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FACULTY OF MECHANICAL ENGINEERING AND NAVAL ARCHITECTURE

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DOCTORAL THESIS

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FAKULTET STROJARSTVA I BRODOGRADNJE

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Planiranje energetskoga sustava u uvjetima povezivanja tržišta primjenom teorije igara

DOKTORSKI RAD

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Assoc. prof. Goran Krajačić, PhD, University of Zagreb, Faculty of Mechnical Engineering and Naval Architecture – Chairman of defence commission

Assoc. prof. Ivan Rajšl, PhD, University of Zagreb, Faculty of Electrical Engineering and Computing– member

Assoc. prof. Felipe Feijoo, PhD, Pontificial Catholic University of Valparaiso, Valparaiso, Chile – external member

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Contents

About the Supervisor

Prof. dr. sc. Neven Duić, PhD, (7,000+ citations, 40+ H-Index) is a full professor at the Power Engineering and Energy Management Chair at the Department of Energy, Power and Environmental Engineering, Faculty of Mechanical Engineering and Naval Architecture, University of Zagreb, Croatia. He is a Vice-president of Croatian Academy of Engineering and the President of the Management Board of The Centre for Sustainable Development of Energy, Water and Environment Systems (SDEWES Centre). He is an editor of the Q1 "Energy Conversion Management" journal, subject editor for the Q1 journal "Energy", a member of the editorial board of the following journals: Q1 journal "Applied Energy", Q3 journal "Thermal Science", Senior Editor of e-Prime, Associate Editor of Energy Storage and Saving, Member of Editorial Board of Smart Energy, Member of Editorial Board of eTransportation, and since 2013 he is Editor-in-Chief of the Journal of Sustainable Development of Energy, Water and Environment Systems (JSDEWES). He has organized the series of conferences on Sustainable Development of Energy, Water and Environment Systems and was a member of the organizing, scientific and programming committees of more than 40 research conferences. He was the coordinator of the Croatian participation in two projects of the Croatian Science Foundation and over 50 international scientific research projects. Prof. Duić has received awards from the University of Zagreb for the improvement of international relations achieved under an international scientific project, the National Award for significant scientific achievement in 2016 in the field of technical sciences, the Great Medal from the Faculty of Mechanical Engineering and Naval Architecture, and the Medal Atanasije Stojković from the Society of Thermal Engineers of Serbia.

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I hereby declare that my Doctoral Thesis is entirely the result of my work and knowledge obtained during my studies, except where otherwise indicated. I have fully cited all used sources, and they can be found in the list of references.

I would like to express deep gratitude to my supervisor, Professor Neven Duić, for providing me with the opportunity to join his research group and carry out research, for his persistent guidance and patience. Also, I would like to thank assoc. prof. Goran Krajačić and assoc. prof. Tomislav Pukšec, who have been of great help and guidance in various stages of my work and research career.

Throughout my PhD studies and work at the Power Engineering and Energy Management Chair, Department of Energy, Power and Environmental Engineering, I had company, help and support of numerous colleagues and friends in the Powerlab group, it has been a pleasure to share work challenges, research collaborations, days and nights of work and fun with all of you. I am profoundly grateful to have met all of you and worked by your side.

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Abstract

Planning of development of energy systems today becomes closely connected to analysis of day-ahead energy markets, market coupling and dynamics of integration of both, renewable energy sources and demand response technologies. A common European energy market would enable larger integration of renewable energy sources but would also influence economic feasibility of new investments in energy production units, depending on the resources available and transmission available for import or export of energy from each market zone. In this research, methods are proposed for analysis of costs of production, storage and demand response technologies, organized in steps of energy transition in the surrounding zones; and use of game theory in assessing the long-term strategic decisions of market coupled zones.

Objectives of this research are 1) To prove the value of the use of game theory in assessing the long-term strategic decisions of market coupled zones; 2) To demonstrate the need to include the influence of market coupled countries' energy strategy on national energy strategy; 3) To analyze the influence of integration of demand response technologies in coupled market zones on the feasibility of strategic decisions in the investigated zone. The hypothesis of this research is that optimal decisions in long term energy planning for each market coupled with neighboring zones can be determined by game theory, through achieving Nash equilibrium with energy strategies of surrounding zones, even in the case of lack of information about them. Results of five published scientific papers bring forward two major scientific contributions: A method for analysis of costs of production, storage and demand response technologies, organized in steps of energy transition in the zones surrounding the zone of interest is elaborated in PAPER 1, PAPER 2 and PAPER 3, providing methodological development of approaches for a single zone and for the interconnected group of zones, which defines outputs for electricity generation technologies, energy storage and demand response in technical context and in the context of economic assessment. The second major contribution is a method which provides robust assessment of strategic decisions using game theory, which can be a new standard for national energy planning. This contribution is realized based on the groundwork done in PAPER 1, PAPER 2 and PAPER 3, through the method developed in PAPER 4 and completed using the game theory in PAPER 5.

The outcome of this research is a new method, which can be proposed as a standard for energy planning of the market zones, which are mostly national energy systems. The hypothesis of this research has been confirmed: optimal decisions in long term energy planning for each market coupled with neighboring zones can be determined by game theory, through achieving Nash equilibrium with energy strategies of surrounding zones, even in the case of lack of information about them - this is achieved through establishing a matrix of possible choices for all the zones included in the consideration and then using the proposed approach to calculate the payoffs of the choices and the developed game to reach a Nash equilibrium or the mixed strategy.

Sažetak

Planiranje razvoja energetskih sustava danas postaje usko povezano s analizom energetskih tržišta dan unaprijed, spajanjem tržišta i dinamikom integracije obnovljivih izvora energije i tehnologija odgovora na potražnju. Zajedničko europsko energetsko tržište omogućilo bi veću integraciju obnovljivih izvora energije, ali bi utjecalo i na ekonomsku isplativost novih ulaganja u energetske proizvodne jedinice, ovisno o raspoloživim resursima i raspoloživom prijenosu za uvoz ili izvoz energije iz svake tržišne zone. U ovom istraživanju predložene su metode za analizu troškova proizvodnje, skladištenja i tehnologija odgovora na potražnju, organiziranih u koracima energetske tranzicije u okolnim zonama; i korištenje teorije igara u procjeni dugoročnih strateških odluka tržišno povezanih zona.

Ciljevi ovog istraživanja su 1) dokazati vrijednost upotrebe teorije igara u procjeni dugoročnih strateških odluka tržišno povezanih zona; 2) Pokazati potrebu uključivanja utjecaja energetske strategije tržišno povezanih zemalja na nacionalnu energetsku strategiju; 3) Analizirati utjecaj integracije tehnologija odgovora na potražnju u povezanim tržišnim zonama na izvedivost strateških odluka u istraživanoj zoni. Hipoteza ovog istraživanja je da se optimalne odluke u dugoročnom energetskom planiranju za svako tržište zajedno sa susjednim zonama mogu odrediti teorijom igara, kroz postizanje Nashove ravnoteže s energetskim strategijama okolnih zona, čak i u slučaju nedostatka informacija o njima.

Rezultati pet objavljenih znanstvenih radova donose dva velika znanstvena doprinosa: Metoda za analizu troškova proizvodnje, skladištenja i tehnologija odgovora na potražnju, organiziranih u koracima energetske tranzicije u zonama koje okružuju zonu interesa razrađena je u RADU 1, RADU 2 i RADU 3, koji pruža metodološki razvoj pristupa za jednu zonu i za međusobno povezanu grupu zona, koji definira rezultate za tehnologije proizvodnje električne energije, skladištenje energije i odgovor na potražnju u tehničkom kontekstu i u kontekstu ekonomske procjene. Drugi veliki doprinos je metoda koja daje robusnu procjenu strateških odluka korištenjem teorije igara, što može biti novi standard za nacionalno energetsko planiranje. Ovaj je doprinos ostvaren na temelju metoda i analiza razvijenih u RADU 1, RADU 2 i RADU 3, te kroz metodu razvijenu u RADU 4 i dovršenu korištenjem teorije igara u RADU 5.

Ishod ovog istraživanja je nova metoda, koja se može predložiti kao standard za energetsko planiranje tržišnih zona, koje su uglavnom nacionalni energetski sustavi. Hipoteza ovog istraživanja je potvrđena: optimalne odluke u dugoročnom energetskom planiranju za svako tržište zajedno sa susjednim zonama mogu se odrediti teorijom igara, kroz postizanje Nashove ravnoteže s energetskim strategijama okolnih zona, čak i u slučaju nedostatka informacija o njih - to se postiže uspostavljanjem matrice mogućih izbora za sve zone uključene u razmatranje, a zatim korištenjem predloženog pristupa za izračunavanje isplativosti izbora i razvijene igre za postizanje Nashove ravnoteže ili mješovite strategije.

Prošireni sažetak

Tržište električne energije je već dulje vrijeme prisutno u Europi kroz odvojena tržišta pojedinih zemalja, a kasnije i regija. Početkom 2014. godine nastupilo je postupno povezivanje tržišta električnom energijom (eng. Price Coupling of Regions – PCR), gdje je sedam najvećih zasebnih tržišta (APX, Belpex, EPEX SPOT, GME, Nord Pool Spot, OMIE i OTE) formiralo jedinstveno tržište. Danas također i subjekti u Hrvatskoj mogu kupovati energiju na tržištu dan-unaprijed te 15-minutnom tržištu unutar dana, koje je povezano s drugim tržištima u Europi preko slovenskog tržišta. Unutar ovog istraživanja, cijena električne energije formira se na tržišnom principu ponude i potražnje, uzimajući u obzir marginalni trošak proizvodnje. Idući korak u povezivanju cijele Europe u jedinstveno tržište električne energije je formiranje i pridruživanje tržišta zemalja jugoistočne Europe. Nakon toga, uslijedit će uvođenje tržišta pomoćnih usluga i rezerve, koje će biti obogaćeno novim tehnologijama, a pogotovo tehnologijama brzog odziva na strani potražnje. Uzimajući u obzir kompleksnost sustava, koja će biti posljedica energetske tranzicije u decentralizirane sustave s visokim udjelom varijabilnih izvora te tržišne uvjete natjecanja za sve sudionike, potrebno je težiti energetskom planiranju koje uzima u obzir lokalne posebnosti i potencijale. Uvođenjem obnovljivih izvora energije (OIE) teoretski je moguće postupno zamijeniti konvencionalne proizvodne sustave (temeljene na ugljenu, nafti i prirodnom plinu). Mnoga su istraživanja provedena s ciljem da istraže jesu li mogući 100% obnovljivi sustavi za pojedine zemlje, regije i cijele kontinente. Za te potrebe, razvijeni su novi alati, poput MultiNode dodatka u EnergyPLAN modelu, da simuliraju mogućnost tržišnog povezivanja sustava. U praksi, međutim, postoje problemi vezani uz regulaciju i vođenje elektroenergetskih sustava (EES) temeljenim na OIE zbog varijabilnosti i kratkoročne predvidljivosti proizvodnje iz OIE. Čak i kad su uvjeti za instaliranje novih OIE kapaciteta dobri, još uvijek je potrebno unutar EES imati rezervne kapacitete u vidu fleksibilnih termoelektrana, koje mogu odgovoriti na pad proizvodnje iz OIE. Nove opcije za pružanje fleksibilnosti otvaraju se u 4. generaciji centraliziranih toplinskih sustava (CTS) povezane s kogeneracijskim postrojenjima s toplinskim spremnicima te dizalice topline na razini kućanstava i na razini CTS-a. Osim toga, elektrifikacija transporta donosi nove zahtjeve i poslovne mogućnosti u području energetskog planiranja, veće iskoristivosti OIE, povećane energetske efikasnosti te povećanja kvalitete života uslijed manje ispuštenih emisija. Također, značajan naglasak u istraživanjima je do sad stavljen na značajno ograničenje prijenosnog kapaciteta. Istraživanja se bave ovim problemom pri trgovanju između velikih zona te također razmatraju utjecaj na socijalnu dobrobit pri podjeli tržišta na zone, uz različite metode spajanja tržišta. Kako bi se procijenili utjecaji različitih strateških odluka u uvjetima povezanih energetskih sustava i tržišta temeljenih na marginalnim troškovima, potreban je alat koji istodobno može izračunati prekogranični prijenos i raspoloživost postrojenja (sate rada) u više zona. Takav je alat predstavljen od strane Sveučilišta Leuven u suradnji sa Zajedničkim istraživačkim centrom Europske Komisije (JRC), a služi optimiziranju rada energetskoga sustava uz zadanu konfiguraciju – Dispa-SET. Općenita upotreba Dispa-SET alata za modeliranje međusobno povezanih energetskih sustava s visokim udjelom varijabilnih obnovljivih izvora energije (VOIE) je razrađena u više objavljenih istraživanja. Teorija igara korištena je na ovom području ranije, na razini konkurencije pojedinih postrojenja i proizvodnih tvrtki.

Detaljni prikazi primjene teorije igara u energetskom planiranju i rješavanju problema vezanih uz razvoj konfiguracije energetskih sustava u recentnoj literaturi su predstavljeni kroz nekoliko preglednih radova, koji donose više od 300 znanstvenih članaka objavljenih u znanstvenim časopisima. Najvažniji zaključak ovih pregleda za ovo istraživanje je da se primjene teorije igara uglavnom bave problemima odozdo prema gore specifičnih generatora, agenata ili aktera na energetskom tržištu, ali ne i pristupom odozgo prema dolje, koji je predmet istraživanja u ovoj disertaciji. U problemima dugoročnog energetskog planiranja zona u međusobnoj interakciji, koji uključuju složene, sveobuhvatne energetske sustave, nema objavljenih istraživanja. Istraživanje objavljeno u ovoj disertaciji popunjava ovaj jaz i nudi novi standard za energetsko planiranje na razini energetskog sustava u danim tržišnim uvjetima.

Disertacija se temelji na pet znanstvenih radova. Fleksibilan rad i integracija proizvodnje električne energije s elektrificiranim transportom putem tehnologije električnog vozila povezanog s mrežom (engl. *Vehicle to grid*, V2G) te korištenje najjeftinije energije za zagrijavanje vode u spremnicima topline uklopljenim u CTS igraju ključnu ulogu u podršci integracije OIE, kao što pokazuju različiti scenariji navedeni u [RADU 2]. U [RADU 3] predložena je metoda za povezivanje EnergyPLAN modela s Python kodom, omogućujući izračun brojnih scenarija. Fokus je na analizi promjena u integraciji VOIE i kritičnog viška proizvodnje električne energije u energetskom sustavu zemlje, ovisno o odabranim opcijama fleksibilnosti. Rezultati naglašavaju značaj indeksa fleksibilnosti, pokazujući njegov utjecaj kroz kriterije energije, troškova, emisija i korištenja biomase. Studija pokazuje ekonomsku isplativost ulaganja u opcije fleksibilnosti, pri čemu se ukupni godišnji trošak visoko obnovljivog energetskoga sustava smanjuje kako raste indeks fleksibilnosti. Štoviše, uvodi se vektor fleksibilnosti kao metodološki alat za razlikovanje scenarija i razumijevanje kompromisa učinjenih u postizanju specifičnih ciljeva udjela obnovljive energije.

Sljedeći dio istraživanja usredotočen je na međusobno tržišno povezane sustave. [RAD 1] predstavio je metodu za planiranje energetskih sustava na mrežno povezanim otocima, fokusirajući se na njihov prijelaz na 100% obnovljive i održive pametne otočne sustave. Koristeći EnergyPLAN 13.0, rad 1 pokazuje izvedivost korištenja V2G koncepta bez tradicionalnih postrojenja za balansiranje (termoelektrane ili hidroelektrane). Korištenje alata MultiNode omogućuje simulaciju međupovezanosti između ovih otočnih sustava, omogućavajući analizu implikacija implementacije tehnologija odziva potrošnje i integriranje više lokalno dostupne obnovljive energije. Rezultati pokazuju značajno povećanje udjela OIE u ukupnoj finalnoj potrošnji energije i pad CEEP-a nakon spajanja na zajednički sustav. Kritični problem koji je ostao, bio je omogućiti praćenje prekograničnih tokova energije za konfiguracije energetskih sustava, koji također uključuju generatore na fosilna goriva. Zbog ovog razloga, u [RADU 4] demonstrirana je metoda koja se temelji na korištenju Dispa-SET modela na slučaju praćenja posljedica različitih strateških odluka između zona na međusobno povezanom tržištu električne energije. Rezultati su pokazali da je opredjeljenje za ambicioznu energetsku tranziciju imalo učinak smanjenja proizvodnje električne energije iz elektrana na lignit u cijelom području studije slučaja (uključujući zone koje se drže fosilne ili strategije bez mjera) zbog izvoza obnovljive energije iz zona koje su proizvele više električne energije iz obnovljivih izvora nego što su uspjeli integrirati u svoj energetski sustav. Nadalje, scenarij s većinom zona koje idu na povećanu integraciju OIE nudi 70% nižu prosječnu cijenu električne energije u usporedbi sa scenarijem umjerene tranzicije opisane aktualnim strateških dokumentima, bez povećanja broja sati zagušenja na prekograničnim dalekovodima električne energije.

Pristup s praćenjem prekograničnih tokova energije omogućio je uključivanje teorije igara u [RADU 5], gdje je predstavljen novi pristup energetskom planiranju zone na međusobno povezanom energetskom tržištu, zajedno s algoritmom koji koristi pristup teorije igara za određivanje optimalne odluke za svaku zonu. Pokazalo se da se optimalne odluke u dugoročnom energetskom planiranju za svako tržište zajedno sa susjednim zonama mogu odrediti na ovaj način, kroz postizanje Nashove ravnoteže s energetskim strategijama okolnih zona. Ovaj pristup se može koristiti za svaku zonu, pretpostavljajući strategije drugih zona, čak i u slučaju nedostatka informacija o njima. U slučaju da se ne pronađe čista Nashova ravnoteža, moguće je koristiti algoritam za pronalaženje rješenja mješovite strategije, koji ipak pomaže u donošenju odluka, čime se daje robusnost pristupu prikazanom u ovom istraživanju.

<u>Ciljevi istraživanja i hipoteza</u>

1. Dokazati vrijednost primjene teorije igara u procjeni dugoročnih strateških odluka u zonama povezanim na zajedničkom tržištu električne energije.

2. Demonstrirati potrebu za uključivanjem u razmatranje utjecaja strategija u tržišno povezanim zonama na energetsku strategiju promatrane zone.

3. Analizirati utjecaj integracije tehnologija brzog odziva u tržišno povezanim zonama na opravdanost strateških odluka u promatranoj zoni.

Hipoteza ovog istraživanja je da se optimalne odluke u dugoročnom energetskom planiranju za svako tržište povezano sa susjednim zonama mogu odrediti teorijom igara, kroz postizanje Nashove ravnoteže s energetskim strategijama okolnih zona, čak i u slučaju nedostatka informacija o njima.

Metode istraživanja

Modeliranje u okviru energetskog planiranja temelji se na uravnoteženju ponude i potražnje za električnom energijom, uzimajući u obzir prednost proizvođača energije s nižim graničnim troškovima proizvodnje dodatnog kilovatsata električne energije. Energetsko planiranje pretpostavlja da su sve varijable, osim varijabli odlučivanja, unaprijed poznate. To uključuje vremenske krivulje potražnje za električnom energijom, dostupnost energije sunca i energije vjetra, razine akumulacije u akumulacijskim hidroelektranama, itd. Također je uobičajeno da modeli za energetsko planiranje uzimaju u obzir krivulje agregatne potražnje bez razlikovanja pojedinih objekata unutar sustava. Elektrifikacija prometa omogućuje da u modelu tržišta električne energije modeli za energetsko planiranje izravno uključuju povećanu potražnju za električnom energijom. Nadalje, budući da svako električno vozilo ima baterijski sustav skladištenja energije, u onim razdobljima kada su vozila parkirana i povezana s mrežom, mogla bi aktivno sudjelovati u uravnoteženju opskrbe električnom energijom i potražnje prema V2G principu, koji je dobro poznat u literaturi. Osim elektrifikacije prometa, također se razmatra i tehnologija pretvaranja viška električne energije proizvedene iz VOIE u toplinu (engl. *Power to heat*, PtH) te proizvodnja i potrošnja sintetičkih goriva (vodik, sintetički plin). Kako bi se istražio utjecaj koji određene strateške odluke, povezane s energetskom tranzicijom i smjerom koji zakonodavstvo i industrija odaberu u određenoj tržišnoj zoni, imaju na mogućnosti isplativog ulaganja u takvu tržišnu zonu, alat koji se koristi mora odražavati te odluke u međuodnosu povezanih zona. Informacija koja regulira te tokove treba biti vidljiva kroz redoslijed uključivanja proizvodnih kapaciteta prema graničnim troškovima proizvodnje energije. Takve informacije su mjerljive i odgovaraju stvarnim trendovima i promjenama na tržištu energije, ideji energetske tranzicije i razvoju tehnologija kojem danas svjedočimo. Iz tih razloga, model Dispa-SET je odabran da se koristi u analizi scenarija u prvom koraku ovog istraživanja. To je model otvorenog koda za optimizaciju energetskog sustava i dispečiranje pojedinih postrojenja. Razvija se u okviru Zajedničkog istraživačkog centra Europske komisije, u bliskoj suradnji sa Sveučilištem Liège i KU Leuven (Belgija). Do sada je Dispa-SET korišten na problemima uravnoteženja i fleksibilnosti u europskim mrežama. Alat je korišten i za modeliranje međusobno povezanog energetskog sustava zemalja zapadnog Balkana. U prvom koraku istraživanja Dispa-SET se koristi za modeliranje povezanog sustava, koji se sastoji od nekoliko tržišnih zona (nacionalnih sustava). Takav međusobno povezani sustav predstavlja tržište na kojem se istražilo različite odluke u svakoj od zona.

Prvo je predložena metoda za analizu troškova proizvodnje, skladištenja i tehnologije brzog odziva, uzimajući u obzir dinamiku energetske tranzicije. Pažnja je posvećena isplativosti različitih tehnologija, ali i istovremenoj integraciji VOIE tehnologija i tehnologija brzog odziva te kakav utjecaj odluka o većoj integraciji VOIE ima na broj radnih sati novo planiranih postrojenja i tokove energije između zona. Rezultat prvog koraka je prikazana metoda za analizu takve energetske tranzicije, koja pruža jasne informacije o utjecaju, koji energetski sustavi na različitim razinama energetske tranzicije (obilježenim stupnjem integracije VRES-a i tehnologija brzog odziva) međusobno, imaju. To je vidljivo kroz broj sati rada postrojenja i tok energije između zona. Cilj drugog koraka istraživanja bio je predložiti metodu koja koristi teoriju igara pri procjeni dugoročnih strateških odluka tržišno povezanih zona. Kada se izrađuju nacionalne energetske strategije, suvremeni pristup ne razmatra strategije ostalih zona/zemalja u okolini kao endogene varijable. Ona se uzima u obzir kroz povijesne podatke o uvozu i izvozu, kroz povijesne podatke o cijenama energije na tržištima i njihovom budućem razvoju kroz stručne pretpostavke i izračune. U ovom koraku istraživanja, za odluke koje se ispituju za odabranu zonu, razvijena je igra temeljena na teoriji igara. Cilj igre je utvrditi kako predložena mjera ili strateška odluka utječe na ekonomsku isplativost novih postrojenja u odabranoj zoni, što dovodi do bolje profitabilnosti planiranih ulaganja, neprofitabilnosti planiranih investicija ili postizanja situacije u kojoj niti jedna zona ne bi poboljšala izvedivost ulaganja (Nashova ravnoteža). Rezultat drugog koraka je nova metoda koja se može predložiti kao standard za energetsko planiranje tržišnih zona, koje su uglavnom nacionalni energetski sustavi. Nova metoda poboljšava dugoročno planiranje energije u kontekstu tržišno povezanih zona, koje su dio većeg tržišta električne energije, pružajući matematički iskazan rezultat za sve zone i jasnu informaciju o najboljoj odluci za sve. Takvo poboljšanje pristupa planiranju je korisno u uklanjanju neučinkovitih i netransparentnih energetskih politika koje su, na kraju, neodržive i neprihvatljive za korisnike u bilo kojoj zoni odabranoj za stvaranje novih strategija i odluka o razvoju energetskog sustava.

Znanstveni doprinosi

Dva znanstvena doprinosa zadana su na početku istraživanja:

1. Metoda za analizu troškova proizvodnje i skladištenja energije te integracije tehnologija brzog odziva, prema koracima energetske tranzicije u okolnim zonama.

2. Metoda koja pruža robusnu procjenu strateških odluka pomoću teorije igara, što može biti novi standard za energetsko planiranje na nacionalnoj razini.

Prvi doprinos ostvaren je u razradi metode za analizu troškova proizvodnje, skladištenja i tehnologija odgovora na potražnju, organiziranih u koracima energetske tranzicije u zonama koje okružuju zonu interesa. U tom kontekstu, [RAD 1], [RAD 2] i [RAD 3] pružaju metodološki razvoj pristupa za jednu zonu i za međusobno povezanu skupinu zona, koji definira rezultate za tehnologije proizvodnje električne energije, skladištenje energije i odziva potrošnje u tehničkom kontekstu i u kontekstu ekonomske procjene isplativosti ulaganja.

Drugi veliki doprinos je metoda koja daje robusnu procjenu strateških odluka korištenjem teorije igara, što može biti novi standard za nacionalno energetsko planiranje. Ovaj doprinos je ostvaren na temelju rada urađenog u [RADU 1], [RADU 2] i [RADU 3], kroz metodu razvijenu u [RADU 4] i dovršenu korištenjem teorije igara u [RADU 5].

Keywords

Long-term energy planning
Integrated energy systems
High share of renewable energy
Demand response technologies
Flexibility options for the energy system
Game theory
Nash equilibrium

Ključne riječi

Dugoročno energetsko planiranje
Integrirani energetski sustavi
Visok udio obnovljive energije
Tehnologije odziva potrošnje
Mogućnosti pružanja fleksibilnosti energetskome sustavu
Teorija igara
Nashova ravnoteža

List of abbreviations

Abbreviation	Meaning
BAU	Business as usual
CEEP	Critical excess of electricity produced
CHP	Combined heat and power generation
CHS	Centralized heating systems
COP	Coefficient of performance
FLH	Full load hours of operation
NE	Nash Equilibrium
NTC	Net transfer capacity
PCR	Price Coupling of Regions
P2H	Power to heat
PP	Power plant
PV	Photovoltaics
RES	Renewable energy sources
V2G	Vehicle-to-grid concept
VRES	Variable renewable energy sources

Nomenclature

	Description	Unit
Chemical formulas		
CO_2	carbon dioxide	
Variables and parameters		
C	cost	EUR
Ch	Charging cost	EUR/MWh
E	Amount of energy generated and discharged to the grid	MWh
F_i	Flexibility index	[-]
F_s	Flexibility vector	[-]
FV	Value of the flexibility index	[-]
H	Amount of heat generated	MWh_t
I	Set of players	[-]
P	Power capacity	MW
P	Price of energy	EUR/MWh
P_t	Heat capacity	MW_t
R	Payoff achieved by player/zone	EUR
Q	thermal energy	MWh
S	Set of strategies	[-]

SOC	state of charge for the electric battery	%
T	temperature	°C
Greek letters		
η	technology efficiency	%
Subscripts		
el	electricity	
$heat$	heat	
i	zone in the coupled market/choice of technology	
Inv	investment	
max	Maximal value	
t	time	
Z_i	Zone "i" in the coupled market	

List of figures

List of Tables

Chapter 1

Introduction

The electricity market has been present for a long time in Europe through the separate markets of individual countries, and later the regions. At the beginning of 2014, the "Price Coupling of Regions" (PCR) started creation of the single EU market, with the seven largest separate markets (APX, Belpex, EPEX SPOT, GME, Nord Pool Spot, OMIE and OTE) forming a common market (current outlay in 2023 shown in Figure 1). Today, entities in Croatia can buy energy on the day-ahead and intraday market, which is coupled to other European markets through Slovenian market. The immediate next step in unifying Europe in the single electricity market is the formation and the joining of the markets of Southeast Europe. After that, the market of auxiliary services and reserves will be introduced, which will be enriched with new technologies, and in particular demand response technologies. Taking into account the complexity of the system, which will be the result of energy transition in decentralized systems with a high share of variable sources and competitive market conditions for all participants, it is necessary to strive for energy planning that takes into account specific local conditions and potentials.

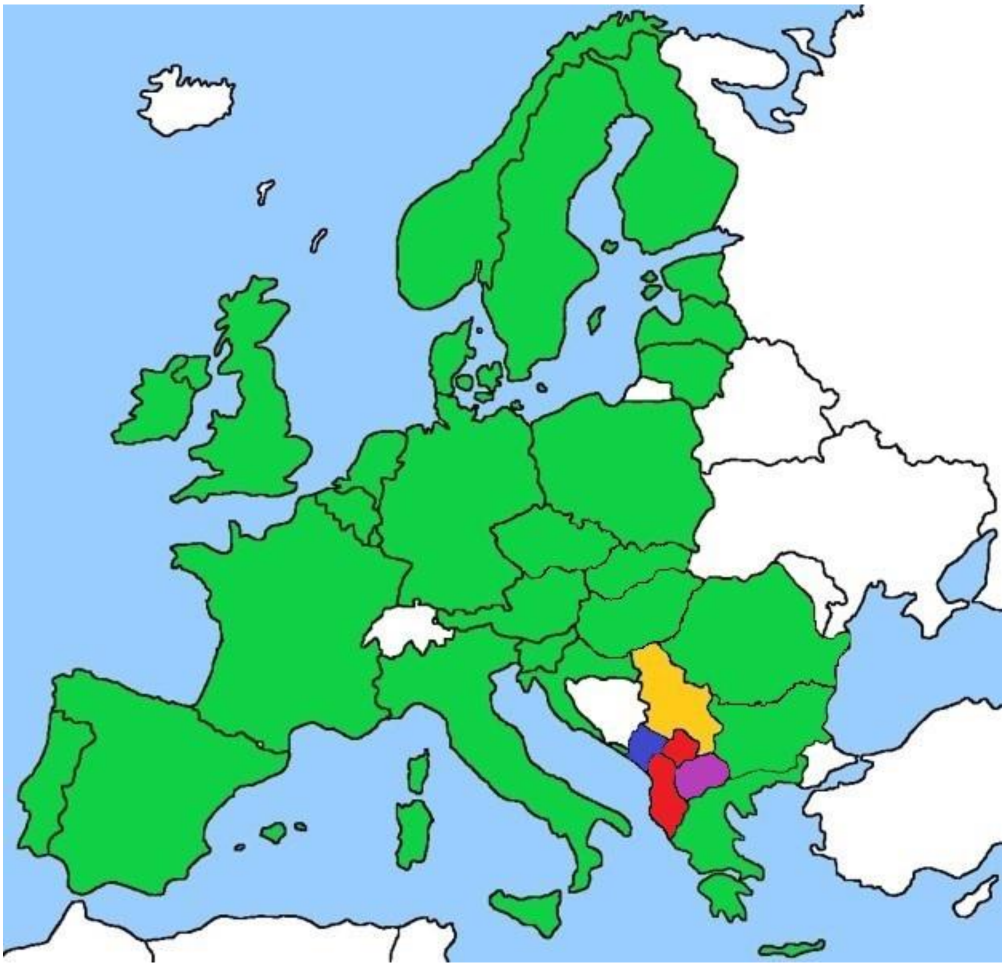

Figure 1 European day-ahead power market layout in 2023

Within the present research, the electricity price is formed on the market principle of supply and demand, taking into account marginal cost of production. By introducing Variable Renewable Energy Sources (VRES), it is theoretically possible to gradually replace conventional production systems (based on oil, coal and natural gas). Many studies have been conducted to investigate whether there are possible 100% renewable systems for individual countries [1], regions like Southeast Europe [2] and the whole EU [3]. New tools, such as MultiNode tool of the EnergyPLAN, are developed to simulate the possibility of coupling of systems [4], but lacking the optimization of unit commitment and influence of import/export to surrounding zones. Market analysis in terms of meeting the upcoming EU regulations and the potential for using a larger share of renewable sources have also been made for Serbia [5] and Bosnia and Herzegovina [6]. In practice, however, there are problems related to the regulation and management of energy systems (ES) based on VRES due to the variability and short-term predictability of VRES production (related to the weather forecast) [7]. Even when the conditions for installing new VRES capacities are good, it is still necessary within ES to have spare capacities in the form of flexible gas-fired thermal power plants that can respond to a drop in production from the RES [8], because using the RES's surplus energy storage system have enough capacity to provide sufficient energy supplies within the ES, still costly and inefficient ('circular' efficiency).

Some new trends are already coming, the 4th generation of centralized heat systems (CTS) associated with cogeneration plants with heat storage tanks as a source, heat pumps at household and CTS level [9], and ongoing electrification of transport. It brings new demands and business opportunities in the area of energy planning, greater utilization of RES, increased energy efficiency and increased quality of life due to lower emissions [10]. The primary access to the market of ancillary services and reserves, which can provide Demand Response (DR) technology on the multilevel market, was explored in [11]. This research demonstrated how these markets increase social welfare.

Research is conducted in the field of market coupling between the two markets [12] and price optimally planned further development of such markets in [13] and [14]. The impact on price difference, its convergence, and the timing of overlapping / closeness of the price level for significant markets, under the influence of increasing the acceptance of renewable sources, was explored in [15]. Also, significant emphasis on research has so far been placed on a significant constraint: the transfer capacity.

Research deals with this problem in trade between large areas [16] and with different methods of market coupling [17]. The use of multi-agent modeling has recently been exploited as a computer learning method, using available information in combination with genetic algorithms [18]. Further research has been conducted by multi-agent simulation [19] and by linking two neighboring markets [20], market-based modeling based on volume of trading [21] and exploring how market consolidation through their merger affects the possibilities of their planning [22]. Detailed terms are related to the correlation of social welfare and the merger of the market - in this case a large market with neighboring systems markets, some of which are of particular interest to this research, namely Southeast Europe, explored in [23].

Modelling in energy planning is reduced to the balancing of supply and demand of electricity, taking into account the advantage of energy producers with lower marginal cost of producing additional kWh of electricity. Energy planning assumes that all variables, apart from decision variables, are known in advance. This includes the time curves of electricity demand, the availability of solar and wind energy, accumulation levels in accumulator hydroelectric power plants, etc. It is also commonplace that energy planning models take into account aggregate demand curves without distinguishing individual entities within the system.

With the electrification of transport, it is possible in the model of the electricity market for the energy planning models to directly involve the increased demand for electricity. Furthermore, as each electric vehicle has an energy storage system, in those periods when the vehicles were parked and connected to the network, they could actively participate in the balancing of electricity supply and demand on the vehicle-to-grid principle (V2G). The principle of vehicle-to-grid is a well-known term. In addition to the electrification of transport, the technology of converting excess of electricity produced from variable renewable energy sources (VRES) to heat (Power-to-heat), the production and consumption of synthetic fuels (hydrogen, synthetic gas) are also considered. All those technologies, including demand response technologies and battery storage, are studied in numerous research papers that address the modelling of 100% RES-based energy systems[24].

In order to investigate influence which certain strategic decisions, connected to energy transition and the direction which legislation and industry in certain market zone chooses, has on the feasibility of investments in such market zone, a tool must reflect these decisions though unit commitment and energy flows between the interconnected zones. The information which governs these flows should be merit order according to marginal cost of energy production. To evaluate impacts which different strategic decisions in the context of connected energy systems and a market based on marginal cost, a tool which can calculate cross-border transmission and unit commitment in several zones at the same time is needed. Such tool was presented in [25], which investigated centralized cogeneration plants with thermal storage, an important technology for energy transition, and its influence on efficiency and cost of the power system in case of optimized operation. The overall use of Dispa-SET tool for modelling of interconnected energy systems with high share of renewable energy is elaborated in [26], for optimized case in a whole year hourly calculation.

The game theory approach has also been used in this field previously on the level of competition of individual generators and production companies. In [27], a game optimization theory was used to solve distribution and distributed production problems, also, the study cites principle definition of the game theory, "*Game theory, as a branch of applied mathematics, is the study of mathematical models of conflict and cooperation between intelligent rational decision-makers. In addition to being used to describe, predict and explain behaviour, game theory has also been used to develop theories of ethical or normative behaviour*." Also, game theory was used to investigate problems of development of new renewable energy (RES) installations in hybrid PV-Wind case in [28] and Wind-Hydropower in case of [29]. Game theory, precisely a Cournot game, was used in [30] to describe the steps necessary to analyse whether the sustainable idea (e.g., environmental innovation) is environmentally compatible, socially acceptable, and economically viable, but the study was aimed towards the small-medium enterprises (SMEs) involved in production processes. In [31], medium run and long run market simulators were presented, based on game theory. The research was focused on an analysis of producers' behaviour during the first operative year of a national power exchange, concerning two games: unit commitment of thermal units and one for strategic bidding and hourly market clearing. In [32], the authors analyse the main electricity bidding mechanisms, based on the signalling game theory, in the electricity auction markets and considers the degree of information disturbance as an important factor for evaluating bidding mechanisms for energy generators. Introducing strategic storage units (EES), authors in [33] developed the method to find pool equilibria in a system and identify profit-maximization behaviours of different ESSs and generators. Energy management and storage optimization problems have also been addressed, for example in [34], where a Stackelberg game is introduced. Players try to increase their payoff while ensuring user comfort and system reliability. Additionally, forecasting of the production form solar power plant is introduced to reach optimal prices. The existence and uniqueness of Nash Equilibrium of energy management algorithm are also proved. Demand response management was investigated by implementing game theory-based approach in [35]. An algorithm was devised to maintain the balance and "shave" the consumption peaks to achieve average energy consumption ratio. Stackelberg game was introduced to obtain a solution based on one leader strategy, where leader first decide their best response and followers select their best response on the basis of leader's strategy, until the Nash equilibrium is reached between consumers and utilities.

Issues with finding Nash equilibria in computer simulations of evolutionary games were investigated in [36], concluding that a final set of strategies can avoid such. For this reason, in the present research, a discrete problem is in the focus (matrix game), with a final set of strategies and scenarios available for players. It is argued that such approach is sufficient for practical purposes. Matrix games have been previously used in the literature in different contexts. For instance, research that delt with matrix games include bidding strategies in deregulated markets [37] and matrix games in power systems and obtaining the Nash equilibria in multi-player matrix games [38], concluding that accurately obtaining Nash equilibria provides improved assessment of market performance and design, making the operation of power market stable and avoid major price spikes. In the case of examining the generation capacity investments, cap and trade programmes for CO_2 were investigated for restructured markets in [39]. Also, a realistic equilibrium model of a pool-base electricity market has been developed in [40] for a single market and multiple competing power companies.

Cooperative games were studied to create an optimization tool for smart energy logistics and economy analysis problems. Such solutions were found to better optimize and allocate the case of smart deregulated structures in [41]. In following of the economic achievements of energy companies in neighbouring countries, the game theory was used by researchers in [42]. In the economic analysis, game was set up optimal solutions and presents all available strategies for the large energy companies and their relationships. Both non-cooperative game in the form of a 'prisoner's dilemma', and a cooperative game were investigated.

In the most recent research [43], the Nash equilibrium method is employed to model interactions between day-ahead and futures markets. The model includes producers, retailers, and speculators, considering uncertain wind power plants output, contract financial settlement, risk preferences, and transmission limits. It identifies optimal strategies, explores transmission congestion's impact on equilibrium, and studies financial contract effects on uncertain factors.

1.1. Knowledge gap identification

Detailed reviews of the implementation of the game theory in energy planning and solving of the problems related with energy systems configuration development were performed in [44], [45] and [46]. All reviews bring up more than 300 scientific articles published in scientific journals. The most important conclusion of these reviews for the present research is that game theory applications deal predominately with bottom-up problems of the specific generators, agents or actors in the energy market, but not with the top-down approach that is the subject of research in this dissertation. In long-term energy planning problems and interaction between zones which include complex, comprehensive energy systems, to the best of our knowledge, there is no published research.

In long-term energy planning problems and interaction between zones which include complex, comprehensive energy systems, there is no published research. This research will fill this gap and offer a new standard for energy planning on the level of energy system in coupled day-ahead market conditions.

1.2. Methodological approach

The simulation part of the research employed the EnergyPLAN tool to analyze the influence of integration of demand response technologies in individual and coupled market zones on the feasibility of strategic decisions in the investigated zone, with the aim to establish suitable methods for the analysis of demand response and flexibility options, according to the steps of energy transition, example of which is shown in the Figure 2.

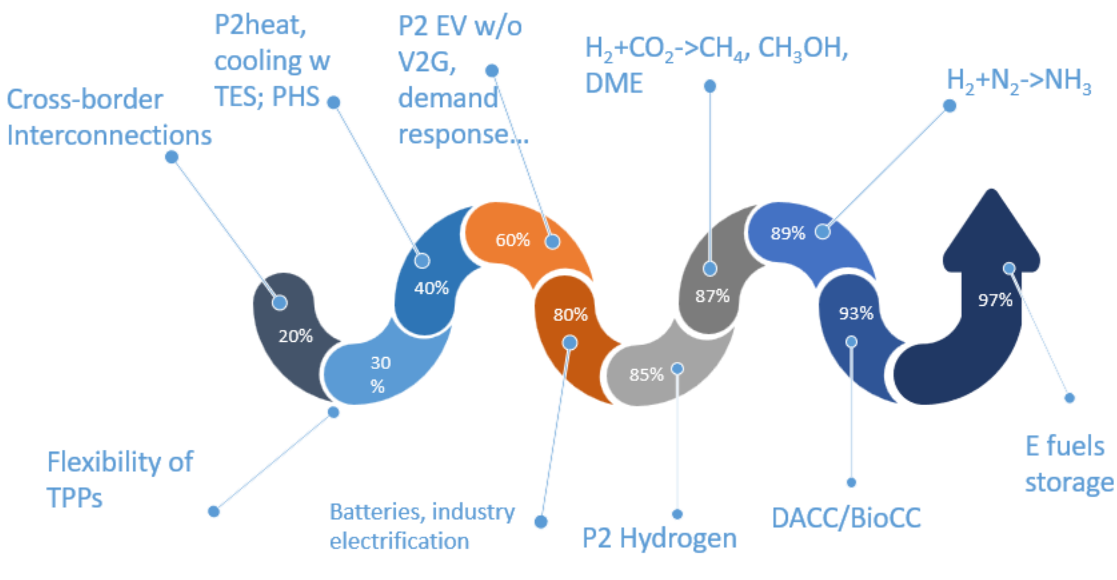

Figure 2 The illustrative steps of the energy transition

In first step of the optimization part of the research, Dispa-SET is used to model the interconnected system, consisting of several trade zones (country systems). Such an interconnected system constitutes a market in which different decisions in each of the zones can be investigated. First, a method is proposed for analysis of costs of production, storage and demand response technologies, organized in steps of energy transition in these zones, taking into account the dynamics of energy transition. Attention is given to the cost-effectiveness of different technologies, but also to simultaneous integration of VRES and demand response technologies and the influence of decisions to go forward with larger integration of VRES have on unit commitment and power flows between the zones.

Result of the first step is a demonstrated method for analysis of such energy transition, which provides clear information about influence which energy systems on different level of energy transition (marked by level of integration of VRES and demand response technologies) have on each other. This is visible through unit commitment and energy flows between the zones.

Aim of the second step of the optimization approach is to propose a method which uses game theory in assessing the long-term strategic decisions of market coupled zones. When the national energy strategies are being developed, the present state-of-the-art approach doesn't take the strategies of other zones/countries as endogenous variable. It is considered through historical data on imports/exports, through historical data on energy prices on the markets and their future development through expert assumptions and calculations. In this step of the research, for decisions which are examined for the chosen zone, a game will be developed. The goal of the game is to determine how proposed measure or strategic decision influences the feasibility of new installations in the chosen zone, leading to better profitability of planned investments, planned investments becoming unprofitable or reaching a situation in which no zone would improve its feasibility of investments (Nash equilibrium).

Result of this step is a new method, which can be proposed as a standard for energy planning of the market zones, which are mostly national energy systems. The new method improves long-term energy planning in the context of market coupled zones, which are part of larger power market. Such update to the planning approach is beneficial in eliminating inefficient and non-transparent energy policies, which are, in the end, unsustainable and unbeneficial for the users in any zone chosen for creation of new strategies and energy system development decisions.

1.3. Objectives of the Thesis

Objectives of this research are:

1. To prove the value of the use of game theory in assessing the long-term strategic decisions of market coupled zones
2. To demonstrate the need to include the influence of market coupled countries' energy strategy on national energy strategy
3. To analyze the influence of integration of demand response technologies in coupled market zones on the feasibility of strategic decisions in the investigated zone

The hypothesis of this research is that optimal decisions in long term energy planning for each market coupled with neighboring zones can be determined by game theory, through achieving Nash equilibrium with energy strategies of surrounding zones, even in the case of lack of information about them.

Scientific contributions of the research are:

1. A method for analysis of costs of production, storage and demand response technologies, organized in steps of energy transition in the surrounding zones

2. A method which provides robust assessment of strategic decisions using the game theory, which can be a new standard for national energy planning

1.4. Structure of the Thesis

The thesis is structured as follows:

- *Chapter 2* reviews the methods used for achieving various objectives of the research;
- *Chapter 3* provides insights in selected results, as well as discussion of their relevance;
- *Chapter 4* presents the conclusions and the future work;
- *Chapter 5* elaborates on the main contributions of the thesis and links them to the publications;
- *Chapter 6* summarizes author's contribution to the publications;

Chapter 2

2.1. Short overview of the used methods

To tackle the challenges of energy transition towards integrated energy systems based on variable renewable energy, described in the introduction, two principally different energy systems' modelling and analysis approaches have been employed. For each approach, a different tool was selected, and the use of those tools has been expanded through proposition of novel approaches or (soft)linking with additional needed component. Both approaches, simulation and optimization one, complemented the research of single zone and multiple interconnected zones, which were proposed as model examples of energy systems undergoing the energy transition. The connection between these approaches and scientific contributions of the research is provided in Figure 3.

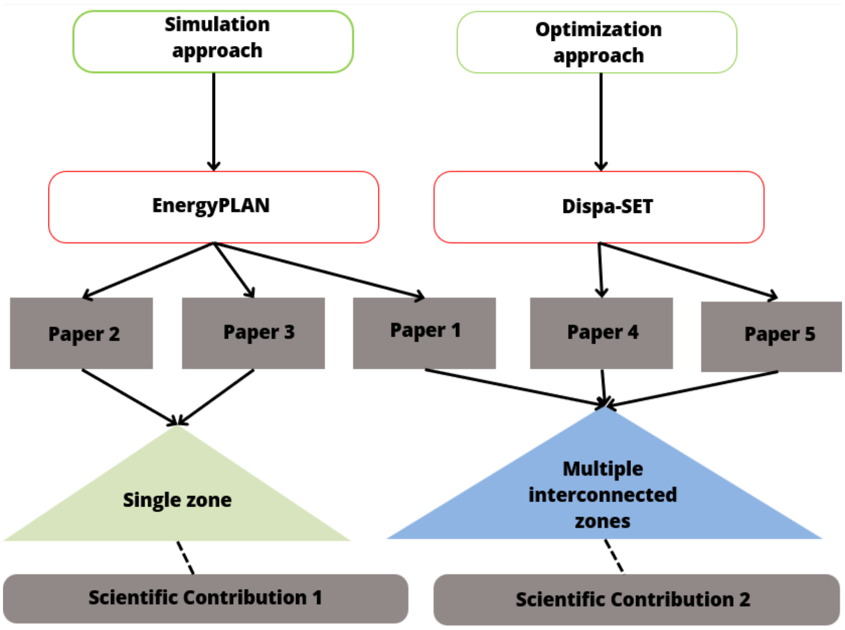

Figure 3 The connection between ES modelling approaches and scientific contributions

2.1.1. Simulation approach

For the simulation approach in this research, EnergyPLAN model was used. The EnergyPLAN is an input/output model which incorporates heat and electricity supplies as well as the transport, individual and industrial sectors, principal scheme of the model is given in Figure 4. It has already been used for the scenario analysis of energy systems with a high share of the VRES as well as for the 100% renewable energy systems and various other analyses, which made it an established tool for similar applications [4], [47].

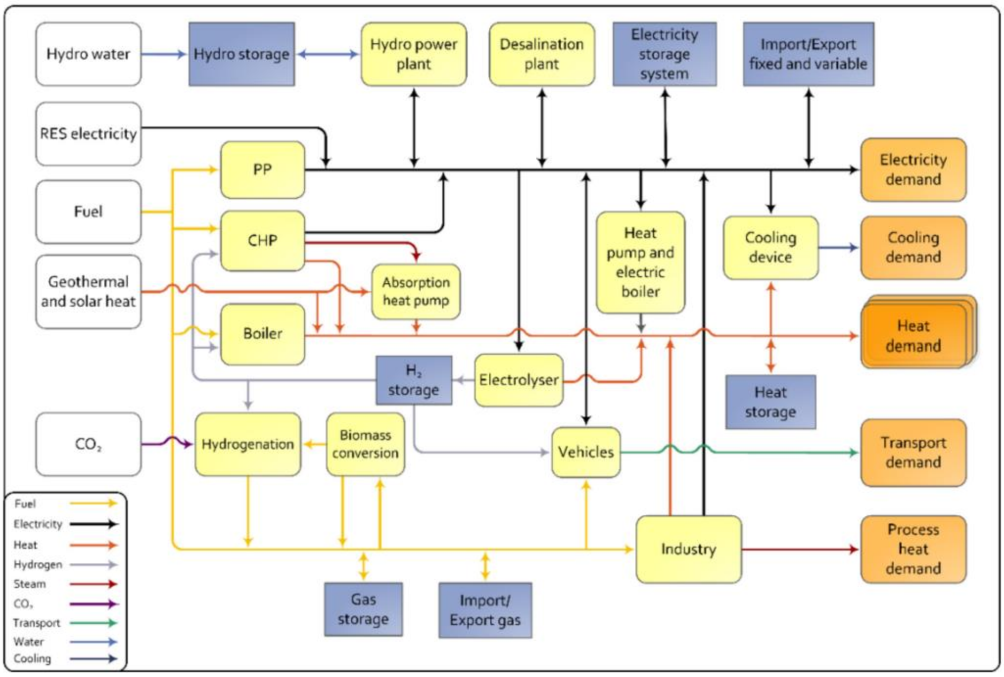

Figure 4 Principal scheme of the EnergyPLAN tool [47]

In this version of the EnergyPLAN model, the option of balancing V2G and Hydropower can be used without Power plants (PP) 1 and PP 2 which represent the aggregated groups of power plants, usually supplied by fossil fuels. Moreover, one more balancing option is available in this version of the EnergyPLAN. V2G can be used to balance the need for PP and reduce Critical Excess Electricity Production (CEEP) but also to balance the Import/Export so that import is not needed if V2G batteries can be used. Otherwise, energy is stored in batteries instead of exporting it from the system. This can be active in the “Simulation” TabSheet.

Critical Excess Electricity Production (CEEP) is an important parameter, followed in the results of the EnergyPLAN model’s calculations, and defined for the purpose of this thesis as the amount of energy in any particular hour, which cannot be used for any process or exported from the system. In reality, that means some of the generators in the system would be curtailed, but in the hourly analysis of the energy system operation, it is used to determine how much energy would be available for possible decarbonization of different sectors of energy demand.

For the purpose of scenario modelling, technical simulation was used, which seeks to find the solution with the minimum fuel consumption.

