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

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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

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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.

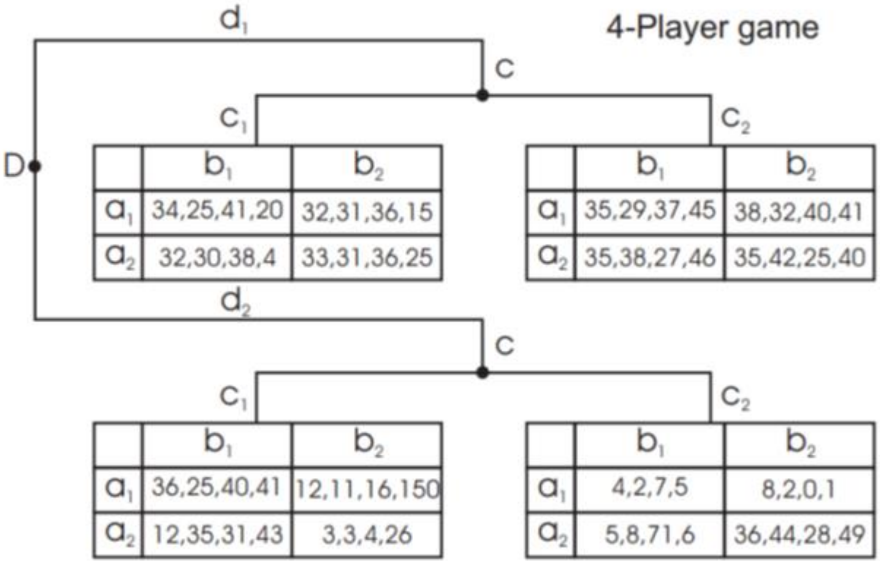
Figure 1 Principal scheme of the proposed approach

<u>Developing models of energy systems using the Dispa-SET tool</u>

A hypothetical model of the case study area, including $\boldsymbol{N}$ 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).



	b_1	b_2
a_1	34,25,41,20	32,31,36,15
a_2	32,30,38,4	33,31,36,25

	b_1	b_2
a_1	35,29,37,45	38,32,40,41
a_2	35,38,27,46	35,42,25,40

	b_1	b_2
a_1	36,25,40,41	12,11,16,150
a_2	12,35,31,43	3,3,4,26

	b_1	b_2
a_1	4,2,7,5	8,2,0,1
a_2	5,8,71,6	36,44,28,49

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

- $I = \{0,\ldots, N-1\}$ 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 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.

