D6.3

Grid and Dispatch in South Eastern Europe – Case Study Report

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About this report

Within the framework of REEEM project, this report constitutes deliverable D6.3 Grid and Dispatch in South Eastern Europe case study report. This case study is led by the research group from Energy Institute Hrvoje Požar and it is part of Work Package 6, Energy Systems Integration. This case study verifies the feasibility of dispatch, calculated in the Integrated European Systems Model (IEM), and analyses the influence of short-term variability on long-term investments and system configurations.

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About REEEM

REEEM aims to gain a clear and comprehensive understanding of the system-wide implications of energy strategies in support of transitions to a competitive low-carbon EU energy society. This project is developed to address four main objectives: (1) to develop an integrated assessment framework (2) to define pathways towards a low-carbon society and assess their potential implications (3) to bridge the science-policy gap through a clear communication using decision support tools and (4) to ensure transparency in the process.

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1 Introduction

Case study on Grid and Dispatch in South Eastern Europe is part of the Work Package 6, (WP6) Energy Systems Integration, in REEEM. The centrepiece of WP6 is the Integrated European Systems Model (IEM) based on TIMES PanEU which is applied to provide in-depth assessments of the pathways identified within the project. In order to investigate details and highlight issues that cannot be resolved in IEM model during the energy system transition, i.e. at a European level, case studies are developed. The main objective of the case study on Grid and Dispatch in South Eastern Europe (further in text: SEE) is to verify the feasibility of yearly balance calculated in the Integrated European Systems Model (IEM), TIMES PanEU, on an hourly level and to analyse the influence of short-term variability on long-term investments and resulting system configurations.

PLEXOS Simulation Software (further in text: PLEXOS) is used to develop the model of power systems in five EU member states in SEE in this case study. PLEXOS is a simulation software, designed for energy market analysis with possibility to analyse a shorter time horizon. It applies more operational details compared to long-term models. PLEXOS is a high-performance simulation platform, operationally used by energy market participants, system planners, investors, regulators, consultants and analysts worldwide.

In this case study, PLEXOS is used to model power systems, i.e. electricity markets in Bulgaria, Croatia, Hungary, Romania and Slovenia. The focus is on a single year with higher temporal resolution than what could be possible in the long-term IEM. TIMES PanEU works with the 12 time slices in a year in the modelling horizon between 2015-2050 split into 5-year time steps. 2030 is chosen as a year in the middle of time horizon in TIMES PanEU to model in PLEXOS as a single year with hourly resolution.

According to outline of the REEEM project, several EU transition pathways are developed. Results of TIMES PanEU from the selected pathways are used as input data to PLEXOS.

The case study report includes three parts. The first part describes methodology, modelling approach and main modelling assumptions, while the second part shows modelling results and analysis. Conclusions based on results analysis relevant for this case study are given in the last chapter.

2 Methodology

2.1 Modelling scope

TIMES PanEU covers energy systems of 28 EU countries as well as Switzerland and Norway. TIMES PanEU works with the 12 time slices in a year in the modelling horizon between 2015-2050 split into 5-year time steps. **To verify the feasibility of yearly balance calculated by TIMES PanEU on an hourly level, a detailed electricity market model is developed in PLEXOS Simulation Software. This model covers the five European Union (EU) countries in South Eastern Europe.**

PLEXOS has a range of features that integrate electric, water and gas systems, but in this case study PLEXOS is applied to model only power systems, i.e. electricity markets in SEE. By analysing a shorter time horizon with more operational details compared to long-term models, optimization results are used to test the influence of short-term variability on long-term investments and resulting system configurations. Year 2030 is chosen as a year in the middle of TIMES PanEU time horizon to model in PLEXOS as a single year.

Bulgaria, Croatia, Hungary, Romania and Slovenia are modelled in this study (Figure 1). Some of these countries, such as Slovenia, have borders only with EU countries, while other countries in the study have borders with EU countries and non-EU countries. Since TIMES PanEU analyses EU member states including Switzerland and Norway, this is identified as an important matter, considering modelling approach and the availability of the input data from TIMES PanEU concerning the electricity trade.

Figure 1: Countries in South Eastern Europe modelled in PLEXOS

2.2 About PLEXOS Simulation Software

PLEXOS Simulation Software is a simulation software designed for energy market analysis. It was first developed as an electricity market simulator. Its functionality was then extended to integrate electric power, gas, heat and water. PLEXOS is a high-performance simulation platform, operationally used by energy market participants, system planners, investors, regulators, consultants and analysts worldwide.

The objective of the market simulation is to minimize the total system cost (including fuel costs and CO_2 emission cost) by taking into account various constraints of the generation and transmission capacities, such as minimum up and down times of power plants, ramp rates of power plants, available generation capacities, transmission lines constraints etc.

The PLEXOS simulations are based on mathematical programming. The software supports various planning horizons from long-term to short-term, and several different time steps: the simulated time frames can be set to minutes, hours, days, weeks, months or years. The PLEXOS models can capture short-term operational limits, as well as the effects of system expansion. After the model is built, PLEXOS formulates a set of equations describing the system behaviour and uses a state of the art mathematical solver[1] to solve the formulated problems, resulting with optimal unit commitment and dispatch, while respecting all the imposed constraints. Once the optimization process is finished, the user interface is applied to analyse, plot and export the simulation results.

2.3 Modelling assumptions

PLEXOS is employed to develop detailed electricity market model of five countries in SEE region in this study.

According to outline of the REEEM project, following EU transition pathways are developed [1]:

- Base pathway,
    - HighRES, as sensitivity of the Base pathway
- Local solution pathway and
- Paris Agreement pathway.

Results of TIMES PanEU from **Base and HighRES pathways** are given as input data to PLEXOS. During the development of PLEXOS model for SEE region, several iterations are realized between TIMES PanEU and PLEXOS to calibrate both of the models. Input data and results shown in this report are based on TIMES PanEU data from **Framework 1, Data V4**. Modelling of the other pathways with TIMES PanEU is currently ongoing process.

Electricity market model developed in PLEXOS requires a significant amount of input data. Figure 2 shows the main input and output data in PLEXOS.

[1] Xpress-MP solver is used in this study

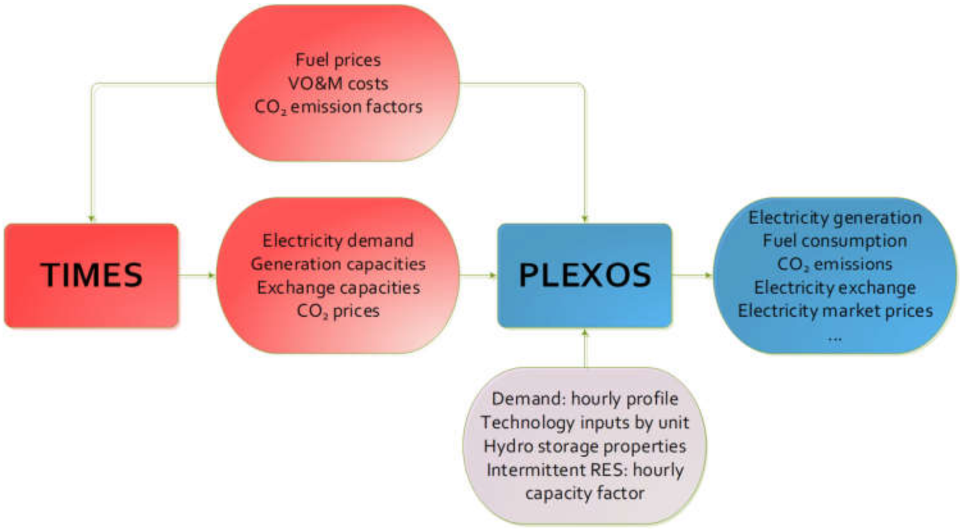

Figure 2: Main input and output data in PLEXOS model of SEE region

Since TIMES PanEU is a long-term energy system planning model, most of the input/output data are available with lower temporal resolution. In this case study, some of the input data are required with higher temporal resolution or higher disaggregation level compared to TIMES PanEU data. Thus, required input data which are not available from TIMES PanEU are obtained from other relevant sources, such as TYNDP 2018[2] and ENTSO-E[3] Pan-European Market Model Database (PEMMDB) used for creation of TYNDP 2018[4].

Two EU transition pathways, Base and HighRES, are diversified regarding cross-border exchange modelled in PLEXOS:

1) Integrated SEE region with cross-border exchange between modelled SEE region and neighbouring countries,
2) Isolated SEE region without cross-border exchange between modelled SEE region and neighbouring countries, which means that exchange is allowed only between countries in SEE region.

These scenarios with integrated SEE region are diversified regarding constraints on electricity generation as well according to following structure:

a) Integrated SEE region with fixed electricity generation – minimum level of yearly electricity generation in PLEXOS is set to yearly values according to TIMES PanEU results by different fuels/technologies to confirm that the results from TIMES PanEU are also possible with hourly optimization,
b) Integrated SEE region without fixed electricity generation – complete optimization of electricity generation by generation units in PLEXOS.

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[2] Ten-Year Network Development Plan 2018
[3] European Network of Transmission System Operators
[4] https://tyndp.entsoe.eu/maps-data/

With the additional diversification in the pathways, six different scenarios are modelled in PLEXOS:

- **Base pathway – Integrated SEE region – fixed generation,**
- **Base pathway – Integrated SEE region – generation optimization,**
- **Base pathway – Isolated SEE region,**
- **HighRES pathway – Integrated SEE region – fixed generation,**
- **HighRES pathway – Integrated SEE region – generation optimization,**
- **HighRES pathway – Isolated SEE region.**

All scenarios are analysed to investigate if power systems of SEE region in 2030 can be dispatched on the hourly level, i.e. if projected generation capacities in SEE based on TIMES PanEU results can ensure to cover:

- projected electricity demand in scenarios with isolated region,
- projected electricity demand and projected cross-border electricity exchange with neighbouring countries in scenarios with integrated region.

Additionally, in scenarios with integrated SEE region PLEXOS optimization results are used to see differences in case when there are no constraints on electricity generation and when electricity generation is set to minimum annual value for each fuel/technology type according to TIMES PanEU results.

Market simulations are carried out to obtain optimal system dispatching. Chronological simulations are carried out for 8.760 hours in 2030, i.e. whole year. The power systems include the generation plants, cross-border transmission lines and hourly electricity demand.

The balance between supply and demand depends on different parameters such as availability of primary energy sources, prices of fuel, bidding strategies etc. It is assumed implicitly that the market operates in perfect competition. In the perfect competition, the system marginal price is determined by the operating cost of the most expensive unit on-line in a given time period. With inelastic consumer bid curve, which is typical in electricity markets, minimizing the total dispatch cost maximizes the social welfare.

For the each country in SEE region, following results are analyzed for all the scenarios:

- electricity generation,
- cross-border electricity exchanges,
- amount of CO_2 emissions,
- wholesale electricity prices,
- electricity balance.

Hourly results are aggregated on a yearly level and compared to TIMES PanEU results.

2.4 Input data overview

This chapter describes in detail, the input data applied in PLEXOS and used to develop model of SEE region.

2.4.1 Generation capacities

Installed generation capacities according to fuel and technology type in 2030 based on TIMES PanEU Base and HighRES pathway are used as input data in PLEXOS. According to TIMES PanEU, there are two categories of power plants for electricity generation:

- public and industrial power plants, and
- public and industrial CHP[5] plants (electrical).

These categories are further disaggregated according to fuel and technology type: coal, lignite, oil, natural gas/non-renewable, nuclear, waste non-renewable + industrial waste heat, biomass solid/waste renewable, biogas/biofuel, hydro, wind, solar, geothermal, electricity storage. These capacities based on TIMES PanEU results for Base pathway and HighRES pathway in 2030 are shown in Appendix A (Table A.1 and Table A.2 respectively).

According to TIMES PanEU results, total installed capacity in SEE is 72,6 GW in Base pathway, and 71,6 GW in HighRES pathway. Share of renewable energy sources (biomass solid/waste renewable, biogas/biofuel, hydro, wind, solar, geothermal) in total installed capacity is 51% in Base pathway and 54% in HighRES pathway in SEE region. Lower total installed capacity and higher share of renewables in this capacity in SEE region brings a challenge in terms of grid and dispatch, thus HighRES pathway is also analysed in addition to Base pathway.

A detailed model on plant-by-plant level is made in PLEXOS for all countries in this case study. Techno-economic parameters considered to analyse generation capacities are listed in Table A.3 in Appendix A. Some of the required input data are not available from TIMES PanEU. These data are obtained from other relevant sources, such EIHP's in-house database, TYNDP 2018 and ENTSO-E Pan-European Market Model Database (PEMMDB) used for creation of TYNDP 2018.

The wind power and solar power are modelled with the hourly time series. The total wind and solar power production result from the resource limits (i.e. natural potential) embedded in the input time series. This is done by modelling one solar and one wind power plant in each country that represent aggregated generation capacity from these renewable sources. This means that there are only one single wind power plant and solar power plant in 2030 which represent the total country capacity. Yearly capacity factors for this single wind and single solar power plant are determined based on installed capacities and electricity generations in 2030 from TIMES PanEU results. Hourly time series are determined based on the datasets available via Renewables.ninja[6] and multiplied

[5] Combined heat and power

[6] www.renewables.ninja, the ninja works by taking weather data from global reanalysis models and satellite observations (papers describing the methods: [2] and [3])

by ratio of yearly capacity factor based on TIMES PanEU results and yearly capacity factor based on Renewables.ninja, in order to obtain hourly time series in line with generation based on TIMES PanEU.

2.4.2 Electricity demand

Since TIMES PanEU does not provide results for electricity demand, total yearly electricity demand in 2030 is determined for each country based on TIMES PanEU results for electricity consumption. Electricity consumption is output from TIMES PanEU and it is expressed as net electricity consumption by sectors (agriculture, industry, commercial, households, transport), conversion, line losses, storage consumption, other energy consumption and net exports. Electricity demand, given as input data to PLEXOS, is determined as sum of electricity consumption by sectors, conversion, line losses and other energy consumption for each of the countries in the case study and the values are shown in Table A.4 and Table A.5 for Base and HighRES pathways respectively.

Since TIMES PanEU provides yearly value of electricity consumption and electricity demand in PLEXOS should be modelled on hourly level, hourly load profile from TYNDP 2018 (scenario Sustainable Transition 2030)[7] is applied in PLEXOS and hourly values are multiplied by ratio of yearly consumption based on TIMES PanEU and yearly demand based on TYNDP 2018 ST scenario, in order to obtain yearly level of demand according to data from TIMES PanEU.

2.4.3 Exchange capacities

Each of the countries is modelled in PLEXOS as a single node, i.e. no inter-country lines are modelled. All the power plants within the country are connected to this aggregate node. The nodes are connected with fictitious lines whose maximum capacity is equal to Net Transfer Capacity (NTC) between two countries which are subjected to trade. PLEXOS includes a simplified DC power flow model that is able to limit the total line flows. Therefore, the interconnection capacity limits are also taken into account during the modelling.

NTC values for borders between countries in SEE region are determined based on TIMES PanEU results in year 2030, i.e. based on category of results 'electricity exchange capacities' and shown in Table A.6. These values do not differ between Base and HighRES pathways.

Besides exchange capacities between countries, for the scenarios with integrated region (scenario description available in section 2.3) exchange capacities (NTCs) between countries of SEE region and other neighbouring countries are also required to be modelled. Exchange capacities for the borders with countries which are not part of EU are not available from TIMES PanEU results. Thus, NTC values based on ENTSO-E TYNDP 2018 are applied for those borders. Detailed information on the modelling assumptions in case of the integrated region is available in section 2.4.6.

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[7] There are three development scenarios under ENTSO-E TYNDP 2018 for year 2030: Sustainable Transition, EUCO and Distributed Generation. According to TYNDP 2018, the Sustainable Transition scenario seeks a quick and economically sustainable CO_2 reduction by replacing coal and lignite by gas in the power sector. Gas also displaces some oil usage in heavy transport and shipping. Regarding electricity demand, this scenario has the lowest demand in both the 2030 and 2040 scenario as this scenario still focuses predominately on gas in the heating sector, but also in the power generation and transport sectors. It also has the lowest growth in electric vehicles.

2.4.4 Fuel and CO_2 emissions prices

Fuel prices, variable costs, CO_2 emission factor (production rate) and CO_2 emission price determine marginal electricity generation costs from the thermal power plants. Table A.7 provides fuel prices in 2030 based on TIMES PanEU data, given as input data to PLEXOS. Prices do not differ between the scenarios.

CO_2 emission factors based on TIMES PanEU data, shown in Table A.8, are also used as input data to PLEXOS.

In addition to CO_2 emission factor, GHG price registered in EU Emission Trading System (ETS) is also used as input data to PLEXOS based on TIMES PanEU results. TIMES PanEU results are calculated according to the Base and HighRES pathways [1] and they differ from each other:

- **28,926** EUR/t in Base pathway, and
- **25,086** EUR/t in HighRES pathway.

2.4.5 Variable operation and maintenance cost

Variable operation and maintenance (VO&M) cost is used as input data for all generation units based on available data from TIMES PanEU and ENTSO-E PEMMDB used for creation of TYNDP 2018. VO&M cost is important in PLEXOS modelling because the value affects marginal cost of generation for each unit of production. Table A.9 provides values of VO&M costs according to fuel and technology type which are used as input data to PLEXOS. These costs are assumed identical for all scenarios and all countries of SEE region.