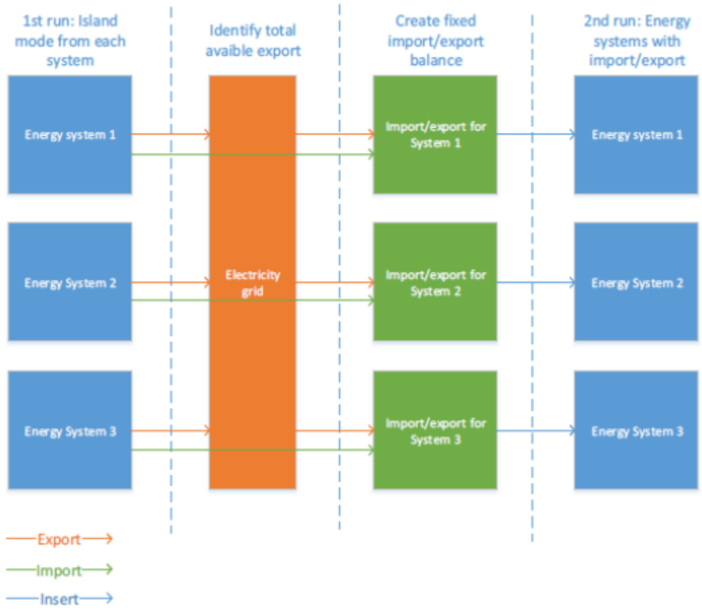

Figure 5 MultiNode tool general scheme [48]

MultiNode is an additional tool in EnergyPLAN, specially designed for analysing integration of local and national systems and plans of their development (Figure 5). The main result from MultiNode analysis is fixed import/export profiles between two or more energy systems. MultiNode seeks hours throughout the year where there is at the same time excess electricity in one system and import demand or condensing thermal power plant (TPP) production in another one. In such way, the first system can integrate its excess production, which is usually a result of the VRES production, while the second system can meet its import demand or decrease the TPP production, thus increasing the share of RES and decreasing the fuel consumption. Method for establishing import/export balances in MultiNode operation is described using the equations (1)-(4), which form the mathematical model of this tool [48].

The simulation approach was used in the elaboration of research contributing to the objective 3: *To analyze the influence of integration of demand response technologies in coupled market zones on the feasibility of strategic decisions in the investigated zone*; and also the contribution 1: *A method for analysis of costs of production, storage and demand response technologies, organized in steps of energy transition in the surrounding zones.*

2.1.2. Optimization approach

For the reasons elaborated in the introduction, the Dispa-SET model is chosen to be used in scenario approach analysis in the first step of this research. Recently, the tool was also used for modelling of the interconnected energy system of the countries of Western Balkans [49], [50].

The Dispa-SET model is an open source energy planning model which aims to represent the short-term operation of large-scale power systems with a high level of detail. Through minimization of the marginal cost of electricity generation, the model offers solutions for energy planning of the particular zone or region of interconnected zones, taking into account power plant operation (unit commitment) and power flows between the zones. This approach minimizes the short-term operation costs for the generation of electricity and heat and enables Dispa-SET to solve the problem of unit commitment and dispatch in large, interconnected networks, such as European power system. Pre-processing and post-processing tools are written in Python, and GAMS is used as the main solver engine. The model is written in the form of Mixed Integer Linear Programming (MILP). Dispa-SET is being developed in by the European Commission's Joint Research Centre (JRC), in cooperation with the University of Liege and KU Leuven (Belgium). It is presumed that the system is managed by a central operator with full information on the technical and economic data of the generation units, the demands in each node, and the transmission network. To solve the unit commitment problem, two steps need to be addressed: scheduling the start-up, operation, and shut down of the available generation units allocation of the total power demand among the available generation units minimizing the electricity systems' operating costs The second part of the problem is the economic dispatch problem, which determines the continuous output of every generation unit in the system and is formulated through the MILP. Major inputs in order to run these steps are [26]:

- Availability factors for RES power plants (hourly, solar, wind, hydro)
- Cross Border Flows (hourly, historical, between zones)
- Net transfer capacities (NTC) between zones, hourly
- Heat demand (hourly for power plants supplying heat / CHP)
- Scaled Inflow for hydropower storage, hourly
- Reservoir Level of hydro storage, hourly
- Electricity Load, hourly
- Outage factors, hourly
- Power plants database describing parameters for all power plants

The optimization function in Dispa-SET minimizes the short-term operation costs of the electricity and heat generation for the region, which includes different countries, representing electricity trading zones in further discussion. Detailed description of the optimization procedure can be found in [50], including the goal function.

The electricity system costs can be divided into fixed costs, variable costs, start-up and shutdown costs, load-change costs, relieving costs, transmission costs between the two zones, and costs of lost load. The fundamental limitation of power systems is the balance between consumption and generation of electricity. It is met by simulating day-ahead supply-demand balance, for each period (1 h) and each zone. The sum of all the power produced or discharged by all the units present in the zone that is observed, energy injected from neighboring zones and the power curtailed from VRES must be equal to the load in that zone, with the addition the energy storage inflow. Other constraints are related to the technological characteristics of generation plants. Further constraints are set at cross-border capacity and consequentially, the flow of electrical energy between two zones cannot be larger than the predefined net transfer capacity (NTC). Before starting the Dispa-SET model calculation, it is necessary to enter data such as hourly load distribution, technical characteristics of generation plants, fuel prices and hourly distribution of cross-border capacity. The optimization problem is split into smaller optimization problems that are run recursively throughout the year. Figure 6 shows an example of such approach, in which the optimization horizon is one day, with a look-ahead period of one day. The initial values of the optimization for day “j” are the final values of the optimization of the previous day. The look-ahead period is modelled to avoid issues related to the end of the optimization period such as emptying the hydro reservoirs or starting low-cost but non-flexible power plants. In the approach used in this research, the optimization is performed over 48 h, but only the first 24 h are conserved.

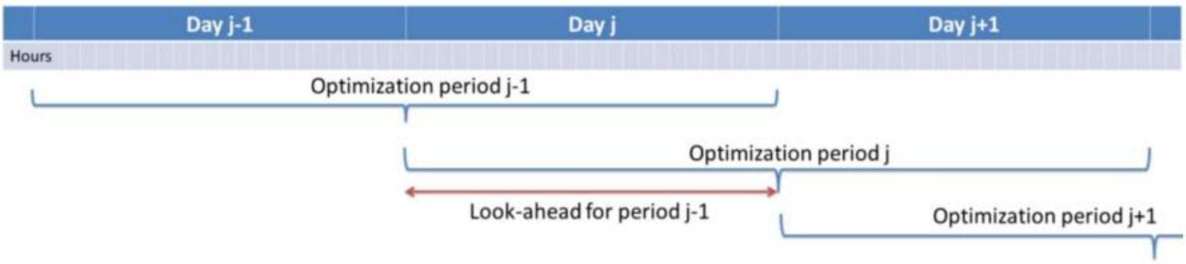

Figure 6 The moving horizon optimization approach of Dispa-SET [26]

In the following sub-chapters, novel contributions to the methods for each application are elaborated.

2.2. Energy systems of a single zone in transition

2.2.1. Flexibility options for the integration of large share of variable renewable energy

When all the options of cheap, cost-effective demand response are used, then further increase in penetration of VRE is possible only by storing energy at a higher cost. If the goal is to increase the share of renewables as soon as possible, then the dynamics of construction is limited only to the techno-economic criteria at a given moment and to the investment cycle rate. However, this will eventually lead to the rapid build-up of new sources at the beginning, and later stalling of the sector when saturation occurs. Although this has the advantage for the climate policy position, as this reduces emissions at a higher percentage, from the social welfare position it is necessary to ensure a constant value added of the VRE sector. As the value added in VRE is largely comprised of Capital Expenditures (CAPEX), although in wind power maintenance costs are significant (while other operating costs are negligible, OPEX), to ensure a continuous flow of added value, a continuous flow of investments should be provided. Wind power plants and solar power plants have a typical lifetime of 20 years, which means that, if one wants to achieve high socioeconomic profit, it can be assumed to install an average of 5% of the technically acceptable VRE share for 20 years on average. The possible integration of VRE into the system was examined using the energy planning model EnergyPLAN, described in *2.1.1. Simulation approach*.

First relevant concept, which allows larger integration of energy from VRE, is the flexibility of existing power plants.

For second concept, the approach to modelling investment in demand response technology relies on existing plans and trends in the sectors of centralized heat systems and electrification of transport. For centralized heat systems, assumed development implies that the goal of 40% of district heating systems (DHS) is achieved by 2050 (According to EU budgets under the new heating and cooling strategy, the estimate is that DHS can meet 40-70% of heating demand in Europe). DHS use fuel more efficiently than individual boilers. They can also use different sources at one location (in one plant) and can support the integration of renewable sources by using the surplus of the generated energy from the VRE while simultaneously reducing the consumption of fossil fuels. When considering centralized heat systems, cogeneration systems and their improvement of heat energy conservation technologies are considered in the moments when electricity is cheap (for example, VRE energy, which is a critical surplus at a given time).

The third major energy-efficient technology concept (electrified transport connected to the grid at times when the vehicles are parked) is used to integrate increased share of renewable energy sources through storage and balancing, reducing CEEP in such way. Electric vehicles can be present in several technological forms: hybrid vehicles, hybrid vehicles with a network connection, electric vehicles with dumb charging, smart electric vehicles and smart electric vehicles using V2G concept. Dump charging can be a technology that increases electricity demand in the period when it is reduced, but renewable energy sources are abundant (for example: wind at night) and in that sense helps to integrate VRE while reducing the consumption of fossil fuels in transport. However, such a solution is not suitable for a higher share of VRE in the system. V2G solutions are in this situation a key technology for integrating high share of VRE, because in a much larger number of hours, when EVs are not in traffic (most of the day), they serve as a fast response battery [51]. The connection to the grid can be achieved by a slow charger at home (3.5 kW per vehicle), which would not have a significant impact on increasing infrastructure costs. Other chargers with higher power and charging speeds will have to be built so that vehicles can be charged and connected to the network, for example in public garages or parking places near the workplace.

A key parameter for determining the economic justification of this level of integration of VRE is the critical excess of electricity produced from VRE technologies, which according to considerations from relevant literature can be assumed up to 5% [52]. Using these concepts, and additional relevant concept of flexibility of PP and CHP operation, scenario approach is used to simulate various levels of integration of these demand response technologies, which in turn enable larger integration of additional VRE without crossing the key parameter limit. Two levels of the scenario approach are:

1. Building scenarios with different use of flexibility options, according to increasing cost of such technologies. From these scenarios, one which achieves the VRE integration goals with the smallest instalments of demand response technologies is further discussed on second level.

2. For the chosen scenario from the previous stage, plans for further instalments of CHP and PP units are discussed in terms of their economic feasibility, expressed through full hours of operation in one year, and their sensitivity to import.

More details can be found in [PAPER 2].

2.2.2. Introducing a flexibility index for the evaluation of large number of possible energy systems' configurations

Further on, the second contribution to the analysis of energy systems using the simulation approach is a method of soft-linking EnergyPLAN model with a Python code, to enable calculation of large number of scenarios. An algorithm of this soft-linking is presented in Figure 7.

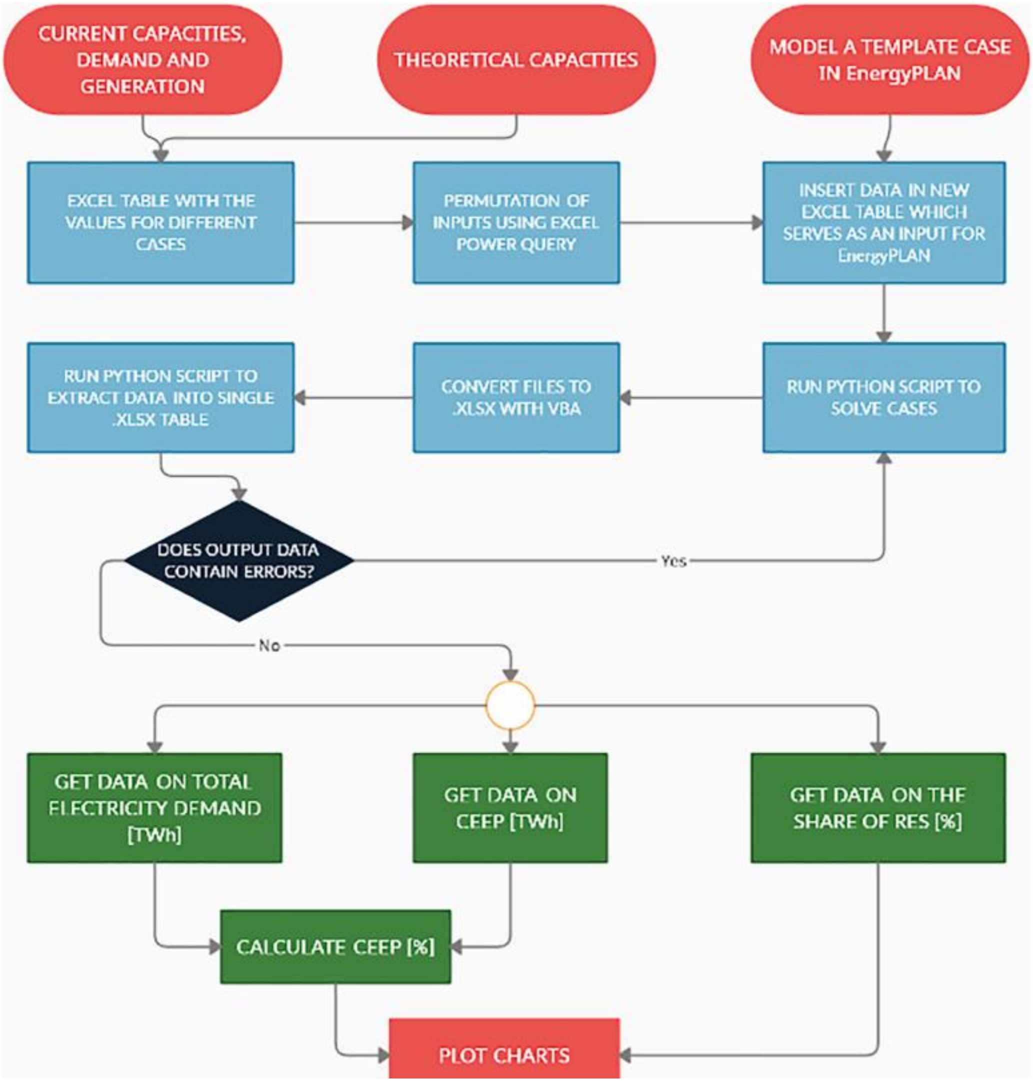

Figure 7 Algorithm for the flexibility index inputs

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[53] and
- pumped hydro storage

Options have been introduced one by one and finally the aggregated impact was demonstrated. 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.

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.

In order to demonstrate the influence of flexibility options, a "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 (equation 1)

$$\boldsymbol{F_s} \stackrel{\text{def}}{=} (F_1, F_2, \dots, F_n) \tag{1}$$

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

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 each flexibility option might be set separately from 0-100 % of its availability. For some options availability is limited physically, but for another the limitations are only financial (e.g. storage). A 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. The increase 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.

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

$$\boldsymbol{F}_{s,i} \stackrel{\text{def}}{=} (F_1, F_2, \dots, F_m) \tag{4}$$

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 Equation 5.

Details of the approach can be found in [PAPER 3].

2.3. Interconnected energy systems and regional approaches

2.3.1. Distributed demand response and storage providers and their influence on the surrounding zones

The method developed for planning energy systems on grid interconnected islands near the mainland serves as a case study for examining energy systems without fossil fuel-based generators. The analysis of these interconnected island systems utilized the EnergyPLAN 13.0 model. The latest version of the model, 13.0, introduced the ability to incorporate the V2G concept without relying on traditional balancing facilities like condensing power plants. This enhancement made EnergyPLAN an effective tool for planning island energy systems and transitioning them to 100% renewable and sustainable smart island systems. Another innovative aspect is the utilization of the MultiNode tool, which enables simulation of interconnections between such island systems within EnergyPLAN 13.0. This feature facilitates the analysis of the impact of deploying Demand Response (DR) technologies on system interactions and their capacity to integrate more locally available renewable energy sources.

The method [4] was used by solving the following equations.

Equation 6 - Sum of available exports - identifies the amount of exportable electricity each system delivers and sums them for each hour. Up to 14 systems can be calculated.

$$export_{total} = \sum_{i=1}^{14} export_i \tag{6}$$

Equation 7 - Amount of potential imports for each system *i* through summation of the import demand the current operation of the power plants which are installed in the system i (PP) in each hour in the year. Imports are limited by the capacity of transmission lines between the systems:

$$P_{import\ i} = import_{demand\ i} + PP_{prod\ i} \tag{7}$$

Equation 8 - Initial balance for each system, that defines the export as positive and the potential import as negative for each system:

$$Balance_{initial\ i} = export_{\ i} + P_{imp\ i} \tag{8}$$

Important condition, which constitutes Equation 9 is, „system can only import if there is available electricity in the grid“. This means that the merit order of the systems (in which they will satisfy their import demand from the grid) is determined by their order in the tool (user defined).

$$\boldsymbol{if}\,(P_{imp\ i} > export\ total)\ \boldsymbol{then}\ Import_i = exportabletotal\ \boldsymbol{else}\ Import_i =\ P_{imp\ i} \tag{9}$$

Balance is obtained by taking the $Balance_{initial}$ (from (3)) and replacing the export with the sum of imports needed in the other system, while the potential import is replaced with the actual calculated import. The consequence is that now the exports are not balanced with the import. The excess accounted electricity is removed by diving the active export in each system (hourly) with the number of systems that exports electricity.

Novel idea to expand on the existing MultiNode tool approach is to exploit the newly introduced (in EnergyPLAN 13.0) balancing strategies which use the V2G concept to examine how the interconnected system would work if V2G is used as the major DR and storage technology. Described tools were used to investigate the impact which grid interconnections between geographically close islands have on their power system, with no fossil fuel powered generators installed. Interconnections accompanied with DR technologies such as V2G concept, and storage technologies such as stationary batteries served to enable higher penetration of RES. Approach was tested on the archipelago represented by Figure 8.

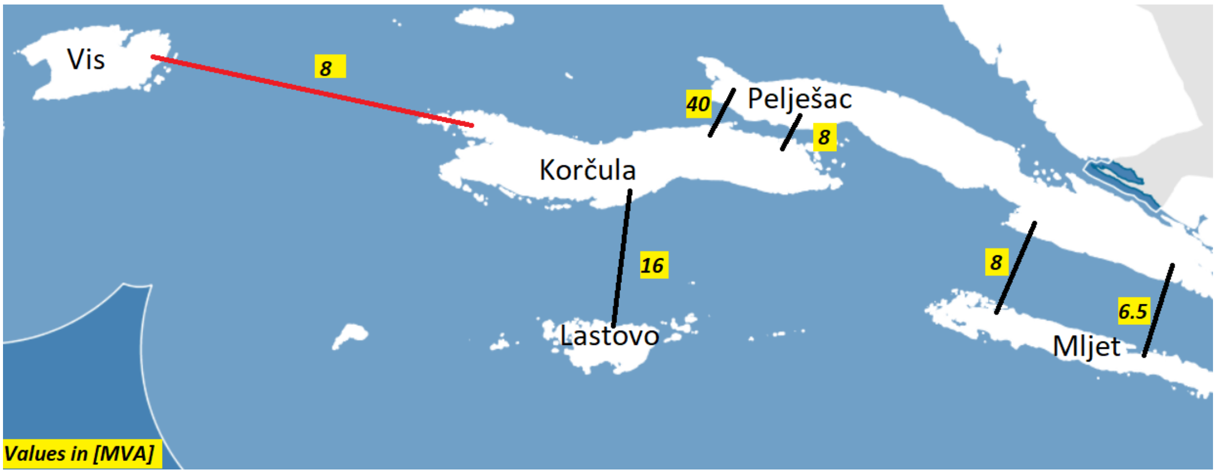

Figure 8 Representation of a case study including an interconnected archipelago

Scenarios for case study areas have been prepared for two categories, which are compared: isolated and interconnected mode. Planning of case study areas was conducted in two different scenarios, an approach novel in the research performed and reported in [PAPER 1]:

- Scenario 1: business as usual, which follows the local Sustainable energy action plans (SEAP-s) and extrapolates the measures towards year 2035, and
- Scenario 2: RES scenario, which aim for maximal use of RES on the local level, with 5% CEEP being the aim for each system, while achieving as high as possible integration of RES.
    - Sub-scenario 2.1: Main DR technology, V2G, is aided by addition of stationary batteries. All stationary batteries are located in one zone, while the other zones supply the leading zone with the excess energy produced locally.

- Sub-scenario 2.2: Main DR technology, V2G, is aided by stationary batteries, which are distributed uniformly in all connected zones.

Interconnected mode was examined by implementing two approaches: using the MultiNode tool and connecting the islands into a single (common) system. Former approach is new and would have the benefit of giving the exact import/export hourly values between the islands. Latter approach was previously used on regions and countries, but not on islands with the aim of examining VRES and V2G without any fossil fuel powered facility for backup.

More details on the method can be found in [PAPER 1].

2.3.2. Influence of strategic decisions in the single zone on the future choices of energy system configuration in the surrounding zones

A method based on the use of Dispa-SET model was developed on the case of following the consequences of different strategic decisions between the zones in an interconnected electricity market. A scenario approach is implemented in order to compare results in particular zones and in the market as whole, when a zone implements a strategic decision, such as following a low-carbon (LC) or decarbonization pathway or sticking to the business-as-usual scenario (BAU). General idea of different possibilities for various zones in the scenario approach is illustrated by Figure 9, depicting zones with energy mix based on different technologies and connected to a common system (region).

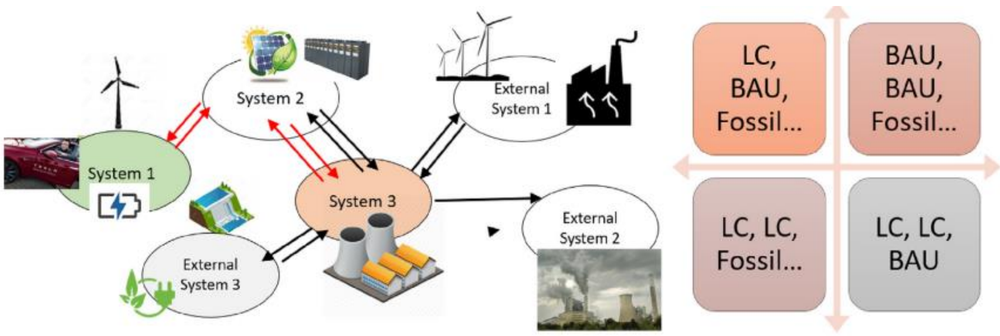

Figure 9 Scenario approaches for different zones

Such can make different strategic decisions regarding their long-term configuration and energy mix. Zone in this research represents a national energy system with autonomy to make strategic decisions. For all zones in the market coupled system, a different strategic decision (in further elaboration called “strategy”) is proposed, reaching from one end of the scale to the other:

- “Fossil” (typically for zones with own reserves of fossil fuels),
- “BAU” (with orientation towards RES, but with moderate dynamics)

- “RES” (integration of RES in higher dynamics, but without demand response)
- “Extreme RES” (high share of RES, but low local integration)
- “LC” (low-carbon, RES with strong integration).

For each of the zones, concrete numbers for installation of RES technologies, demand response and storage are derived from local potential and data for the zone in question. Significant limitation of the approach lies in the fact that Dispa-SET unit commitment and dispatch does not consider lifetime costs associated with changing the portfolio of electricity generation capacities. However, the results of such analysis offer the guideline about the possible stranded costs (e.g. coal power capacities which do not enter the merit order on the electricity market) resulting from a strategic decision. Results can indicate if the strategic decision made in the observed zone leads to more stranded costs for that zone or leads to the outcome in which the zone in question exploits other zones for the balancing of electricity supply and demand. Such conclusions can be made based on unit commitment observations. Also, following of the load flows between the zones is a very significant feature for the exploitation in the last step of the research described in this thesis. More details on the method developed for this purpose can be found in [PAPER 4].

2.4. Game theory application to the long-term energy planning of the interconnected energy systems

During the development of national energy strategies, the current approach typically does not consider the strategies of neighboring zones or countries as an inherent variable. Instead, it relies on historical data related to imports/exports and energy prices, as well as expert assumptions and calculations regarding future market developments. After the model of hypothetical zones was created in Dispa-SET, and a set of scenarios for all relevant zones was defined (limited to the fast transition scenario and slow transition scenario or similar choice), a game is formulated to evaluate decisions for the specific zone under examination. The objective of this game is to determine how a proposed measure or strategic decision will impact the viability of new installations in that zone. The aim is to improve the profitability of planned investments, make them unprofitable, or reach a situation where no zone can enhance the feasibility of investments (reaching a Nash equilibrium). In principle, the novel, two-level approach proposed in this research is presented in Figure 10.

Figure 10 Principal scheme of the proposed approach

A hypothetical model of the case study area, including ***N*** zones, is developed in the first step of the approach, followed by the definition of strategic decision matrices. There are a lot of examples in the literature with two-player games with two possible decisions each. In this step of the research, it is important to provide the opportunity for the investigation of conditions for a target zone (zone 1) that is surrounded by other zones and has the interconnection with them in different ways (only with one, with several, bilateral with one zone, but multilateral with others etc.). For this reason, the demonstration of the proposed approach is focused on more than two players. A game for four players is built based on the concept and algorithm for nontrivial strategic form games by Oikonomou and Jost [54], where an algorithm for games with more than two players was developed. Basic example of a payoff scheme for 4 players, each of them with two strategies, is given in Figure 11.

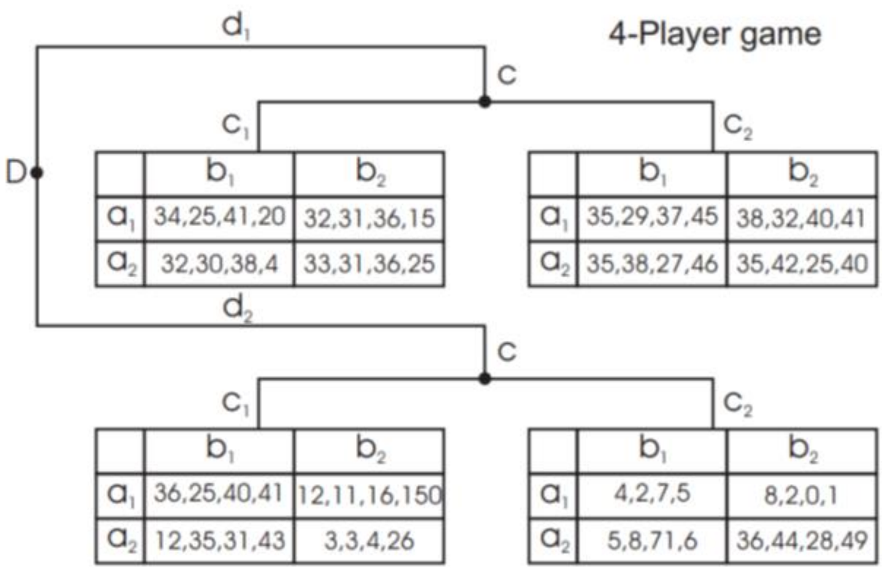

Figure 11 A 4-player game payoff scheme based on [54]

<u>Defining the payoffs and payoff matrices</u>

Results of Dispa-SET modelling include shadow prices of electricity in each hour, production for all generators in each hour, heat prices for district heating systems and delivered heat from each of the units equipped with CHP or heat generator. Also, results include inputs and outputs of transformation technologies and storage technologies, whose inputs depend on the local balancing in the energy system, but also on the presence of low-cost energy in the surrounding zones.

For each strategic decision, the payoff of each zone is calculated considering new investments (generators) in the following way:

- The CAPEX is calculated for all new generators, calculated using data from [55].
- The OPEX is observed through the standard Dispa-SET calculation and the shadow price is found (for electricity and heat) [50].
- The overall delivered energy from new generators is calculated in the zone, as well as the export to other zones. Earnings of the generator *j* are calculated as amount of electricity (E_i) (H_i is heat generated in case of combined heat and power generation units, with $P_{heat,i}$ being the price of heat in the considered zone) in the “home” zone i of *n*, multiplied with the local price of electricity ($P_{el,Zi}$), and exported electricity is multiplied with the price of electricity ($P_{el, Zm}$) in the zone of delivery (Z_m).Calculation is performed according to Equation 10.
  In this way, the welfare induced (payoff R) for the zone in question equals the sum of earnings of all generators/technologies in that zone.

$$\sum_{i=0}^{n} R = E_i \times P_{el,Zi} + H_i \times P_{heat} + E_i \times P_{el,Zm} \tag{10}$$

- Storage and transformation technologies generate earnings (R_s) in the “home” zone (Z1) though comparison of the expenditure when charging (Ch_i), with the price in that moment ($P_{el,Zi}$) and earnings when discharging (E_{is}), with the price in that moment ($P_{el,Zi}$) . Calculation is performed according to Equation 11.

$$\sum_{i=0}^{n} R_{s,Z1} = E_{is} \times P_{el,Z1} - Ch_i \times P_{el,Z1} \tag{11}$$

- For each zone (*i*), further information can be obtained, such as the return on investment (ROI), expressed in percentage, in the conditions depicted by the strategic decisions of all zones. Calculation is performed according to Equation 12, where R_i is a sum of discounted yearly payoffs for the period between the base year and end year of the calculation.

$$ROI_i = \frac{R_i}{CAPEX_i} \tag{12}$$

Defining the game to obtain the Nash equilibrium (equilibria) or best response

The algorithm for obtaining Nash equilibrium for a 4-player game with 2 strategies is based on the works of Oyama [56], and the algorithm for mixed best response strategy (mixed equilibrium) from [57] and [58]. Next, we formally define the N-Player game (Normal Form Game) and the concepts of best response, pure equilibrium, and mixed equilibrium.

The N-player Normal Form Game is defined as a triplet $g=(I,(A_i)_{i\in I},(u_i)_{i\in I})$ where

- $I = \{0,\ldots, N-1\}$ represents the set of players,
- $S_i = \{0,\ldots, s_j\}$ represents the set of strategies of player $i\in I$, and
- u_i: $A_0\times A_1\times\cdots\times A_{i-1}\times A_i\times A_{i+1}\times\cdots\times A_{N-1}\rightarrow$R represents the payoff function of player $i\in I$.

Given the Normal Form Game $g=(I,(S_i)_{i\in I},(u_i)_{i\in I})$, the *Nash* Equilibrium of the game is defined by the best response concept of each player in the game. A best response is defined as: *A strategy $s_i \in S_i$ of player $i \in I$ is a best response of player i against $s_{-i} \in S_{-I}$ (strategy of all other players) if $u_i(s_i, s_{-i}) > u_i(s'_i, s_{-i})$ for all $s'_i \in S_i$*. Therefore, the strategy profile s* = ($s^*_0, s^*_1, \ldots, s^*_{N-1}$) is *said to be a Nash Equilibrium* if s^*_i is a best response for every player $i \in I$. The Nash Equilibrium thus represents a solution of a game where no player can unilaterally change its strategy and improve its payoff. Also, note that every Normal Form game has at least one Nash Equilibrium. Such equilibrium is then defined as a Pure Nash Equilibrium if all players play their strategy with a probability of 1 (certainty), or a Mixed Nash Equilibrium if at least one player opts for a strategy with a probability less than 1.

2.5. Connection to the Contributions

The five published papers correspond to contributions that were objectives of the research in the following way (connecting the objectives and papers that address them):

1. To prove the value of the use of game theory in assessing the long-term strategic decisions of market coupled zones ([PAPER 4], [PAPER 5])

2. To demonstrate the need to include the influence of market coupled countries' energy strategy on national energy strategy [PAPER 1], [PAPER 4], [PAPER 5]

3. To analyze the influence of integration of demand response technologies in coupled market zones on the feasibility of strategic decisions in the investigated zone [PAPER 2], [PAPER 3]

A method for analysis of costs of production, storage and demand response technologies, organized in steps of energy transition in the surrounding zones was presented in [PAPER 2] and [PAPER 3].

A method which provides robust assessment of strategic decisions using the game theory, which can be a new standard for national energy planning was built up through initial steps of considering interconnected systems and simulation as the method in [PAPER 1], followed by the optimization methods and load flow following in [PAPER 4], and completed in [PAPER 5], through the use of game theory and payback calculations based on the previously considered optimization method.

Section 3

Selected results and discussion

3.1. Simulation approach in the modelling of flexibility options for the increased integration of VRES in a national energy system

To integrate a larger share of VRE into the energy system, this EES transition needs to be followed by the installation of other technologies that integrate the sectors and achieve synergies. These are energy-efficient consumption technologies that use excess energy produced and VRE for water heating and power-to-heat storage and energy storage in V2G batteries. The PtH technology is related to increasing the share of centralized heat systems, powered by cogeneration plants, to meet the needs for heat energy in households. The input configuration of the considered system is given in Table 1.

Table 1 Input configuration of the energy system for modelling in the EnergyPLAN model

NUR	2014	2030 (NUR)
Total installed capacity (MW)	4,469	6,732
Nuclear PP (MW)	348	348
Gas PP (MW)	1,140	1,225
Coal PP (MW)	330	210
Fuel oil PP (MW)	320	0
Hydro PP (MW)	2,095	2,784
Wind PP (MW)	340	1,200
Solar PV PP (MW)	33	120
Biomass and waste PP (MW)	8	135
Biogas and landfill gas PP (MW)	17	80
Geothermal PP (MW)	0	30
Small hydro PP (MW)	33	100

Main support for integration of VRE, demonstrated by scenarios, is the combination of flexible operation and integration of electricity production and electrified transport system through V2G technology. Input data for scenario analysis is given in Table 2.

Table 2 Input data for all considered scenarios of the flexibility options use

Year 2030	S1	S2	S3	S4	S5	S6	S7	S8	S9	S10
Minimum CHP [MW]	0	0	150	0	0	0	0	0	0	0
Minimum PP [MW]	0	200	200	200	200	200	200	200	200	0
PTH Storage [GWh]	2.25	2.25	2.25	4.5	10	2.25	2.25	2.25	2.25	10
HP COP	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5
HP [MW]	90	90	90	180	180	180	180	100	100	100
EV consumption [TWh]	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.72	0.72
EV battery size [kWh]	15	15	15	15	15	15	20	20	20	20

Results are represented in Figure 12. In scenario S1, 100% flexible operation of PP and CHP, combined with low level of PTH and V2G contribution provided for integration of 2200 MW of solar PV, while in scenario S10, higher level of V2G enabled integration of 2450 MW of solar PV.

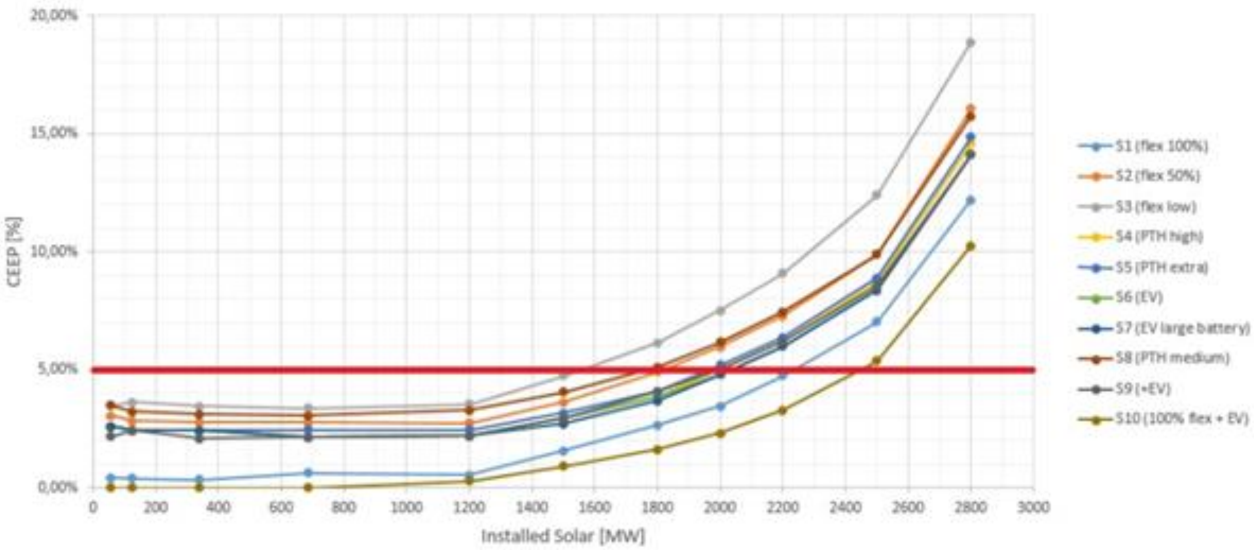

Figure 12 Results of different scenarios compared to the 5% CEEP limit

For scenario S7, which is characterized by larger EV batteries on disposal for V2G, enabling higher consumption of CEEP controlled by smart charging and discharging to shift the loads and balance the VRE, perspective for operation of new PP and CHP facilities was examined. The higher VRE integration will be achieved, more limited number of working hours remains for new CHP installations, with scenario B2 providing the most opportunities for affordable operation of PP and CHP, since this is scenario with lowest installed capacity of new facilities. These results can be observed in Table 3.

Table 3 Results of second level scenario approach - FLHs of CHP facilities

	A1	A2	B1	B2	C1	C2
CEEP [TWh]	0.25	0.11	0.25	0.24	0.25	0.12
Import [TWh]		-5.44		-5.44		-5.44
FLHe CHP	2946	1449	2946	2581	2946	1992
FLHe PP	1888	1526	1888	2302	1888	2249

Implied reduced number of operating hours for fossil fuel powered PP and CHP causes corresponding reduction in GHG emissions. When discussing future scenarios and the energy transition towards an energy system based on VRE and demand response technologies, the approach presented in the paper gives a valuable initial insight for avoiding the lock-in with excess capacities with dubious long-term competitiveness. More details on the results can be found in [PAPER 2].

3.2. The results of the use of flexibility vector in defining the steps of energy transition for a single market zone

Lessons learned from [PAPER 1] and [PAPER 2] fostered the establishment of the method that would follow the technologies that are known and appropriate for the use in different steps of energy transition. In order to formulate such a method, a large number of scenarios were simulated in EnergyPLAN, using a new proposed soft-linking approach with a Python code, as described in 2.2.2. *Introducing a flexibility index for the evaluation of large number of possible energy systems' configurations*.

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). On the case study of Bulgaria and it's NECP until 2030, an analysis of large number of scenarios was made, using the input data (energy systems' configuration) presented in Figure 13.

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

Figure 13 Bulgarian energy systems' configuration data used in calculations

Results show that the use of flexibility options (higher flexibility indexes) tend to lower CEEP, emissions, cost and achieve higher share of RES. An example in Figure 14 shows the combination of flexibility options and the composition of flexibility vector in relation to CEEP. 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.

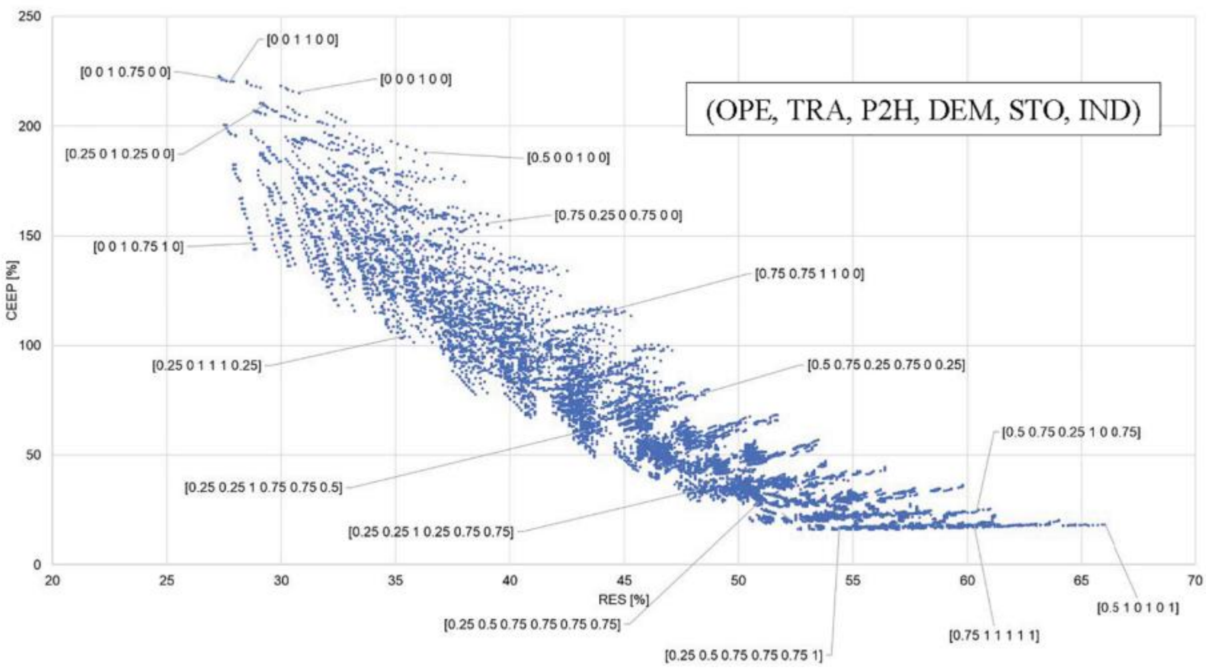

Figure 14 Relation of CEEP, share of RES and distribution of some of the cases with their flexibility vector values (OPE, TRA, P2H, DEM, STO, IND).

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.

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.
- The total annual cost of highly renewable energy system falls with flexibility index increase, which suggests 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 tool 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.

Similar to Figure 14, correlations were made for GHG emissions, total annual cost and share of RES, with a thorough analysis, on which more can be found in [PAPER 3].

3.3. The simulation approach in modelling of the interconnected energy systems

Following the studies of the single zones and national energy systems, further analysis was expanded to the interconnected energy systems, zones that represent either different national systems or systems of islands connected with the power grid.

Such an example, represented an interconnected archipelago of islands in Croatia, was used to apply the method of MultiNode add-in tool of the EnergyPLAN model on a case without fossil fueled generators. The goal was to test the possibility to follow the power flows between the zones in case of different configurations of the systems, that would include demand response and energy storage technologies. Models of energy systems of four islands were created in EnergyPLAN (Korčula, Lastovo, Mljet and Vis), with the scenario analysis including high shares of RES installed locally and different choices of location for stationary batteries and V2G integration.

Two scenarios examine these differences, with details on scenarios presented in *2.3.1. Distributed demand response and storage providers and their influence on the surrounding zones* and details on the inputs for the energy systems' configurations, as well as the RenewIsland methodology [59] implemented for all islands presented in [PAPER 1].

The results show the increase in the share of energy from RES in total final energy consumption after connecting to a common system, which reaches 85% for systems examined in case study, and decline of total CEEP of all systems from 28-35% individually to 13% after connecting to a common system for the scenario 2.1. For such scenario, Figure 15 shows the efficient use of storage and V2G to cover the demand in case no RES is available.

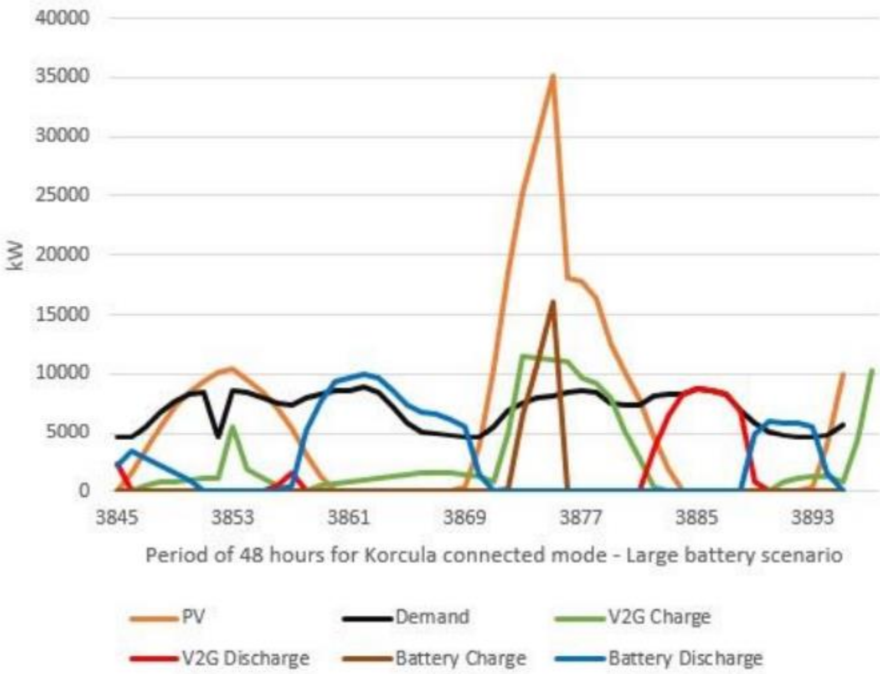

Figure 15 Illustration of the system operation for an indicative period on the island of Korcula,

Decrease in net import / export can be observed in correlation to the increase in the independence of island energy systems, but the deployment of storage technologies, analyzed through interactions between systems, has influence on the intensity of load on the transmission lines, which occurred in 417 hours for scenario 2.1 and only in 17 hours for scenario 2.2. In scenario 2.2, however, the intensity of interaction was 2.5 times higher than in scenario 2.1, with peak export being 2.536 MW compared to peak of 0.957 MW in scenario 2.1. (Figure 16 & Figure 17).

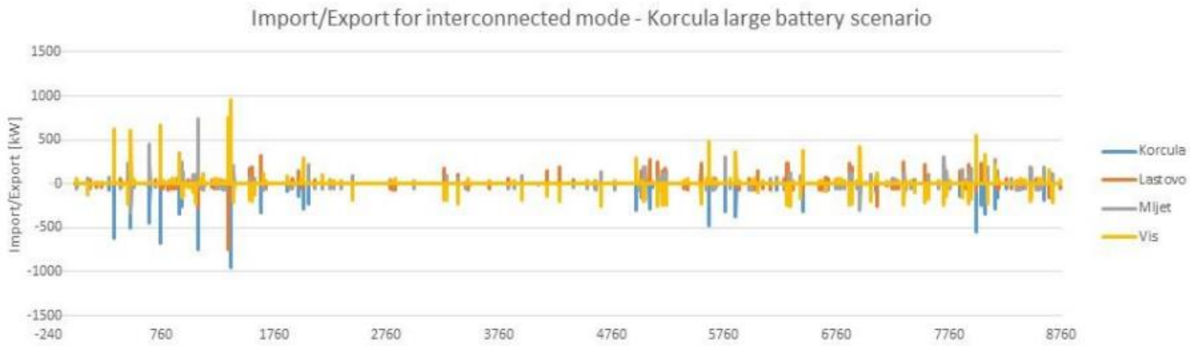

Figure 16 Electricity Import/Export distribution for the interconnected mode of scenario 2.1

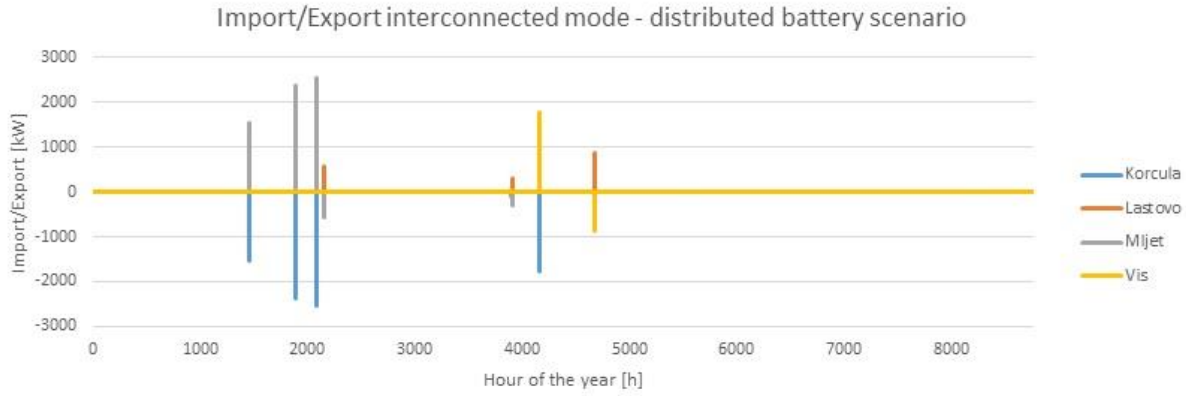

Figure 17 Electricity Import/Export distribution for the interconnected mode of scenario 2.2

From this data, it can be concluded that distributed storage systems provide more energy security for every single system, compared to the case of storage being concentrated in only one of the connected systems, but it has to be carefully designed to avoid large peaks in some hours. The combination of VRES and V2G would be the combination of technologies which offer most synergies with least environmental impact in island systems. However, it was concluded that the similar attempt including generators with different fuels would not enable the power flows following that is needed for the game theory implementation, as MultiNode tool took care of the technical supply of each zone with the existing generators in that particular zone, and only after that considers import using the interconnected systems scheme (state of the art in 2018). And for this reason, another tool was elected to be used in the following research – Dispa-SET.

More details on the results of this approach can be found in [PAPER 1].

3.4. The optimization approach and following of the power flow between the interconnected market zones – Dispa-SET model

The Dispa-SET tool was chosen to perform the analysis of the influence of different strategic decisions in interconnected market zones, as described in *2.3.2. Influence of strategic decisions in the single zone on the future choices of energy system configuration in the surrounding zones.*

The case study area includes electricity generation and district heating systems of Croatia (HR), Slovenia (SI), Serbia (RS), Bosnia and Herzegovina (BA), Albania (AL), Kosovo (XK), Montenegro (ME) and North Macedonia (MK) connected in a coupled day-ahead electricity market. The data is more detailed for the zone of Croatia (HR), while the input data for all other zones was already elaborated in several papers, such as [50] with the emphasis on the model formulation and data for 2030, and [49] dealing with the Western Balkans region. In scenario analysis, the outputs such as electrical energy flows between the zones and generation from technologies in all zones have been analyzed to discuss the influence of different strategic decisions across the region (combinations of low carbon, RES, BAU and fossil strategies), consequences of different strategies of zones are illustrated in Figure 18.

In scenario “2030a”, the leading zone (opting for “RES” strategy) does not generate excessive amounts of electricity from RES. At the same time, all other zones (except for SI) opt for “BAU” strategy, which includes larger installations of RES compared to “fossil” strategy. In scenario “2030b”, half of the zones that were developing according to “BAU” strategy, now opt for “RES”, which further hindered the generation of electricity from coal in all the zones. In scenario “2030c”, all the zones that were previously developing in accordance with “RES” strategy, now opt for “Extreme RES”, which results in complete abandonment of coal in all zones except for RS and XK. Although the overall capacity of the newly built portfolio of RES power plants is high, the investments would still be lower than in the case of investment in “fossil” strategy, which proves to result in a lot of stranded cost, due to very low operating hours of coal power plants in all scenarios.