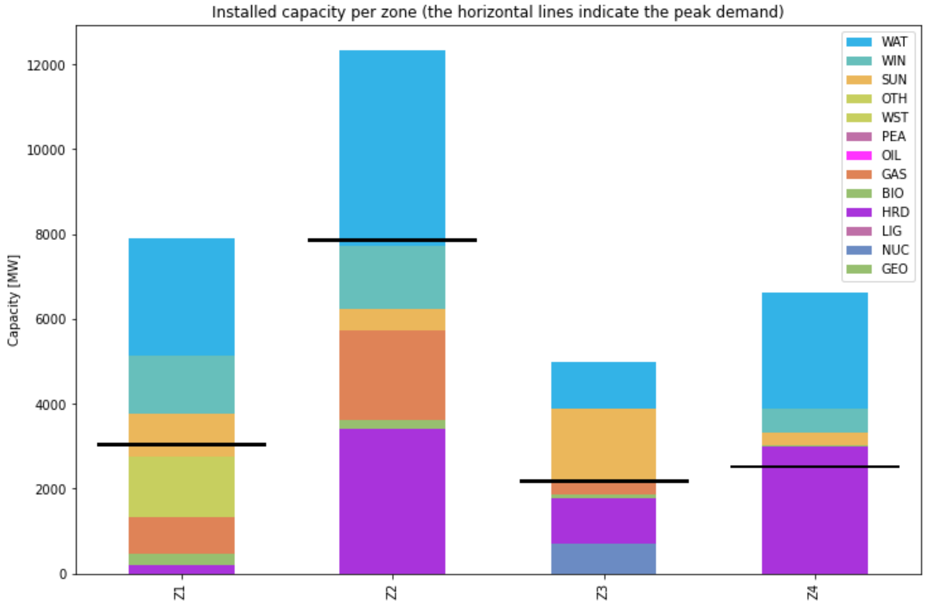
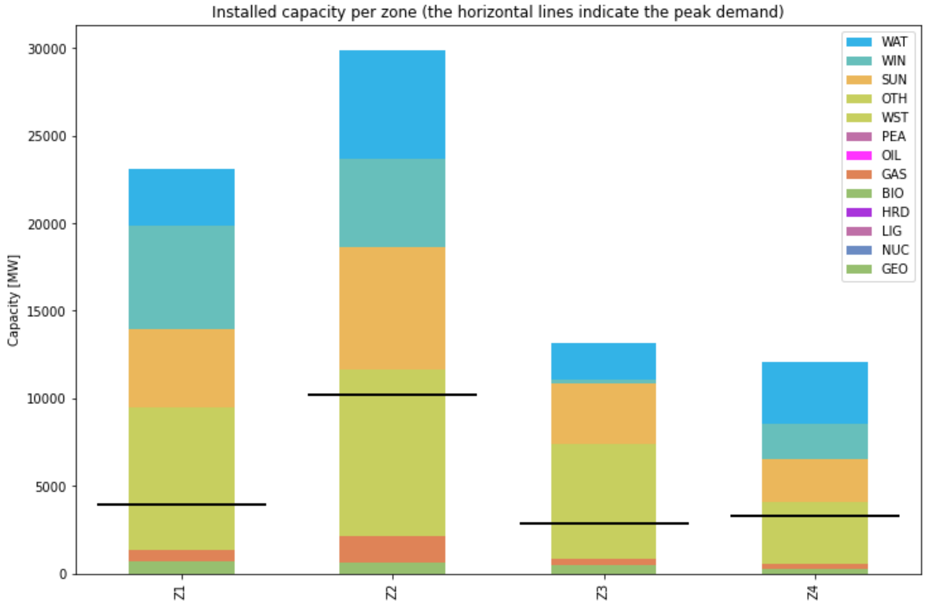
Table 5 Prices of relevant fuels and services

