Batas-Bjelic, Ilija; Rajaković, Nikola; Pfeifer, Antun; Herc, Luka; Duić, Neven, Flexibility Options in 100% Renewable Energy World Regions *// Proceedings of 16th Conference on Sustainable Development of Energy, Water and Environment Systems – SDEWES* / Ban, Marko et. al. (ur.). Zagreb: SDEWES, 2021. 0064, 18

Flexibility Options in 100% Renewable Energy World Regions

Ilija Batas Bjelic[1]
Institute of Technical Sciences of SASA, Knez Mihailova 35/IV, Belgrade, Serbia
e–mail: ilija.batas-bjelic@itn.sanu.ac.rs

Nikola Rajakovic
School of Electrical Engineering
University of Belgrade, Bulevar kralja Aleksandra 73, Belgrade, Serbia
e–mail: rajakovic@etf.rs

Antun Pfeifer, Luka Herc[2], Neven Duic
Faculty of Mechanical Engineering and Naval Architecture
University of Zagreb, Zagreb, Croatia
e–mail: Neven.Duic@fsb.hr

ABSTRACT

Designing the energy systems for high variable renewable energy penetrations, one should look for the flexibility of an energy systems that may be provided from various sources at supply, demand or network level. The flexibility can be provided from different options including, but not limiting to: (1) electricity demand (household and industry), (2) thermal (power, CHP) plants, (3) power to heat (CHP, heat pump district/individual), (4) transport (V2G + smart charge, synthetic fuels), (5) interconnection and (6) storage (batteries, pumped hydro, rockbed, compressed air, hydrogen…). The flexibility might be provided according to different criteria: economics, technical complexity, utilization, acceptability, feasibility, material use. Further, different constraints regarding percentages, shares, emission reductions… might be set according to proclaimed sustainable energy policy in certain region. Therefore, we will simulate various flexibility options according to their availability and priority assumed by authors for each region of nine World regions (USMCA, Latin America, United Kingdom, China, Russia, South-East Asia and Oceania, Rest of the world,) using EnergyPLAN-Python permutation framework . This way number of synthetically generated temporary scenarios before finding optimal one and the execution time is increased in comparison to optimization approach.

KEYWORDS

Flexibility, energy systems, simulation, optimization, 100% renewable, World

INTRODUCTION

Decarbonisation of European energy system, according to the Paris agreement, which is dominantly based on the increased use of renewable energy of up to 100% is technically feasible due to the different technology options of flexibility, although the discussion is still open regarding definition of this feasibility [1], [2]. The question to be solved in this manuscript (corresponding to WILIAM deliverable D7.4[3]) is rather how to optimally achieve this needed flexibility and ensure its scalability to the World levels. Therefore, this

---

[1] Corresponding author
[2] Presenting author
[3] https://www.locomotion-h2020.eu/resources/main-project-reports

manuscript is mainly EU focused to show the proof of concept, but it might be applied where justified.

The energy planning of the EU has being guided through policy objectives. The energy system also faces the electrification of the economic sectors in order to avoid activities currently based on fossil fuels. Therefore, the decarbonisation of the power sector is only possible through a high deployment of renewable technologies. The nature of such technologies demands flexibility in the power system that must be solved with some strategies, most of them based on dispatchable technologies and sector coupling with the transport and heat sectors.

To achieve ambitious goal of 100% renewable European power system, 90% more generation capacity and 240% more transmission capacity would be needed than today [3], but the question is are these figures smaller or higher in the scenarios of 100% RE system for the whole world.

The need for additional flexibility of the existing (and future) energy systems, comes from the need for integration of VRE sources without balancing issues between energy supply and demand. The flexibility options portfolio should be customized to the energy system with demand for flexibility. In addition, this portfolio can be optimized to accommodate as much as possible VRE with lowest possible investments, or any other criteria or their combination (multicriteria). According to the literature review, an increase in the level of VRE integration above 30% requires additional flexibility within the existing power system, while above 80% the flexibility becomes very costly due to the inclusion of more expensive options [4].

In order to reach the decarbonisation objectives, the model must cover the range up to 100% renewable power systems. However, logical constraints (technical, material, and economical) will be modelled in WILIAM to have coherence and consistency in the RES development.

The flexibility gap as a measure of missing flexibility might be defined via various metrics, among which one is using CEEP and EnergyPLAN simulations [5]. The flexibility gap might be created either adding more inflexible generation sources, such as but not limiting to VRES, or by performing energy efficiency measures. For the sake of simulations for reaching 80-100% in energy systems [6], even without demand flexibility [7], a significant amount of VRES should be added, at the same time with performing energy efficiency measures. Therefore this creates a flexibility gap to be filled with various flexibility options.

METHOD

The motivation for further electrification as an principle for the solving the flexibility needs of 100% RE system (based mainly on variable renewable sources of electricity) comes from the nature of electric power which is highly flexible and controllable, and it is storable at declining cost and increasing number of options. Another motivation comes from the fact that electricity is worldwide most used energy type in households without any emissions occurred during end-use. The further electrification will include not just the household as traditional end-use sector, but also transport (especially private - personal) and heating/cooling sector. Respecting the current technology options, the 100% electrification of residential and commercial sectors is viable [8], while in transport and industry some more cost efficient options may remain up to 2050. The further electrification without smartness of decreasing peak-to-average demand ratio from almost 2 to close to 1 is the key for the transition [9].

On sector coupling for managing variability

Sector coupling approach is based on the flexibility options (please refer to [10] for inflexible sector coupling) and 100% RE generation technologies, providing the electricity, heating/cooling and transport at lower costs and environmental burdens. However, sector coupling approach, nor 100% RE scenarios have not yet proposed from the IAMs community [11]. It shows some inertia regarding keeping the carbon capture and storage and nuclear energy as the “piece of puzzle” of decarbonisation, but they will face fundamental change in the operation and thus economic difficulties. Electrification of transport and heating / cooling sector coupling with power generation sector are fundamental concepts for increasing the share of variable RES - without sector coupling there is no easy solution and no hope for reaching net zero carbon integrated energy systems. Sector coupling of electricity and heat sectors appears to be most promising strategy to address decarbonisation and increased VRE shares [12] , but depends on the level of heat demand satisfied through district heating and heat pumps (in individual households). The integration of large scale of PV and wind energy at the global level should be followed with electrification and sectors coupling with transport, heat and industry sectors and further use of flexibility options such as power-to-x technologies [13], which include transformation of electricity to other useful forms of energy or e-fuels. The central flexible and highly flexible coupling scenarios enable more solar capacity to be procured: 13 and 16 percentage points by 2050 respectively more than in the inflexible coupling scenario [10]. Additional source of flexibility option is coupling with industry processes using fuel and other chemicals known as polygeneration [14]. This is a premise of 4.0 Industry concept enabling the bulk production of materials (gases, fuels…) at times of excess electricity production from VRE occurs and therefore at lowest possible environmental and material requirements. An illustration of the dynamics of energy transition are given in the Fig.1.