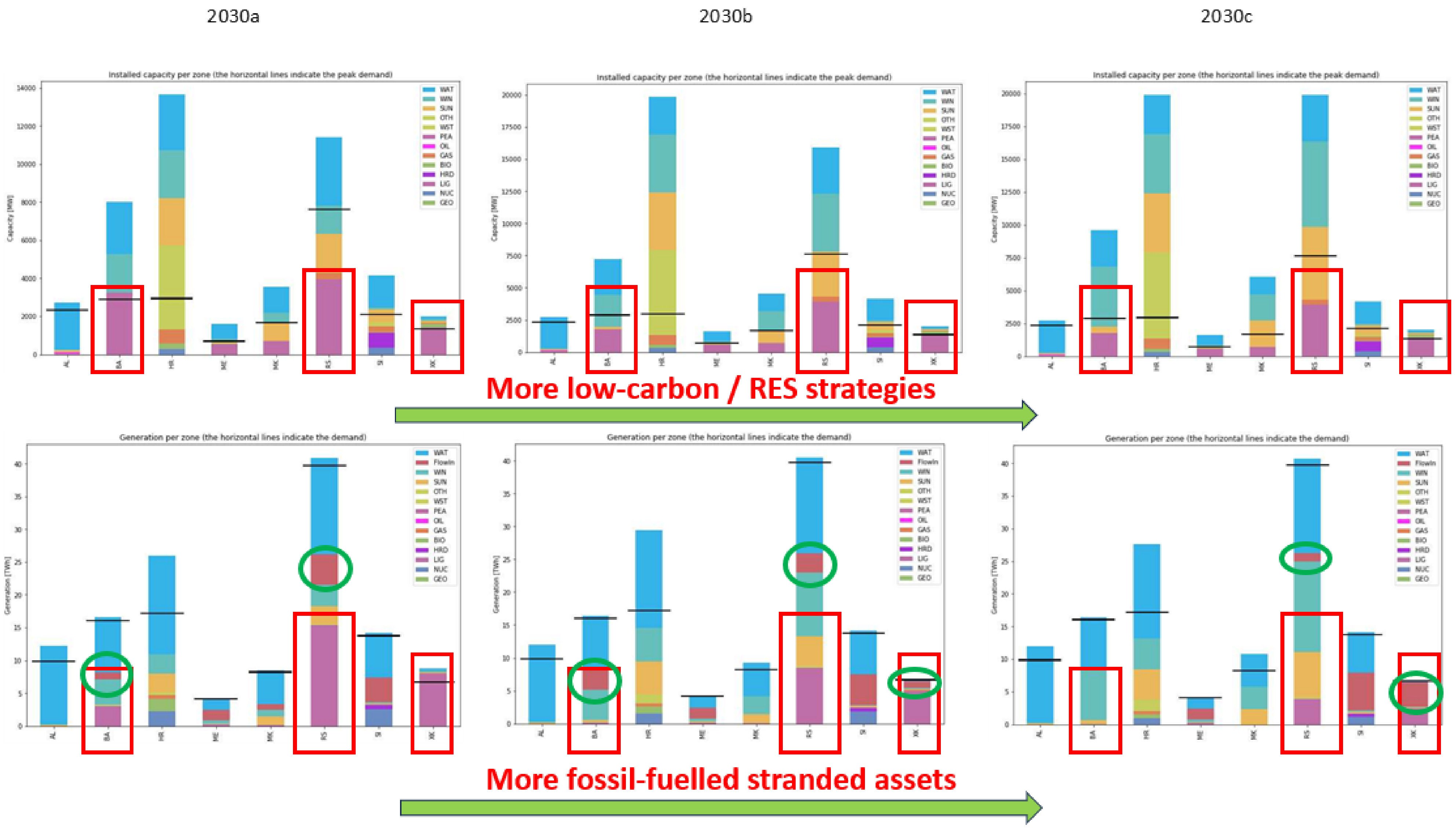

Figure 18 Effects of increased number of zones going for low-carbon and RES strategies

Solutions of the dispatch problem for the zone “HR” and the unit commitment for the zone in case of scenario 2030a are shown, for the illustration, in Figure 19 and Figure 20.

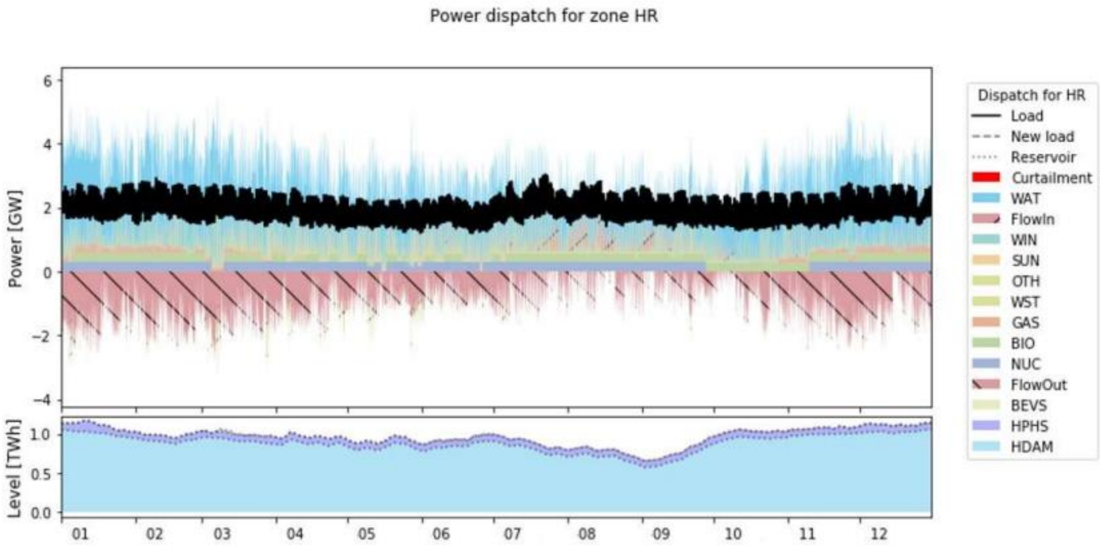

Figure 19 Solutions of the dispatch problem for the zone “HR” in scenario 2030a

For all zones, similar outputs are available, but the focus was on the zone “HR”.

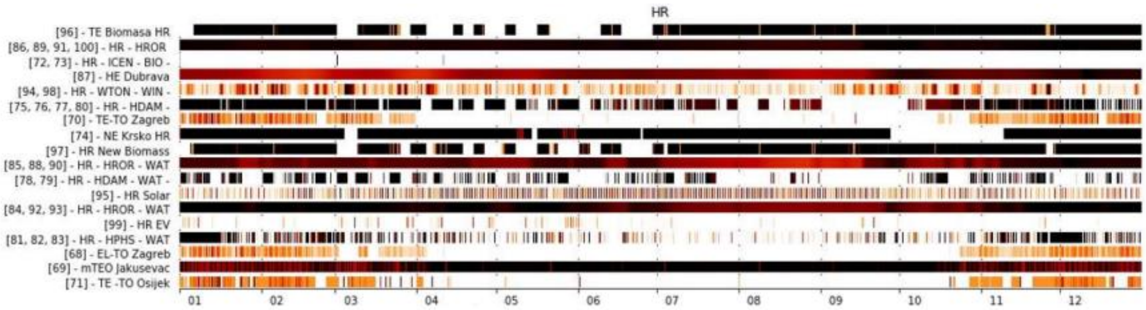

Figure 20 The unit commitment for zone "HR" in scenario 2030a

Some sensitivity parameters were observed as well. In strategic decision making for the chosen case study area, the price of greenhouse gas emissions, namely CO_2, can play an important role in economic feasibility of the future energy system’s configuration. Scenario “2030” is discussed in terms of CO_2 cost. Cost of CO_2 is 50 €/t CO_2, compared to 9 €/t CO_2 considered in previous chapter in “2030”. Resulting average marginal electricity cost for new price of CO_2 is 21.18 €/MWh. Resulting generation from technologies in all zones is given in Figure 21.

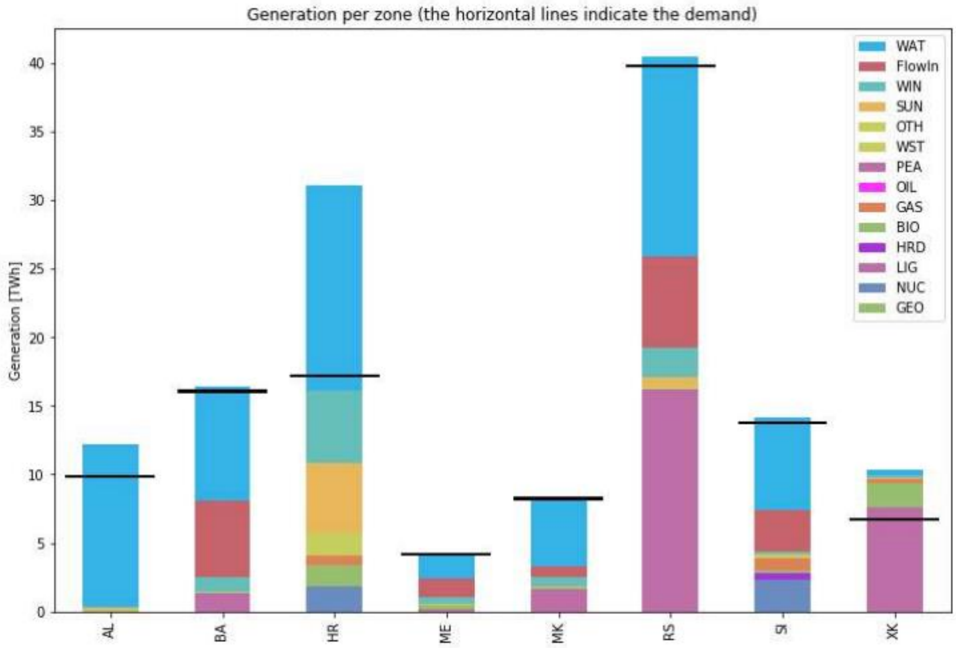

Figure 21 Generation of electricity per zone in case of high cost of CO_2

It is noticeable that in zones previously dominated by coal, a combination of import (from the zones rich with RES and hydropower) and gas have larger share of the energy mix. This applies to MK (energy from gas) and SI, while XK export from coal remains 50% of the amount exported in the case with 9 €/t CO2. BA and ME also import energy and energy produced from coal remains at less than 50% of the case with lower CO_2 cost.

In case that scenario 2030 would be run without V2G implemented in Croatia (HR), curtailment becomes more regular issue, with more than 100 hours of occurrence. In terms of supply, the discharge of V2G is now covered by gas power plants, while surrounding zones absorb the increased exports (BA, ME, SI). In this case, the resulting average marginal electricity cost is 21.70 €/MWh and the number of congestion hours between zones HR and two large neighbors: BA and RS are at record high, amounting to 7065 and 7143 hours respectively. Such results suggest that demand response installations influence the interaction between the zones and the average electricity costs for the market-coupled region more significantly than the proposed change in the CO2 emissions cost.

Main findings can be summarized as follows:

Decisions for ambitious energy transition (LC and Extreme RES) had the effect of reducing the electricity generation from lignite blocks throughout the case study area (including the zones sticking with fossil or BAU strategy) due to exports of renewable energy from the zones that generated more renewable electricity than they were able to integrate in their energy system.

The scenario with most zones going for the increased RES integration (2030c) offers the 70% lower average marginal cost of electrical energy compared to “2030” scenario, without causing increase in congestion hours on the cross-border electricity transmission lines (Figure 22).

Results show that the zones with ambitious decisions benefit at the expanse of less ambitious zones in terms of avoiding stranded cost, while the marginal electricity cost drops for the whole considered region with increase of RES installations. Perspective for this method can be found in creating the appropriate algorithms for creation of larger number of possible scenarios for each of the zones (including LC scenario for all zones) and creating long-term scenarios (until 2050) for the zones, to investigate the dynamics of energy transition for connected power markets.

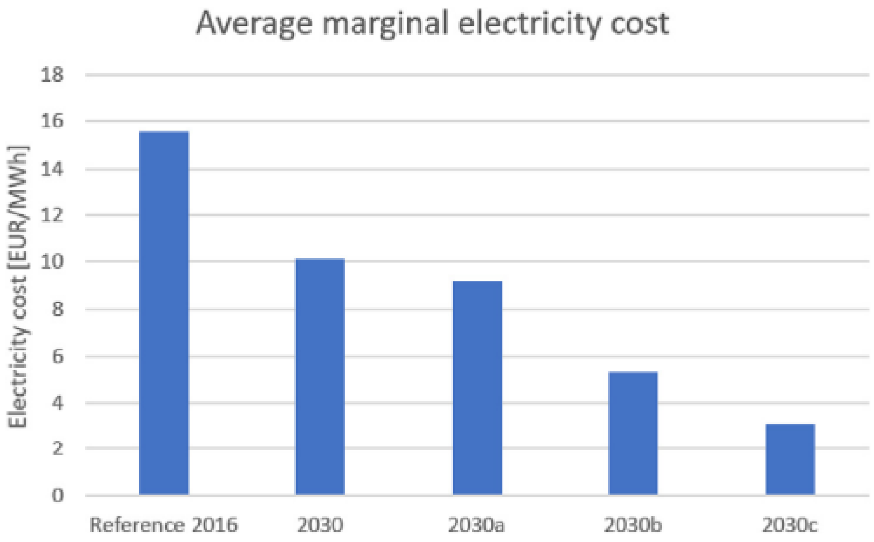

Figure 22 Average marginal electricity costs in all scenarios

More details and discussions can be found in [PAPER 4].

3.5. Use of game theory in the long term strategic decision making based on the interconnected energy system model – results and the Nash equilibrium

Using the method described in 2.4. *Game theory application to the long-term energy planning of the interconnected energy systems*, calculations in Dispa-SET for a group of four hypothetical zones interconnected in the one energy market are used to generate payoffs for each zone and each combination of choices, as inputs to the game matrix. Payoffs are based on considering the power follows between the zones and calculating the earnings and costs that appear when different flexibility options are in operation.

Resulting values are presented in Table 4.

Table 4 The payoff matrix for each zone in all scenarios [BEUR]

	Matrix of payoffs			
No. of scenario	Z1	Z2	Z3	Z4
1	1.660	3.526	0.171	1.152
2	2.843	3.782	0.149	2.103
3	1.910	5.631	0.733	2.224
4	11.159	6.871	-0.598	3.959
5	1.579	2.961	0.902	1.265
6	2.322	5.679	1.009	2.055
7	1.088	3.739	1.088	1.588
8	1.715	5.464	4.313	3.201
9	2.854	6.410	0.157	0.652
10	3.943	7.109	0.326	2.104
11	1.188	7.629	0.948	1.767
12	2.189	6.970	1.499	3.083
13	2.108	5.406	0.848	0.618
14	3.168	7.134	1.488	-0.589
15	1.697	6.768	2.017	1.236
16	3.239	10.309	3.957	1.808

Game results and Nash equilibria

The values from Table 4 were used as an input data for a *gt.NormalFormGame*, defined in the methods chapter with 4 players that have 2 strategies each, forming the payoff matrix. After using the attached code to search for a Nash Equilibrium for such a game, the solution that was found is that the game has a single pure Nash Equilibrium: scenario 1, with the strategy (1,1,1,1). In this way, the scenario with fast transition for all zones was found to be the best strategy of all players. This is due to the large incomes from generators that was moved to flexibility options, such as vehicle to grid, power to heat, and storages in form of stationary batteries, hydropower plants' dams or pumped hydro. Weather the information about the other zones' strategies is publicly available or not, the scenario analysis and a game, like the one analysed above, can be created for various possible scenarios and the Nash equilibrium can be sought, with the goal to identify what would be the best strategy for all involved zones.

Discussion on the mixed strategies

In many cases, a situation arises with less clear solution, i.e. without a pure Nash. For example, if the payoff matrix was slightly different compared to Table 4, the following situation, with inputs given in the Table 5 can arise. The main difference between the tables is in the fact that the Table 5 presents values that don't take into account end-users flexible demand, nor do they penalize curtailments and shed load.

Table 5 Alternative payoff matrix with changes [BEUR]

	Matrix of payoffs			
No. of scenario	Z1	Z2	Z3	Z4
1	1.724	3.194	0.237	1.124
2	3.126	3.728	0.237	2.107
3	2.046	5.849	0.908	2.259
4	11.596	6.754	-0.178	3.992
5	1.579	2.961	0.902	1.265
6	3.440	6.770	1.399	0.688

7	1.315	3.858	1.078	1.582
8	2.104	5.551	4.353	3.195
9	3.012	6.767	0.234	0.609
10	3.140	3.500	0.330	0.345
11	2.210	5.950	1.100	0.850
12	3.050	0.040	0.100	1.600
13	2.253	5.768	0.850	0.578
14	3.517	6.883	1.466	-0.667
15	1.500	3.990	1.020	0.800
16	3.149	0.003	3.907	1.716

After the pure Nash equilibrium was calculated for such game, none were found for inputs from Table 5. The next step was applying the McLennan-Tourky algorithm for mixed Nash equilibrium. The results show that Zone 1 ideally opts for the strategy “FT” in 100% of cases, Zone 2 opts for the strategy “FT” in 95% of the cases, Zone 3 opts for the strategy “ST” in 72% of the cases, while Zone 4 opts for the strategy “ST” in 100% of the cases. In such a mixed strategy case, it is noticeable that the largest system has the highest influence on the best strategy for all. In such situation, smaller systems, like Z3 and Z4 compared to Z2, have less incentive to opt for FT and stick with ST instead, while being mostly supplied with cheap energy from other zones. This leads to detriment of investments in such, smaller zones with slow development. More details and discussions can be found in [PAPER 5].

Section 4

Conclusions and future work

Development of the day-ahead power markets, as well as introduction of various markets for auxiliary services, together with forming a common market, demands a new view on the energy planning of national and regional energy systems. Today, entities in Croatia can buy energy on the day-ahead and intraday market, which is coupled to other European markets through Slovenian market. Within the present research, the electricity price is formed on the market principle of supply and demand, taking into account marginal cost of production. Next step in these developments of electricity market is the formation and the joining of the markets of Southeast Europe. After that, the market of auxiliary services and reserves will be introduced, which will be enriched with new technologies, and in particular demand response and storage (flexibility) technologies. Taking into account the complexity of the system, which will be the result of energy transition in decentralized systems with a high share of variable sources and competitive market conditions for all participants, it is necessary to strive for energy planning that takes into account specific local conditions and potentials.

To increase the integration of variable renewable energy (VRE) into the energy system, the installation of technologies that promote sector integration and synergies is essential. These include energy-efficient consumption technologies, such as power-to-heat storage and vehicle-to-grid (V2G) batteries, alongside efforts to reduce greenhouse gas emissions in other sectors. Flexible operation and the integration of electricity production with electrified transport through V2G technology play a crucial role in supporting VRE integration, as demonstrated by various scenarios outlined in the [PAPER 2]. In [PAPER 3] a method was proposed to soft-link the EnergyPLAN model with a Python code, enabling the calculation of numerous scenarios. The focus is on analyzing the changes in variable renewable energy source (VRES) integration and critical excess electricity production in a country's energy system, depending on the chosen flexibility options. The results highlight the significance of the flexibility index, showing its influence on energy, cost, emissions, and biomass criteria. The study demonstrates the economic viability of investing in flexibility options, with the total annual cost of a highly renewable energy system decreasing as the flexibility index increases. Moreover, a flexibility vector is introduced as a methodological tool to distinguish between scenarios and understand the trade-offs made in achieving specific renewable energy share goals. The findings emphasize the need to explore the effects of implementation measures, the role of smart technologies, and the optimal level of critical excess electricity production for high shares of renewable energy in the energy system.

The following part of the research then focused on the interconnected systems. [PAPER 1] introduced a method for planning energy systems in grid interconnected islands, focusing on their transition to 100% renewable and sustainable smart island systems. Using EnergyPLAN 13.0, the study demonstrates the feasibility of incorporating the (V2G) concept without traditional balancing facilities. The utilization of the MultiNode tool enables the simulation of interconnections between these island systems, allowing for analysis of the implications of deploying demand response technologies and integrating more locally available renewable energy. The results showcase a significant increase in the share of renewable energy in total final energy consumption and a decline in the CEEP after connecting to a common system. A critical issue that remained was to enable the power flow following for energy systems' configurations that also included fossil-fueled generators. For this reason,

In [PAPER 4], a method based on the use of Dispa-SET model was demonstrated on the case of following the consequences of different strategic decisions between the zones in an interconnected electricity market. Results have shown that

- Decisions for ambitious energy transition (LC and Extreme RES) had the effect of reducing the electricity generation from lignite blocks throughout the case study area (including the zones sticking with fossil or BAU strategy) due to exports of renewable energy from the zones that generated more renewable electricity than they were able to integrate in their energy system.
- The scenario with most zones going for the increased RES integration offers the 70% lower average marginal cost of electrical energy compared to "2030" scenario, without causing increase in congestion hours on the cross-border electricity transmission lines.
- The zones with ambitious decisions benefit at the expanse of less ambitious zones in terms of avoiding stranded cost, while the marginal electricity cost drops for the whole considered region with increase of RES installations.

Important take-away from the approach is also a noticeable incompatibility of lignite power plants (especially new generators, which quickly become stranded assets) with increase of VRES installations in the observed region. Figure 23 is illustrative of this incompatibility.

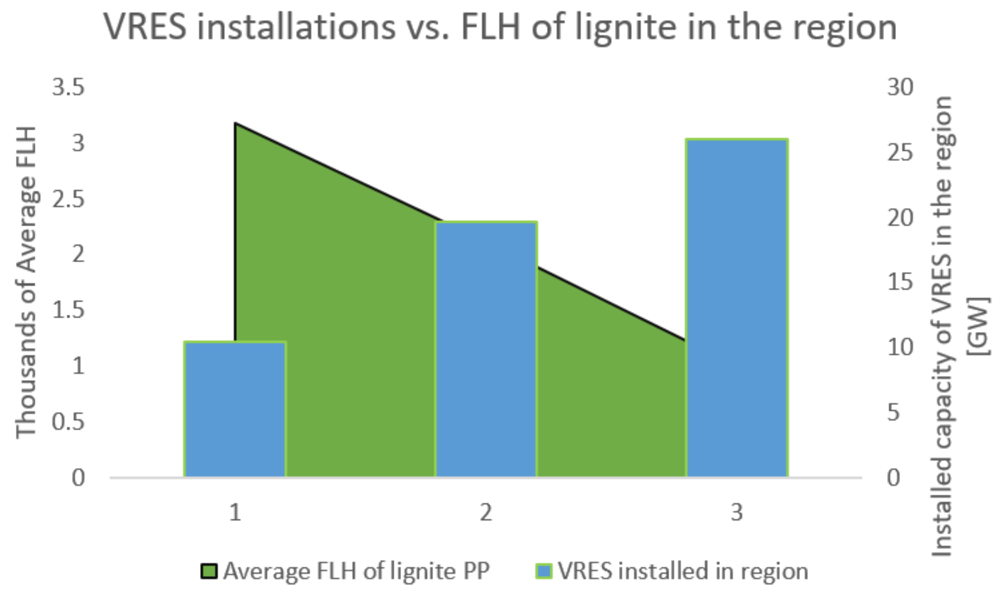

Figure 23 Illustration of the incompatible operation of non-flexible lignite PPs with new VRES installations in the region

For the observed case, although some zones in the scenario “2030c” invested in new lignite/coal PPs, overall average FLH for such facilities fell below 1000 hours per year, making them stranded assets.

This approach enabled the inclusion of game theory in [PAPER 5], where a novel two-stage approach to energy planning of a zone in the interconnected energy market was presented, together with an algorithm that uses game theory approach to determine the optimal decision for each zone. It was shown that optimal decisions in long term energy planning for each market coupled with neighboring zones can be determined in this way, through achieving a Nash equilibrium with energy strategies of surrounding zones. This approach can be used for every zone, assuming the other zones’ strategies, even in the case of lack of information about them. In case of not finding the pure Nash equilibrium, it is possible to use the algorithm for finding the mixed strategy solutions, which still helps in decision-making, thus providing robustness to the approach presented in this research.

Outcome of this research is a new method, which can be proposed as a standard for energy planning of the market zones, which are mostly national energy systems. The new method can be proposed as an improvement of the long-term energy planning in the context of market coupled zones, which are part of larger power market. **In the described way, the hypothesis of this research has been confirmed:** optimal decisions in long term energy planning for each market coupled with neighboring zones can be determined by game theory, through achieving Nash equilibrium with energy strategies of surrounding zones, even in the case of lack of information about them - this is achieved through establishing a matrix of possible choices for all the zones included in the consideration and then using the proposed approach to calculate the payoffs of the choices and the developed game to reach a Nash equilibrium or the mixed strategy.

Some constraints on the method remain, as features of the energy planning tool used in the study. In future work, the method can be applied using a long-term energy systems configuration optimization tool, which would enable the users to follow the difference throughout the period, although at present, making conclusions on the basis of the final year (as an average year) in combination with game-theoretic approach still represents a step forward in the top-down energy planning approaches.

Chapter 5

Main Scientific Contributions

The thesis has been built around two major scientific contributions.

First one is in elaborating a method for analysis of costs of production, storage and demand response technologies, organized in steps of energy transition in the zones surrounding the zone of interest. In this context, PAPER 1, PAPER 2 and PAPER 3 provide methodological development of approaches for a single zone and for the interconnected group of zones, which defines outputs for electricity generation technologies, energy storage and demand response in technical context and in the context of economic assessment.

The second major contribution is a method which provides robust assessment of strategic decisions using the game theory, which can be a new standard for national energy planning.

This contribution is realized based on the groundwork done in PAPER 1, PAPER 2 and PAPER 3, through the method developed in PAPER 4 and completed using the game theory in PAPER 5.

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Curriculum vitae

Antun Pfeifer, mag. ing. mech., graduated at the Faculty of Mechanical Engineering and Naval Architecture of the University of Zagreb in the academic year 2014/2015. After graduation, he started working at the SDEWES Centre as an associate, on a Horizon 2020 project FosterREG. He has enrolled in a PhD programme under the mentorship of prof. dr. sc. Neven Duić and has begun working in his research group in the academic year 2016/2017, working on the Interreg MED project PRISMI, and as a research associate and since 2019 as a research assistant. He was involved also in research projects funded by the Croatian Science Foundation (RESFLEX, INTERENERGY) and a number of other projects funded by the Horizon, IPA, Interreg, EUKI and other funding bodies, 15 projects overall.

Antun was involved in numerous research collaborations with research groups from other countries, such as energy planning group of prof. Henrik Lund in Aalborg, Denmark, research group of prof. Francesco Calise from Naples, Italy, research group of prof. Davide Astiaso Garcia from Rome, Italy, and prof. Felipe Feijoo from Valparaiso, Chile. He became an expert in energy planning and modelling of energy systems with main scientific contributions focused on the modelling of energy systems in transition from fossil fuel-based ones towards zero-emissions energy systems based on renewable energy. His main field of interest includes energy planning, modelling of energy systems, integration of variable renewable energy sources, use of demand response and storage technologies and energy markets. He develops new solutions for modelling of energy systems with comprehensive approach, using simulation approach, optimization approach, market integration and mathematical approaches as the game theory for multiple interconnected energy systems planning on a coupled day-ahead power market. Antun was a member of the local organizing committee of 9 International scientific conferences of the SDEWES series from 2015 until 2023, of which he was also a member of Scientific Advisory Board on 4 International scientific conferences. Antun is a co-author of 25 scientific journal publications indexed on Scopus. He serves as a reviewer for international scientific journals such as Energy, Applied Energy, Renewable and Sustainable Energy Reviews, Energy Conversion and Management, Renewable Energy, and others.

Chapter 6

List of Publications with summary

The publications considered as part of this thesis are listed below. The connection between the listed publications, scientific contributions of the research and the research objectives has been elaborated in previous chapters.

[PAPER 1] Pfeifer, Antun; Dobravec, Viktorija; Pavlinek, Luka; Krajačić, Goran; Duić, Neven. Integration of renewable energy and demand response technologies in interconnected energy systems // Energy, 161 (2018), 447-455 doi:10.1016/j.energy.2018.07.134

[PAPER 2] Pfeifer, Antun; Krajačić, Goran; Ljubas, Davor; Duić, Neven. Increasing the integration of solar photovoltaics in energy mix on the road to low emissions energy system – Economic and environmental implications // Renewable energy, 143 (2019), 1310-1317 doi:10.1016/j.renene.2019.05.080

[PAPER 3] Pfeifer, Antun; Herc, Luka; Batas Bjelić, Ilija ; Duić, Neven. Flexibility index and decreasing the costs in energy systems with high share of renewable energy // Energy conversion and management, 240 (2021), 114258, 18 doi:10.1016/j.enconman.2021.114258

[PAPER 4] Pfeifer, Antun; Krajačić, Goran; Haas, Reinhard; Duić, Neven. Consequences of different strategic decisions of market coupled zones on the development of energy systems based on coal and hydropower. Energy 2020;210. https://doi.org/10.1016/j.energy.2020.118522.

[PAPER 5] Pfeifer, Antun; Feijoo, Felipe; Duić, Neven. Fast Energy Transition as a Best Strategy for All? The Nash Equilibrium of Long-Term Energy Planning Strategies in Coupled Power Markets. Energy, Volume 284, 2023, 129109, https://doi.org/10.1016/j.energy.2023.129109

Summary of the papers

Paper 1

Pfeifer, Antun; Dobravec, Viktorija; Pavlinek, Luka; Krajačić, Goran; Duić, Neven. Integration of renewable energy and demand response technologies in interconnected energy systems // Energy, 161 (2018), 447-455 doi:10.1016/j.energy.2018.07.134

This paper proposes that interconnections of a group of islands can be used to integrate the production from locally available renewable energy sources. Besides interconnection, electric vehicles were used as a demand response technology to provide storage for electrical energy from variable sources. Electric vehicles were connected to the grid using smart charging systems (vehicle-to-grid). In addition, stationary batteries were explored in sub-scenarios for the year 2035. This enabled to analyse the influence of the battery location through two main different scenarios, i.e. one big central battery and several smaller distributed batteries. Scenarios with different integration dynamic of variable renewable energy sources and electrical vehicles were modelled with EnergyPLAN model, while the interconnection analysis was carried out with the MultiNode tool expansion. The results showed that the interconnections increased the share of energy from renewable energy sources in the final energy consumption and declined the total critical excess electricity production, while vehicle to grid technology enabled exploitation of synergies between sectors.

The paper contributes to the objective 2 of the research (*To demonstrate the need to include the influence of market coupled countries' energy strategy on national energy strategy*) and to the method 2 (*A method which provides robust assessment of strategic decisions using the game theory*) through consideration of the simulation-based methodology, which was in the next step of the research replaced with the optimization-based solution.

Antun Pfeifer (Main author, 90%): Writing - original draft, Investigation, Conceptualization, Methodology, Software, Visualization. Viktorija Dobravec: Writing – Reviewing and Editing. Luka Pavlinek: Software and Investigation. Goran Krajačić: Writing-Reviewing and Editing. Neven Duić: Conceptualization, Resources, Supervision, Funding acquisition.

Paper 2

Pfeifer, Antun; Krajačić, Goran; Ljubas, Davor; Duić, Neven. Increasing the integration of solar photovoltaics in energy mix on the road to low emissions energy system – Economic and environmental implications // Renewable energy, 143 (2019), 1310-1317 doi:10.1016/j.renene.2019.05.080

The EU policy aims towards low carbon economy by establishing a goal of reduction of 93- 99% in greenhouse gas emissions in energy sector by 2050. This means a complete energy transition from the fossil fuel based systems to mostly renewable and low-carbon based energy systems. In order to integrate variable renewable energy sources, day-ahead and intraday electricity markets influence, demand – response technologies implementation and fossil fuel powered thermal power plants' flexibility considerations need to be analysed. Along with the integration of solar photovoltaics, demand – response technologies (power-to-heat and vehicle-to-grid concepts) needed to balance the system, were deployed. In calculations performed on the case study of Croatia in years 2014 and 2030, a moderate introduction of heat storages in Croatian combined heat and power plants, introduction of electric vehicles and flexible operation of power plants enabled the integration of up to 2000 MW installed capacities of solar photovoltaic plants. The main integration criteria, a cumulative critical excess electricity production from solar and wind power, was kept under 5%. Results of this approach are the reduction in full load hours of economically feasible operation for Croatian power plants up to 2000 and combined heat and power plants to up to 3000.

The paper contributes to the objective 3 of the research (*To analyze the influence of integration of demand response technologies in coupled market zones on the feasibility of strategic decisions in the investigated zone*) and the method 1 (*A method for analysis of costs of production, storage and demand response technologies, organized in steps of energy transition in the surrounding zones*) by providing a demonstration of the use of demand response, storage and power-to-heat technologies in the steps of energy transition.

Antun Pfeifer (Main author, 90%): Writing - original draft, Investigation, Conceptualization, Methodology, Software, Visualization. Goran Krajačić: Conceptualization, Writing-Reviewing and Editing. Davor Ljubas: Conceptualization, Writing- Reviewing and Editing. Neven Duić: Conceptualization, Resources, Supervision, Funding acquisition.

Paper 3

Pfeifer, Antun; Herc, Luka; Batas Bjelić, Ilija ; Duić, Neven. Flexibility index and decreasing the costs in energy systems with high share of renewable energy *// Energy conversion and management,* 240 (2021), 114258, 18 doi:10.1016/j.enconman.2021.114258

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.

The paper contributes to the objective 3 of the research (*To analyze the influence of integration of demand response technologies in coupled market zones on the feasibility of strategic decisions in the investigated zone*) and method 1 (*A method for analysis of costs of production, storage and demand response technologies, organized in steps of energy transition in the surrounding zones*) by providing the method for analysis of costs of production, storage and demand response technologies.

Antun Pfeifer (main author, 60%): 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

Paper 4

Pfeifer, Antun; Krajačić, Goran; Haas, Reinhard; Duić, Neven. Consequences of different strategic decisions of market coupled zones on the development of energy systems based on coal and hydropower. Energy 2020;210. https://doi.org/10.1016/j.energy.2020.118522.

Long term planning of energy system's development becomes closely connected to analysis of day-ahead power markets, market coupling and dynamics of integration of both, renewable energy sources and demand response technologies. In this study a scenario approach with minimization of marginal cost of generated electricity is used to investigate and quantify the influence of investments in generation units for the observed zone and the commitment of units in the surrounding zones. Dispa-SET software was used for modelling of a case study which included eight zones connected in the electricity market. Year 2016 was selected as referent, while future scenarios in 2030 are created with different strategic decisions made in each of the zones. Results demonstrate the influence of different strategic pathways in different zones, through electricity generation and levels of storage capacities in the investigated zone and neighbouring zones and cross-border electrical energy flows. If most of the zones are pursuing unambitious strategies (2030a), marginal cost of electricity is double in comparison to the most ambitious case, while moderate approach in the most zones bring the cost reduction of 20%. The ambitious scenario 2030c for all zones results in the least cost of electricity, 30% of the cost in scenario 2030.

The paper contributes to the objective 1 of the research (To prove the value of the use of game theory in assessing the long-term strategic decisions of market coupled zones) and to the method 2 (*A method which provides robust assessment of strategic decisions using the game theory*) by providing an optimization-based approach that enables the researcher to follow the energy flows between the market coupled zones and establishing the base for the calculation of payoffs that each zone would obtain from different strategic decisions. In that aspect, the paper contributes to confirming the hypothesis of the research.

Antun Pfeifer (Main author, 90%): Writing - original draft, Investigation, Conceptualization, Methodology, Software, Visualization. Goran Krajačić: Conceptualization, Writing-Reviewing and Editing. Reinhard Haas: Conceptualization, Writing- Reviewing and Editing. Neven Duić: Conceptualization, Resources, Supervision, Funding acquisition.

Paper 5

Pfeifer, Antun; Feijoo, Felipe; Duić, Neven. Fast Energy Transition as a Best Strategy for All? The Nash Equilibrium of Long-Term Energy Planning Strategies in Coupled Power Markets. Energy, Volume 284, 2023, 129109, https://doi.org/10.1016/j.energy.2023.129109

In this research, a two-level method is proposed for decision-making in long-term energy systems' development strategies. It is hypothesized that a novel approach, using game theory in the second stage of energy systems' modelling, is beneficial for choosing the best strategy for a zone in the price coupled electricity market, when strategies of the surrounding zones are considered. In the first step, the zones are modelled in a unit commitment and dispatch optimization software, obtaining results for generation of electricity and heat from various generators, storage units and transformation technologies, as well as electricity flows between the zones, for different combination of strategic decisions. In the second step, a game is developed based on the payoff for each zone in accordance with different strategic decisions made in terms of the energy transition dynamics, integration of variable renewables, flexibility options and demand response. This game is a matrix game with multiple players and dual strategy, for the scope of this research. Results show that it is possible to find the pure Nash equilibrium for such a game, under given strategies, allowing the zones in the market to choose deterministically their best strategy. In the presented hypothetical case, the best strategy for all zones (the pure Nash Equilibrium) is to pursue fast energy transition towards a system based on renewable energy and flexibility options that arise from synergies between the power sector and different sectors of energy consumption, namely scenario 1, with strategies (1,1,1,1). The proposed approach represents a step forward in the long-term energy planning, as it provides a more robust decision-making approach compared to previous approaches, through endogenization of the previously exogenously considered decisions of other zones that are neighbouring the zone of interest.

The paper contributes to the objective 1 of the research (To prove the value of the use of game theory in assessing the long-term strategic decisions of market coupled zones) and to the method 2 (*A method which provides robust assessment of strategic decisions using the game theory*) by defining the payoffs of the each market coupled zone in different scenarios, formulating and solving the game using the game theory and providing the demonstration of finding the Nash equilibrium for the hypothetical case. Results of the paper confirm the hypothesis of the research.

Antun Pfeifer (Main author, 90%): Writing - original draft, Investigation, Conceptualization, Methodology, Software, Visualization. Felipe Feijoo: Methodology, Writing-Reviewing and Editing. Neven Duić: Conceptualization, Resources, Supervision, Funding acquisition.

PAPER 1

Integration of renewable energy and demand response technologies in interconnected energy systems

Antun Pfeifer*, Viktorija Dobravec, Luka Pavlinek, Goran Krajačić, Neven Duić

Faculty of Mechanical Engineering and Naval Architecture

University of Zagreb, Zagreb, Croatia

e–mail: antun.pfeifer@fsb.hr

ABSTRACT

Sustainable island energy systems have been a subject of academic research for some time. Real-life examples of highly renewable and sustainable island energy systems can be found all over the World. Islands on small geographic proximity provide the potential for the development of 100% renewable island energy systems by exploiting their grid interconnections. This paper proposes that interconnections of a group of islands can be used to integrate the production from locally available renewable energy sources. Besides interconnection, electric vehicles were used as a demand response technology to provide storage for electrical energy from variable sources. Electric vehicles were connected to the grid using smart charging systems (vehicle-to-grid). In addition, stationary batteries were explored in sub-scenarios for the year 2035. This enabled to analyse the influence of the battery location through two main different scenarios, i.e. one big central battery and several smaller distributed batteries. Scenarios with different integration dynamic of variable renewable energy sources and electrical vehicles were modelled with EnergyPLAN model, while the interconnection analysis was carried out with the MultiNode tool expansion. The results showed that the interconnections increased the share of energy from renewable energy sources in the final energy consumption and declined the total critical excess electricity production, while vehicle to grid technology enabled exploitation of synergies between sectors.

Keywords: Sustainable island systems, Renewable energy sources, EnergyPLAN, MultiNode, Interconnection

Table of acronyms

CEEP	Critical Excess Electricity Production
DR	Demand-response
DSM	Demand-side management
EV	Electric vehicle
GIS	Geographic information system
PES	Primary energy supply
PP1	Power plant
PV	Photovoltaic
RES	Renewable energy sources
SE	Solar energy

* Corresponding author

SEAP	Sustainable energy action plan
TPP	Thermal power plant
V2G	Vehicle to grid
VRES	Variable renewable energy sources

INTRODUCTION

In recent years, increasing penetration of renewable energy sources (RES) through integration of different sectors of energy system, i.e. power system, heating and cooling sector and transport sector is becoming one of the most investigated solutions for achieving more self-sufficient local island communities. Therefore, scientific research in this field has made a lot of effort to develop methods and tools particularly designed for carrying out analysis of energy systems on islands. RenewIslands methodology in Duić, N. et al. [1] provides assessment of technical feasibility of various options for integrated energy and resource planning. The methodology systematically approaches the analysis of needs, available resources, appropriate technologies and creation of scenarios for development of island energy systems in transition to sustainable and independent energy systems powered by locally available renewable energy. It provides the tables with the level and density of particular demands, qualitative potential of particular source and qualitative assessment of technologies which can be used to balance demand for, for example electricity, cooling energy and water with energy supply from locally available sources. Krajačić G. et al. [2] described H2RES software for analysis of islands energy systems as well as micro grid operations. The software is also suitable for modelling 100% renewable energy system. Möller B. et al. in [3] developed a tool for examining islands energy systems as a part of the project "Cradle to Cradle Islands" funded by the EU Interreg IVb North Sea Region Programme. The tool facilitates the identification of islands possibilities for sustainable development. Initially, the tool was developed on a basis of energy system inventories for the case of four islands Samsø (Denmark), Spiekeroog (Germany), Runde (Norway) and Ameland (Netherlands). Inventories were developed and could be used for analysis of the effects on carbon emissions, fuel consumption and investments made for the energy technologies. Moreover, the tool through SWOT analysis contributes to a learning process which can help to develop renewable energy systems on examined islands. Apart from using already developed models, new algorithms have also been examined, for example Gašparović, G. et al. [4] updated the H2RES model by adding the modules for electric vehicle (EV) simulation. Bačelić Medić, Z. et al. [5] highlighted the importance of optimal solar and wind energy integration with storage solution together with energy savings and improvements in energy efficiency in the energy production on the case study of an island Hvar conducted in EnergyPLAN software. Impact that energy production and transport system integration have on the electricity demand curve was investigated in Šare, A. et al. [6], hourly energy demand of the transport system and influence of integration of EV on electricity grid has also been examined in Novosel, T. et al. [7] and, through agent-based modelling of the transport demand, in Novosel, T. et al. [8]. Commercial energy planning software HOMER was used in Sadrul Islam et al. [9] for optimized hybrid RES, storage and diesel generator system for large island communities on an isolated island, while H2RES software was further developed for analyses in already mentioned cases of renewable islands and others, such as cutting the consumption of fossil fuels through hydrogen conversion and storage solutions for energy transition of Malta [10], further investigations of hydrogen as an energy vector in isolated island systems was conducted for the case of Porto Santo [11], and for optimization of annual costs when using hybrid system, which consist of wind power plant, pump hydro storage and water desalinization units on San Vincente and Cape Verde [12]. Moreover, H2RES was used in Segurado, R. et al. [13] to integrate energy and water supply for Cape Verde. For smaller island, and with different approach, penetration of RES into fragile environment was examined in Katsaprakakis, D.A., et al. [14]. Similar research was conducted for wind energy in Europe [15], providing the wind onshore and offshore potential and for Croatia, using geographic information system (GIS), in Međimorec, D., et al. [16], which provided the potential locations for future wind power installations in Croatia, using the GIS.

Modelling of renewable energy systems on islands requires research on technology implementation and research on the impact of renewables on the overall energy system. Balancing of the system is having a crucial role for energy system stability as the energy generation from wind and solar have variable nature. In the Mediterranean region, which is the focus region of this paper, wind and solar are the most promising RES. However, the visual impact and environmental issues caused by wind turbine installation could lead to the limited possibility of their installation close to the coastline. As an example of such restrictions the national legislative framework in Croatia prohibits the wind power installations in the 1000 m from the coastline. Therefore, the focus of this research was placed on the solar energy. Solar energy was elaborated in Haas, R. et al. [17], in relation to power market, as formidable in order to replace fossil fuels on islands with RES installations. Recent research in Lau KY, et al. [18] investigated economic feasibility of photovoltaics (PVs) in island communities in relation to fossil fuel prices and load sizes but did not take into account the integration of systems, for example water supply or transport. Replacement of fossil fuel with solar power, i.e. electricity generation from rooftop photovoltaics for the case of Canary Islands was studied in Schallenberg-Rodriguez, J. [19]. The study focused on development of the method for determining the potential of rooftop PVs showing that electricity can be generated at competitive price and that the potential is sufficient to cover electricity demand of each examined island. Nevertheless, the study did neither take into account ground based PV plants nor synergies with other sectors. Another study [20] emphasized the complexity of PV system installation in urban areas. Detailed geographical and economic analysis was carried out stressing that self-sufficiency can lead to achievement of economic benefits. The implementation of renewable energy technologies can also be fostered through application of incentive measures. This was discussed in K. Reinsberger et al. [21] where the authors analysed the effects of two different bottom-up initiatives for installation of PVs taking into account potential incentives and barriers. It was proved that a quality framework that can contribute to the creation of value added should be promoted for initiation and development of projects such as PVs installation.

Nowadays, balancing of the renewable energy production can be done in several different ways. One of the possibility is integration of sectors and various types of energy. Here, smart energy system is the best way of such integration leading to detection and utilization of synergies between different sectors, as shown in Dominković, DF. et all.[22]. Moreover, this enables to design better technical system which is capable of managing the VRES. In [22] it has also been proven that smart energy systems are cheaper considering the socio-economic costs. Single and multi-action initiatives for transforming island power systems into smart ones were assessed in Sigrista, L. et all. [23]. The research included an assessment of initiatives for implementation of five actions wind, PV, energy storage systems, demand-side management (DSM) and EV. Each initiative consists of a particular combination of different penetration level of mentioned energy technologies. Islands were grouped into clusters in order to identify their similarities for implementation potential of RES. The results of the assessment shows that type of initiative depends on the island size where smaller islands are more suitable for renewable energy source initiative, whereas larger islands for DSM. In Calise, F., et al. [24], the polygeneration system, combining electricity and water supply systems, as well as heating and cooling supply was investigated on the case study of Pantalleria island. The research results show that polygeneration approach can fulfil the water demand of the community and supply significant amounts of electricity, heating and cooling energy with acceptable payback period.

Another solution for balancing of the energy systems with high share of VRES are energy storage technologies, which are crucial for achieving self-sufficiency of islands. Comprehensive study and analysis of leading storage technologies has been reported in Rodrigues E.M.G., et all. [25]. Besides well-known stationary batteries technology, batteries from EVs, i.e. vehicle to grid (V2G) technology can serve as a storage system. Integration of the EVs into a micro-grid was examined in Mortaz, E. et al. [26] where authors proposed an optimisation model for managing the energy in a grid-connected smart grid that includes RES and a parking facility for EVs. The results show that longer parking times and higher price fluctuation ratios produce higher expected savings whilst a high price fluctuation ratio does not necessarily mean high expected savings. A case study for an entire energy system of Croatia was designed including different renewable sources where EVs served as a battery storage in Prebeg, P. et all [27], proving V2G concept for long-term planning on the national level in H2RES software. Various studies investigated the integration of EVs into energy system where the V2G technology was used, also in EnergyPLAN, as shown by Østergaard in [28]. In Colmenar-Santos, A. et all. [29], authors emphasized the importance of EV penetration for the operation of smart grids. The analysis done on the case study for the island of Tenerife show that usage of V2G technology can efficiently support the management of smart grids by significantly reducing the amplitude difference between valleys and peaks of the electric energy demand curve. High penetration level of EVs increases the participation of conventional generation units in the generation mix. In order to provide sustainability of the electric system on island authors advised to examine parallel penetration of RES and EVs in future research. Combination of solar PV, EVs, supercapacitor and diesel generator were used to test the performances of micro grid as an island solution in Yin et all. [30].

Furthermore, interconnections between islands and connection to the mainland grid could serve to balance the variability of renewables. The advantages of the interconnected energy systems were proven on many cases of regionally integrated energy systems. The benefits that regionally integrated electricity supply system has in relation to power generation systems of individual countries was examined in Gnansounou E, et all. [31] for the case study of Western Africa. Integrated system resulted in 38% lower total electricity production. Moreover, the advantages that countries and regions with high penetration of RES have from cross-border electricity transmission were presented in Lynch MÁ, et all. [32]. Benefits of interconnection between energy system of larger scale such as countries and regions can be also used on the case of islands. In Lobato E, et all. [33], the authors dealt with the technical and economic value of island interconnections for the several remote islands of the Spanish Balearic and Canary archipelagos. The results showed that interconnections in the considered case studies enable the flow of cheaper generation power between islands, however economic savings of each interconnection depends on the island characteristics. The RES energy scenarios have been also analysed for a group of interconnected islands in H. C. Gils et al. [34] and M. Child et. al.[35].

In [34], energy system included smart V2G option, however, batteries discharge was not examined in detail. On the other hand, [35] focused on high electrification of transport including both, charging and discharging of EVs. It has been concluded that V2G technology has important role in energy system with high share of VRES. It increases the flexibility because of accepting excess energy from wind and solar PV and providing electricity back to the grid. Nevertheless, the analysed group of the islands in the Baltic Sea which show significant variations in the need for heating and cooling in relation to the Mediterranean islands which is the case of this study. Northern and southern islands require a different combination of technology where northern islands provide significant potential in VRES balancing capabilities due to high heating demand which can serve as a storage system. Direct coupling of solar energy and EVs was investigated in Figueiredo, R. et al. [36], showing the potential to reduce the need for storage with controlled charging, but also demonstrating the compatibility of two technologies. Use of Multinode add-on tool in EnergyPLAN software to model the smaller zone inside a larger one, for example one county inside the national energy system, was employed in Bačeković et- al.[37].

The systematic overview of the most relevant studies presented in the Introduction section is provided in Table 1. The relevance is defined according to the main goal of this research and divided into several characteristic criteria.

Table 1 Systematic overview of the most relevant studies

Author	Software/ Methodology/ Tool	Single island / Group of interconnected islands	100% RES system, sectors included	Closed/ Open system (export to mainland allowed)	Type of transport electrification
Duić, N. et al. [1]	Renewisland methodology	Single island			
Krajačić G. et al. [2]	H_2RES	Single island	Yes, transport and electricity	Open	No
Möller B. et al. in [3]	C2CI insular model	Single island	Model allows 100% RES	Open	Yes, not specified in detail
Bačelić Medić, Z. et al. [5]	EnergyPLAN	Single island	Yes, all sectors	Closed	Yes, not specified in detail
Sadrul Islam et al. [9]	HOMER	Single island	No	Not specified	No
Busuttil, A. et al. [10]	H_2RES	Group of islands	No	Closed	No
Martins, R. et al [11]	H_2RES	Single island	Yes	Closed	
Segurado, R. at al. [12]	H_2RES	Single island	No	Not specified	No
Segurado, R. at al. [13]	H_2RES	Single island			
Katsaprakakis, D.A., et al. [14]	L.C.C. method	Single island	No		No
Calise, F., et al. [24]	Dynamic simulation models, tailor made	Single island	electricity and water supply systems, heating and cooling supply	Closed	No
Yin et all. [30]	Novel method	Single island	No	Closed	No
Lobato E, et all. [33]		Group of islands	No	Not specified	No
H. C. Gils et al.[34]	Mesap-PlaNet, REMix.	Group of islands			
M. Child et. al.[35]	EnergyPLAN	Group of islands	Yes	Open	V2G

I. Bacekovic et. al. [37]	EnergyPLAN	Smaller zone inside the larger zone	No	Open	No
Dorotić et al.[43]	EnergyPLAN	Single island	Yes, all sectors	Open	V2G, partially smart charge

In this paper, a new strategy for the simulation of the energy system was utilized. The novelty of this paper is in utilization of V2G technology as the only balancing demand response (DR) technology in operation without fossil fuel generators and tackling the last part of the supply share with stationary batteries, providing fully electrified systems in the interconnected archipelago. Another novelty is the analysis of interconnected operation of systems without installed fossil fuelled generators combined with discussion of different location possibilities of additional storage technologies.

As shown in the introduction, previous approaches utilized either other technologies or fossil fuel powered generators as a balancing technology. Furthermore, after the exploitation of V2G capacities additional storage technologies were added in order to investigate the influence of their location. The location was examined on the island scale, where one island was considered as one location available for the installation of the large battery banks and small household-size batteries. Here, the specific placement of batteries within the island itself was not taken into account.

