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Flexibility index and decreasing the costs in energy systems with high share of renewable energy

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ABSTRACT

Recent European Green Deal includes decision to become carbon neutral and even carbon negative region in order to tackle the climate crisis. Main technical challenge and a key factor in techno-economic analysis of the energy system of the future, based on variable renewable energy sources, is their variable production and its integration. In order to deal with this problem in long-term energy planning, different approaches have been tried, focusing on overcapacity, storage capacities and sectors coupling with heating and transport. In this research, different flexibility options, storage and demand response technologies are modelled on a national energy systems level. With the case study area modelled in EnergyPLAN model, the goal of the research is to show how each flexibility option influences the economically feasible generation capacities of renewable energy sources, storage technologies and demand response in order to reach a certain share of renewable energy in final energy consumed. To follow the numerous possible configurations of the system, flexibility index for each option and a flexibility vector for each scenario are introduced. Results show which flexibility options play key role in important steps of energy transition to 70%, 80%, 90% and 100% RES energy system.

1. Introduction

To achieve ambitious targets from Paris Agreement, various scenarios are being calculated by the scientists. Approaches vary and integrated assessment models are used to compare various measures and pathways and to get better insight in the alternatives, with the aim to diversify the transition pathway, while simultaneously benefiting other sustainability goals [1]. Such Mitigation-Process Integrated Assessment Models (MP-IAMs) are used for analysis of long-term energy transition pathways that are needed to achieve climate change mitigation goals. Since they usually use high level of temporal aggregation, IAMs cannot represent all detailed issues of integrating the variable renewable energy sources (VRES): wind and solar in power systems, so they rely on parameterized modelling approaches. Electrification will play a new key role in the energy transition, through "electricity triangle" involving power generation system based on VRES, use of electricity as a vector and electrification of final energy users from all consumption sectors [2]. For such development based on the VRES, flexibility of the system is of paramount importance. According to [3], flexibility of the power system is defined as its ability to handle the variability of generation and demand. The solutions are continuously being developed, with entire business models being based on storage technologies and demand response. The decoupling of electricity generation and consumption in systems with high share of VRES cannot be implemented only by use of electricity storage, but rather by using synergies between sectors and converting electricity into many different energy services, for example into thermal energy – which is better suited for storage. Also, demand response (DR) can be implemented in such contexts [4]. A recent research implemented different concepts to integrated demand response strategies for end users in households (model predictive control of heating and cooling) and industry (optimization of automation systems) [5]. In the [6], improved load profiles comparison method for the DR

Abbreviations: CEEP, Critical Excess Electricity Production; CHP, Combined Heat and Power generation; DR, Demand Response; GHG, Green House Gasses; IAM, Integrated Assessment Model; ICE, Internal Combustion Engine; LCOE, Levelized cost of energy produced; NECP, National Energy and Climate Plan; P2H, Power to Heat technology; P2G, Power to Gas technology; PHS, Pump Hydro Storage; PV, Solar Photovoltaic plants; RES, Renewable Energy Sources including sustainable biomass and hydropower; ROR, Run-of-river hydropower; V2G, Vehicle-to-grid concept for electric vehicles; VRES, Variable Renewable Energy Souces: wind, solar and run-of-river hydropower.

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capacity estimation in various supply areas was investigated for similar times of the year, but in different weather conditions. The approach (normalization of differences) enables more precise estimation of available DR capacity. A research of the residential sector flexibility, through simulations done by [7], has shown that the flexibility to increase consumption in residential sector can supplement the needed flexibility without significant changes in the current market design.

In the conditions of constantly rising share of VRES, energy systems need to be reconfigured. Main issues are discussed in [8], demonstrating relevance of demand and VRES generation profiles, as well as flexibility instruments. The generally low share of VRES can be handled by existing systems and existing balancing options, since there is still a significant excess capacity of dispatchable generation and transmission capacities to neighbouring systems that can balance the variable generation. According to [9] a significant higher balancing energy demand appears with the expansion of photovoltaic and battery systems, making standard load profile unsuitable for differential balancing groups. Therefore, solely relying on such combinations is not sufficient and there is a need for the wider spread of flexibility options. Also, wind energy exploitation without other RES leads to additional balancing needs. In [10] a model of electricity production from wind farms and a combined cycle gas turbine power plant developed in the commercial energy planning tool PLEXOS. Real hourly input data and all characteristics of combined cycle gas turbine power plant were used in the model. A detailed analysis of techno-economic characteristics of ramp rates and different types of ramp-ups and ramp-downs of the plant was made, from the investors point of view. From these studies, it can be noted that particular approach, using only one RES technology in combination with a measure for their integration leads to high investments in balancing technologies and lock-in effect appears. Better approach is to take wider picture in consideration on the system level and include options that enable synergetic effects between different sectors of demand and the sector of power generation.

2. Energy transition to the systems with very high levels of VRES

A handful of technologies represent a spearhead of energy transition and the use of synergies between different sectors of an integrated energy system. In [11], integration of additional solar photovoltaics into the energy system in transition was investigated using the synergies with heating and transport systems. It was concluded that higher VRES integration is easier to achieve if it is harmoniously followed by the implementation of technologies such as power-to-heat (P2H) and vehicle-to-grid (V2G), which help to decarbonize sectors of transport and heating. In [12], the renewable heating strategies were indicated as a crucial factor for reaching a 100% renewable energy solution and grid balancing. Also, fuel in CHP can be displaced using different taxing approaches, as shown in [13] using multi-objective optimization, which in turn enables large P2H implementation. A method for the integration of VRES in coal-based energy system is introduced in [14], where an emphasis was on using P2H technologies for the case of Kosovo. Decarbonized and integrated energy system of Italy by 2050 was analysed in [15]. The results have shown that in addition to using VRES, their integration requires integration with other technologies such as cogeneration, trigeneration, V2G, P2H and thermal energy storage. According to a recent review of best practice examples in P2H implementation [16], the influence of economic and policy framework factors on the implementation of P2H as demand response is larger issue compared to the technological development. A number of researchers also addressed the flexible operation of the last steps of energy transition, namely the issues of electrification of fuels, producing electro-fuels, synthetic fuels [17] from biofuels and captured CO_2 and similar applications. In [18], economic and environmental indicators were used on the basis of results from the HOMER energy planning tool. Results show that the implementation of a hybrid storage system with batteries and electrolyser can be an adequate and reliable option for increasing energy independency of small island and decarbonizing transport sector optimizing economic and environmental sustainability. The Power-to-Gas concept was investigated in [19], analyzing the performance of such innovative storage system. A possibility to integrate the co-electrolyzer and the high temperature methanation section was demonstrated, resulting in energy savings. In [20] a decision-making tool for determining the most sustainable use of biomass for carbon management was investigated. The mathematical principles are based on break-even analysis. The tool allows the Emissions-Cost Nexus to be considered in identifying the most sustainable biomass utilization pathway under different baseline conditions. The possibility of using electrodialysis coupled with a hybrid power plants (solar or wind) was investigated in [21]. Such hybrid plants are of very attractive in order to increase the stability of electricity generation. At the same time, electrodialysis is claimed to be a more flexible process compared to reverse osmosis. The results show that the electrodialysis process is suitable for the integration as a storage within polygeneration systems.

In terms of modelling approaches and scenario analyses, different approaches can be observed. In [22], the case of France was modelled and contrasted scenarios produced, from 0% to 100% renewable energy penetration by 2050. Authors tested different configurations of VRES: production, imports, demand flexibility and biomass potential. It was shown that high renewable energy penetration would need significant investments in new capacities, new flexibility options along with imports and demand-response, and that it is likely to deteriorate power system reliability if no technologies dedicated to this issue are installed. In [23] zero-emission pathway for the Nordic and Baltic region in Europe was investigated and modelled, concluding that high share of VRES with sector coupling would be the most economically feasible way forwards. Also, energy system optimizations indicate that most of the investments needed for the zero-emission pathway until 2050 would take place already by 2030.

In Pietzckeret al. [24], a framework was developed for IAMs, consisting of 18 features of power sector dynamics and VRES integration, after which a review of novel modelling approaches was done. According to the results, new modelling approaches represent different emerging features of the power sector (with increased solar and wind capacities), but there is a need for further research on inclusion of synergies and decarbonize other sectors of the energy system. In Ram et al. [25], the authors investigate components of the levelized cost of energy (LCOE), emphasizing that the external costs in estimating the LCOE of power generation technologies was neglected in the past. As LCOE is a critical indicator for policy and decision makers, there is a need to juxtapose actual costs of renewable and conventional power generation technologies. Ram et al. attempted to internalize some of these external and GHG emission costs across various power generation and storage technologies in all the G20 countries, as they account for 85% of global power consumption. Results show that renewables are far cheaper than fossil and nuclear sources by 2030, providing statistically display that all the G20 countries have the opportunity to decrease their energy costs significantly. Furthermore, in [26] the marginal prices forecasting method was developed for the future energy planning models to use. The presented “K-SVR” method required also significantly less computational time compared to best known models. In [27], the paradox of energy transition was found in the falling prices of energy. To offer better future electricity prices forecast, the authors proposed modelling the prices from the residual load obtained by non-flexible productions from the load. Armed with the resulting economic indicator, authors investigated future revenues for European power plants with various degree of flexibility. The approach is limited to the power generation sector.

Nikolaev and Konidari [28] modelled the case of Bulgaria to determine what targets for RES would be realistic for the country until 2030. They used LEAP software and the multi-criteria evaluation method AMS (described in [29]). LEAP simulated three developed scenarios aiming to different RES targets for 2030 supported by different policy mixtures.

Results and official information are used as inputs to AMS. The AMS outputs allow the identification of the most appropriate scenario for the country [28]. However, this method does not allow for the hourly analysis of the VRES integration.

According to [30], where IAM “MESSAGE” was used to study the role of hydrogen and storage technologies in low-carbon energy transition, large VRES shares are supported in carbon-constrained futures by the deployment of other low-carbon flexible technologies, such as hydrogen combustion turbines and concentrating solar power with thermal storage. The importance of analysis of flexibility options was emphasized in [31] as well. The study examined an extended version of an open source energy system model (OSeMOSYS), simulating operating reserve and related investments on an Irish case study. That case study examined the effects of linking a long-term energy system model (TIMES) with a unit commitment and dispatch model (PLEXOS). Results have shown that investment mismatches decrease from 21.4% to 5.0%. Automation of the energy planning process, as a tool for the experienced planner has been suggested by [32] to show that deviations in annualize total costs from the optimal energy system structure may be at the level of 13% for Republic of Serbia. As a continuation of that research, here it will be shown that using brute force, instead of optimization algorithm, these deviations are going to be even higher. Therefore, significance of the automation of the planning process is increased.

