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Coupling of the planning and power system analysis software for high-level penetration of renewable energy sources☆

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ABSTRACT

The ambitious electricity production investments might have a degree of uncertainty if current or planned power grid is not analyzed. Strategic planning of the national energy system using only EnergyPLAN annual simulations could be inaccurate resulting in wrong planning decisions because EnergyPLAN does not take power grid into account. Therefore, there is a need to analyze power grid using power system solver in order to complete evaluation of electricity production investments. To address this need, EnergyPLAN and the power system solver CASE are coupled by upgrading CASE to import output files generated by EnergyPLAN. Once the data is imported, CASE allocates the total electricity production across individual power plants based on predefined distribution coefficients, and distributes total consumption to system nodes proportionally to the existing connected loads. Thus, a power system model for load flow calculation is automatically created and calculations are performed for each hour of the year. The goal of this paper is to present original implementation of the coupling of two software tools in the first place, which has not been realized until now, as well as the presentation of the calculation results in the second place. The presented results were selected for being the most interesting among the numerous hours of the year using simulation model of real power system of Republic of Serbia upgraded with planned large renewable electricity production. The result of the work is the coupling of two software tools with a goal of more accurate power system planning. The coupling provides a way to investigate if various scenarios of planned electricity production could be realized regarding transmission grid load flows.

Introduction

A great number of computer programs, which are used for different power system needs, have been developed by now. Some of them include specific set of functions while the others encompass another functionalities. However, there is no single program that include all of the functionalities. Analyses that are carried out by particular program sometimes need to be extended by analyses that are provided by another program. This is the reason why simulation model or its specific parts, created in one program, should be exchanged with another program. Data exchange between programs can be categorized by: mode of exchange (synchronous, asynchronous, …), format or protocol (JSON/XML, CSV/Excel, binary protocols, …), directionality (unidirectional, bidirectional, and multicast), integration level (loose coupling, tight coupling,…), and security and compliance (encrypted, authenticated, …). In addition, hard-linking between programs is defined as formal links where data are transferred without any user judgement while soft-linking is transfer of data by the user [1].

The review given in [2] provides a comprehensive overview of hybrid energy system integration strategies, emphasizing the role of predictive and real-time control frameworks in solar energy management. The focus of this article is on the architectural and operational aspects of integrated energy management systems. However, the article also implicitly underscores the importance of software interoperability although the discussion remains largely conceptual, with limited attention to the technical challenges of coupling distinct simulation environments.

EnergyPLAN is a software tool for modeling and analyzing energy systems. This tool simulates quantities of interest in national energy systems on an hourly basis for the purposes of calculating the energy balance, greenhouse gas emissions and costs on an annual time frame

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Nomenclature

DC	Direct Current
HPP	Hydro Power Plant
NPP	Nuclear Power Plant
NTC	Net Transfer Capacities
OTDF	Outage Transfer Distribution Factor
PTDF	Power Transfer Distribution Factors
PV	Photovoltaic power plant
RE	Renewable Energy
RES	Renewable Energy Sources
SS	Substation
SSP	Solar Power Plant
TPP	Thermal Power Plant
TSO	Transmission System Operator
UCTE	Union for the Co-ordination of Transmission of Electricity
WPP	Wind Power Plant

[3]. These analyses include energy production and consumption in the electricity, heat, and transport sectors, as well as carbon dioxide emissions. In addition, the analyses include actualized annual costs which take into account investment and operational costs. Moreover, EnergyPLAN provides smart energy systems paradigm which is introduced and elaborated in [4]. This article discusses EnergyPLAN's deterministic simulation approach, compares it with optimization and equilibrium models, and explains why EnergyPLAN avoids endogenous optimization.

SimCES platform was developed to simulate complex energy systems that involve multiple stakeholders, distributed energy resources, and dynamic conditions like weather and energy pricing [5]. The platform uses message-oriented middleware to enable asynchronous communication between simulation components. For power system calculations, such as load flows, SimCES relies on external power grid solvers like DIgSILENT PowerFactory, OpenDSS or MATPOWER. However, interface between SimCES and power grid solvers as well as results of calculation of power grid solvers based on data imported from SimCES have not been presented.

A multi-objective optimization model, EPLANopt, designed to support energy transition planning is presented in [6]. EnergyPLAN. The EPLANopt model is coupled with EnergyPLAN using scripting framework. Actually, EPLANopt is essentially a Python-based script that wraps around EnergyPLAN simulation tool to perform multi-objective optimization. In this paper, the model was applied to Italy's energy system for the year 2030. No power grid analyses are available in EPLANopt model.

Planning of the national energy system by analyzing alternative electricity production investments using annual simulations performed by EnergyPLAN does not include power grid. However, analysis of power grid is necessary to complete evaluation of electricity production investment [7]. Power (load) flow is basic power system calculation which is used to investigate various power system development scenarios [8]. In addition, power flow calculation could be used to analyze transmission grid losses in cases of outages of particular generating units [9]. CASE is used for numerous system calculations such as power flows, short circuits, open-conductor faults, small-signal stability, voltage stability and transient stability. Computations based on the calculation of power flows are also implemented in the program: network reduction, security analyses (N-1 and N-X), Net Transfer Capacities (NTC), Outage Transfer Distribution Factor (OTDF), Power Transfer Distribution Factors (PTDF). The coupling of the CASE and EnergyPLAN programs was implemented using EnergyPLAN output text file that contains the total production of power plants separated by type, the total consumption of the system divided into several subtypes, and export and import from the control area for all hours of the year. CASE loads EnergyPLAN output file and distributes total electricity production to each individual power plant unit in a power system in accordance with predefined distribution coefficients. Additionally, CASE distributes total consumption proportionally to existing power system loads. In this way, CASE automatically creates power system models for load flow calculations for each hour of the year. CASE provides the option to run load flow for all 8784 scenarios or only those specified by the user. Calculation results for each hour are stored in the CASE working memory and can be sorted in several ways, such as by the most loaded element of the system, the largest exchange of the observed control area, losses in the control area, production by a certain type of power plant, consumption, etc. Thus, it is possible to efficiently analyze the operation of the system according to different criteria.

Soft-linking between energy system models is favored over hard-linking [10]. As explained in previous paragraph, soft–linking based on user-controlled file exchange was used to implement the coupling of EnergyPLAN and CASE.