METHOD

To simulate the energy system of islands in this research, EnergyPLAN 13.0 model was used. The EnergyPLAN is an input/output model which incorporates heat and electricity supplies as well as the transport, individual and industrial sectors. It has already been used for the scenario analysis of energy systems with a high share of the VRES as well as for the 100% renewable energy systems and various other analyses, which made it an established tool for similar applications [38]. In this version of the EnergyPLAN model, the option of balancing V2G and Hydropower can be used without Power plants (PP) 1 and PP 2 which represent the aggregated groups of power plants, usually supplied by fossil fuels. Moreover, one more balancing option is available in this version of the EnergyPLAN. V2G can be used to balance the need for PP and reduce Critical Excess Electricity Production (CEEP) but also to balance the Import/Export so that import is not needed if V2G batteries can be used, or, otherwise, energy is stored in batteries instead of exporting it from the system. This can be active in the “Simulation” TabSheet. For the purpose of scenario modelling, technical simulation was used. The technical simulation, seeks to find the solution with the minimum fuel consumption.

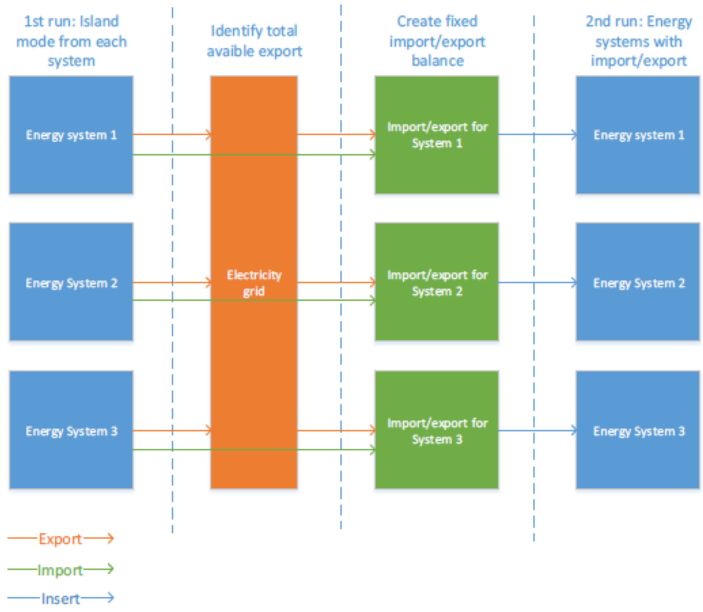

Figure 1 MultiNode tool general scheme [39]

MultiNode is an additional tool in EnergyPLAN, specially designed for analysing integration of local and national systems and plans of their development. The main result from MultiNode analysis is fixed import/export profiles between two or more energy systems. MultiNode seeks hours throughout the year where there is at the same time excess electricity in one system and import demand or condensing thermal power plant (TPP) production in another one.

In such way, the first system can integrate its excess production, which is usually a result of the VRES production, while the second system can meet its import demand or decrease the TPP production, thus increasing the share of RES and decreasing the fuel consumption.

Method for establishing import/export balances in MultiNode operation is described using the equations (1)-(4), which form the mathematical model of this tool [39].

Equation 1 Sum of available exports - identifies the amount of exportable electricity each system delivers and summs them for each hour. Up to 14 systems can be calculated.

$$export_{total} = \sum_{i=1}^{14} export_i \tag{1}$$

Equation 2 Amount of potential imports for each system *i* through summation of the import demand the current operation of the power plants which are installed in the system *i* (PP) in each hour in the year. Import is limited by the capacity of transmission lines between the systems.

$$P_{import\ i} = import_{demand\ i} + PP_{prod\ i} \tag{2}$$

Equation 3 Initial balance for each system, that defines the export as positive and the potential import as negative for each system

$$Balance_{initial\ i} = export_{\ i} + P_{imp\ i} \tag{3}$$

Important condition, which constitutes Equation 4 is, „system can only import if there is available electricity in the grid“. This means that the merit order of the systems (in which they will satisfy their import demand from the grid) is determined by their order in the tool (user defined).

$$\boldsymbol{if}(P_{imp\,i} > export\ total)\ \boldsymbol{then}\ Import_i = exportabletotal\ \boldsymbol{else}\ Import_i = P_{imp\,i} \quad (4)$$

Balance is obtained by taking the $Balance_{initial}$ (from (3)) and replacing the export with the sum of imports needed in the other system, while the potential import is replaced with the actual calculated import. The consequence is that now the export is not balanced with the import. The excess accounted electricity is removed by diving the active export in each system (hourly) with the number of systems that exports electricity [39]. Through this procedure, now import/export hourly distributions are being created and this distributions replace the previously user-inputed ones. Those new distributions are used in running systems in a connected mode.

Novel idea in this work is to exploit the new balancing strategies which use the V2G concept to examine how the interconnected system would work if V2G is used as the major DR and storage technology. In this paper, above described tools are used to investigate the impact which grid interconnections between geographically close islands have on their power system, with no fossil fuel powered PP installed. Interconnections accompanied with DR technologies such as V2G concept, and storage technologies such as stationary batteries served to enable higher penetration of RES.

Scenarios for case study areas have been prepared for two categories, which are compared: isolated and interconnected mode. Planning of case study areas was conducted in two different scenarios:

- Scenario 1: business as usual, which follows the local Sustainable energy action plans (SEAP-s) and extrapolates the measures towards year 2035, and
- Scenario 2: RES scenario, which aim for maximal use of RES on the local level, with 5% CEEP being the aim for each system, while achieving as high as possible integration of RES.
  - Sub-scenario 2.1: Main DR technology, V2G, is aided by addition of stationary batteries. All stationary batteries are located in one zone, while the other zones supply the leading zone with the excess energy produced locally.
  - Sub-scenario 2.2: Main DR technology, V2G, is aided by stationary batteries, which are distributed uniformly in all connected zones.

Stationary batteries in EnergyPLAN 13.0 were modelled as pump hydro. This was possible due to the due to the similar behaviour of the energy technology, having the same key parameters, such as total capacity, charging power, discharging power and efficiencies for charging and discharging. Interconnected mode was examined by implementing two approaches: using the MultiNode tool and connecting the islands into a single (common) system. Former approach is new and would have the benefit of giving the exact import/export hourly values between the islands. Latter approach was previously used on regions and countries, but not on islands with the aim of examining VRES and V2G without any fossil fuel powered facility for backup. The approach presented in this paper is most suited for islands which are not far away from the shore and have relatively good connection to the grid or between themselves.

CASE STUDIES

Islands of Vis, Korcula, Lastovo, Mljet have been chosen as case studies. For the islands, RenewIsland methodology has been implemented and results of first two steps are given in tables 1 and 2. The archipelago, including the transmission lines, which are elaborated in Table 4, is presented in Figure 2.

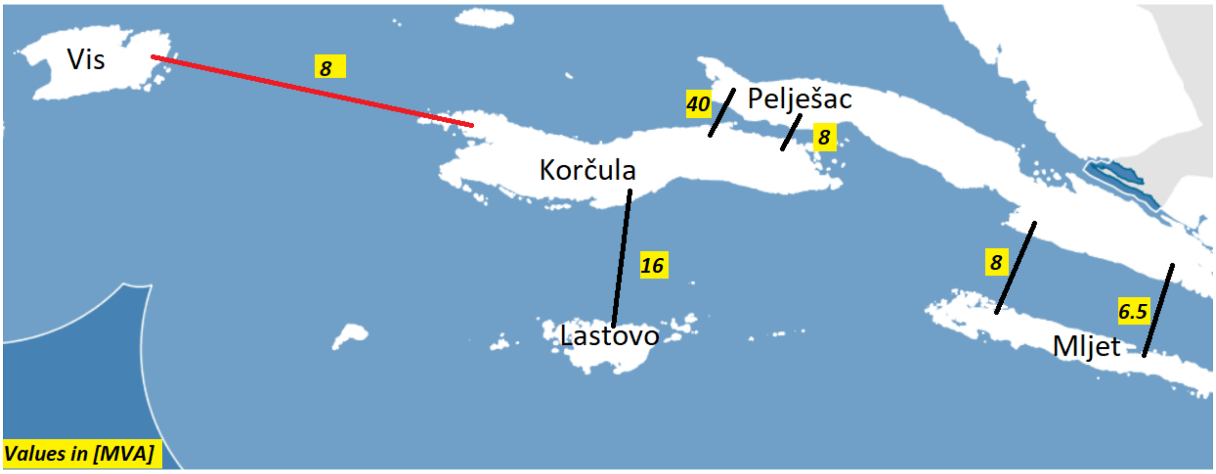

Figure 2 Case study area with transmission lines

A common system was observed, since there are many similarities between the islands, but the difference in size and population provides opportunity for different setting of VRES and DR technologies. Potential was analysed in detail in Pavlinek L. [40], taking into account the input data for all four systems, local VRES potential and consumption. For RES potential, local availability was determined using the data obtained from METEONORM software [41]. The analysis showed that solar PV is the most promising technology for all of the islands in the case study. In the mentioned master thesis [40], scenarios were developed for years 2025, 2030 and 2035. The aim of the work was to cover all the demand with the electricity produced from the locally available VRES, i.e. solar energy (SE). Two scenarios with different penetration level of PVs were developed. In the first scenario, the electricity production from SE was equal to annual electricity demand. In the second scenario, beside the SE technologies integrated V2G as DR technology.

Table 2 RenewIsland methodology - first step, determining the needs

Needs	Level	Geographical Distribution	Code
Electricity	Medium	Concentrated	ElectMC
Heat	Low	dispersed	HeatLD
Cooling energy	Medium	dispersed	ColdLD
Fuel for transportation	Low	Short dist.	TranLS

Water	Medium	dispersed	WaterMD
Processing waste	Low	dispersed	WasteLD
Wastewater treatment	Low	dispersed	WWTLD

The electricity production in the second scenario had a limitation of maximum 5% CEEP. Besides island, this case study area included Peljesac peninsula, with installed wind power plant. In reality, electricity generated from wind is supplied to the mainland grid, whereas in [40] all the generated energy from wind was exploited in the case study area. This allowed to investigate the effect which connections between islands have on the integration of wind power plant in local energy system. The results of this research were presented in Pfeifer, A. et al. [42]. The research was improved by using new version of EnergyPLAN (13.0). New functions enabled to draw the attention from connecting the island's energy systems to deployment of DR technologies. Moreover, this provided the possibility to investigate the influence of different deployment on the transmission capacities between the systems and changes in import/export distributions on an hourly level. For the purpose of this paper, Peljesac peninsula was excluded from the case study area. However, the transmission line between Korcula and Mljet remained in calculations (see footnote 1). In order to simulate the interconnections between island systems in MultiNode tool, connection capacities given in Table 4 were used. Voltage level of connection lines is 35 kV between the islands, while Korcula has supply connection line of 110 kV from the mainland (via Peljesac). Even though In real there is no connection between Vis and Korcula islands, for the purpose of this research the connection capacities which exist on island of Vis were used as if they are interconnected to Korcula, which can be considered as a future investment in the view of opportunities it provides, as shown in analysis below Consumption of energy, installed VRES capacities and number of EVs in all scenarios, in the case of investigating a common connected system, are given in Table 5.

Table 3 RenewIsland methodology – second step for the common system - resources

Resources	Level	Code	Resources	Level	Code	Resources	Level	Code
Local primary energy			Infrastructure for energy imports			Water		
Wind	Medium	WindM	Network connection	Medium	GridS	Rainfall	Low	H2OPL
Solar	High	SolarH	pipeline natural gas	n/a	NGplN	Groundwater	Low	H2OGL
Water potential (altitude drop)	Medium	HydroM	Terminal LNG	n/a	LNGtN	Water supply	Yes	AquaY
Biomass	Medium	BIOMM	Oil terminal / refinery	n/a	OilRN	Seawater	Yes	H2OSY
Geothermal potential	Low (46)	GeothL	Terminal petrol. production	n/a	OildDN			

Table 4 Connection capacities used in calculations

Islands	Connection capacities [kVA]
Korcula-Peljesac	8000
Mljet-Peljesac[1]	8000
Korcula-Lastovo	16000
Vis-Korcula[2]	8000

Table 5 Energy consumption, VRES capacities and number of EVs for all scenarios of the common connected system

	Year	2012	2025 S1	2030 S1	2035 S1	2035 S2
Yearly consumption [MWh]	Electricity	87,000	86,000	94,000	104,000	112,000
	Diesel	40,000	20,000	17,000	13,000	0
	Gasoline	46,000	24,000	20,000	15,000	0
Electric vehicles [no.]		0	1682	2457	3851	7702
PV [MW]		0	5.22	7.225	9.22	61.0

[1] The islands of Korcula and Mljet are connected by the transmission line which is installed accross the Peljesac peninsula
[2] There is no physical link in reality, this link is equivalent of the link that actually supplies the island of Vis with electricity, but via the island of Hvar

Scenario 1 in the year 2012 does not include any variable energy sources in the case study area and all energy demand is supplied by imports from the mainland.

The capacities of stationary batteries in sub-scenarios were designed according to the calculation from Dorotić, H. et al. [43]. This paper introduced V2G technology without PP support in the system. for the island of Korcula.

Table 6 Stationary batteries types and capacities[43]

Smaller battery capacity	Smaller (household) battery charging/discharging power	Bigger (municipality) battery capacity	Bigger battery charging/discharging power
13.5 kWh	5 kW	210 kWh	50 kW

Table 6 represents the installed capacity of different types of stationary batteries in scenarios 2.1 and 2.2. The overall calculated installed capacity was 64.5 MW with the storage capacity of 179 MWh.

The base scenario and dynamics of scenario development through years 2020, 2025 until 2035 have been elaborated in Pfeifer, A. et al. [42] for the case with Peljesac peninsula included in calculations.

The wind power plant from Peljesac peninsula was sufficient to supply all the connected island systems and to deliver 11-30% of energy to the mainland grid, depending on the scenario. This abundant supply of electricity, which is in reality aimed to the mainland grid, makes it difficult to test in more detail the interactions between particular island systems and was therefore removed from calculations in the present paper. Particular peak loads, number of EVs and installed PV capacities on each island are given in Table 7.

Table 7 Peak loads, EV numbers and installed PV capacities for two major scenarios in all island systems in year 2035

	Korcula	Mljet	Lastovo	Vis
Peak load [MW]	16.51	2.79	1.87	5.07
2035 S1				
EV [no.]	3075	182	111	483
PV installed [MW]	5.87	1.04	1.00	1.31
2035 S2				
EV [no.]	6150	364	222	966
PV installed [MW]	40.0	5.0	4.0	12.0

In Table 8, the most relevant inputa data is listed for all island systems in 2035.

Scenarios 2.1 and 2.2 are calculated with the same overall battery power and storage capacity in order to be comparable for discussion.

Table 8 Input data for scenarios in 2035

Year 2035	Korcula	Lastovo	Mljet	Vis
Demand [MWh]	62,200	6,860	7,390	18,860
Installed PV [MW]	40	4	5	12
Installed batteries power [MW] / storage [MWh]				
Scenario 2.1	64.5/179	0	0	0
Scenario 2.2	42.5/118	4.38/12	4.77/13	12.2/34
V2G demand [MWh]	8,500	530	520	1,950

RESULTS AND DISCUSSION

The most relevant results to discuss are those of the scenario 2.1 and scenario 2.2 in the year 2035, when the measures described in [40] have been implemented and further discussion is aimed towards the analysis of interaction between the systems, using the MultiNode tool. In Figure 3, the representative period of operation of Korcula's energy system is illustrated, in this case for scenario 2.1 in the year 2035, showing the synchronisation between production and demand response technologies.

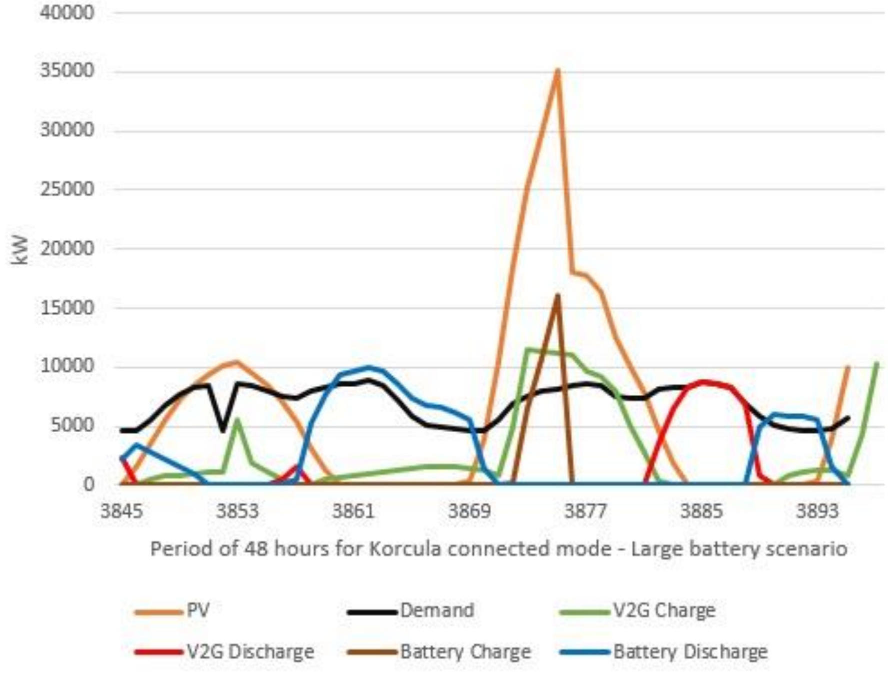

Figure 3 Ilustration of the system operation for an indicative period on the island of Korcula, scenario 2.1 in year 2035

The power generation system was balanced by the stationary batteries for storage and V2G as DR technology. Both V2G and battery banks manage to store energy from the PV plants and use it to satisfy demand during the night. Therefore, MultiNode tool can produce scenarios for connected systems without dispatch able PP, balanced by DR and storage technologies. For scenario 2.1, relevant interactions between the systems are illustrated by Figure 4, which shows the electricity import and export distributions for all island systems. Since the additional storage capacities were placed on Korcula, other islands were supplying Korcula, most of the time, with their excess electricity produced. Overall number of hours in which export/import takes place is 417 hours in the year, with maximum flows between systems reaching 0.957 MW peak hourly export from Vis to Korcula.

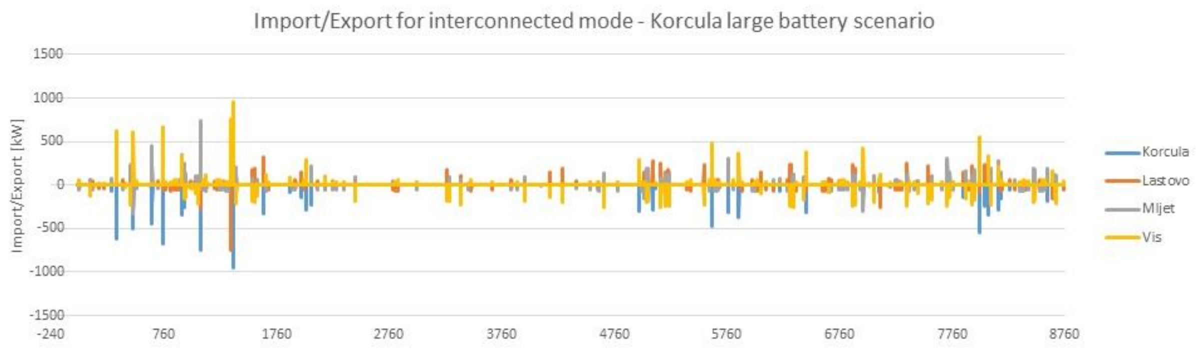

Figure 4 Electricity Import/Export distribution for the interconnected mode of scenario 2.1

In the case of scenario 2.2, the storage capacities were distributed on all islands, so demand and supply were balanced better on local level, which reduced the CEEP in each of the island systems. This resulted in fewer hours in which interconnections were exploited for the purpose of the electricity import/export from a particular island. The total number of hours was 17. In most of the cases, electricity was imported to the island of Korcula as this island has the highest electricity demand. However, in the scenario 2.2 the import/export values were much higher than in the scenario 2.1, reaching 2.539 MW peak hourly export between Korcula and Mljet.

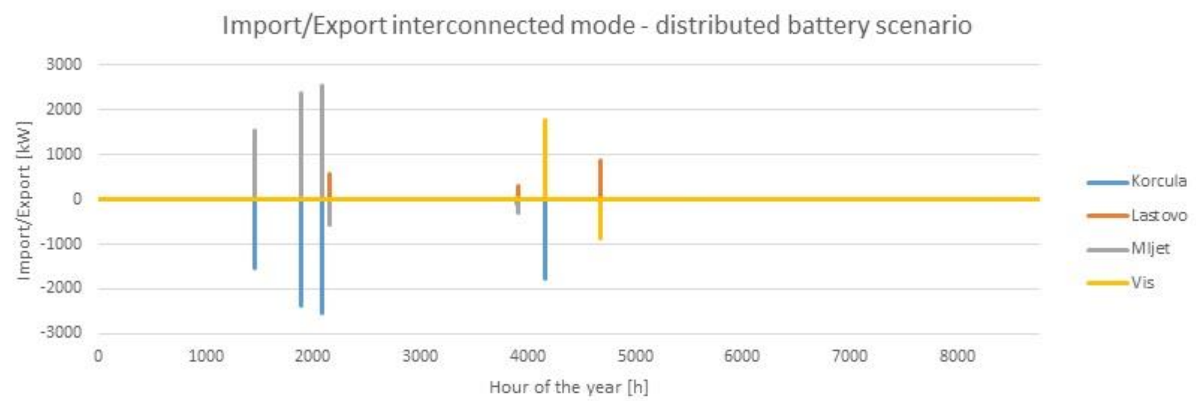

Figure 5 Electricity Import/Export distribution for the interconnected mode of scenario 2.2

At the same time, although comparison of Figure 4 and Figure 5 indicate that the interaction between the systems is lower in scenario 2.2, this is visible in the number of hours in which transmission systems are in operation, but the overall numbers provide different picture regarding the intensity of interaction, as it is demonstrated in Table 9. This is due to 4-5 times higher energy transfers in hours when other systems export energy to the island of Korcula in scenario 2.2.

Table 9 Values of electricity exchange between the systems in 2035, for both scenarios

Import/Export [MWh]	Korcula	Lastovo	Mljet	Vis
Scenario 2.1	-13.05	8.12	8.44	-3.52
Scenario 2.2	-15.55	2.48	12.33	0.75

It can be concluded that Korcula would still need larger capacities of DR technologies or stationary batteries to limit the need for imports, although others systems in scenario 2.2 now have much more independent and balanced operation thanks to their local storage. In Figure 6, the results are given in terms of CEEP for each system.

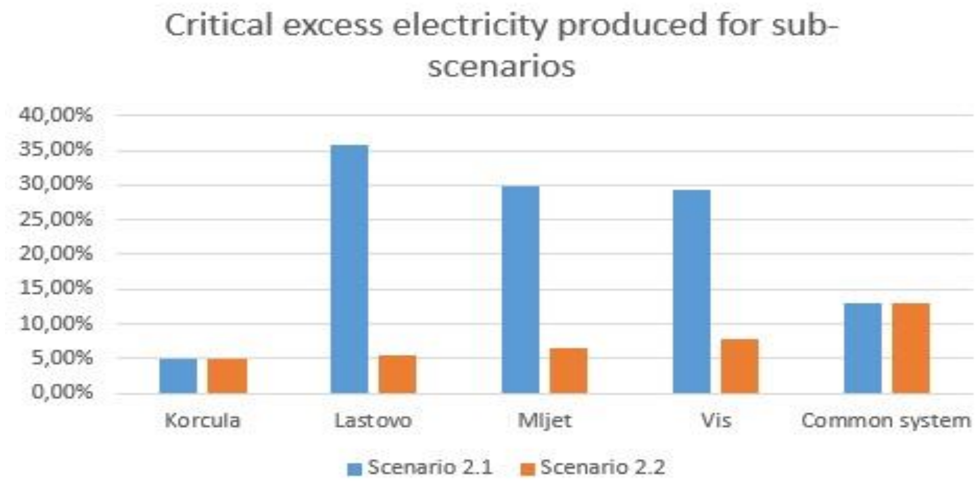

Figure 6 Critical excess electricity production for all systems and a common system in both sub-scenarios

In the case of scenario 2.1, CEEP was limited for the case of Korcula, due to locally available additional storage capacity, while other islands were used as additional suppliers, with lower ability to balance the production and supply locally. In scenario 2.2, the CEEP remains almost the same on Korcula, due to relatively large remaining storage capacities, which are still able to balance and store the energy produced from RES and respond to the needs in almost all hours, except for the cases which are illustrated by Figure 5. Connected system, which does not reflect the interconnections between the islands, has lower overall CEEP then the sum of the systems in scenario 2.1. In general, the transition from the base year, 2012 to 2035 brings the group of islands close to energy independence, which is also demonstrated in Table 10, taking into account the transition from the base year, in which the share of VRES in primary energy supply (PES) was roughly zero.

Table 10 Share of VRES in all systems in 2035

RES share in PES [%]	Korcula	Lastovo	Mljet	Vis
Scenario 2	74.1	85.6	84.3	80.1
Electricity from import	25.9	14.4	15.7	19.9

CONCLUSION

This paper presented the method for planning the energy systems of the grid interconnected islands which are close to the mainland. The analysis of the interconnected island systems was done with EnergyPLAN 13.0 model. The version 13.0 of the model enabled to use the V2G concept without any balancing facilities, such as conventional condensing power plants. This addition made EnergyPLAN a suitable tool for planning the island energy systems and their transition to 100% renewable and sustainable smart island systems.

Further novelty is the use of MultiNode tool, which is able to simulate interconnection between such island systems in EnergyPLAN 13.0. This allowed for the analysis of implications which DR technologies deployment has on the interaction between systems and their ability to integrate more locally available renewable energy.

The results show the increase in the share of energy from RES in total final energy consumption after connecting to a common system, which reaches 85% for systems examined in case study, and decline of total CEEP of all systems from 28-35% individually to 13% after connecting to a common system for the scenario 2.1. Decrease in net import / export can be observed in correlation to the increase in the independence of island energy systems, but the deployment of storage technologies, analysed through interactions between systems, has influence on the intensity of load on the transmission lines, which occurred in 417 hours for scenario 2.1 and only in 17 hours for scenario 2.2. In scenario 2.2, however, the intensity of interaction was 2.5 times higher than in scenario 2.1, with peak export being 2.536 MW compared to peak of 0.957 MW in scenario 2.1. From this data, it can be concluded that distributed storage systems provide more energy security for every single system, compared to the case of storage being concentrated in only one of the connected systems, but it has to be carefully designed to avoid large peaks in some hours.

The combination of VRES and V2G would be the combination of technologies which offers most synergies with least environmental impact in island systems. Proof for this correlation and analysis of combination of VRES which would be able to produce more balanced system is left for future work. Also, in future work, the economic analysis of VRES, V2G and battery storage technologies will be examined, considering solutions such as local energy markets.

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PAPER 2

Increasing the integration of solar photovoltaics in energy mix on the road to low emissions energy system – economic and environmental implications

Antun Pfeifer*, Goran Krajačić, Davor Ljubas, Neven Duić
Faculty of Mechanical Engineering and Naval Architecture
University of Zagreb, Zagreb, Croatia
e–mail: antun.pfeifer@fsb.hr

ABSTRACT

The EU policy aims towards low carbon economy by establishing a goal of reduction of 93-99% in greenhouse gas emissions in energy sector by 2050. This means a complete energy transition from the fossil fuel based systems to mostly renewable and low-carbon based energy systems. In order to integrate variable renewable energy sources, day-ahead and intraday electricity markets influence, demand – response technologies implementation and fossil fuel powered thermal power plants' flexibility considerations need to be analysed. Along with the integration of solar photovoltaics, demand – response technologies (power-to-heat and vehicle-to-grid concepts) needed to balance the system, were deployed. In calculations performed on the case study of Croatia in years 2014 and 2030, a moderate introduction of heat storages in Croatian combined heat and power plants, introduction of electric vehicles and flexible operation of power plants enabled the integration of up to 2000 MW installed capacities of solar photovoltaic plants. The main integration criteria, a cumulative critical excess electricity production from solar and wind power, was kept under 5%. Results of this approach are the reduction in full load hours of economically feasible operation for Croatian power plants up to 2000 and combined heat and power plants to up to 3000.

KEYWORDS

Low-carbon energy system, Solar energy, Demand response, EnergyPLAN, Variable sources integration.

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* Corresponding author

1. INTRODUCTION

Different rates of integration of variable renewable energy sources (VRE) into the energy system are possible, depending on goals. The price of VRE is getting lower, and has already achieved competitiveness compared to other sources, which is documented in research [1] and reports such as IRENA [2] and [3] and IEA [4] . The solar PV technology is competitive and has reached grid parity on many locations in Europe. Integration of smaller quantities of VRE does not have a significant impact on system's costs.

Up to about 20% of wind energy and 10% of solar energy share per annum, there is an impact on reducing the cost-effectiveness of base power plant construction, which is not necessarily adverse in the context of decarbonisation. Also, occasional curtailment up to a maximum of 5% of critical excess electricity produced (CEEP) can occur, and, in case of poor planning and balancing cost allocation, VRE integration may have an impact on increased cost of balancing. Problems can appear in network building, if network is not adequately designed and in ancillary services, if the market of auxiliary services is inefficient or non-existent. All this is true only if the system is not set in the optimal way. Above this limited share, it is necessary to plan for demand management, in the form of demand response technologies for the conversion of excess electricity to heat, manageable industrial consumption and electro-mobility.

Lund and Kempton [5] compared two energy systems with significant storage technologies and scenario approach discussing electric vehicles (EVs) within "vehicle to grid" concept (V2G). Limitations of aggregated battery model and EV driving cycles were shown, which is usually tackled using pool-based modelling and traffic flow estimates. These issues can be avoided to some extent, as shown by Pukšec et. al. [6], by intelligent long-term forecasting of demand in the transport sector. In another research Connolly et. al. [7] have shown the techno-economic analysis of energy transition of Ireland energy system. The research is comparable to Croatian case in the areas of grid regulation. In the work by Mathiesen et. al. [8], smart energy systems in the electricity sector and management of energy storages were discussed. A solution for long-term design of large energy systems, which can be applied for national level energy system design problem, was suggested by Prebeg et. al. [9] using H2RES. Novel approach was used in Reichenberg et. al. [10] to investigate the demand response in general, for integration of variable sources, such as solar photovoltaics (PV) and wind in the systems with high installed base load units, concluding that it can be facilitated with low curtailment if transmission capacities are available over large geographic area.

For the case of Croatia, Krajačić et. al. [11] demonstrated, using both EnergyPLAN and H2RES models, the role of storage technologies such as pumped storage hydro, heat storage and heat pumps, batteries and electrical vehicles in achieving the VRE share of 78.4% in gross final energy consumption in year 2020 and CO_2 emissions were reduced to 20 Mt, compared to the reference year, 2008. The research was focused on integrating wind power. Using the multi-criteria analysis and Pareto front to determine optimal integration of wind and PV in Croatian energy system, Komušanac et. al. [12] demonstrated that PV will have larger role in Croatian energy transition than expected, with 1650 MW of wind and 1600 MW of solar PV newly installed in 2050. However, demand response developments were not taken into consideration. Integration of wind, with special attention to balancing with dammed hydro power, was demonstrated in [13] by Cerovac et. al.. Benefits of a common low-carbon energy approach for the whole South East Europe was demonstrated in Dominković et. al. [14], taking into account various demand response and storage technologies, such as 100% electrification of light road transport with 85% of transport on smart charging, solar – thermal for space heating with additional storage among other measures aggregated for the Southeast Europe area. With complete transition, this research demonstrated 100% zero carbon South East Europe (SEE) system in the year 2050. Role and flexibility of district heating was investigated in connection to energy efficiency measures in Pavičević et. al. [15] and with waste management and heat markets as factors of synergy in Tomić et. al. [16].

In this paper, the influence of large integration of major VRE sources, solar and wind power, on the feasibility of other technologies and the reduction of greenhouse gas emissions is investigated.

Particular analysis of integration of combination of VRE such as solar and wind power, and challenges of their integration in different energy systems was performed in Ueckerdt et. al. [17]. Another recent study by Atia et. al. [18] shows how profitable V2G operation can significantly affect renewable energy sources (RES) sizing, in particular for micro-grids, demonstrating how V2G will take very relevant position in VRE integration. Also, in Weitmeyer et. al. [19], role of storage is discussed in the scenarios with integration of 50% VRE and 80% VRE and beyond, on the pathway towards 100% RES system. The combination of wind and solar PV was used in Weitmeyer's study, too. Further on, recent studies on synergies of energy production and electrified transport sectors in smaller island systems emphasize the role of V2G technology in Dorotić et al. [20], showing the economically optimal mix of solar and wind power, supported by V2G with minimal import and export of electricity. In Dominković et al. [21], it was demonstrated that in some cases, for small islands and integrated planning case, smart charging can reach similar effect as V2G in a simulation with PLEXOS employed as a modelling tool. In most recent study, Groppi et al. [22] it was shown, using EnergyPLAN and HOMER tools, that for islands similar to those from [20] and [21] dump charge and V2G have the opposite effect on electric grid, which is relevant for the present study. Spiegel [23] was investigating how different balancing groups integrate solar and storage units, concluding that power-to-heat technologies offer an option for reduction of balancing issues for such combination of technologies.

Regarding the long-term decision making for development of VRE based energy systems, Vidal-Amaro and Sheinbaum-Pardo in [24] model the energy transition for Mexico, using EnergyPLAN to implement a Minimum total capacity mix method, but without taking into account the synergies between the sectors.

A main criterion for the integration in this research is a cumulative critical excess electricity produced (CEEP) from both solar and wind power plants. In multi-level scenario approach, different demand response technologies are combined to balance the VRE and then, in level 2 scenario simulation, different options for combined heat and power (CHP) facilities are chosen.

2. METHOD

When all the options of cheap, cost-effective demand response are used, then further increase in penetration of VRE is possible only by storing energy at a higher cost. If the goal is to increase the share of renewables as soon as possible, then the dynamics of construction is limited only to the techno-economic criteria at a given moment and to the investment cycle rate. However, this will eventually lead to the rapid build-up of new sources at the beginning, and later stalling of the sector when saturation occurs. Although this has the advantage for the climate policy position, as this reduces emissions at a higher percentage, from the social welfare position it is necessary to ensure a constant value added of the VRE sector. As the value added in VRE is largely comprised of Capital Expenditures (CAPEX), although in wind power maintenance costs are significant (while other operating costs are negligible, OPEX), to ensure a continuous flow of added value, a continuous flow of investments should be provided. Wind power plants and solar power plants have a typical life time of 20 years, which means that, if one wants to achieve high socioeconomic profit, it can be assumed to install an average of 5% of the technically acceptable VRE share for 20 years on average.

Since a strong investment sector has not yet been developed for solar power, it is possible that it would be beneficial to start at a lower yearly installation rate, and to increase the growth rate later. For this reason, a future relevant year needs to be chosen for calculations, and plan for integration of VRE can be backtracked to the base year. For the purpose of establishing the technical potential for new installations of solar PV, calculation can be based on population, aiming for 10 MW of solar PV installed per 1% of population in the cities and corresponding rooftop area needed to accommodate integrated solar PV installation. The rest (if any) installations will then be implemented as ground-based larger solar PV plants.

The possible integration of VRE into the system was examined using the energy planning model EnergyPLAN, which is already known in the scientific literature and used for the research of the energy system development in many countries [25].

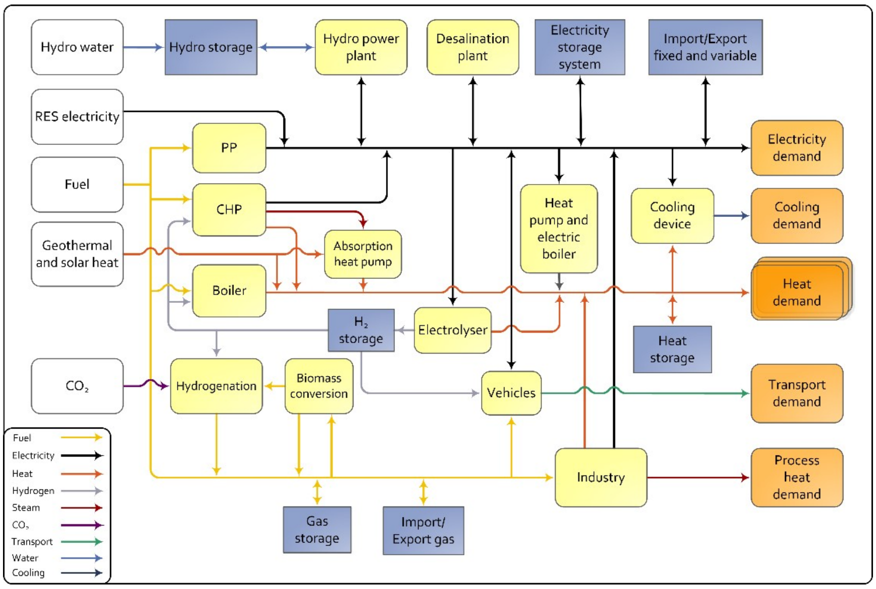


Figure 1 Principal scheme of energy system in EnergyPLAN

First relevant concept, which allows larger integration of energy from VRE, is the flexibility of existing power plants. This is already elaborated in all the research mentioned in the introduction.

For second concept, the approach to modelling investment in demand response technology relies on existing plans and trends in the sectors of centralized heat systems and electrification of transport. For centralized heat systems, assumed development implies that the goal of 40% of district heating systems (DHS) is achieved by 2050 (According to EU budgets under the new heating and cooling strategy, the estimate is that DHS can meet 40-70% of heating demand in Europe). DHS use fuel more efficiently than individual boilers. They can also use different sources at one location (in one plant) and can support the integration of renewable sources by using the surplus of the generated energy from the VRE while simultaneously reducing the consumption of fossil fuels. When considering centralized heat systems, cogeneration systems and their improvement of heat energy conservation technologies are considered in the moments when electricity is cheap (for example, VRE energy, which is a critical surplus at a given time). The third major energy-efficient technology concept (electrified transport connected to the grid at times when the vehicles are parked) is used to integrate increased share of renewable energy sources through storage and balancing, reducing CEEP in such way. Electric vehicles can be present in several technological forms: hybrid vehicles, hybrid vehicles with a network connection, electric vehicles with dumb charging, smart electric vehicles and smart electric vehicles with energy discharge to the network (V2G concept). Dumb charging can be a technology that increases electricity demand in the period when it is reduced, but renewable energy sources are abundant (for example: wind at night) and in that sense helps to integrate VRE while reducing the consumption of fossil fuels in transport. However, such a solution is not suitable for a higher share of VRE in the system. Smart charging and discharging (V2G) solutions are in this situation a key technology for integrating high share of VRE, because in a much larger number of hours, when EVs are not in traffic (most of the day), they serve as a fast response battery. The connection to the grid can be achieved by a slow charger at home (3.5 kW per vehicle), which would not have a significant impact on increasing infrastructure costs. Other chargers with higher power and charging speeds will have to be built so that vehicles can be charged and connected to the network, for example in public garages or parking places near the workplace. A key parameter for determining the economic justification of this level of integration of VRE is the critical excess of electricity produced from VRE technologies, which according to considerations from relevant literature can be assumed up to 5% [26]. The price of photovoltaic systems has dropped below 40 c€/watt (2017), in last tenders even below 20 c€/watt of installed power and the trend continues so far, with LCOE between 0.18 €/kWh and 0.22 €/kWh in 2010, falling to between 0.05 €/kWh and 0.08 €/kWh in 2020, according to European Photovoltaic Industry Association. There are already prices from 0.20 €/kWh to 0.06 €/kWh achieved in tenders, so the price is falling faster than expected, since these numbers were projected for 2030. Since the price of the PV panel technology, especially integrated in the roofs of residential buildings, makes a significantly smaller share of the final investment, the cost of laying and designing makes an even bigger share and generates workplaces locally.

Using this concepts, and additional relevant concept of flexibility of power plant (PP) and CHP operation, scenario approach is used to simulate various levels of integration of these demand response technologies, which in turn enable larger integration of additional VRE without crossing the key parameter limit.

Two levels of the scenario approach are:

1. Building scenarios with different use of demand response technologies, according to increasing cost of such technologies. From these scenarios, one which achieves the VRE integration goals with the smallest instalments of demand response technologies is further discussed on second level.
2. For the chosen scenario from previous stage, plans for further instalments of CHP and PP units are discussed in terms of their economic feasibility, expressed through full hours of operation in one year, and their sensitivity to import.

Further considerations after the second level of scenario approach include sensitivity factors and the environmental implications of second level scenarios. The sensitivity factors such as precision of VRE production predictions (factors like geographical distributions and technology advances), greenhouse gas (GHG) emissions originating from imported energy and market prices are to be analysed. To explore the long term strategic choices, following the same method as described above as an introduction to level 1, scenarios for transition to a system based on renewable energy sources can be developed.

3. CASE STUDY AND RESULTS

The reference scenario model of Croatia in 2014 was verified by comparing the known data from [27], [28], and [29] for the Croatian energy system in corresponding year. After aligning the scenario with the results of the recent proposal of Strategy of Low-carbon development of Croatia until 2030, with a view towards 2050 (NUR – low-carbon business as usual scenario) [30] for 2014, the focus of modelling has become the year 2030, for which further elaboration has been made. The Proposal of Strategy of Low-carbon development of Croatia until 2030, with a view towards 2050 discusses three scenarios: business as usual (NUR), gradual transition (NU1) and strong transition (NU2). Scenarios will be mentioned in context of calculations during the further elaboration of results. Data for base year (2014) and business as usual scenario (NUR) and gradual transition is given in Table 1.

Table 1 Installed capacities in base year and in year 2030 according to [30]

NUR	2014	2030 (NUR)
Total installed capacity (MW)	4,469	6,732
Nuclear PP (MW)	348	348
Gas PP (MW)	1,140	1,225
Coal PP (MW)	330	210
Fuel oil PP (MW)	320	0
Hydro PP (MW)	2,095	2,784
Wind PP (MW)	340	1,200
Solar PV PP (MW)	33	120
Biomass and waste PP (MW)	8	135
Biogas and landfill gas PP (MW)	17	80
Geothermal PP (MW)	0	30
Small hydro PP (MW)	33	100

The data from table 1 is chosen from the business-as-usual scenario in order to give the method for approaching the formulation of further scenarios, such as NU1 and NU2, which can later be found in public reports and data. Once such scenarios of development are formulated, the decision regarding the installations in second level of the approach presented in this paper was already made.

In order to realize the possibility of significant increase in plans for 2030, in particular for the case of increasing the planned installations of solar PV power plants, the technical potential of solar energy in Croatia is elaborated in short. Croatia has a significant potential for use of solar energy due to the geographical location and climate. Solar irradiation, presented in Figure 2, indicates the regions in Croatia, which would be suitable for exploitation of solar energy on larger scale. Being predominately in coastal area, such regions would need to focus on implementing solar PV technology. This focus can be twofold: supporting the installations of building-integrated solar PV or securing the locations for ground-based solar PV power plants. Former should come first, since it achieves different socio-economic benefits, such as continuous “green” employment needed for installation of numerous systems and local reduction of consumption (“prosumers” concept).

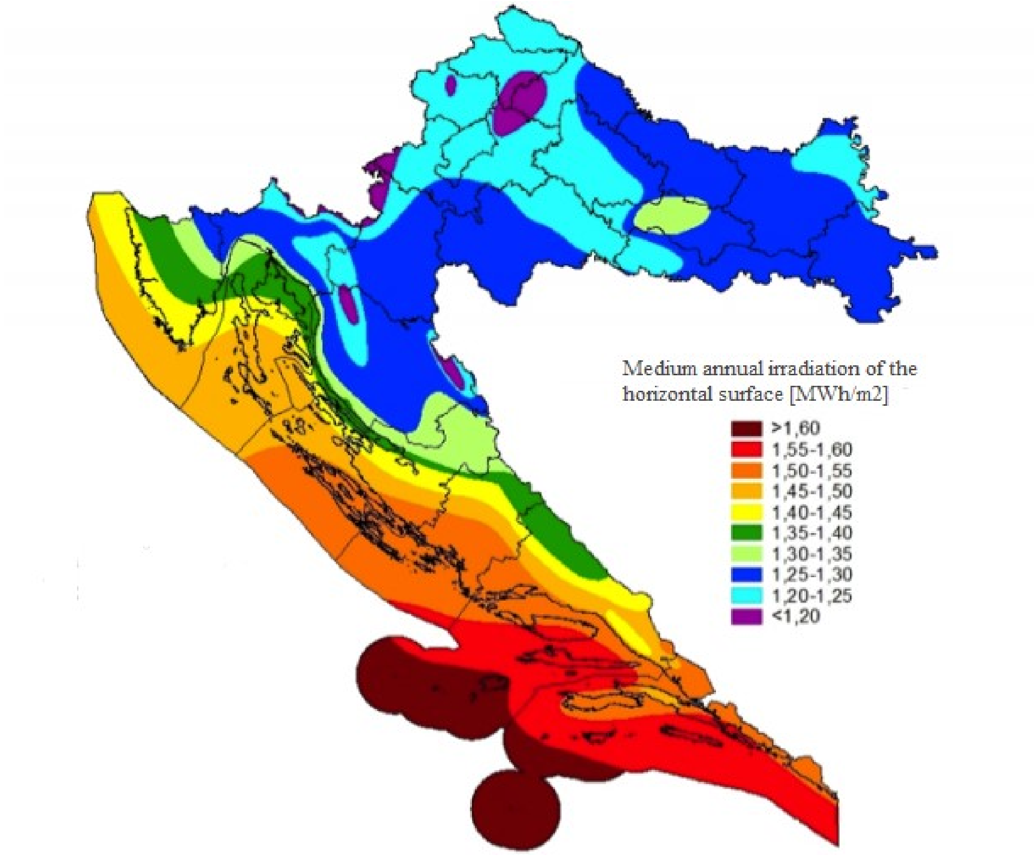


Figure 2 Medium annual irradiation on the horizontal surface in Croatia [31]

In Table 2 Solar irradiation and estimated production for characteristic cities solar irradiation for some characteristic cities in Croatia is given and the specific production from solar PV (on 10 kW) basis estimated by [32].

Table 2 Solar irradiation and estimated production for characteristic cities [32],[33],[34]

Characteristic cities	Irradiation on optimal angle [kWh/m^2]	Specific produced energy per year [kWh/kW]
Hvar	1780	1481
Split	1720	1431
Dubrovnik	1720	1431
Zadar	1660	1381
Pula	1580	1315

Rijeka	1470	1223
Zagreb	1370	1140
Osijek	1370	1140
Sisak	1350	1123
Varaždin	1330	1107

Demonstrated potential can be exploited if there is enough rooftop area in the cities. In Table 3, this area is calculated and compared to population in Croatia. On the basis of calculation, with 6.25 m^2/kW we conclude that at least 1000 MW of solar PV can be installed as building integrated installations, while, in order to reach goal of 2000 MW in 2030, the rest of the installations would be ground-based, aiming for the sub-urban areas of the coastal regions in Croatia.

Table 3 Estimation of available area for integrated solar power in Croatian cities in 2030

City	Percentage in Croatian population	PV [MW]	Surface for panels [m^2]
Zagreb	38.10%	381	2,383,811
Split	8.06%	81	504,274
Rijeka	6.19%	62	387,388
Osijek	4.06%	41	253,777
Zadar	3.45%	34	215,658
Pula	2.77%	28	173,381
Sisak	2.14%	21	133,738
Varaždin	1.87%	19	117,193
Dubrovnik	1.37%	14	85,797
Overall (on sample)	68.01%	680	4,255,018

To use surplus electricity produced in centralized heat systems using electric heaters and hot water tanks, it is calculated with equipping the largest centralized heat system in Croatia with tanks equivalent to that already built in CHP plant TE-TO Zagreb, 750 MWh of thermal tank capacity. By building such a system in the other two largest thermal power plants – CHP plant EL-TO Zagreb and CHP plant TE-TO Osijek, the total tank capacity would reach 2.25 GWh, with the electric heaters' installed power of 250 MW. Adequate heat tanks can be added to all sites that have the need for heat energy and, above all, for flexible cogeneration plants on gas or biomass. With all the other parameters equal to the reference scenario, for the integration of additional 1750 MW from solar PV panels (total 2000 MW in 2030), there should be available over 300 000 electric vehicles with unchanged integration of wind power plants with a total capacity of 1200 MW in 2030. Calculation has been conducted through scenario approach, with varying system flexibility and the level of development of technologies such as the integration of electric vehicles and heat tanks using the surpluses of electricity produced in 2030 (Figure 3).

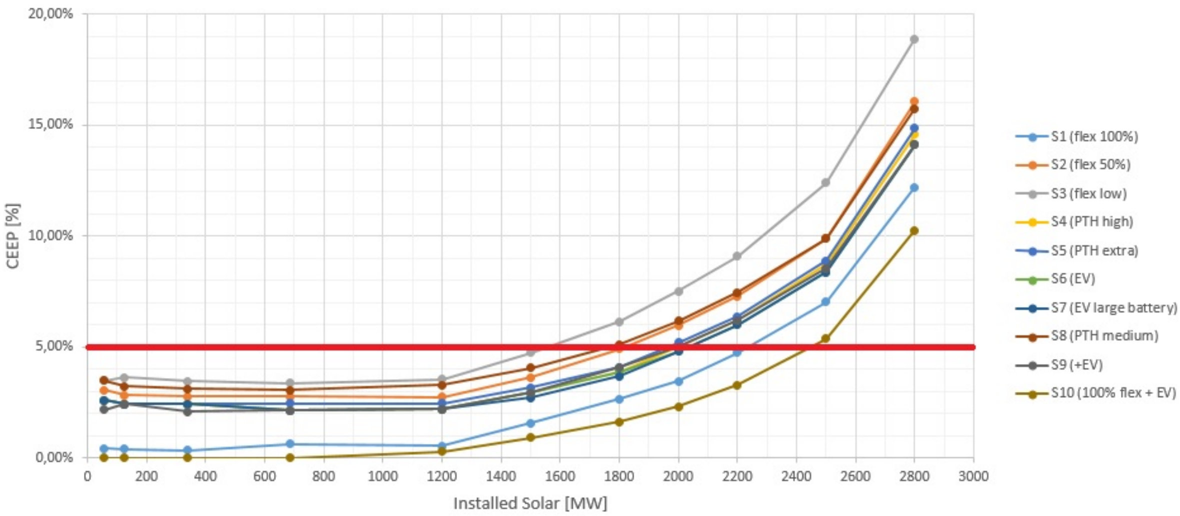


Figure 3 Results of different scenarios compared to the 5% CEEP limit

Input values for all scenarios are given in detail in the Table 4. It is evident that it is possible to integrate, with the input values above, 2000 MW solar PV and 1200 MW wind power without exceeding the techno-economically acceptable critical excess of the electricity produced. Calculating with an annual installment rate of 100 MW, in 2030 the installed solar power would be 1300 MW. For such a level of integration of this technology, the NU2 scenario [30], which envisages 150,000 electric vehicles (with characteristics described above), would still provide an acceptable rate of curtailment below 5% of the energy produced from VRE.

For further analysis, scenario S7 which integrates 2000 MW of solar PV in the year 2030 is chosen. It is illustrated by Figure 4.