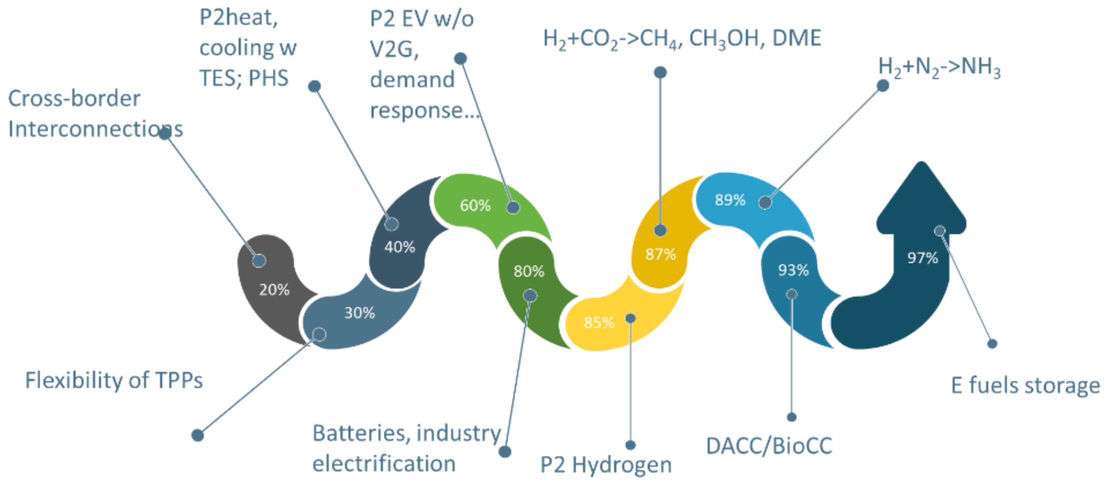

Figure 1 Flexibility options on the road to 100% RES based energy system

Capacity factors resulting from EnergyPLAN simulations

Capacity factors are most important result from EnergyPLAN simulations, since they depict unknown operation of various types of power plants in an energy system. Historical approach in energy planning was to assume CF for each power plant, without simulating its operation. This simplified approach has been used so far in the most yearly and multiyear planning studies. But, with this approach problem of capacities has not been visible in detail until recent study [15] but for U.S. One may assume infinite introductions of new capacities without a reality of competition between generation technologies to provide energy for each hour, which occurs in reality.

Since 2000s many planning tools have temporal resolution of one hour which enables the operation of different types of power plants to be simulated. The simulation ensures energy balance at hourly level, so that in each hour production and consumption is equal. As result real CFs of each plant type are obtained.

CF is defined as a relation of generated electricity and maximal generation, assuming that considered power plant works with full power during the whole considered time span, in this case 355 days (8760 hours). In EnergyPLAN year of 366 days is assumed (8784 hours) for simulation. Therefore CF for each power plant type is calculated in postprocesing as:

$$CF = \frac{E_{gen}}{8784 \cdot P} \cdot 100$$

Where:

- E_{gen} – generated electricity during one year [MWh/a]
- P – installed capacity [MW]

In the presence of flexibility options, the CFs are affected. This effect cannot be presented analytically (via equations) per se. The effect of flexibility options has to be simulated in order to obtain realistic CFs. Therefore the changes to the CFs due to the influence of flexibility options are of interest in this case.

RESULTS

This Chapter shows the results for the different WILIAM regions, as shown in Table 1 and the discusses the differences in decarbonisation priorities and flexibility strategies to be applied in each of them.

Table 1. Legend for region descriptions

Region name	Short name
European Union	EU27
India	IND
USMCA	USMCA
Latin America	LA
Rest of the world	RoW
United Kingdom	UK
China	CHN
Russia	RUS
South-East Asia and Oceania	EAO

They are implemented according regional narratives, which have explained separately in each subchapter.

EU27

In creation of numerous scenarios for EU27 region optimization approach has the goal of finding optimal solution after minimal number of simulations [16]. The brute force method is used in this case as a necessity to provide high resolution and provide full diverse data set of all possible scenarios, which optimization approach tends to hide. Provision of high quantity of data is also pointed towards achieving better regression results if possible. Also, the diversity of data points is required in order to capture as much of variability in energy system structure as possible. These two goals cannot be achieved with optimization algorithms as these algorithms quickly discard suboptimal datasets and focus only on best performing cases. The difference appears also in the post-processing of the results: while in the optimization approach no post processing is needed, in the brute force approach post-processing is needed to select some among many scenarios. Optimization approach searches for the solution, therefore final scenario is not known at the beginning. On another hand, in brute force approach, the final scenario is created from the beginning, and then only the pathways from base scenario (current situation) to the final scenario (in future) are explored.

The display of flexibility options influence on the share of RES and CF can also be displayed. **Figure 2**. Displays the results of wind CF and the share of RES under the influence of values of flexibility index in 3 ranges. First range includes the results for flexibility indicator between 0 and 10 %, second for the results between 45 and 55 % while final set of data displays the results for flexibility index above 90 %. With increase of flexibility index, maximum theoretical values of CF can be obtained. Also, higher value of flexibility index allows RE to displace fossil fuel consumption as reflected through the increase of RES share. Alternatively saying, the inflexibility of energy system is the barrier of decarbonisation and reaching the higher RE shares in an energy system.

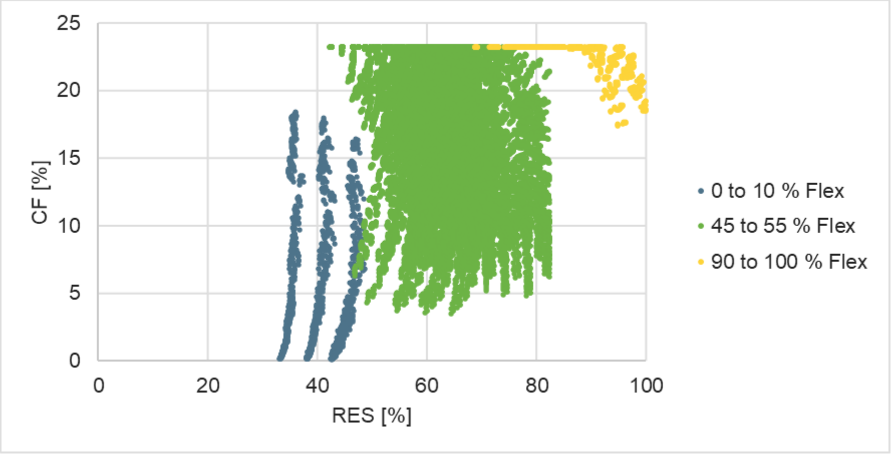

Figure 2. EU27: Influence of flexibility options on wind power CF and RES

Similar results can be observed in **Figure 3**. displaying the influence of flexibility index on the CF of PV and share of RES. It may be noted that the systems with high share of RES do not display low CF values due to all or most of the generated energy being used up in various high intensity processes such as generation of hydrogen.