The further achievement of the work is to present power system operation at high penetration of renewable energy sources in the total energy mix of Serbia. Previously, transition to renewable energy sources in Serbia was considered in [11] as well as construction of huge solar power plant [12]. Development and implementation of generating unit connection codes in Germany was analyzed in order to present secondary legislation of the country with high penetration of renewables [13].

The paper presents how calculation results of 8784 cases (each hour during the leap year) are analyzed considering loads of branches, i.e. transformers and lines, control area export and import, and total active power losses. This approach would have significant advantages and provide numerous benefits in power system planning primarily due to the efficiency and speed of calculations. EnergyPLAN model of Serbia has been developed [14] and used to analyze flexibility of consumer as virtual storage [15]. Necessity to extend EnergyPLAN simulation results with power grid analysis was also recognized [16].

The least-cost solution for achieving climate neutrality is only identifiable when electricity, heating, cooling, transport, industry, and materials are modeled together. Affordable and flexible energy storage options are key to minimizing outages and ensuring system reliability [17].

In this article, the first approximation how the increased RE generation in Serbia affects cross-border and internal transmission grid of Serbia is provided.

Multiple node approach in energy planning

Using more than one node in national energy planning and modelling a network of nodes instead of one node is a source of complexity [18] which could lead to beneficial results. Therefore, the mentioned add-on for EnergyPLAN could be used, as well as other multi-node, multi-vector approaches in so called "mosaic of the tools" approach.

The EnergyPLAN multi-node helps capture internal bottlenecks and the spatial smoothing effect for the renewables [19]. By linking two EnergyPLAN models electricity transmission excess electricity could be decreased from 13 % [20] for a single EnergyPLAN node, and up to 28–35 % for multi-node see island system [21], resulting in better utilization and increased system efficiency [22].

Multiple node approach and explicit modeling of network is further observed as beneficial for smoother RE integration in various sectors with focus on conceptual and methodological overview of multi-energy systems [23] and scenario-based analysis of sector coupling in multi-node energy systems [24]. Our approach to increasing ambition for the integration of RES through sector coupling concept [25] is based on power sector. Power sector serves as a backbone for other sectors in the sector coupling concept. This is reason why explicit modeling of power

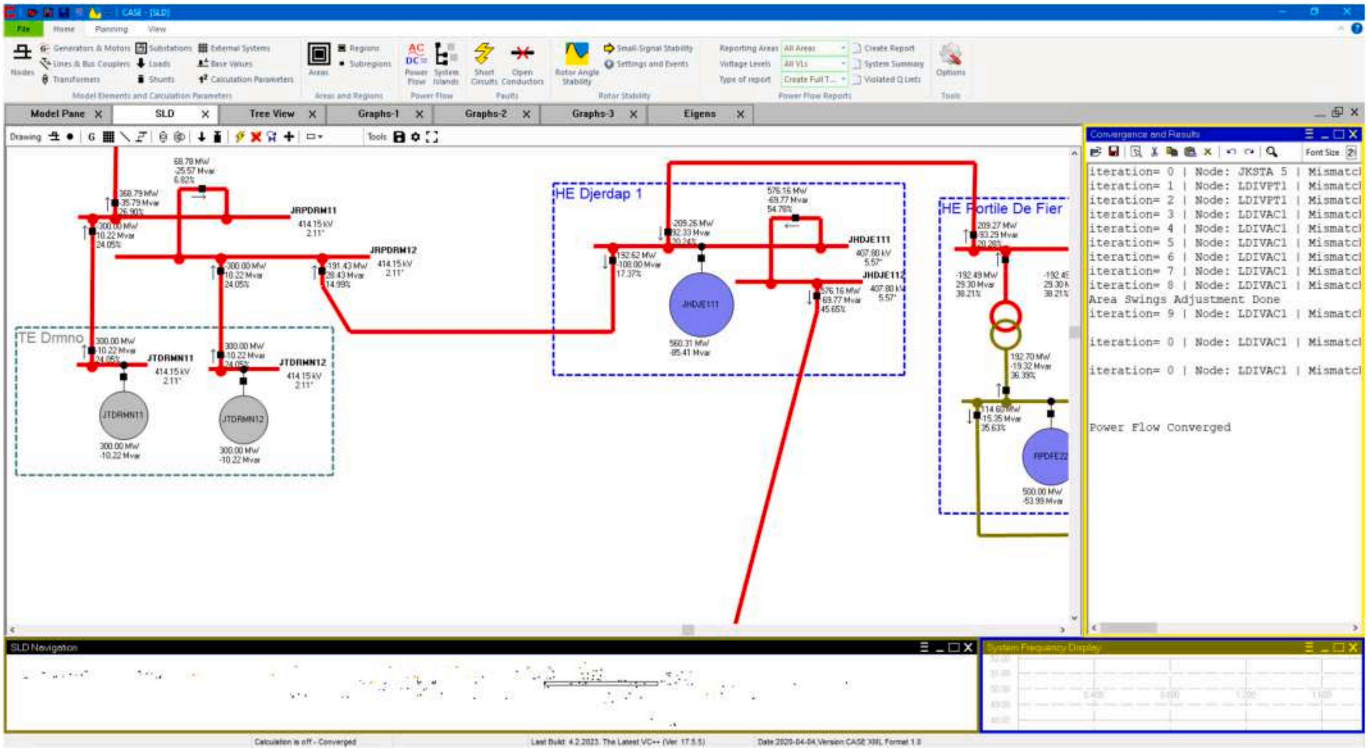

Fig. 1. Layout of the CASE application.

sector is important [26], especially in ambitious, i.e. higher than 40 % shares of RE. At the European scale, mitigating renewable energy bottlenecks will require a substantial expansion of transmission infrastructure – up to 1.8 times the current transmission capacity (TW·km) and up to fourfold for cross-border transmission capacity (TW) [27]. These requirements underscore the importance of detailed power system development within coupled energy systems [28].

Developing a model and hierarchically dividing the problem into spatio-temporal subcomponents, so as to minimize deviations from reality, remains an open challenge in energy planning [29]. A concept for using many simulators integrated into single co-simulation platform for a detailed representation of a smart grid [30] down to, for example, load limits imposed by a certain transformer in power system [31] or a certain branch has been demonstrated in the case study for North Macedonia [32]. Such „mosaic“ concept is applied in our work with particular focus on transmission system, recognizing electricity as the primary energy carrier in future energy systems that are fully renewable, multi-nodal, interconnected, and sector-coupled [33]. Also, large-scale transmission between countries can reduce the energy system flexibility requirements [34] and further reduce the overall costs of highly renewable energy scenarios [35].