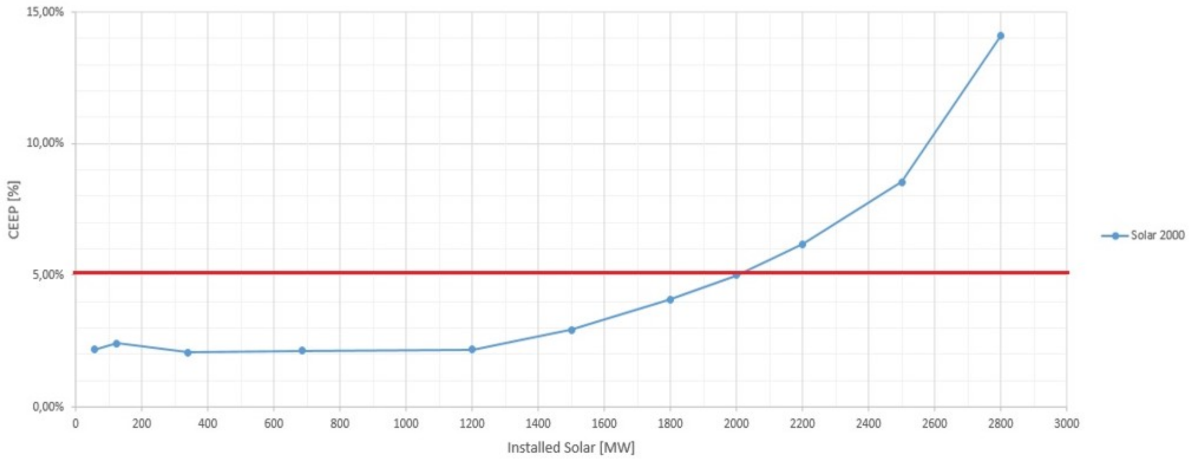


Figure 4 Chosen scenario for fossil fuel technologies feasibility study

Different scenarios for future PP and CHP blocks are given in Table 5.

Table 4 Input data for all scenarios

Year 2030	S1	S2	S3	S4	S5	S6	S7	S8	S9	S10
Minimum CHP [MW]	0	0	150	0	0	0	0	0	0	0
Minimum PP [MW]	0	200	200	200	200	200	200	200	200	0
PTH Storage [GWh]	2.25	2.25	2.25	4.5	10	2.25	2.25	2.25	2.25	10
HP COP	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5
HP [MW]	90	90	90	180	180	180	180	100	100	100
EV consumption [TWh]	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.72	0.72
EV battery size [kWh]	15	15	15	15	15	15	20	20	20	20

With the increased share of the installed VRE power, the question is how many working hours remain for the affordable operation of condensing and cogeneration plants and which blocks need to be built in order to meet the electricity demand. Considering the three scenarios, firstly without import (with index 1) , and then with 30% net import-related proportional imports (with index 2), the number of working hours for cogeneration plants and condensing plants on full load ("full load hours", FLH) was calculated.

Table 5 Different options for future CHP blocks

2030		Sisak C	TE-TO Zagreb	EL-TO Zagreb	Osijek 500	CHP total
A	MW_{el}	230	320	180	450	1180
	MW_t	50	366	352	160	928
B	MW_{el}	230	320	48	200	798
	MW_t	50	366	232	110	758
C	MW_{el}	230	320	180	200	930
	MW_t	50	366	352	110	878

The first scenario, A, follows the plans for the introduction of new plants into the system according to NUR, including CCGT Osijek 500, CCGT EL-TO Zagreb and Sisak C in operation. Scenario B is a scenario with minimal construction, without CCCGT EL-TO Zagreb, and with CCGT Osijek in reduced power (200 MWe + 110 MWt). Scenario C is a compromise scenario with CCGT EL-TO Zagreb (this is a new 132 MWe + 120 MWt block) and a reduced block of CCGT Osijek. In all scenarios, Coal PP Plomin 2 runs inflexible (minimum 200 MW), Nuclear PP Krško runs all the time. Full capacity hours are calculated from electricity produced (result of EnergyPLAN simulation – differentiates between PP and CHP) and rated capacity of CHP and PP blocks, which is represented in Table 6.

Table 6 Results of second level scenario approach - FLHs of CHP facilities

	A1	A2	B1	B2	C1	C2
CEEP [TWh]	0.25	0.11	0.25	0.24	0.25	0.12
Import [TWh]		-5.44		-5.44		-5.44
FLHe CHP	2946	1449	2946	2581	2946	1992
FLHe PP	1888	1526	1888	2302	1888	2249

The results indicate that the construction of larger new capacities would be unprofitable in terms of the number of working hours (FLHs - full capacity hours in a year) that such plants can achieve. Scenarios that include the assumption of system operation without import are in fact always the same, because they have to supply the needs, so the construction of smaller capacities cannot be discussed in those scenarios. In order to achieve the full supply of the consumption, it would be necessary to build plants that would work very few hours per year, while the number of operating hours according to NUR is shown. Scenarios with index "2" include imports and show that at minimum construction of new plants, existing condensing and cogeneration plants can remain in operation for a longer number of hours, while the new one would be unprofitable, with a workload less than 2000 hours.

Also, less hours of operation on fossil fuels means less emissions of GHG, which is illustrated in Figure 5.

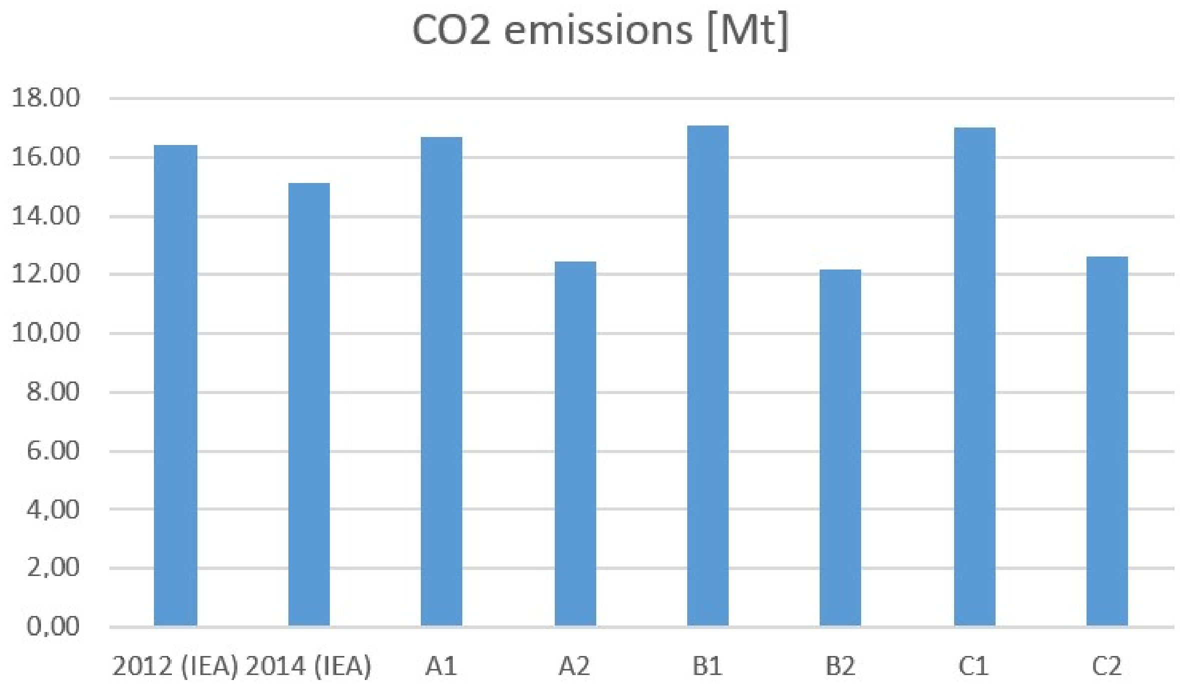


Figure 5 Emissions of GHG for all scenarios

4. DISCUSSION

As it can be concluded from the two steps of the method, applied on the case study, first level's scenario S7 and second level's scenario B2 can be chosen for further discussion regarding the long term planning of the system, in order to better understand the implications of choices resulting from described method. By demonstrating the appropriate synergetic effect of combining increase in VRE installations and storage and demand response technologies, the method aims to prevent the lock-in effect of sub-optimal choices in fossil fuel capacities expansion. In level 2 the influence of harmonious implementation of VRE and demand technologies on potential full load hours of new power plants and cogeneration plants is presented. After the choice in scenario B2 was made about capacities expansion, further models can be created to investigate the path towards an energy system based on renewable energy sources and demand response technologies.

For the presented case study, data for such scenario, which would achieve zero carbon energy system based on locally available VRE is given in table 7 for year 2040 and table 8 for year 2050.

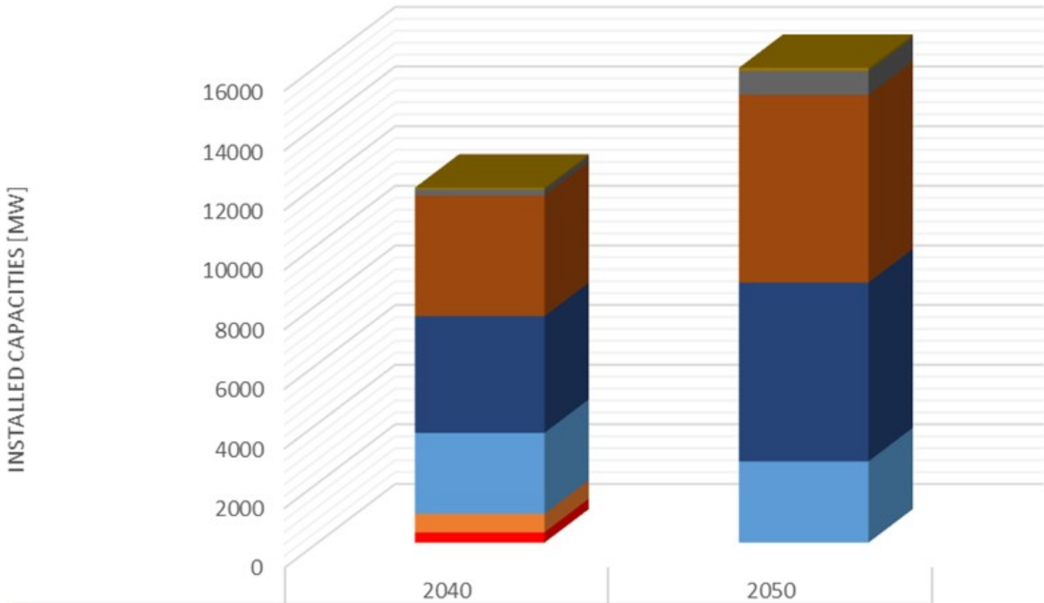
Table 7 Fuel consumption in 2040

Fuel consumption in the transition scenario in year 2040 [TWh]					
Households		Transport		Industry and other	
Coal	0	Jet fuel	0.83	Coal	0
Oil	0	Diesel	2	Oil	0
Natural gas	0.8	Gasoline	0.83	Natural gas	1.15
Biomass	4.11	Natural gas	0.02	Biomass	1.29
Heat	4.33	LPG	2.77		
Electricity	1.44	Electricity	4.82		
Solar heat	3.45	Biofuels	4.77		

Table 8 Fuel consumption in 2050

Fuel consumption in the transition scenario in year 2050 [TWh]					
Households		Transport		Industry and other	
Coal	0	Jet fuel	0	Coal	0
Oil	0	Diesel	0	Oil	0
Natural gas	0	Gasoline	0	Natural gas	2
Biomass	1.2	Natural gas	0.05	Biomass	0.9
Heat	3.09	LPG	0		
Electricity	1.03	Electricity	6		
Solar heat	2.79	Biofuels	5.9		

Installed capacities of production units are given in Figure 6. Additionally, EV batteries capacities are assumed to amount to 60 kWh per vehicle in years 2040 and 2050, while V2G connection amounts to 4400 MW in 2040 and 5400 MW in 2050.

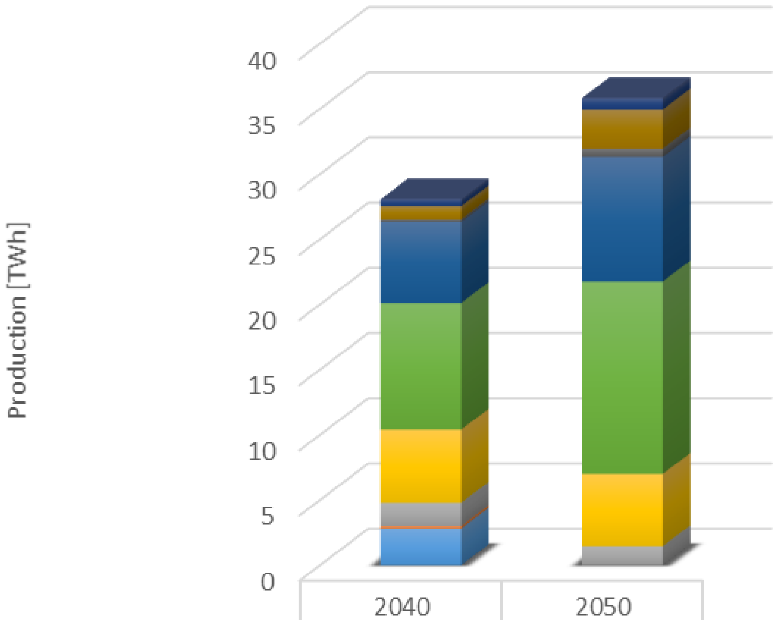


	2040	2050
Geothermal	60	100
Biomass and biogas CHP	200	800
Solar PP	4047	6300
Wind PP	3918	6000
Hydro PP	2713	2726
Coal PP	0	0
Gas PP/CHP	620	0
Nuclear PP	348	0

Figure 6 Installed capacities for energy production in 2040 and 2050

Due to avoiding the lock-in with higher installations of fossil fuels, future scenarios can rely on the homogenous implementation of VRE power plants and demand response technologies. In scenarios in 2040 and 2050, model relies on V2G technology to provide balancing. Calculated on a case of hydrologically poor year, results in terms of energy produced are given in Figure 7.

It is important to notice that discharge from the batteries of electric vehicles becomes a new, flexible "power plant", which returns to the grid more energy then it was produced from nuclear power plant in previous years. Taking this into account, the method proposed by this paper becomes clear and it should be considered as the possible approach to avoid lock-in situations with investments in technologies which will have dubious long-term competitiveness. The method, demonstrated on the case study of Croatia, offers clear guidance on achieving homogenous implementation of VRE and demand response technologies as the most sustainable combination and supports it with long-term scenarios for planning of the energy system development.



	2040	2050
Geothermal	0.53	0.88
EV Batteries	1	3
Biomass and biogas	0.21	0.65
Solar PP	6.21	9.54
Wind PP	9.71	14.76
Hydro PP	5.61	5.54
Cogeneration	1.79	1.46
Condensing (coal and gas)	0.18	0
Nuclear	2.82	0

Figure 7 Production from all technologies in 2040 and 2050

5. CONCLUSION

The price of VRE falls significantly every year, often reaching half of the previous value. Consequently, it can be expected that these technologies will be, in the near future, economically most cost-effective solution on which future low-carbon energy systems should be based. To integrate a larger share of VRE into the energy system, this EES transition needs to be followed by the installation of other technologies that integrate the sectors and achieve synergies. These are energy-efficient consumption technologies that use excess energy produced and VRE for water heating and power-to-heat storage and energy storage in vehicle-to-grid vehicle (V2G) batteries. These technologies are accompanied by efforts to reduce greenhouse gas emissions in other sectors and jointly achieve greater integration of VRE and reduction of polluting emissions. Power to heat technology is related to increasing the share of centralized heat systems, powered by cogeneration plants, to meet the needs for heat energy in households. Main support for integration of VRE, demonstrated by scenarios, is the combination of flexible operation and integration of electricity production and electrified transport system through V2G technology. In scenario S1, 100% flexible operation of PP and CHP, combined with low level of PTH and V2G contribution provided for integration of 2200 MW of solar PV, while in scenario S10, higher level of V2G enabled integration of 2450 MW of solar PV. For scenario S7, which is characterized by larger EV batteries on disposal for V2G, enabling higher consumption of CEEP controlled by smart charging and discharging to shift the loads and balance the VRE, perspective for operation of new PP and CHP facilities was examined. The higher VRE integration will be achieved, more limited number of working hours remains for new CHP installations, with scenario B2 providing the most opportunities for affordable operation of PP and CHP, since this is scenario with lowest installed capacity of new facilities. Implied reduced number of operating hours for fossil fuel powered PP and CHP causes corresponding reduction in GHG emissions. When discussing future scenarios and the energy transition towards an energy system based on VRE and demand response technologies, the approach presented in the paper gives a valuable initial insight for avoiding the lock-in with excess capacities with dubious long-term competitiveness. Further work should address the cost-effectiveness of demand response technologies and further improvements in context of calculating emissions from CHP and PP units and influence of market prices on feasibility of CHP and PP operation.

6. ACKNOWLEDGEMENTS

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PAPER 3

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

Antun Pfeifer [a,*], Luka Herc [a], Ilija Batas Bjelić [b], Neven Duić [a]

[a] University of Zagreb, Faculty of Mechanical Engineering and Naval Architecture, Zagreb, Croatia
[b] Institute of Technical Sciences of Serbian Academy of Sciences and Arts, Belgrade, Serbia

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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.

* Corresponding author.
E-mail address: antun.pfeifer@fsb.hr (A. Pfeifer).

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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

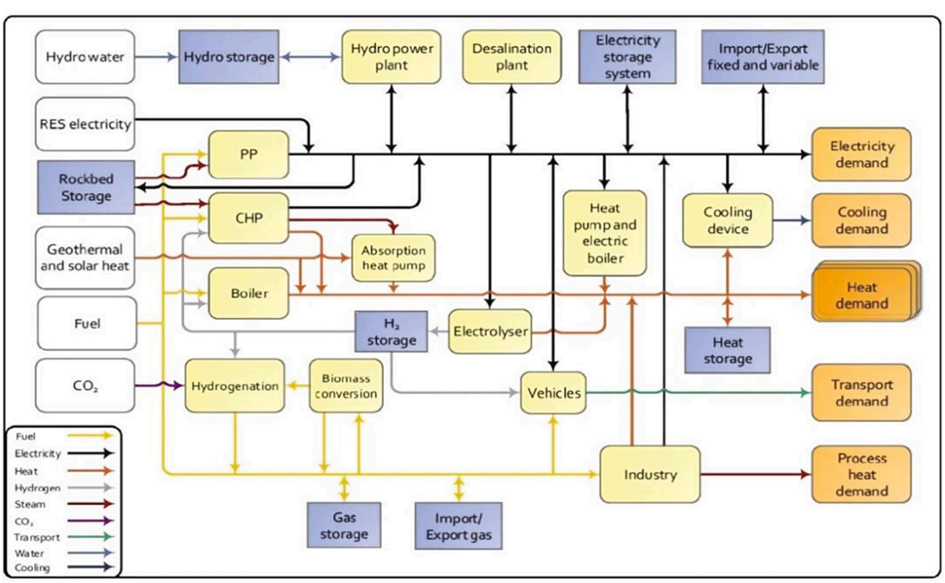

Fig. 1. Schematic diagram of the EnergyPLAN model [42].

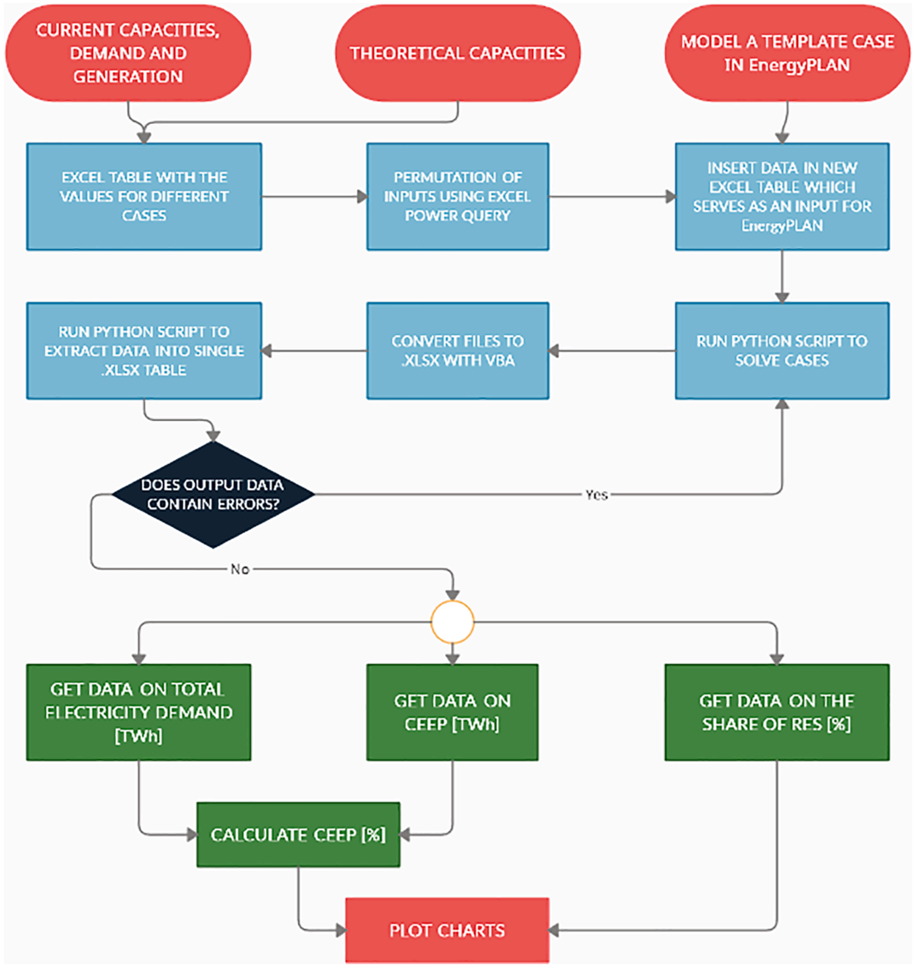

Fig. 2. Flow chart of the proposed method.

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))

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

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

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*

$\boldsymbol{n}$ - 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.

$$N = n + k \quad (3)$$

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

$$\boldsymbol{F}_{s,i} \stackrel{\text{def}}{=} (F_1, F_2, \cdots, F_m) \quad (4)$$

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:

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

$FV_{i,j,s}$ – 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

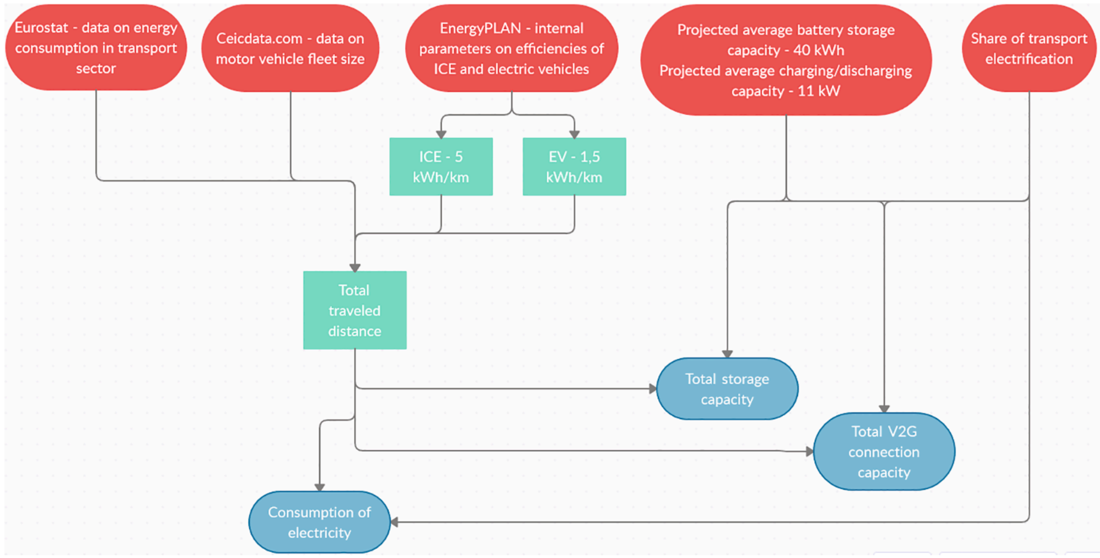

Fig. 3. Flow chart of estimation of energy consumption in transport sector and the parameters of V2G.

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

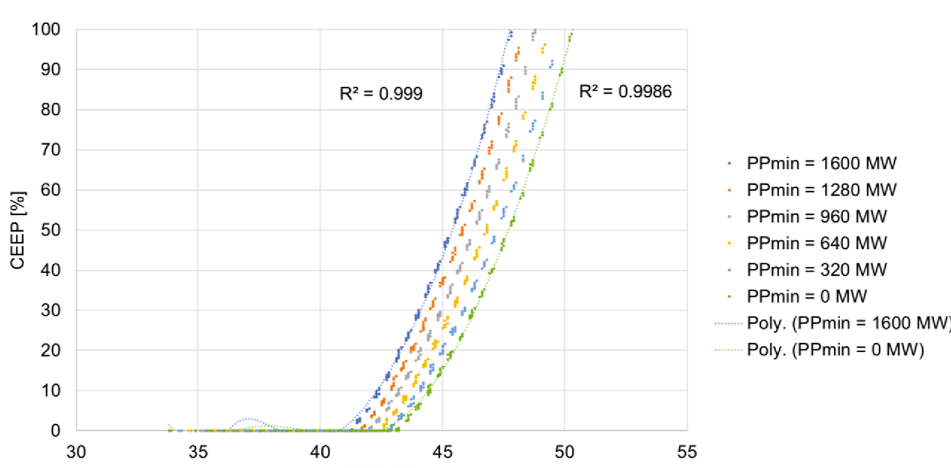

Fig. 4. Thermal power plant flexibility.

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.

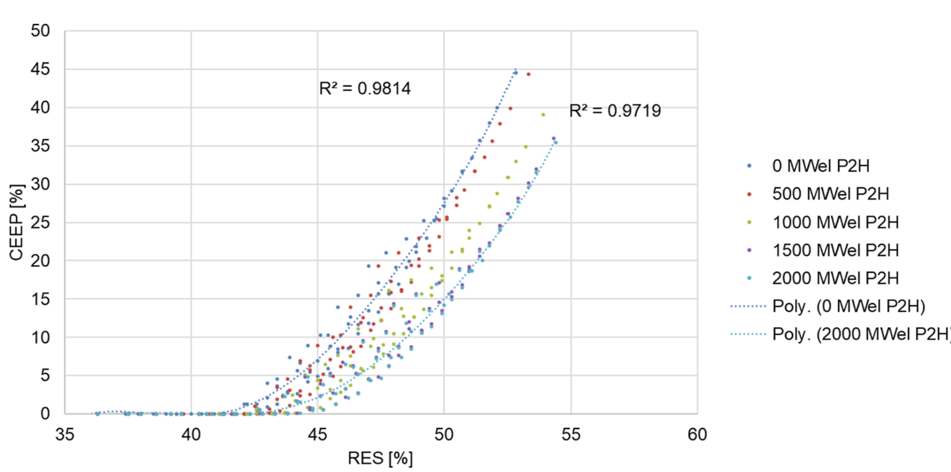

Fig. 5. Power to heat.

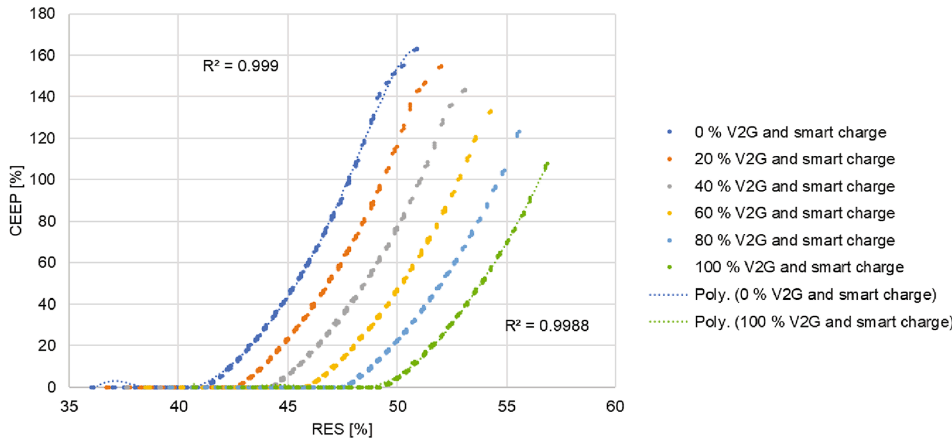

Fig. 6. Vehicle to grid.

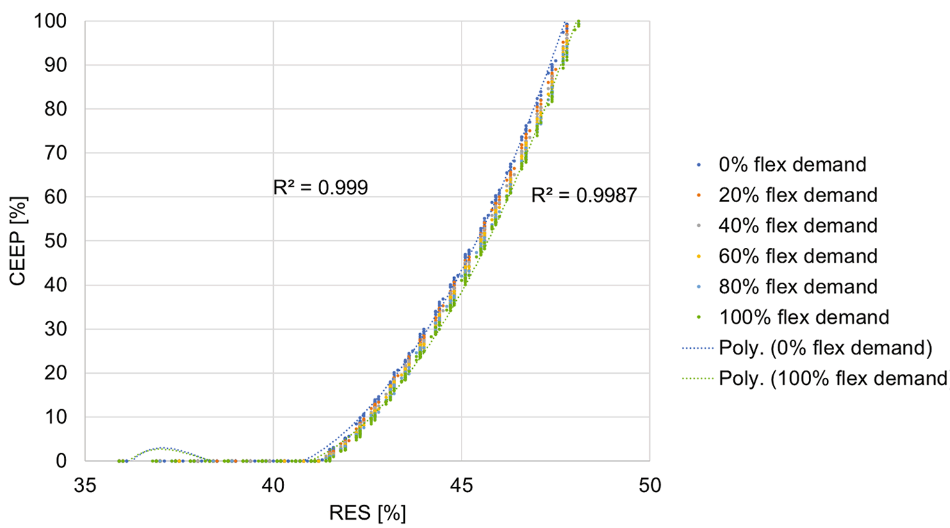

Fig. 7. Flexible demand.

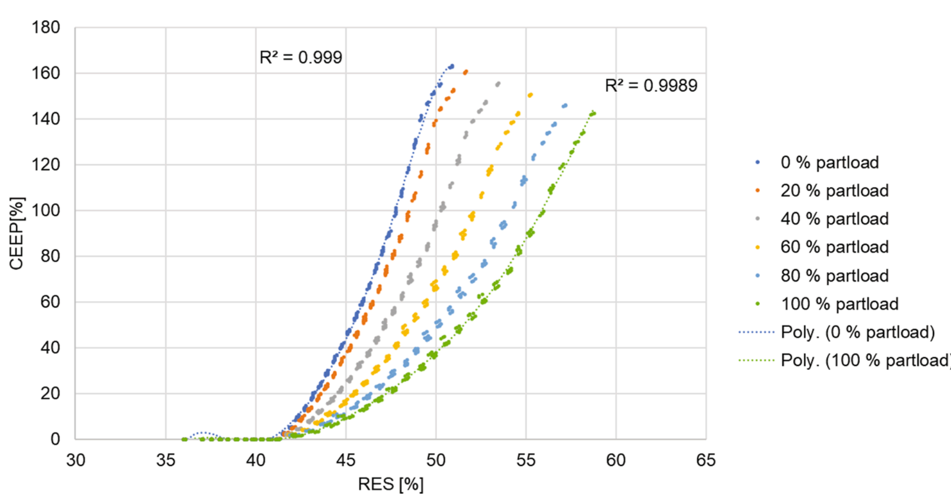

Fig. 8. Results for flexible operation of nuclear power plant.

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

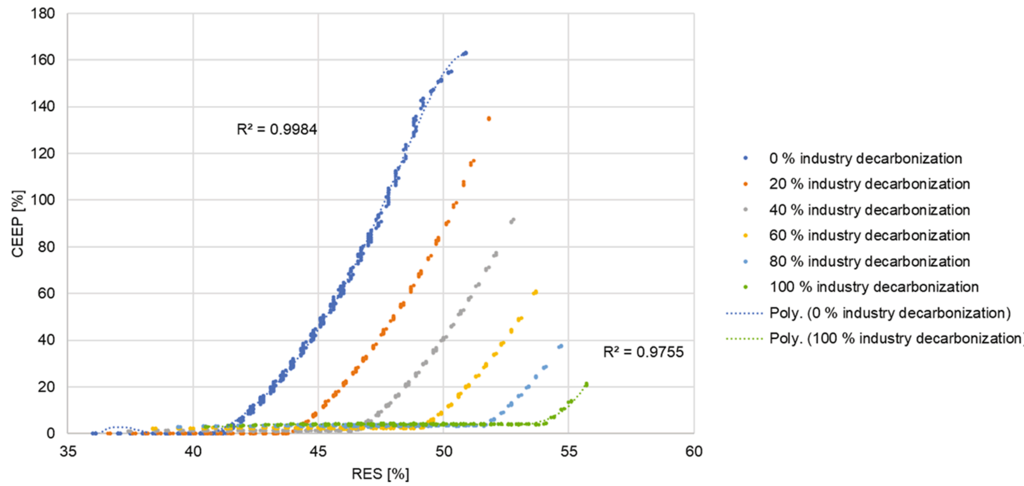

Fig. 9. Results for industry decarbonization.

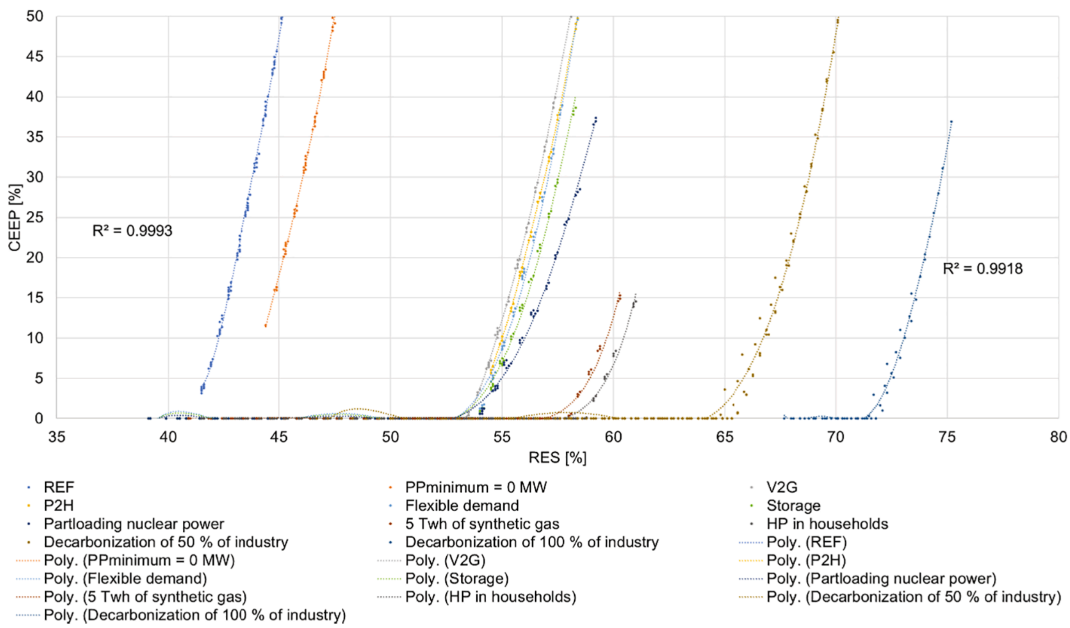

Fig. 10. Aggregated results.

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

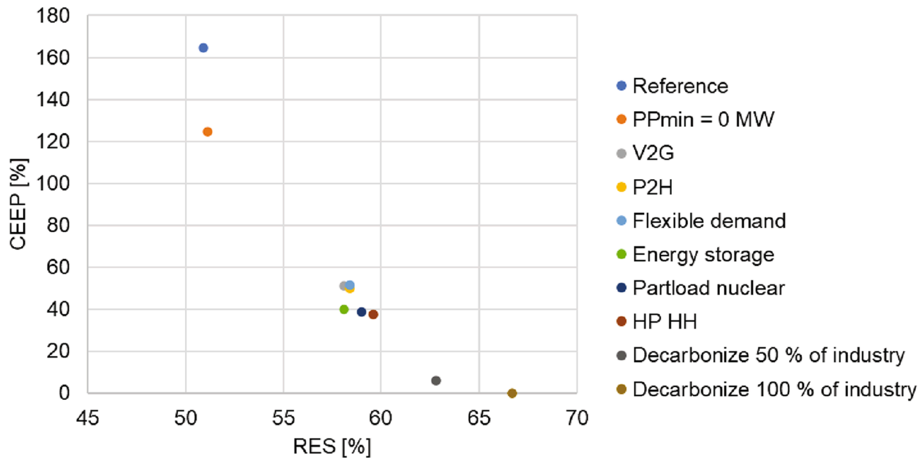

Fig. 11. Results for CEEP at wind = 20,000 MW, PV = 20,000 MW.

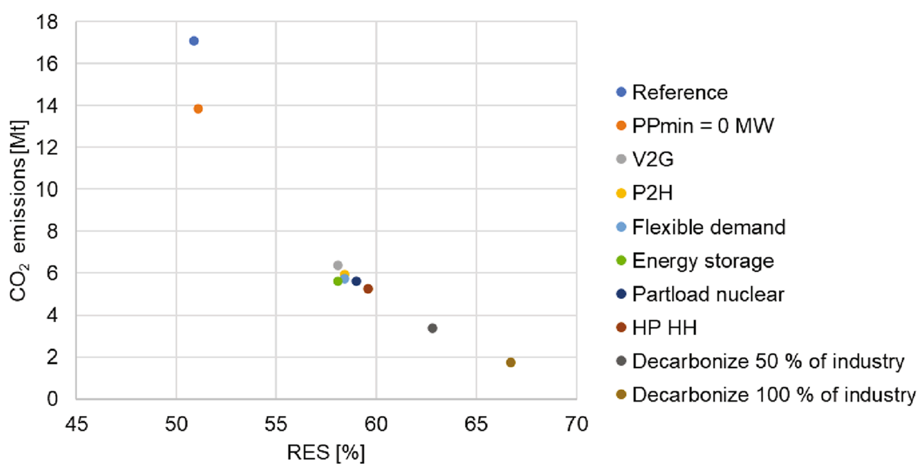

Fig. 12. Results for CO_2 at wind = 20,000 MW, PV = 20,000 MW.

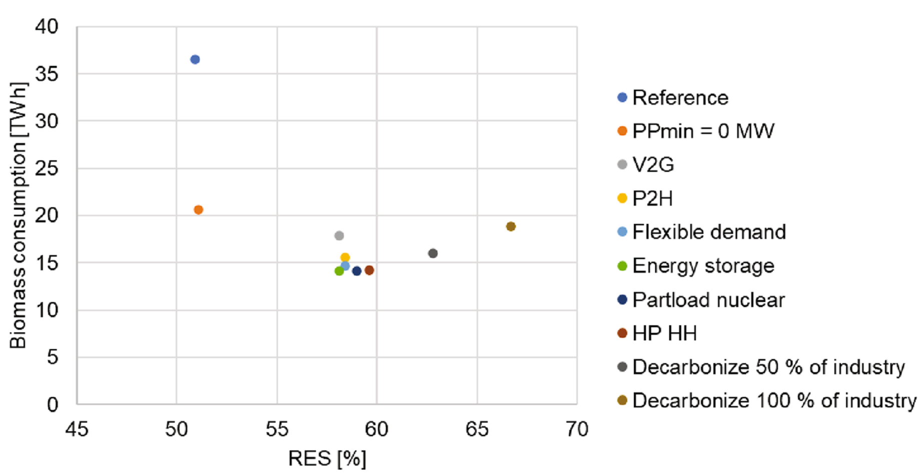

Fig. 13. Results for Biomass consumption at wind = 20,000 MW, PV = 20,000 MW.

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

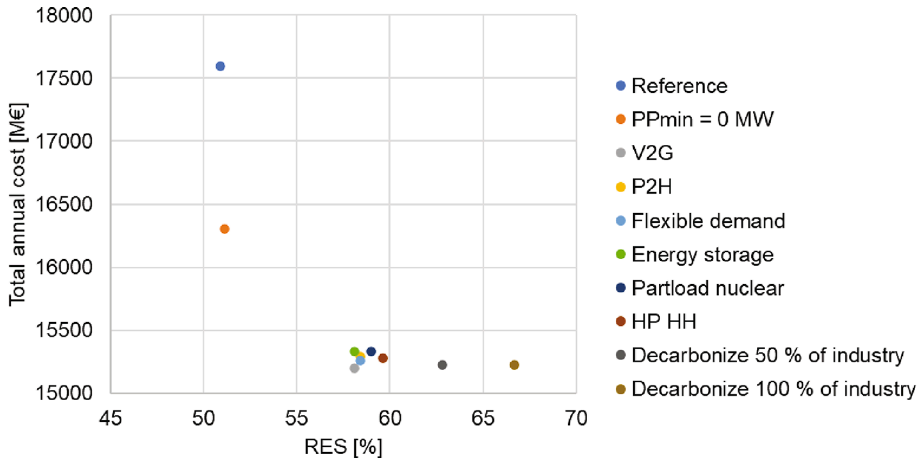

Fig. 14. Results for Total annual cost at wind = 20,000 MW, PV = 20,000 MW.

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

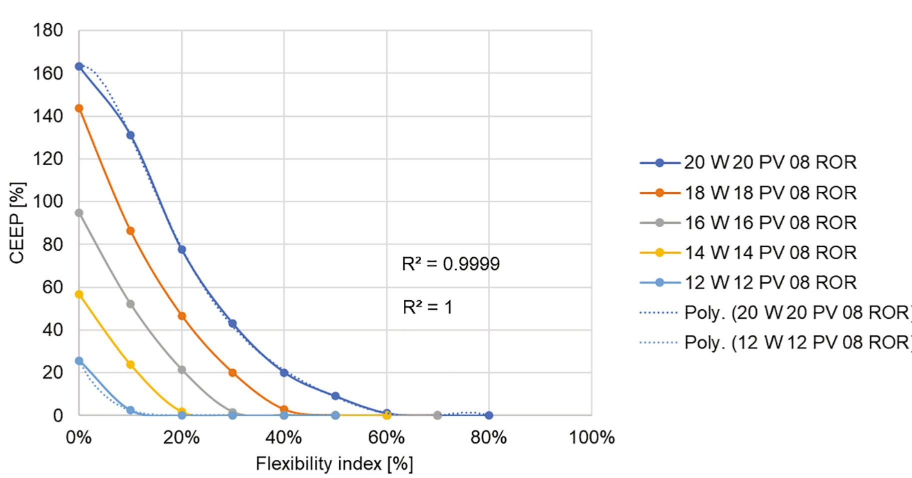

Fig. 15. Relation of CEEP and flexibility index.

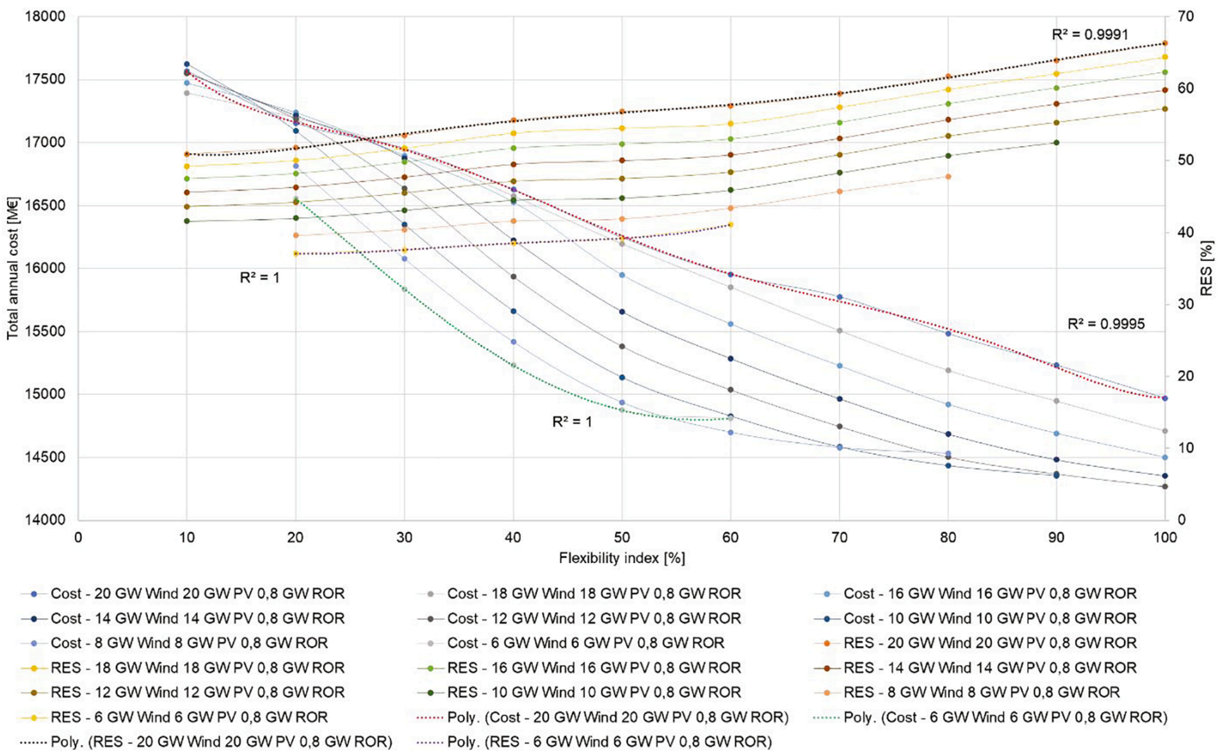

Fig. 16. Relation of Total annual cost and flexibility index.

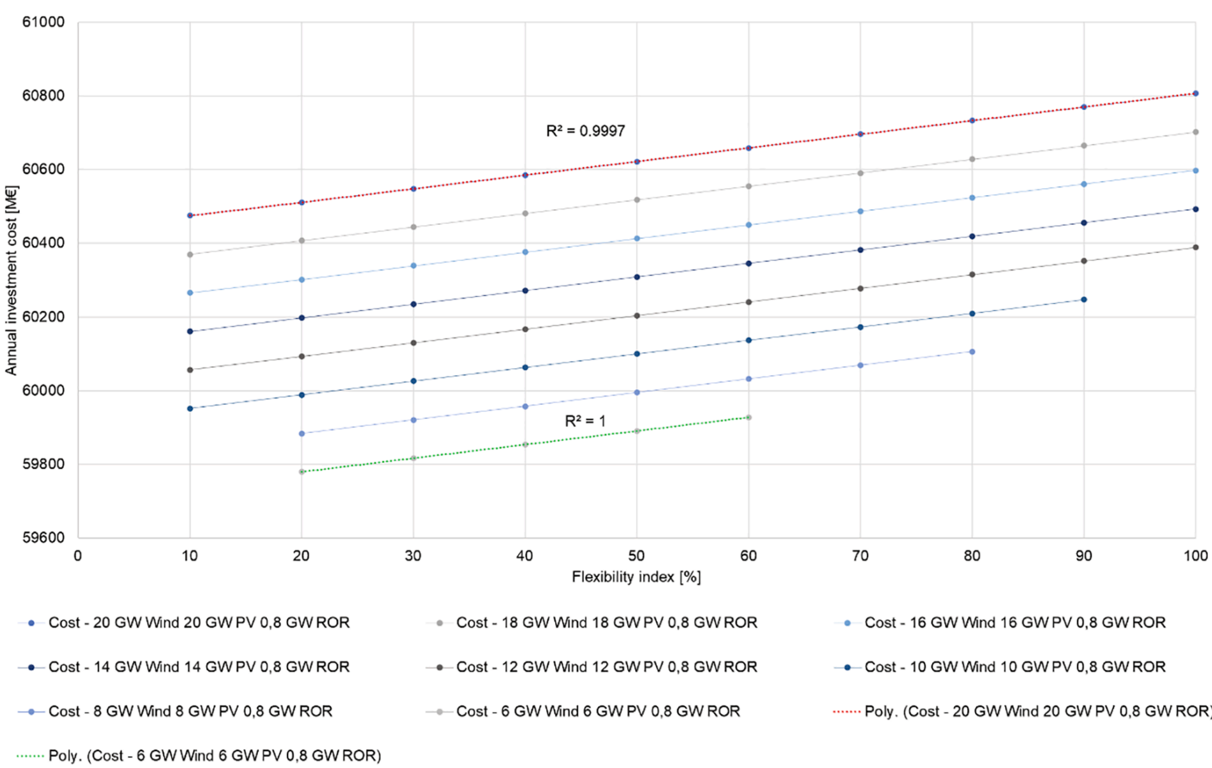

Fig. 17. Relation of Annual investment and flexibility indicator.

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

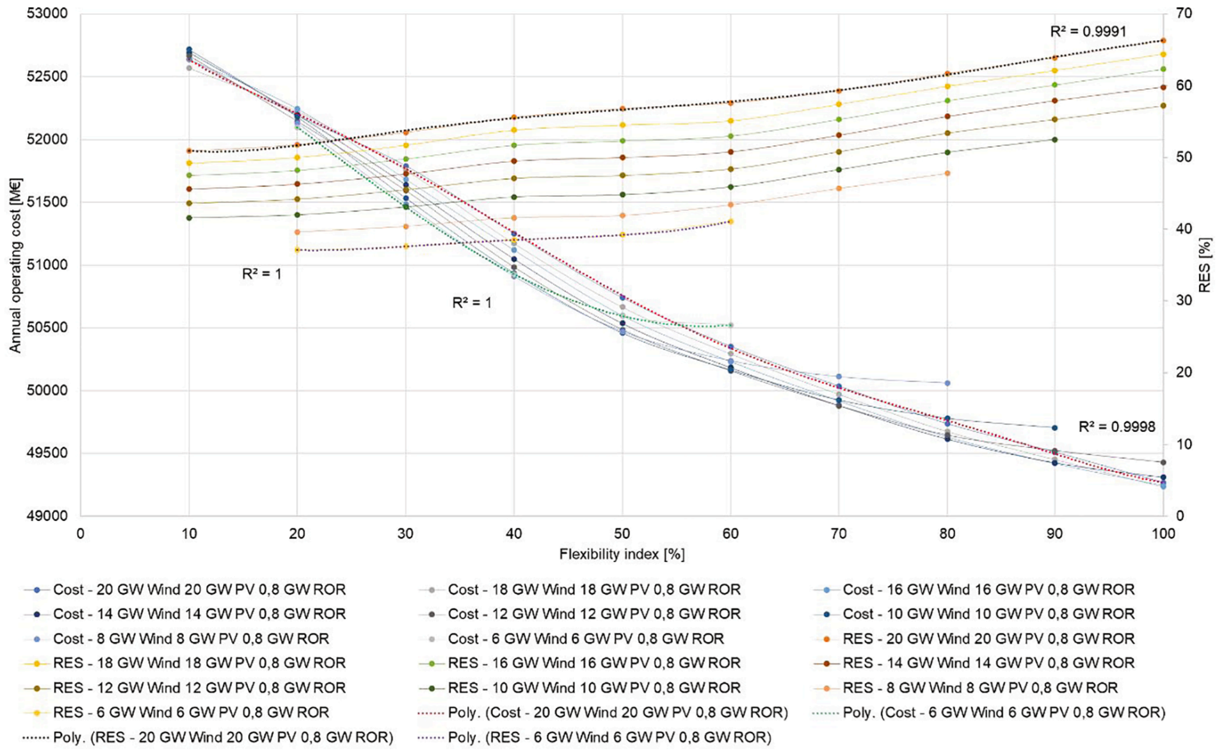

Fig. 18. Operating cost.

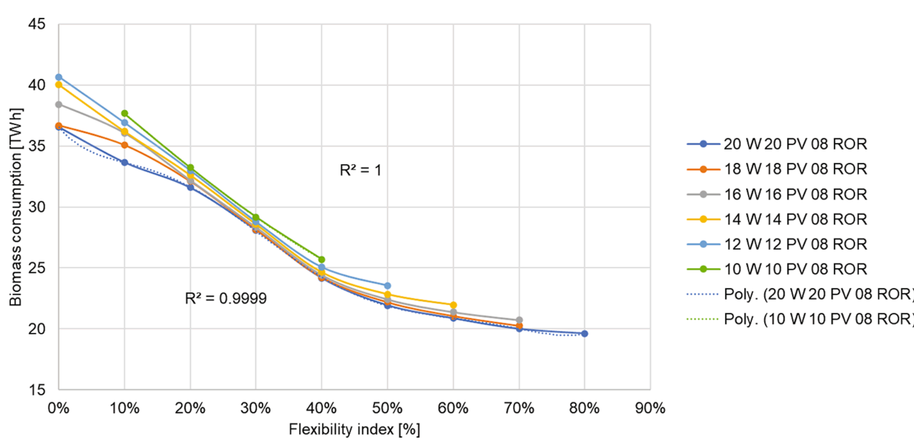

Fig. 19. Relation of Biomass consumption and flexibility index.