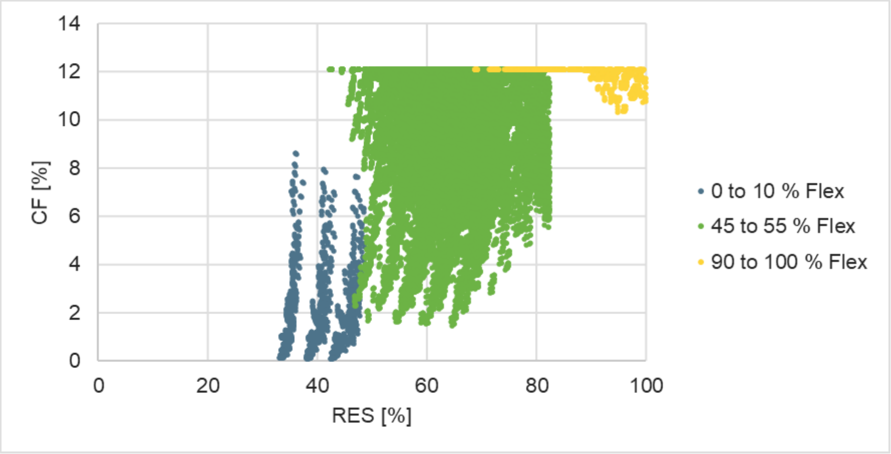

Figure 3. EU27: Influence of flexibility options on CF of PV and RES

India

The approach of decarbonisation for India, which is different from EU27, has been prepared according to the vision assuming mainly PV and batteries approach [17]. Based on the available data two scenarios have been crated base (present state) and final (100% RES) first, followed with introduction of permutation options grouped into clusters. Outputs of interest for India are presented in Fig. 4

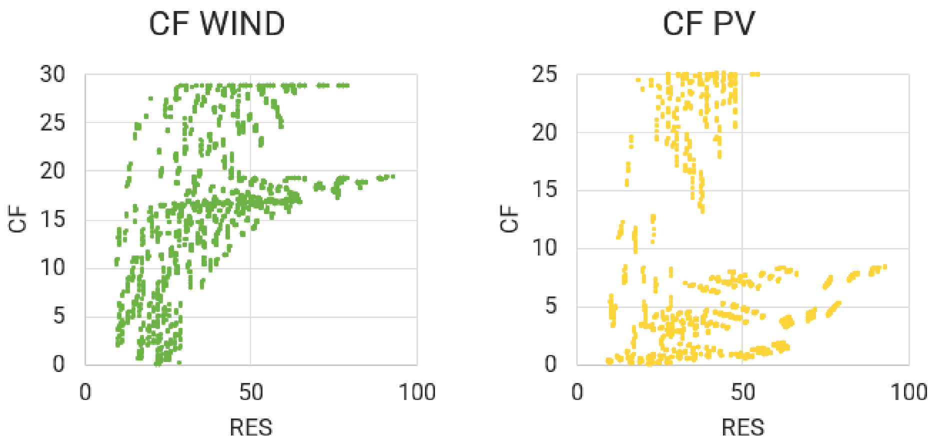

Figure 4 Variation of the CF (0-100%) of wind power plants, solar-PV for different RES share in PES (0-100%) for WILIAM region: INDIA

USMCA

USMCA region covers United States, Canada and Mexico. Therefore, wide range of differing climate zones and population centres are covered, each with differing requirements. Region is characterized by its significant energy demand, mainly due to U.S.. Total electricity demand of this region is 5,239,000 TWh while heating demand is 3,062,000 TWh. This is the reason behind the challenge of the transition of this region into carbon neutral region. Fortunately, due to its unique geographic features with major population centres on pacific or Atlantic cost, a wide, sparsely area is left open for implementation of renewable generating technologies.

Technologies used in this region include installation of wind generating capacities onshore as well as offshore. Also, major part of generation is relied upon solar energy in a form of PV and CSP. Wind energy is used with the values ranging from 1 to 6 TW, for the onshore installations, while offshore installations may have installed capacity between 100 and 600 GW. PV is also limited between 1 and 6 TW, while CSP is available in the range between 10 and 60 GW. The continent has a great geothermal potential so geothermal energy with capacity up to 100 GW is being used.

On the side of flexibility, options such as flexible operation of TPPs, transport electrification with V2G and smart charge, P2H, P2G, energy storage, demand side flexibility as well as grid operation parameters are being used.

Base case scenario assumes the implementation of some of the measures such as phasing out of fossil fuels in heating systems and replacement with electricity based heating with heat pumps and electric heaters or the use of biomass, solar energy and district heating.

The transition from base to final scenario trough 30.609 permutations has been shown in Figure 5. The 100% RE has been achieved as well as CFs for VRES which have been sustained all the way up to 100 % RES.

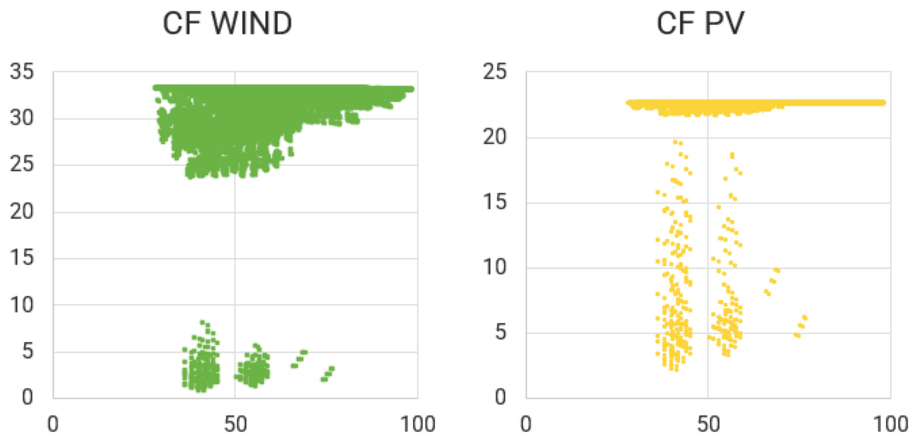

Figure 5 Variation of the CF (0-100%) of wind power plants, solar-PV for different RES share in PES (0-100%) for WILIAM region: USMCA

Final scenario includes 6 TW of installed capacity of wind power and PV as well as complete transport electrification with V2G and smart charge. Also 50 % of electricity demand have been made flexible demand. Total of 11.4 TWh of short and mid-term energy storage is used in a form of stationary battery storage, high temperature thermal storage and pumped hydro storage. P2G option is also utilized in a form of hydrogen generation mainly for industry processes as well as synthetic gas generation. Additionally, parts of the industry which can be electrified are being electrified. Operation of TPPs is also considered as operation in the "baseload" manner may inhibit the integration of VRES. This way, TPPs have been made completely flexible in final scenario. This notion correlates to the requirements of grid minimum stabilization parameter. This parameter determines the amount of generation which has to come from the generators with capability to provide spinning reserve. This factor has been reduced to 0 as reserve is provided by other means such as energy storage applications.

Latin America

This region encompasses the portion of the countries located in South America including Argentina, Brazil, Chile, Colombia, Panama and Peru. Total electricity demand is 1,004,000 TWh while heating demand is 441 GWh.

Generating technologies used in this region include onshore wind capacity in the range from 50 to 500 GW, offshore wind from 5 to 50 GW, solar PV in the range from 50 to 500 GW and up to 50 GW of geothermal capacity. Also, flexibility options such as the increase of TPP flexibility, short and mid-term energy storage, demand side flexibility, transport electrification, P2H and P2G are also used.

Latin America is abundant with the generation from hydropower and because of that already sources 49 % of its primary energy from renewable sources. This is the reason that smaller capacities of VRES are used in this region.

The transition from base to final scenario through 39.366 permutations has been shown in Figure 6. Simulations have reached up to 100 % of RES and achieved high CFs of VRES generating capacities.