From our standpoint, it is more convenient to use one-node approach for EnergyPLAN’s hourly simulations and then switch to detailed power system model in CASE for grid analysis. Geographic distribution of generation from one using EnergyPLAN to more nodes is done using CASE whose load flow simulation model contains power grid branches, generators, and loads. Thus, the focus of this article is to introduce multi-node complexity of power system using CASE.

The coupling of CASE and EnergyPLAN

As mentioned before, the coupling of the CASE and EnergyPLAN programs was implemented using the EnergyPLAN output text file. The EnergyPLAN output file contains hourly information about total power plant production by type, total system consumption divided into several subtypes, export and import from the control area, etc.

The EnergyPLAN simulates the behavior of national power systems on an hourly basis. The energy balance, emissions and costs are calculated on an annual basis. These analyzes include energy production and consumption of electricity, heat, and energy in transport sectors, as well as carbon dioxide emissions and actualized annual costs by taking into consideration investment and operational costs. As renewable energy becomes more prominent in power systems, the flexibility of the complete power system has already become a serious topic. One of the most affordable methods of creating flexibility is the coupling (integration) of the power, heat and transport sectors using technologies such as combined heat and power plants, heat pumps, energy storage and electric vehicles. The main purpose of applying these two software tools is to assist in the creation of national energy planning strategies based on technical and economic analysis resulting from different scenarios with high and very high share of renewables in the total energy mix [3].

Energy Plan is designed as an input/output model. The input parameters are planned energy consumption in all sectors of interest, renewable energy sources capacities and generations, power plant capacities, costs and planned import and export of electricity, surplus of produced energy, types of available energy sources, specific costs of energy sources and equipment, etc. The output data are the power balance and annual energy production, fuel consumption, import and export of electricity and total costs including income from the sale of electricity [3].

CASE software has been developed for the needs of a wide range of power system calculations. Power system simulation models can be created in a simple way by using drag-and-drop technique. For this work, the possibility of importing the transmission system model of Serbia and its neighbors from the so-called UCTE format, in which all power plants are modeled at high voltage, has been used. The layout of the CASE application is shown in Fig. 1. Its interactive single-line diagram shows a part of the 400 kV transmission system in eastern part of the Republic of Serbia. Development of CASE was financed by the European Union within the project “Study on modalities to integrate electricity from RES into the distribution network and smart grids” [36]. CASE has been designed and developed to perform power system calculations for any type of power grid (transmission, distribution and industrial as well as their mixtures) without limits. Source code of CASE is property of the authors of this article, so it was possible to efficiently upgrade CASE with the module that interfaces with EnergyPLAN.

The results of EnergyPLAN simulation are hourly production and consumption of electricity for the entire power system of Serbia. However, EnergyPLAN does not provide an option to calculate network power flows. Load flow calculation is performed by CASE for each hour of the year. Newton-Raphson method is used to perform load flow calculation. Classic Newton-Raphson method is extended with two iteration loops, outer and outermost, in which:

1. Outer loop – Generator, i.e. PV, nodes that violated reactive power limits are converted into consumer, i.e. PQ, nodes with active power injection equal to generator specified active power and reactive power equal to violated, upper or lower, limit. At the same time, those PQ nodes that were originally PV nodes and previously converted to PQ nodes in some of previous outer iterations are converted back into PV nodes if certain conditions are met. For instance, if calculated voltage is greater than the specified one and the reactive power injection is equal to the upper limit, the condition for the PQ node to be converted back to PV node is met. This is so–called backward looking algorithm the details of which are beyond the scope of this paper.
2. Outermost loop – Balance powers of the areas are controlled at the specified values. This is done by changing the active power of the areas' swing generators.

Conceptual load flow algorithm is shown in the next figure. The algorithm shown in the figure does not provide details, such as maximum number of iterations in the inner, outer and outermost loops; convergence control; relative error tolerance; etc. It only shows the principle of load flow calculation applied in this case.

Using EnergyPLAN program, the power produced by all energy sources is calculated to meet the consumption. Priority to supply consumption is given to variable renewable energy sources. The rest of the consumption (residual load), which is not supplied by renewables, is in our case study (Republic of Serbia) mainly supplied by electricity produced in thermal power plants that produce greenhouse gases. The output from the EnergyPLAN is the aggregate power for each power plant type. However, it does not separate whole power to the individual power per power plant. Total power of each power plant type, exported by EnergyPLAN, is distributed to each generator according to its distribution factor that is specified within the separate file which contains these distribution factors based on authors experience. Sum of all generators' distribution factors for a particular power plant type must be 1. In the next step, power flow calculations are performed by CASE. Calculation results are automatically stored in operating memory after calculations are completed. These calculation results provide information whether there are overloaded lines or transformers.

Basic coupling architecture of EnergyPLAN and CASE is shown in the next figure. There are three files loaded by CASE: 1) power system model, 2) EnergyPLAN output, and 3) generators' distribution factor list. These three files could be loaded in any order.

CASE module developed to import EnergyPLAN output file and generators' factor list is shown in the next figure. More precisely, next figure shows CASE dialog window "EnergyPLAN" while calculation is in progress. When calculation starts, button "Run" becomes button "Stop" and several dialog controls are disabled as shown in the next figure. Calculation is implemented in the separate execution thread, outside the main application thread in which the user and the operating system messages are processed. In this way, the user has full control over the execution of the calculation in the sense that it can be interrupted at any time. Load flow calculation can be performed for all the imported scenarios, i.e. hours, or just for those that are specified by user.

There are two spreadsheets in the dialog window. The upper one with six tabs shows generator distribution coefficients, i.e. participation factors as they are named in the column heading, for each type of power plant. This spreadsheet is populated after generators' distribution factor list is loaded. The lower and wider spreadsheet, named "Scenarios", is populated after EnergyPLAN output file is imported.

Case study: Serbian power system simulation model

The aim of this section to present Serbian power system simulation model in a case of high penetration of 4.5 GW of variable RE sources, especially wind and solar. The assumed prospective situation for the year 2030 is taken to be analyzed based on increased RE ambitions of Republic of Serbia. The annual production of each type of power plant is calculated separately by EnergyPLAN.