2.4.6 External markets

In the scenarios without cross-border electricity exchange between modelled SEE region and neighbouring countries, electricity exchange is only allowed between countries in SEE region. These scenarios are named as Base pathway – Isolated region and HighRES pathway – Isolated region.

In the other scenarios, electricity exchange between countries of SEE region and neighbouring countries is allowed. Neighbouring countries in PLEXOS are aggregated as 'one neighbour' for each of the five countries in SEE region and modelled as external nodes, i.e. markets with prices set to zero. Generation capacities and load demand are not modelled for these nodes. NTC values and electricity exchange values based on TIMES PanEU results and ENTSO-E PEMMDB are used to constrain cross-border energy exchange between countries of SEE region and their neighbouring markets.

Figure A.1 and Figure A.2 show net electricity cross-border exchange and its direction for each country and their neighbouring external market based on TIMES PanEU results in 2030 in Base and HighRES pathways. The values from Figure A.1 and Figure A.2 are used as constraints on annual cross-border exchange in PLEXOS, i.e. to set minimum electricity export in 2030 if the country is a net exporter or maximum electricity import in 2030 if the country is a net importer. The main objective of these constraints is to verify technical possibilities to export or import the amount of electricity according to TIMES PanEU results.

Cross-border exchange values between countries in SEE based on TIMES PanEU are not used as input data. These values are calculated in PLEXOS as well and compared with the values from TIMES PanEU in sections 3.1.2 and 3.2.2.

2.4.7 Modelling assumptions on heat demand

Short-term optimization of power system in PLEXOS is affected by hourly electricity demand and marginal costs of generation of available units to supply this demand in the system with the possibility to import electricity from neighbouring power systems. In long-term optimization of the entire energy system in TIMES PanEU heat demand is also part of the optimization process as TIMES PanEU covers the whole energy system. Heat demand is not considered in PLEXOS. As mentioned, PLEXOS is used in this case study to model only the power systems of the selected countries in SEE region. However, generation capacities of CHP plants based on TIMES PanEU results are also included in PLEXOS (more detailed in section 2.4.1). These plants operations should not be optimized only according to electricity demand because dispatch of CHP plants is also affected by heat demand. Therefore, in order to ensure that CHP plants operate to provide the heat required demand in the system, a constraint on minimum daily capacity factor in CHP plants is applied in PLEXOS. Minimum daily capacity factor differs according to months in a year. These capacity factors are estimated based on typical operation of CHP units for heating purposes in SEE region considering the required heat demand in the specific time of the year. These values are shown in Table A.10 in Appendix A. Heat demand for industrial processes is not considered in the model.

3 Results analysis

This chapter presents the results for all scenarios modelled in PLEXOS and their comparison with TIMES PanEU results for Base and HighRES pathway.

PLEXOS results for:

- electricity generation,
- cross-border electricity exchange,
- CO_2 emissions based on electricity production,

in each scenario are shown and compared to TIMES PanEU results on the yearly basis.

Wholesale electricity market prices based on modelling results in PLEXOS for countries of SEE region are also shown.

All scenarios are used to verify **if power systems of SEE region in 2030 can be dispatched on the hourly level**. Therefore, electricity balance (load, generation, import, export) considering the projected electricity demand and cross border electricity exchange is analysed for each scenario.

3.1 Base pathway scenarios

As described in section 2.3, three scenarios are modelled in PLEXOS based on TIMES PanEU data for Base pathway:

- **Base pathway – Integrated SEE region – fixed generation,**
- **Base pathway – Integrated SEE region – generation optimization,**
- **Base pathway – Isolated SEE region.**

Assumption in terms of the electricity demand, installed capacities according to fuel and technology type , fuel prices, GHG ETS prices and CO_2 emission factors determined based on TIMES PanEU data for Base pathway, described in section 2.4 as well, and these assumptions do not differ between scenarios. The main difference between these scenarios is that in isolated scenario there is no cross-border electricity exchange with neighbouring countries outside of SEE region, while in scenarios with integrated region, cross-border electricity exchange is allowed. Scenarios with integrated region are diversified regarding constraints on electricity generation additionally.

3.1.1 Electricity generation

In this section, electricity generation results from PLEXOS are given and compared to TIMES PanEU results based on scenarios structured according to Base pathway.

Base pathway – Integrated SEE region – fixed generation

In this scenario constraints are implemented in PLEXOS. According to these constraints, minimum electricity generation per fuel/technology on a yearly level must be equal or higher than the TIMES PanEU results for Base pathway which are shown in Table 1 in columns 'TIMES'. The objective of this scenario is to investigate if TIMES PanEU yearly results for generation in Base pathway are feasible on an hourly level according to projected electricity demand based on TIMES PanEU.

Table 1: Electricity generation according to PLEXOS results in scenario Base pathway – Integrated SEE region – fixed generation and TIMES PanEU results in Base pathway (in GWh)

Country / Fuel	Bulgaria		Croatia		Hungary		Romania		Slovenia	
	TIMES	PLEXOS	TIMES	PLEXOS	TIMES	PLEXOS	TIMES	PLEXOS	TIMES	PLEXOS
Coal	1.487	1.486	993	3.215	67	67	6.077	6.076	559	606
Lignite	13.510	13.496	1	0	11.900	11.920	3.593	4.913	1.278	1.280
Oil	220	220	22	24	236	296	673	1.096	0	0
Natural gas	2.647	2.647	2.943	2.980	21.376	21.375	15.685	15.686	3.766	3.767
Nuclear	6.987	6.929	0	0	22.391	20.886	10.705	9.110	5.623	5.487
Waste	367	367	2	2	544	544	758	758	59	59
Biomass	702	702	2.555	2.556	1.653	1.652	4.140	4.140	868	868
Biogas	7.679	7.680	298	298	266	266	849	849	189	189
Hydro	8.590	8.476	10.138	10.159	382	384	22.035	22.011	8.983	8.987
Wind	1.880	1.881	5.177	5.180	604	604	14.356	14.367	723	722
Solar	1.384	1.387	464	464	1.021	1.020	1.946	1.945	169	169
Geothermal	0	0	129	130	2	3	348	349	3	4
Batteries	1	0	1	0	1	0	1	0	1	0
Total	**45.454**	**45.271**	**22.723**	**25.007**	**60.443**	**59.018**	**81.166**	**81.302**	**22.221**	**22.138**

Optimization results in this scenario show that electricity generation capacities based on TIMES PanEU Base pathway can provide the projected electricity demand on an hourly level. However, there are some differences in generation according to different fuel types between TIMES PanEU and PLEXOS results. While most of the technologies generate approximately equal or more electricity according to PLEXOS results, which is in line with the constraint in this scenario, in some cases yearly electricity generation is lower compared to TIMES PanEU results, for example lignite in Bulgaria or nuclear in all countries with nuclear power plants. Thermal generation units in PLEXOS are modelled with additional parameters such as minimum stable level, minimum and maximum time in operation, or scheduled and forced maintenance rates which can affect power plant dispatch on an hourly level. Because of these additional parameters, in some cases it is not possible to produce exactly the same amount of electricity as in TIMES PanEU. In such cases, the electricity demand is provided either through the import or with the generation from alternative power plants.

Electricity generation for some fuel types is higher according to PLEXOS results compared to TIMES PanEU results, for example, electricity generation from coal in Croatia. Since coal has relatively low fuel price (2,9 EUR/GJ) and PLEXOS optimizes generation according to marginal cost of generation, it is expected that technologies with lower fuel costs and consequently marginal generation costs have priority in dispatching order compared to more 'expensive' units. It should also be pointed out that there are differences between fuel prices in SEE countries for the same fuel type (see Table A.7). Considering that, and other technical and economic characteristics for each unit, marginal generation costs for units with the same fuel type can differ, which affects dispatching order.

Hydro, wind and solar achieve the same yearly generation in PLEXOS with TIMES PanEU, as the same assumptions on the yearly capacity factor are used in both models. Negligible differences in wind and solar generation are result of modelling in PLEXOS with hourly time series (as described in section 2.4.1), while in case of hydro due to modelling on a plant-by-plant level with reservoirs for storage hydro power plants.

In Bulgaria, Hungary and Slovenia, total electricity generation is lower according to PLEXOS results, and in Croatia and Romania, total electricity generation is higher compared to TIMES PanEU results. Higher electricity generation in Croatia comes from coal generation and in Romania from lignite compared to TIMES PanEU results. If entire region is considered, total electricity generation according to PLEXOS results (232.736 GWh) is slightly higher in comparison to TIMES PanEU results (232.007 GWh). In both models (PLEXOS and TIMES PanEU) electricity demand is satisfied, but due to different modelling approach regarding level of details and regarding modelling of heat demand, slightly different generation mix to meet the same electricity demand can be expected.

Base pathway – Integrated SEE region – generation optimization

Base pathway – Integrated SEE region – generation optimization scenario does not contain any constraints on yearly electricity generation. Electricity generation is completely optimized in PLEXOS in this scenario. Electricity generation results in 2030 from PLEXOS for this scenario and TIMES PanEU Base pathway are shown in Table 2.

Table 2: Electricity generation according to PLEXOS results in scenario Base pathway – Integrated SEE region – generation optimization and TIMES PanEU results in Base pathway (in GWh)

Country / Fuel	Bulgaria		Croatia		Hungary		Romania		Slovenia	
	TIMES	PLEXOS	TIMES	PLEXOS	TIMES	PLEXOS	TIMES	PLEXOS	TIMES	PLEXOS
Coal	1.487	2.463	993	4.989	67	112	6.077	6.702	559	836
Lignite	13.510	12.552	1	0	11.900	16.085	3.593	17.059	1.278	1.280
Oil	220	89	22	0	236	295	673	1.095	0	0
Natural gas	2.647	1.929	2.943	3.115	21.376	13.852	15.685	9.810	3.766	1.270
Nuclear	6.987	6.929	0	0	22.391	20.886	10.705	9.110	5.623	5.487
Waste	367	486	2	1	544	1.071	758	356	59	19
Biomass	702	277	2.555	2.788	1.653	1.816	4.140	2.774	868	321
Biogas	7.679	7.650	298	6	266	88	849	853	189	58
Hydro	8.590	8.439	10.138	10.164	382	384	22.035	22.014	8.983	8.986
Wind	1.880	1.881	5.177	5.180	604	604	14.356	14.367	723	722
Solar	1.384	1.387	464	464	1.021	1.020	1.946	1.945	169	169
Geothermal	0	0	129	130	2	3	348	349	3	4
Batteries	1	0	1	0	1	0	1	0	1	0
Total	**45.454**	**44.082**	**22.723**	**26.837**	**60.443**	**56.216**	**81.166**	**86.434**	**22.221**	**19.152**

When electricity generation is optimized in PLEXOS without minimum yearly generation constraints based on TIMES PanEU results, PLEXOS modelling results show significant differences compared to TIMES PanEU results. For example, electricity generation from natural gas according to PLEXOS results is lower in four of five countries compared to TIMES PanEU results. In optimization process, generating units with lower marginal costs of generation have priority in dispatching. Natural gas power plants have higher fuel costs which results in higher marginal costs of generation compared to lignite or coal. Due to lower marginal costs of the generation, coal-fired and lignite units have higher yearly capacity factor compared to natural gas units according to PLEXOS results. Also, in TIMES PanEU there is CO_2 emission limitation for the entire EU, while in PLEXOS there are no limitations on CO_2 emissions in SEE region and generating units which use fuels with higher CO_2 emission factor (see Table A.8), like coal and lignite, are generating more electricity compared to TIMES PanEU results.

In this scenario, according to PLEXOS results electricity generation in 2030 is lower in Bulgaria, Hungary and Slovenia compared to TIMES PanEU results, and higher in Croatia and Romania. If entire region is considered, total electricity generation according to PLEXOS results (232.722 GWh) is slightly higher in comparison to TIMES PanEU results (232.007 GWh) due to differences in generation by fuel types. As in scenario Base pathway – Integrated SEE region – fixed generation, generating units can ensure to cover electricity demand, but with different generation mix compared to TIMES PanEU results.

Base pathway – Isolated SEE region

Electricity generation results in 2030 from PLEXOS for scenario Base pathway – Isolated SEE region and TIMES PanEU Base pathway are shown in Table 3. This scenario does not contain any constraints on yearly electricity generation according to TIMES PanEU results which means that electricity generation is completely optimized by

PLEXOS. The aim of this scenario is to simulate optimal dispatch of power plants in SEE region without electricity exchange with other power systems outside SEE region and to verify if the existing capacities in the region are sufficient for the projected demand.

Table 3: Electricity generation according to PLEXOS results in scenario Base pathway – Isolated SEE region and TIMES PanEU results in Base pathway (in GWh)

Country / Fuel	Bulgaria		Croatia		Hungary		Romania		Slovenia	
	TIMES	PLEXOS	TIMES	PLEXOS	TIMES	PLEXOS	TIMES	PLEXOS	TIMES	PLEXOS
Coal	1.487	1.856	993	4.243	67	100	6.077	5.557	559	792
Lignite	13.510	7.680	1	0	11.900	14.339	3.593	12.873	1.278	1.208
Oil	220	89	22	0	236	294	673	1.094	0	0
Natural gas	2.647	1.987	2.943	3.038	21.376	14.312	15.685	9.849	3.766	1.271
Nuclear	6.987	6.880	0	0	22.391	20.879	10.705	9.107	5.623	5.471
Waste	367	319	2	1	544	871	758	353	59	19
Biomass	702	276	2.555	1.583	1.653	1.476	4.140	2.348	868	320
Biogas	7.679	7.650	298	6	266	87	849	853	189	57
Hydro	8.590	8.613	10.138	10.167	382	384	22.035	22.069	8.983	8.990
Wind	1.880	1.881	5.177	5.180	604	604	14.356	14.367	723	722
Solar	1.384	1.387	464	464	1.021	1.020	1.946	1.945	169	169
Geothermal	0	0	129	130	2	3	348	349	3	4
Batteries	1	0	1	0	1	0	1	0	1	0
Total	**45.454**	**38.617**	**22.723**	**24.812**	**60.443**	**54.369**	**81.166**	**80.764**	**22.221**	**19.023**

In this scenario, there are some differences compared to TIMES PanEU results for some fuels/technologies. Electricity generation from natural gas according to PLEXOS results is lower compared to TIMES PanEU results, while electricity generation from lignite and coal in this scenario is higher compared to TIMES PanEU results. This is in line with results for generation in scenario Base pathway – Integrated region – generation optimization. If there are no constraints on electricity generation, in PLEXOS generating units on coal and lignite have preference over gas-fired units.

In this scenario, according to PLEXOS results electricity generation is lower in all countries of SEE region, except Croatia, compared to TIMES PanEU results. Generation from coal in Croatia compensates more expensive fuels/technologies in other countries. According to the TIMES PanEU results, SEE region is a yearly net exporter of electricity. In this scenario, total electricity generation according to PLEXOS and TIMES PanEU results are 217.585 GWh and 232.007 GWh respectively. Since there is no cross-border electricity exchange between countries of the region and neighbouring countries, entire electricity generation in this scenario is used to satisfy electricity demand only in SEE countries which explains the reason for the total generation difference between two models.

3.1.2 Cross-border exchange

Cross-border electricity exchange results according to scenarios structured with Base pathway are given in Table 4 below. Flow refers to the yearly power flow on the interconnection line in the 'reference direction' (as modelled from 1st to 2nd node), whereas flow back is the flow in the counter-reference direction. For example, Croatia - Hungary line flow indicates exchange in the direction from Croatia to Hungary, while flow back indicates exchange from Hungary to Croatia.

Table 4: Cross-border electricity exchange according to PLEXOS results in different scenarios based on Base pathway

Border	Base pathway – Integrated region – fixed optimization		Base pathway – Integrated region – generation optimization		Base pathway – Isolated SEE region	
	Flow (GWh)	Flow back (GWh)	Flow (GWh)	Flow back (GWh)	Flow (GWh)	Flow back (GWh)
Croatia - Hungary	6.540	4.263	9.066	3.419	9.038	4.231
Croatia - Slovenia	8.122	5.083	6.843	5.343	6.162	6.396
Hungary - Slovenia	4.617	7.577	6.813	5.242	6.996	5.484
Romania - Bulgaria	4.271	3.741	7.065	5.374	3.116	5.911
Romania - Hungary	4.299	4.827	7.250	3.811	7.574	2.551
Bulgaria - External market	10.147	0	10.141	0		
Croatia - External market	0	528	0	528		
Hungary - External market	1.040	0	1.043	0		
Romania - External market	2.806	0	2.813	0		
Slovenia - External market	1.918	0	1.926	0		

According to PLEXOS results, cross-border electricity exchange (sum of electricity imports and export) between the countries in SEE region is higher compared to TIMES PanEU results in all scenarios. The highest sum of electricity imports and export is in scenario Base pathway – Integrated region – generation optimization (60,2 TWh). According to TIMES PanEU results for Base pathway, sum of electricity imports and export between countries of SEE region amounts around 3 TWh. It is necessary to point out that electricity market model of SEE region in PLEXOS assumes fully integrated market and perfect competition, which facilitate cross-border electricity exchange considering projected NTCs for 2030.

Figures B.4 - B.6 in Appendix B show net electricity exchange according to TIMES PanEU results in Base pathway and according to PLEXOS results in three different scenarios based on Base pathway.