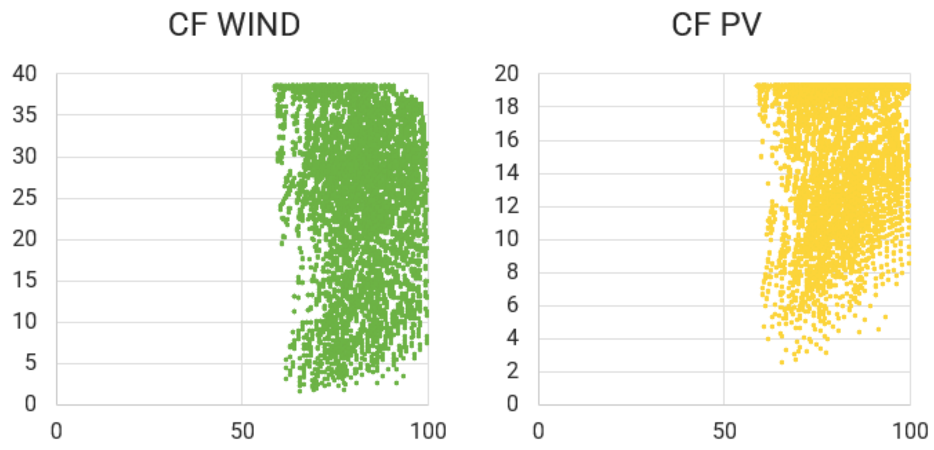

Figure 6 Variation of the CF (0-100%) of wind power plants, solar-PV for different RES share in PES (0-100%) for WILIAM region: LATIN

High CF of VRES is achieved with the use of energy storage in stationary batteries, high temperature thermal storage and pumped hydro amounting in total to 2.15 TWh as well with complete transport electrification. Also, V2G and smart charge are implemented in transport sector. Industry sector is decarbonized with the use of hydrogen and electricity while P2G is also implemented to reach complete decarbonisation.

Rest of the World

This region consists of all the remaining countries not included in separate regions. ROW region is specific due to its geographic distribution all around the world. Individual countries in this region are often not interconnected. Exception is Africa and parts of Asia which are the only major section of this region connected at least on geographical basis.

The addition of wind capacity represented by the onshore wind and solar energy with emphasis on PV is assumed. Wind capacity ranges between 0.5 and 5 TW while PV is assumed to be between 1 and 4 TW.

Flexibility options include flexible operation of TPPs, transport electrification with V2G, P2H, P2G, demand side flexibility, energy storage and grid stability parameters.

Base case scenario has 22 % of RES. Total electricity demand is 3.63 TWh, while heating demand is 5.02 TWh. Base case scenario introduces some simplifications and improvements to the system such as phasing out of the coal and oil in heating sector. Also, the industry is simplified with placing of all of the fossil demand to the natural gas which enables simpler integration of natural gas and electricity into the model.

The transition from base to final scenario through 8,586 permutations has been shown in Figure 7. Integration of VRES is successful as CFs display. The real impact of flexibility is observed at higher installed capacity of VRES where flexibility options become meaningful and actually help in reaching 100 % RES system.

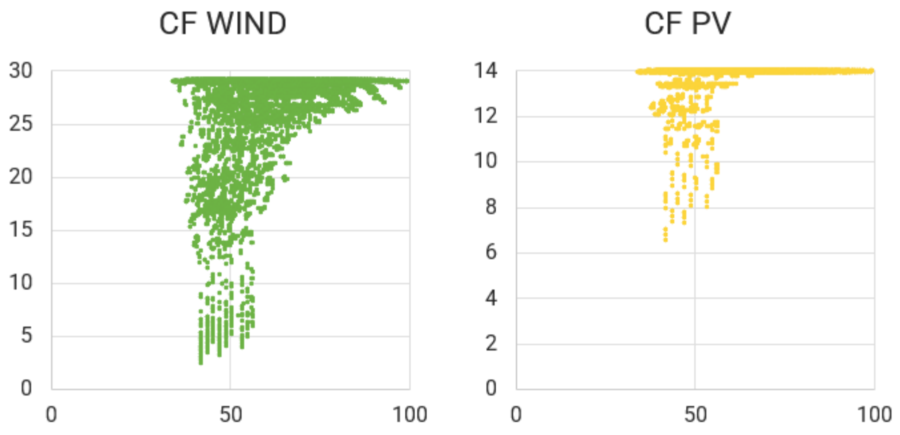

Figure 7 Variation of the CF (0-100%) of wind power plants, solar-PV for different RES share in PES (0-100%) for WILIAM region: ROW

United Kingdom

United Kingdom is examined separately from the European Union. It has different energy potentials in relation to the mainland. Electricity demand of this region is 298 TWh while heating demand is 383 TWh. Region uses VRES generation capacities in a form of onshore wind, offshore wind and PV. Onshore wind is used with the values between 50 and 700 GW, offshore between 5 and 70 GW while PV is in the range between 100 and 200 GW. Flexibility options include flexible operation of TPPs, transport electrification with V2G, P2H, P2G, demand side flexibility, energy storage and grid stability parameters.

United Kingdom currently has only 10 % of its energy supplied with renewable sources. In power sector, 52 % of its electricity is generated by low carbon energy sources. The problem is in the heating, transport and industry sectors which heavily rely on fossil fuels.

Assumptions in base case scenario include partial decarbonisation of heating with 50 TWh supplied with natural gas, 120 TWh with biomass, 220 TWh with heat pumps and 1 TWh with the use of solar heating. For the purposes of simplification, industry sector is rearranged in a way that all of the fossil demand is placed to the natural gas. High CF of VRES, especially PV has been maintained all the way up to 100 % of RES. The transition from base to final scenario through 3,881 permutations has been shown in Fig. 8.

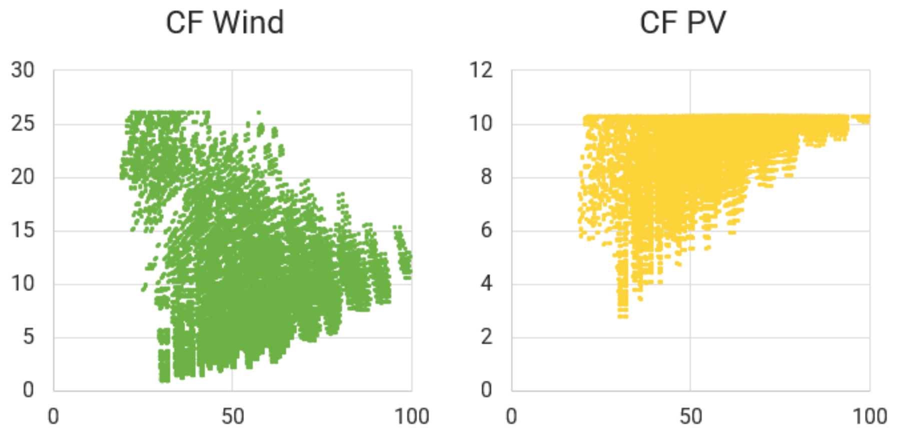

Figure 8 Variation of the CF (0-100%) of wind power plants, solar-PV power plants, TPPs and NPPfor different RES share in PES (0-100%) for WILIAM region: UK

China

China has the large industry and uses lot of fossil fuels, therefore its energy transition before 2060 can be illustrated as “turning super tanker” [18]. The decarbonisation method for China is based on 50% of wind energy production, around 30% of PV energy production in combination with flexibilization of the demand and sector coupling with electrified transport. The decarbonisation challenge lies in the industry sectors, which is decarbonised mainly on hydrogen and electricity. Base scenario has been created from existing EnergyPLAN [19] database of country models. Final scenario has been created based on the [20]. The transition from base to final scenario through 4,364 permutations has been shown in Fig. 9.