In addition to complete Serbian transmission system, parts of transmission systems of the countries that have common border with Serbia as well as a part of Slovenian transmission system are modeled in CASE to realistically calculate power exchanges of Serbia with neighboring countries. The Bulgarian NPP Kozloduy has been selected to be system slack node (swing bus). Modeled part of European continental synchronous interconnection is bordered by dashed line in the next figure, while slack node is encircled by solid line.

As shown in the previous figure, Hungarian transmission system is modeled up to NPP Pakš and SS Liter including interconnected lines to Croatia, Romania and Serbia: Pécs-Ernestinovo (double 400 kV line), Heviz-Žerjavinec (double 400 kV line), Sandofalva-Arad and Sandorfalva-Subotica. NPP Krško and TPP Podlog are modeled in Slovenia. Croatia does not have large power plants, so that only its 400 kV network to Zagreb and towards NPP Krško is included. TPP Ugljevik, TPP Gacko, HPP Trebinje and HPP Višegrad are modeled in B&H. These are the power plants that have the greatest influence on the power system of Serbia. Concerning Montenegro, TPP Pljevlja and HPP Piva and consumption of a submarine cable in substation (SS) Lastva are introduced. Planned future capacity of the submarine cable is 1000 MW (current capacity of this cable is 500 MW). Because of the cable, SS Lastva is SS with the highest consumption in the region. Regarding Bulgaria, the 400 kV ring around Serbian transmission system is closed. The NPP Kozloduy, which is a system swing machine, is connected to this 400 kV ring. Simulation model also encompasses a 400 kV interconnected line between SS Divača in Slovenia and SS Redipuglia in Italy. Large power export to Italy of about 500 MW is realized by this interconnected line. SS Divača is specific from the point of view of active power control since it has two phase-shift transformers 400/400 kV, with capacity of 2x600 MVA, for control of active power flows in that part of the network.

In this particular case, only balance power for Serbian control area is specified. CASE controls specified balance power of particular area by modifying production of area swing generator, which is HPP Đerdap 1 for Serbia. This is also the case in practice, since over 90 % of secondary control in Serbia is performed using HPP Đerdap 1.

The prospective year is 2030. Existing wind farms Košava, Čibuk, Kovačica, and Alibunar are included in the simulation model. A solar power plant with a capacity of 200 MW and a wind farm with a capacity of 400 MW are connected to the 400 kV "concentration" (as referred to in the Serbian TSO plan) switchyard in Banat. Further, a wind farm with a capacity of approximately 120 MW is connected to 400 kV busbars of SS 400/220/110 kV Pančevo 2 by double 400 kV line. In addition, a solar power plant with a capacity of 120 MW is connected to 400 kV busbars in the SS Bor 2 because the plan is to place one solar power plant in eastern Serbia (Negotin). There is also a solar power plant with a capacity of 100 MW connected to the 110 kV busbars of the SS 220/110 kV Valjevo 3. Finally, solar power plants with a capacity of 150 MW each are connected to the 400 kV busbars at the SS 400/110 kV Vranje 4 and SS 400/110 kV Kragujevac 2. In summary, total wind power of 2000 MW and solar power of 2500 MW are simulated, which makes 4.5 GW in total of renewable capacity in solar and wind power