In scenario Base pathway – Integrated SEE region – fixed generation, on borders between Slovenia, Hungary, Romania and their external markets, net electricity exchange is lower compared to minimum values determined based on TIMES PanEU results. In terms of PLEXOS optimization process, it means that these constraints are 'repaired' due to some other limitations in the model in a certain period which could be technical constraints of units or constraints on minimum electricity generation by fuel/technology in this scenario.

In scenario Base pathway – Integrated SEE region – generation optimization, constraints on net electricity exchange with external markets based on TIMES PanEU results are satisfied, i.e. Slovenia, Hungary, Bulgaria and

Romania export equally or more electricity compared to TIMES PanEU results, and Croatia imports equal amount of electricity compared to TIMES PanEU results.

3.1.3 CO_2 emissions

PLEXOS calculates CO_2 emissions from electricity generation based on power plant dispatch, fuel consumption and fuel emission factors. Emission factors are given as input data based on TIMES PanEU data (section 2.4.4). CO_2 emission prices are also considered in PLEXOS analyses and included in the optimization objective function.

Amounts of CO_2 emissions from electricity generation in PLEXOS scenarios based on Base pathway are shown in this section for each country of SEE region. CO_2 emissions based on PLEXOS results are compared to amount of CO_2 emissions from electricity and heat production in public and industrial power plants according to TIMES PanEU results for Base pathway. In TIMES PanEU model there is CO_2 emission limitation for the entire EU and in PLEXOS model only the CO_2 emission price is used as input which is resulted from TIMES PanEU according to the EU level targets, without specific limitation to total amount of CO_2 emissions in SEE region.

Table 5 shows total amount of CO_2 emissions from electricity generation in SEE region in three PLEXOS scenarios and total amount of CO_2 emissions from electricity and heat production in public and industrial power plants based on TIMES PanEU results for Base pathway.

Table 5: CO_2 emissions from electricity production in PLEXOS scenarios and in TIMES PanEU Base pathway (tonnes)

Scenario	Base pathway (TIMES)	Base pathway – Integrated SEE region – fixed generation (PLEXOS)	Base pathway – Integrated SEE region – generation optimization (PLEXOS)	Base pathway – Isolated SEE region (PLEXOS)
CO_2 emissions in SEE region	62.674.116	63.004.542	77.064.361	62.341.558

Results in Table 5 show that there is no significant difference in CO_2 emissions between TIMES Base pathway and PLEXOS scenarios Base pathway – Integrated SEE region – fixed generation and Base pathway – Isolated SEE region. Based on these results, it can be concluded that amount of CO_2 emissions calculated by TIMES PanEU for SEE region is also verified in short-term optimization of power systems.

The greatest difference in amount of CO_2 emissions is in scenario Base pathway – Integrated SEE region – generation optimization due to significant differences in generation by fuel/technologies compared to Base pathway (described in section 3.1.1). Since there is no limitation in PLEXOS to amount of CO_2 emissions and no constraints on minimum electricity generation, power plant dispatch is determined based on units' marginal costs of generation which depend on fuel price, efficiency, variable operation and maintenance costs and fuel emission factors. CO_2 emission price also affects marginal costs of generation. Some technologies such as coal and lignite power plants can have higher CO_2 emission factor, but lower marginal costs due to lower fuel prices. In general, due to lower marginal costs of generation, coal and lignite generation units produce more electricity in PLEXOS scenarios compared to TIMES PanEU results which causes higher CO_2 emissions. In PLEXOS different units with the same fuel type and technology can have different marginal costs of generation, depending on unit's efficiency and VO&M costs. In TIMES PanEU, all units with the same fuel type and technology have the same marginal cost of generation because modelling approach considers modelling of technologies, not modelling on a plant-by-plant level.

In Figures 3-5 CO_2 emissions in each country are shown for all PLEXOS scenarios and TIMES PanEU Base pathway.

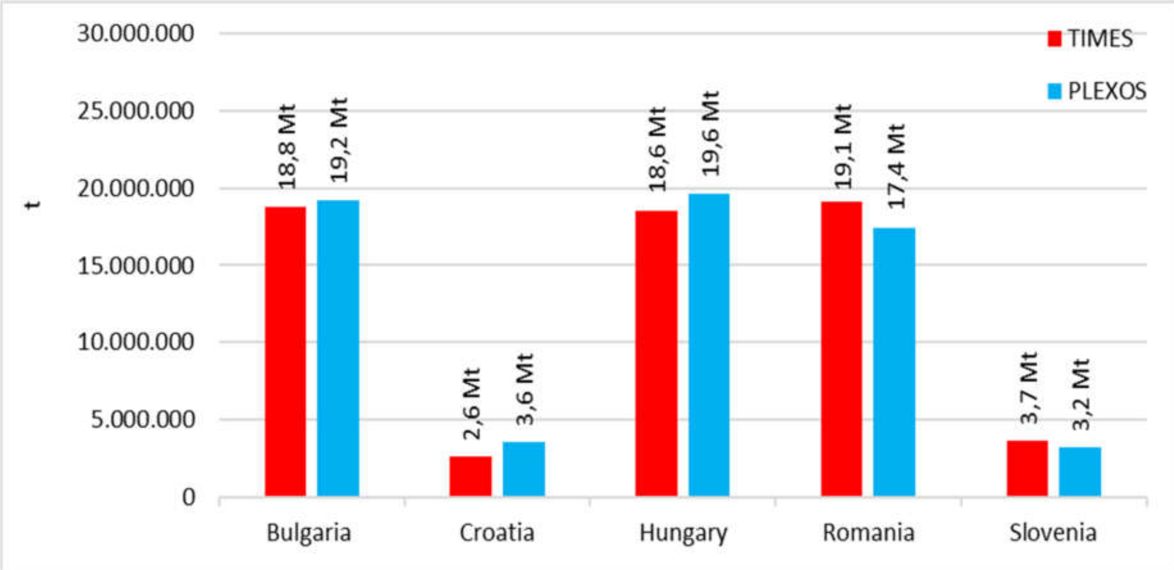

Figure 3: CO_2 emissions from electricity generation in scenario Base pathway – Integrated SEE region – fixed generation according to PLEXOS results and in Base pathway according to TIMES PanEU results

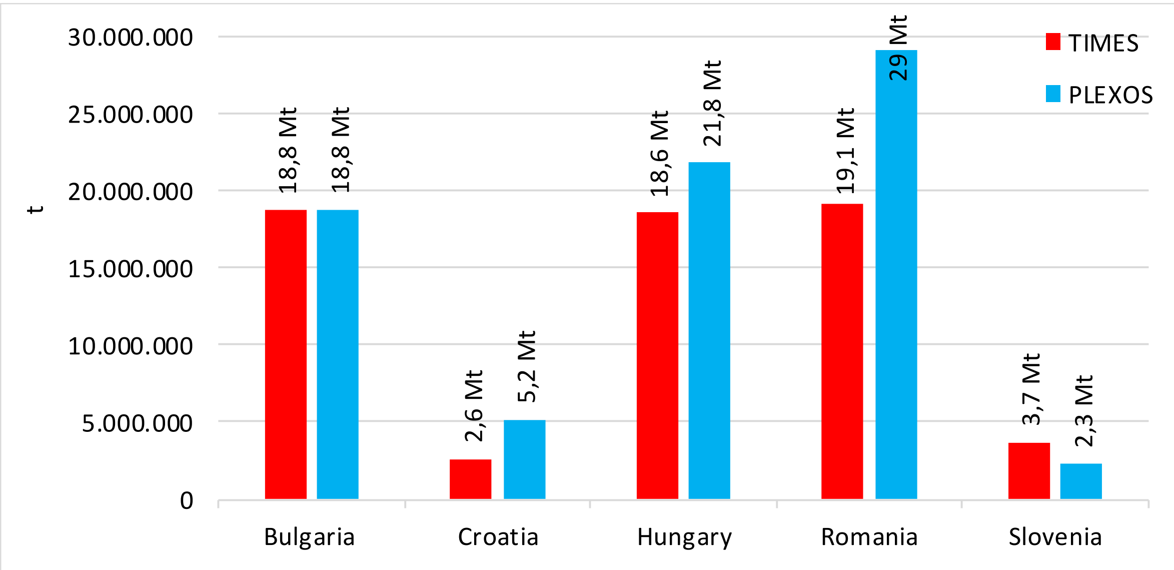

Figure 4: CO_2 emissions from electricity generation in scenario Base pathway – Integrated SEE region – generation optimization according to PLEXOS results and in Base pathway according to TIMES PanEU results

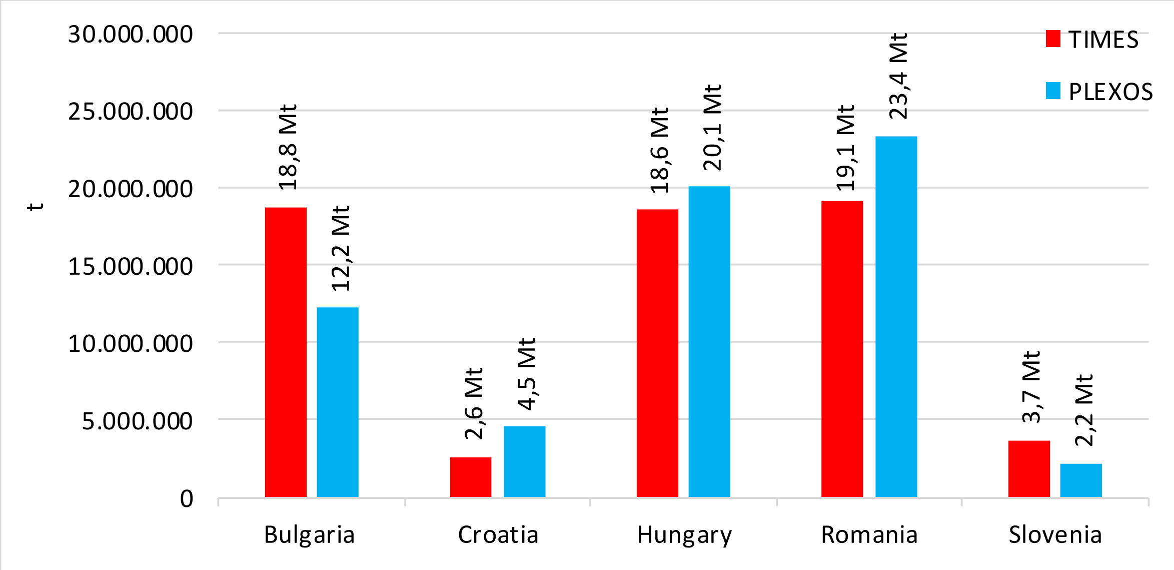

Figure 5: CO_2 emissions from electricity generation in scenario Base pathway – Isolated SEE region according to PLEXOS results and in Base pathway according to TIMES PanEU results

In each scenario Croatia produces more electricity from coal, which causes higher CO_2 emissions compared to TIMES PanEU results. In case of Hungary, total electricity generation in all scenarios is lower compared to TIMES PanEU results, but generation from coal and lignite is higher which also affects higher CO_2 emissions in PLEXOS. Even if the generation values from a certain fuel/technology are equal according to TIMES PanEU and PLEXOS results, it cannot be expected that CO_2 emissions are also at the same level. Thermal generation units in PLEXOS are modelled on a detailed plant-by-plant level according to existing units with different heat rates for each unit which affects fuel consumption in each unit, and consequently CO_2 emissions, which means that for the same amount of generated electricity in PLEXOS and TIMES PanEU, fuel consumption and CO_2 emissions can be different.

3.1.4 Electricity market prices

In PLEXOS electricity market price in each hour in one country is determined by marginal cost of generation (i.e. the system marginal price is set by the operating cost of the most expensive unit on-line during a given period). If there is electricity import from the other countries, this import is treated as extra generators and their price is also considered to determine the most expensive unit. Annual prices represent the average load-weighted price in a given country.

In TIMES PanEU, electricity market price is the long-run marginal cost of production, which represents the full cost of serving the load taking into account the cost of expansion as well as the cost of production.

Due to different definitions, electricity market prices from TIMES PanEU and PLEXOS are not comparable. Thus, in this section only market prices based on PLEXOS modelling results are shown (Figure 6). Comparison of prices from different PLEXOS scenarios shows how different optimization of the same generation capacities results in different electricity prices in each country.

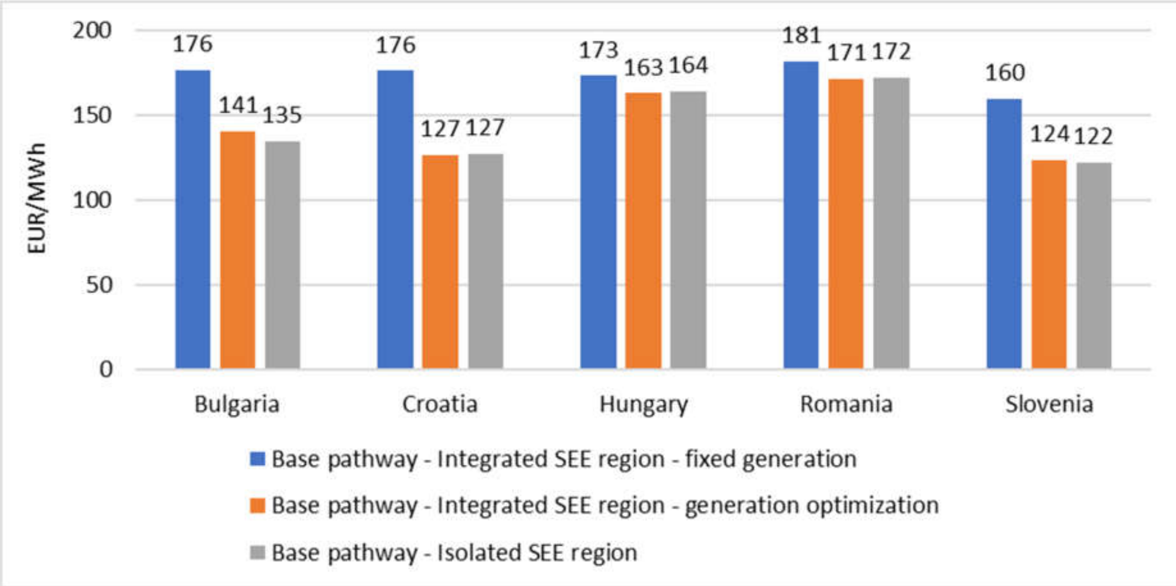

Figure 6: Electricity market prices in SEE region based on PLEXOS modelling results in scenarios based on Base pathway

Scenario Base pathway – Integrated SEE region – fixed generation has the highest market prices for all the countries, seen in Figure 6. As this scenario has constraints based on TIMES PanEU results for the minimum electricity generation, this means that some technologies with higher marginal cost of generation according to principle in PLEXOS actually operate in a certain period to satisfy these constraints. Since market price is determined based on marginal cost of generation of the most expensive unit on-line during a given period, power plant dispatch based on these constraints increases the electricity prices. As the results in other scenarios (Base pathway – Integrated SEE region – generation optimization and Base pathway – Isolated SEE region) are based on minimizing the cost of the generation, the electricity prices are also lower compared to Base pathway – Integrated SEE region – fixed generation scenario.

3.1.5 Electricity balance

Electricity balances, i.e. yearly load, generation and exchange values (import and export) for each of the SEE countries in three scenarios based on Base pathway are given in Tables 6-8 (and Figures B.7 - B.9 in Appendix B). Load in each country refers to sum of the projected yearly electricity demand according to TIMES PanEU results (section 2.4.2) and pump load, if existing pumped-storage hydro power plants are in operation.

Table 6: Electricity balance according to PLEXOS results in scenario Base pathway – Integrated SEE region – fixed generation

Category	Bulgaria	Croatia	Hungary	Romania	Slovenia	TOTAL
Load (GWh)	35.654	20.219	62.687	78.494	20.298	**217.352**
Generation (GWh)	45.271	25.007	59.018	81.302	22.138	**232.736**
Import (GWh)	4.271	9.873	18.416	8.569	12.738	**53.867**
Export (GWh)	13.888	14.662	14.747	11.376	14.578	**69.251**
Net interchange (GWh)	9.617	4.789	-3.669	2.808	1.840	**15.384**

Table 7: Electricity balance according to PLEXOS results in scenario Base pathway – Integrated SEE region – generation optimization

Category	Bulgaria	Croatia	Hungary	Romania	Slovenia	TOTAL
Load (GWh)	35.633	20.218	62.687	78.491	20.297	**217.327**
Generation (GWh)	44.082	26.837	56.216	86.434	19.152	**232.722**
Import (GWh)	7.065	9.289	21.557	9.185	13.656	**60.754**
Export (GWh)	15.515	15.908	15.086	17.129	12.511	**76.149**
Net interchange (GWh)	8.449	6.619	-6.471	7.943	-1.145	**15.395**

Table 8: Electricity balance according to PLEXOS results in scenario Base pathway – Isolated SEE region

Category	Bulgaria	Croatia	Hungary	Romania	Slovenia	TOTAL
Load (GWh)	35.822	20.239	62.687	78.536	20.302	**217.585**
Generation (GWh)	38.617	24.812	54.369	80.764	19.024	**217.585**
Import (GWh)	3.116	10.627	22.097	8.462	13.158	**57.459**
Export (GWh)	5.911	15.200	13.778	10.690	11.880	**57.459**
Net interchange (GWh)	2.795	4.573	-8.318	2.228	-1.278	**0**

In scenarios with integrated region SEE region is a net exporter of electricity. Total electricity generation and load are slightly higher in scenario Base pathway – Integrated SEE region – fixed generation, while net interchange (difference between total export and total import) is slightly higher in scenario Base pathway – Integrated SEE region – generation optimization. Differences in total load in three scenarios are due to pump load from pumped-storage hydro power plants (electricity demand is the same in all Base pathway scenarios). In scenario with isolated region total sum of net interchange is zero since this scenario does not take into account the external markets.