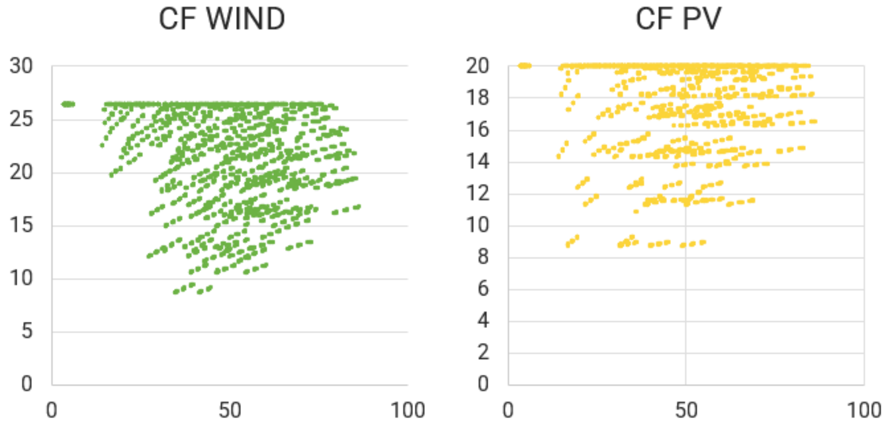

Figure 9 Variation of the CF (0-100%) of wind power plants, solar PV for different RES share in PES (0-100%) for WILIAM region: CHINA

Russia

Not a many studies so far have been done assuming highly RE policy scenarios for the Russian Federation, which is more oriented toward using own mineral resources [21]. At least some studies are available with strong grid interconnection to neighbouring countries [22], [23], [24], but these scenarios have been criticized regarding significant challenges for achievement [25]. According to [26] three steps should be taken from base to future scenario. 1st step include increase in VRES capacity: PV to 14% and wind to 60% of the total (of the 550 GW, currently at around 400 GW). The 2nd step will include mobility and heating. The 3rd step should be, natural gas replacement with power-to-gas, i.e. converting electricity into gases, such as hydrogen and synthetic natural gas. Therefore, P2G technology is used not only as a storage option within the system, but also covering the industrial gas demand [27].

The total electric power plant capacity of 190 GW from the UN data (excluding hydro and nuclear) has been assumed to cogeneration, assuming that total efficiency could be at 30 and 80% respectfully. Additional only heat boiler capacity has been assumed to 120 GW. The energy use has been obtained from IEA in addition to renewables obtained from IRENA.

The synthetic electricity load curve [28] has been used, although data from the official source are existing (br.so-ups.ru/BR/GenConsum). The heating demand curve during whole year, was obtained as average normalised demand from Kazakhstan and Latvia, assuming that majority of settlement in Russia is located between these neighbouring countries. The wind and solar hourly data have been obtained from [29] for one location (lat: 52.05012738 lon: 42.68181718) for the year 2019 using usual pre-processing. Hydro data are obtained from monthly hydro profiles data for 20 different power plants and post processing with assumption of 37% year average efficiency, and 8 hours of possible delay in production. Pumped hydro power plant capacity of 1.2GW with storage of 24 hours is assumed.

For the EnergyPLAN industry tab the industry and services are combined together.

Share of RES in TPES is 4%, while RES accounts for 16% of electricity, mainly due to large hydro production. The 77GW of PV and 330 GW of wind power plants are installed in the first step, to reach 17% of RES in TPES and 75% of electricity production. In the 2nd step for DH, heat pump replacement for individual heating, and 20 GWel to DH heat pump additional to thermal storage of 1TWh has been added (group 3) to reach 22% and 70% RES share in TPES and electricity respectfully. Adding electricity in transport instead of diesel 24.5% RES share in TPES while electric demand will increase and therefore decrease share of RES in it. The 3rd and final step has been based on synthetic electro fuels: gas 2,500 for transport, thermal power and industry sector and liquid 1.000 TWh/a for TPP produced from hydrogen. In order to produce such amount of hydrogen, renewable capacities have been increased to 2,400 GW wind, 500 GW PV and 83 GW geothermal. Additional flexibility has been provided from heat storage of 100 GWh and responsive electricity demand in amount of 300 TWh per day, week and month and up to 100 GW, resulting with RES share in TPES of 102%. These results should be compared with findings in [27].

The transition from base to final scenario through 4,374 permutations has been shown in Fig. 10.

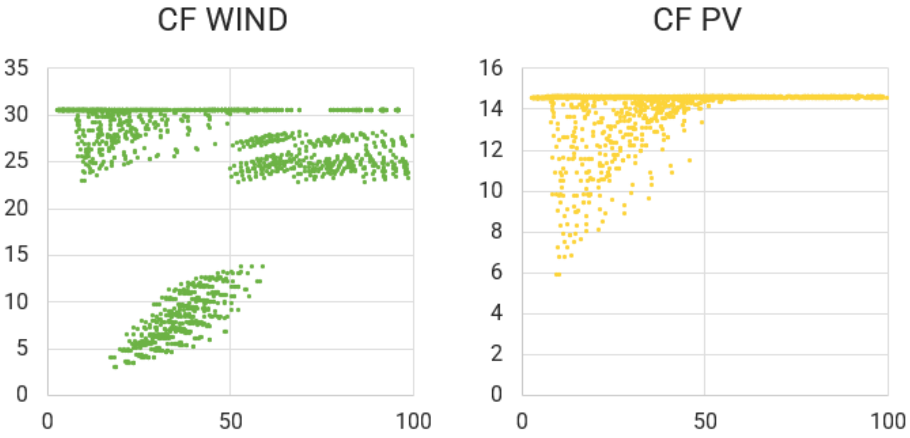

Figure 10 Variation of the CF y-axis (0-100%) of wind power plants, solar-PV power plants, for different RES share in PES (0-100%) x-axis for WILIAM region: RUSSIA

South-East Asia and Oceania (EAO)

The WILIAM region of East Asia and Oceania (EAO) is consisted of 38 countries, out of which most energy significant 4 are: Australia, New Zealand, Japan, and South Korea. Other countries are geographically spread and difficult to model separately, therefore some of them will be excluded, while other will be modelled integrally. The 10 countries are integrated into Association of Southeast Asian Nations (ASEAN) are: Brunei, Cambodia, East Timor, Indonesia, Malaysia, Philippines, Singapore, Thailand, Vietnam and Myanmar. Myanmar is only country in ASEAN which doesn't belong to the EAO region (but Rest of the World region) and therefore has been excluded. The ASEAN has been interesting for different studies e.g. [30], [31], [32], [33]. The base and future scenarios of EAO region have been created based on the one significant study [34] and its extension where needed. The data from this study are used grouping together (summing or averaging) regions of: New Zealand, East Australia, West Australia, Indonesia-Papua + Papua New Guinea, Sumatra, Java + Timor Leste, East Indonesia, Malaysia + Singapore + Brunei, Philippines, Vietnam + Laos + Cambodia, South Korea + North Korea, and Japan. The existing generation capacities for