3. Indicators and indexes

In relation to performance indicators for energy systems in transition, various research articles have been reporting such attempts, which focused on more constrained system boundary, for example one building [33]. Results of the analysis of one building provide insight in the correlations between 26 indicators, elaborating on the importance of appropriate system boundaries, time resolution and constructional footprint to describe flexible systems. If electricity generation mix has low emissions, it has a high impact on strategic planning and brings conflicted effects with decentralized, self-sufficient energy systems. When such approaches are expanded to the large number of dwellings [34], results become very useful for the long-term energy planning considerations: Switching from fuel to electric-driven heating systems could play a key role. It suggests modifications in the building stock due to the change in the temperature of the supplied heat by new heat pumps compared to existing boilers and in power demand to the electricity meter. A set of key performance indicators were selected for energy and environmental performance. The changes in the energy flexibility led to the viable participation of all the dwellings in a demand response programme. In [35] the prosumers and energy exchanges between them was the focus of research, showing the potential of photovoltaic panels and small-scale CHPs reduce the needed supply from traditional generators. Results reveal that short-range interactions among prosumers are preferred when planning to reduce the electricity supply from the main grid. In addition, the spatial configuration of the buildings within the area as well as the capacity of the installed energy production systems significantly affect the distribution. Finally, simulations highlight the noticeable impact of seasonality on both the distribution and the emissions’ reduction. In [36] the demand flexibility is quantified using different performance indicators that sufficiently characterize flexibility in terms of size (energy), time (power) and costs. To fully describe power flexibility, the paper introduces the instantaneous power flexibility as power flexibility indicator. The instantaneous power flexibility shows the potential power flexibility of thermal energy storage and P2H in any case of charging, discharging or idle mode.

In case of industrial demand side management and potential flexibility, [37] presents a formulation of the flexibility index for industrial systems. In [38], a case of energy intensive industrial process was modelled, using MILP, to find the cost-optimal solution for the operation of a plant with energy supply, conversion and varying thermal storage in conditions of varying electricity and emissions prices. Operational costs were reduced for around 5% when the storage capacity accounted for 7% of the steam conversion capacity. Additional rise of 7% only achieved the further cost decrease of approximately 1%. Contrary to previous static approaches to quantify Energy Flexibility, the dynamic nature of the Flexibility Function enables a Flexibility Index elaborated in [39], which describes to which extent a building is able to respond to the grid’s need for flexibility. In order to validate the proposed methodologies, a case study is presented, demonstrating how different Flexibility Functions enable the utilization of the flexibility in different types of buildings, which are integrated with VRES.

Some attempts for the national level of power system are also present in the literature. In Papaefthymiou et al. [40] the Flexibility Tracker was presented, with the aim to compare the readiness of a power system for higher VRES shares. This comprehensive approach introduces 14 flexibility assessment domains, by screening systems across the possible flexibility sources (supply, demand, energy storage) and enablers (grid, markets), via 80 standardised Key Performance Indicators scanning the potential, deployment, research activities, policies and barriers regarding flexibility. The results show that the although flexibility deployment depends on the specifics of each system, a coordinated approach would be beneficial as there are clear no-regret options that face barriers in some systems. The approach does not take into account the decarbonization efforts for other sectors and the goal of modelling a 100% RES based energy system. In [41] a review of methodologies for assessing the impact of flexible resources in distribution systems on Security of Supply was given. Four main aspects of security of electricity supply are distinguished in this article: energy availability, power capacity, reliability of supply, and power quality. Flexibility services are classified in relation to each of these aspects, and the literature is reviewed for methods and indicators for quantifying their impact. The approach of the review is dedicated to the power system without synergies between sectors. The integrated approach, that takes all the synergies between the sectors of power and heat generation and various sectors of energy consumption was identified as the research gap.

The hypothesis of this research is that the method proposed in this paper enables the comparison of numerous different trajectories of energy transition according to the achieved reduction of critical excess electricity production from VRES, total costs of the system and achieved percentage of RES integration. The method differentiates between different flexibility options in the energy systems with high share of RES, enabling the choice of the order of their implementation and provides feedback on the total system costs and achieved reduction in emissions of CO_2. Also, using the method, it is possible to assess the differences between large number of system configurations that are proposed with the same goal: to achieve certain share of RES in total primary energy supply. For the further comparison, the new indicator for energy systems with high share of RES is introduced and named “flexibility index”. Flexibility index is defined for each flexibility option, while the complete unique scenario that potentially includes integration of all sectors in order to reach decarbonized and integrated energy system based on high share of VRES is defined by the flexibility vector that includes all used flexibility technology’s indexes. Such approach builds on the body of literature as it is the first time that a proposed method enables a comprehensive following of the used options that are needed to create a configuration of the energy system that is based 100% on RES.

4. Method

To examine the changes in the energy systems ability to integrate VRES, if one wants to examine all the options one by one and find the functions that connect the increase in VRES integration and the measures of systems flexibility, large number of scenarios need to be calculated. This research proposes a process of soft-linking of an established energy planning model, EnergyPLAN and a new code in Python programming language to produce large number of scenarios for the development of future energy system’s configuration. EnergyPLAN is an analysis tool for the energy system in which the input defines the energy system in terms of demand, capacity and efficiency. Principal scheme of EnergyPLAN is given in Fig. 1.

The output is the performance of the energy system in terms of costs, CO_2 emissions, fuel consumption and amount of renewable energy included. EnergyPLAN simulates energy systems based on certain operation objectives such as hourly balancing the production of heat and electricity within the system or minimizing operating costs [43]. Model is focused on interactions and synergies between the sectors such as power production, heating, cooling, gas supply, transport, water supply and industry, and therefore suitable for sectors coupling approach. EnergyPLAN is set by the user with different types of inputs and, based on these inputs, the tool simulates the energy system based on user-defined and predefined criteria to identify the energy system outputs [42]. The inputs provided by the user are the energy demand, the capacities and efficiencies of the plants already present or to be installed, the use of fuels, the CO_2 emissions associated with the different fuels and the costs of energy conversion technologies. EnergyPLAN requires hourly distributions to be inputted regarding to the electricity demand, the residential heating energy demand, the electricity import–export, the productivity of renewable-based production units. Furthermore, the user has the possibility to choose the simulation strategy and how to manage excess electricity during the hourly operation. Fig. 2 shows the flow chart of a process of soft-linking the EnergyPLAN and the new proposed code. In order to run a simulation, a set of values for input data are required. These values are different in each of the cases. Exact values of the input data are sourced from powerplant database featuring existing and planned capacities, while theoretical capacities are sourced from national strategic documents, to provide BAU data. Next step is to make a table containing values for each of the parameters which are being changed from case to case. These parameters include:

- Capacity in dammed hydro
- Run of the river hydro capacity
- PV capacity
- Wind capacity
- Share of transportation electrification
- Share of V2G and smart charge in electrified transportation
- Power to heat capacity and storage
- Share of DH
- Flexibility of thermal powerplants and CHP plants – expressed as a minimum operating power
- Fuel distribution in thermal power plants and CHP plants
- Import/export capacity

Manipulation with data and use of Python libraries is described in Annex 1 of this paper. The process is completed with postprocessing and creation of appropriate visual representations. The main advantage of soft-linking in general, as shown in this method, is an ability to process large amount of various cases which could not be done manually in a reasonable time.

A template case in this approach is the initial model of the observed energy system that will be analysed in cases produced through this approach. Errors can include a mismatch between the saved output results and name of the case. In other words, the wrong case is run. This error can occur when there is not enough available memory. Other option is that the system fails to save output data and leaves empty output file which is also caused by the lack of memory. Both of these cases are accounted for and corrected in later stage.

In order to calculate CEEP expressed as a percentage of total electricity demand, one has to know the total electricity demand and CEEP, both expressed in TWh. EnergyPLAN's output file has electricity demand spread over multiple data points depending on the used technologies. All electricity demand data points are summed up. Furthermore, CEEP [TWh] is divided with calculated sum of electricity demand and multiplied with 100 to display CEEP as a percentage of total electricity demand. Finally, charts are plotted.

The simulations are run on two computers to reduce run time. Primary computer is the Dell Ideapad 330 with Intel i5 8300H processor and 8 GB 2400 MHz of memory, while secondary computer is Acer Aspire V5 552 g with AMD A10 5757 M and 8 GB of 800 MHz memory. Run time for the primary computer is on average 8 s per case, while for secondary computer it accounts to 18 s. As can be seen, run time is primarily dictated by the memory frequency. Total run time for the final results shown in figures in Results section, consisting of 72,576 cases, is about 144 h or 6 days.

Such approach is then used on any given national energy system or a region. First step in the application is to identify the potential sources of flexibility in the system: demand response and storage technologies which can balance the system that would be based on VRES. After such sources of flexibility are identified, the procedure described above is used to calculate the critical excess electricity production (CEEP), a parameter that is unique to the EnergyPLAN approach, in the case of increased integration of VRES. The CEEP is used in the results analysis as

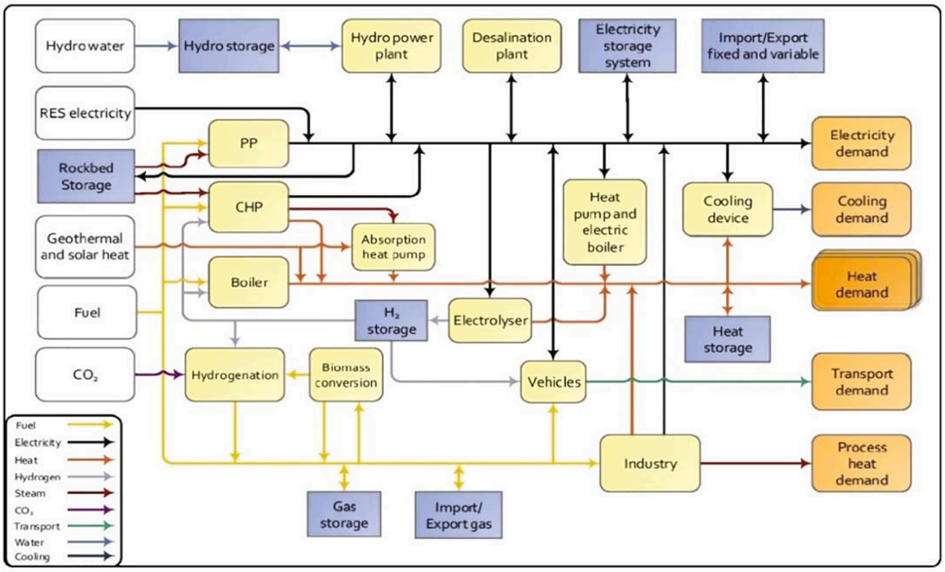

Fig. 1. Schematic diagram of the EnergyPLAN model [42].