In scenario Base pathway – Integrated SEE region – fixed generation, Bulgaria, Croatia, Romania and Slovenia are net exporters of electricity and Hungary is a net importer. This is in line with TIMES PanEU results for Base pathway. In scenarios Base pathway – Integrated SEE region – generation optimization and Base pathway – Isolated region Bulgaria, Croatia and Romania are net exporters of electricity, while Hungary and Slovenia are net importers. This shows that generation based on PLEXOS optimization, without setting constraints on generation according to TIMES PanEU results, also affects electricity exchange, both in amount and direction.

According to this analysis, TIMES PanEU Base pathway yearly balance results are feasible on an hourly level, considering all implemented constraints regarding generation and transmission capacities.

3.2 HighRES pathway scenarios

As described in section 2.3, there are three scenarios modelled in PLEXOS based on TIMES PanEU results for HighRES pathway:

- **HighRES pathway – Integrated SEE region – fixed generation,**
- **HighRES pathway – Integrated SEE region – generation optimization,**
- **HighRES pathway – Isolated SEE region.**

All scenarios have the same assumptions for electricity demand, installed capacities by fuel/technology, fuel prices, CO_2 emission prices and CO_2 emission factors which are determined based on TIMES PanEU data for HighRES pathway and described in section 2.4. The main difference between these scenarios are in line with assumptions for Base pathway scenarios (described in section 3.1).

3.2.1 Electricity generation

In this section electricity generation results in 2030 by fuel/technology type according to PLEXOS modelling results in scenarios based on HighRES pathway are shown and compared to TIMES PanEU results.

HighRES pathway – Integrated SEE region – fixed generation

In this scenario, constraints are implemented in PLEXOS according to which minimum electricity generation per fuel/technology on a yearly level must be equal or higher to values based on TIMES PanEU results for HighRES pathway which are shown in Table 9 in columns 'TIMES'.

Table 9: Electricity generation according to PLEXOS results in scenario HighRES pathway – Integrated SEE region – fixed generation and TIMES PanEU results in HighRES pathway (in GWh)

Fuel \ Country	Bulgaria		Croatia		Hungary		Romania		Slovenia	
	TIMES	PLEXOS	TIMES	PLEXOS	TIMES	PLEXOS	TIMES	PLEXOS	TIMES	PLEXOS
Coal	1.465	1.465	1.177	3.253	78	108	3.733	3.733	498	771
Lignite	19.017	18.993	1	0	13.382	14.081	7.091	7.384	1.279	1.280
Oil	218	218	22	22	236	241	641	1.149	0	0
Natural gas	1.936	1.936	3.482	3.482	12.281	12.281	12.525	12.521	2.657	2.657
Nuclear	6.987	6.929	0	0	22.391	20.845	10.705	9.110	5.623	5.487
Waste	329	329	2	2	530	530	770	770	59	59
Biomass	552	552	2.556	2.557	2.542	2.542	4.117	4.115	912	912
Biogas	7.680	7.680	299	298	263	263	849	849	187	187
Hydro	8.590	8.477	10.137	10.149	383	383	24.868	24.887	8.995	8.994
Wind	2.066	2.067	5.189	5.192	604	604	16.627	16.640	723	722
Solar	1.383	1.385	464	464	1.022	1.021	1.946	1.946	169	169
Geothermal	0	0	129	129	989	989	349	348	41	42
Batteries	1	0	1	0	1	0	1	0	1	0
Total	**50.224**	**50.031**	**23.459**	**25.548**	**54.702**	**53.888**	**84.222**	**83.452**	**21.144**	**21.280**

PLEXOS modelling results in this scenario show similarities with scenario Base pathway – Integrated SEE region – fixed generation. Electricity generation capacities, based on TIMES PanEU HighRES pathway, can meet projected electricity demand on an hourly level, but there are some differences in generation according to different fuel types between TIMES PanEU results and PLEXOS results. While most of the technologies generate nearly equal or more electricity according to PLEXOS results, in some cases, yearly electricity generation is lower compared to TIMES PanEU results. Lignite in Bulgaria or nuclear generation can be given as examples. As explained in section 3.1.1 for Base pathway results, thermal generation units in PLEXOS are modelled with detailed parameters on an hourly level. Therefore, it is not always possible to produce the same amount of electricity resulted in TIMES PanEU and the rest of the electricity demand is either covered by the production from other technologies or import.

As explained in section 3.1.1 for Base pathway results, hydro, wind and solar achieve the same yearly generation in PLEXOS with TIMES PanEU as the same assumptions on yearly capacity factor are used in both models.

According to PLEXOS results, total electricity generation is lower in Bulgaria, Hungary and Romania, and higher in Croatia and Slovenia, compared to TIMES results. If entire region is considered, total electricity generation according to PLEXOS results (234.198 GWh) is higher in comparison to TIMES PanEU results (233.751 GWh). Higher generation in PLEXOS is mostly based on higher production of thermal power plants on fossil fuels compared to TIMES PanEU. Generation from these power plants in TIMES PanEU High RES pathway is restricted by CO_2 emission reduction targets and also with high renewable share target in the final energy consumption. In PLEXOS there are no constrains on the amount of CO_2 emissions which affects higher generation from thermal power plants with higher CO_2 emission factors.

HighRES pathway – Integrated SEE region – generation optimization

In scenario HighRES pathway – Integrated SEE region – generation optimization, constraints are not implemented on yearly electricity generation according to TIMES PanEU results by fuel/technology, i.e. electricity generation is completely optimized in PLEXOS. Electricity generation results in 2030 from PLEXOS for this scenario and TIMES PanEU HighRES pathway are shown in Table 10.

Table 10: Electricity generation according to PLEXOS results in scenario HighRES pathway – Integrated SEE region – generation optimization and TIMES PanEU results in HighRES pathway (in GWh)

Country / Fuel	Bulgaria		Croatia		Hungary		Romania		Slovenia	
	TIMES	PLEXOS	TIMES	PLEXOS	TIMES	PLEXOS	TIMES	PLEXOS	TIMES	PLEXOS
Coal	1.465	3.311	1.177	4.897	78	126	3.733	4.757	498	795
Lignite	19.017	17.182	1	0	13.382	14.320	7.091	16.598	1.279	1.281
Oil	218	88	22	0	236	237	641	1.145	0	0
Natural gas	1.936	1.573	3.482	3.062	12.281	10.309	12.525	8.428	2.657	840
Nuclear	6.987	6.929	0	0	22.391	20.890	10.705	9.110	5.623	5.487
Waste	329	522	2	0	530	1.101	770	443	59	19
Biomass	552	221	2.556	2.708	2.542	1.961	4.117	1.779	912	336
Biogas	7.680	7.937	299	6	263	85	849	1.046	187	56
Hydro	8.590	8.449	10.137	10.152	383	383	24.868	24.893	8.995	8.995
Wind	2.066	2.067	5.189	5.192	604	604	16.627	16.640	723	722
Solar	1.383	1.385	464	464	1.022	1.021	1.946	1.946	169	169
Geothermal	0	0	129	129	989	989	349	348	41	42
Batteries	1	0	1	0	1	0	1	0	1	0
Total	**50.224**	**49.665**	**23.459**	**26.610**	**54.702**	**52.025**	**84.222**	**87.133**	**21.144**	**18.741**

PLEXOS modelling results in this scenario show similarities regarding electricity generation with the scenario Base pathway – Integrated SEE region – generation optimization. If electricity generation is optimized in PLEXOS without yearly generation constraints based on TIMES PanEU results, PLEXOS results show certain differences compared to TIMES PanEU results. Electricity generation from natural gas according to PLEXOS results is lower in all the countries. Since in this scenario there are no constraints on yearly electricity generation according to TIMES PanEU, PLEXOS to optimizes generation only according to marginal costs of generation. Due to lower marginal costs of generation, coal-fired and lignite generation units have higher yearly capacity factors compared to natural gas units according to PLEXOS results. Also, due to targets on the high share of renewables in the whole energy system in High RES pathway according to TIMES PanEU, which are not considered in PLEXOS, electricity generation from RES is higher in TIMES PanEU compared to PLEXOS.

Electricity generation is lower in Bulgaria, Hungary and Slovenia compared to TIMES PanEU results, and higher in Croatia and Romania. If entire region is considered, total electricity generation according to PLEXOS results (234.173 GWh) is higher in comparison to TIMES PanEU results (233.751 GWh). Higher generation in PLEXOS is mostly affected by higher generation in Croatia and Romania which produce more electricity from coal and lignite, compared to TIMES PanEU, which is in line with results in scenario Base pathway - Integrated SEE region – generation optimization.

HighRES pathway – Isolated SEE region

The aim of this scenario is the same with Base pathway – Isolated SEE region, to simulate optimal dispatch of power plants in SEE region without electricity exchange with other regions outside SEE region. According to the TIMES PanEU results for HighRES pathway, SEE region is a yearly net exporter of electricity. Since there is no cross-border electricity exchange in countries outside SEE region and electricity is needed only to cover domestic electricity demand in SEE region, in this scenario power plants in SEE region produce lower amount of electricity compared to TIMES PanEU results in 2030. Electricity generation results from PLEXOS for this scenario and TIMES PanEU HighRES pathway are shown in Table 11.

Table 11: Electricity generation according to PLEXOS results in scenario HighRES pathway – Isolated SEE region and TIMES PanEU results in HighRES pathway (in GWh)

Country / Fuel	Bulgaria		Croatia		Hungary		Romania		Slovenia	
	TIMES	PLEXOS	TIMES	PLEXOS	TIMES	PLEXOS	TIMES	PLEXOS	TIMES	PLEXOS
Coal	1.465	1.899	1.177	4.297	78	117	3.733	3.728	498	768
Lignite	19.017	9.629	1	0	13.382	13.628	7.091	14.487	1.279	1.249
Oil	218	88	22	0	236	238	641	1.145	0	0
Natural gas	1.936	1.462	3.482	3.021	12.281	10.755	12.525	8.377	2.657	829
Nuclear	6.987	6.905	0	0	22.391	20.887	10.705	9.110	5.623	5.487
Waste	329	390	2	0	530	950	770	431	59	19
Biomass	552	220	2.556	1.555	2.542	1.663	4.117	1.766	912	336
Biogas	7.680	7.937	299	6	263	85	849	1.046	187	56
Hydro	8.590	8.621	10.137	10.161	383	383	24.868	24.922	8.995	8.996
Wind	2.066	2.067	5.189	5.192	604	604	16.627	16.640	723	722
Solar	1.383	1.385	464	464	1.022	1.021	1.946	1.946	169	169
Geothermal	0	0	129	129	989	989	349	348	41	42
Batteries	1	0	1	0	1	0	1	0	1	0
Total	**50.224**	**40.605**	**23.459**	**24.826**	**54.702**	**51.319**	**84.222**	**83.944**	**21.144**	**18.673**

Certain differences compared to TIMES PanEU results for some fuels/technologies are also observed in this scenario. Electricity generation from natural gas according to PLEXOS results in the entire SEE region is lower compared to TIMES PanEU results. As described in case of other HighRES scenarios, in TIMES PanEU in HighRES pathway targets are set to meet certain share of generation from renewables, which is not the case with PLEXOS. This explains for example higher generation from biomass according to TIMES PanEU results.

Total electricity generation in SEE region according to PLEXOS results amounts 219.367 GWh and 233.751 GWh according to TIMES PanEU results. In this scenario, according to PLEXOS results electricity generation is lower in Bulgaria, Hungary, Romania and Slovenia, and higher in Croatia compared to TIMES PanEU results. The greatest difference in generation is in Bulgaria. In TIMES PanEU results for HighRES pathway, Bulgaria exports more than

14 TWh of electricity outside SEE region (see Figure A.2). Since in scenario HighRES pathway – Isolated region there is no exchange with external markets, total electricity generation in Bulgaria is lower. In general, in this scenario generation from thermal power plants on fossil fuels is lower compared to TIMES PanEU results.

3.2.2 Cross-border exchange

Table 12 shows cross-border electricity exchange between countries of SEE region in scenario with isolated region and between countries of SEE region, including cross-border electricity exchange with neighbouring countries (external markets) outside of SEE region in scenarios with integrated SEE region.

Table 12: Cross-border electricity exchange according to PLEXOS results in different scenarios based on HighRES pathway

Border	HighRES pathway – Integrated region – fixed optimization		HighRES pathway – Integrated region – generation optimization		HighRES pathway – Isolated SEE region	
	Flow (GWh)	Flow back (GWh)	Flow (GWh)	Flow back (GWh)	Flow (GWh)	Flow back (GWh)
Croatia - Hungary	8.301	3.445	10.217	2.692	8.989	4.158
Croatia - Slovenia	6.975	5.896	5.881	6.412	6.325	6.487
Hungary - Slovenia	4.641	6.806	7.010	5.026	6.995	5.312
Romania - Bulgaria	4.283	3.854	5.777	5.006	2.766	6.922
Romania - Hungary	4.465	4.820	6.519	3.532	8.867	1.364
Bulgaria - External market	14.184	0	14.184	0		
Croatia - External market	0	528	0	528		
Hungary - External market	0	1.415	0	1.415		
Romania - External market	2.811	0	2.809	0		
Slovenia - External market	1	0	1	0		

According to PLEXOS results, cross-border electricity exchange (sum of electricity imports and export) between countries of SEE region is higher compared to TIMES PanEU for HighRES pathway results in all scenarios. As in case with Base pathway scenarios, electricity market model of SEE region in PLEXOS assumes fully integrated market and perfect competition, which facilitate cross-border electricity exchange considering projected NTCs for 2030.

Figures B.13 - B.15 show net electricity exchange according to TIMES PanEU results in HighRES pathway and PLEXOS results in the scenarios based on HighRES pathway.

Both in scenarios HighRES pathway – Integrated SEE region – fixed generation and Base pathway – Integrated SEE region – generation optimization, constraints on net electricity exchange with external markets based on TIMES PanEU results are satisfied, i.e. Slovenia, Bulgaria and Romania export equally or more electricity compared to TIMES PanEU results, and Croatia and Hungary import equal amounts of electricity compared to TIMES PanEU results. That means that net electricity exchange between each country of SEE region and its external market according to TIMES PanEU results is also possible on an hourly level, which is verified based on PLEXOS results.

3.2.3 CO_2 emissions

Amounts of CO_2 emissions from electricity generation in PLEXOS scenarios based on HighRES pathway are shown in this section for each country of SEE region. CO_2 emissions based on PLEXOS modelling results are compared to amount of CO_2 emissions from electricity and heat production in public and industrial power plants according to TIMES PanEU results for HighRES pathway. In TIMES PanEU model there is CO_2 emission limitation for the entire EU and in PLEXOS model only the CO_2 emission price is used as input, without specific limitation to total amount of CO_2 emissions in SEE region.

Table 13: CO_2 emissions from electricity production in PLEXOS scenarios and in TIMES PanEU HighRES pathway (tonnes)

Scenario	HighRES pathway (TIMES)	HighRES pathway – Integrated SEE region – fixed generation (PLEXOS)	HighRES – Integrated SEE region – generation optimization (PLEXOS)	HighRES pathway – Isolated SEE region (PLEXOS)
CO_2 emissions in SEE region	66.259.208	67.721.660	77.605.312	62.040.774

Due to higher total electricity generation from thermal power plants on fossil fuels in scenario HighRES pathway – Integrated SEE region – fixed generation compared to TIMES PanEU results, total CO_2 emissions in SEE region are higher in this scenario. In scenario HighRES pathway – Integrated SEE region – generation optimization electricity generation from thermal power plants on fossil fuels is higher than in scenario HighRES pathway – Integrated SEE region – fixed generation, which causes significantly higher CO_2 emissions compared to TIMES PanEU results and results for HighRES pathway – Integrated SEE region – fixed generation. In scenario HighRES pathway – Isolated SEE region total CO_2 emissions are lower compared to TIMES PanEU results due to lower electricity generation in SEE region in this scenario, especially from thermal power plants, such as lignite power plants in Bulgaria (explained in section 3.2.1).

In Figures 7-9 CO_2 emissions in each country are shown for all PLEXOS scenarios based on HighRES pathway and TIMES PanEU HighRES pathway.