ASEAN are taken from [30], while for 4 most significant countries are taken from UN and IRENA databases. The fuel mix is obtained from IEA for 4 most significant countries and ASEAN for 2018.The electricity load at hourly level has been obtained summing the 4 significant and 9 of the ASEAN countries into one, using synthetic load data from [35]. Solar and wind hourly curve have been obtained using PLEXOS data for two average locations in Australia, "AUS_Sol_Uterne" and "AUS_Win_Canunda" respectfully. The hourly data for hydro run of river plant are obtained from PLEXOS database for the locations in Japan and Vietnam, as most significant ones. This way "better than average" resources are used in simulations in order to show the effect of integration of the region. For the EnergyPLAN industry tab the industry and services are combined together. For the pumped hydro storage, 50GWh energy is assumed for base, as 50% of the final scenario [20]. The base scenario share of RES in PES reaches 21% which is probably higher than in reality due to allocation of all RE capacities (PV, wind and RoR) from less viable location to the locations with better CF in the region. The solar PV peak capacity is increased to 4.7 TW, wind peak to 5.2 TW, and run of river hydro to 100GW, PHS of 100GW, Electro fuels demand 2,000 TWh/year, fresh water demand for desalinization of $12x10^9$ m3/year from [34]. These assumptions resulted with reaching the 38% of RES in TPES, and 95% of RES in electricity production. Additional assumptions for 100% RES are made in the direction of:

- Transport demand transformation to: biodiesel 1,000, biogas 500, hydrogen 200, dump charge 200, and smart charge 200 TWh per year (keeping the 4.850 billion km per year)
- Industry demand transformation to biogas 500, biomass 500, hydrogen 900 and electricity 1.000 TWh per year
- Household individual demand transformation to biomass 505, and heat pump heat demand 528 TWh per year with COP 5

Resulted with reaching 97% share of RES in TPES and 91% RES in elec. production. Additional flexibilization of demand is performed to the whole household and additional industry demand assuming it is flexible to the amount of: 2,255TWh for a day, 1,230 TWh for a week, 6,15 TWh for a month, each with capacity of 99,999MW for maximal effect, reaching 98% and 93% RES in PES and electricity production, respectfully. The transition from base to final scenario through 2,916 permutations has been shown in Fig. 11.

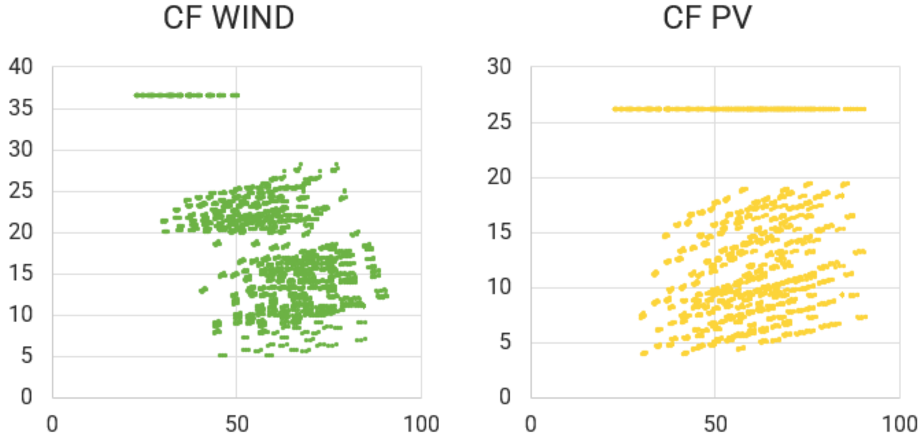

Figure 11 Variation of the CF y-axis (0-100%) of wind power plants, solar-PV power plants, for different RES share in PES (0-100%) x-axis for WILIAM region: EAO

OPTIMIZING FLEXIBILITY OPTIONS IN 100% RE SYSTEMS

After performing numerous simulations and reaching 100% RE systems, the discussion how to reach 100% using available flexibility options, can be performed using the optimization approach. This approach is used to prioritize usage of strategies reaching 100% RES in different WILIAM regions and according to different criteria e.g. of technical nature. Designing the energy systems for high VRE penetrations, one should look for the flexibility of an energy systems that may be provided from various sources at supply, demand or network level. The flexibility can be provided from different options including, but not limiting to: (1) electricity demand (household and industry), (2) thermal (power, CHP, nuclear) plants, (3) P2H (CHP, heat pump district/individual), (4) transport (V2G + smart charge, synthetic fuels), (5) interconnection and (6) storage (batteries, pumped hydro, rocked, compressed air, hydrogen…). The flexibility provided might be optimal according to different criteria: economic, technical complexity, utilization, acceptability, feasibility, material use. Further, different constraints regarding percentages, shares, emission reductions… might be set according to proclaimed sustainable energy policy. Therefore, we will simulate various flexibility options according to their availability and priority assumed by authors for each scenario using simulation-based optimization approach and previously defined flexibility vector. This way number of synthetically generated temporary scenarios before finding optimal one and the execution time is decreased in comparison to brute force, while flexibility is provided optimally.

The purpose of strategic level optimization is to find an optimal plan for flexibility strategy (planning problem) for the increased use of VRES. Flexibility may be provided from various sources of flexibility at supply, demand or network level, as shown in that 90% Bulgarian RE system plan is technically feasible [36] , but the question is which technology approach (pathway) is optimal and should be applied.

The flexibility strategy can be combination among following flexibility options:

i. DR of electric power demand
ii. Sectors coupling of heating and transport with electric power system
iii. Diversification of VRES geographically to employ stronger interconnections to provide smoothing effect
iv. Overcapacity of the economically most efficient VRES
v. Storing significant amounts of variable energy sources (batteries, hydrogen.)

all of them, and their combinations, will be explored to find optimal flexibility strategy. The simplest question of optimality strategy is either to go for more flexibility options, or to increase the VRE generation capacity above levels when their curtailment is inevitable. The answer is in the economy domain and depends on price curves, but also on the availability of technologies, the potential of their implementation etc. For the most of materials there is not scarce at this time frame, but the question of price is still open for different scales of their demand. The WILIAM model will show “red lines”, if certain decarbonisation strategy is infeasible. Since batteries are one of the critical technologies, their cycles should be incorporated into modelling framework to avoid misuse. In addition, they are recyclable [37] which mean that same materials can be reused. On the other hand, the optimality of this strategy could be defined based on:

a. Least total annualized costs of energy supply and demand
b. Minimal critical electricity export, during the year - calculated hourly (CEEP)
c. Maximal utilization of RES in final energy demand
d. Highest level of energy security
e. Highest level of dynamic energy return on investment
f. Reaching the broader social participation in energy transition

and therefore we will define optimality criteria (criteria function).

Therefore, we are going to deal with issue of reaching the exact level of RE in final energy consumption (up to 100%) by applying listed (I-V) flexibility strategy options, under previously defined (A-F) optimality criteria to find optimal flexibility strategy.