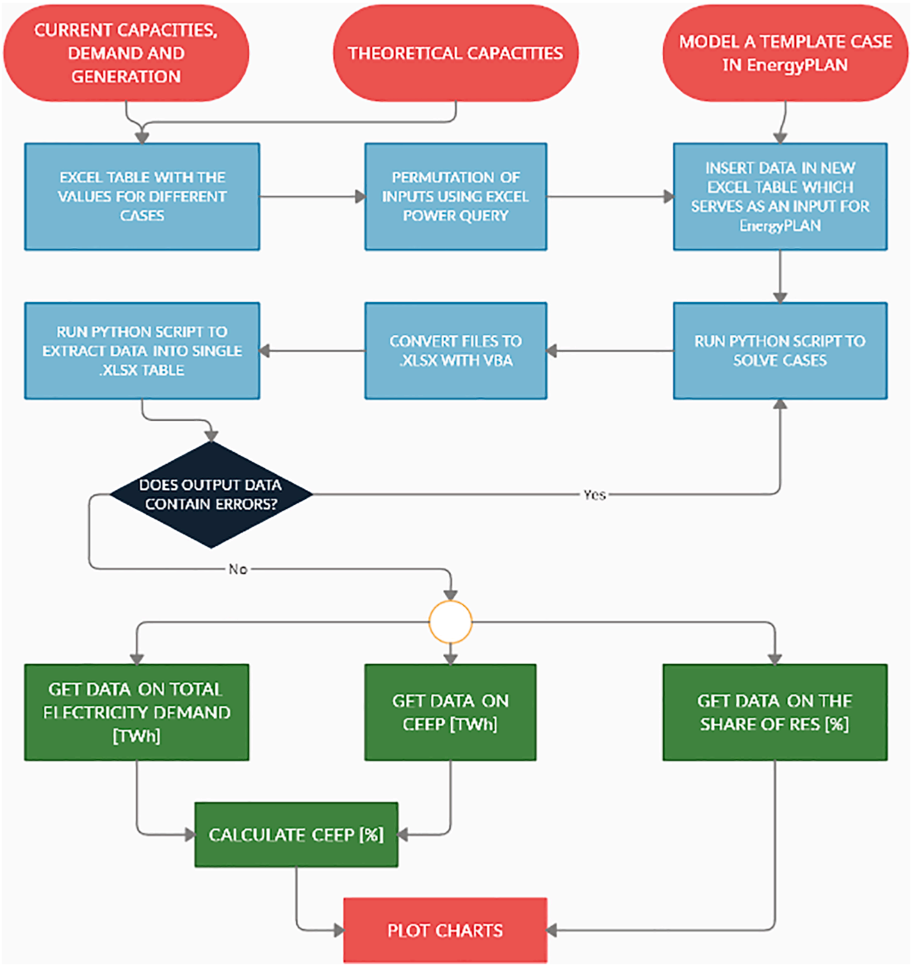

Fig. 2. Flow chart of the proposed method.

an indicator of inflexibility of the energy system to integrate higher shares of VRES, summarizing the production consumption mismatch in each hour in one year (8774 h in EnergyPLAN). With flexibility provided, either on supply, demand or network side, this mismatch is decreased. The yearly CEEP (mismatch) under 5% is considered acceptable.

Sources of flexibility usually considered in flexibility vector, consisted of six (6) flexibility options:

1. Flexible operation of thermal power plants. Flexible operation of the dispatchable power plants, including all plants powered by oil, coal, gas and biomass. This is taken into account through a minimal operational load of such production units. If the minimal load is high (close to the nominal capacity), the flexibility is low.
2. Flexible Heat. Power to heat option as a synergy between electricity and heat energy production sectors
3. Flexible electrified transport. Road transport electrification can be simulated as dump charge, smart charge and vehicle to grid mode of operation. While dump charge is just an additional load, smart charge is a demand response option, while V2G mode is a smart storage option.
4. Flexible Demand. Flexible demand representing demand response in households, services and industry. These can be expressed as daily, weekly and monthly flexibility of demand.
5. Flexible Short and mid-term Storage. Stationary batteries, PHS and high temperature heat storage
6. Flexible Long term Storage. Hydrogen and synthetic fuels storage and use

In order to demonstrate the influence of flexibility options, firstly, named “flexibility vector” is introduced. The goal of flexibility vector is to give information of amount of flexibility being used in comparison to the maximal identified flexibility on disposal for the given system (Eq. (1))

$$\boldsymbol{F}_s \overset{\text{def}}{=} (F_1, F_2, \cdots, F_n) \tag{1}$$

$$F_i \in [0, 100], \forall NRES \tag{2}$$

Where:

$\boldsymbol{F}_s$ – is flexibility vector of the scenario s for the national energy system $NRES$

F_i – is flexibility index of the flexibility option i scenario s for the national renewable energy system $NRES$

n - number of flexibility options for the national energy system $NRES$

$NRES$ – National Renewable Energy System

Such definition of flexibility vector allows that it each flexibility option might be set separately from 0 to 100 % of its availability. For some options availability is limited (by consumption limits, technical limits, geography, legally …) but for another the limitations are only financial mater (e.g. storage). Number of flexibility might be limited as well for different reasons (e.g. computation) and therefore only certain levels of renewable energy into the system penetration might be achieved. Talking about 100% renewable energy system number of needed flexibility options progresses dramatically (as well as computation requirements). The increase of the of flexibility after the usual flexibility options are exhausted, therefore might be achieved with additional flexibility options.

$$N = n + k \tag{3}$$

Where:

k - is number of additional flexibility options.

The each flexibility option has several parameters which also need to be defined therefore flexibility option vector is defined

$$\mathbf{F}_{s,i} \overset{\text{def}}{=} (F_1, F_2, \cdots, F_m) \tag{4}$$

Where:

$\mathbf{F}_{s,i}$– is vector of flexibility option i for the scenario s

A number of needed flexibility options is achieved through iterative process, after screening of installed capacities and storage capacities of the technologies listed above. Firstly, the desired level of renewable energy is calculated from final energy demand and added into the reference energy system scenario. Then, usual flexibility options are included into the search space. Search space is created by defining the flexibility vectors and simulation of the multiple scenarios. After the flexibility vectors are defined, a value for each flexibility option and flexibility option parameter is obtained:

$$FV_{i,j,s} = F_{i,j,s} * \frac{FV_{max,i,j}}{100} \tag{5}$$

$FV_{i,j,s}$ – used value of parameter j of flexibility option i for the national renewable energy system *NRES* in scenario s

$F_{i,j,s}$ – is flexibility index value of parameter j of flexibility option i for the national renewable energy system *NRES* in scenario s

$FV_{max,i,j}$ – maximal available value of the of parameter j of flexibility option i

This approach allows that each flexibility option parameter, or flexibility index might be set separately when the higher quality of the results is needed. For the first approximation, the flexibility index might be defined for all flexibility options and flexibility options parameter using the Eq. (5). In the fully separated introduction of flexibility options to each scenario, flexibility index will be a matrix dimension of n × m, to define each of m parameters of n flexibility options. If parameters within single flexibility options are uniform, then flexibility index will be a vector of n values, for each of n flexibility options. For the simplest scenario, all flexibility options are applied uniformly (from 0 to their maximal values) the flexibility index for one scenario will be an index (number 0–100).

5. Case study and results

5.1. Case study of Bulgaria

Bulgarian energy system consists of 4000 MW of condensing thermal power plants of which 1541 MW is available in back pressure mode. While in condensing mode, 99% power plant capacity is supplied by coal, while natural gas supplies 43% CHP energy generation. Biomass contributes with 5% of energy demand in CHP. Bulgaria operates Kozloduy nuclear power plant with 4 active units at nameplate capacity of 440 MW each accounting to 1966 MW in total. It also plans to construct new 1250 MW unit in the following years. Accounting for decommission of older units, it is estimated to operate 2000 MW in the year 2030. Hydropower has limited potential in Bulgaria. It currently operates 1537 MW of hydropower plants with yearly production of about 2.5 TWh. Heating demand accounts to 21 TWh of which 56% is supplied with district heating systems. Road transportation mainly relies on diesel fuel accounting for 53% with the rest being petrol and LPG. Electric propulsion corresponds to 11% of total mileage travelled, but it does not participate in grid regulation because it is assumed as "dump charge".

Several options to add flexibility vector are included in the research:

- Flexible operation of the dispatchable power plants, including all plants powered by oil, coal, gas and biomass, aggregated on the country level
- Power to heat option using electric heaters, heat pumps and heat storage
- Road transport electrification: Vehicle to grid
- Flexible power demand (demand response in households, services and industry)
- Modelling of PHS and batteries other than EV batteries

Share of RES in primary energy supply is observed in all figures. Critical excess electricity production is expressed in the results as a percentage of electricity demand. RES share represents share of energy from RES in total primary energy supply. Power plant flexibility is expressed through PP minimum – a minimal must run capacity. In Table 1 data for the energy system of Bulgaria is given, ranges for VRES are examined in calculations, flexibility options are on top of the Bulgarian National Energy and Climate Plan [44]. The table shows the ranges of possible installed capacities between NECP situation and the possible installed capacities in a system configuration that would remain in the techno-economic limits of having CEEP lower than 5% of electricity demand if appropriately followed-up with the use of flexibility options. Such calculations are performed and reported in the next chapters.

In Bulgarian NECP 2030, up to 3000 MW Solar PV is considered and up to 1000 MW new Wind installations is projected. In the calculations presented in Results chapter, values of VRES are considered for the future configuration of the system, up to the technical potential for wind, solar photovoltaic and run-of-river hydropower [45].

Determination of maximum values of each flexibility providing technology used: In order to provide replicability of this method and its application on some other case, it is required to provide the method used to determine available potential of each technology.

Sizing of V2G parameters: The amount of electricity, battery storage and charging capacity required is determined on the basis of Eurostat's data on energy consumption in transport sector and the data on motor vehicles fleet size. Furthermore, this data is combined with estimated efficiencies of electric and ICE drivetrains. From this data, a yearly traveled distance is calculated. Also, average battery capacity and charging/discharging capacity is estimated. With all of this data, an energy consumption by electric vehicles, battery storage capacity and charging/discharging capacities can be calculated. For the purposes of this paper, a maximum electrification share of 100% is assumed. Fig. 3 displays the flow chart with description of the procedure of calculating the parameters of V2G technology.

Sizing of P2H parameters: P2H is an integral part of district heating system. Its maximum capacity used in this paper is calculated to be able to satisfy 6 h of average heating season heat demand with stored thermal energy.

Battery storage and rock bed storage: Battery and rock-bed storage

Table 1
Data on Bulgarian energy system used in calculations.