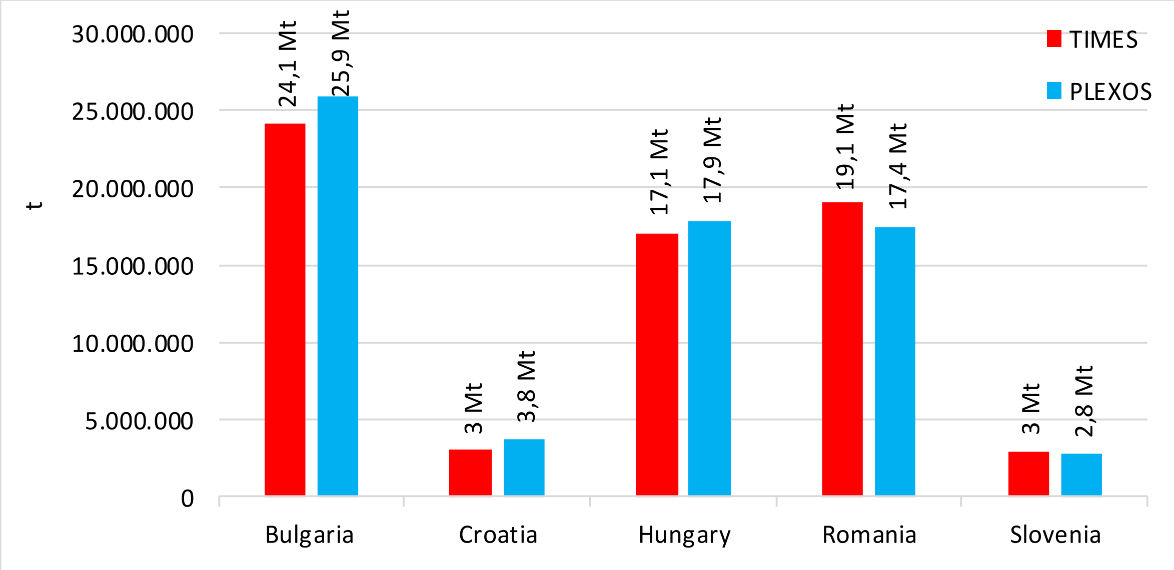

Figure 7: CO_2 emissions from electricity generation in scenario HighRES pathway – Integrated SEE region – fixed generation according to PLEXOS results and in HighRES pathway according to TIMES PanEU results

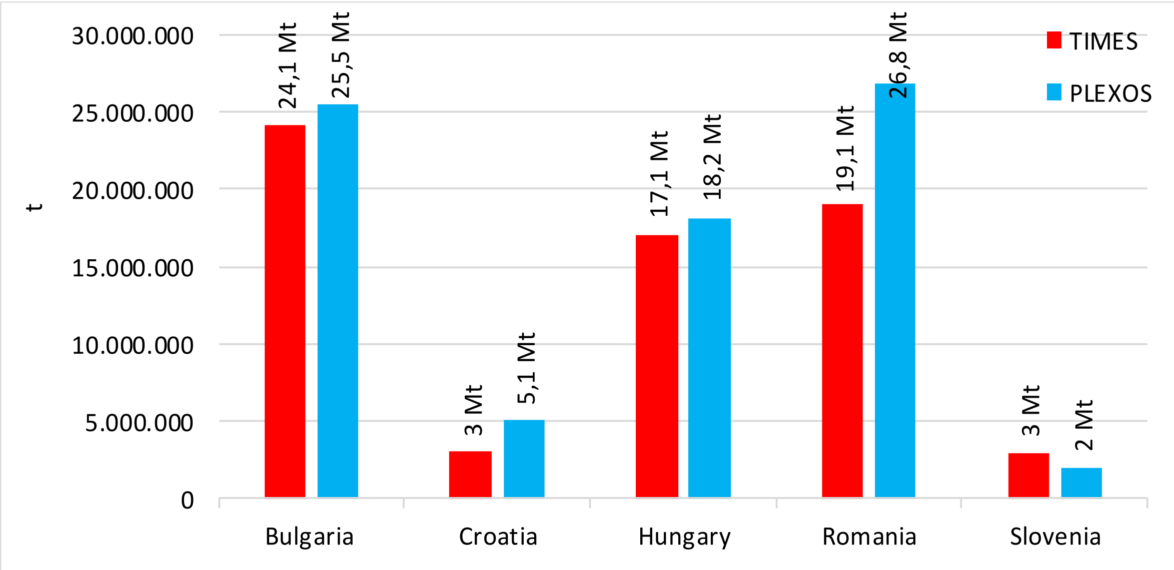

Figure 8: CO_2 emissions from electricity generation in scenario HighRES pathway – Integrated SEE region – generation optimization according to PLEXOS results and in HighRES pathway according to TIMES PanEU results

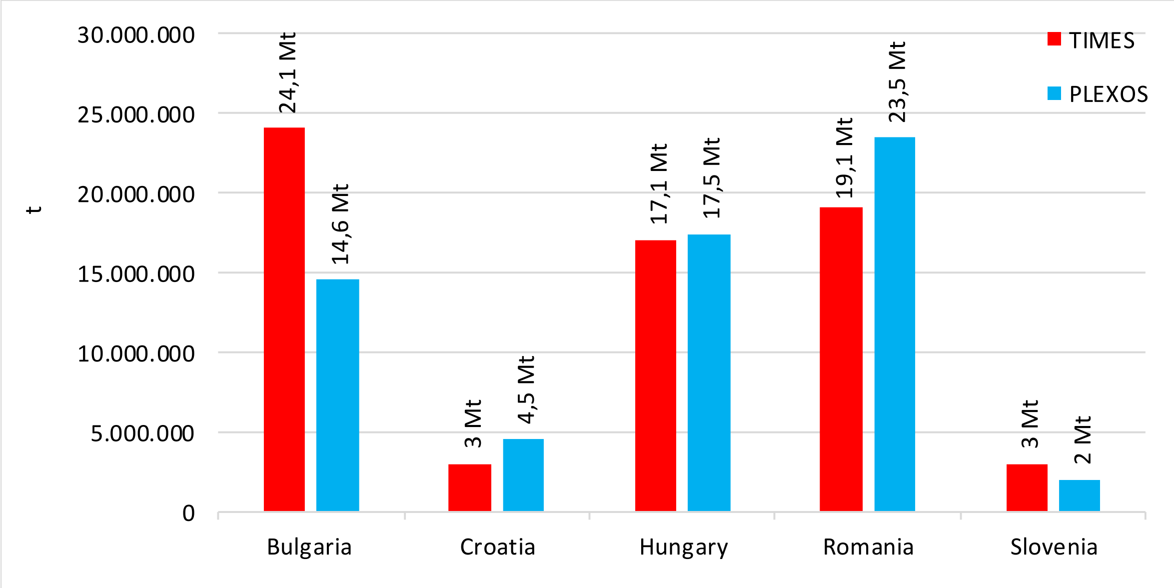

Figure 9: CO_2 emissions from electricity generation in scenario HighRES pathway – Isolated SEE region according to PLEXOS results and in HighRES pathway according to TIMES PanEU results

3.2.4 Electricity market prices

As described in section 3.1.4, due to different definitions, electricity market prices from TIMES PanEU and PLEXOS are not comparable. Market prices from PLEXOS results for three scenarios based on HighRES pathway are shown in Figure 10.

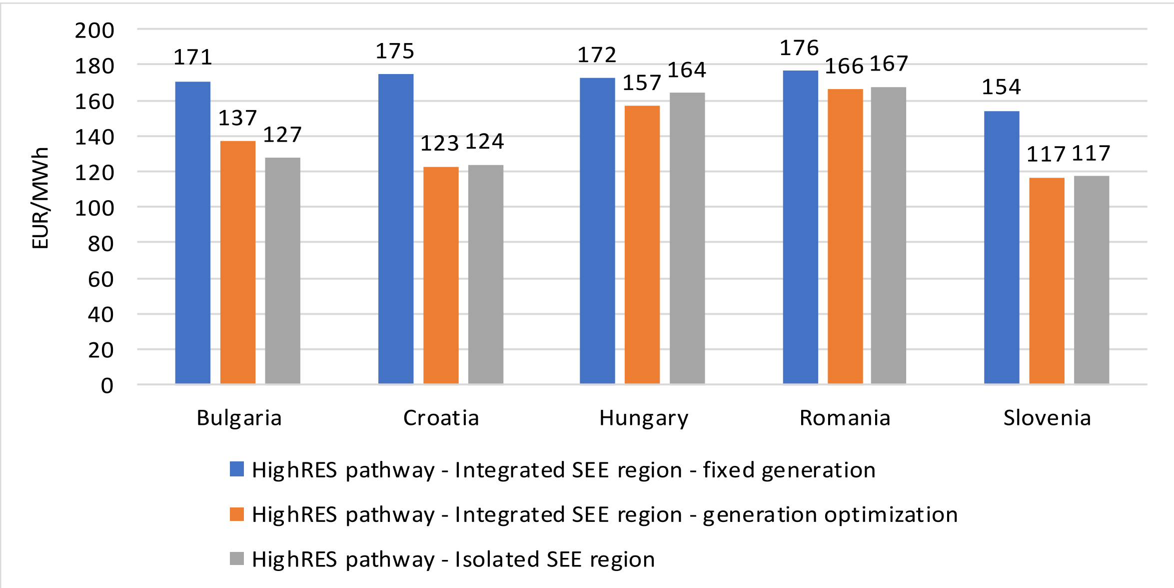

Figure 10: Electricity market prices in SEE region based on PLEXOS modelling results in scenarios based on HighRES pathway

Market prices in all countries are the highest in scenario HighRES pathway – Integrated SEE region – fixed generation, similar to Base pathway results.

3.2.5 Electricity balance

Electricity balances, i.e. yearly load, generation and exchange values (import and export) for each of the modelled SEE countries in three scenarios based on HighRES pathway are given in Tables 14-16 (and Figures B.16 - B.18 in Appendix B).

Table 14: Electricity balance according to PLEXOS results in scenario HighRES pathway – Integrated SEE region – fixed generation

Category	Bulgaria	Croatia	Hungary	Romania	Slovenia	TOTAL
Load (GWh)	36.276	20.142	61.969	80.566	20.192	**219.145**
Generation (GWh)	50.031	25.548	53.888	83.452	21.280	**234.198**
Import (GWh)	4.283	9.869	20.986	8.673	11.615	**55.427**
Export (GWh)	18.038	15.275	12.905	11.559	12.703	**70.480**
Net interchange (GWh)	13.755	5.406	-8.081	2.886	1.088	**15.053**

Table 15: Electricity balance according to PLEXOS results in scenario HighRES pathway – Integrated SEE region – generation optimization

Category	Bulgaria	Croatia	Hungary	Romania	Slovenia	TOTAL
Load (GWh)	36.253	20.143	61.969	80.566	20.192	**219.124**
Generation (GWh)	49.665	26.610	52.025	87.133	18.741	**234.173**
Import (GWh)	5.777	9.632	23.178	8.538	12.891	**60.015**
Export (GWh)	19.190	16.098	13.233	15.105	11.439	**75.066**
Net interchange (GWh)	13.413	6.466	-9.944	6.567	-1.451	**15.051**

Table 16: Electricity balance according to PLEXOS results in scenario HighRES pathway – Isolated SEE region

Category	Bulgaria	Croatia	Hungary	Romania	Slovenia	TOTAL
Load (GWh)	36.449	20.157	61.969	80.598	20.195	**219.367**
Generation (GWh)	40.605	24.826	51.318	83.944	18.674	**219.367**
Import (GWh)	2.766	10.644	23.168	8.286	13.320	**58.184**
Export (GWh)	6.922	15.314	12.518	11.633	11.798	**58.184**
Net interchange (GWh)	4.156	4.669	-10.651	3.347	-1.522	**0**

Total electricity generation, load and net interchange are slightly higher in scenario HighRES pathway – Integrated SEE region – fixed generation, compared to scenario Base pathway – Integrated SEE region – generation optimization. In scenario with isolated region total sum of net interchange is zero since this scenario does not take into account the external markets.

In scenario HighRES pathway – Integrated SEE region – fixed generation Bulgaria, Croatia, Romania and Slovenia are net exporters of electricity and Hungary is a net importer. This is in line with TIMES PanEU results for HighRES pathway. In scenarios HighRES pathway – Integrated SEE region – generation optimization and HighRES pathway – Isolated region Bulgaria, Croatia and Romania are net exporters of electricity, while Hungary and Slovenia are net importers. These results are showing correlation with results for electricity balance in Base pathway scenarios (section 3.1.5). Generation based on PLEXOS optimization in HighRES scenarios, without setting constraints on generation according to TIMES PanEU results, also affects electricity exchange, both in amount and direction.

Even though HighRES pathway represents a greater challenge for SEE region compared to Base pathway in terms of grid and dispatch, due to lower total installed generation capacities, higher share of renewables and higher electricity demand, PLEXOS electricity balance results confirm the feasibility of TIMES PanEU yearly balance results on an hourly level, considering all implemented constraints regarding generation and transmission capacities.

4 Conclusions

Power systems in five countries in SEE region are modelled in detail in PLEXOS and TIMES PanEU results for Base pathway and HighRES pathway are verified for one year (2030). Three scenarios are developed under each pathway according to different constraints on electricity generation and exchange. In total, 6 scenarios are analysed. Installed capacities for electricity generation, electricity demand, exchange capacities, fuel and CO_2 emission prices, and variable operation and maintenance costs are given as input data to PLEXOS either from TIMES PanEU results or input data. In HighRES pathway in SEE region in 2030, share of renewable energy sources in total installed capacity for electricity generation is slightly higher compared to Base pathway (54% in HighRES pathway compared to 51% in Base pathway), while total installed capacity for electricity generation is lower. Electricity demand in SEE region is higher in HighRES pathway compared to Base pathway. In terms of case study's scope, HighRES pathway represents a greater challenge for grid and dispatch analysis compared to Base pathway.

When PLEXOS results in scenarios based on Base pathway are compared to results in scenarios based on HighRES pathway, there are no significant differences, i.e. results in scenarios based on both pathways lead to same conclusions regarding grid and power dispatch in SEE region in 2030. Thus, the main messages resulting from scenario analysis are aggregated both for Base and HighRES pathway and described hereinafter.

Power systems in SEE region in 2030 can be dispatched on the hourly level, i.e. projected generation capacities in SEE based on TIMES PanEU can ensure to cover projected electricity demand and projected cross-border exchange with neighbouring countries. Important issue is also hourly balancing of intermittent renewable energy sources. These points are verified by analysing electricity balance (load, generation, import and export) calculated in PLEXOS on an hourly basis, by modelling scenarios which consider yearly generation results from TIMES PanEU for both Base and HighRES pathway (PLEXOS scenarios named 'Base pathway – Integrated SEE region – fixed generation' and 'HighRES pathway – Integrated SEE region – fixed generation').

Short-term optimization of power system with objective to minimize total operational costs **results in different generation mix** by fuels/technologies **compared to long-term optimization of entire energy system** with objective to minimize discounted system costs (including investment costs). Following reasons can be considered for the differences:

- Short-term optimization is determined based on hourly electricity demand and marginal costs of generation of available units to meet the hourly demand (and also possibility to import electricity from neighbouring power systems),
- Technologies with lower generation costs have priority in short-term dispatching of power system compared to more 'expensive' units, i.e. in PLEXOS generating units on coal and lignite have preference over gas-fired units.

This is investigated by analysing PLEXOS modelling results for scenarios which allow power system optimization without considering yearly generation results from TIMES PanEU for both Base and HighRES pathway (PLEXOS scenarios named 'Base pathway – Integrated SEE region – generation optimization' and 'HighRES pathway –

Integrated SEE region – generation optimization'). Short-term optimization of power system is additionally examined in scenarios without electricity exchange with other power systems outside SEE region (PLEXOS scenarios named 'Base pathway – Isolated SEE region' and 'HighRES pathway – Isolated SEE region') in order to simulate optimal dispatch of power plants for covering only domestic electricity demand in SEE region. According to TIMES PanEU results, SEE region is a yearly net exporter of electricity, so in these scenarios total electricity generation and generation costs in SEE region are lower compared to 'fixed generation' and 'generation optimization' scenarios. Lower generation and lower fuel consumption result also in lower amount of CO_2 emissions.

In TIMES PanEU, ETS emissions reduction targets are determined at the EU level according to pathway definitions in REEEM [1]. Only GHG emission price which resulted in TIMES PanEU based on this target is used as input data to PLEXOS. Comparison of the CO_2 emissions between TIMES PanEU and PLEXOS scenario results particularly, Base pathway – Integrated SEE region – fixed generation' and 'HighRES pathway – Integrated SEE region – fixed generation', show that **amount of CO_2 emissions estimated by TIMES PanEU for SEE region is also verified in short-term optimization of power systems.** TIMES PanEU gives lower CO_2 emissions compared to PLEXOS results because of the different electricity generation mix resulted from two models and different modelling principle between two models.

CO_2 emissions are also compared between scenarios with 'fixed generation' and 'generation optimization' for both Base and HighRES pathways. In scenarios with 'generation optimization' (PLEXOS scenarios named 'Base pathway – Integrated SEE region – generation optimization' and 'HighRES pathway – Integrated SEE region – generation optimization'), CO_2 emissions are higher compared to Base pathway – Integrated SEE region – fixed generation' and 'HighRES pathway – Integrated SEE region – fixed generation' due to higher electricity generation from thermal power plants on fossil fuels. However, total generation costs and electricity market prices are lower in the generation optimization scenarios. Considering the objective function of PLEXOS without having any limitation on the total CO_2 emission level, these results show that coal and lignite are preferred over natural gas due to the lower marginal generation cost. However, it should be pointed out that different assumptions on fuel and CO_2 emission prices (given as an input data to PLEXOS based on TIMES PanEU) would result in different PLEXOS optimization results.

Aside from the conclusions on grid and dispatch for all analysed PLEXOS scenarios, there are messages that can be extracted regarding feasibility and influence of Base and HighRES pathways on power systems of SEE region. HighRES pathway results in higher electricity generation, but lower resulting wholesale electricity market prices. However, **both pathways are feasible in terms of grid and dispatch on an hourly level, so there are no obstacles for the implementation of either of pathways in SEE region**.

5 References

[1] Avgerinopoulos, Georgios et al, “D1.2 First Integrated Impact Report,” 2018.