For that purpose, we will simulate various flexibility options (as decision variable in the optimization problem) according to availability assumed by authors for each scenario. The VRE in the model is increased from the base scenario to reach at least 50%, 60%...90% percent (this is a constraint in the optimization problem) in the total demand, but with different availability of flexibility options for each WILIAM region. With the limited flexibility options, the utilization of VRE will be lower (lower CF), and therefore more investments for more capacities will be needed. More flexibility options will bring additional investment costs (these have to be specified in Table 8), but will open room for better utilization of VRES. The better utilization will result in decreased operational costs calculated by simulation tool[4]. Therefore, optimal strategy will be based on these two effects trade off, which is possible to show only via multiple simulations performed in the automated procedure.

Each flexibility strategy options should be defined with investment cost, unit, lifetime of investment, operation and maintenance (O&M) costs as percentage of investment costs, step of the granularity for optimization algorithm and availability (upper limit for optimization):

Table 2 Flexibility option X input for optimization

Flexibility Option	Unit	Granularity	Availability / potential
DR	€/kW	1 kW	90% of electric water heaters, AC units, refrigerators, …
Batteries	€/MWh	1 kWh	Household %, Transport % …
P2H			90% of existing district heating
Power to hydrogen		100 MW	
PHS plants		50 MW	Limited availability
Flexible TPP operation			
Electrification of industry			

The choice of flexibility options is done by optimization algorithm, not by brute force where number of scenarios is permutation of all options availability divided by its granularity. This way number of synthetically generated temporary scenarios before finding optimal one is decreased in comparison to brute force. This will be done via simulation-based optimization using available optimizers to EnergyPLAN e.g. GENOPT, EPLANopt…

CONCLUSION

For the conclusion it should be noted that: changes in CF are confirmed at hourly level, the decarbonisation is technically achievable, and the framework is open for further research and is in accordance with latest published reports.

The research presented in the previous sections clearly demonstrates the decrease of CF of all power plants in all WILIAM regions with increase of widely available VRES (wind, solar and river water) shares in energy mix. The WILIAM approach to endogenise inputs as much as possible in the case of energy model is applied to the calculation of real CFs through hourly simulations of generation and flexibility technologies during one year for the nine different regions.

---

[4] The operation costs are not subject of minimization via simulation tool, but as resulting minimal total cost achieved with optimal investment decision into renewable energy and flexible option.

Secondly, these high shares may be achieved only with significant use of specific flexibility options in WILIAM regions. Decarbonisation is achieved through sector coupling of power sector with heating and transportation sectors, but depending on the region electrification of all sectors. Also, heat storage, and power-to-x-to-power technologies are inevitable. The selected flexibility options are based on existing technologies which are mature but have some resource constraints on the World level mass adoption. The same technologies are modelled where they are expected to be adopted, at various sides of the energy system: supply, network and demand, which may be used for approximate calculation of energy flows, and further maybe also for losses calculations.

Finally, instead of deeper conclusions at this moment, comparing this study with latest publications [38], [39] demonstrates that it is an actual topic. In the study [38] the applied flexibility options (they call them main pillars) are identical: demand side flexibility + grid infrastructure, electrification + sector coupling, green hydrogen with addition to energy efficiency which could also be modelled in WILIAM, and will ease the constraints. The [39] shows decrease in energy intensities, which has to be also expected in the WILIAM model. In all three studies, electricity system based on VRE production (with backup from highly dispatchable power plants) becomes a backbone of future decarbonised (zero emission) energy system.

ACKNOWLEDGMENT

Funds for I.B.B. are provided by the Ministry of Education, Science and Technological Development of the Republic of Serbia, the Agreement on the implementation and financing of scientific research of the Institute of Technical Sciences of SANU in 2020 (Registration number: 451-03-68 / 2020-14 / 200175). The authors acknowledge the support from the "LOCOMOTION" Horizon 2020 project from EASME grant Nr. 821105.

REFERENCES

[1] B. P. Heard, B. W. Brook, T. M. L. Wigley, and C. J. A. Bradshaw, “Burden of proof: A comprehensive review of the feasibility of 100% renewable-electricity systems,” *Renew. Sustain. Energy Rev.*, vol. 76, pp. 1122–1133, 2017.

[2] T. W. Brown, T. Bischof-Niemz, K. Blok, C. Breyer, H. Lund, and B. V Mathiesen, “Response to ‘Burden of proof: A comprehensive review of the feasibility of 100% renewable-electricity systems,’” *Renew. Sustain. Energy Rev.*, vol. 92, pp. 834–847, 2018, doi: https://doi.org/10.1016/j.rser.2018.04.113.

[3] W. Zappa, M. Junginger, and M. van den Broek, “Is a 100% renewable European power system feasible by 2050?,” *Appl. Energy*, vol. 233–234, pp. 1027–1050, 2019, doi: 10.1016/j.apenergy.2018.08.109.

[4] D. P. Schlachtberger, T. Brown, M. Schäfer, S. Schramm, and M. Greiner, “Cost optimal scenarios of a future highly renewable European electricity system: Exploring the influence of weather data, cost parameters and policy constraints,” *Energy*, vol. 163, pp. 100–114, 2018, doi: https://doi.org/10.1016/j.energy.2018.08.070.

[5] I. Batas Bjelić, N. Rajaković, G. Krajačić, and N. Duić, “Two methods for decreasing the flexibility gap in national energy systems,” *Energy*, vol. 115, pp. 1701–1709, 2016, doi: http://dx.doi.org/10.1016/j.energy.2016.07.151.

[6] P. Denholm and M. Hand, “Grid flexibility and storage required to achieve very high penetration of variable renewable electricity,” *Energy Policy*, vol. 39, no. 3, pp. 1817–1830, Mar. 2011, doi: http://dx.doi.org/10.1016/j.enpol.2011.01.019.

[7] V. Krakowski, E. Assoumou, V. Mazauric, and N. Maïzi, “Feasible path toward 40-100% renewable energy shares for power supply in France by 2050: A prospective analysis,” *Appl. Energy*, vol. 171, pp. 501–522, 2016, doi: 10.1016/j.apenergy.2016.03.094.

[8] P. Sterchele, A. Palzer, and H.-M. Henning, “Electrify Everything?: Exploring the Role of the Electric Sector in a Nearly CO<sub>2<\/sub>-Neutral National Energy System,” *IEEE Power Energy Mag.*, vol. 16, no. 4, pp. 24–33, Jul. 2018, doi: 10.1109/MPE.2018.2824100.

[9] T. Mai, D. Steinberg, J. Logan, D. Bielen, K. Eurek, and C. McMillan, “An Electrified Future: Initial Scenarios and Future Research for U.S. Energy and Electricity Systems,” *IEEE Power Energy Mag.*, vol. 16, no. 4, pp. 34–47, Jul. 2018, doi: 10.1109/MPE.2018.2820445.

[10] BNEF, “Electrification Can Cut Emissions of Transport, Buildings and Industry in Europe by 60% by 2050,” 2020. [Online]. Available: https://about.bnef.com/blog/electrification-can-cut-emissions-of-transport-buildings-and-industry-in-europe-by-60-by-2050/.

[11] C. Breyer, “A Global Overview of Future Energy,” in *Future Energy*, Elsevier, 2020, pp. 727–756.

