.593637	.4655374	-5.57	0.000	-3.506074	-1.681201
17	-1.730225	.1860462	-9.30	0.000	-2.094869	-1.365581
19	-1.663952	.2070569	-8.04	0.000	-2.069777	-1.258128
20	-.0299155	.2396709	-0.12	0.901	-.4996618	.4398309
21	-.8275189	.2222784	-3.72	0.000	-1.263177	-.3918612
22	-2.110991	.1571079	-13.44	0.000	-2.418917	-1.803065
23	-1.619817	.1937194	-8.36	0.000	-1.9995	-1.240134
24	-7.364895	1.80493	-4.08	0.000	-10.90249	-3.827297
25	-9.047994	.6033754	-15.00	0.000	-10.23059	-7.8654
26	-3.427857	.2768459	-12.38	0.000	-3.970465	-2.885249
27	-3.557653	.260568	-13.65	0.000	-4.068357	-3.046949
28	-5.192113	.5348383	-9.71	0.000	-6.240377	-4.143849
29	-2.2792	.3786012	-6.02	0.000	-3.021245	-1.537155
30	-1.099972	.1529995	-7.19	0.000	-1.399846	-.8000989
32	-7.762452	.4487669	-17.30	0.000	-8.642019	-6.882885
33	-7.539135	.4135886	-18.23	0.000	-8.349754	-6.728516
34	-5.297847	.275106	-19.26	0.000	-5.837045	-4.758649
year						
1996	-.1410695	.0006033	-233.84	0.000	-.1422519	-.1398871
1997	-.6023715	.0022294	-270.19	0.000	-.6067411	-.5980019
1998	-.6209303	.0029109	-213.31	0.000	-.6266355	-.615225
1999	-.9584701	.0035585	-269.35	0.000	-.9654446	-.9514956
2000	-.4409	.0025998	-169.59	0.000	-.4459955	-.4358045
2001	-.5225745	.0018801	-277.95	0.000	-.5262595	-.5188895
2002	-.2778671	.0007794	-356.49	0.000	-.2793948	-.2763394
2003	-.1696511	.0016721	-101.46	0.000	-.1729283	-.1663738
2004	-.4142808	.000867	-477.82	0.000	-.4159801	-.4125815
2005	.0349322	.0001494	233.78	0.000	.0346393	.0352251
2006	-.208232	.0038125	-54.62	0.000	-.2157044	-.2007596
2007	-.0526085	.0003079	-170.88	0.000	-.0532119	-.0520051
2008	.0545766	.0062762	8.70	0.000	.0422755	.0668777
2009	.6311387	.0044679	141.26	0.000	.6223818	.6398955
_cons	0	(omitted)				
rho	.6617003					

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 691287

Construction

```
1 . regress logGFCF logLAB L.logCAP

      Source |       SS       df       MS              Number of obs =      14
-------------+------------------------------           F(  2,    11) =   15.96
       Model |  1.02271911     2  .511359556           Prob > F      =  0.0006
    Residual |  .352345094    11  .032031372           R-squared     =  0.7438
-------------+------------------------------           Adj R-squared =  0.6972
       Total |  1.37506421    13   .10577417           Root MSE      =  .17897

------------------------------------------------------------------------------
     logGFCF |      Coef.   Std. Err.      t    P>|t|     [95% Conf. Interval]
-------------+----------------------------------------------------------------
      logLAB |   1.396806   .3866699     3.61   0.004     .5457515    2.247861
             |
      logCAP |
         L1. |   1.318579   .4922219     2.68   0.021     .2352055    2.401952
             |
       _cons |  -16.69079   4.323822    -3.86   0.003    -26.20746   -7.174125
------------------------------------------------------------------------------
```

As mentioned in the text, Construction sector was not significantly different than the others enough to separately estimate it in Austria. Nevertheless, it was for Bulgaria as can be seen above. Sector 31 was not estimated for Bulgaria because it is equall to zero.