[2] Pfenninger, Stefan and Staffell, Iain (2016). Long-term patterns of European PV output using 30 years of validated hourly reanalysis and satellite data. Energy 114, pp. 1251-1265. doi: 10.1016/j.energy.2016.08.060

[3] Staffell, Iain and Pfenninger, Stefan (2016). Using Bias-Corrected Reanalysis to Simulate Current and Future Wind Power Output. Energy 114, pp. 1224-1239. doi: 10.1016/j.energy.2016.08.068

[4] TYNDP 2018 - ENTSO Gas and Electricity joint scenarios for consultation. http://tyndp.entsoe.eu/tyndp2018/

Appendix A

Table A.1: Installed generation capacities in 2030 based on TIMES PanEU results for Base pathway (in MW)

Fuel/technology	Bulgaria	Croatia	Hungary	Romania	Slovenia
Coal	715,8	701,0	15,0	1.242,8	112,2
Lignite	3.675,5	0,2	2.177,0	2.596,5	171,7
Oil	65,1	328,4	199,8	502,0	0,6
Natural gas/non-renewable	1.179,6	1.778,1	7.475,3	5.571,3	750,2
Nuclear	953,0	0,0	2.960,0	1.300,0	696,0
Waste non-renewable + industrial waste heat	78,6	12,9	168,4	161,9	13,1
Biomass solid/waste renewable	146,8	432,2	615,7	768,8	166,7
Biogas/biofuel	1.408,5	47,3	52,3	162,3	36,3
Hydro	3.614,3	4.251,0	93,2	7.672,7	2.506,9
Wind	998,1	2.066,4	316,9	5.877,3	280,9
Solar	1.495,3	501,2	1.100,8	2.096,7	183,6
Geothermal	0,0	24,7	0,6	66,4	0,8
Electricity Storage	1,1	1,0	1,0	1,0	1,0
Sum	**14.331,7**	**10.144,4**	**15.175,9**	**28.019,8**	**4.920,0**

Table A.2: Installed generation capacities in 2030 based on TIMES PanEU results for HighRES pathway (in MW)

Fuel/technology	Bulgaria	Croatia	Hungary	Romania	Slovenia
Coal	711,0	700,8	17,0	800,8	106,9
Lignite	3.675,3	0,1	1.938,5	2.596,4	171,8
Oil	64,6	327,8	161,1	525,6	0,3
Natural gas/non-renewable	1.010,4	1.776,3	6.521,8	4.982,3	513,1
Nuclear	953,0	0,0	2.960,0	1.300,0	696,0
Waste non-renewable + industrial waste heat	77,1	12,6	161,9	176,8	16,0
Biomass solid/waste renewable	118,2	423,9	734,1	799,6	175,4
Biogas/biofuel	1.461,3	47,0	51,1	199,0	35,7
Hydro	3.613,9	4.250,7	92,9	8.239,0	2.508,9
Wind	1.085,2	2.069,3	317,0	6.504,6	280,9
Solar	1.494,2	501,1	1.100,8	2.096,2	183,2
Geothermal	0,0	24,6	188,2	66,3	8,0
Electricity Storage	0,6	0,6	0,6	0,6	0,6
Sum	**14.264,8**	**10.134,8**	**14.245,0**	**28.287,2**	**4.696,8**

Table A.3: Techno-economic parameters considered to analyse generation capacities in PLEXOS

Thermal power plants
General data (plant name, number of units, fuel type)
Maximum net output power per unit
Minimum net output power per unit
Heat rates at maximum net output power per unit
Heat rates at minimum net output power per unit
Variable O&M costs per unit
Outage rates (forced outage rate – FOR, maintenance outage rate - MOR) and maintenance periods per unit
Operational constraints (ramping limits, minimum up/down time) per unit
Must-run constraints per unit
Hydro power plants
General data (plant name, number of units
Plant type (run of river, storage (seasonal, weekly, daily), pump storage plant)
Maximum net output power per unit
Minimum net output power per unit
Reservoir size
Maximum net output power in pumping mode per unit in case of PS power plants
Minimum net output power in pumping mode per unit in case of PS power plants
Average monthly inflows for storage plants
Average monthly generation for run of river plants
Yearly production
Renewable energy sources (wind and solar)
Installed capacities
Hourly capacity factor

Table A.4: Electricity consumption in 2030 based on TIMES PanEU results for Base pathway used as input data to PLEXOS (in GWh)

Consumption category	Bulgaria	Croatia	Hungary	Romania	Slovenia
Agriculture	412	63	847	952	3
Industry	8.251	3.033	13.904	18.480	6.572
Commercial	6.695	4.347	14.567	9.342	2.628
Households	9.046	5.918	10.795	19.513	3.087
Transport	7.003	4.913	17.742	20.302	6.788
Conversion	656	167	786	4.330	24
Line losses	3.542	1.777	4.037	5.534	1.150
Other energy consumption	0	0	9	38	45
Sum	**35.605**	**20.218**	**62.687**	**78.491**	**20.297**

Table A.5: Electricity consumption in 2030 based on TIMES PanEU results for HighRES pathway used as input data to PLEXOS (in GWh)

Consumption category	Bulgaria	Croatia	Hungary	Romania	Slovenia
Agriculture	408	63	835	951	5
Industry	8.381	3.072	13.469	18.698	6.521
Commercial	6.780	4.327	15.907	9.457	2.534
Households	9.103	5.873	10.736	19.621	3.093
Transport	6.994	4.913	15.681	21.520	6.790
Conversion	643	167	722	4.119	28
Line losses	3.901	1.726	4.537	6.055	1.176
Other energy consumption	0	0	82	142	45
Sum	**36.210**	**20.141**	**61.969**	**80.563**	**20.192**

Table A.6: Electricity exchange capacities for countries of SEE region in 2030 based on TIMES PanEU (in MW)

Border	NTC
Romania - Bulgaria	2.180
Bulgaria - Romania	2.180
Croatia - Hungary	2.000
Hungary - Croatia	2.000
Croatia - Slovenia	1.785
Slovenia - Croatia	1.785
Hungary - Slovenia	1.800
Slovenia - Hungary	1.800
Romania - Hungary	2.000
Hungary - Romania	2.000

Table A.7: Fuel prices in 2030 based on TIMES PanEU (in EUR/GJ)

Fuel	Bulgaria	Croatia	Hungary	Romania	Slovenia
Hard coal	3,03	2,91	4,03	3,03	2,91
Lignite	2,29	2,29	2,29	2,29	2,29
Oil	16,53	17,23	16,53	16,53	17,23
Natural gas	9,00	9,00	9,00	9,00	9,00
Nuclear	0,84	0,84	0,84	0,84	0,84
Biogas	1,34	17,89	11,14	18,70	11,89
Municipal waste	7,57	5,21	6,13	8,03	7,51
Wood - biomass	6,00	5,55	5,68	4,88	5,55
Waste (non-renewable)	1,40	5,91	1,34	3,00	5,91

Table A.8: CO_2 emission factors by different fuel types based on TIMES PanEU

Fuel	Emission factor (kg/GJ)
Hard coal	94,0
Lignite	108,8
Oil	78,0
Natural gas	56,0
Waste (non-renewable)	91,5

Table A.9: Variable operation and maintenance costs used in PLEXOS

Fuel/technology	VO&M (EUR/MWh)
Coal	3,3
Lignite	3,3
Oil	3,3
Natural Gas/non renewable	1,6
Nuclear	9,0
Waste non renewable + Industrial Waste Heat	2,6
Biomass solid/Waste renewable	2,6
Biogas / Biofuel	8,9-11,7*
Hydro	5,0
Geothermal	1,1

**Different values for VO&M costs are used in thermal power plants on biogas and combined heat and power plants on biogas based on available data from TIMES PanEU.*

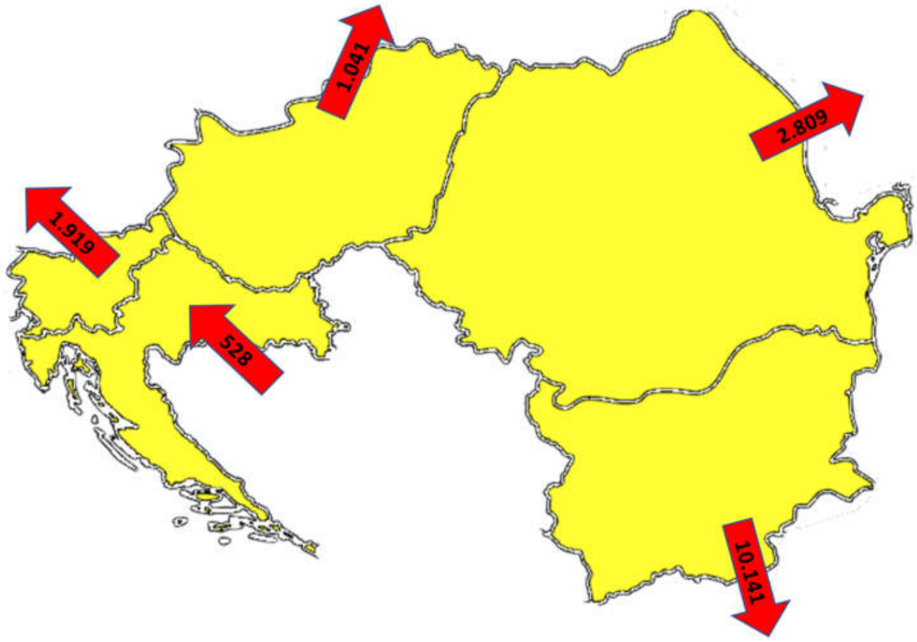

Figure A.1: Cross-border net electricity exchange between countries of SEE region and external markets according to TIMES PanEU results in Base pathway

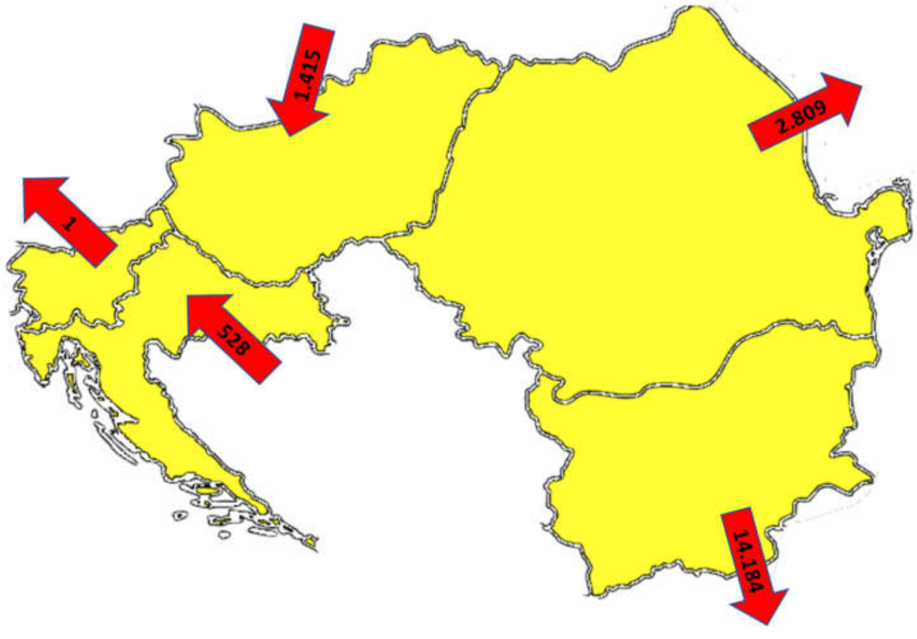

Figure A.2: Cross-border net electricity exchange between countries of SEE region and external markets according to TIMES PanEU results in HighRES pathway

Table A.10: Minimum daily capacity factor in CHP plants in PLEXOS by different months of the year

Month	Capacity factor (%)
January	60
February	50
March	35
April	25
May	10
June	0
July	0
August	0
September	5
October	25
November	40
December	50

Appendix B

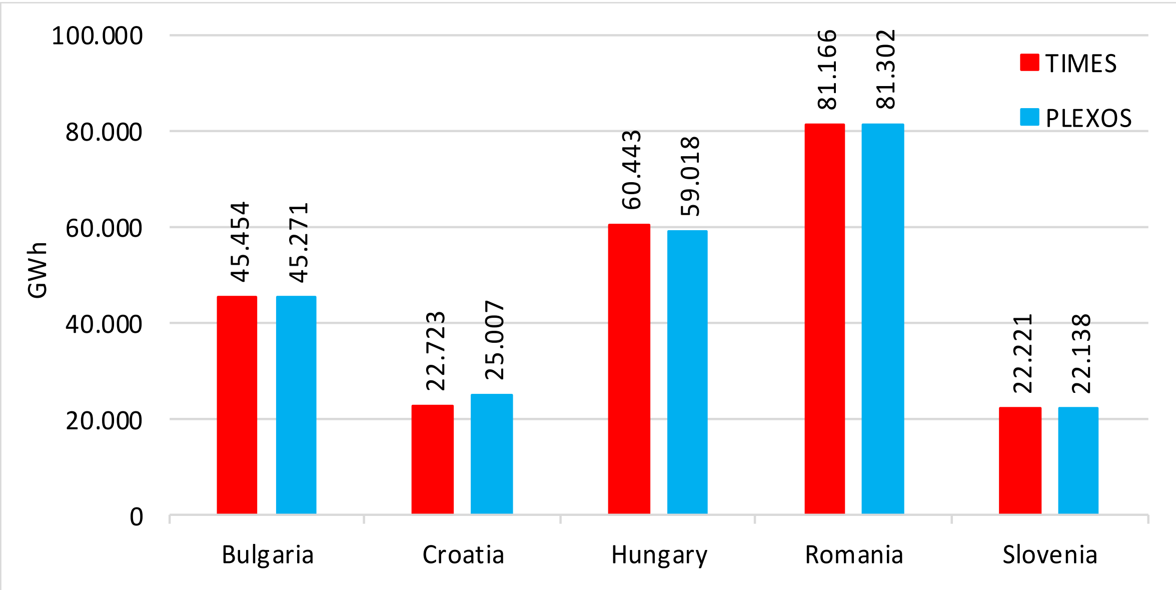

Figure B.1: Electricity generation according to PLEXOS results in scenario Base pathway – Integrated region – fixed generation and TIMES PanEU results in Base pathway

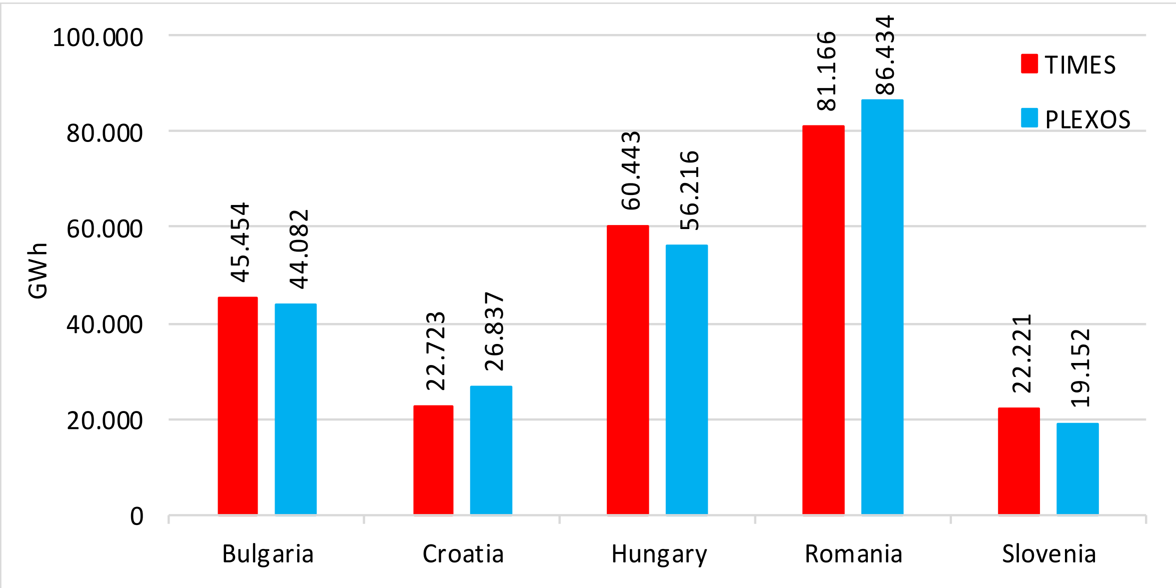

Figure B.2: Electricity generation according to PLEXOS results in scenario Base pathway – Integrated region – generation optimization and TIMES PanEU results in Base pathway