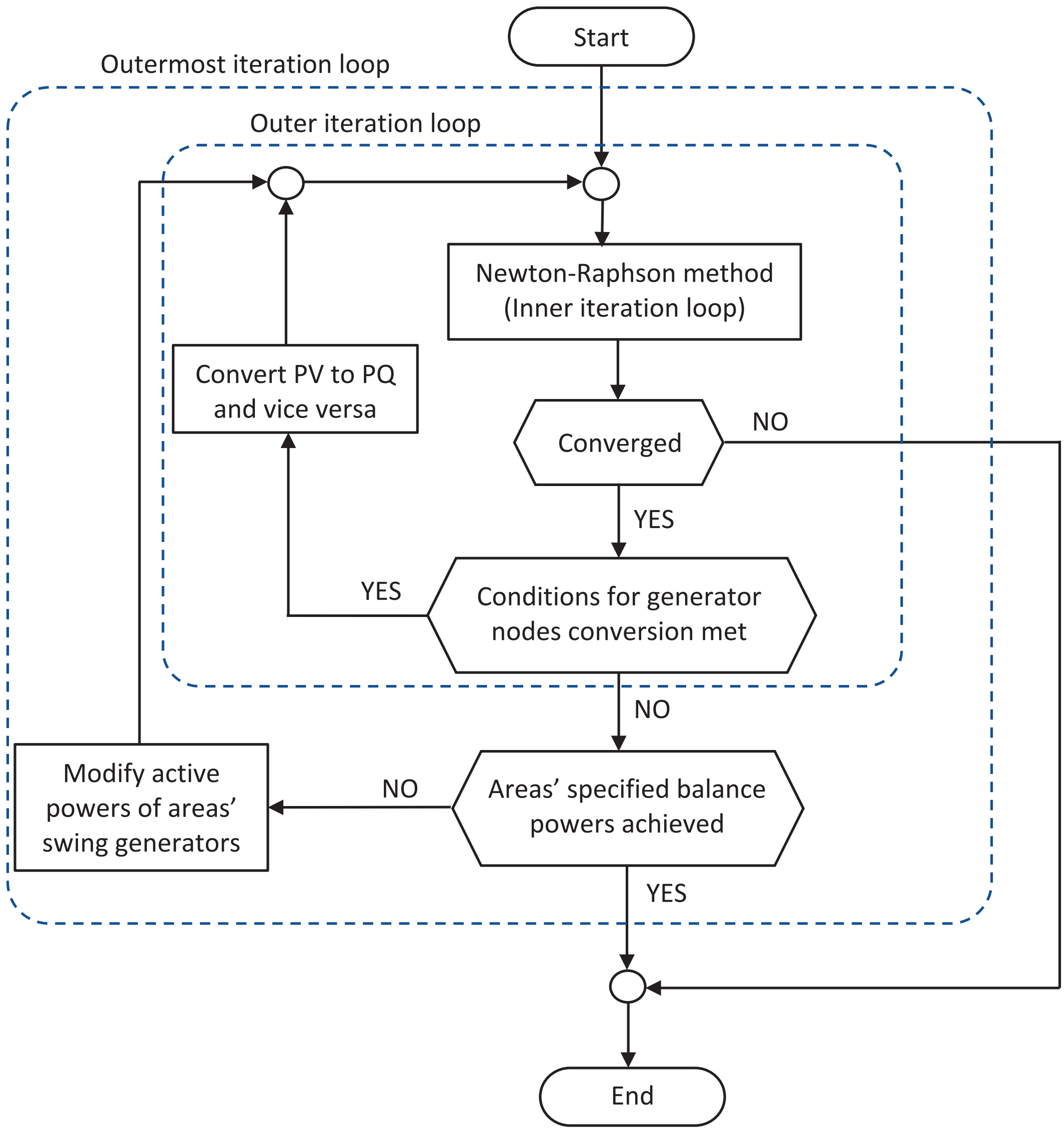

Fig. 2. Conceptual algorithm of the load flow calculation.

plants.

Distribution factors for each generator for year 2030 are specified in accordance with: 1) engagement of existing generators, which will be in operation in 2030, in specific operating regimes; 2) type and capacity of generating units that will committed until 2030; 3) Planned active power balance of Serbian control area and generating units that will take part to control this balance.

Improvements to the Serbian transmission grid comparing to its current state are as follows:

- Double 400 kV transmission line Pančevo – Resita is introduced into the so-called "concentration" 400 kV switchyard by which power from renewable sources in southern Banat is evacuated. This 400 kV switchyard will gradually be extended into the substation 400/110 kV according to the ten-year development plan of Serbian TSO for the period 2021–2030.
- Introduction of the 400 kV voltage into SS Zrenjanin 2.
- Double 400 kV transmission line from SS Obrenovac to SS Bajina Bašta and 400/220 kV transformation with a capacity of 2x400 MVA at the SS Bajina Bašta.

In this model, Serbian power system has 10 interconnected 400 kV transmission lines:

- Three with Romania: Đerdap I – Portile de Fier and double circuit Pančevo – Resita,
- One with Bulgaria: Niš – Sofia,
- Two with North Macedonia: Vranje 4 – Štip and Uroševac – Skopje,
- One with Montenegro: Peć 3 – Ribarevine,
- One with Bosnia and Herzegovina: S. Mitrovica – Ugljevik,
- One with Croatia: S. Mitrovica – Ernestinovo,
- One with Hungary: Subotica – Šandorfalva.

Results of calculation

It is assumed that the year is a leap year which contains 366 days, i.e. 8784 h. The power flow simulation model is well–conditioned and Newton-Raphson method converges for all 8784 h. The calculation time of all of 8784 h along with the generation of reports in the operating memory of a desktop computer is less than 9 min. The basic characteristics of the computer are: processor Intel i5-10400 2.9 GHz, RAM 8 GB, operating system MS Windows 10 Pro.

The report for a particular hour is generated based on the results of power flow calculation. It contains power system summary (by areas:

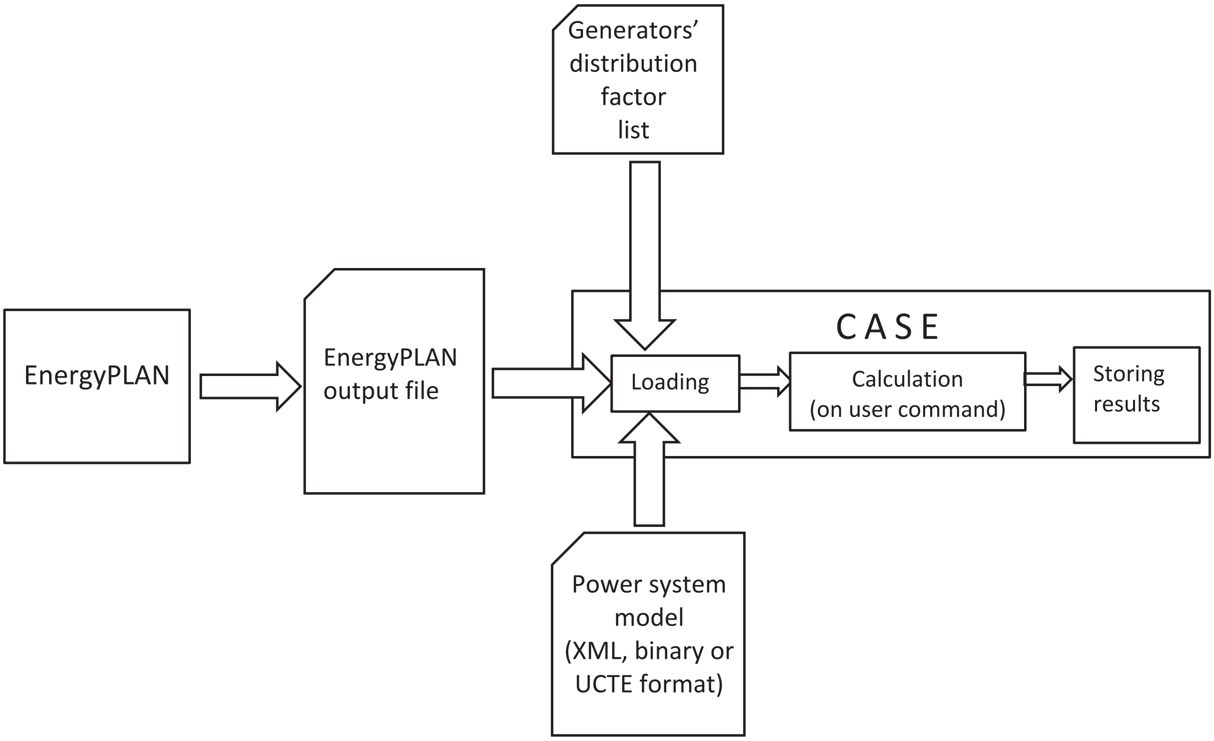

Fig. 3. Basic coupling architecture of EnergyPLAN and CASE.