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 691287

Exports to RoW

AUSTRIA

```
Prais-Winsten regression, heteroskedastic panels corrected standard errors

Group variable:   sector                         Number of obs      =       510
Time variable:    year                           Number of groups   =        34
Panels:           heteroskedastic (balanced)     Obs per group: min =        15
Autocorrelation:  common AR(1)                                  avg =        15
                                                                max =        15
Estimated covariances      =        34           R-squared          =    0.8080
Estimated autocorrelations =         1           Wald chi2(34)      =   4405.00
Estimated coefficients     =        35           Prob > chi2        =    0.0000
```

logEXProw	Coef.	Het-corrected Std. Err.	z	P>|z|	[95% Conf.	Interval]
logGDPWorld	2.377253	.2892872	8.22	0.000	1.81026	2.944245
sector						
2	-2.475381	.3446325	-7.18	0.000	-3.150848	-1.799914
3	2.284561	.1347316	16.96	0.000	2.020492	2.54863
4	1.232127	.2687437	4.58	0.000	.7053988	1.758855
5	.0721525	.2778932	0.26	0.795	-.4725081	.6168131
6	-.7000938	.2429351	-2.88	0.004	-1.176238	-.2239498
7	.6152732	.1911637	3.22	0.001	.2405994	.9899471
8	-.1224549	.2360133	-0.52	0.604	-.5850324	.3401226
9	2.327983	.138854	16.77	0.000	2.055834	2.600131
10	.4685982	.1437966	3.26	0.001	.1867621	.7504343
11	-.304179	.1713493	-1.78	0.076	-.6400174	.0316595
12	1.295556	.1200903	10.79	0.000	1.060183	1.530928
13	3.317938	.1207094	27.49	0.000	3.081352	3.554524
14	2.696219	.1314978	20.50	0.000	2.438488	2.95395
15	2.444687	.3566879	6.85	0.000	1.745591	3.143782
16	1.752035	.1359194	12.89	0.000	1.485638	2.018432
17	-.868572	.2701516	-3.22	0.001	-1.398059	-.3390846
18	.6387075	.2309621	2.77	0.006	.18603	1.091385
19	-1.836811	.2359429	-7.78	0.000	-2.299251	-1.374372
20	2.313614	.1760101	13.14	0.000	1.968641	2.658587
21	-.1824265	.2183108	-0.84	0.403	-.6103078	.2454549
22	-1.086775	.3725866	-2.92	0.004	-1.817031	-.3565184
23	1.576383	.1345802	11.71	0.000	1.312611	1.840156
24	-2.246009	.3531661	-6.36	0.000	-2.938202	-1.553816
25	-.7174319	.3639184	-1.97	0.049	-1.430699	-.0041649
26	-.0440667	.1856731	-0.24	0.812	-.4079792	.3198458
27	-.2815242	.1648604	-1.71	0.088	-.6046447	.0415963
28	1.588147	.1836579	8.65	0.000	1.228184	1.948109
29	-1.945837	.4097545	-4.75	0.000	-2.748941	-1.142733
30	.7120625	.1946712	3.66	0.000	.3305139	1.093611
31	-1.281496	.3660042	-3.50	0.000	-1.998851	-.5641407
32	-4.131138	.6571791	-6.29	0.000	-5.419186	-2.843091
33	-3.313599	.5107526	-6.49	0.000	-4.314656	-2.312543
34	-1.385136	.2285147	-6.06	0.000	-1.833017	-.9372558
_cons	-36.67201	5.030649	-7.29	0.000	-46.5319	-26.81212
rho	.6401471					