Bulgaria 2030	NECP + 5% CEEP calculation
Demand [TWh]	39.94
PP [MW]	4000
CHP [MW]	1464
PV [MW]	1000–7500
Wind [MW]	3000–15,000
Hydro [MW]	3637–5537
Flexibility of power plants	0.6–1
Emissions CO2 [Mt]	32.42
RES share TPES[%]	22.3
Nuclear [MW]	2000
Total non-VRES [MW]	9849
Total VRES [MW]	2000–17,100
Peak Load [MW]	7316

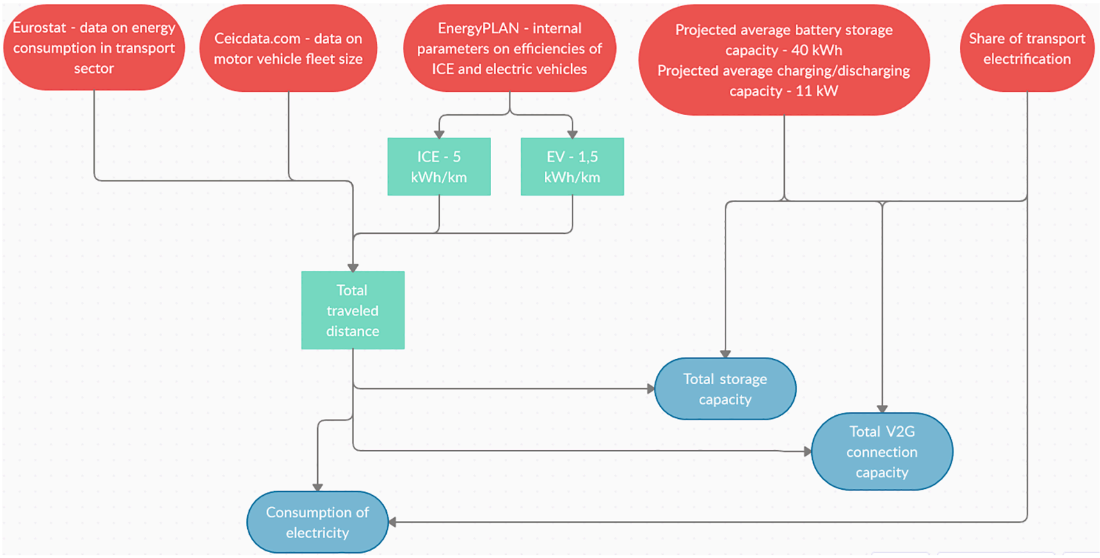

Fig. 3. Flow chart of estimation of energy consumption in transport sector and the parameters of V2G.

are also estimated each to be able to provide 6 h of uninterrupted yearly average electricity supply.

Pumped hydro storage: PHS on the other hand is because of limiting environmental constrains estimated to be able to provide 3 h of average electricity supply.

Flexible demand: It is estimated that 50% of electricity demand can offer a flexible demand response. Furthermore, this flexible demand is divided in the part that is flexible on daily basis, weekly basis and monthly basis. The division used in this case is 40% on daily, 30% on weekly and 30% on monthly basis.

6. Results

All technologies are calculated first as separate measures and aggregated effect is illustrated in Fig. 10. In each of the following figures, first curve represents the reference case with no flexibility options and only the option which values are varied is considered.

6.1. *Impact of a singular flexibility option*

First considered flexibility option deals with flexible operation of large thermal power plants. Thermal power plants that run on steam cycle have limitations in their exploitation. Critical problem is the inability to ramp up and down quickly [46,47]. Because of this limitation, this type of power plants is often dispatched even when cheaper VRES are available so this situation results in VRES curtailment. Fig. 4 shows the results of improvements in thermal power plant flexibility. Flexibility of thermal power plants in EnergyPLAN is represented with the technical minimum operating power of thermal power plants. This value is 1600 MW in the base scenario. The reduction of technical minimum to 0 MW is considered, which can be achieved by implementing technical solutions for fast start or replacing large steam cycle power plants with the smaller and more flexible gas turbine plants. Alternative to this solution are reciprocating engines that can run on variety of fuels including biofuel and synthetic fuels. As can be seen in Fig. 4, reduction of technical minimum has a significant impact on CEEP reduction and VRES penetration. This is due to ability of thermal to quickly lower or rise electricity generation in response to variations in VRES electricity generation. This flexibility option provides CEEP reduction in the range of 30 percentage points, at penetration level of 45% VRES.

Second considered measure is P2H technology. P2H acts as a coupling of electrical and heating sector [48]. It considers the use of electricity in a form of heat pumps or electric resistive heaters. The idea behind implementation of this technology is to use excess electricity from VRES for heating purposes. In that way, it is possible to utilize more

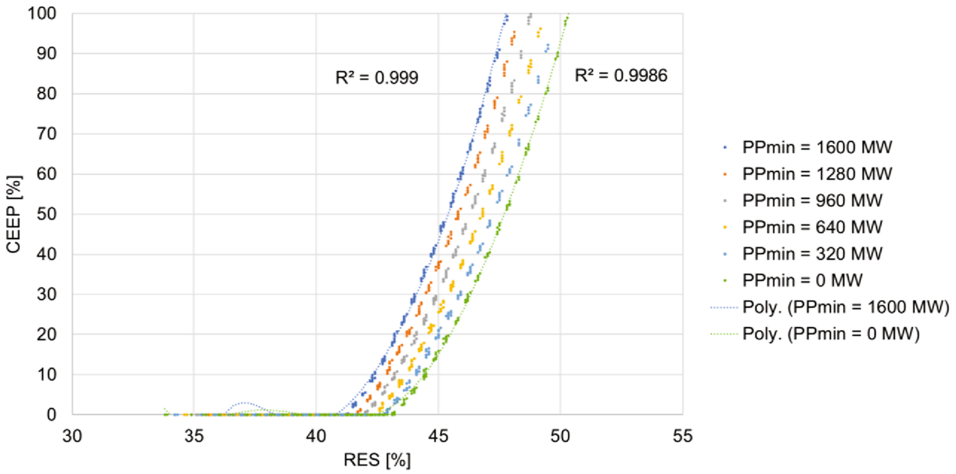

Fig. 4. Thermal power plant flexibility.

of the renewable energy which would otherwise be curtailed and in the same time reduce the usage of fossil fuels in heating sector. Due to variability of generating capacities P2H also includes the use of energy storage which allows it to shift electrical load. Fig. 5 shows the results for introduction of power to heat technology on CEEP. In this case 2000 MW of P2H capacity is introduced in a form of heat pumps in combination with 24 GWh of thermal storage. Reduction of CEEP is in this case in the range of up to 10 percentage points with difference growing larger as the share of renewables increases. This occurrence can be explained with more of the excess electricity being available and thus greater possibility of using electricity for heating purposes being available.

Another relevant energy consumption sector is transport sector. The electrification of transport provides additional possibilities such as smart management of electricity inflows with the use of technology “smart charge”. Smart charge can dictate the rate and schedule of electric vehicle’s battery charging. The goal of this technology is also mitigation of CEEP, insurance of grid stability and to provide higher share of RES. Additional component to this system is V2G which allows flow of electricity back to the grid [49]. Fig. 6 displays the results for the road transport electrification and introduction of V2G technology. In this case, 100% of road transport is electrified based on share of total number of kilometres traversed. For the purpose of V2G connection, a charging/discharging capacity of 11 kW is considered. This power level is available in most of Bulgarian households since 3 phase power supply is widely available. Available battery capacity dedicated for V2G operation is considered to be 40 kWh per vehicle. The results for this technology are very good allowing substantial reduction of CEEP from 160% to below 2% at the share of RES at 50%.

Flexible electricity demand allows shifting and modifying the electrical loads [50]. The procedure is carried out in relation to variable electricity prices. Fig. 7 shows the results for the introduction of flexible power demand. In this case, 50% of demand is considered to be flexible. Out of flexible demand, 40% is estimated to be on daily basis, while 30% is on weekly and monthly basis. Results provide CEEP reduction in the range of 10 percentage points.

Nuclear power plants regularly operate at constant power levels, but same as conventional power plants have an ability to modify its output [51]. Fig. 8 displays the results for flexible operation of nuclear power plants. Achievable CEEP reduction is in the range up to 120% of electricity demand.

Decarbonization of industry offers demand response through P2G technology and demand response for some processes [50]. In this case half of the decarbonized energy demand is switched to electricity, while the other half is satisfied with hydrogen. Production of hydrogen is an energy intensive process and requires large amounts of electricity, which can in turn be flexibly operated. Also, hydrogen as an energy carrier can be stored for later use. Fig. 9 displays the results for industry decarbonization. In this case there is also significant increase of the share of RES as fossil fuels are being displaced by electricity and hydrogen.

6.2. Combined effect of the implementation of flexibility options

When all the proposed flexibility options are considered as implemented harmoniously and present at the same time in the energy system’s configuration, high share of VRES in the total energy consumption can be achieved. Fig. 10 shows the results of combination of all above mentioned technologies. Blue curve at the range of RES integration from 40 to 45% shows reference Bulgaria scenario. This scenario does not include any of the flexibility measures, while the large capacities of RES including PV, wind power and hydro power are added to the system. Substantial increase of CEEP occurs at as low as 40% of RES in total energy consumption. Every following curve marks the addition of one new technology and its effect on CEEP reduction. Relations between the curves thus may not reflect the relations in the previously discussed figures. With every new technology addition, the improvements are smaller than in the previous step and thus it is important to choose the optimal combination of technologies and order of implementation. This figure shows that it is possible to achieve even 73% of total RES share with CEEP below 5% and with the implementation of RES capacities within Bulgaria’s technical potential [44,45].

6.3. Economic comparison

The cost of the change of configuration of the energy system is also considered from economic perspective, taking into account investment and operational costs. Technology lifetime, operation and maintenance and predictions of fuel prices in the future are calculated based on the data from Danish Energy Agency [52] and EnergyPLAN Cost Database [53]. The cost for fuels were sourced from Heat Roadmap Europe project [54]. In such way, various cases are compared on the basis of Total annual cost. Results are shown in Table 2, and in Figs. 11–14. It is visible that the systems with lower CEEP have lower annual costs. This is due to the fact that systems with higher CEEP tend to have higher share of unused capacities in RES. Instead, expensive to run, fossil fuel power plants continue to operate while RES capacities are being forced to switch off.

Table 3 gives an overview of the costs and conditions used for the calculation with various flexibility options.

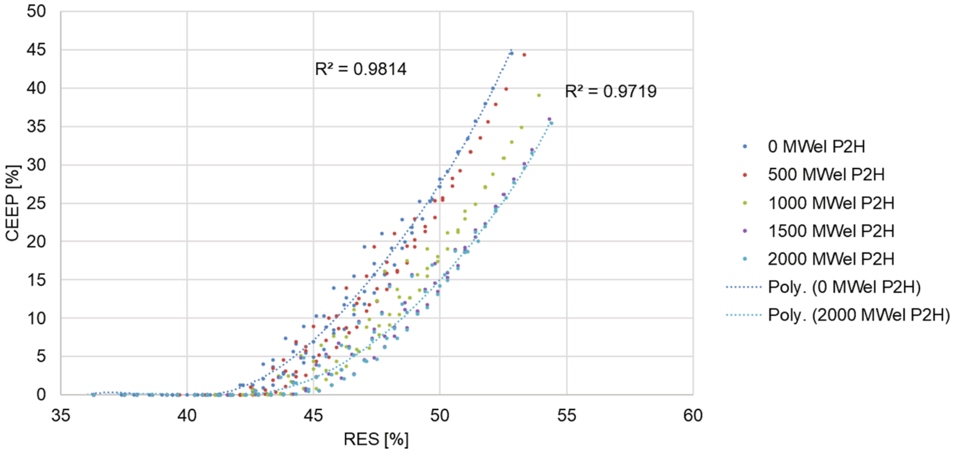

Fig. 5. Power to heat.