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,

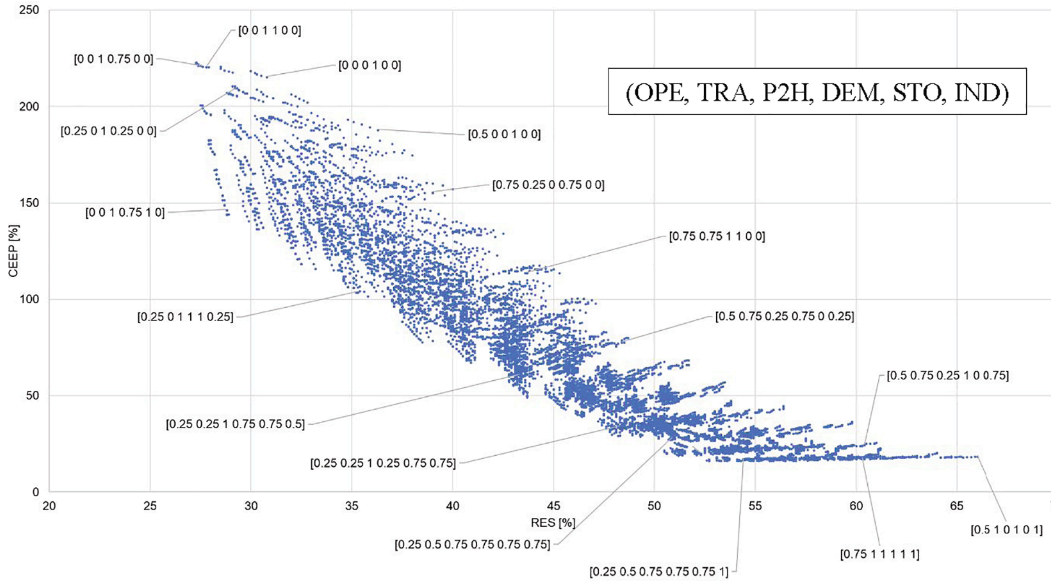

Fig. 20. Relation of CEEP, share of RES and distribution of some of the cases with their flexibility vector values (OPE, TRA, P2H, DEM, STO, IND).

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

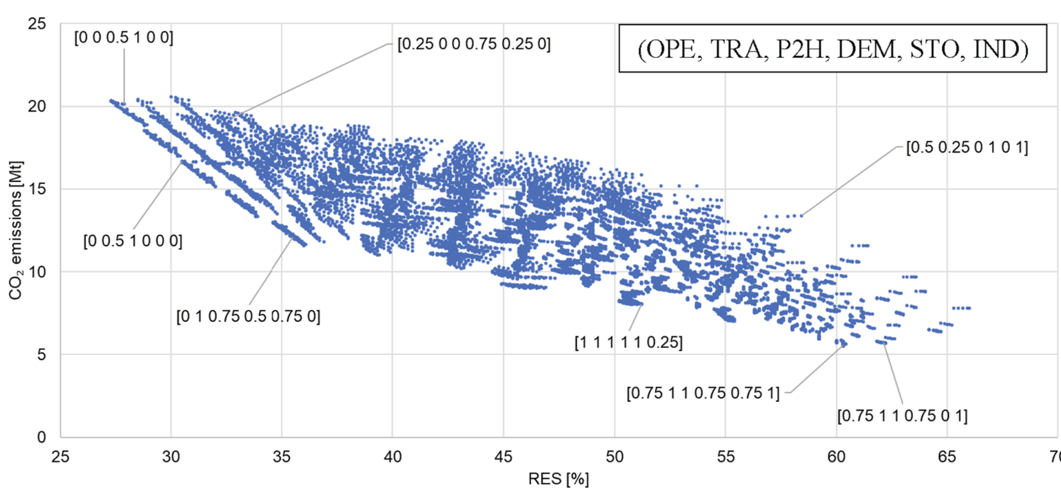

Fig. 21. Values of flexibility vector with relation to the share of RES and CO_2 emissions.

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

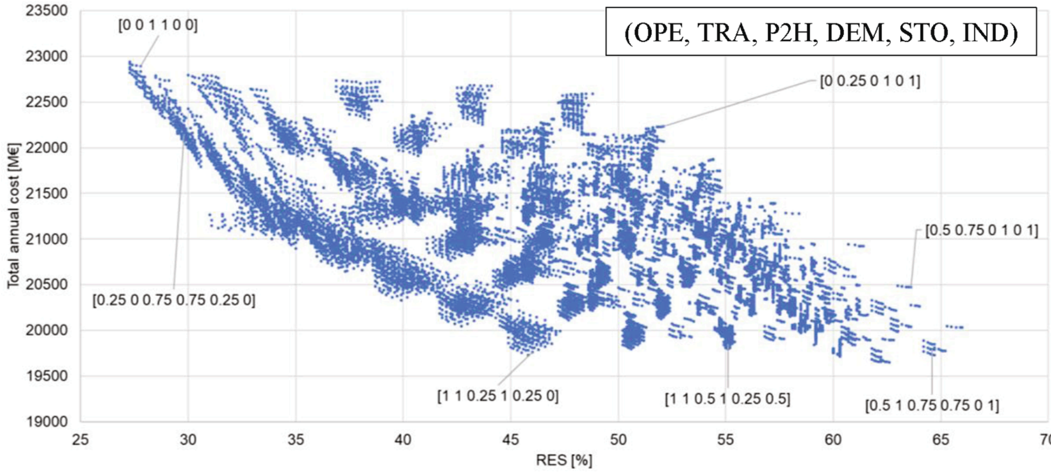

Fig. 22. Values of flexibility vector in relation to total annual cost and share of RES.

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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PAPER 4

Consequences of different strategic decisions of market coupled zones on the development of energy systems based on coal and hydropower

Antun Pfeifer[1*], Goran Krajačić[1], Reinhard Haas[2], Neven Duić[1]

[1]University of Zagreb, Faculty of Mechanical Engineering and Naval Architecture

Zagreb, Croatia

[2]Vienna University of Technology, Institute of Energy Systems and Electric Drives, Energy Economics Group, Vienna, Austria

Abstract

Long term planning of energy system's development becomes closely connected to analysis of day-ahead power markets, market coupling and dynamics of integration of both, renewable energy sources and demand response technologies. In this study a scenario approach with minimization of marginal cost of generated electricity is used to investigate and quantify the influence of investments in generation units for the observed zone and the commitment of units in the surrounding zones. Dispa-SET software was used for modelling of a case study which included eight zones connected in the electricity market. Year 2016 was selected as referent, while future scenarios in 2030 are created with different strategic decision made in each of the zones. Results demonstrate the influence of different strategic pathways in different zones, through electricity generation and levels of storage capacities in the investigated zone and neighbouring zones and cross-border electrical energy flows. If most of the zones are pursuing unambitious strategies (2030a), marginal cost of electricity is double in comparison to the most ambitious case, while moderate approach in the most zones brings the cost reduction of 20%. Ambitious scenario 2030c for all zones results in the least cost of electricity, 30% of the cost in scenario 2030.

Keywords: Common power market, Demand response, Dispa-SET, Variable sources integration.

1. Introduction

By introducing Variable Renewable Energy Sources (VRES), it is theoretically possible to gradually replace conventional generation systems (based on oil, coal and natural gas). Many studies have been conducted to investigate whether there are possible 100% renewable systems for individual countries [1], regions like Southeast Europe [2] and the whole EU [3]. New tools, such as MultiNode tool of the EnergyPLAN, are developed to simulate the coupling of systems [4] but lacking the optimization of unit commitment and influence of electricity import/export to surrounding zones. Also, flexibility of certain types of generation units is not explicit for each unit, rather presented for the aggregation of all units with the similar technology (e.g. condensing plants) as a single point value. Market analysis in terms of meeting the upcoming EU regulations and the potential for using a larger share of renewable sources have also been made for Serbia [5] and Bosnia and Herzegovina [6]. In practice, however, there are problems related to the regulation and management of energy systems (ES) based on VRES due to the

[1] Corresponding author, e–mail: antun.pfeifer@fsb.hr, Ivana Lučića 5, Zagreb, 10002, Croatia

variability and short-term predictability of VRES generation (related to the weather forecast) [7]. Even when the conditions for installing new VRES capacities are good, it is still necessary within ES to have spare capacities in the form of flexible thermal power plants that can respond to a drop-in generation from the RES, according to [8]. Using the RES's surplus electrical energy in storage systems which would have enough capacity to provide enough electrical energy supplies within the ES, was previously deemed costly and inefficient ('circular' efficiency). Although the flexible system is crucial for integration of VRES, these ideas are contested in the present study, by showing the amounts of electrical energy generated from such flexible peak thermal power plants in comparison to the use of demand response (DR), storage inflows and storage levels in the electricity market-coupled environment. Previous research did not consider the possibilities provided by such environment and the present research aims to fill this gap.

In following paragraphs, a review on the relevant literature is provided on the influence of various possible strategic decisions in zones coupled in the same electricity market, such as integration of various technologies that provide flexibility, on the development of energy systems. New trends in integrated energy systems are being studied, such as the 4th generation of district heating (DH) systems associated with cogeneration plants with heat storage tanks for power to heat applications as a source. Also, heat from renewable sources, waste heat integration, heat pumps at household and DH level [9], and ongoing electrification of transport are investigated in various studies. It brings new demands and business opportunities in the area of energy planning, greater utilization of RES, increased energy efficiency and increased quality of life due to lower emissions [10]. A recent study [11] analysed the heat DR in connection to the day-ahead electricity market prices, which is an important step in connecting two sectors on the market basis. In the study, it was concluded that slight variations in the temperature in the distribution grid compared to the baseline operation (±3.5 K) could result in relative socio-economic savings of up to 5.4%, pick pointing the importance of such demand response. In the research on the increase of RES integration, Buonomano et al. [12] developed a simulation model in TRNSYS for bottom-up analysis of economic performance of systems based on solar PV, wind and energy storage for end users, showing how these technologies would be adopted in an economic way, on the case of Italy. The research demonstrated that, for different types of end-users, most economic use of such hybrid (PV, wind and battery) systems is to be connected to the grid and participate in the electricity market. [A scenario analysis for the limited region (Istrian peninsula) was performed in [13], to investigate a battery storage as an option for the security of operation of the power system, in comparison to a lengthy project of a new electricity transmission line. For majority of scenarios the research confirmed that batteries would be beneficial, while for the worst-case scenario ultimate solution would be a new transmission line. In that event, battery storage would continue to benefit the power network on the broader scale. The primary access to the market of ancillary services and reserves, which can provide DR technology on the multilevel market, was explored in [14]. In the observed cases, participation of DR in reserve market was shown to result in 25-27% reduction of the reserve's costs. In [15], two different approaches in a smart grid environment were presented to enable the participation in DR programmes in groups of users such as office buildings and industry. Approaches were elaborated through simulation-based demand control strategies based on simulation and optimization and include control of heating and cooling as well as process control in the industry. The aim was to connect these approaches to the day-ahead electricity market. It was shown that differed loads from households' and industries smart grids will have significant impact on the operation of the future systems. Differed loads' modelling capability was therefore one of the parameters for the choice of the energy planning tool. Research is also conducted in the field of market coupling between the two electricity markets [16] and price-optimally planned development of such markets in [17] and [18]. The impact on price difference, its convergence, and the timing of overlapping / closeness of the price level for significant electricity markets, under the influence of increasing the acceptance of renewable sources, was explored in [19]. Also, emphasis has so far been placed on a significant constraint: the electricity cross-border transmission capacity. Research deals with the problem in trade between large areas [20] and with different methods of market coupling [21]. Zakeri et al. [22] used the Enerallt model (market-based multi-area power and district heating model) to investigate the influence that possible interconnection between UK and Norway would exert on both electricity markets. It was found that the link of 1400 MW would reduce average electricity prices for consumers in the UK, while UK producers would lose some of the economic benefits. Nevertheless, the interconnection would increase the social welfare (defined as socio-economic gain in three possible lines of revenue: consumer's surplus, producer's surplus, and congestion rent) on both electricity markets in optimal scenario for 110 M€/a. The use of multi-agent modelling has been exploited as a machine learning method, using available information in combination with genetic algorithms [23]. Further research has been conducted by multi-agent simulation [24] and by linking two neighbouring electricity markets [25], market-based modelling based on volume of trading [26] and exploring how market consolidation through their merger affects the possibilities of their planning [27]. Detailed terms are related to the correlation of social welfare and the merger of the market - in this case a large market with neighbouring systems' electricity markets, some of which are of interest to this research, namely Southeast Europe, explored in [28]. Results have shown the benefit of electricity markets' coupling for the large market (in this case Italy), which reduced its net imports and provided the opportunity to sell generated electricity at higher prices. Reviewed research, aimed at the electricity markets' coupling, underlined the need to model long-term energy planning problems in the context of the energy system and its neighbouring systems, instead of closed system or a system development which considers prices on neighbouring electricity markets as exogenous variable.

Important flexibility options for an energy system with high share of VRES will be offered through synergies with heating/cooling and electrification of transport sector. Analysis of the possible development of Colombian energy system with integration of VRES [29] shows that the transport sector would remain the main producer of emissions if it is not electrified and coupled to the energy mix with lower emissions, such as VRES based system. As each electric vehicle has an energy storage system, in those periods when the vehicles were parked and connected to the network, they could actively participate in the balancing of electricity supply and demand on the vehicle-to-grid principle (V2G). Dump and smart charge of electric vehicle's batteries was investigated in [30], showing on cases of Germany and Italy the influence of electrification of road transport through scenario analysis in EnergyPLAN. Electricity generation mix based on RES was shown to be crucial for sustainability of electric transport, while smart charge also helped to reduce greenhouse gas emissions (for example, 22% for Italy). In addition to the electrification of transport, the technology of converting excess of electricity produced from VRES to heat (power-to-heat), the production and consumption of synthetic fuels (hydrogen, synthetic gas) are also considered. Use of power to heat and V2G to increase the share of renewable energy was demonstrated in [31], with results showing that starting to implement these technologies can double the projected integration of VRES by 2030 on a case study of Croatia. Electrification of transport and use of V2G mode to integrate excess VRES is analysed as the major storage technology and source of flexibility in the present research as well, in the "LC" scenario described in the Methods. In [32], the study shows that PV, storage and EV battery storage will be economically feasible in this period and gives additional forecasts of cost reduction for lithium-ion batteries and PV panels. In a very recent study [33], electrification of heating and transport sectors has been analysed. The effects of increased shares of EVs and heat pumps, which follow the increase of the VRES share were studied. Techno-economic analysis of the optimal scenario showed the CO_2

emissions reduction of 47% compared to 2017 level and total costs increase of 34% annually. Variables were VRES, EV and HP installations and energy savings.

Different scenarios of the energy system configuration development can be observed as strategic decisions made by the decision makers in each national energy system. In order to evaluate the impacts which different strategic decisions have on electricity market-coupled zones, a more precise tool is needed, compared to the solutions presented in the body of research. Such tool needs to produce outputs such as marginal cost of electricity generation, cross-border power flows and unit commitment in several zones of trading in the same time frame, for example one hour. These outputs would allow comparison of performance for various energy system configurations of the interconnected zones: the cost of generation of electricity, ability to follow the flows of energy between the zones and the ability to answer the question which unit supplied the electricity in each hour of the year. A tool with relevant features was presented in [34] and used to investigate the influence of centralized cogeneration plants with thermal storage, an important technology for energy transition, on efficiency and the marginal cost of electricity generation in case of optimal operation. The overall use of Dispa-SET tool for modelling of interconnected electricity systems with high share of renewable energy is elaborated in [35], for optimized case in a whole year hourly calculation. In [36], four model formulations in Dispa-SET were compared on a case of Western Balkans: “No clustering”, which means considering each power plant separately and using a lot of computer time, “Per unit” - aggregates small and flexible units into larger ones with averaged characteristics, ”Per typical unit” considers one typical power plant per technology and “Per technology” clustering all units using the same technology together without modelling different flexibility capabilities. Results have shown that alternative formulations in Dispa-SET are reliable for estimating the electricity generation mixes in future energy systems, particularly for systems with high shares of RES. The deviation from the baseline formulations decreases significantly with the number of conventional and inflexible units.

In this paper, a model including electricity and heat generation systems of Croatia (HR), Slovenia (SI), Serbia (RS), Bosnia and Herzegovina (BA), Albania (AL), Kosovo (XK), Montenegro (ME) and North Macedonia (MK) as observed zones is created in Dispa-SET. Different dynamics of the energy transition in the year 2030 are proposed. Scenario approach is employed to investigate the influence of different decision for the development of each zone, on unit commitment in the observed zone, electricity generation in all zones and electricity flows between the zones in a coupled day-ahead electricity market. In the method proposed in this paper, operating costs of electricity generation are minimized.

2. Method

The Dispa-SET model is an open source energy planning model which aims to represent the short-term operation of large-scale power systems with a high level of detail. Through minimization of the marginal cost of electricity generation, the model offers solutions for energy planning of the particular zone or region of interconnected zones, taking into account power plant operation (unit commitment) and power flows between the zones. This approach minimises the short-term operation costs for the generation of electricity and heat and enables Dispa-SET to solve the problem of unit commitment and dispatch in large interconnected networks, such as European power system. Pre-processing and post-processing tools are written in Python, and GAMS is used as the main solver engine. The model is written in the form of Mixed Integer Linear Programming (MILP). Dispa-SET is being developed in by the European Commission's Joint Research Centre (JRC), in cooperation with the University of Liège and KU Leuven (Belgium). It is presumed that the system is managed by a central operator with full information on the technical and economic data of the generation units, the demands in each node, and the transmission network. To solve the unit commitment problem, two steps need to be addressed:

- scheduling the start-up, operation, and shut down of the available generation units
- allocation of the total power demand among the available generation units minimizing the electricity systems' operating costs

The second part of the problem is the economic dispatch problem, which determines the continuous output of every generation unit in the system and is formulated through the MILP. Major inputs in order to run these steps are [37]:

- Availability factors for RES power plants (hourly, solar, wind, hydro)
- Cross Border Flows (hourly, historical, between zones)
- Net transfer capacities (NTC) between zones, hourly
- Heat demand (hourly for power plants supplying heat – CHP)
- Scaled Inflow for hydropower storage, hourly
- Reservoir Level of hydro storage, hourly
- Electricity Load, hourly
- Outage factors, hourly
- Power plants database describing parameters for all power plants

The optimization function in Dispa-SET minimizes the short-term operation costs of the electricity and heat generation for the region, which includes different countries, representing electricity trading zones in further discussion. Detailed description of the optimization procedure can be found in [37]. The electricity system costs can be divided into fixed costs, variable costs, start-up and shutdown costs, load-change costs, relieving costs, transmission costs between the two zones, and costs of lost load. The fundamental limitation of power systems is the balance between consumption and generation of electricity. It is met by simulating day-ahead supply-demand balance, for each period (1 hour) and each zone. The sum of all the power produced or discharged by all the units present in the zone that is observed, energy injected from neighbouring zones and the power curtailed from VRES must be equal to the load in that zone, with the addition the energy storage inflow. Other constraints are related to the technological characteristics of generation plants. Further constraints are set at cross-border capacity and consequentially, the flow of electrical energy between two zones cannot be larger than the predefined net transfer capacity (NTC). Before starting the Dispa-SET model calculation, it is necessary to enter data such as hourly load distribution, technical characteristics of generation plants, fuel prices and hourly distribution of cross-border capacity. The optimization problem is split into smaller optimization problems that are run recursively throughout the year.

Figure 1 shows an example of such approach, in which the optimization horizon is one day, with a look-ahead period of one day. The initial values of the optimization for day "j" are the final values of the optimization of the previous day. The look-ahead period is modelled to avoid issues related to the end of the optimization period such as emptying the hydro reservoirs or starting low-cost but non-flexible power plants. In the approach used in this research, the optimization is performed over 48 hours, but only the first 24 hours are conserved.

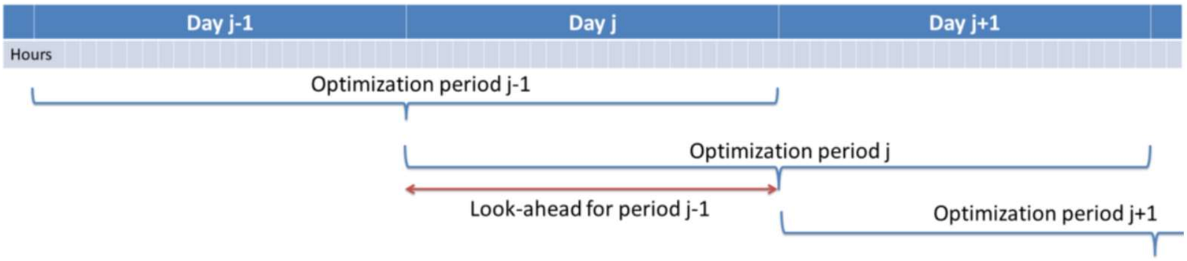

Figure 1 Moving horizon optimization [35]

In this research, scenario approach is implemented in order to compare results in particular zones and in the market as whole, when a zone implements a strategic decision, such as following a low-carbon (LC) or decarbonization pathway or sticking to the business as usual scenario (BAU). General idea of different possibilities for various zones in the scenario approach is illustrated by Figure 2, depicting zones with energy mix based on different technologies and connected to a common system (region). Such zones can make different strategic decisions regarding their long-term configuration and energy mix. Zone in this research represents a national energy system with autonomy to make strategic decisions.

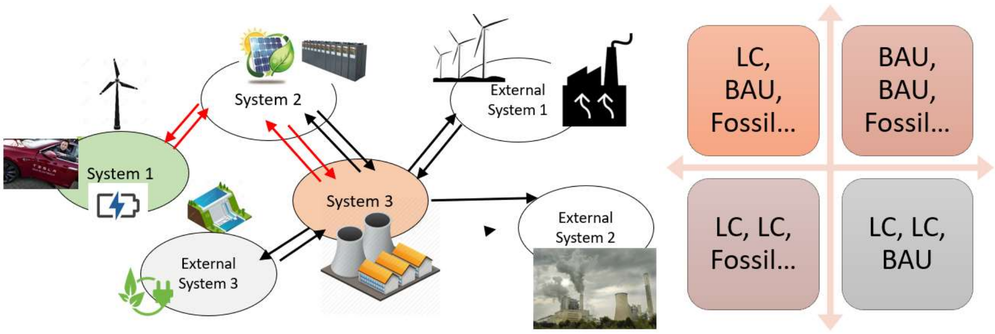

Figure 2 Scenario approach for different zones

For all zones in the market coupled system, a different strategic decision (in further elaboration called "strategy") is proposed, reaching from one end of the scale to the other:

- "Fossil" (typically for zones with own reserves of fossil fuels),
- "BAU" (with orientation towards RES, but with moderate dynamics)
- "RES" (integration of RES in higher dynamics, but without demand response)
- "Extreme RES" (high share of RES, but low local integration)
- "LC" (low-carbon, RES with strong integration).

For each of the zones, concrete numbers for installation of RES technologies, demand response and storage are derived from local potential and data for the zone in question.

Significant limitation of the approach lies in the fact that Dispa-SET unit commitment and dispatch does not consider lifetime costs associated with changing the portfolio of electricity generation capacities. However, the results of such analysis offer the guideline about the possible stranded costs (e.g. coal power capacities which do not enter the merit order on the electricity market) resulting from a strategic decision. Results can indicate if the strategic decision made in the observed zone leads to more stranded costs for that zone or leads to the outcome in which the zone in question exploits other zones for the balancing of electricity supply and demand. Such conclusions can be made based on unit commitment observations.

3. Case study and results

Case study area includes electricity generation and district heating systems of Croatia (HR), Slovenia (SI), Serbia (RS), Bosnia and Herzegovina (BA), Albania (AL), Kosovo (XK), Montenegro (ME) and North Macedonia (MK) connected in a coupled day-ahead electricity market. The data is more detailed for the zone of Croatia (HR), while the input data for all other zones was already elaborated in several papers, such as [36] with the emphasis on the model formulation and data for 2030, [38] dealing with the Western Balkans region, and [39], which collected the relevant data on generation units. Inputs related to VRES for the observed zone (HR) are available in the Annex. In addition to VRES such as solar photovoltaic or wind power plants, the HR zone also has hydroelectric power plants in portfolio, whose availability coincides with river flows. Large hydroelectric power installations are characteristic for all the zones in the region, with usual power generation mix including hydro and coal power plants. Data and river flows can be obtained using the publicly accessible SMHI HypeWeb [40] database. If the zone is located at the border of the studied region, then historical cross-border electricity flows represent a limitation of the model, the flow to zones outside the studied region is not optimized. Data related to historical cross-border flows can be found in the public database ENTSO-E [41]. In this case, HR is surrounded by zones that are part of the modelled region, cross-border flows are in this case the result of the optimization model of the Dispa-SET. However, for each zone, it is necessary to have information about the net transfer capacity to know the limits related to the transmission of electricity from one zone to another. Data related to the NTC from an to Croatia can be found in the annual reports of the transmission system operator for each zone or country. For Croatia (HR) NTC is given in Figure 3.

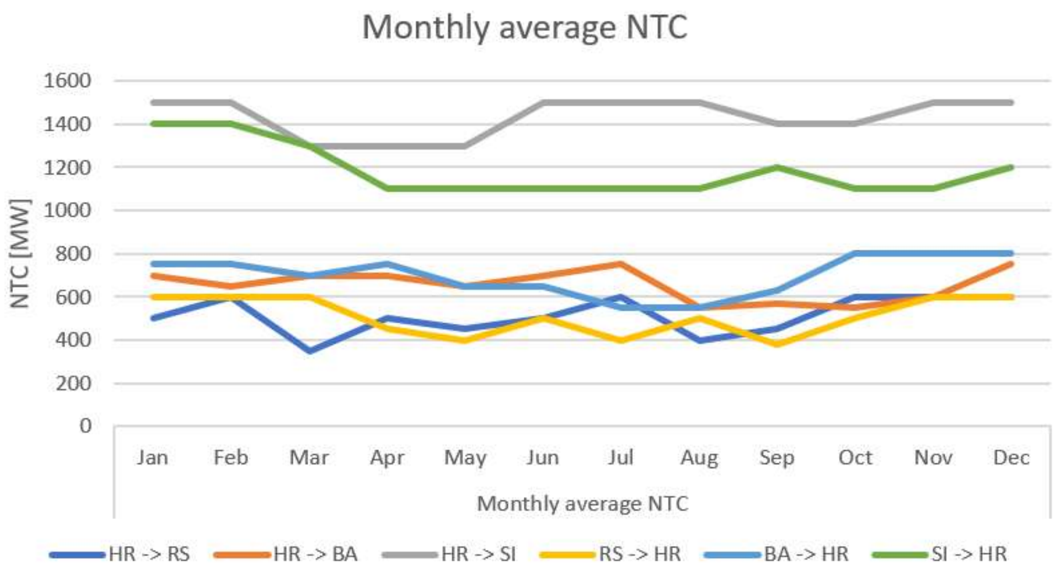

Figure 3 Monthly average NTC for zone HR

The electrical load of a specific zone, the power consumption at the hourly level for the whole year is a required input. This data is available from the public database, such as ENTSO-E [41]. Figure 4 shows the electrical load for the HR model reference year (2016).

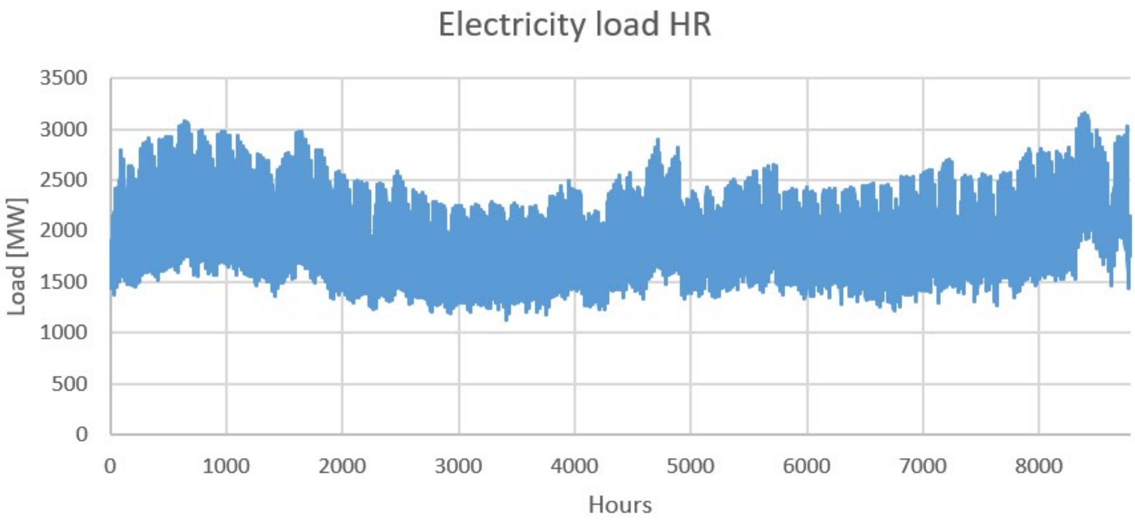

Figure 4 Electricity load for the zone HR

Installed capacities of different technologies are given in Figure 5. This includes Hydro (WAT), Wind power plants (WIN), Solar PV (SUN), Peat Moss (PEA), Oil power plants (OIL), Gas power plant (GAS), Biomass power plants (BIO), Hard coal power plants (HRD), Lignite power plants (LIG) and Nuclear power plants (NUC) and Other, such as connection of EV's chargers to the grid (OTH).

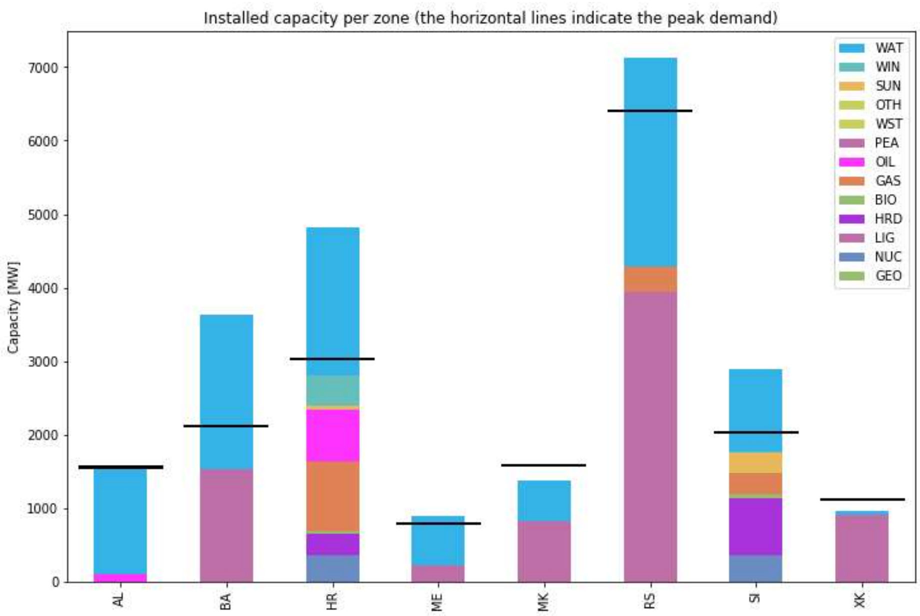

Figure 5 Installed generation capacities for all zones in 2016

For the given inputs, Figure 6 shows generated electricity and imports for each of the zones (Flow In). For the case of nuclear power plant (NPP) Krško, located in SI, the installed capacity, as well as energy produced from the plant is split in half between HR and SI instead of modelling it in SI and arranging a constant export to HR. Compared to the historical data of the zone HR from IEA statistics [42], results are within 15% difference in case of coal (2.6 TWh) and hydro (7 TWh). Imports (5.5 TWh) are expressed as generation from NPP Krško (2.8 TWh) and import of 2.8 TWh. The difference between historical data and calculated data are satisfactory because the Dispa-SET is an optimization tool, while historical data was not a result of the optimal dispatch.

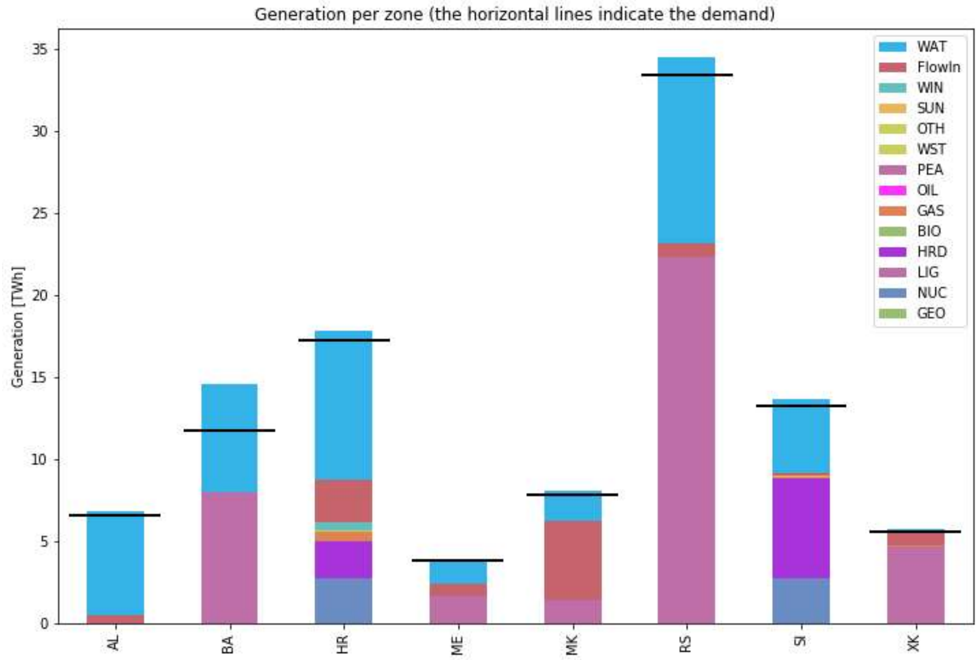

Figure 6 Electricity generation from each technology and imports in 2016

Figure 7 shows solution to dispatch problem in 2016 for HR, considering the electricity demand, dam hydro (HDAM) and pump hydro (HPHS) reservoir levels and export/import balances, as well as other storage. It is characteristic to see the conditions in period of NPP Krško maintenance.

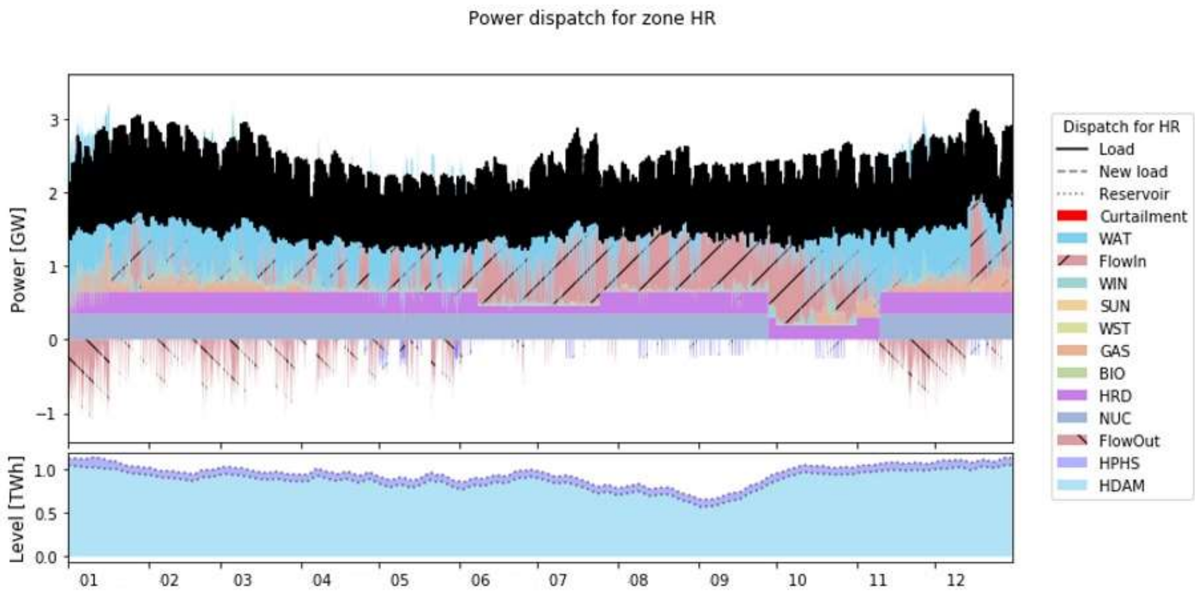

Figure 7 Solution to dispatch problem in HR in 2016

For the same year, Figure 8 shows the unit commitment for all available electricity generation units in HR. It is noticeable that CHP units run only when they are needed for heat production, while the rest of the time the needs are covered by NPP Krško, hydro power plants and import, while two blocks of Coal power plant Plomin work according to their nominal capacity, with modern block 2 working significantly more hours with a lot of ramp up and ramp down.

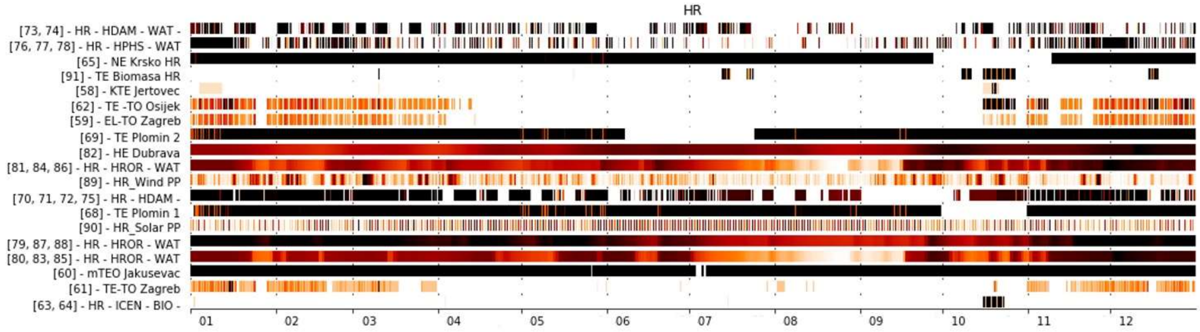

Figure 8 Unit commitment in HR in 2016

Costs used for the optimization of dispatch in future scenarios are given in Table 1. Costs are assessed in the context of the case study area, to represent a best-case scenario [43] for a region rich with locally produced lignite [38].

Table 1 Marginal costs as inputs to the model for future scenarios

Marginal costs [EUR/MWh]	
CO_2 emissions [EUR/t CO_2]	9
Unserved Heat	50
Load Shedding	400
Nuclear	3
Black coal	10
Natural Gas	20
Fuel Oil	35
Biomass	18
Lignite	8
Peat	8
Value of Lost Load (VOLL)	100000
Spillage	1
Water Value	400

Future scenarios in 2030

Four scenarios for the year 2030 were analysed, taking into account the business-as-usual decision making for all zones as a benchmark. Table 2 shows the strategic decision supposed per zone and per scenario.

Table 2 Strategic decisions of zones in different scenarios

	2030	2030a	2030b	2030c
AL	Fossil	BAU	BAU	BAU
BA	Fossil	BAU	RES	extreme RES

ME	Fossil	BAU	BAU	BAU
MK	Fossil	BAU	RES	RES
RS	Fossil	BAU	RES	extreme RES
XK	Fossil	BAU	BAU	BAU
HR	LC	RES	LC	LC
SI	RES	RES	LC	LC

Table 3 gives an overview of the specific changes made in a couple of zones, to investigate scenarios in which one zone (HR) aims to integrate RES and demand response technologies, while other zones integrate RES to higher or lower extent, but do not follow up with demand response (remaining data is given in the Annex). The numbers in all scenarios reflect the decisions, taking into account different starting energy mix, in the following way:

- Low Carbon (LC) decision proposes achievement of minimum of 80% of electrical energy produced from RES and includes demand response and storage technologies (V2G in HR and SL). Such decision proposes for over 300 MW of Solar PV and Wind installations per year until 2030
- Extreme RES decision proposes high share of RES, with over 50% of electrical energy produced from RES. Such decision proposes for over 300 MW of Solar PV and Wind installations per year until 2030
- RES decision proposes moderate increase in RES installations, with 150-200 MW of new Solar PV and Wind capacities per year until 2030, but without special attention given to demand response technologies
- BAU decision proposes reaching shares of RES noted in current public plans
- Fossil decision proposes slow integration of RES and new fossil capacities to be installed until 2030

Table 3 Specific changes compared to BAU for all scenarios

Scenario	2030	2030a	2030b	2030c	Unit
HR EV Connection	6600	4400	6600	6600	MW
HR EV Storage	80	60	80	80	GWh
HR Solar	4460	2460	4460	4460	MW
HR Wind	4500	2500	4500	4500	MW
RS Wind	1000	1500	4500	6500	MW
RS Solar	500	2000	3500	5500	MW
BA Wind	564	2000	2500	4564	MW
BA Solar	0	0	200	500	MW
MK Wind	350	500	1500	2000	MW
MK Solar	100	1000	1000	2000	MW

Scenario 2030

In the “2030” scenario, all zones except HR (LC) and SI (RES) made a decision of relying on local coal capacities combined with hydropower (“Fossil”). Installed capacities are given in Figure 9. The type “OTH” in the figure represents the connection capacity of EV’s batteries to the grid.

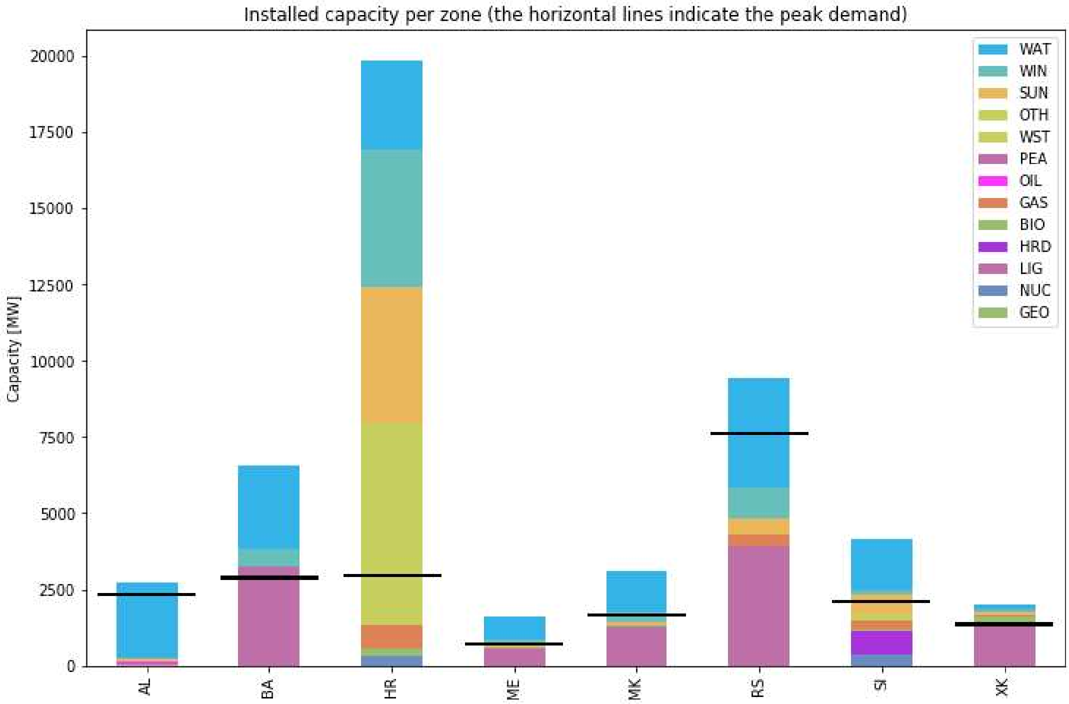

Figure 9 Installed capacities in initial 2030 scenario

After optimization, electricity generation from all technologies in all zones is given in Figure 10. In zones RS, BA and ME, 30-40% of energy is produced from coal while XK exports part of electricity generated from coal. Import has higher share in BA (33%) and lower in ME and MK (less than 10%), at the expense of local electricity generated from coal. Net export occurs from HR, AL and XK (from the former due to large wind and hydro capacities and from the latter due to inflexible coal).

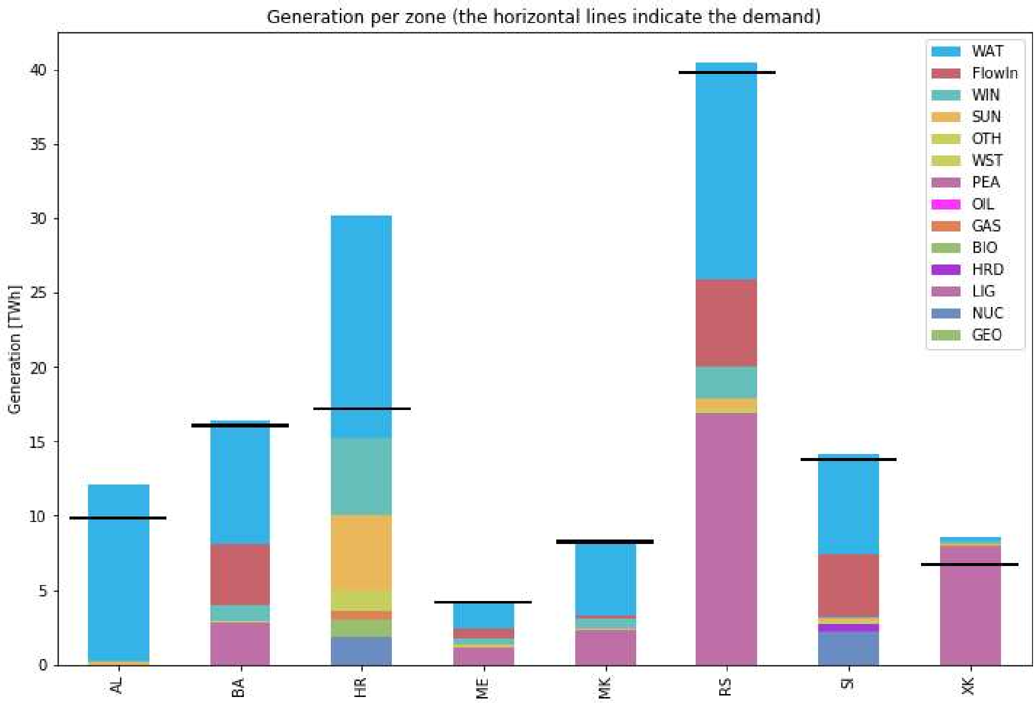

Figure 10 Electricity generation for the energy mix in scenario 2030

Focusing at the leading zone with LC strategic decision, HR, Figure 11 shows the dispatch of energy from all technologies, storage inflows, import/export and energy stored in EV batteries, as well as storage levels in hydro power plants. EV batteries participate in the balancing and RES integration, while their discharge is visible in Figure 10 as “OTH” generation.

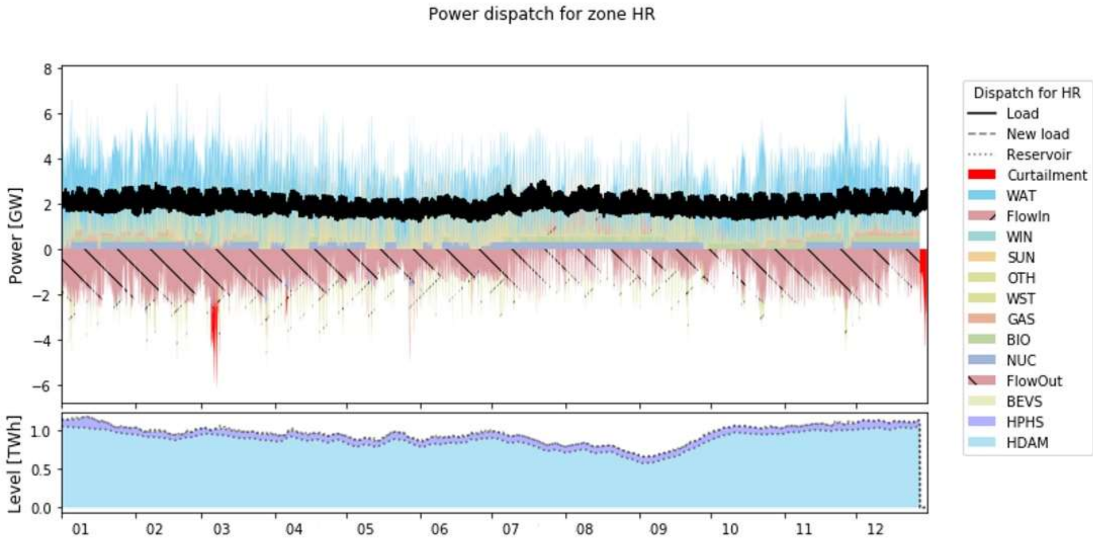

Figure 11 Power dispatch for HR in 2030 scenario

In Figure 12 unit commitment for the HR zone is given, showing in more detail how certain groups of electricity generation unit are operating during the year.

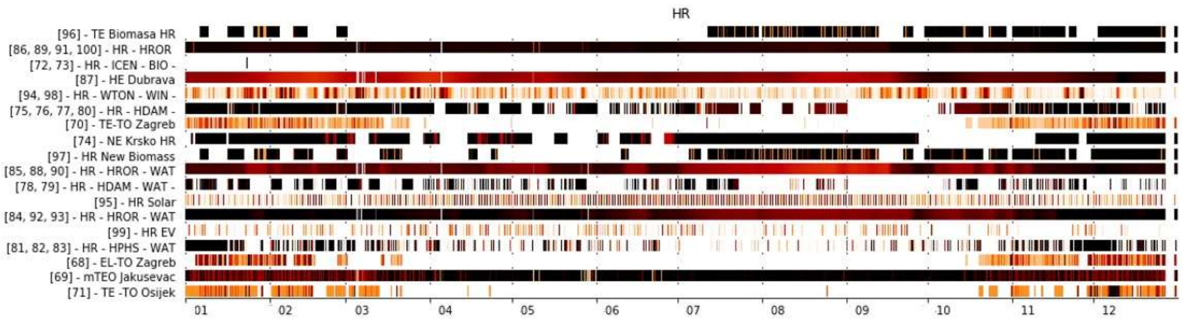

Figure 12 Unit commitment in HR in 2030 scenario

Apart from the hydro power plants, which are operational throughout the year, commitment of solar PV (5.05 TWh), wind (5.24 TWh) and EV vehicle battery discharge (1.2 TWh) is dominating the energy mix. CHP plants are operating during the winter heating season, which leaves up to 4000 hours a year for operation, while NPP Krško works with cycling periods and 1000 hours less compared to the base case in 2016. Curtailment in HR is 0.32 TWh, which is acceptable, as elaborated in [31]. In this scenario, results show that every zone which opted for “fossil” strategy imports electricity from the zone with “LC” strategy. Due to good interconnections and geographical location, even SI zone, with “RES” strategy, imports electricity from HR zone, which is comparatively leading the energy transition of the whole interconnected region, exporting most of the electricity generated from RES. In case of absence of interconnected electricity market, the observed zone would not be able to integrate such amounts of renewable electricity.