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 691287

BULGARIA

```
Prais-Winsten regression, correlated panels corrected standard errors (PCSEs)

Group variable:    sector                      Number of obs      =       510
Time variable:     year                        Number of groups   =        34
Panels:            correlated (balanced)       Obs per group: min =        15
Autocorrelation:   common AR(1)                               avg =        15
                                                              max =        15
Estimated covariances      =       595         R-squared          =    0.7258
Estimated autocorrelations =         1         Wald chi2(29)      =  6.98e+13
Estimated coefficients     =        48         Prob > chi2        =    0.0000
```

logEXP_ROW	Coef.	Panel-corrected Std. Err.	z	P>|z|	[95% Conf.	Interval]
logWORLD_GDP	.3134857	.0105607	29.68	0.000	.292787	.3341843
sector						
2	-2.966641	.5110309	-5.81	0.000	-3.968243	-1.965038
3	-.1283759	.2434528	-0.53	0.598	-.6055348	.3487829
4	-.6279678	.210388	-2.98	0.003	-1.040321	-.2156149
5	-3.208738	.2700607	-11.88	0.000	-3.738048	-2.679429
6	-4.064095	.3161367	-12.86	0.000	-4.683711	-3.444478
7	-2.883912	.2813679	-10.25	0.000	-3.435383	-2.332441
8	.1387812	.3691377	0.38	0.707	-.5847154	.8622777
9	-.3002714	.3309567	-0.91	0.364	-.9489345	.3483918
10	-2.63393	.3002937	-8.77	0.000	-3.222495	-2.045365
11	-2.782503	.2535965	-10.97	0.000	-3.279543	-2.285463
12	-2.343292	.3751394	-6.25	0.000	-3.078552	-1.608032
13	-.2342211	.2057131	-1.14	0.255	-.6374114	.1689693
14	-2.198119	.2300088	-9.56	0.000	-2.648928	-1.74731
15	-1.751396	.6394959	-2.74	0.006	-3.004785	-.4980067
16	-2.527526	.2627116	-9.62	0.000	-3.042431	-2.012621
17	-1.522915	.4754576	-3.20	0.001	-2.454795	-.5910357
18	-1.927905	.3026503	-6.37	0.000	-2.521089	-1.334721
19	-2.218818	.1897381	-11.69	0.000	-2.590698	-1.846939
20	-.6300894	.3418551	-1.84	0.065	-1.300113	.0399343
21	-.3488442	.2135937	-1.63	0.102	-.7674802	.0697917
22	-3.63045	.2590619	-14.01	0.000	-4.138202	-3.122698
23	-.8722545	.2565655	-3.40	0.001	-1.375114	-.3693955
24	-.9588724	.3277763	-2.93	0.003	-1.601302	-.3164426
25	-1.992126	.3533971	-5.64	0.000	-2.684772	-1.29948
26	-2.404008	.4590703	-5.24	0.000	-3.30377	-1.504247
27	-3.73439	.2396043	-15.59	0.000	-4.204006	-3.264774
28	-3.523957	.6692332	-5.27	0.000	-4.83563	-2.212284
29	-3.061065	.2657843	-11.52	0.000	-3.581992	-2.540137
30	-3.733943	.2686148	-13.90	0.000	-4.260418	-3.207467
31	-3.341603	.3890078	-8.59	0.000	-4.104044	-2.579161
32	-7.358824	.5194019	-14.17	0.000	-8.376833	-6.340815
33	-7.417106	.5125969	-14.47	0.000	-8.421778	-6.412434
34	-4.778497	.3693396	-12.94	0.000	-5.50239	-4.054605
year						
1996	-.2791447	.0002022	-1380.41	0.000	-.2795411	-.2787484
1997	.1083407	.0005131	211.16	0.000	.1073351	.1093463
1998	.327318	.0008278	395.42	0.000	.3256956	.3289404
1999	.0816285	.0011166	73.10	0.000	.0794399	.0838171
2000	.0532152	.0015297	34.79	0.000	.050217	.0562135
2001	-.2149613	.0017134	-125.46	0.000	-.2183195	-.211603
2002	-.0310596	.0017696	-17.55	0.000	-.0345279	-.0275913
2003	-.3986235	.0019217	-207.43	0.000	-.40239	-.3948571
2004	.1473152	.0021978	67.03	0.000	.1430075	.1516229
2005	-.1597962	.0024472	-65.30	0.000	-.1645926	-.1549997
2006	.29112	.0028471	102.25	0.000	.2855397	.2967003
2007	.34345	.0031519	108.97	0.000	.3372723	.3496276
2008	.5383054	.0032283	166.74	0.000	.531978	.5446328
2009	.4778329	.0027015	176.88	0.000	.4725382	.4831277
_cons	0	(omitted)				
rho	.6024307					