[12] A. Bloess, W.-P. Schill, and A. Zerrahn, “Power-to-heat for renewable energy integration: A review of technologies, modeling approaches, and flexibility potentials,” *Appl. Energy*, vol. 212, pp. 1611–1626, 2018, doi: 10.1016/j.apenergy.2017.12.073.

[13] E. Pursiheimo, H. Holttinen, and T. Koljonen, “Inter-sectoral effects of high renewable energy share in global energy system,” *Renew. Energy*, vol. 136, pp. 1119–1129, 2019, doi: https://doi.org/10.1016/j.renene.2018.09.082.

[14] K. Boblenz, V. Frank, and B. Meyer, “Energy system analysis for evaluation of sector coupling technologies,” *Fuel*, vol. 254, p. 115658, 2019, doi: 10.1016/j.fuel.2019.115658.

[15] B. Frew *et al.*, “The curtailment paradox in the transition to high solar power systems,”

Joule, vol. 0, no. 0, Apr. 2021, doi: 10.1016/j.joule.2021.03.021.

[16] I. Batas Bjelić and N. Rajaković, “Simulation-based optimization of sustainable national energy systems,” *Energy*, vol. 91, pp. 1087–1098, Nov. 2015, doi: http://dx.doi.org/10.1016/j.energy.2015.09.006.

[17] A. Gulagi, D. Bogdanov, and C. Breyer, “The role of storage technologies in energy transition pathways towards achieving a fully sustainable energy system for India,” *J. Energy Storage*, vol. 17, pp. 525–539, Jun. 2018, doi: 10.1016/j.est.2017.11.012.

[18] “Turning the Supertanker,” 2021. [Online]. Available: https://www.transitionzero.org/insights/turning-the-supertanker.

[19] H. Lund, J. Z. Thellufsen, P. A. Østergaard, P. Sorknæs, I. R. Skov, and B. V. Mathiesen, “EnergyPLAN – Advanced analysis of smart energy systems,” *Smart Energy*, vol. 1, p. 100007, Feb. 2021, doi: 10.1016/j.segy.2021.100007.

[20] D. Bogdanov and C. Breyer, “North-East Asian Super Grid for 100% renewable energy supply: Optimal mix of energy technologies for electricity, gas and heat supply options,” *Energy Convers. Manag.*, vol. 112, pp. 176–190, Mar. 2016, doi: 10.1016/j.enconman.2016.01.019.

[21] H. Balzer, “Vladimir Putin’s academic writings and Russian natural resource policy,” *Problems of Post-Communism*, vol. 53, no. 1. M.E. Sharpe Inc., pp. 48–54, 2006, doi: 10.2753/PPC1075-8216530105.

[22] S. Mano *et al.*, “Gobitec and Asian super grid for renewable energies in Northeast Asia,” *Spotinov print Ltd*, 2014.

[23] A. Churkin and J. Bialek, “Analysis of the prospective energy interconnections in Northeast Asia and development of the data portal,” in *E3S Web of Conferences*, Jan. 2018, vol. 27, p. 01003, doi: 10.1051/e3sconf/20182701003.

[24] N. Voropai, S. Podkovalnikov, L. Chudinova, and K. Letova, “Development of electric power cooperation in Northeast Asia,” *Glob. Energy Interconnect.*, vol. 2, no. 1, pp. 1–6, Feb. 2019, doi: 10.1016/j.gloei.2019.06.001.

[25] C. Cooper and B. K. Sovacool, “Miracle or mirage? The promise and peril of desert energy part 1,” *Renew. Energy*, vol. 50, pp. 628–636, Feb. 2013, doi: 10.1016/j.renene.2012.07.027.

[26] “A Renewable Supergrid in Russia - IEEE Spectrum.” https://spectrum.ieee.org/energywise/energy/renewables/a-renewable-supergrid-in-russia-by-2030 (accessed May 14, 2021).

[27] D. Bogdanov and C. Breyer, “Eurasian Super Grid for 100% renewable energy power supply: Generation and storage technologies in the cost optimal mix,” in *ISES Solar World Congress 2015, Conference Proceedings*, 2015, pp. 1574–1588, doi: 10.18086/swc.2015.06.01.

[28] A. Toktarova, “Long-term load forecasting in high resolution for all countries globally,” 2017. Accessed: Feb. 25, 2021. [Online]. Available: https://lutpub.lut.fi/handle/10024/143609.

[29] I. Staffell and S. Pfenninger, “Using bias-corrected reanalysis to simulate current and future wind power output,” *Energy*, vol. 114, pp. 1224–1239, 2016, doi: https://doi.org/10.1016/j.energy.2016.08.068.

[30] Y. W. Huang, N. Kittner, and D. M. Kammen, “ASEAN grid flexibility: Preparedness for grid integration of renewable energy,” *Energy Policy*, vol. 128, pp. 711–726, May 2019, doi: 10.1016/j.enpol.2019.01.025.

[31] W. Eichhammer, *The 4th ASEAN Energy Outlook 2013 - 2035*. Jakarta: ACE, 2015.

[32] Y. Chang and Y. Li, “Power generation and cross-border grid planning for the integrated ASEAN electricity market: A dynamic linear programming model,” *Energy Strateg. Rev.*, vol. 2, no. 2, pp. 153–160, Sep. 2013, doi: 10.1016/j.esr.2012.12.004.

[33] P. Fragkos *et al.*, “Energy system transitions and low-carbon pathways in Australia, Brazil, Canada, China, EU-28, India, Indonesia, Japan, Republic of Korea, Russia and the United States,” *Energy*, vol. 216, p. 119385, Feb. 2021, doi: 10.1016/j.energy.2020.119385.

[34] A. Gulagi, D. Bogdanov, M. Fasihi, and C. Breyer, “Can Australia Power the Energy-Hungry Asia with Renewable Energy?,” *Sustainability*, vol. 9, no. 2, p. 233, Feb. 2017, doi: 10.3390/su9020233.

[35] A. Toktarova, L. Gruber, M. Hlusiak, D. Bogdanov, and C. Breyer, “Long term load projection in high resolution for all countries globally,” *Int. J. Electr. Power Energy Syst.*, vol. 111, pp. 160–181, Oct. 2019, doi: 10.1016/j.ijepes.2019.03.055.

[36] A. Pfeifer, L. Herc, I. Batas Bjelić, and N. Duić, “Flexibility index and decreasing the costs in energy systems with high share of renewable energy,” *Energy Convers. Manag.*, vol. 240, p. 114258, Jul. 2021, doi: 10.1016/j.enconman.2021.114258.

[37] P. Greim, A. A. Solomon, and C. Breyer, “Assessment of lithium criticality in the global energy transition and addressing policy gaps in transportation,” *Nat. Commun.*, vol. 11, no. 1, p. 4570, 2020, doi: 10.1038/s41467-020-18402-y.

[38] D. Möst, A. Herbst, M. Jakob, W.-R. Poganietz, S. Schreiber, and C. Zöphel, “Summary, Conclusion and Recommendations,” in *The Future European Energy System*, Cham: Springer International Publishing, 2021, pp. 293–309.

[39] “Net Zero by 2050 – Analysis - IEA,” 2021. https://www.iea.org/reports/net-zero-by-2050 (accessed May 26, 2021).