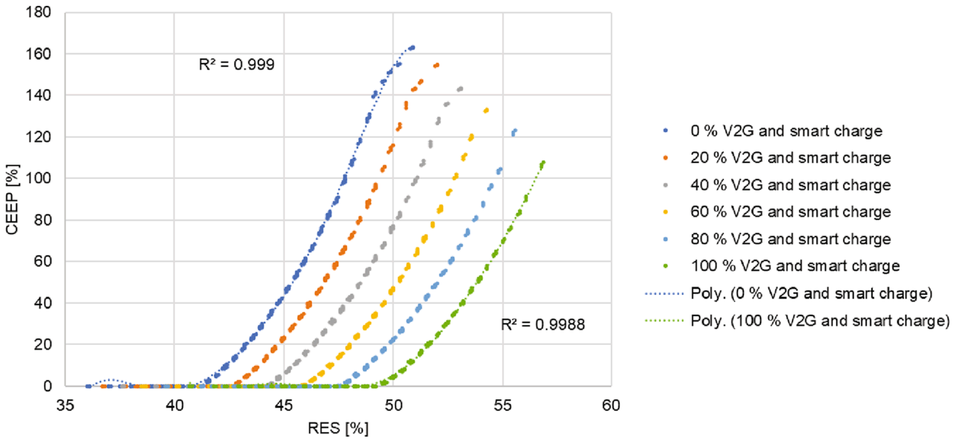

Fig. 6. Vehicle to grid.

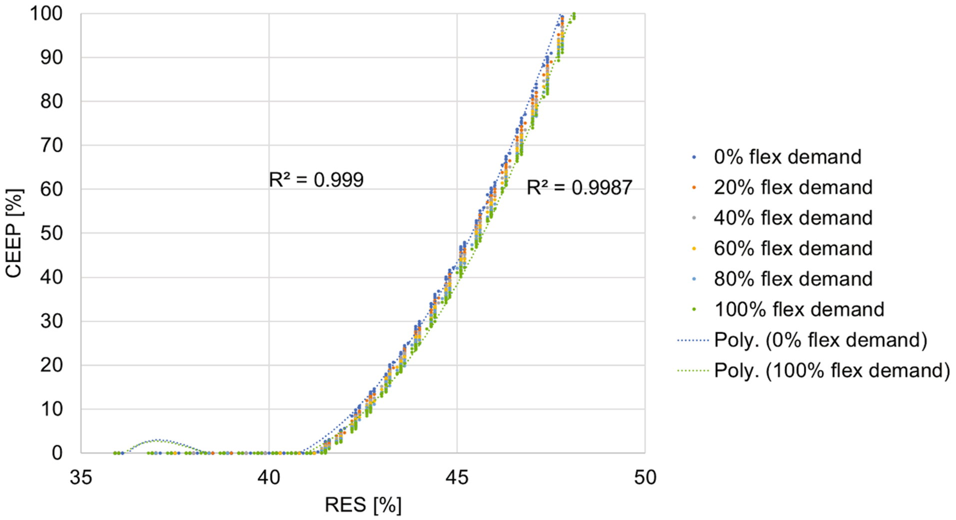

Fig. 7. Flexible demand.

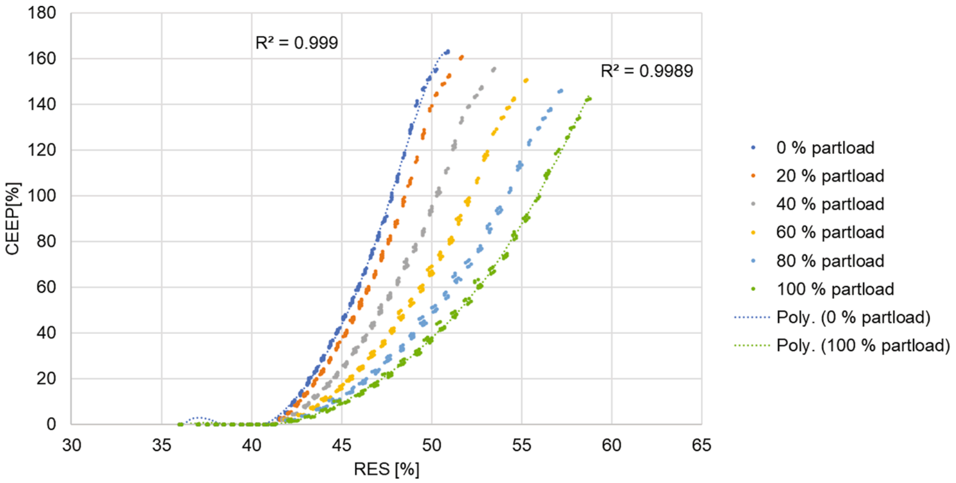

Fig. 8. Results for flexible operation of nuclear power plant.

7. Discussion

The results which display the relations between the share of RES, CEEP, biomass consumption, total annual cost and CO_2 emissions are displayed in Figs. 11–14. All of these charts are made using the same installed capacity of VRES such as wind power (at 20,000 MW) and Solar PV (at 20,000 MW) respectively. The measures are introduced gradually and in a way that each data point represents the data from the previous

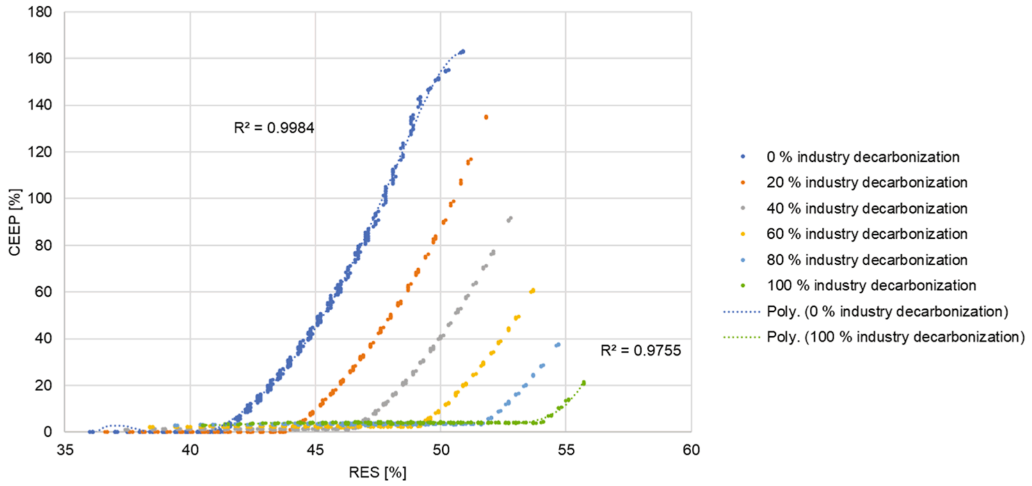

Fig. 9. Results for industry decarbonization.

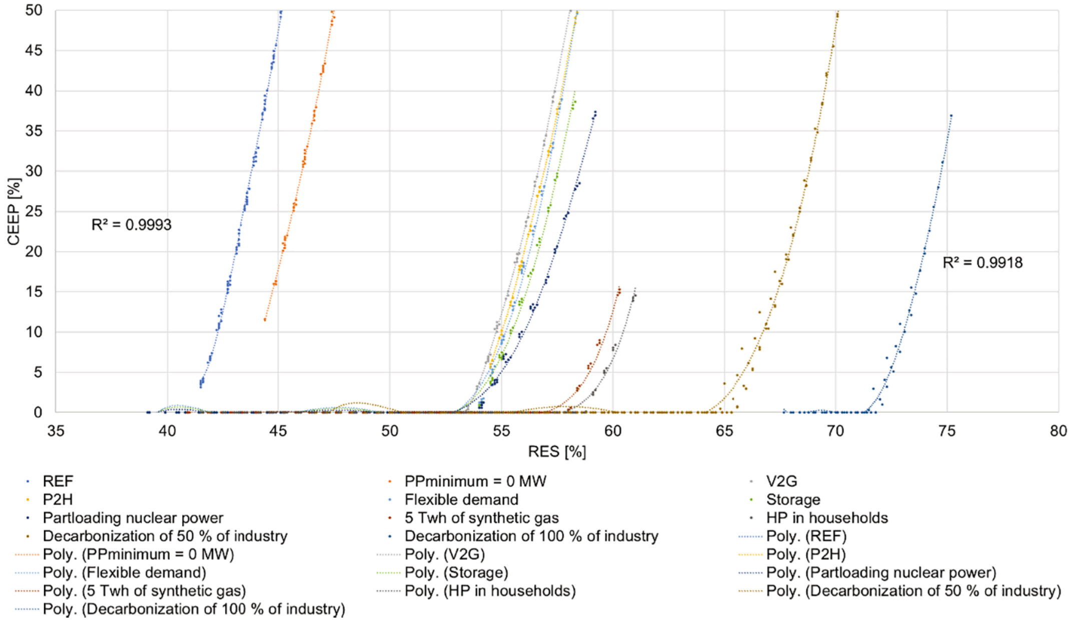

Fig. 10. Aggregated results.

Table 2
Results for Wind = 20,000 MW and PV = 20,000 MW.

Scenario	RES	CEEP	Total annual cost	CO_2 emissions	Biomass consumption
Unit	%	%	M€	Mt	TWh
Reference	50.9	164.44	17595.84	17.1	36.54
PPmin reduction from 1600 MW to 0 MW	51.1	124.70	16304.04	13.84	20.61
V2G	58.1	51.30	15197.26	6.40	17.87
P2H	58.4	49.78	15292.92	5.93	15.6
Flexible demand	58.4	51.58	15257.06	5.75	14.7
Energy storage	58.1	39.79	15333.06	5.63	14.13
Partload nuclear	59	38.61	15333.06	5.63	14.14
HP HH	59.6	37.63	15276.32	5.25	14.2
Decarbonize 100% of industry	66.7	0	15225.02	1.76	18.85

case with the addition of one new technology.

The base case, with no flexibility options implemented, provides 51% of RES share, but the CEEP is extremely high (162% of total electricity demand). Gradual introduction of flexibility options in this case leads the given configuration towards 67% RES based energy system. The flexibility options are introduced in the order given in the legend of Fig. 11, from the top one (Reference case) to the lowest one (industry decarbonization). The addition of flexibility options causes the reduction of CEEP to 0. This also means that all of the generated energy from VRES is being used up and thus providing the increase of the share of RES.

CO_2 emissions reduce in this case from 17 Mt to under 2 Mt (Fig. 12).

Biomass use decreases as shown in Fig. 13 from 36 TWh in reference case to below 20 TWh for the systems with higher installed flexibility options capacity.

Fig. 14 displays the results for the total annual cost of the system. With introduction of flexibility, total annual cost decreases from 17,600 M€ for the case with no flexibility to the range between 15,000 and 15,500 M€ for the cases with higher amount of flexibility. High cost of the reference case is because of that it considers high capacities of VRES

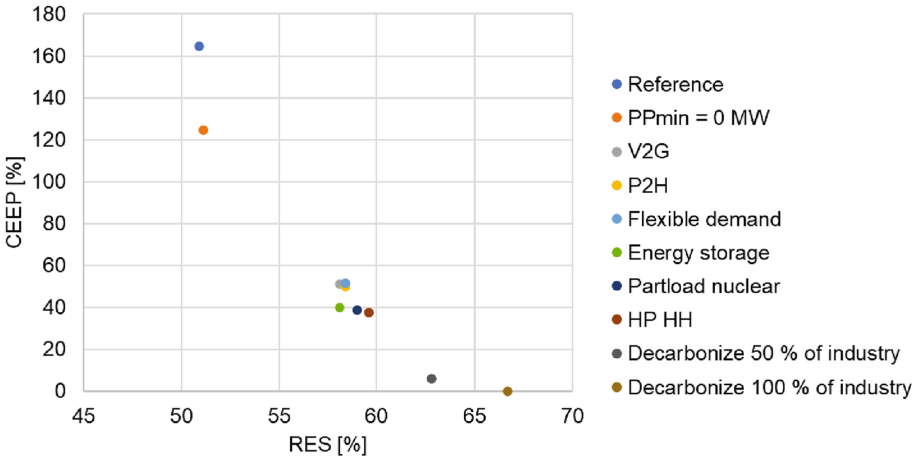

Fig. 11. Results for CEEP at wind = 20,000 MW, PV = 20,000 MW.