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 691287

Exports to RoEU

AUSTRIA

Prais-Winsten regression, correlated panels corrected standard errors (PCSEs)

Group variable:	sector	Number of obs =	510
Time variable:	year	Number of groups =	34
Panels:	correlated (balanced)	Obs per group: min =	15
Autocorrelation:	common AR(1)	avg =	15
		max =	15
Estimated covariances =	595	R-squared =	0.8453
Estimated autocorrelations =	1	Wald chi2(15) =	2882.17
Estimated coefficients =	35	Prob > chi2 =	0.0000

logEXP_EU	Coef.	Panel-corrected Std. Err.	z	P>|z|	[95% Conf.	Interval]
logEUGDP	3.830911	.3624722	10.57	0.000	3.120478	4.541343
sector						
2	-2.50512	.5683771	-4.41	0.000	-3.619119	-1.391121
3	2.179583	.1026564	21.23	0.000	1.978381	2.380786
4	1.681884	.1060985	15.85	0.000	1.473935	1.889833
5	.618761	.1151973	5.37	0.000	.3929785	.8445434
6	-1.747862	.1545422	-11.31	0.000	-2.050759	-1.444965
7	.8271668	.0779864	10.61	0.000	.6743163	.9800173
8	-.435905	.2096259	-2.08	0.038	-.8467642	-.0250458
9	1.508116	.0884617	17.05	0.000	1.334734	1.681498
10	.0933731	.0751187	1.24	0.214	-.0538568	.2406031
11	-1.360851	.1251001	-10.88	0.000	-1.606043	-1.11566
12	.8113816	.0727564	11.15	0.000	.6687817	.9539815
13	2.710582	.0809558	33.48	0.000	2.551911	2.869252
14	2.465693	.0887968	27.77	0.000	2.291655	2.639732
15	2.842182	.124188	22.89	0.000	2.598778	3.085586
16	1.628785	.0894386	18.21	0.000	1.453489	1.804082
17	.3029105	.1782189	1.70	0.089	-.0463922	.6522131
18	.1956628	.2539966	0.77	0.441	-.3021615	.693487
19	-3.147583	.2031522	-15.49	0.000	-3.545754	-2.749412
20	.3702711	.0908521	4.08	0.000	.1922043	.548338
21	-.915447	.1755333	-5.22	0.000	-1.259486	-.571408
22	-.8362283	.6075289	-1.38	0.169	-2.026963	.3545065
23	.2600657	.1474441	1.76	0.078	-.0289194	.5490509
24	-3.419232	.2956815	-11.56	0.000	-3.998757	-2.839707
25	-.9486044	.4544236	-2.09	0.037	-1.839258	-.0579505
26	-.3150721	.1075328	-2.93	0.003	-.5258325	-.1043117
27	-.0475995	.12626	-0.38	0.706	-.2950646	.1998656
28	.3477297	.1229064	2.83	0.005	.1068375	.5886218
29	-2.828811	.3875613	-7.30	0.000	-3.588418	-2.069205
30	.6380315	.1465945	4.35	0.000	.3507116	.9253514
31	-1.839781	.1296283	-14.19	0.000	-2.093848	-1.585714
32	-5.123979	.6294088	-8.14	0.000	-6.357598	-3.89036
33	-4.022454	.5829617	-6.90	0.000	-5.165038	-2.87987
34	-.6375908	.2437224	-2.62	0.009	-1.115278	-.1599036
_cons	-56.24755	5.848454	-9.62	0.000	-67.71031	-44.78479
rho	.7243842					