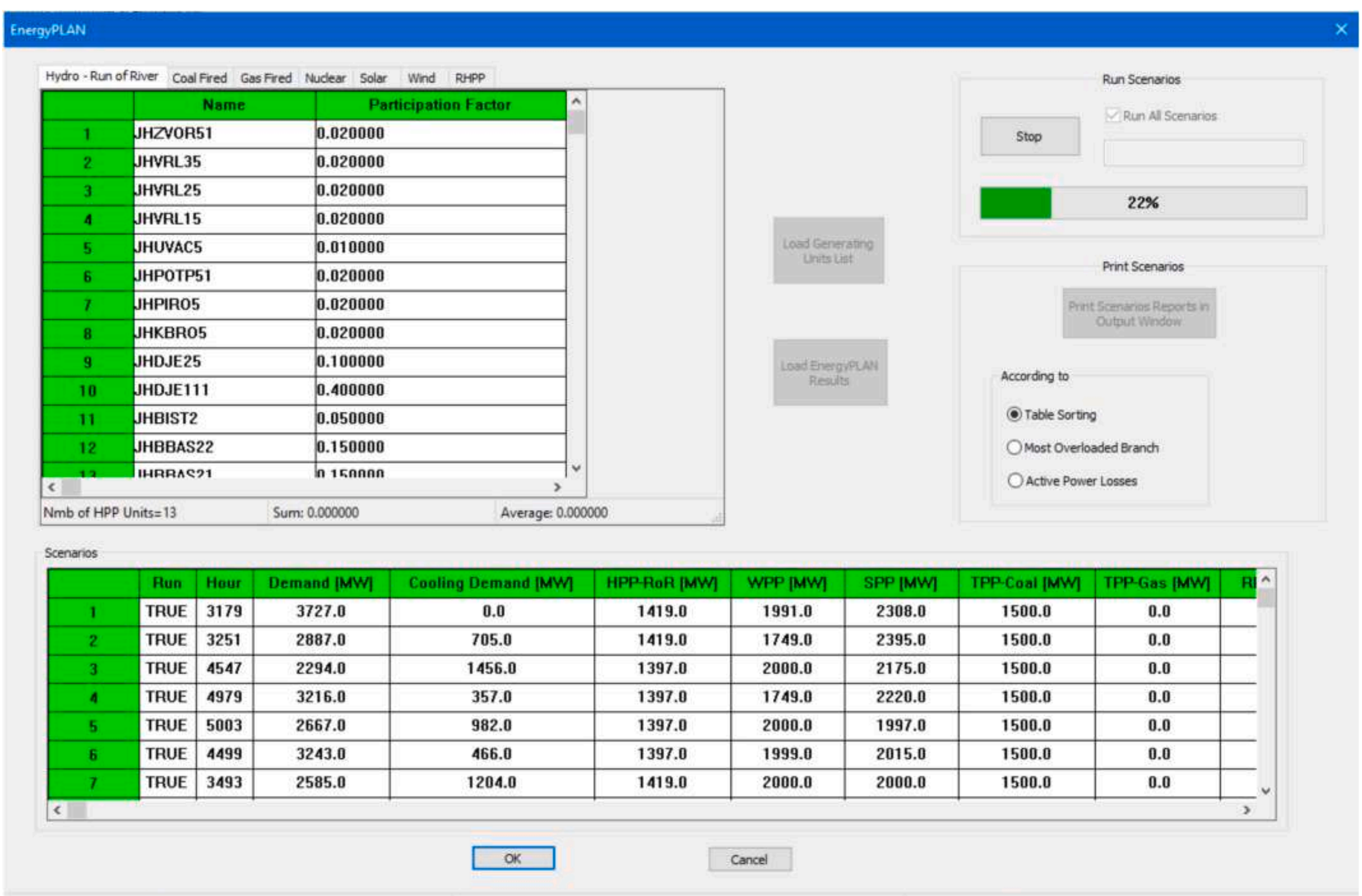

Fig. 4. CASE "EnergyPLAN" dialog window while calculation is in progress.

Fig. 5. Part of European synchronous interconnection modeled for calculation purposes.

production, consumption, import, export, losses), swing bus generation, overloads of lines and transformers, and violations of voltage limits by nodes of the network. All of the reports are stored in the computer operating memory and could be printed in order in which scenarios are sorted in the table, by the most overloaded branch or by active power losses. For instance, the following figure shows sorting of scenarios in

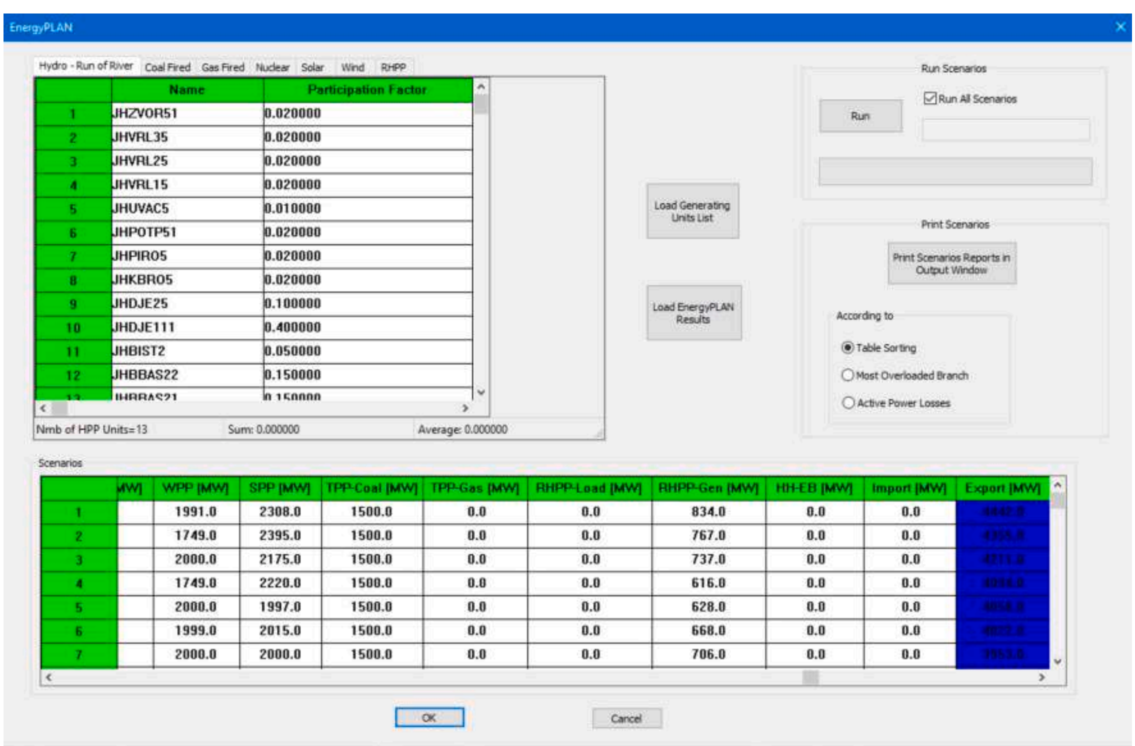

Fig. 6. Scenarios for each hour sorted by area export.