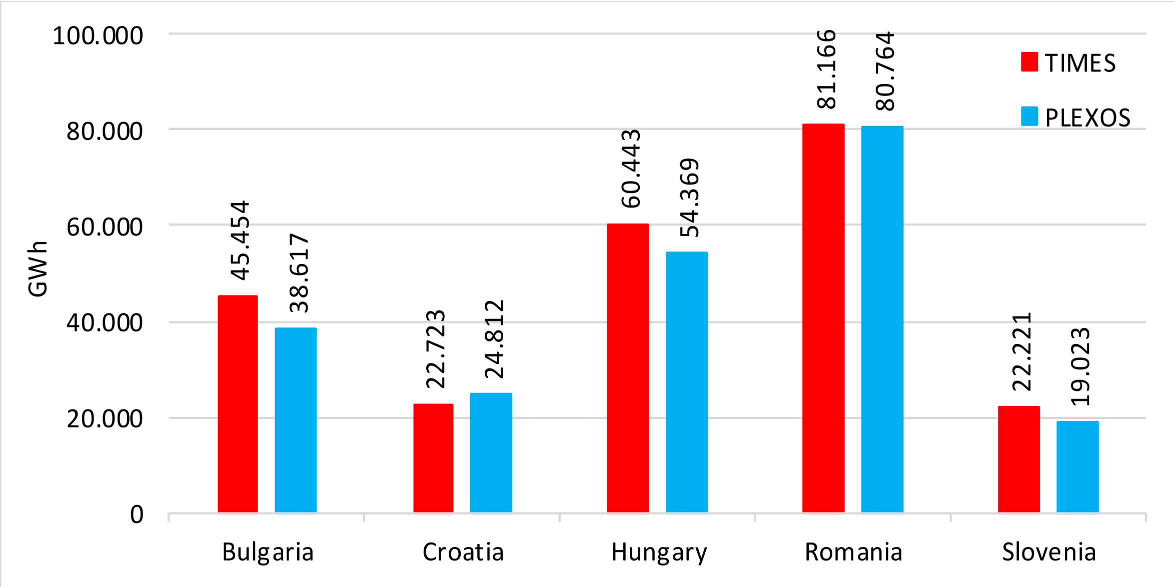

Figure B.3: Electricity generation according to PLEXOS results in scenario Base pathway – Isolated region and TIMES PanEU results in Base pathway

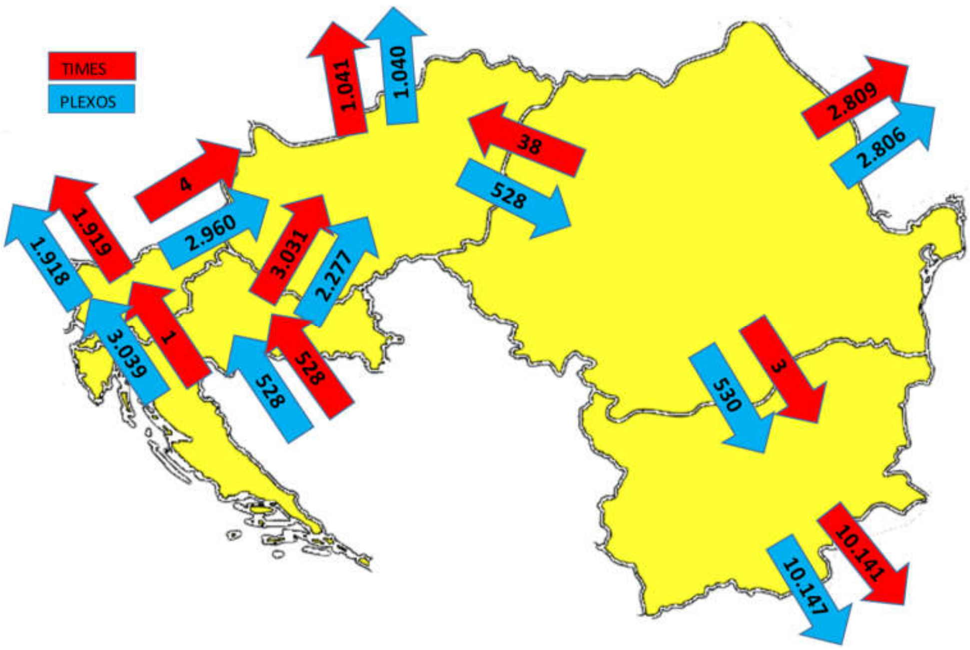

Figure B.4: Net electricity exchange (GWh) according to TIMES PanEU results in Base pathway and PLEXOS results in scenario Base pathway – Integrated SEE region – fixed generation

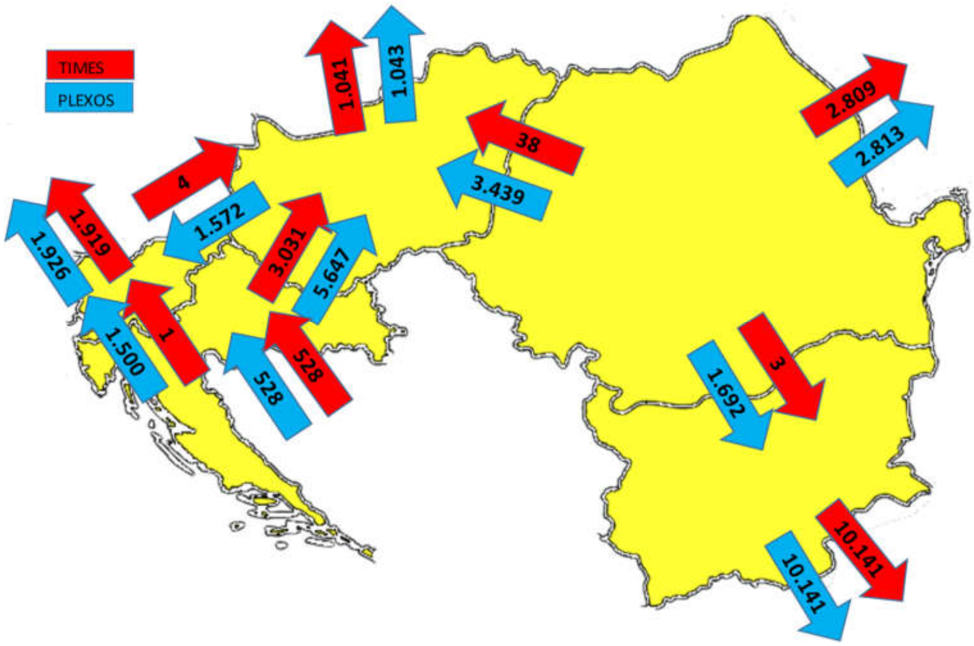

Figure B.5: Net electricity exchange (GWh) according to TIMES PanEU results in Base pathway and PLEXOS results in scenario Base pathway – Integrated SEE region – generation optimization

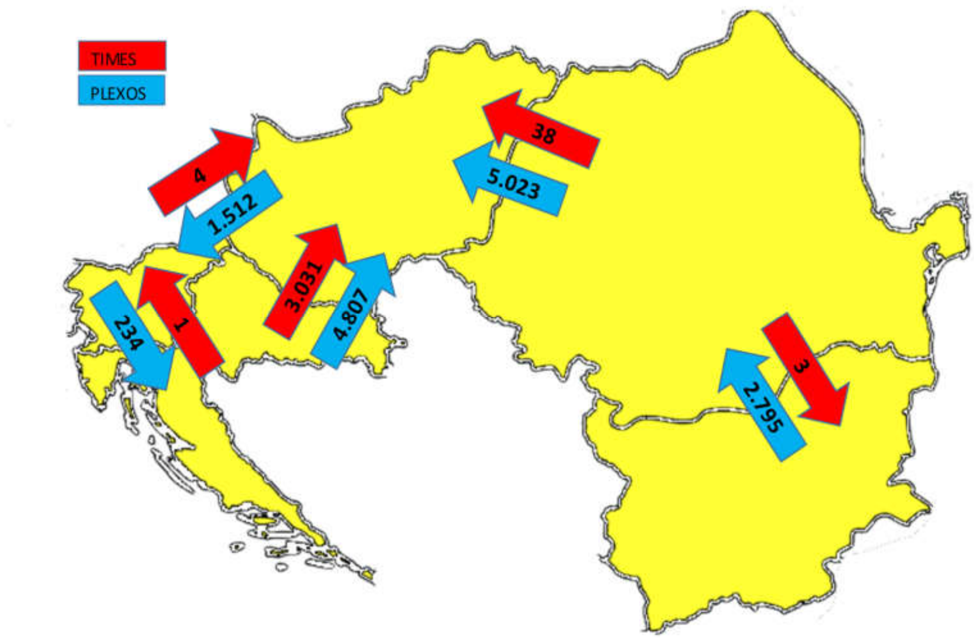

Figure B.6: Net electricity exchange (GWh) according to TIMES PanEU results in Base pathway and PLEXOS results in scenario Base pathway – Isolated SEE region

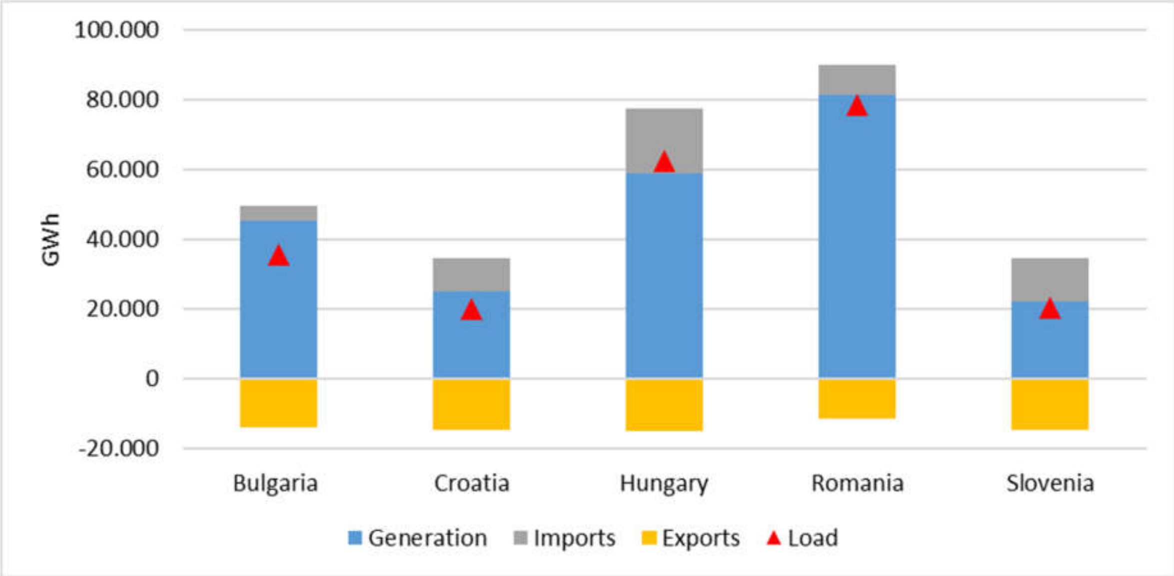

Figure B.7: Electricity balance in SEE region in scenario Base pathway – Integrated SEE region – fixed generation

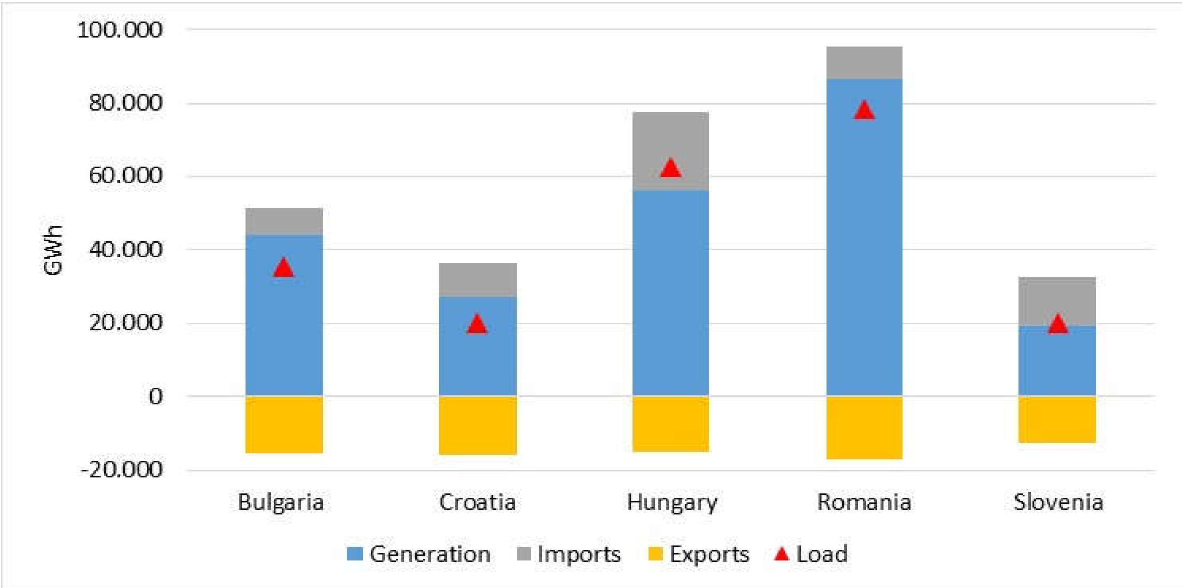

Figure B.8: Electricity balance in SEE region in scenario Base pathway – Integrated SEE region – generation optimization

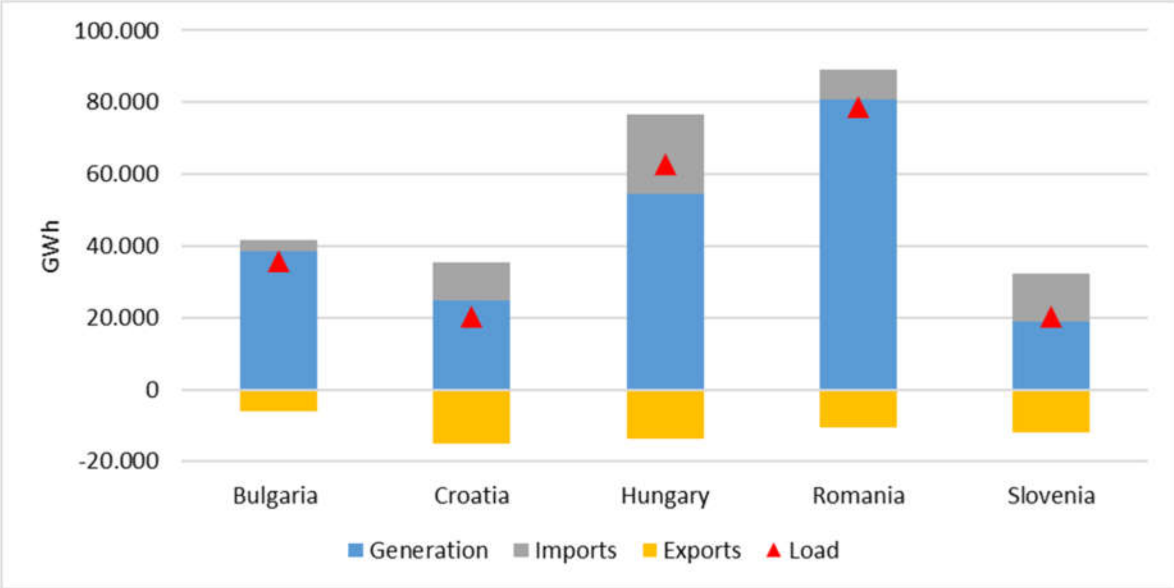

Figure B.9: Electricity balance in SEE region in scenario Base pathway – Isolated SEE region

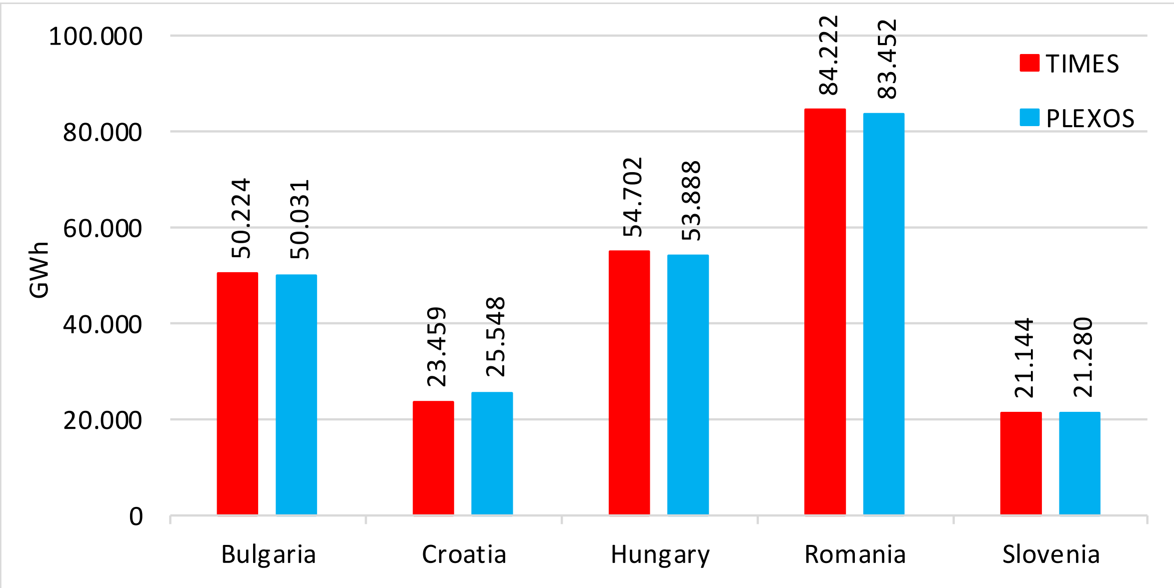

Figure B.10: Electricity generation according to PLEXOS results in scenario HighRES pathway – Integrated region – fixed generation and TIMES PanEU results in HighRES pathway