	€/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	

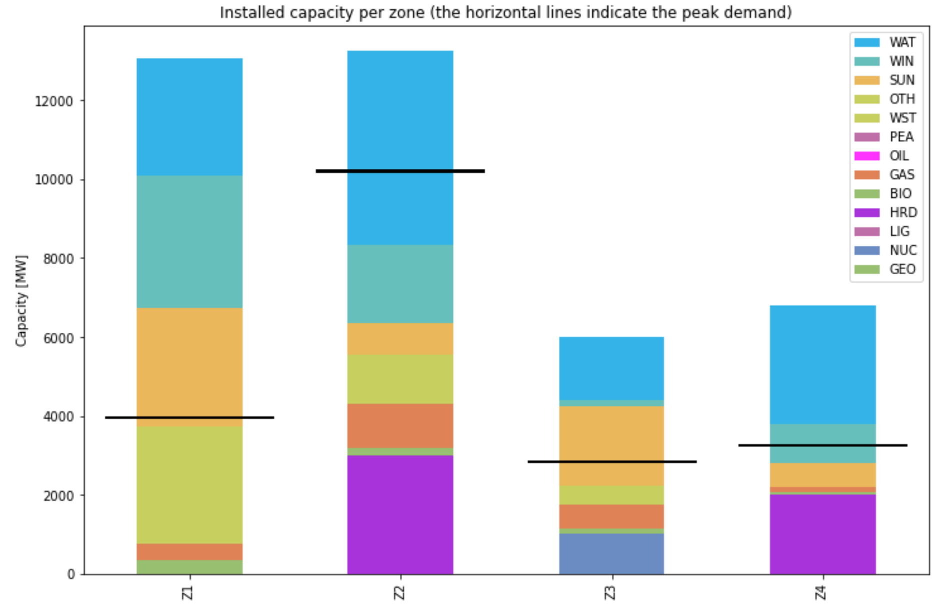
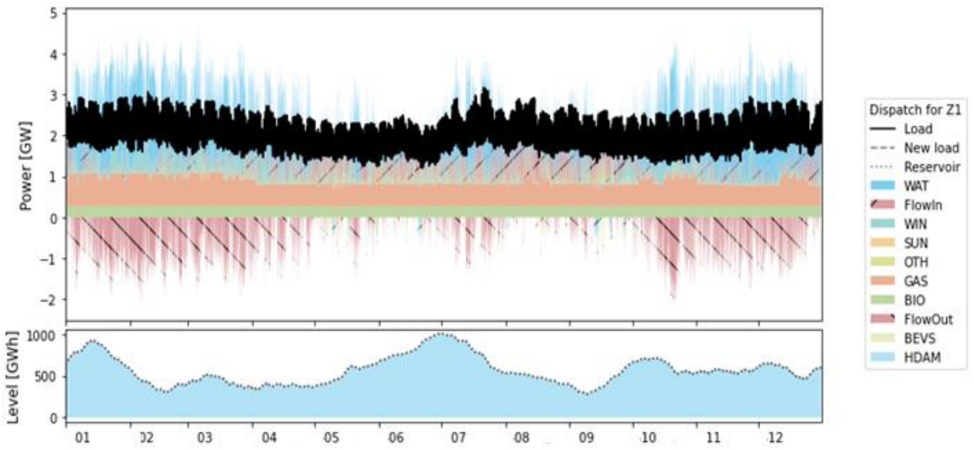
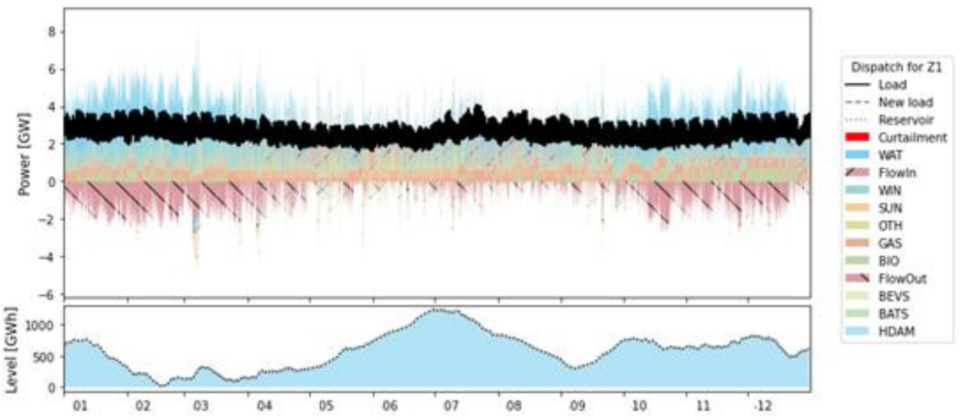
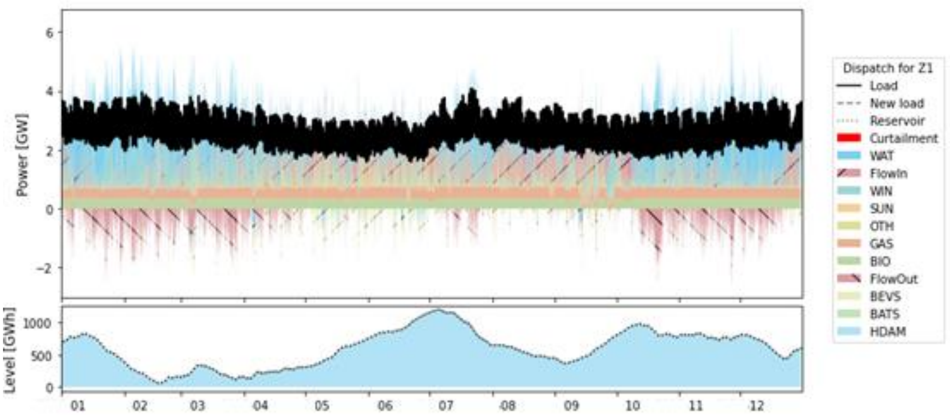
2050 scenario 16	

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.

Discussion on the return on investment

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)).