Scenario 2030a

In scenario "2030a", all zones except HR and SI are following BAU strategic decision, while HR and SI are focusing on RES installations. Installed capacities for all zone in scenario 2030a are given in Figure 13.

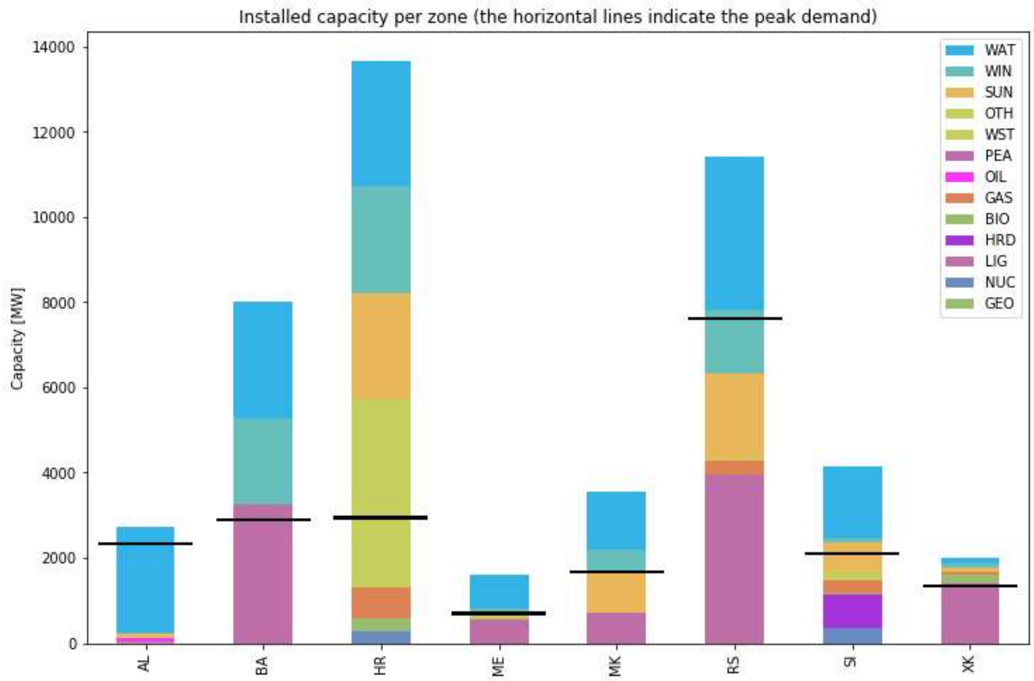

Figure 13 Installed capacities for all zones in 2030a

With the given inputs from Table 3 and Figure 13, electricity generated in all zones is given in Figure 14.

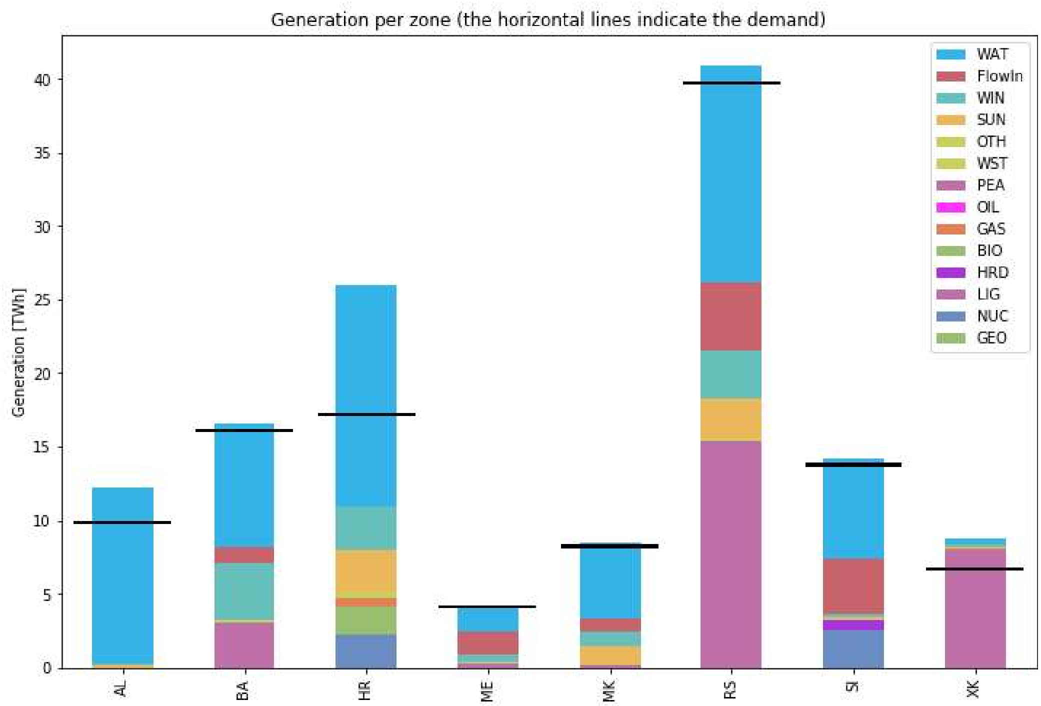

Figure 14 Electricity generated from all technologies in 2030a

Reduction in needed import is visible and amounts to 43% compared to 2030 scenario in zones that have decided to invest in renewable energy (BA, RS), while Croatia (HR) has remained export oriented in the process (in reference case, HR is import oriented). Kosovo remains noticeably non-flexible and exports the energy from the lignite power plants. BA imports around 1.1 TWh of energy from RES in the surrounding zones and, together with local output from wind power (3.9 TWh), this amounts to more energy than it produces from lignite power plants.

The solution to dispatch problem in 2030a scenario for HR zone is shown in Figure 15. There is no significant occurrence of curtailment (amounts to 6 GWh across the market coupled region), not even in September, with reservoir levels being at 60% of initial level. Reduced investments in V2G, with 60 GWh of storage and 4400 MW of interconnection instead of 80 GWh/6600 MW in other scenarios, still provide enough balancing. In all zones, combination of newly installed RES and import from the zone with the high RES share (HR) supress the electricity generation from lignite power plants, although some inflexible lignite blocks remain the main producers for zones such as XK.

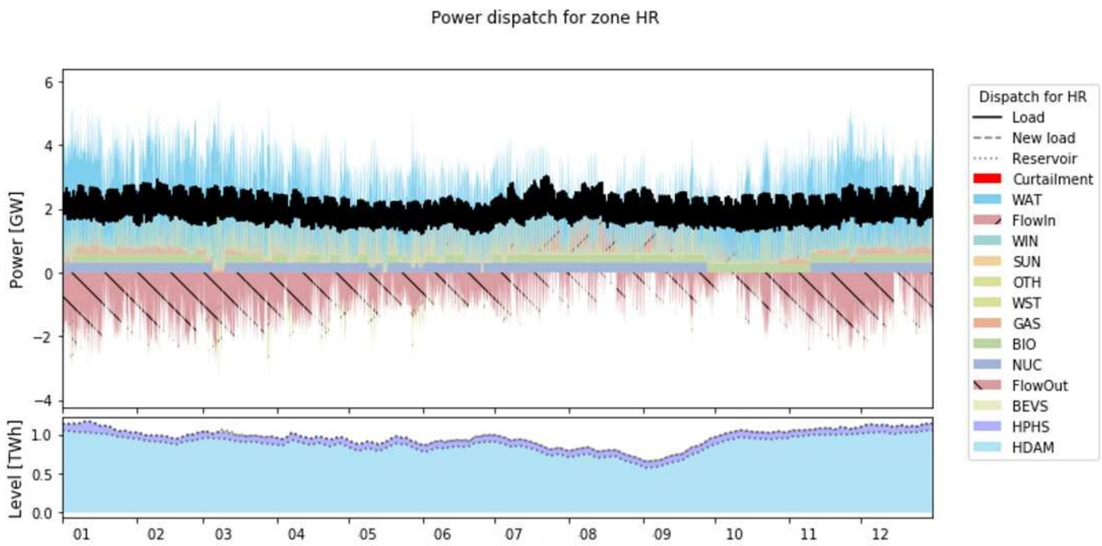

Figure 15 Solution to dispatch problem in HR in 2030a

For the unit commitment it is important to note that in HR, coal power plants are no longer in operation in 2030 and new RES capacities are operating in most of the hours. EV batteries are participating in supply by discharging electricity back to the grid in some hours. These dynamics are visible in Figure 16.

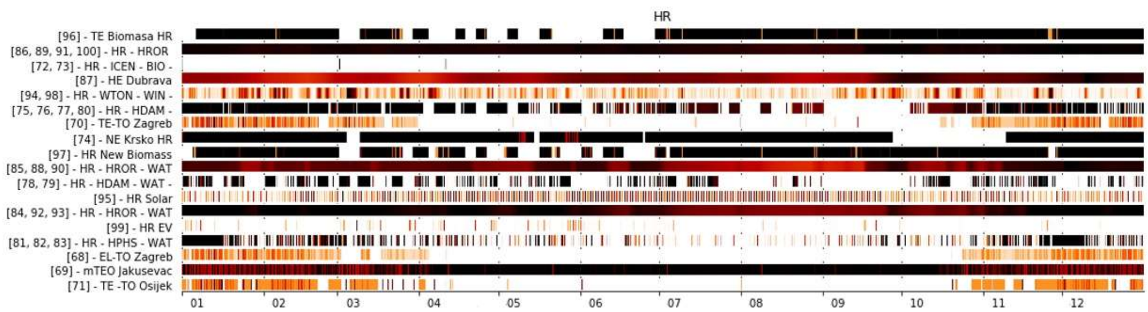

Figure 16 Unit commitment in HR in 2030a

In scenario “2030a”, the leading zone (opting for “RES” strategy) does not generate excessive amounts of electricity from RES. At the same time, all other zones (except for SI) opt for “BAU” strategy, which includes larger installations of RES compared to “fossil” strategy. Resulting situation is still favourable for the zones opting for “RES” strategy, in terms of balancing their generation, but the rest of the zones have increased export. This configuration results in only 10% reduction of short-term operation costs compared to “2030” scenario. However, it is more favourable for the zones opting for “BAU” in terms of stranded costs, due to larger generation from coal.

Scenario 2030b

For the “2030b” scenario, installed capacities of all technologies are given in Figure 17. Capacities of wind and solar power are now 2-3 times larger compared to 2030a (Table 3) and more exports from the zones without demand response or additional storage technologies are expected. “OTH” represents the V2G connection to the grid.

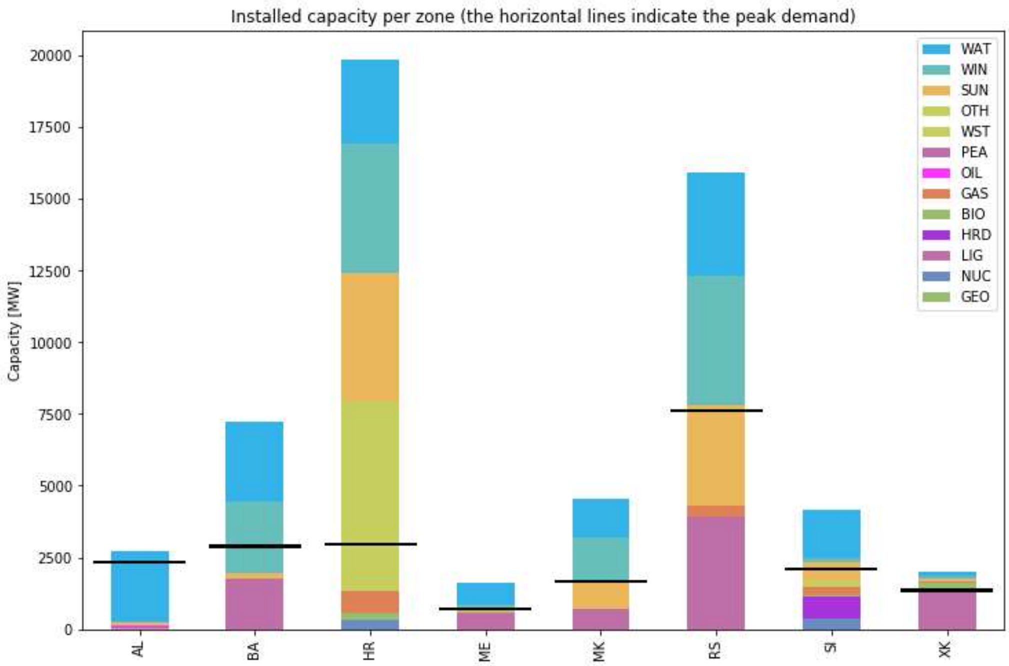

Figure 17 Installed capacities in all zones in 2030b

For this set of inputs, Figure 18 gives the electricity generation from all technologies in 2030b. Due to high installation capacities and availability of renewable energy sources, HR remains export oriented. There is still net import in BA and RS amounting to 1.35 TWh, which is connected to the fact that there are other countries in the region with over 80% of VRES penetration (HR, MK), but without storage and demand response technologies which would enable them to integrate all produced energy. In gross consideration of import and export it is visible that major exporters are HR, MK and AL. Also, XK starts to be import oriented zone, producing only about 80% of their energy from lignite in comparison to 110% in scenario 2030a.

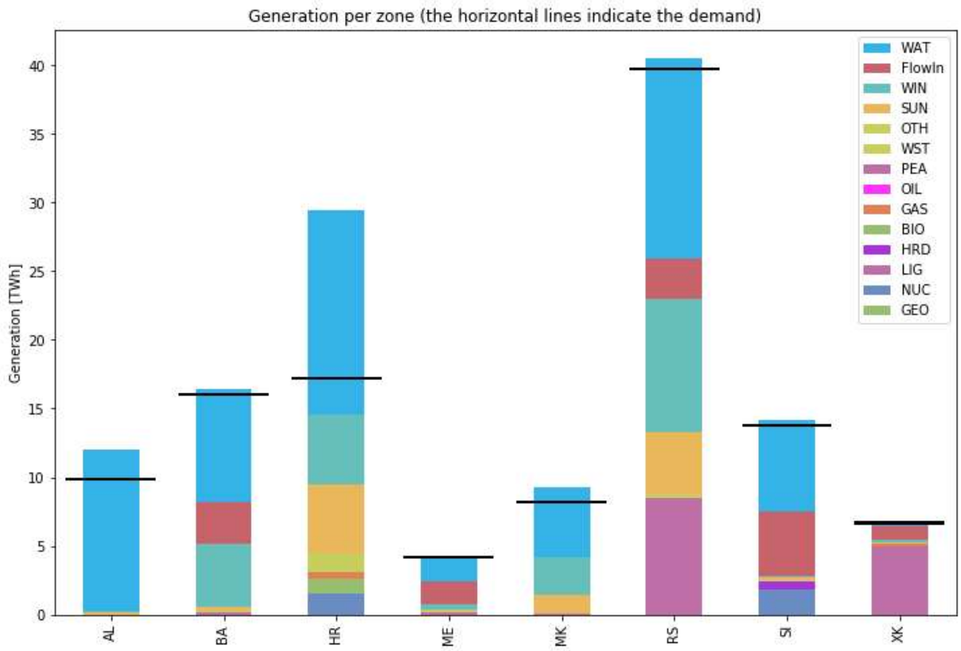

Figure 18 Electricity generated from all technologies in all zones in 2030b

In the other zones, output from VRES supresses the operation of local coal power plants (visible in particular for XK) and the common market enables for energy produced from VRES to be distributed between the zones, in case of inability of a certain zone to integrate all the produced energy. The solution to dispatch problem for HR is shown in Figure 19. In 541 hours, a curtailment occurs in HR (in total 0.67 TWh), mostly in spring, due to high hydropower availability combined with high VRES installations and lower load.

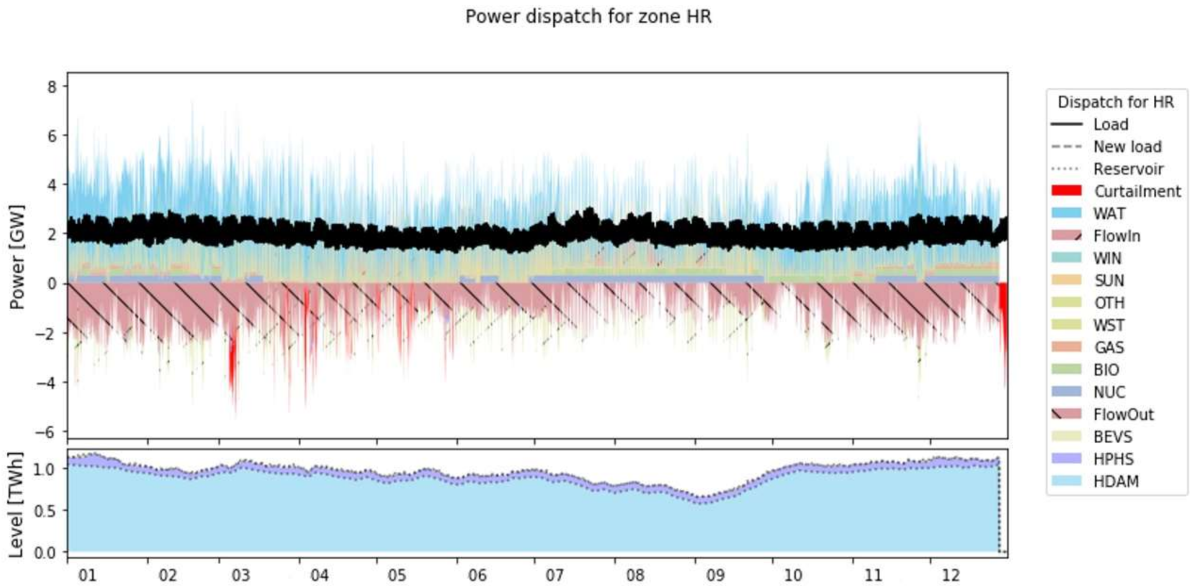

Figure 19 Solution to dispatch problem for HR in 2030b

Figure 20 illustrates the commitment of all available electricity generation units in HR in 2030b. High availability of VRES technologies is visible (HR-WTON-WIN and HR Solar producing), as well as larger number of hours with EV discharge (HR EV in Figure 20 and “OTH” in Figure 19) back to the grid. Biomass power plants take over some of the flexibility and balancing roles that were previously held by large electrical blocks in Plomin and they have more ramp up and ramp down hours, to provide additional balancing of the system.

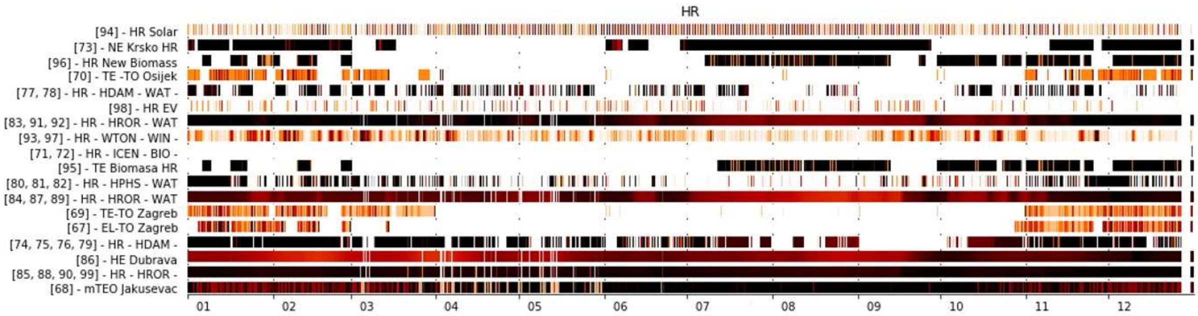

Figure 20 Unit commitment in HR in 2030b

In scenario “2030b”, half of the zones that were developing according to “BAU” strategy, now opt for “RES”, which further hindered the generation of electricity from coal in all the zones and reduced the short-term operation costs for 50% compared to “2030”. Such decision portfolio benefits the zones with “LC” decision the most, but also benefits the zones with “RES” decision.

Scenario 2030c

In scenario 2030c, HR and SI remain at LC strategic decision, while some zones: RS, BA and MK are relying on extreme RES strategy, installing large capacities of RES (Table 3), but without a lot of flexibility options. Installed capacities are shown in Figure 21.

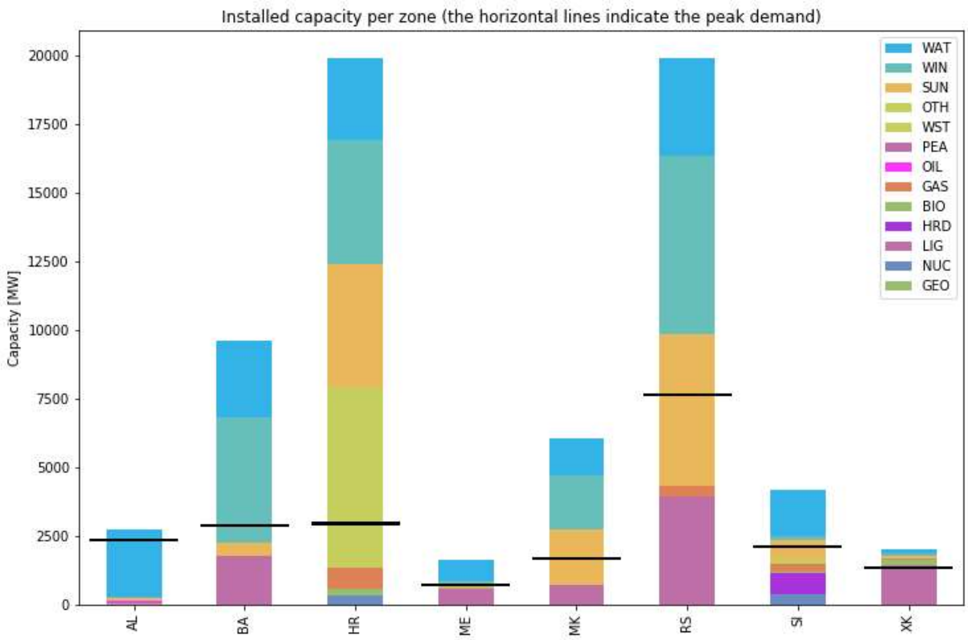

Figure 21 Installed capacities in scenario 2030c

Generation of electricity, shown in Figure 22, is based on RES in majority of zones, while zones previously relying on lignite power now import majority of energy instead of producing it from lignite.

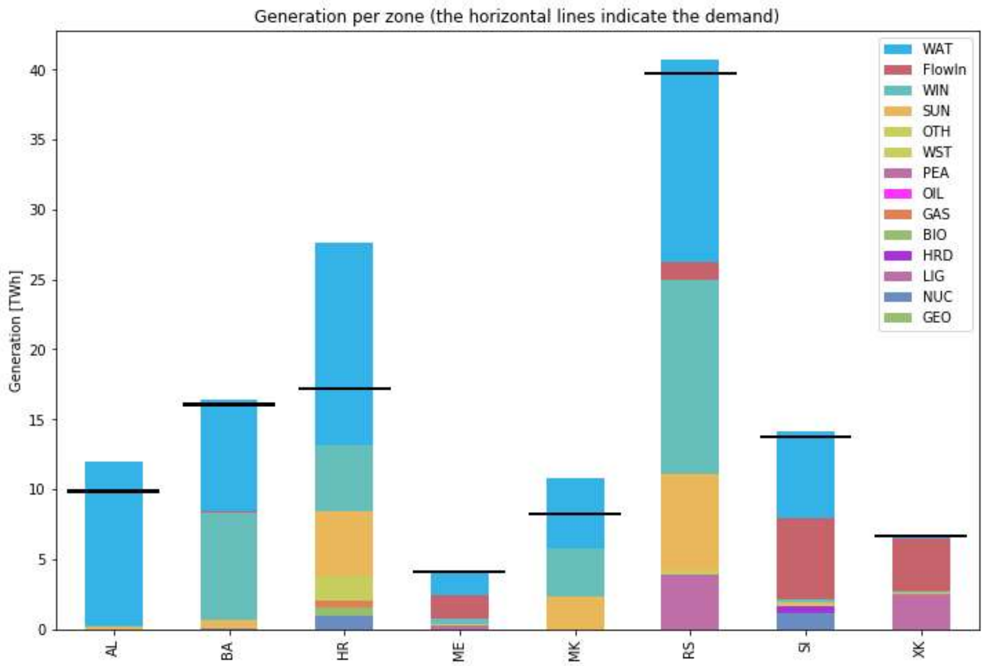

Figure 22 Electricity generated for all zones in 2030c scenario

XK imports 60% of energy, ME imports 40%, while RS produces less than 50% of energy from lignite in comparison to 2030b scenario. In BA and MK there is no electricity generated from coal. The solution to dispatch problem in 2030c scenario for HR zone is shown in Figure 23. The occurrence of curtailment became more significant, amounting to 1.7 TWh. This suggests that additional demand response would be needed across the region, to accommodate the RES penetration levels in scenario 2030c, since curtailment appears in RS (1 TWh) and BA (1.7 TWh) as well.

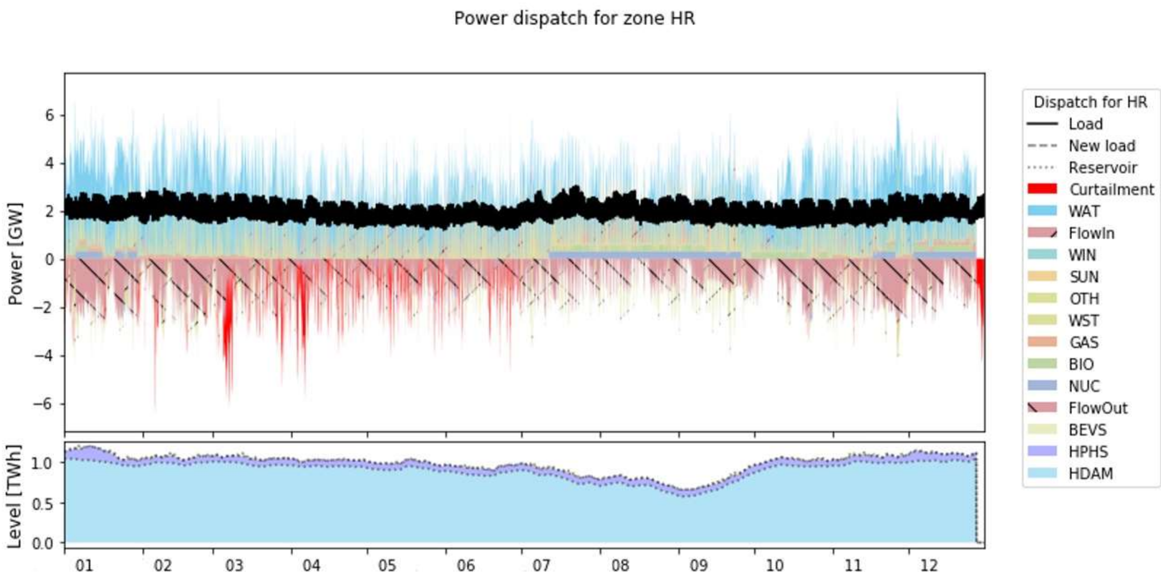

Figure 23 Power dispatch for scenario 2030c, zone HR

The Figure 24 shows unit commitment for scenario 2030c for the duration of the year in zone HR. The HDAM and HPHS units operate during spring and summer seasons, adding on the electricity generated from wind and solar power. In such an energy mix, NPP Krško does not enter the merit order during the spring, due to high availabilities of VRES and HROR.

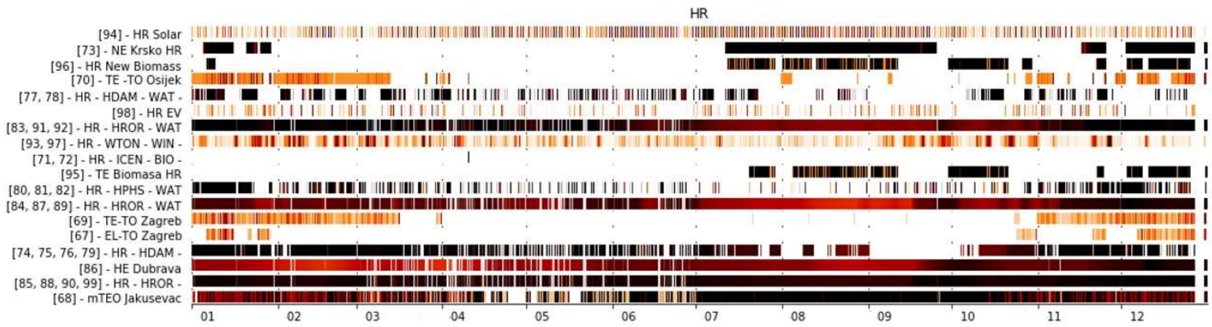

Figure 24 Unit commitment for zone HR in scenario 2030c

In scenario "2030c", all the zones that were previously developing in accordance to "RES" strategy, now opt for "Extreme RES", which results in complete abandonment of coal in all zones except for RS and XK. Consequently, this scenario results in the lowest short-term operation costs (only 30% compared to "2030" scenario). Although the overall capacity of the newly built portfolio of RES power plants is high, the investments would still be lower than in the case of investment in "fossil" strategy, which proves to result in a lot of stranded cost, due to very low operating hours of coal power plants in all scenarios. Also, economic and social costs of such stranded assets in the electricity generation system are increasing in EU towards 2030 [44].

Results of cross-border lines congestion and average marginal cost

The results of cross-border lines' congestion are relevant for consideration of upgrades of the infrastructure, either of the lines themselves or the local demand response and storage. In Table 4, congestion hours on the electricity transmission lines connecting zones in common electricity market are presented for all scenarios. It can be noted that, as the integration of VRES get to a higher level (scenarios with more zones opting for "RES decision"), number of congestion hours rises in general, although some of the interconnections become less congested. Congestion rises in direction of export from the zones that are integrating VRES, but not demand response technologies, as can be seen on connections between Serbia (RS) and all other countries and Bosnia and Herzegovina (BA) and other countries.

Table 4 Number of congestion hours on each line connecting the zones for both scenarios

Number of hours of congestion on each line:	2030	2030a	2030b	2030c
BA -> HR':	342	824	474	1711
BA -> ME':	2371	3195	2617	3131
BA -> RS':	2214	3002	2780	3304
HR -> BA':	6214	3795	5145	3620
HR -> RS':	6116	4573	5410	3994
HR -> SI':	56	45	146	593
ME -> AL':	1145	1293	1210	1094
ME -> BA':	1636	1345	1575	1262
ME -> RS':	2333	2142	2308	2221
ME -> XK':	4293	3814	3172	3820

MK -> AL':	1840	1889	1908	2450
MK -> RS':	4285	3657	4245	4848
MK -> XK':	1297	1002	2317	3098
RS -> BA':	1615	1541	1785	1894
RS -> HR':	522	892	1031	2129
RS -> ME':	2610	2808	2790	2867
RS -> MK':	1266	1762	1426	994
RS -> XK':	486	592	2118	2741

At the same time, congestion in direction from Croatia (HR) to Serbia (RS) is significantly lower in “2030c” than in “2030”. In scenario “2030c”, electricity generated from coal in BA and RS is replaced with import from the zones with increased RES share. At the same time, BA is not integrating all renewable energy that is generated but is exporting it to surrounding zones. Similar can be observed for MK and RS. The zone that was in other scenarios exporting its energy generated from coal – XK, in 2030c becomes a net importer. The scenario with HR and SI going for energy transition (“LC”), while other zones stick to “BAU” or “Fossil” decisions (2030) incur more congestion on the transmission lines from the leading zone (HR), but also reduce the energy generated from fossil fuels in the region. When other zones follow with “RES” or “extreme RES” decisions, the congestion hours reduce between them, but remain high towards zones that stick lower energy transition intensity.

In Figure 25 the average marginal electricity cost for all scenarios is given. Marginal cost is the highest in scenarios with more energy generated from various fossil fuels and notably from coal, like it is the case in scenario 2030 (most zones had the strategic decision to remain in “fossil” or “BAU” strategy).

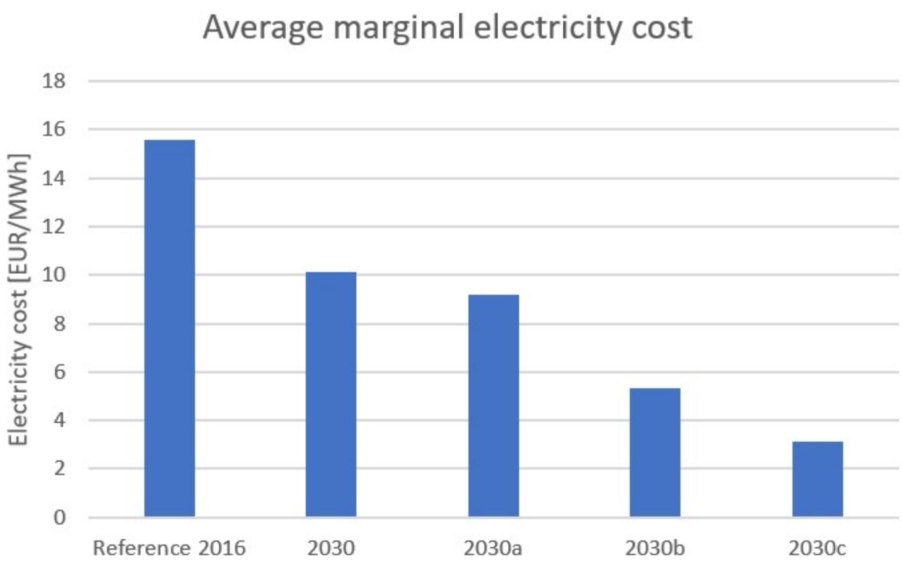

Figure 25 Average marginal electricity costs in all scenarios

From the results presented in the previous chapter, it can be noted that the marginal cost of electricity generated will be lowest in the scenario maximising RES capacities, “2030c”, reaching only 30% of the cost of “2030” scenario. The direction of energy transmission provides additional information about the benefits that certain zone had due to strategic decisions it decided to implement. The zones with LC decision will also be the ones to benefit most from all the capacities in the connected electricity market. These zones will use electricity available at lowest price in the hours of abundant generation to store it and use it for decarbonisation of other sectors, such as heating and transport. Observations about the zones that “lead“ the energy transition and those that “follow” are important for future development of energy systems in the observed region and regions with similar characteristics. Results point towards the conclusion that the most favourable way for all zones to move forward would be to follow the “leading zones” (e.g. the ones LC decision) first as soon as possible. In that way, further refinement on the scenario 2030c could be done, since all the zones would include DR technologies and decarbonize the system while achieving the lowest average marginal generation cost of electricity. A boundary condition of the original energy mix of all zones, which is a combination of hydropower and coal power, must be kept in mind. This analysis could be used as a guideline for the regions with similar energy mix. It can be noted that the first zone with the 100% RES based energy system is AL, relying on hydropower.

Some sensitivity parameters need to be observed. In strategic decision making for the chosen case study area, the price of greenhouse gas emissions, namely CO_2, can play an important role in economic feasibility of the future energy system’s configuration. Scenario “2030” is discussed in terms of CO_2 cost. Cost of CO_2 is 50 €/t CO_2, compared to 9 €/t CO_2 considered in previous chapter in “2030” and all other scenarios. This value vas used due to applying the emissions trading rules on all zones, while previously only HR and SI were included in emissions trading system of the EU and the cost of CO_2 was calculated to represent the average across all zones. Resulting average marginal electricity cost for new price of CO_2 is 21.18 €/MWh. Resulting generation from technologies in all zones is given in Figure 26.

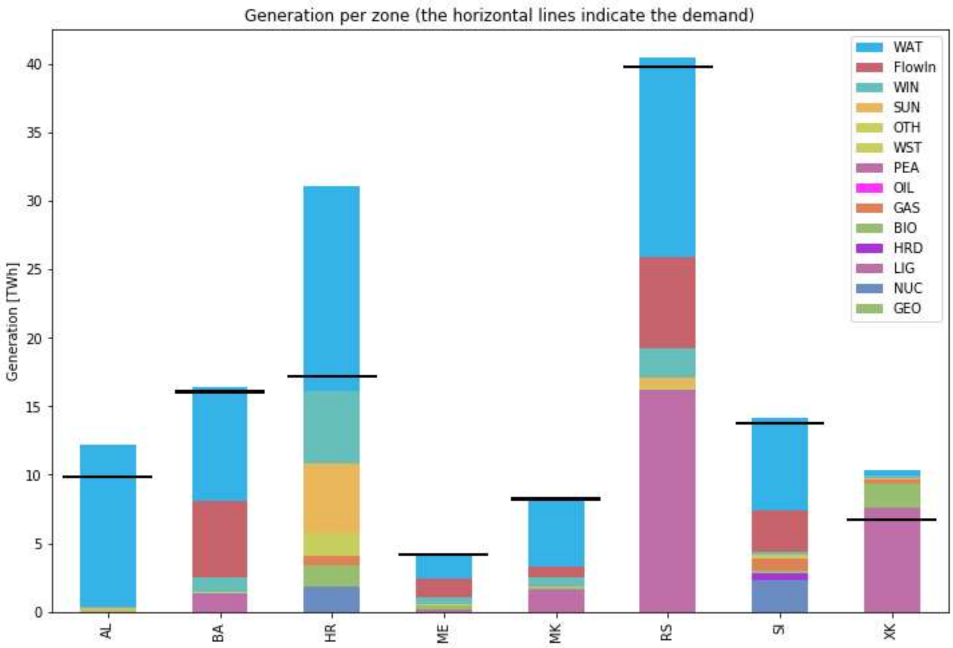

Figure 26 Generation of electricity per zone in case of high cost of CO2

It is noticeable that in zones previously dominated by coal, a combination of import (from the zones rich with RES and hydropower) and gas have larger share of the energy mix. This applies to MK (energy from gas) and SI, while XK export from coal remains 50% of the amount exported in the case with 9 €/t CO_2. BA and ME also import energy and energy produced from coal remains at less than 50% of the case with lower CO_2 cost. In Figure 27, the power dispatch in the case with higher CO_2 price is presented. It can be compared with Figure 11 to notice the change in storage profiles. The comparison suggests that the zone with most ambitious strategic decision (HR) participates more in balancing of the region than it was the case with lower CO_2 price.

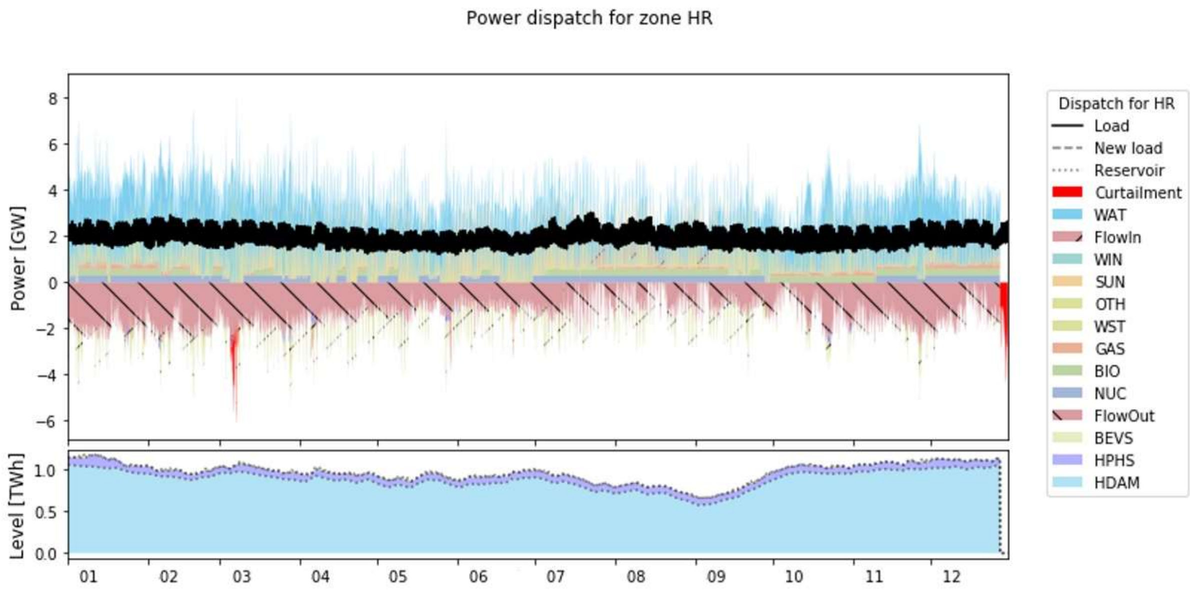

Figure 27 Dispatch for zone HR in the analysis with high CO2 prices

In case that scenario 2030 would be run without V2G implemented in Croatia, the Figure 28 shows the solution to the dispatch problem for zone HR. It is visible that curtailment becomes more regular issue (in red), with more than 100 hours of occurrence.

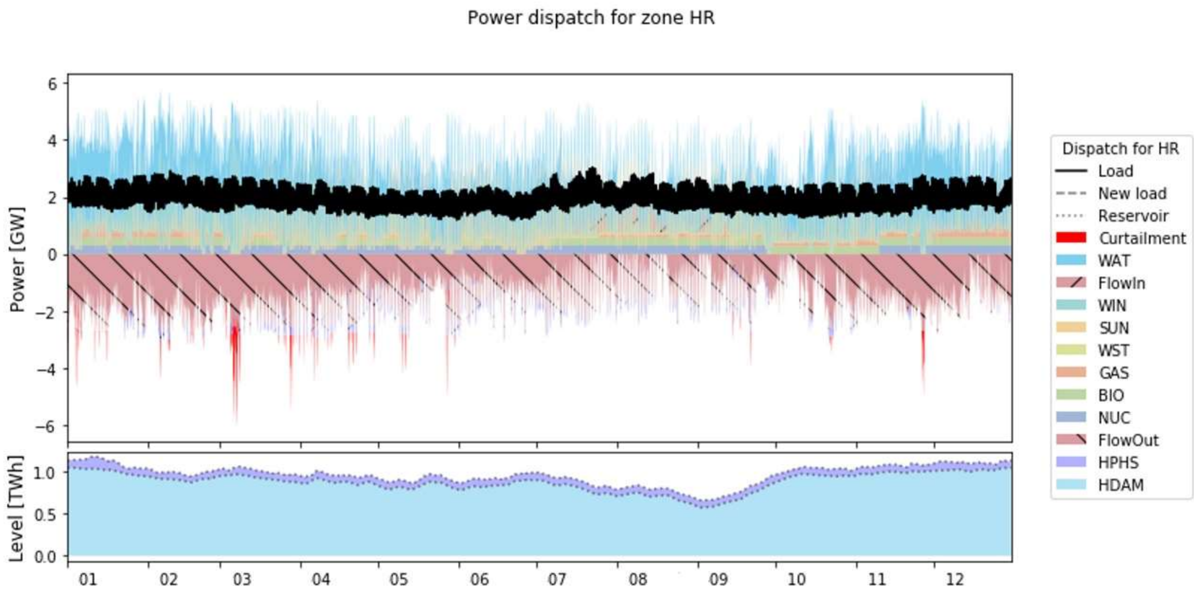

Figure 28 Dispatch for the zone HR in scenario 2030 without V2G

In terms of supply, the discharge of V2G is now compensated by gas, while surrounding zones absorb the increased exports (BA, ME, SI), as shown in Figure 29.

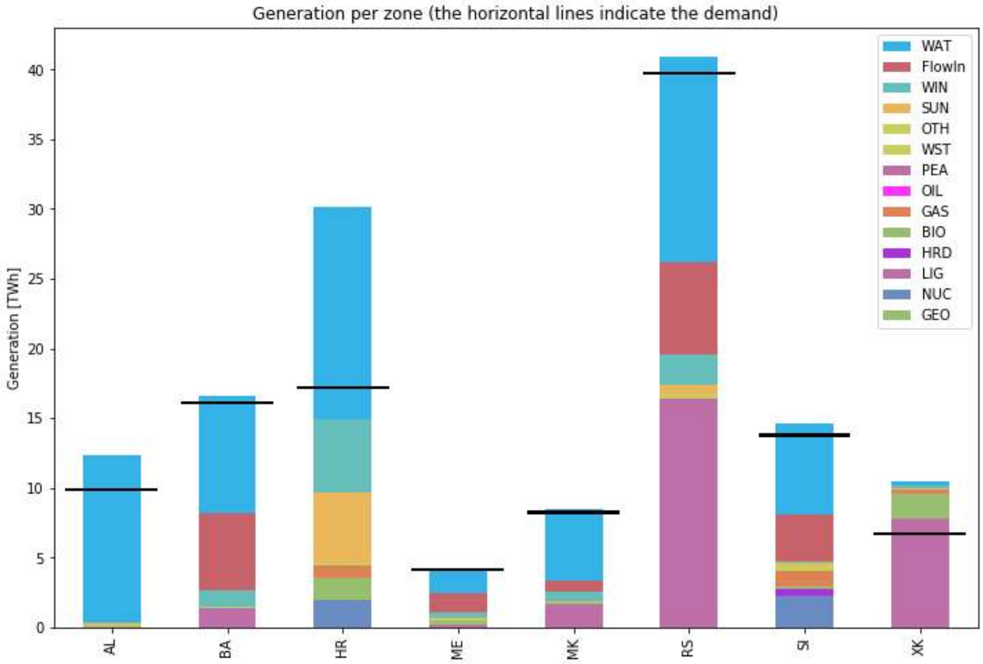

Figure 29 Generation for scenario 2030 without V2G in zone HR

In this case, the resulting average marginal electricity cost is 21.70 €/MWh and the number of congestion hours between zones HR and two large neighbours: BA and RS are at record high, compared to figures from Table 4, amounting to 7065 and 7143 hours respectively. Such results suggest that demand response installations influence the interaction between the zones and the average electricity costs for the market-coupled region more significantly than the proposed change in the CO_2 emissions cost.

4. Conclusion

A method based on the use of Dispa-SET model was demonstrated in this research, on the case of following the consequences of different strategic decisions between the zones in an interconnected electricity market. In scenario analysis, the outputs such as electrical energy flows between the zones and generation from technologies in all zones have been analysed to discuss the influence of different strategic decisions across the region. Main findings can be summarized as follows:

- Decisions for ambitious energy transition (LC and Extreme RES) had the effect of reducing the electricity generation from lignite blocks throughout the case study area (including the zones sticking with fossil or BAU strategy) due to exports of renewable energy from the zones that generated more renewable electricity than they were able to integrate in their energy system.
- The scenario with most zones going for the increased RES integration (2030c) offers the 70% lower average marginal cost of electrical energy compared to “2030” scenario, without causing increase in congestion hours on the cross-border electricity transmission lines.
- Results show that the zones with ambitious decisions benefit at the expanse of less ambitious zones in terms of avoiding stranded cost, while the marginal electricity cost drops for the whole considered region with increase of RES installations.

Perspective for this method can be found in creating the appropriate algorithms for creation of larger number of possible scenarios for each of the zones (including LC scenario for all zones) and creating long-term scenarios (until 2050) for the zones, to investigate the dynamics of energy transition for connected power markets. In the course of such future work, closer attention should be given to various DR and storage technologies, like vehicle to grid, power to heat and other solutions that would provide local flexibility and storage in each of the observed zones and their appropriate mix for different dynamics of energy transition.

5. Acknowledgements

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6. Annex

All the data used for the calculation of scenarios:

- Availability factors for RES power plants (hourly, solar, wind, hydro)
- Cross Border Flows (hourly, historical, between zones)
- Net transfer capacities (NTC) between zones, hourly
- Heat demand (hourly for power plants supplying heat – CHP)
- Scaled Inflow for hydropower storage, hourly
- Reservoir Level of hydro storage, hourly
- Electricity Load, hourly
- Outage factors, hourly
- Power plants database describing parameters for all power plants

can be found on the link: https://github.com/APfeFSB/Strategic-Decisions-Research-2020.git

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PAPER 5

Fast Energy Transition as a Best Strategy for All? The Nash Equilibrium of Long-Term Energy Planning Strategies in Coupled Power Markets

Antun Pfeifer*
Faculty of Mechanical Engineering and Naval Architecture
University of Zagreb, Zagreb, Croatia
e–mail: Antun.Pfeifer@fsb.hr

Felipe Feijoo
School of Industrial Engineering
Pontificia Universidad Católica de Valparaíso, Chile
e–mail: felipe.feijoo@pucv.cl

Neven Duić
Faculty of Mechanical Engineering and Naval Architecture
University of Zagreb, Zagreb, Croatia
e–mail: Neven.Duic@fsb.hr

ABSTRACT

The research links energy system development planning to day-ahead energy markets, market coupling, and renewable energy integration, with a novel approach based on game theory. A two-level method is suggested for long-term energy strategy decisions. In the first stage, four hypothetical zones are simulated using an energy system's operation optimization model, emphasizing electricity flows. Game theory is employed in the second stage to select the best market-coupled zone strategy. A game reflecting transition dynamic, renewables integration, and demand response is formulated in the second step of the approach, where each of the four zones have two possible strategies (fast or slow transition), resulting in 16 sets of strategies (scenarios). Results demonstrate the feasibility of determining a Nash equilibrium, enhancing decision-making compared to prior methods. For the observed hypothetical case, a pure Nash equilibrium is found, where all zones opt for a rapid energy transition.

KEYWORDS

Energy planning, Game theory, Demand response, Flexibility options, Capacity investment, Energy dispatch, Energy transition, Dispa-SET.

1. Introduction

Different approaches have been attempted in the contemporary scientific literature to model the energy transition of a region with an interconnected power system. For example, in a case of South East Europe, different national energy systems have been modelled with the assumption of perfect transmission between the zones, connected as one, in EnergyPLAN [1]. Attempt to model multiple zones with EnergyPLAN was presented for an archipelago in [2], and proven to be useful for simpler systems, without dispatchable generators fuelled by fossil fuels. However, to evaluate impacts of different strategic decisions in the context of connected energy systems and a market based on marginal cost, a tool which can calculate cross-border

* Corresponding author

transmission and unit commitment in several zones at the same time is needed. Such tool was presented in [3], which investigated centralized cogeneration plants with thermal storage, an important technology for energy transition, and it's influence on efficiency and cost of the power system in case of optimized operation. The overall use of Dispa-SET tool for modelling interconnected energy systems with high share of renewable energy is elaborated in [4], for optimized case in a whole year hourly calculation. Authors in [5] used Dispa-SET to test different configurations, with clustered or non-clustered technological formulations. Also, such a tool is well placed in the literature, having in mind hourly calculations on an example of one year of system's operation, which has been underlined as relevant in comparison of energy planning tools with different treatment of a time slice in [6]. Further on, emission taxes as the local restraining method have been used to optimize the long term configuration of an energy system of Chile in [7], with mixed-integer linear programming. Such constraints, appearing in the form of a CO_2 emission price, will appear in this study as well. For the energy system of EU, the expansion of district heating networks powered by combined heat and power plants was analysed using Dispa-SET in [8], to study the relationship between expansion of district heating and integration of renewable energy.

Models describe above (for instance, EnergyPLAN and Dispa-SET) provide the least cost solution for the system or connected systems under study. However, they do not consider individual system preferences. On the other side, game theoretical approaches can analyse such individual preferences. The game theory approach has also been used in this field previously on the level of competition of individual generators and production companies. In [9], a game optimization theory was used to solve distribution and distributed production problems, also, the study cites principle definition of the game theory, "*Game theory, as a branch of applied mathematics, is the study of mathematical models of conflict and cooperation between intelligent rational decision-makers. In addition to being used to describe, predict and explain behavior, game theory has also been used to develop theories of ethical or normative behavior*."

In this context, emissions and transmission capacity constraints were studied in a bilevel game-theoretic approach to model emissions allowance and electricity market interactions in [10], but restrained to the one energy system. The energy system configuration solutions under an emissions trading system were studied also using bi-level programs as well as Pareto optimal programs in [11], and generic framework that used Shapley value from cooperative game theory with the aim to include and study flexibility providers [12] as well. Shapley value from the algorithm that sought the Nash equilibrium for a system of PV, wind power plant, CHP and compressed air unit as a storage was also investigated in [13], yielding better economic performance in cooperative game model, for group and individual cases.