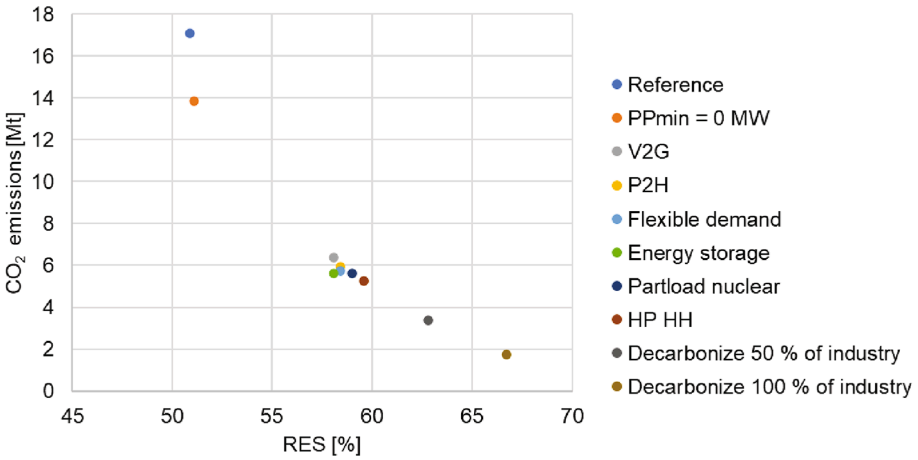

Fig. 12. Results for CO_2 at wind = 20,000 MW, PV = 20,000 MW.

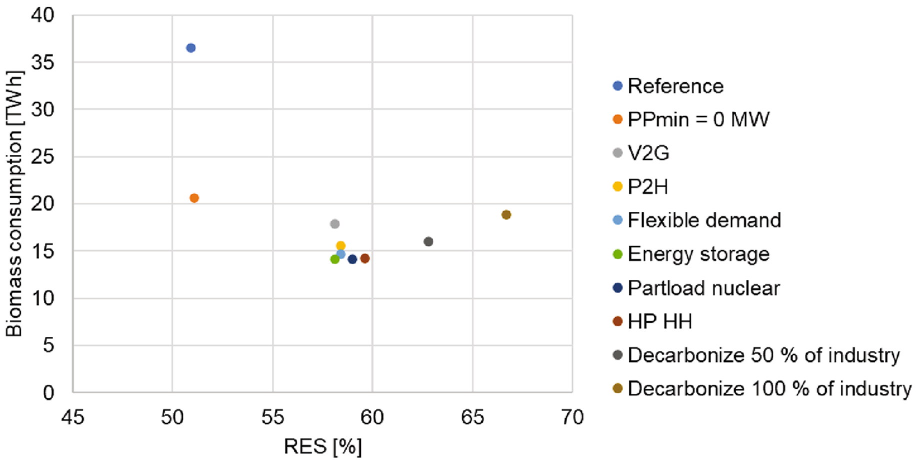

Fig. 13. Results for Biomass consumption at wind = 20,000 MW, PV = 20,000 MW.

with no flexibility options. That means that VRES have low capacity factor and thermal power plants have to provide big part of electricity demand. Therefore, system has high investment cost for VRES as well as high operational cost for the fuels. Additional reason for the decrease of the cost is projected lower cost for the electric vehicles in relation to the ICE vehicles.

7.1. Flexibility index

With the introduction of flexibility measures correlated to the flexibility index, average CEEP decreases from unsustainable values above 150% of electricity demand for the value of “flexibility index” bellow 10% to the values of CEEP below 5% for the higher amount of flexibility

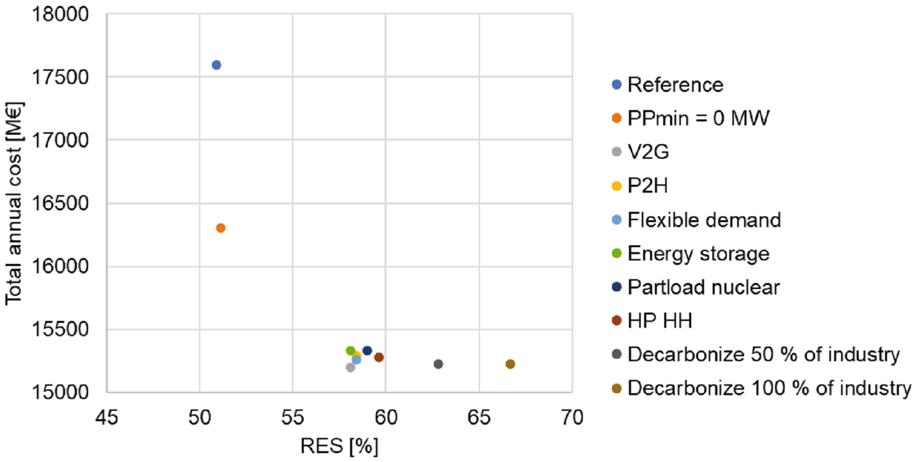

Fig. 14. Results for Total annual cost at wind = 20,000 MW, PV = 20,000 MW.

Table 3
Cost of flexibility measures [47,52,53,55,56].

Measure	Cost [M€/ unit]	Lifetime [years]	Operation and maintenance [%]
Power plant flexibilization	6 (per 100 MW unit)	10	1.5
Conventional vehicle (2030)	0.031	12	1.5
Electric vehicle (2030)	0.025	12	1.5
Smart meters (demand flexibilization) for households and commercial sector	0.0002	20	1.5
Smart meters (demand flexibilization) for industry sector	0.0006	20	1.5
Electric battery storage	60 M€/ GWh	20	1.5
High temperature storage	4.25 M€/ GWh	50	1.5
DH Heat pump	3.18 M€/ MW	25	0.3

being used as indicated by flexibility index above 60%. The results are displayed in Fig. 15. The notation of legend displays the capacities of wind power, PV and ROR. For example, the first case has a notation of [20 W 20 PV 08 ROR] which means that this case has installed capacity of 20 GW wind power, 20 GW PV and 800 MW of ROR.

Fig. 16 displays the Total annual cost as it decreases with the introduction of flexibility from 17,500 M€ at lower installed capacity of flexibility to the range between 14,300 and 15,000 for the value of flexibility index = 100%. In other words, this equates to reduction of annual cost up to 18%. The same figure displays the increase of the RES share as an inverse relation with the costs.

Fig. 17 displays the results for annual investment cost which's average value increases with the increase of the flexibility index's value. For the case with lower amount of flexibility, the value of annual investment is in the range from 59,800 M€ to 60,500 M€, while for the value of flexibility index at 100%, value of annual investment is between 59,900 and 60,800 M€. The increase of investment cost equates to increase of about 0.5% of baseline cost with flexibility index equal to 10%. There is a wide range of values due to the differing VRES configurations.

Fig. 18 displays the results for the operating costs. Operating costs tend to be higher for low flexibility index value with approximate value of 52,700 M€. Application of flexibility options causes the reduction in operating costs and can reduce it all the way to 49,300 M€ or 7% or original value. Additional observation is that not all of the cases reach the value of flexibility index = 100%. The cause of this can be inability of the system to satisfy all of the operating requirements and system stability requirements. For example, the lower most line represents the system with 6 GW of wind and PV and 800 MW of Run of the river hydropower. This system cannot maintain stability when there is a necessity for high energy intensity technologies such as electrolysis and synthetic gas production due to the lack of required energy for such operations.

Fig. 19 displays the results for biomass consumption. It can be observed that the consumption of biomass is lower at the systems with

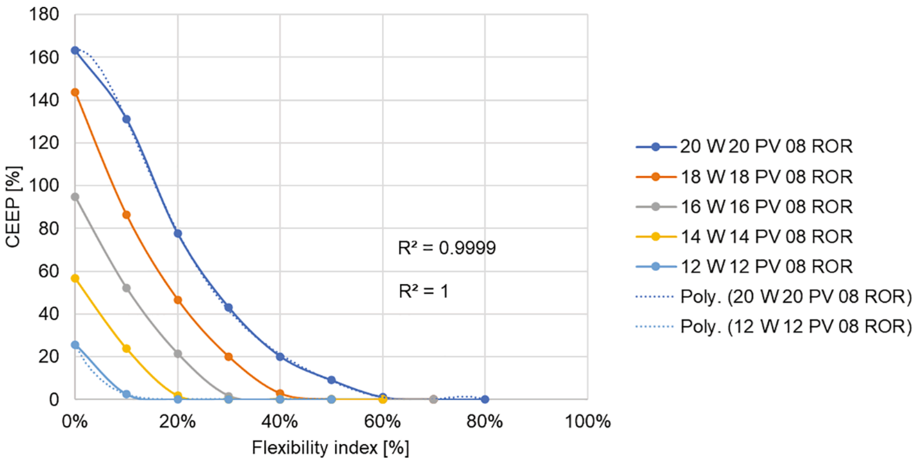

Fig. 15. Relation of CEEP and flexibility index.

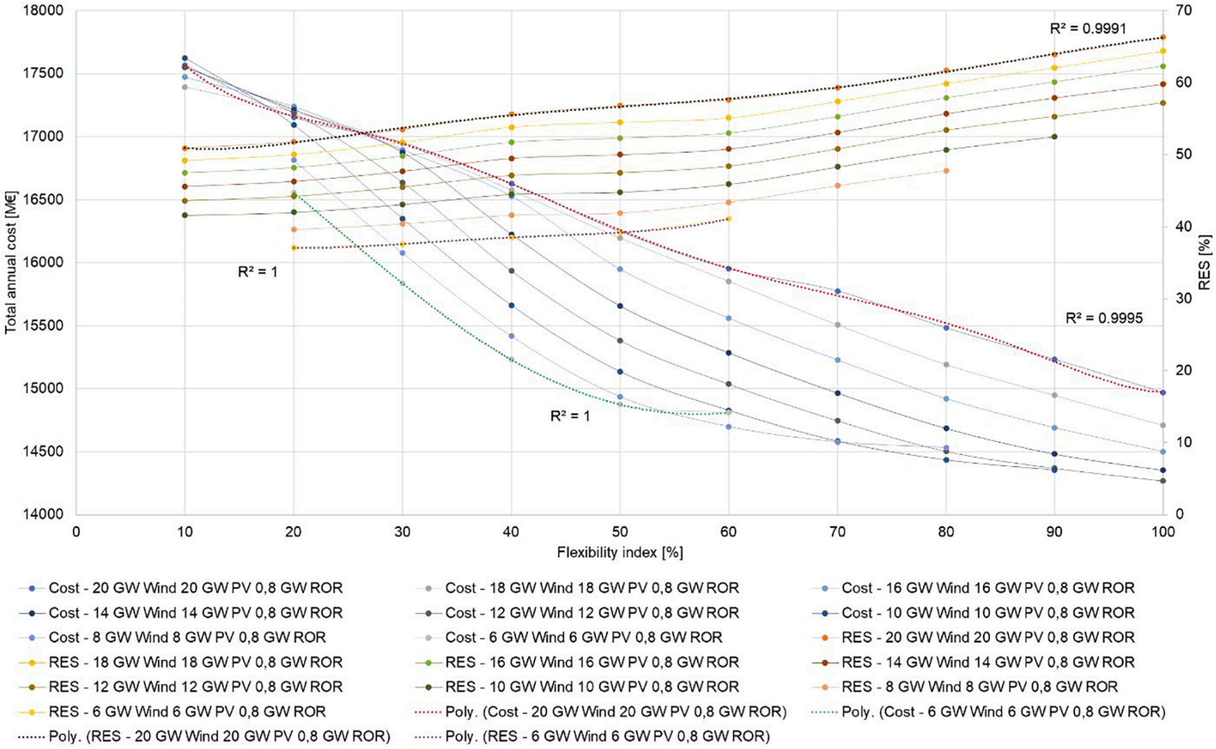

Fig. 16. Relation of Total annual cost and flexibility index.