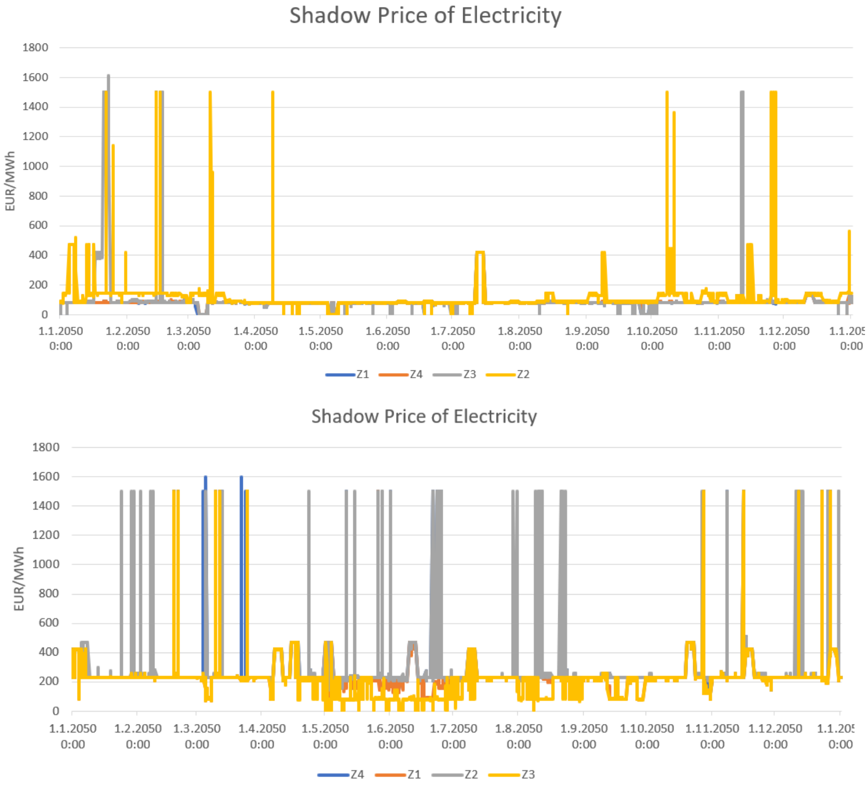


Figure 3 Comparison of Shadow Prices of Electricity in Scenarios 1 (upper distribution) and 16 (lower distribution)

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.

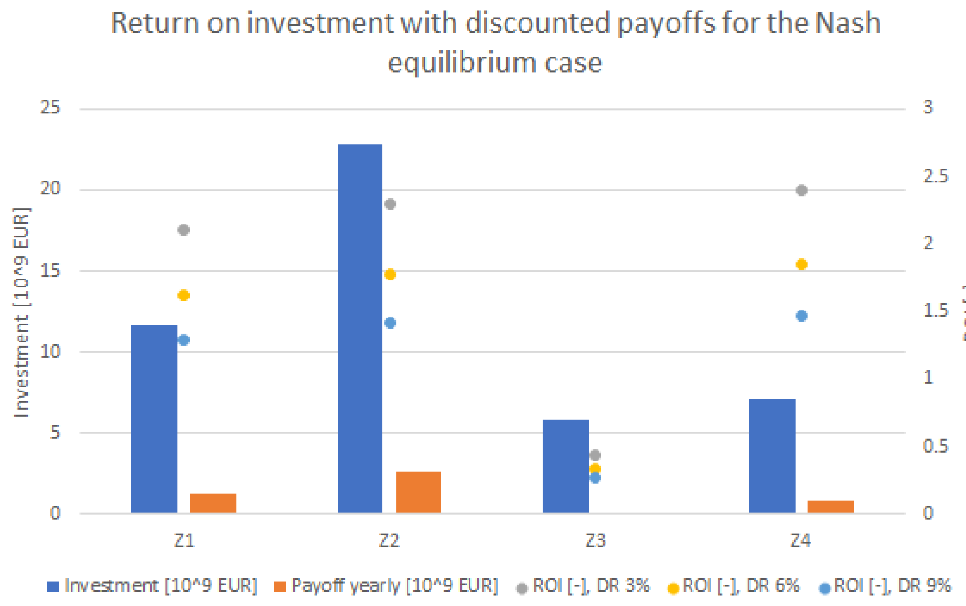


Figure 4 Return on investment with discounted payoffs for the Nash equilibrium scenario

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.

Constraints and limitations of the approach

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.

Discussion in comparison with state-of-the-art approaches

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