Also, game theory was used to investigate problems of development of new renewable energy (RES) installations in hybrid PV-Wind case in [14] and Wind-Hydropower in case of [15]. For a single facility, it was used in [16], defining a Nash-equilibrium constrained optimization strategy to sequentially synthesize heat exchanger networks (HENs). In, [17] the multi-time-interval non-cooperative game with Nash equilibrium condition is derived for the regulation competition process in clusters of generators using the same technology in the same market. Game theory, precisely a Cournot game, was used in [18] to describe the steps necessary to analyse whether the sustainable idea (e.g., environmental innovation) is environmentally compatible, socially acceptable, and economically viable, but the study was aimed towards the small-medium enterprises (SMEs) involved in production processes. In [19], medium run and long run market simulators were presented, based on game theory. The research was focused on an analysis of producers' behaviour during the first operative year of a national power exchange, concerning two games: unit commitment of thermal units and one for strategic bidding and hourly market clearing. In [20], the authors analyse the main electricity bidding mechanisms, based on the signalling game theory, in the electricity auction markets and considers the degree of information disturbance as an important factor for evaluating bidding mechanisms for energy generators. Introducing strategic storage units (EES), authors in [21] developed the method to find pool equilibria in a system and identify profit-maximization behaviours of different ESSs and generators. Similarly, an iterative Nash equilibrium model for power markets, suitable for application in short and long-term analysis of pool-based electricity markets from the perspective of power companies (bottom-up) bidding on a national or regional power market is presented in [22]. Energy management and storage optimization problems have also been addressed, for example in [23], where a Stackelberg game is introduced. Players try to increase their payoff while ensuring user comfort and system reliability. Additionally, forecasting of the production form solar power plant is introduced to reach optimal prices. The existence and uniqueness of Nash Equilibrium of energy management algorithm are also proved. Demand response management was investigated by implementing game theory-based approach in [24]. An algorithm was devised to maintain the balance and "shave" the consumption peaks to achieve average energy consumption ratio. Stackelberg game was introduced to obtain a solution based on one leader strategy, where leader first decide their best response and followers select their best response on the basis of leader's strategy, until the Nash equilibrium is reached between consumers and utilities. Interesting research [25] uses Cournot game models to devise a behavioural framework of imperfect competition among electricity producers, natural gas and power systems were considered in a case study of a national market.

Issues with finding Nash equilibria in computer simulations of evolutionary games were investigated in [26], concluding that a final set of strategies can avoid such. For this reason, in the present research, a discrete problem is in the focus (matrix game), with a final set of strategies and scenarios available for players. It is argued that such approach is sufficient for practical purposes. Matrix games have been previously used in the literature in different contexts. For instance, research that delt with matrix games include bidding strategies in deregulated markets [27] and matrix games in power systems and obtaining the Nash equilibria in multi-player matrix games [28], concluding that accurately obtaining Nash equilibria provides improved assessment of market performance and design, making the operation of power market stable and avoid major price spikes. In the case of examining the generation capacity investments, cap and trade programmes for CO_2 were investigated for restructured markets in [29].

Cooperative games were studied to create an optimization tool for smart energy logistics and economy analysis problems. Such solutions were found to better optimize and allocate the case of smart deregulated structures in [30]. In following of the economic achievements of energy companies in neighbouring countries, the game theory was used by researchers in [31]. In the economic analysis, game was set up optimal solutions and presents all available strategies for the large energy companies and their relationships. Both non-cooperative game in the form of a 'prisoner's dilemma', and a cooperative game were investigated. A distributed Nash Equilibrium seeking methods were demonstrated in [32] for energy trading in microgrids, with dynamic and non-quadratic payoffs.

Research gap identification

Detailed reviews of the implementation of the game theory in energy planning and solving of the problems related with energy systems configuration development were performed in [33], [34] and [35]. All reviews bring up more than 300 scientific articles published in scientific journals. The most important conclusion of these reviews for the present research is that game theory applications deal predominately with bottom-up problems of the specific generators, agents or actors in the energy market, but not with the top-down approach that is the subject of research in the present paper. In long-term energy planning problems and interaction between zones which include complex, comprehensive energy systems (which include synergies with sectors of energy demand, such as transport and heating), to the best of our knowledge, there is no published research. Additionally, we have not found a research paper that considers the long-term equilibrium of linked energy systems (zones) considering payoffs based on a model that takes decisions at a hourly-level resolution. Most of the published research does consider long-term strategies by calculating payoffs based on, for instance, average availability of renewable sources (yearly capacity factors), or time slices (not fully hourly resolution in a year). Therefore, the approach followed here allow us to estimate payoffs of different zones, and the resulting strategies and Nash Equilibrium, based on hourly level prices and dispatch decisions of different technologies that take into account the variability associated with renewables and the corresponding challenges, such as curtailment or issues associated with the duck-curve.

This research fills the research gap by following the interaction between the zones in a coupled market, that includes demand response, storage and energy transformation technologies in the first stage and proposing the use of game theory in the second stage.

The hypothesis of this research is that optimal decisions in long term energy planning for each market coupled zone can be determined by game theory, through achieving Nash equilibrium with energy strategies of surrounding zones, even in the case of lack of information about them.

Research goals and scope

In a previous research, Dispa-SET was used to model the interconnected system, consisting of several trade zones (country systems). Such interconnected system constitutes a market on which different decisions in each of the zones were investigated [36]. Result demonstrated the influence which energy systems on different level of energy transition (marked by level of integration of VRES and demand response technologies) have on each other. This is visible through unit commitment and energy flows between the zones.

Aim of this research is to propose a method which uses game theory in assessing the long-term strategic decisions of market coupled zones. Such issues have been taken in the current practice as an exogenous variable that was based on: historical data on imports/exports, through historical data on energy prices on the markets and their future development through expert assumptions and calculations.

Result of this research is a new method, which can be proposed as a standard for energy planning of the market zones, which are mostly national energy systems. The new method improves long-term energy planning in the context of market coupled zones, which are part of a larger power market. Such update to the planning approach is beneficial in eliminating inefficient and non-transparent energy policies, which are, in the end, unsustainable and unbeneficial for the users in any zone chosen for creation of new strategies and energy system development decisions.

Structure of the paper

In the chapter 2, proposed two step method is elaborated, in chapter 3 a hypothetical case study is introduced and described, in chapter 4 results are reported and elaborated, with discussion of the possible different results and approach to handle such outcomes. In the last chapter, conclusions are provided.

2. **Methods**

In order to investigate influence which certain strategic decisions, connected to energy transition and the direction which legislation and industry in certain market zone chooses, has on the feasibility of investments in such market zone, an energy planning tool must reflect these decisions though unit commitment and energy flows between the interconnected zones. The information which governs these flows should be merit order according to marginal cost of energy production. Such information is measurable and corresponds to real trends and changes on the energy market, to the idea of energy transition and to development of technologies which we witness today. For these reasons, the Dispa-SET model is chosen to be used in scenario approach analysis in the first step of this research. It is an open-source unit commitment and optimal dispatch model. It is developed within the Joint Research Centre of the EU Commission, in close collaboration with the University of Liège and the KU Leuven (Belgium). Pre-processing and post-processing tools are written in Python, and GAMS is used as the main solver engine. The model is written in the form of Mixed Integer Linear Programming (MILP).

When the national energy strategies are being developed, the present state-of-the-art approach does not take the strategies of other zones/countries in the surrounding as endogenous variable. It is considered through historical data on imports/exports, through historical data on energy prices on the markets and their future development through expert assumptions and calculations. In the second step of the method (after elaborating the cohort of scenarios for all involved zones), for decisions which are examined for the chosen zone, a game will be developed. The goal of the game is to determine how proposed measure or strategic decision influences the feasibility of new installations in the chosen zone, leading to better profitability of planned investments, planned investments becoming unprofitable or reaching a situation in which no zone would improve its feasibility of investments (Nash equilibrium). In principle, the novel, two-level approach proposed in this research is presented in Figure 1.

Figure 1 Principal scheme of the proposed approach

Developing models of energy systems using the Dispa-SET tool

A hypothetical model of the case study area, including ***N*** zones, is developed in the first step of the approach. Detailed description of the build-up of national energy system models in Dispa-SET was presented in [36], and in the same way it should be followed for the first step of the presently proposed approach. Several zones from [36] were selected and the current hypothetical case study is based on them. As mentioned earlier, the Dispa-SET model is a Unit Commitment model that optimizes the energy system under consideration. The optimization takes into account the dispatch of all power units, their status (on-off) and the use of all other technologies (e.g., EV storage) with the goal of finding the least cost operation of the system. The optimization is carried out considering an hourly-level resolution for a whole year. This allows to assess the impact of variable renewable sources and the resulting implication of the payoffs of different zones (see Methods section). Finally, Dispa-SET is chosen over other energy system models (e.g., EnergyPLAN) since it considers the modelling of electricity trade among regions, a key component for this study. Details of the mathematical model behind the Dispa-SET tool are not described here since it is out of our scope and it has also been fully and well documented in related literature, for example in [3], [4], [5], [8], [36] and [37].

Defining the strategic decision matrices

There are a lot of examples in the literature (see Introduction) with two-player games with two possible decisions each. In this step of the study, it is important to provide the opportunity for the investigation of conditions for a target zone (zone 1) that is surrounded by other zones and has the interconnection with them in different ways (only with one, with several, bilateral with one zone, but multilateral with others etc.). For this reason, the demonstration of the proposed approach is focused on more than two players. A game for four players is built based on the concept and algorithm for nontrivial strategic form games by Oikonomou and Jost [38], where an algorithm for games with more than two players was developed. Basic example of a payoff scheme for 4 players, each of them with two strategies, is given in Figure 2. The figure presents the order of calculation of payoffs in such games, which is used in Table 1 to define values corresponding to the strategies chosen by each player (numbers in the figure are from [38] and are not relevant for this study).

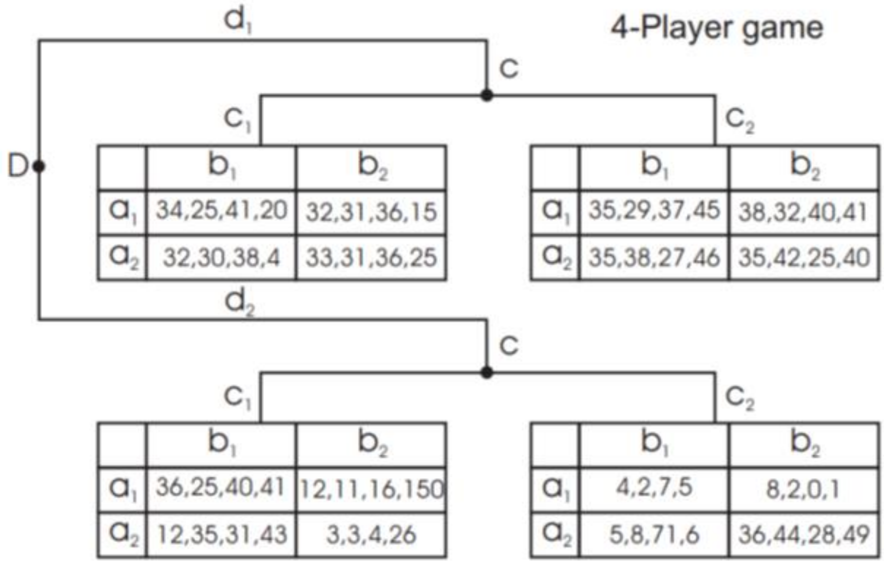


Figure 2 A 4-player game payoff scheme based on [38]

Defining the payoffs and payoff matrices

Results of Dispa-SET modelling include shadow prices of electricity in each hour, production (and resulting capacity factor) for all generators in each hour, heat prices for district heating systems and delivered heat from each of the units equipped with combined heat and power (CHP) or heat generator. Also, results include inputs and outputs of transformation technologies and storage technologies (power-to-heat, vehicle-to-grid, stationary batteries, pump hydro power plants, etc), whose inputs depend on the local balancing in the energy system, but also on the presence of low-cost energy in the surrounding zones. Therefore, the payoff of each zone in the coupled market depends not only on its strategic decisions, but also on the strategic decisions made by its neighbouring zones.

For each strategic decision, the payoff of each zone is calculated considering new investments (generators) in the following way:

- The CAPEX is calculated for all new generators, calculated using data from [39] (Annex 4).
- The OPEX is observed through the standard Dispa-SET calculation and the shadow price is found (for electricity and heat) [4],[5].
- The overall delivered energy from new generators is calculated in the zone, as well as the export to other zones. Earnings of the generator j are calculated as amount of electricity (E_i) (H_i is heat generated in case of combined heat and power generation units, with $P_{heat,i}$ being the price of heat in the considered zone) in the "home" zone i of n, multiplied with the local price of electricity ($P_{el,Zi}$), and exported electricity is multiplied with the price of electricity ($P_{el,\,Zm}$) in the zone of delivery (Z_m).Calculation is performed according to Equation 1.

In this way, the welfare induced (payoff R) for the zone in question equals the sum of earnings of all generators/technologies in that zone.

Equation 1 Payoff from generators

$$\sum_{j=0}^{n} R = E_i \times P_{el,Zi} + H_i \times P_{heat,i} + E_i \times P_{el,Zm} \tag{1}$$

- Storage and transformation technologies generate earnings (R_s) in the "home" zone (Z1) though comparison of the expenditure when charging (Ch_i), with the price in that moment ($P_{el,Zi}$) and earnings when discharging (E_{is}), with the price in that moment ($P_{el,Zi}$) . Calculation is performed according to Equation 2.

Equation 2 Payoffs from storage and transformation technologies

$$\sum_{j=0}^{n} R_{s,Z1} = E_{is} \times P_{el,Z1} - Ch_i \times P_{el,Z1} \tag{2}$$

- For each zone (i), further information can be obtained, such as the return on investment (ROI), expressed in percentage, in the conditions depicted by the strategic decisions of all zones. Calculation is performed according to Equation 3, where R_i is a sum of discounted yearly payoffs for the period between the base year and end year of the calculation.

Equation 3 Return on investment based on the strategic decision

$$ROI_i = \frac{R_i}{CAPEX_i} \tag{3}$$

Defining the game to obtain the Nash equilibrium (equilibria)

The algorithm for obtaining Nash equilibrium for a N-player game with 2 strategies is based on the works of Oyama [40], and the algorithm for mixed best response strategy (mixed equilibrium) from [41] and [42]. Next, we formally define the N-Player game (Normal Form Game) and the concepts of best response, pure equilibrium, and mixed equilibrium.

The N-player Normal Form Game is defined as a triplet $g=(I,(A_i)_{i\in I},(u_i)_{i\in I})$ where

- $I = \{0,\dots, N-1\}$ represents the set of players,
- $S_i = \{0,\dots, s_j\}$ represents the set of strategies of player $i\in I$, and
- u_i: $A_0\times A_1\times\cdots\times A_{i-1}\times A_i\times A_{i+1}\times\cdots\times A_{N-1}\rightarrow$R represents the payoff function of player $i\in I$.

Given the Normal Form Game $g=(I,(S_i)_{i\in I},(u_i)_{i\in I})$, the *Nash* Equilibrium of the game is defined by the best response concept of each player in the game. A best response is defined as: *A strategy $s_i \in S_i$ of player $i \in I$ is a best response of player i against $s_{-i} \in S_{-I}$ (strategy of all other players) if $u_i (s_i, s_{-i}) > u_i (s'_i, s_{-i})$ for all $s'_i \in S_i$.* Therefore, the strategy profile $s^* = (s^*_0, s^*_1, \dots, s^*_{N-1})$ is ***said to be a Nash Equilibrium*** if s^*_i is a best response for every player $i \in I$. The Nash Equilibrium hence represents a solution of a game where no player can unilaterally change its strategy and improve its payoff. Also, note that every Normal Form game has at least one Nash Equilibrium. Such equilibrium is said be a Pure Nash Equilibrium if all players play their strategy with probability of 1 (certainty), or a Mixed Nash Equilibrium if at least one player plays a strategy with a probability less than 1. For a formal definition of pure and mixed equilibrium, readers are referred to [43].

The principal table of strategies per player based on the 4-player game with 2 possible strategies used in this article is given in Table 1. Each combination of strategies represents a scenario (set of strategies) of different evolutions of the energy system of different zones, which is being calculated using the Dispa-SET model.

Table 1 Payoff table for a 4-player game with 2 possible strategies

No. of scenario	Set of strategies in 4-player game with 2 strategies (0, 1)			
1	1	1	1	1
2	1	0	1	1
3	0	1	1	1
4	0	0	1	1
5	1	1	0	1
6	1	0	0	1
7	0	1	0	1
8	0	0	0	1
9	1	1	1	0
10	1	0	1	0
11	0	1	1	0
12	0	0	1	0
13	1	1	0	0
14	1	0	0	0
15	0	1	0	0
16	0	0	0	0

3. Case study of a principal example

Four hypothetical zones are introduced, with configurations in the year 2030 as an initial year of “BAU” target (presented in Table 2), and different decision for the development of their configurations until 2050, which can result from a strategy to go for slow transition (ST) or fast transition (FT) from the configuration in 2030 towards a system based on RES and various flexibility options: heat pumps in district heating and heat storage (P2H), stationary batteries, electric vehicles in vehicle-to-grid mode (V2G). Also, combined cycle gas turbines (CCGT) do not imply the necessity that only fossil gas is used, but rather different gaseous fuels, with either synthetic, biogas or hydrogen base. Such CCGT units offer more flexible operation, while remaining cheaper and faster option to be built instead of, for example nuclear power plants, especially having in mind H_2-readiness that is being discussed already by 2030, even though their competitiveness is lowered in the presence of storage and V2G technologies [44]. Nuclear energy is considered only as a part of slow transition scenarios, as it is found that scenarios without relying on it are more feasible [45]. Inputs were based (configuration in Table 2) on the zones from [36], which was focused on the interesting region of Western Balkans, where national energy systems are on the border of different legislative conditions (bordering EU) and are based predominantly on the combination of coal power plants and hydro power plants. Similar category of problems may in future be encountered in other parts of the World. The complete data set is available in Annex 2. For the hydro scheduling, regional and annual option was selected for all scenarios.

Such configurations (tables 2-4) are expertly constructed, proposing a stable configuration (tested in Dispa-SET) for the hypothetical zones. As the hypothetical case serves for the illustration of the approach, configurations are proposed with the goal to include typical case of achieving the pure Nash equilibrium.

Table 2 Energy systems configuration in 2030

	2030			
Installed capacity [MW]	Z1	Z2	Z3	Z4
Coal	192	3402	1063	3000
Gas	480	353	297	0
Nuclear	0	0	700	0
Hydro	2788	3598	1122	2746
Wind	1368	1000	154	564
Solar	1000	200	1668	300
P2H	200	0	0	0
V2G	317	0	0	0
Battery storage	0	0	0	0
Biomass	275	30	93.33	14.5
El. Demand [TWh]	17.699	40.969	14.2	14.443

In Table 3, the configuration of the energy system of each zone when all zones opt for a slow transition scenario is presented.

Table 3 Energy systems configuration in 2050 in case of slow transition (scenario 16)

	2050 slow transition			
Installed capacity [MW]	Z1	Z2	Z3	Z4
Coal	0	3000	0	2000
Gas	350	1100	500	150
Nuclear	0	0	1000	0
Hydro	2988	4900	1600	3000
Wind	3368	2000	154	1000
Solar	3000	800	2000	600
P2H	400	0	0	0
V2G	2317	750	500	0
Battery storage	250	500	0	0
Biomass	350	200	150	50
El. Demand [TWh]	23.01	53.26	18.46	18.78

In Table 4, the configuration of all zones is presented for the case where all zones opt for the fast transition scenario.

Table 4 Energy systems configuration in 2050 in case of fast transition (scenario 1)

	2050 Fast transition			
Installed capacity [MW]	Z1	Z2	Z3	Z4
Coal	0	0	0	0
Gas	550	750	350	300
Nuclear	0	0	0	0
Hydro	3288	6200	2000	3500
Wind	5868	5000	200	2000
Solar	4500	7000	3500	2500
P2H	500	0	0	0
V2G	5617	6000	5500	3000
Battery storage	2000	3500	1000	500
Biomass	350	700	450	250
El. Demand [TWh]	23.01	53.26	18.46	18.78

Further information needed for the modelling in Dispa-SET includes prices of fuels, emissions, and particular operations/services. Such information is presented in Table 5.

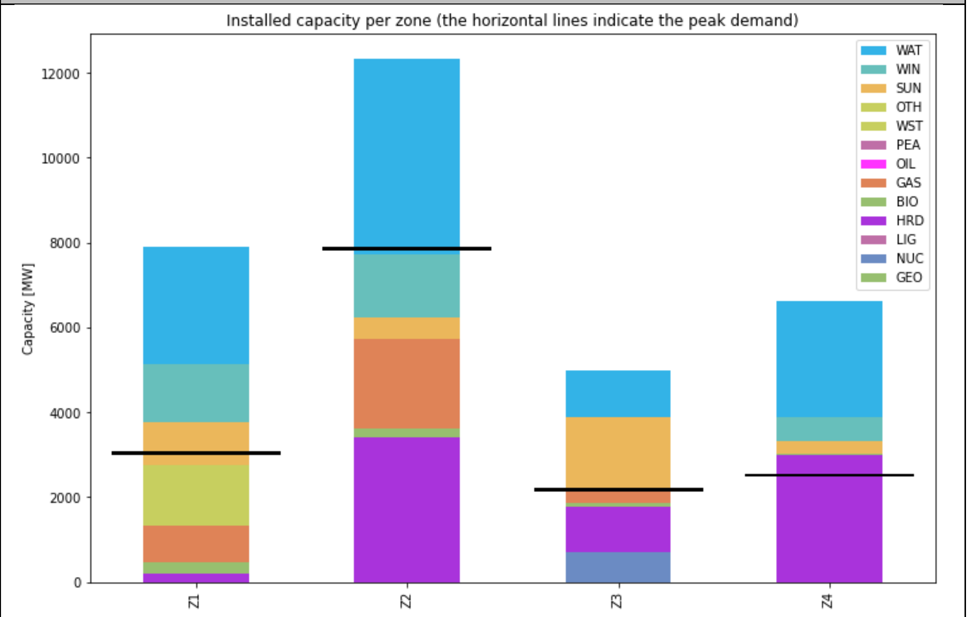
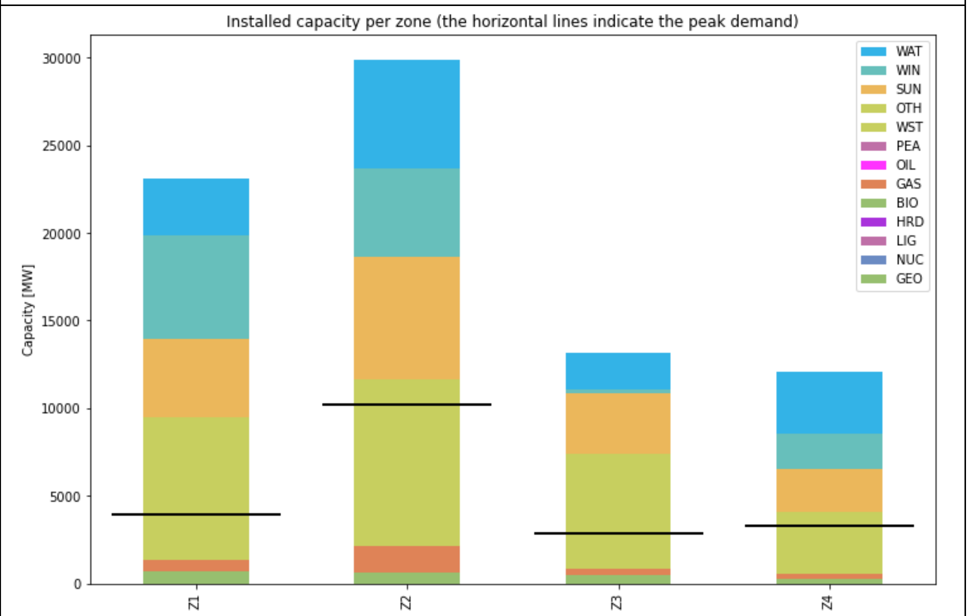
Table 5 Prices of relevant fuels and services

	€/MWh
Price of CO_2 (€/tonne)	150
Price of Unserved Heat	200
Load Shedding Cost	1500
Price of Nuclear	3
Price of Black coal	35
Price of Gas	40
Price of Fuel-Oil	75
Price of Biomass	37
Price of Lignite	48
Price of Peat	48
Value of Lost Load (VOLL)	100000
Price of Spillage	1
Water Value	400

4. **Results**

Results of the calculations in Dispa-SET tool are attained for all scenarios, with Table 6 showing 3 typical cases described above (benchmark case in 2030, scenario 1 and scenario 16) and Table 7 showing the results of unit commitment and dispatch optimization, with representation of whole year (hourly resolution, months in the year on the horizontal axis). The typical cases are used to illustrate the reductions in installed coal power plants and CCGT/GT generators in different scenarios. In scenario 1, CCGT is of significantly smaller capacity compared to base case in 2030 or scenario 16 in 2050.

Table 6 Dispa-SET results for the typical cases – input redouts of generation capacities

Year	Inputs readout – generation capacities
2030	
2050 scenario 1	

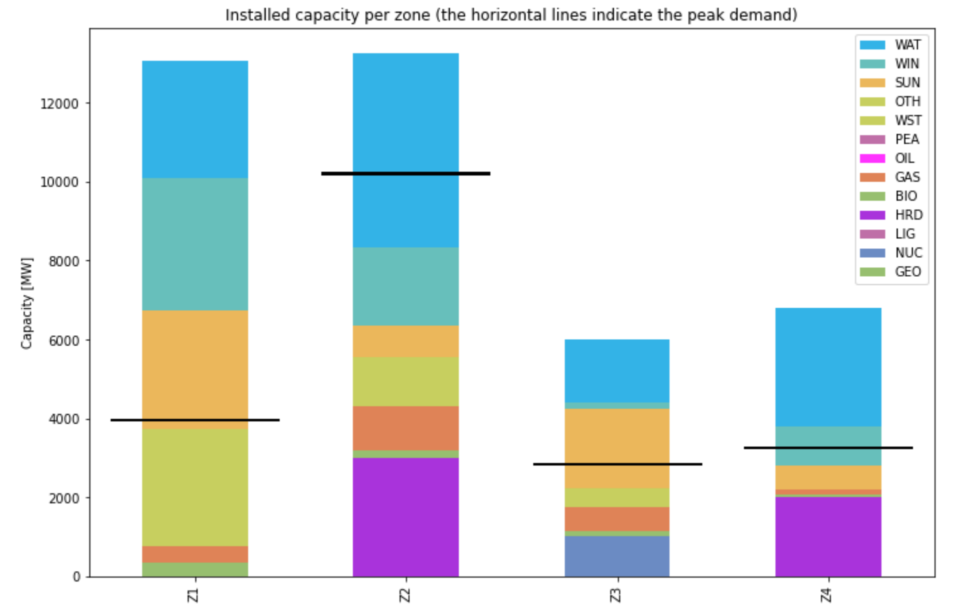
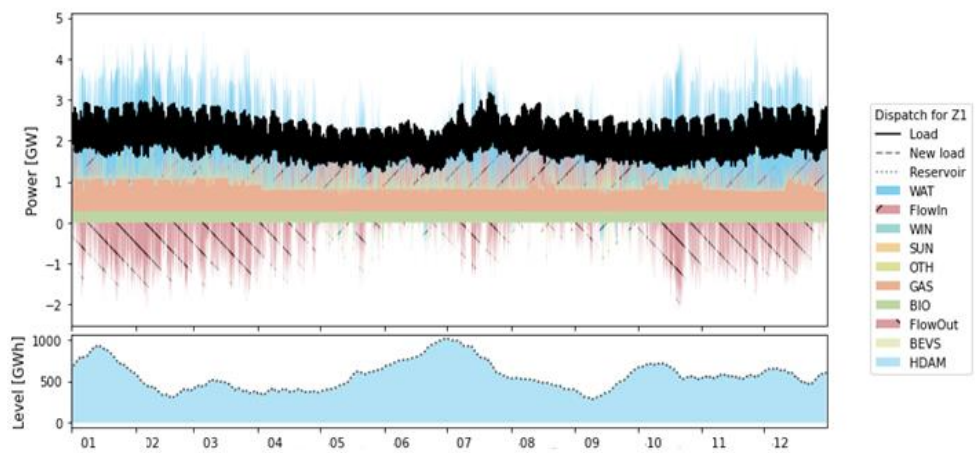
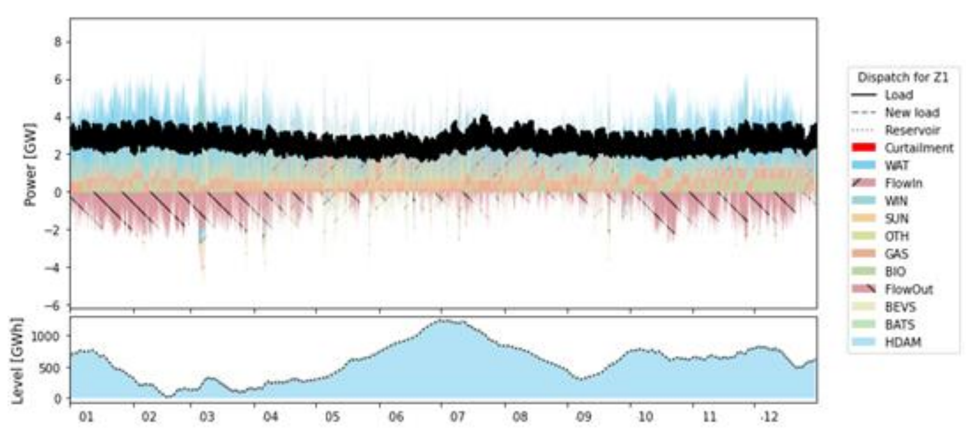
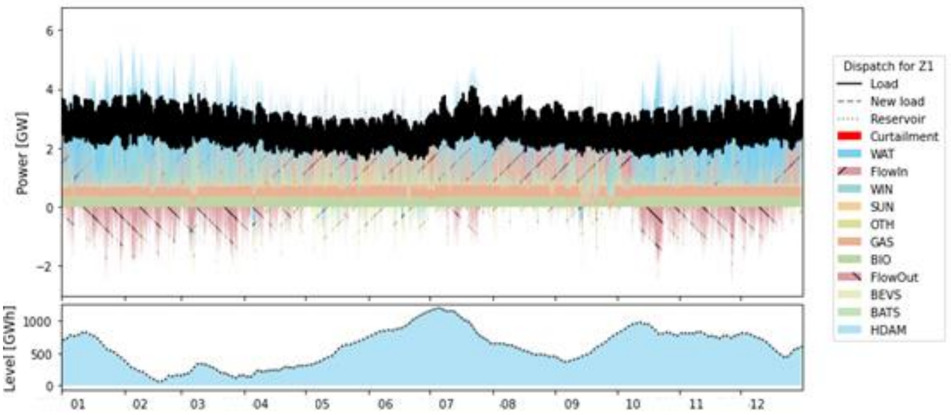
2050 scenario 16	

Table 7 Dispa-SET results for the typical cases – unit commitment and dispatch for selected zone

Year	Unit commitment and dispatch for Z1
2030	
2050 scenario 1	

2050 scenario 16	

Visible changes between dispatch in 2030 and the scenario 1 dispatch in 2050 underline the transition from coal and gas towards VRES. Generators of the type CCGT or GT are used as peak units in flexible operation. This is to the lesser degree noticeable also for scenario 16 in 2050.

Payoffs as inputs to the game matrix

Payoffs are calculated based on the results of Dispa-SET models for all scenarios and the equations (Equation 1, Equation 2). Resulting values are presented in Table 8. Post-processing necessary for this calculation is done in Microsoft Excel and includes calculating the revenue of all generators, revenues from imports/exports and different storage and flexibility providing units.

Table 8 The payoff matrix for each zone in all scenarios [10^9 EUR]

	Matrix of payoffs			
No. of scenario	Z1	Z2	Z3	Z4
1	1.660	3.526	0.171	1.152
2	2.843	3.782	0.149	2.103
3	1.910	5.631	0.733	2.224
4	11.159	6.871	-0.598	3.959
5	1.579	2.961	0.902	1.265
6	2.322	5.679	1.009	2.055
7	1.088	3.739	1.088	1.588
8	1.715	5.464	4.313	3.201
9	2.854	6.410	0.157	0.652
10	3.943	7.109	0.326	2.104
11	1.188	7.629	0.948	1.767
12	2.189	6.970	1.499	3.083
13	2.108	5.406	0.848	0.618
14	3.168	7.134	1.488	-0.589
15	1.697	6.768	2.017	1.236
16	3.239	10.309	3.957	1.808

Game results and Nash equilibria

The values from Table 8 were used as an input data for a *gt.NormalFormGame*, defined in the methods chapter with 4 players that have 2 strategies each, forming the payoff matrix. After using the attached code to search for a Nash Equilibrium for such a game, the solution that was found is that the game has a single pure Nash Equilibrium: scenario 1, with the strategy (1,1,1,1). In this way, the scenario with fast transition for all zones was found to be the best strategy of all players. This is due to the large incomes from generators that was moved to flexibility options, such as vehicle to grid, power to heat, and storages in form of stationary batteries, hydropower plants' dams or pumped hydro. Weather the information about the other zones' strategies is publicly available or not, the scenario analysis and a game, like the one analysed above, can be created for various possible scenarios and the Nash equilibrium can be sought, with the goal to identify what would be the best strategy for all involved zones. To show an illustration of the above consideration, one can argue why (1,1,1,0) is not good for Z4, for example: **(**1,1,1,1) is in payoff values equivalent to (1.660, 3.526, 0.171, 1.152), while (1,1,1,0) is in payoff values equivalent to (2.853, 6.410, 0.157, 0.652). In the first case (all FT), Z4 fares relatively best, while in the second case, it achieves only 56% of the payoff, while other zones increased their payoff comparatively. Additionally, the payoff is being distributed to flexibility options, which use cheaper energy and make profit in their zone, which is the occurrence that is prevalent in the case of zone choosing the FT strategy.

Discussion on the mixed strategies

In many cases, a situation arises with less clear solution, i.e. without a pure Nash equilibrium. For example, if the payoff matrix was slightly different compared to Table 8, the following situation, with inputs given in the Table 9 can arise. The main difference between the tables is in the fact that the Table 9 presents values that don't take into account end-users flexible demand (demand response schemes), nor do they penalize curtailments and shed load. For this reason, different values become the final result of the calculation.

Table 9 Alternative payoff matrix with changes [10^9 EUR]

	Matrix of payoffs			
No. of scenario	Z1	Z2	Z3	Z4
1	1.724	3.194	0.237	1.124
2	3.126	3.728	0.237	2.107
3	2.046	5.849	0.908	2.259
4	11.596	6.754	-0.178	3.992
5	1.579	2.961	0.902	1.265
6	3.440	6.770	1.399	0.688
7	1.315	3.858	1.078	1.582
8	2.104	5.551	4.353	3.195
9	3.012	6.767	0.234	0.609
10	3.140	3.500	0.330	0.345
11	2.210	5.950	1.100	0.850
12	3.050	0.040	0.100	1.600
13	2.253	5.768	0.850	0.578
14	3.517	6.883	1.466	-0.667
15	1.500	3.990	1.020	0.800
16	3.149	0.003	3.907	1.716

After the pure Nash equilibrium was calculated for such game, none were found for inputs from Table 9. The next step was applying the McLennan-Tourky algorithm for mixed Nash equilibrium, which returned the results displayed in Table 10.

Table 10 Mixed Nash equilibrium results

Mixed equilibrium	[1, 0], [0.948, 0.052], [0.282, 0.718], [0, 1]
Epsilon	0.001
Initial step	(0, 0, 0, 0)

The results are interpreted as follows: Zone 1 ideally opts for the strategy "FT" in 100% of cases, Zone 2 opts for the strategy "FT" in 95% of the cases, Zone 3 opts for the strategy "ST" in 72% of the cases, while Zone 4 opts for the strategy "ST" in 100% of the cases. In such a mixed strategy case, it is noticeable that the largest system has the highest influence on the best strategy for all. In such situation, smaller systems, like Z3 and Z4 compared to Z2, have less incentive to opt for FT and stick with ST instead, while being mostly supplied with cheap energy from other zones. This leads to detriment of investments in such, smaller zones with slow development.

<u>Discussion on the return on investment</u>

Major repercussion of a different strategic choice between zones is the return on investment and its distribution between generators. In general, higher and more stable shadow price of electricity signals the lower distribution of benefits (i.e., benefits staying with the vertically integrated power companies, larger and centralized power generation), while lower prices are associated with larger share of RES, more flexibility options distributed among different companies and end users. In Figure 3, this difference is underlined for scenarios 1 (all FT, strategy (1, 1, 1, 1) and 16 (all ST, strategy (0, 0, 0, 0)).

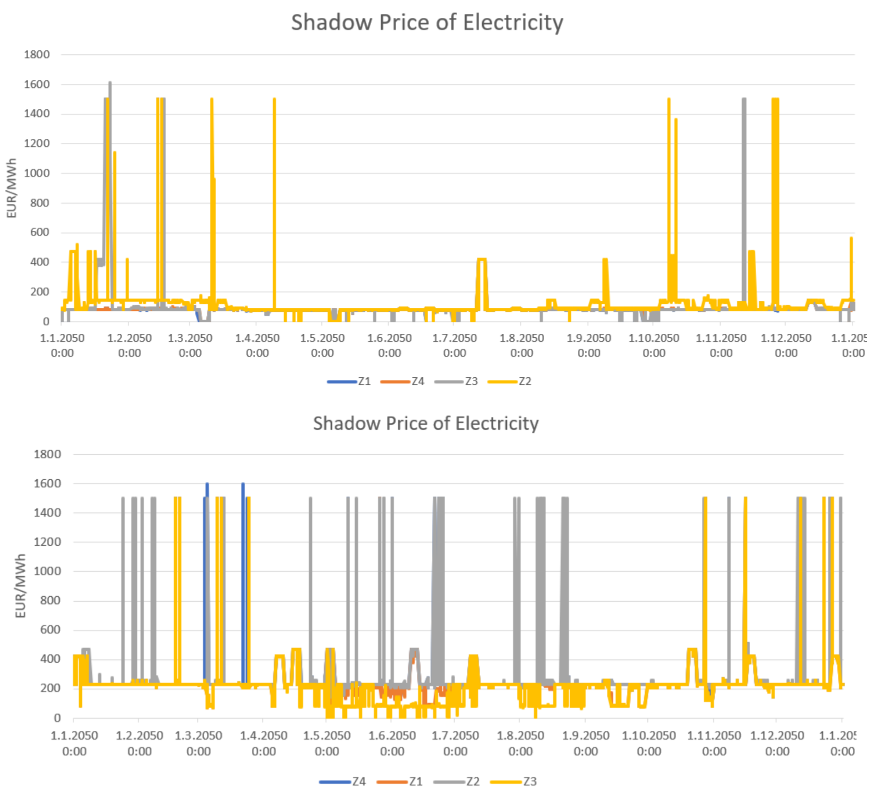


Figure 3 Comparison of Shadow Prices of Electricity in Scenarios 1 (upper distribution) and 16 (lower distribution)

To calculate the ROI, the investment costs for additional generation and storage facilities have been taken from [46]. By assuming the calculated year to be the typical year of the period 2030-2050, the ROI was calculated for each zone and for all scenarios. A diagram in Figure 4 for the case of (1,1,1,1) demonstrates the positive ROI for such case, with payoffs discounted using three different discount rates (“DR” in figure), 3%, 6% and 9% respectively.

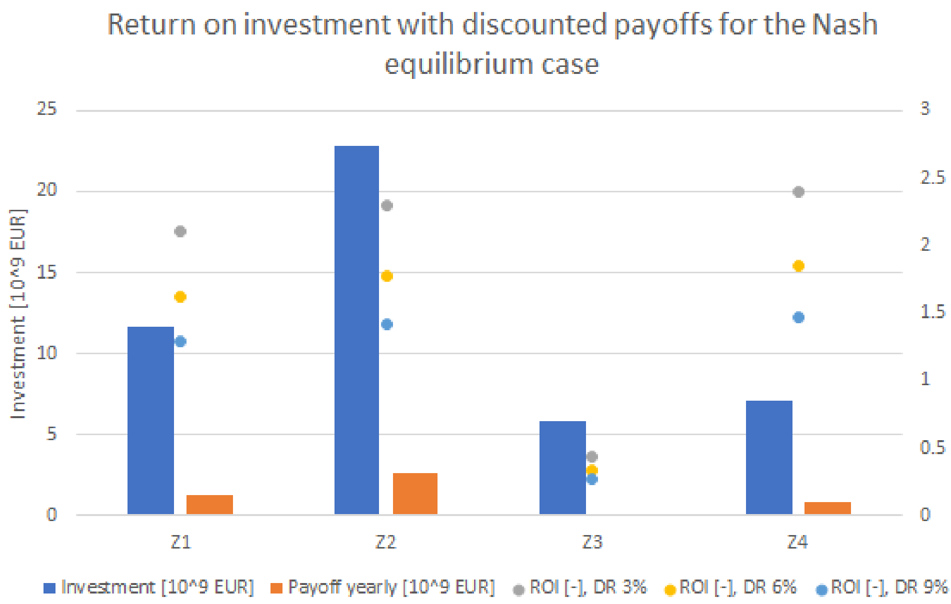


Figure 4 Return on investment with discounted payoffs for the Nash equilibrium scenario

This demonstrates the positive ROI for all zones in the case of the Nash Equilibrium scenario. ROI can sometimes be much larger for some zone in cases of different scenario and strategic choice, but the difference in such cases between zones opting for ST and FT is found in the larger resulting shadow prices of electricity, higher incomes of the generators that emit more greenhouse gasses and particles, while distributed generation, distributed storage, flexibility options and end users with own power generation do not receive benefits. If all zones opt for such strategies, energy transition is stopped. In that way, strategy (0, 0, 0, 0) secures that payoff remains in vertically integrated power companies, does not provide access to the energy markets for the end-users and provides persistent high emissions of greenhouse gasses.

<u>Constraints and limitations of the approach</u>

Major constraint of the approach in the first step is in the fact that Dispa-SET is a model that runs for a year with a set energy systems’ configuration. For this reason, the observed year always represents an average year of operation of the coupled region (set of energy systems).

This limitation makes the current research only a conceptual showcase but offers a good starting ground for development in terms of more precisely defined inputs and development of the future model, which would combine ability to model unit commitment and dispatch of all technologies present in the configuration of energy system (used in Dispa-SET), with the long-term optimization of such a configuration. A novel tool that could be developed in this direction is presented in [47].

In the second stage, use of game theory depends on the inputs from post-processing of the Dispa-SET results in MS Excel, which would benefit from automation.

A relevant issue of the sensitivity of the approach and results on the changes of prices from Table 5 can be observed in comparison to [36], where it was discussed through the significant rise in emissions prices. In the present case, the prices are already much higher. Increase of the prices of fuel would shift the operation of the system more towards investments in storage technologies or import of electricity from the rest of the World, as fossil-fuelled generators become even less competitive. Reduction in prices of fuel, depending still on the price of emissions, might slow down the transition towards storage technologies and demand response solutions, in favour of gas-fuelled generators. Such considerations are relevant for the first stage of the calculation (using unit commitment and dispatch optimization). For future work, more detailed analysis could be performed using long-term energy system's configuration optimization models, such as the one presented in [47].

The proposed modelling approach is generally enough to account for different input parameter values. Indeed, the idea of the second stage (game theory), is to find an equilibrium (pure or mixed) under the market conditions defined in the first stage. These market conditions depend, among others, on fuel prices, technology investment costs, learning curves, demand estimates, etc. Hence the proposed approach allows the user to assess how an interconnected system would evolve (country or regions strategies) under such market conditions.

<u>Discussion in comparison with state-of-the-art approaches</u>

In some previous approaches, the energy system of interest was modelled in various software packages, either simulation [48] or optimization approaches, but the external market (of the surrounding zones) was exogenously modelled using the prices of regional day-ahead power markets [49]. In terms of the simulation approaches, interconnected archipelago was considered in [2], but without the ability to follow the power flows between the connected zones in case the strategic decisions were different and would include dispatchable generators, possibly with the use of fossil fuels or synthetic fuels. In [31], the idea to use game theory for the power companies of two neighbouring countries and to analyse their interaction was elaborated, but without modelling the energy systems, technical applications and technologies that would appear in the future configurations of energy systems (owned by some particular company or not) and any considerations from the discipline of energy planning. Two forms of game theory were presented: non-cooperative game in the form of a 'prisoner's dilemma', and a cooperative game between two gas companies, concluding that cooperation strategy would be the Nash equilibrium of the studied case. In the field of energy systems planning and analysis, most recent review papers [33], [34] and [35] have shown that the game theory was mostly used for individual generators, groups of generators, market opportunities analysis and similar bottom-up approaches (good example is found in [22]), while the approach similar to [31] and the method proposed in this research, were not studied.

The present research builds upon the above-mentioned efforts by proposing a method that connects the modelling of integrated energy systems, which include concepts and technologies mentioned, non-exhaustively, in the European Green Deal, Fit for 55 strategy, and RED II, and recognized as instrumental for the energy transition. Further on, the approach endogenizes the strategy of zones neighbouring the studied zone in the interconnected energy market, which is a step forward in robustness of the energy planning approach compared to studies such as [48] or [49] and improvement in the implementation (due to power flow following) compared to [2]. Finally, it is more complex and comprehensive approach in the field of game theory and energy planning compared to [31].

As such, the proposed approach can be useful for applications in the regions of the world which include multiple zones with different legislation and strategic layouts, such as Southeast

Europe, which includes EU and non-EU countries. It offers more robust help for decision-making, as it connects energy system modelling, context of the interconnected market and the use of game theory to better showcase the best options for all involved market zones.

5. Conclusions

In this study, a novel two-stage approach to energy planning of a zone in the interconnected energy market was presented, using energy system modelling in Dispa-SET and an algorithm that uses game theory approach to determine the optimal decision for each zone. It was shown that optimal decisions in long term energy planning for each market coupled with neighbouring zones can be determined in this way, through achieving a Nash equilibrium with energy strategies of surrounding zones. This approach can be used for every zone, assuming the other zones' strategies, even in the case of lack of information about them. In case of not finding the pure Nash equilibrium, it is possible to use the algorithm for fining the mixed strategy solutions, which still helps in decision-making, thus providing the robustness to the approach presented in this research.

Outcome of this research is a new method, which can be proposed as a standard for energy planning of the market zones, which are mostly national energy systems. The new method is proposed as an improvement of the long-term energy planning in the context of market coupled zones, which are the part of larger power market. In the presented results, the approach has been demonstrated on a hypothetical case study, showing how the Nash Equilibrium is found for a 4-player game with 2 available strategic choices, which generated 16 scenarios. Also, return on investment for the pure Nash Equilibrium of the scenario (1,1,1,1) is positive for all zones, offering the lowest average shadow prices of electricity and higher distribution of benefits among different producers and service providers. The case of an approach for finding the mixed strategy when no pure NE is present is also demonstrated and discussed. The approach that is used for such cases is employing the McLennan-Turkey algorithm for finding a mixed strategy. Result for the discussed case emphasizes problems that smaller systems can have with investments in energy transition, as in mixed strategy, their strategy of choice remains slow transition.

Current research is conceptual, but for the implementation in the energy planning and decision-making, the method can be applied using a long-term energy systems configuration optimization tool, which would enable the users to follow the difference throughout the observed period. Currently such tools, available on the market, do not offer similar solutions using the game theory and considering interconnected energy systems as market zones. Crucial next step in the proposed method would be the integration of the presented method with the software solution that offers interconnected market with zones, ability to follow the power flows between them and optimization or simulation of the investments between the initial and final year of the calculation.

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CRediT authorship contribution statement

Antun Pfeifer: Conceptualization, Data curation, Writing - original draft, Investigation, Software, Methodology, Writing - review & editing. **Felipe Feijoo**: Conceptualization, Methodology, Writing - review & editing. **Neven Duić**: Conceptualization, Resources, Supervision, Funding acquisition.

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8. Annexes

Annex 1 – code for pure NE and added code for the mixed strategy

```
import numpy as np

import quantecon.game_theory as gt


matrix = [[[[[1.723914597, 3.194019468, 0.237381426, 1.124395533], [3.126414336, 3.728367225, 0.237510482, 2.106827014]],

   [[2.046564428, 5.849487245, 0.907841443, 2.258619589], [11.59626367, 6.754134253, 0.07815991, 3.992328831]]],


  [[[1.579736804, 2.960789234, 0.902110104, 1.264741331], [3.44, 6.77, 1.399, 0.688]],

   [[1.314823356, 3.857824702, 1.078298267, 1.581875913], [ 2.103802984, 5.550787453, 4.353334659, 3.195112566]]]],
```

```
 [[[[3.011688553, 6.767498642, 0.233594034, 0.608640459],     [3.14, 3.5,
0.33, 0.345]],
  [[2.21, 5.95, 1.1, 0.85],    [ 3.05,  0.04,  0.1,  1.6]]],


  [[[2.253315447, 5.767640774, 0.850340372, 0.577714048],    [ 3.51679587,
6.882590945,  1.466068594,  0.166665528]],
   [[ 1.5,  3.99,  1.02,  0.8],   [  3.148592619,  0.00270673,  3.907311058,
1.715562937]]]]]


User = gt.NormalFormGame(matrix)


print(User)


def print_pure_nash_brute(User):
    """
    Print all pure Nash equilibria of a normal form game found by brute force.


    Parameters
    ----------
    g : NormalFormGame


    """
    NEs = gt.pure_nash_brute(User)
    num_NEs = len(NEs)
    if num_NEs == 0:
        msg = 'no pure Nash equilibrium'
    elif num_NEs == 1:
        msg = '1 pure Nash equilibrium:\n{0}'.format(NEs)
    else:
        msg = '{0} pure Nash equilibria:\n{1}'.format(num_NEs, NEs)


    print('The game has ' + msg)


print_pure_nash_brute(User)


NE = gt.mclennan_tourky(User)
NE, res = gt.mclennan_tourky(antun, full_output=True)
```

```
res
print(NE)
print(res)
```

Annex 2 – Dispa-SET database (made available on GitHub)

https://github.com/APfeFSB/GameTheoryResearch

Annex 3 – A table of the database mix for all scenarios

The following database matrix, presented in the Table 11, is used to create different configurations of energy systems Z1-Z4 depending on the strategic decisions of different zones. It uses configuration from Table 3 and Table 4 to permutate between the strategies and generate scenarios 2-15.

Table 11 Database matrix

	Database configuration			
No. of scenario	Z1	Z2	Z3	Z4
1	FT	FT	FT	FT
2	FT	ST	FT	FT
3	ST	FT	FT	FT
4	ST	ST	FT	FT
5	FT	FT	ST	FT
6	FT	ST	ST	FT
7	ST	FT	ST	FT
8	ST	ST	ST	FT
9	FT	FT	FT	ST
10	FT	ST	FT	ST
11	ST	FT	FT	ST
12	ST	ST	FT	ST
13	FT	FT	ST	ST
14	FT	ST	ST	ST
15	ST	FT	ST	ST
16	ST	ST	ST	ST

Annex 4: CAPEX calculations data

Table A4. CAPEX of electricity generation technologies based on [39]. Difference between configuration in 2030 and 2050 is established for each technology and multiplied with the specific CAPEX from the table below.

CAPEX of technologies	
Technology	MEUR/MW
Wind	1.01
Solar	1.35
Hydro	2.5
Gas	0.8

Biomass	1.44
Battery	0.508