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BULGARIA

Prais-Winsten regression, correlated panels corrected standard errors (PCSEs)

Group variable:	sector	Number of obs =	510
Time variable:	year	Number of groups =	34
Panels:	correlated (balanced)	Obs per group: min =	15
Autocorrelation:	common AR(1)	avg =	15
		max =	15
Estimated covariances =	595	R-squared =	0.8417
Estimated autocorrelations =	1	Wald chi2(15) =	6920.51
Estimated coefficients =	35	Prob > chi2 =	0.0000

logEXP_EU	Coef.	Panel-corrected Std. Err.	z	P>|z|	[95% Conf.	Interval]
logEU_GDP	4.32217	.9608342	4.50	0.000	2.43897	6.20537
sector						
2	-3.001736	.2000562	-15.00	0.000	-3.393839	-2.609633
3	-.216369	.1558324	-1.39	0.165	-.5217948	.0890569
4	.8432832	.1447802	5.82	0.000	.5595192	1.127047
5	-.9742459	.0944382	-10.32	0.000	-1.159341	-.7891504
6	-4.483177	.2417209	-18.55	0.000	-4.956942	-4.009413
7	-3.311624	.1425619	-23.23	0.000	-3.591041	-3.032208
8	-1.261715	.3170223	-3.98	0.000	-1.883067	-.6403627
9	-1.329768	.1609822	-8.26	0.000	-1.645287	-1.014249
10	-2.41908	.1585981	-15.25	0.000	-2.729927	-2.108234
11	-2.757889	.2646566	-10.42	0.000	-3.276606	-2.239171
12	-2.603902	.2080783	-12.51	0.000	-3.011728	-2.196076
13	.5107354	.1878222	2.72	0.007	.1426106	.8788602
14	-1.30362	.1576718	-8.27	0.000	-1.612651	-.9945891
15	-1.355631	.3089158	-4.39	0.000	-1.961094	-.7501668
16	-1.350498	.2101371	-6.43	0.000	-1.76236	-.9386371
17	-.1129019	.1508221	-0.75	0.454	-.4085078	.1827041
18	-2.206677	.1568751	-14.07	0.000	-2.514147	-1.899208
19	-4.205526	.2939229	-14.31	0.000	-4.781604	-3.629447
20	-1.93119	.2101861	-9.19	0.000	-2.343147	-1.519232
21	-3.208923	.1785615	-17.97	0.000	-3.558898	-2.858949
22	-4.090834	.1439126	-28.43	0.000	-4.372897	-3.80877
23	-2.451778	.4606188	-5.32	0.000	-3.354575	-1.548982
24	-3.265891	.4881683	-6.69	0.000	-4.222683	-2.309098
25	-1.630853	.2252683	-7.24	0.000	-2.07237	-1.189335
26	-2.751881	.3141149	-8.76	0.000	-3.367535	-2.136227
27	-1.943569	.1696555	-11.46	0.000	-2.276088	-1.611051
28	-2.411951	.2105622	-11.45	0.000	-2.824645	-1.999257
29	-3.011049	.2477555	-12.15	0.000	-3.496641	-2.525457
30	-3.40354	.1188574	-28.64	0.000	-3.636497	-3.170584
31	-3.709472	.3813899	-9.73	0.000	-4.456982	-2.961961
32	-9.615171	.414386	-23.20	0.000	-10.42735	-8.802989
33	-8.51174	.4335523	-19.63	0.000	-9.361487	-7.661993
34	-3.779127	.2504395	-15.09	0.000	-4.269979	-3.288274
_cons	-64.95162	15.507	-4.19	0.000	-95.3448	-34.55845
rho	.508179					

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