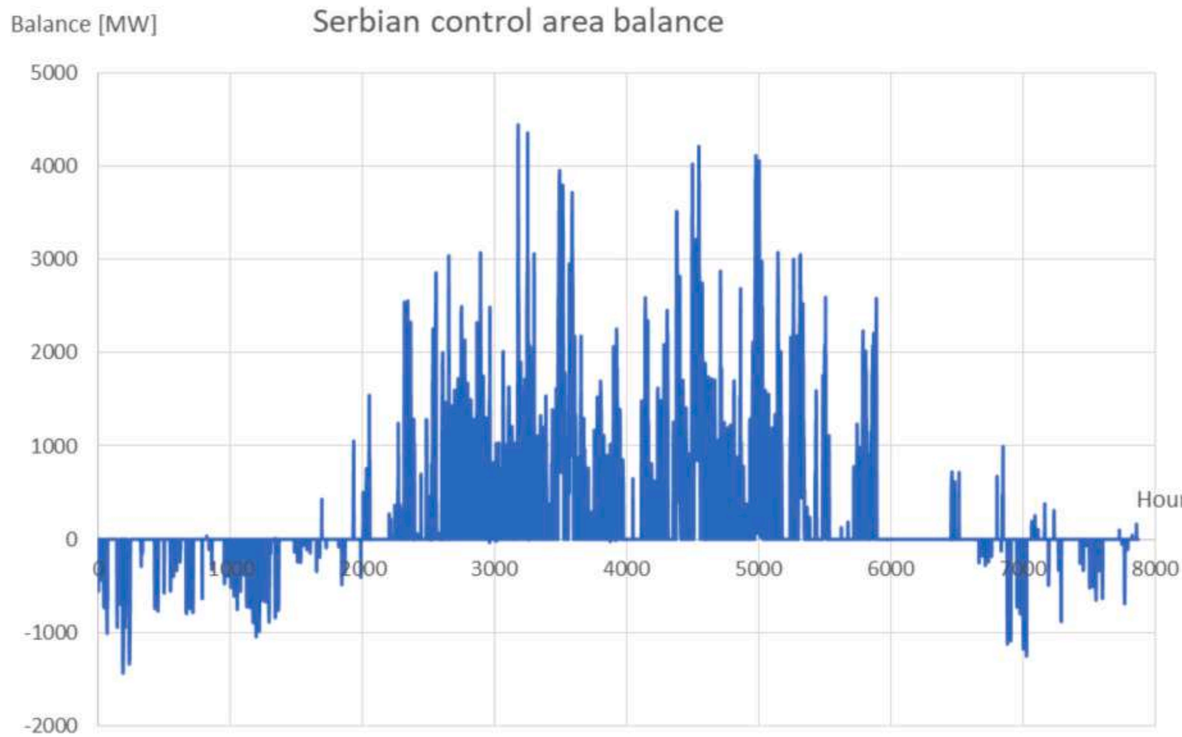

Fig. 7. Balance of Serbian control area by hours.

descending order by area export. If option "Table Sorting" is selected, as shown in the next figure, all of the reports are printed according to the current table sorting.

Regarding high export values, the issue is that there is no significant consumption in the surrounding areas. The closest large consumption nodes are DC submarine cable in Montenegro and Redipuglia on the border of Italy and Slovenia. Consumption of Redipuglia is approximately 700 MW. Current capacity of DC submarine cable in Montenegro is 500 MW, while the future capacity of this cable will be 1000 MW. On the other hand, in the scenario with the highest export of 4442 MW, consumption of the Serbian area is approximately 3700 MW which is less than the area export.

Analyzing reports for the highest power exports from Serbian control area (4442 MW and lower, according to sorting shown in the previous figure), it should be noted there is no overloaded branch, whether it is an internal branch (line or transformer) or an interconnected line. In