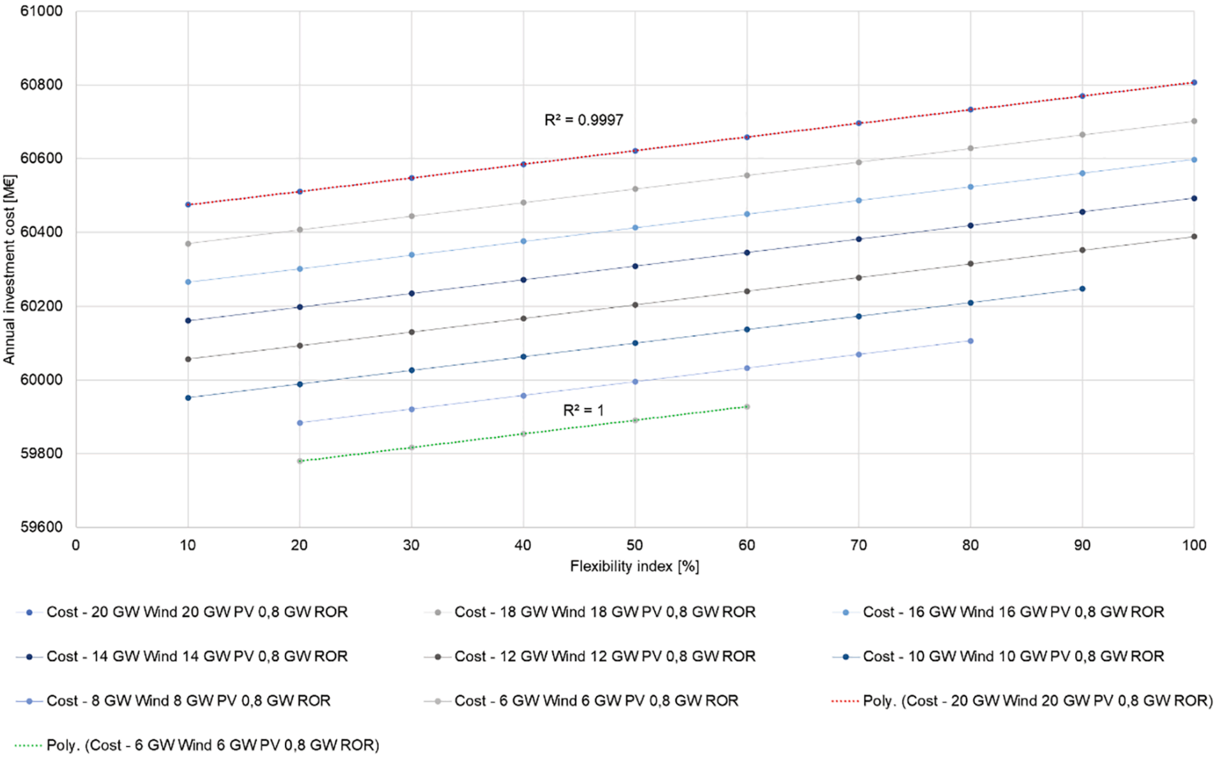

Fig. 17. Relation of Annual investment and flexibility indicator.

higher value of flexibility index which is due to the higher utilization of electricity of VRES facilities.

It can be also beneficial to display the values of flexibility index and their results as reflected with the share of RES and CEEP. Fig. 20 displays the results for the installed capacity of wind power at 20 GW, PV at 20 GW and run of the river at 800 MW. Each of the values displayed in brackets on the chart displays the level of flexibility option utilization. Level of utilization is between 0 and 1. Table 4 displays the notation for flexibility index used in Fig. 20. The difference in relation to the results in Fig. 15–19 is that in this case the values of VRES generation capacities

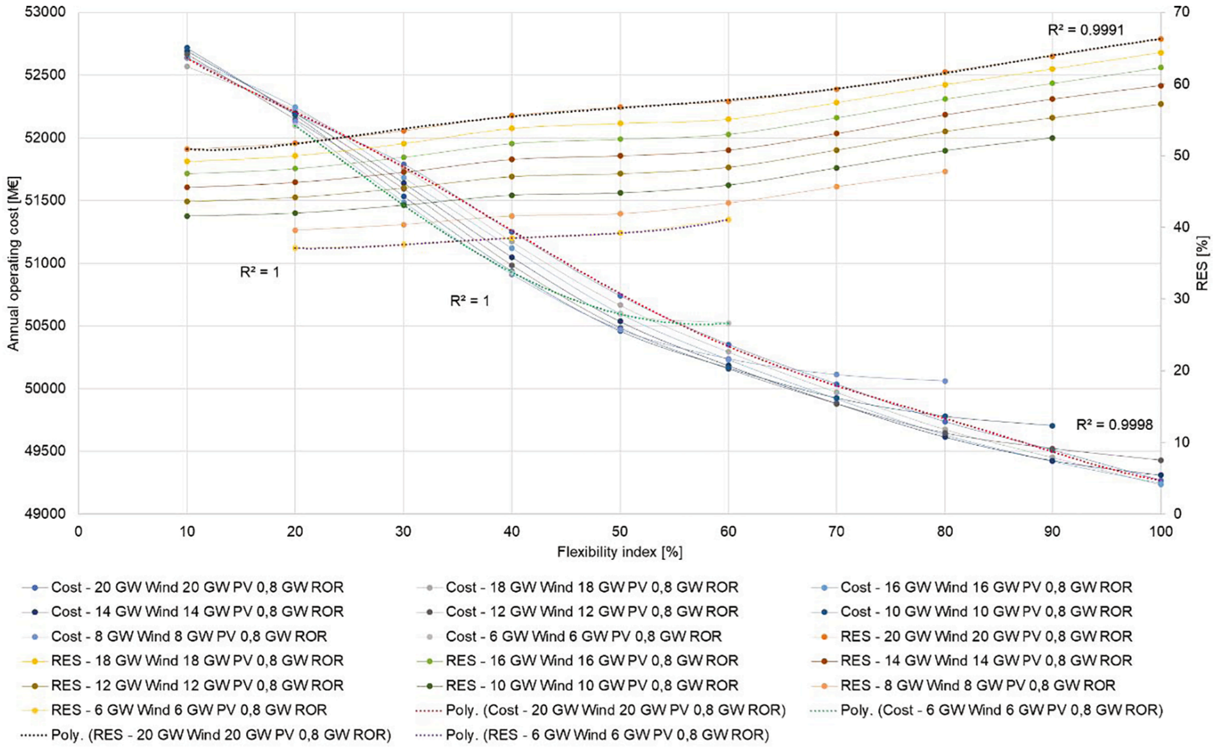

Fig. 18. Operating cost.

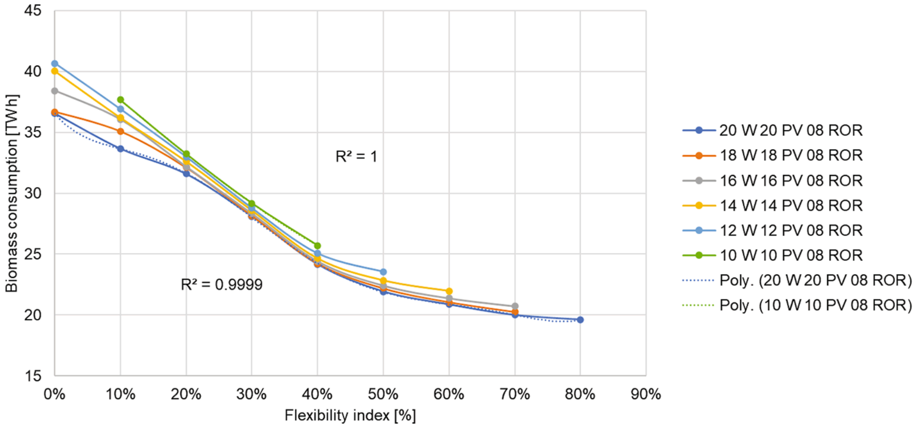

Fig. 19. Relation of Biomass consumption and flexibility index.

are fixed, while considered flexibility options can come up in various combinations.

Generally, the use of flexibility options (higher flexibility indexes) tend to lower CEEP, emissions, cost and achieve higher share of RES. Following charts display the combination of flexibility options and the composition of flexibility vector in relation to factors such as CEEP, emissions, total annual cost and share of RES. For example, the composition of flexibility vector's parameters for the cases with lower CEEP has more flexibility index values close (or equal) to 1. Case with values [0 0 0 1 0 0] has high CEEP value and relatively low share of RES achieved, while the case with flexibility vector composition [0.75 1 1 1 1 1] has one of the lowest CEEP values and high share of RES achieved.

An additional observation some flexibility options have different contribution to the goal functions. For example, primarily short and mid-term energy storage which has significant effect in achieving minimal CEEP as goal but lagging in reaching the maximal possible share of RES goal. On the other hand, industry decarbonization has greater contribution in the increase of the share of RES and is more intensively used in scenarios with higher (50–70%) share of RES. The industry flexibility option (IND = 1) dominates the lower part of the solution space, while contrary (IND = 0) dominates upper space, which is visible from the Fig. 20.

The emissions of carbon dioxide as sustainability indicator also decreases with the increase of flexibility index. For example, the case with high emissions presented in Fig. 21. has a flexibility vector composition of [0 0 0.5 1 0 0] which are predominantly low values. On the other hand, the system with low emissions in the same figure has a flexibility vector composition of [0.75 1 1 0.75 0 1] which are predominantly high values and represent high utilization of flexibility options (high flexibility indexes).