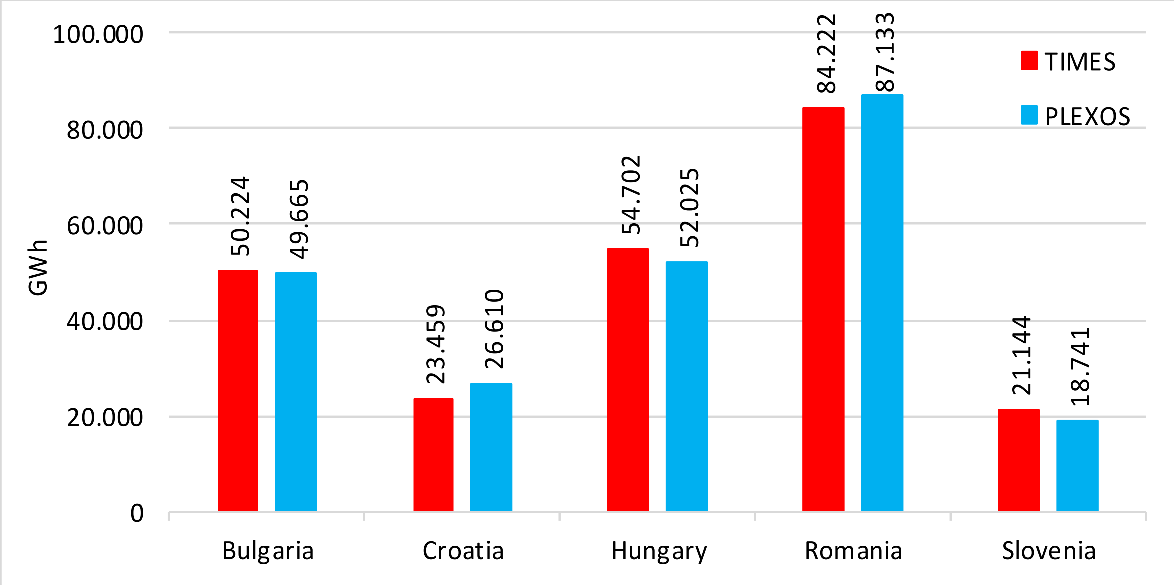

Figure B.11: Electricity generation according to PLEXOS results in scenario HighRES pathway – Integrated region – generation optimization and TIMES PanEU results in HighRES pathway

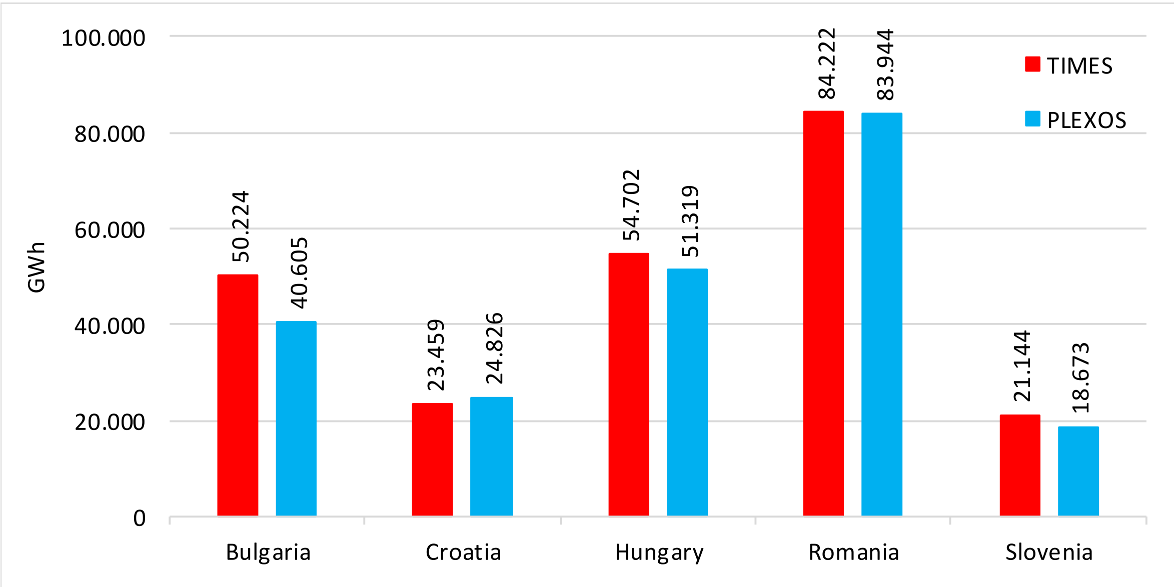

Figure B.12: Electricity generation according to PLEXOS results in scenario HighRES pathway – Isolated region and TIMES PanEU results in HighRES pathway

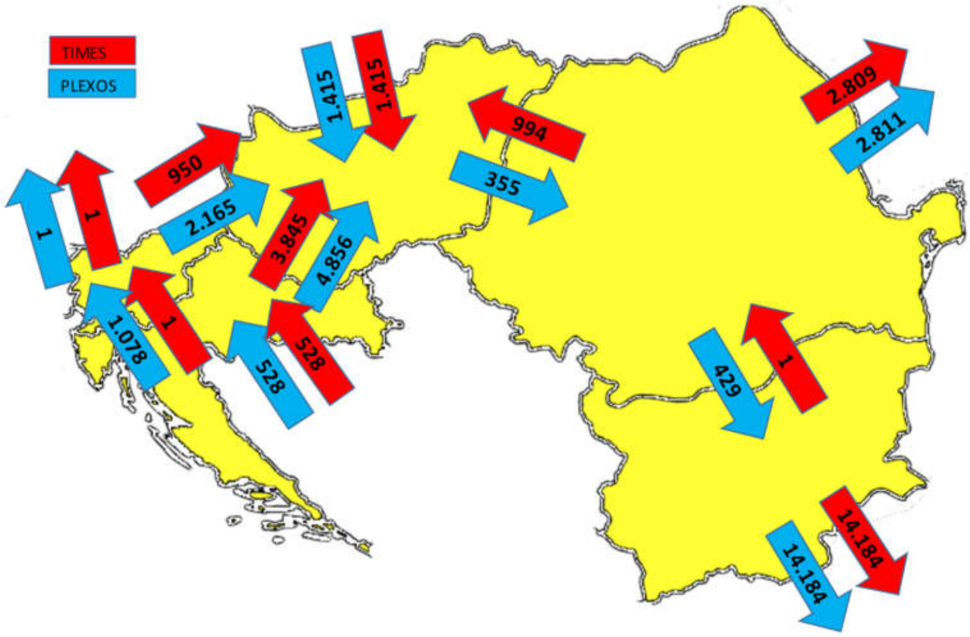

Figure B.13: Net electricity exchange (GWh) according to TIMES PanEU results in HighRES pathway and PLEXOS results in scenario HighRES pathway – Integrated SEE region – fixed generation

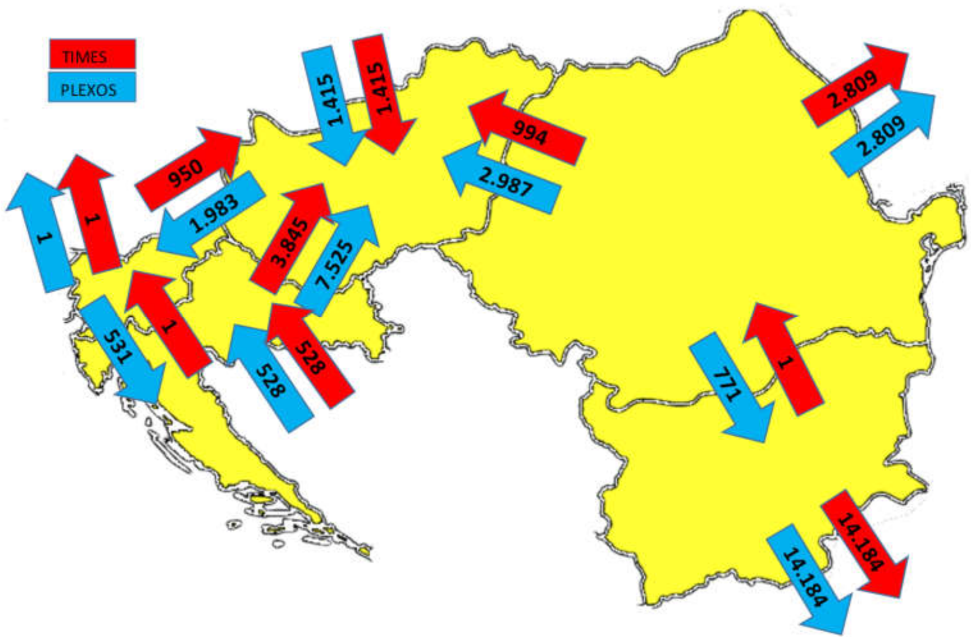

Figure B.14: Net electricity exchange (GWh) according to TIMES PanEU results in HighRES pathway and PLEXOS results in scenario HighRES pathway – Integrated SEE region – generation optimization

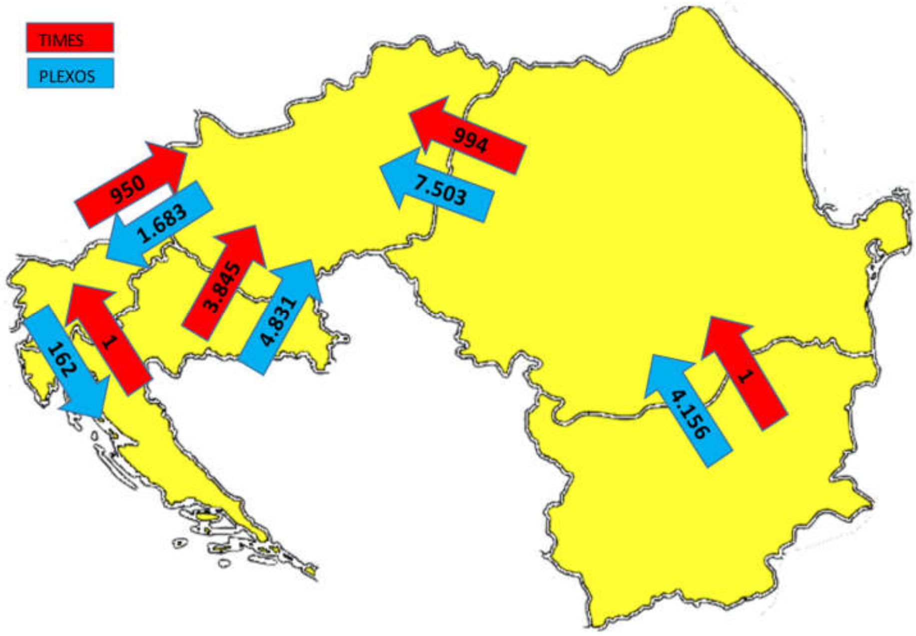

Figure B.15: Net electricity exchange (GWh) according to TIMES PanEU results in HighRES pathway and PLEXOS results in scenario HighRES pathway – Isolated SEE region

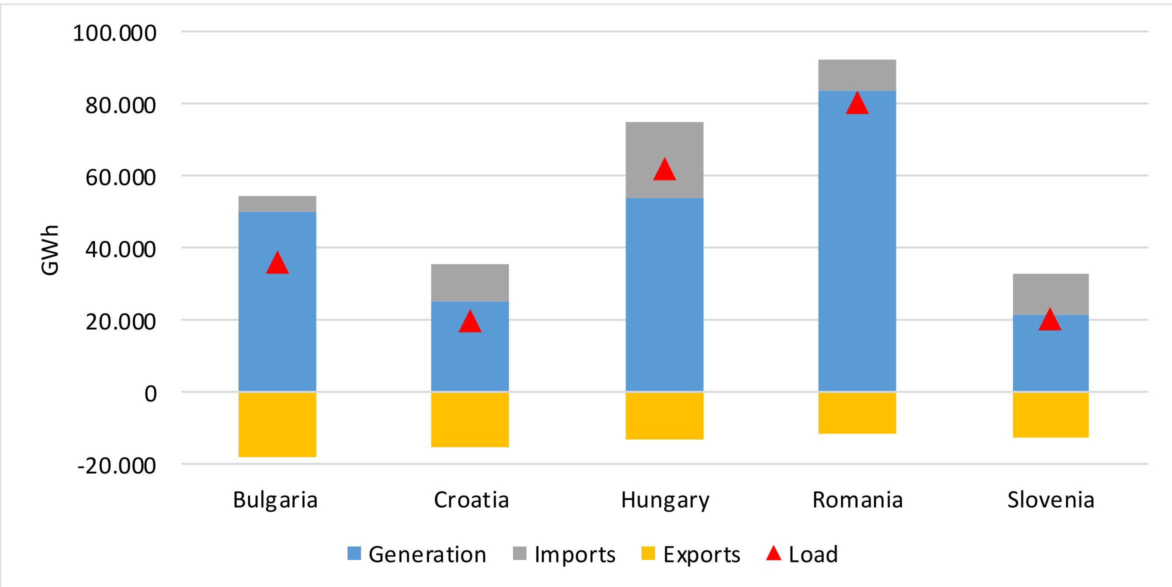

Figure B.16: Electricity balance in SEE region in scenario HighRES pathway – Integrated SEE region – fixed generation

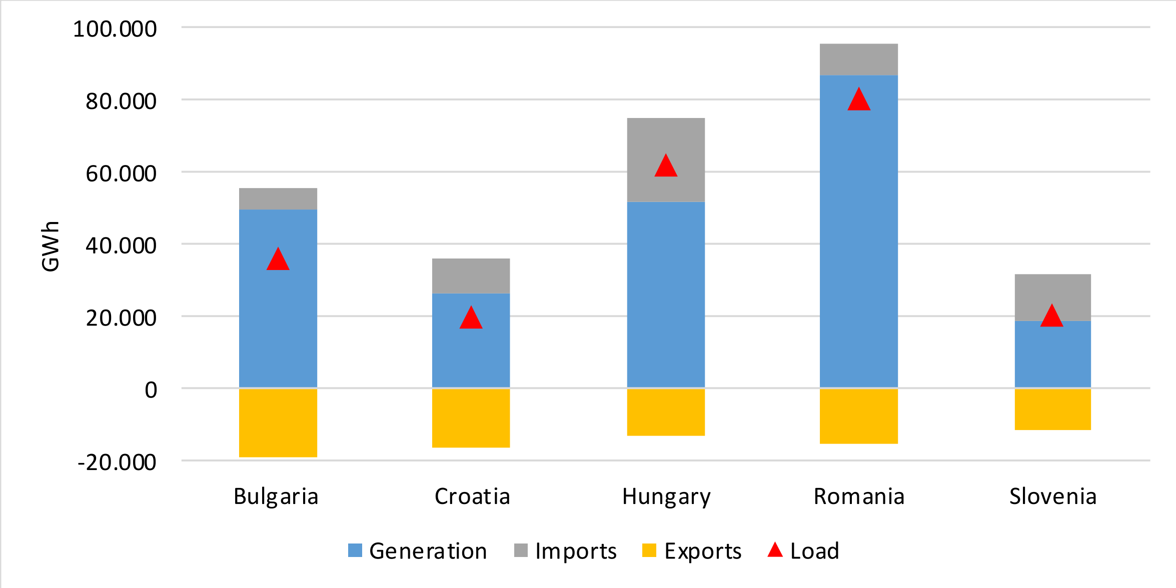

Figure B.17: Electricity balance in SEE region in scenario HighRES pathway – Integrated SEE region – generation optimization

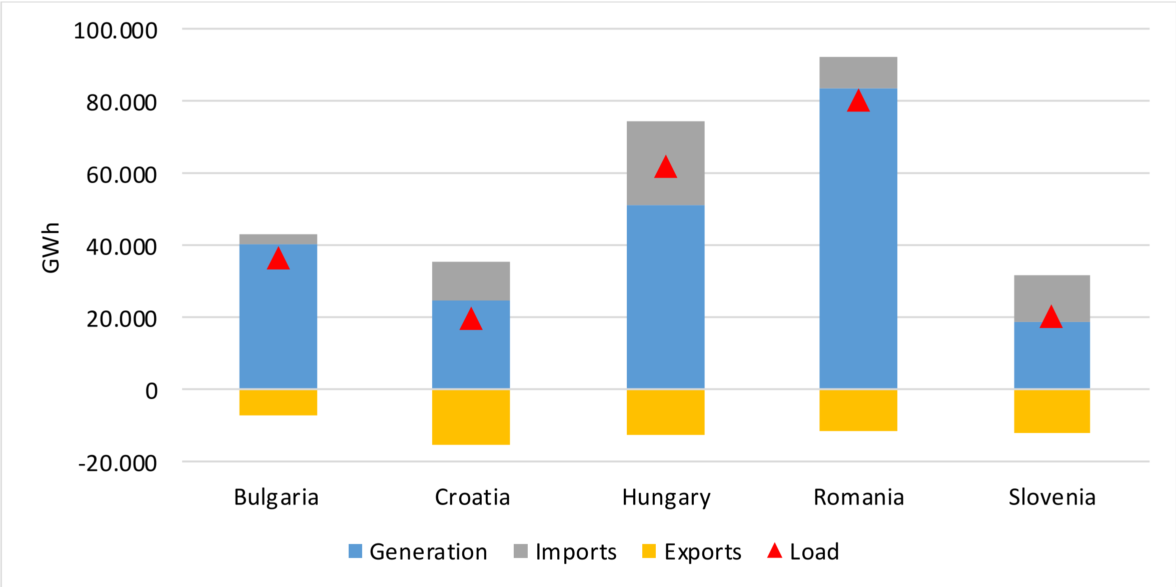

Figure B.18: Electricity balance in SEE region in scenario HighRES pathway – Isolated SEE region