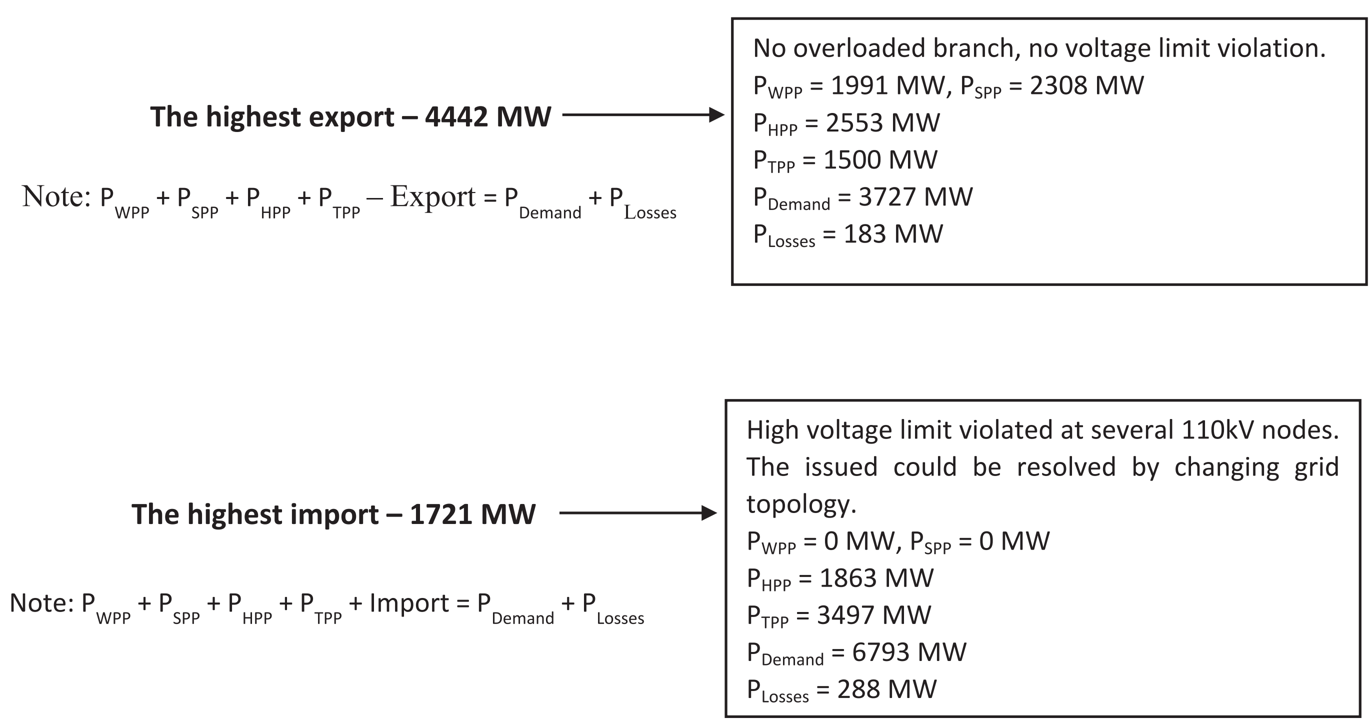

Fig. 8. Summary of Serbian transmission system in the regimes of the highest export and import.

addition, there is no node with violated voltage limits.

Considering all analyzed scenarios, i.e. hours, there are several of them in which low overloads (up to 10 %) of branches appear along with violations of voltage limits at some nodes. These scenarios are those in which high power, greater than 1500 MW, is imported into Serbian control area. However, these overloads and violations of voltage limits occur in 110 kV grid and could be resolved by changing grid topology.

Balance of Serbian control area by hours, defined as Export-Import, is shown in the next figure. Values of Balance are negative during first three and last two months of the year which means Serbia imports electricity during winter period in which electricity is used for heating by some parts of the population. Control area balance is adjusted at the specified value by modifying active power of area balance generator, which HPP Djerdap 1 for Serbian control area. This is done in outermost iteration loop of power flow calculation as shown in Fig. 2.

The hour of the highest import is 8778, which is December 31 at 18 h, while the hour of the highest export is 3179, which is May 11 at 11 h. Summary of Serbian transmission system operation in distinct operation regimes of the highest export of 4442 MW and the highest import of 1721 MW is given in the following figure. Serbian control area total active powers of HPPs, TPPs, SPPs and WPPs are denoted in the figure by P_{HPP}, P_{TPP}, P_{SPP} and P_{WPP}, respectively. In this case P_{TPP} denotes total active power of coal-fired TPPs. Active power losses and demand of Serbian control area are denoted by P_{Losses} and P_{Demand}, respectively. As summary shows, high export from Serbian control area is caused by high power production of SPPs and WPPs when system demand is low. On the other hand, in scenarios where electricity is not produced in WPPs and SPPs (night or evening hours without wind), Serbia imports more than 1500 MW, more precisely 1721 MW in hour 8778. Transmission grid active power losses are approximately 100 MW lower the regime of the highest export than in the regime of the highest import. This is due to significantly lower system consumption and consequently mainly lower load of branches (lines and transformers) in the regime of the highest export (Figs. 3-8).

Direct implication of RES large–scale integration is large changes or control area balance from high exports to high imports due to RES production variability. On the territory of Serbia, big changes of RES production occurs on daily, weekly, monthly and seasonal level. This is the reason why short-term planning of power system operation is made more complex by large–scale integration of RES.

Disadvantage of high control area export/import is reduced energy security of the state because a situation may arise in which high export/import cannot be realized due to: a) outage of an interconnected or internal transmission line and b) failure of a large power plant in a control area from which electricity is imported. Considering that electricity in Serbia is used for heating in some areas and that electricity is mainly imported during the winter, a situation in which import of electricity is not possible could be critical for the parts of population that use electricity for heating. This critical situation could be prevented by strengthening transmission grid and providing electricity import backup plan.

Conclusion

This paper presents an innovative coupling of the CASE and EnergyPLAN software tools. The integration was achieved by upgrading CASE to read the output text file generated by EnergyPLAN. This file contains hourly data on total power plant production (by type), total system consumption (divided into subcategories), and import/export values for the control area. In other words, CASE imports the EnergyPLAN output file and allocates the total production by plant type to individual power plants in the system according to predefined distribution coefficients, while total consumption is proportionally distributed to grid nodes in accordance with the existing load profile. In this way, simulation models for power flow calculation are made automatically by CASE for each hour of the year. CASE then calculates power flows and generates reports based on the results of power flow calculation for each hour of the year, or for those hours that are specified by the user.

Power flow calculations were performed using Serbian power system model with parts of neighboring power systems that affect Serbian transmission grid. NPP Kozloduy in Bulgaria was selected as system slack node since it is large power plant located outside of Serbia as analyzed control area. HPP Đerdap 1 was selected as Serbian area slack node in order to adjust area exchange at a specified value. Newton-Raphson method converged in all 8748 scenarios despite the huge differences among them, which ranged from approximately 4500 MW of export from Serbian control area to approximately 1700 MW of import to this control area. Voltage limit violations occurred at a few nodes, and several branches were overloaded in several scenarios with high import levels, while highest export level was without overload or violations. These results provide clear evidence that the proposed coupling of CASE and EnergyPLAN is practically applicable to real power systems, representing the second key contribution of this paper.

The analyses performed demonstrate that the described approach is highly effective, as it combines two reliable software tools and produces results that can support valuable conclusions in power system planning. In particular, scenarios with a high share of renewable energy in the generation mix were investigated over a long-term planning horizon. These conditions, dominated by renewable energy production, often led to significant exports from Serbia's control area. This outcome highlights the final contribution of our approach: the coupling enables extensive analyses of power systems under scenarios with dominant renewable energy generation.

CRediT authorship contribution statement

Nikola Rajakovic: Supervision, Methodology, Conceptualization. **Bojan Ivanović:** Writing – review & editing, Software, Investigation. **Ilija Batas Bjelic:** Writing – original draft, Software, Methodology. **Tomislav Rajić:** Writing – review & editing, Visualization, Validation.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Data availability

Data will be made available on request.

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