Total annual cost also decreases with the increase of flexibility indexes. Fig. 22 displays the results for flexibility vector in relation to total annual cost. It can be noted that it is also in this figure visible that not all of the options have the same significance in cost reduction. For example,

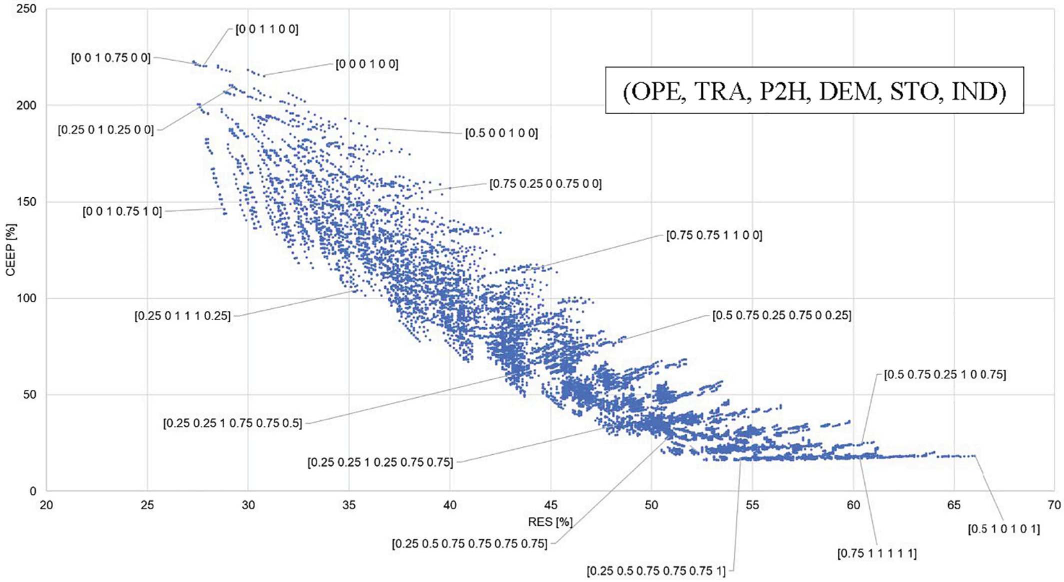

Fig. 20. Relation of CEEP, share of RES and distribution of some of the cases with their flexibility vector values (OPE, TRA, P2H, DEM, STO, IND).

Table 4
Flexibility index notation of flexibility option.

Place in the vector	1	2	3	4	5	6
Flexibility option	Thermal and nuclear power plant operation flexibility	Transport electrification with the use of smart charge and V2G	P2H	Demand flexibility	Short and mid-term energy storage	Industry decarbonization with hydrogen and electrification
Abbreviation	OPE	TRA	P2H	DEM	STO	IND

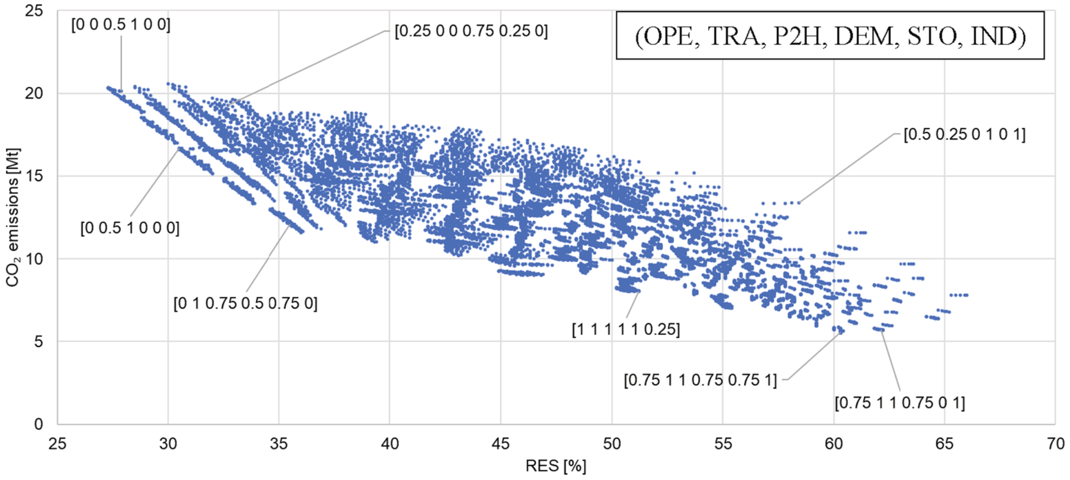

Fig. 21. Values of flexibility vector with relation to the share of RES and CO_2 emissions.

the introduction of smart charge and V2G is in a strong correlation with decrease of total annual costs.

This can be measured comparing the k in the equation $y = kx + n$, where: $y = \Delta$ Total annual cost and $x = \Delta$ RES share. The k value is higher for two scenarios with constant flexibility vector except TRA index, then for other scenarios where other index is variated.

The progressing of goal functions with changing of flexibility vector can be further documented by variation of only one index and keeping the other constant, which will primarily be the direction of future work.

8. Conclusion

In this research, a method is proposed for soft-linking EnergyPLAN model with a Python code, to enable calculation of large number of scenarios. Such method is used to study the changes in VRES integration and critical excess electricity production for a single country energy system, depending on the use of chosen flexibility options. Flexibility options which were studied are: flexible operation of power plants, implementation of P2H concept in district heating systems, V2G concept in electrified road transport, flexible load as demand response of the end user groups, high temperature heat storage, stationary batteries, synthetic fuels and pumped hydro storage. The considered flexibility

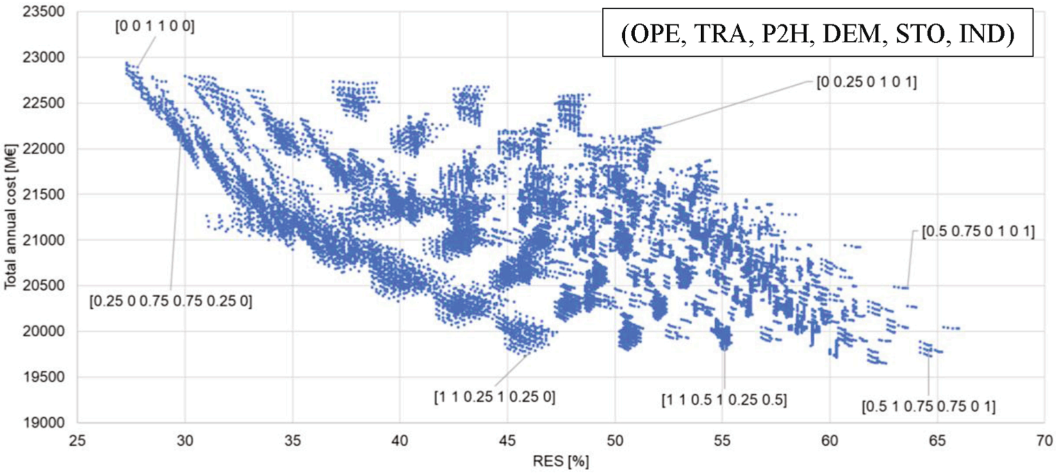

Fig. 22. Values of flexibility vector in relation to total annual cost and share of RES.

options have been introduced one by one and finally the aggregated impact was demonstrated on the case of Bulgaria. Also, the flexibility options have been compared in terms of the influence on the system: RES share, CEEP, CO_2 emissions, Total Annual Investment and Total Annual O&M cost. Based on results, the following conclusions can be made:

- The spread of values of planning criteria (energy, costs, emission, and biomass) for the constant flexibility index reached is shown to be significant, which underlines the need of soft linking and the automation of the energy planning process. Each scenario should be carefully analyzed by the planners, afterwards.
- The total annual cost of highly renewable energy system falls with flexibility index increase, which suggest that investments in flexibility options is economically reasonable.
- The total annual cost of highly VRES energy system falls with CEEP decrease based on utilization (more operation hours during the year) of certain infrastructures (generation, storage, transmission …).
- New flexibility index and flexibility vector have been introduced as a methodological tools to distinguish between different scenarios, where flexibility index reports on the use of particular flexibility option, while flexibility vector defines the whole scenario by listing all the flexibility indexes for all the implemented technologies.

Compared to the previous approaches, results of this study bring forward a method that can be used to decarbonize the energy system from both ends, power and heat generation and energy consumption (per sector). It is based on a simulation approach, which leaves the possibility for informed political decision on the particular scenario to choose. Flexibility vector offers the unique designation to each of scenarios, so the interested party can understand the trade-off that is made through the choice of scenario (e.g. the technology mix used to obtain the goal in form of the RES share in total primary energy supply). One of the important observations that can be deduced from the results is that Total annual cost of the observed system decreases with the introduction of flexibility from 17,500 M€ (at lower installed capacity of flexibility) to the range between 14,300 and 15,000 M€ for the value of flexibility index = 100% (Fig. 16).

The effect of order and time span of the implementation of applied measures to CEEP deserves to be explored in future. Also, relevant flexibility options change with the share of RES in the energy mix and the level of their integration in the energy system. For the last portion of the energy transition, between 80% and 100% RES energy systems, the open question for research remains which smart technologies and synergies should be employed to decarbonize the system and if the level of CEEP that is acceptable in such system remains the same as it was considered in this study.

CRediT authorship contribution statement

Antun Pfeifer: Conceptualization, Data curation, Writing - original draft, Investigation, Software, Methodology, Writing - review & editing. **Luka Herc:** Data curation, Writing - original draft, Investigation, Conceptualization, Methodology, Software, Writing - review & editing, Visualization. **Ilija Batas Bjelić:** Conceptualization, Methodology, Writing - review & editing. **Neven Duić:** Conceptualization, Resources, Supervision, Funding acquisition.

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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Annex 1.

Manipulation with inputs and all the sub-steps are organized as follows. The data from the set of tables is processed with the "Power Query" tool in "Excel" in order to make combinations of data that provide similar final solution in terms of achieving the targeted share of RES. The next step is to create a scenario in EnergyPLAN and save it. This is required because not all of the input data variables are being changed from case to case, but only one. Also, this .txt file in which previously mentioned EnergyPLAN model is saved, serves as a template in the next step among 5000 steps of brute force calculations of permutated inputs. Such data is used in excel with the permutations of input variables from table mentioned before, to create final input data table. In the table created in that process, each column corresponds to a different scenario. For the next step, the Python code (version 3.8) is introduced. First part of the code reads previously created .xlsx file and creates a series of .txt files each corresponding to one column, lately used as input files to EnergyPLAN. This is done with the use of "openpyxl" addon in "Pycharm" compiler. This .txt files are in second part of the code used as an input one by one. Second add-on, “pyautogui”, is used in this step. It executes EnergyPLAN.exe and then with the use of “pyautogui”, runs simulations and loads input files one by one in EnergyPLAN. The results from EnergyPLAN are after that post-processed in Excel. After the process is completed, the results of each of the simulations are saved in corresponding .csv file. These files are consequently converted to .xlsx files in order to be readable by “openpyxl”. This is done with the VBA script. When all files are converted to .xlsx, a new part of python code is executed. This step uses “openpyxl” add-on to read predetermined cells from consecutive .xlsx files and write data in predetermined rows, one column at a time.

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