Energy security, policy and technology in South East Europe: Presenting and applying an energy security index to Croatia

Vladimir Franki*, Alfredo Višković

Faculty of Engineering Rijeka, University of Rijeka, Vukovarska 58, 51 000 Rijeka, Croatia

Abstract

During the last decade a number of long-held tenets of the energy sector have been rewritten. With the rise of new technologies and the help of policies favouring renewable energy sources (RES) a transformation of our understanding of the energy system and its possibilities has encouraged dramatic changes in the World's energy landscape. As some importers became exporters, countries long-defined as significant energy exporters became centres of demand growth. In these turbulent times, it is the awareness of the dynamics underpinning energy markets that is crucial for both decision-makers and investors to form informed opinions on how to reconcile a string of technical, environmental, economic and social factors in order to provide for best solutions regarding country specifics and demands. The right combination of policies and technologies could fuel economic growth, whilst still providing secure and affordable energy in line with low-carbon goals. Those that might successfully anticipate energy developments can derive a significant advantage on the market, while those that fail to recognise the importance of new movements risk making poor policy and investment decisions. In this light and following the accession of Croatia in the European Union, a number of questions are raised regarding the country's energy sector legal framework and development policy and their ability to cope with the demands faced. Taking Croatia as a practical example, the impact of different development strategies is considered through the application of a novel approach suggested by the paper. This study presents an overview aimed to help clarify some of the aspects behind forming a successful framework capable of making the right decisions for the future, today.

Key words: Energy Security, Generation Mix, Portfolio Diversification, Electricity Markets, South East Europe

---

* Corresponding author. Tel.: +385 51 651444; fax.: +385 51 651416. E-mail address: vladimir.franki@gmail.com (V. Franki).

1. *Introduction*

Influenced by a string of factors, the electricity sector has gone through some extensive changes during the last few decades that led to new understandings of optimal generation mix selection and inevitably caused the generating portfolios to dramatically change their landscape. In addition, raised concerns over the environmental issues started to present a determining factor when forming energy policies and environmental pollution emerged as a global issue, directly related to the quality of life [1]. There has been an estimated temperature increase between 0.6 and 1 °C in the last 150 years and an estimated potential increase by 1.4-5.8 °C for the period 1990-2100 [2] sparked mostly by CO_2 emissions [3]. The European Union (EU) is striving to be the leader in implementing renewable energy solutions as main sources of electricity in an effort to overcome the greenhouse gas (GHG) problem achieving a low carbon electricity sector in line with global concerns regarding the environmental issues caused by the greenhouse effect [4]. At present, the electricity sector is the single largest contributor to GHG emissions. It is, therefore, also expected that this sector will have to be called upon to carry the biggest load when the required reductions in emissions are concerned requiring the adoption of low-carbon generation technologies [5]. In other words, it is now necessary to evaluate not only the economic efficiency per type of generation technology, but also to take into account the associated effects it has on the environment [6]. As energy sources and consumption are directly related to environmental quality and crucial resources [7], energy development has, over recent years, been increasingly accompanied by major global concerns of over-population, pollution, water depletion, deforestation, biodiversity loss, and global climate deterioration [8]. Due to the raised awareness of the negative environmental impact of the energy sector, there has been a strong shift towards focusing on renewable energy and sustainable development. While some studies focused on designing strategies for achieving sustainable development in practice [9][10], others based their approach on determining the positive influence of encouraging sustainable development on jobs and public expenditures [11], as well as on economic growth [12]. This raised awareness resulted in renewable energy sources (RES) gaining momentum, as environmental concerns about pollution raised public awareness and encouraged governments to start adopting policies aimed at preserving and protecting the environment. This resulted in numerous studies being published over the past couple of years regarding this very topic. While some addressed their efforts in creating scenarios for successful incorporation of RES into a robust sustainable generation mix [13][14][15], others studied the subject through various scopes such as energy efficiency [16], renewable islands [17], locally integrated energy systems [18], energy restructuring [19], carbon capture & storage (CCS) [20] and the effect on the employment rates [21]. In addition, despite significant potential increases in costs [22], a number of studies discusses the possibilities of reaching 100 percent renewable energy systems in the future both on a local [23][24] and even national level [25][26].

It should be noted that although the implementation of RES has primarily been driven on achieving environmental goals, its contribution to energy security has also been explored [27]. It should be noted that, while connections between low carbon goals and the competitiveness of RES have been researched [28], the relationship between RES and energy security has not received the attention it deserves [29]. The necessary changes that are occurring, coupled with the fact that energy is a commodity essential for the well-being of the society, raise the importance of awareness about all the possibilities and inner-connections between factors influencing the quality of an energy sector – this is needed in order to successfully form a coherent strategy able to fulfil the goals set before it. Although, historically speaking, the availability of low cost energy has been one of the main driving factors of economic development [30], the new energy paradigm faces the energy sector with demands not only linked to achieving low costs. The quality of a country's energy sector is difficult to quantify as it depends on a number of factors and can be viewed from different perspectives. Looking at the present situation, however, it might be noticed that this quality is threefold. As mentioned, it does not simply depend on economic viability, but also security of supply and environmental impact. None of these terms are new to energy policies and investments, but the new insights and technologies caused forming different views on the energy sector and forced the emphasis on the latter two instead of simply choosing to go with the portfolio which guarantees minimal costs.

Although traditional electricity planning models pursue defining costs, their construction often results in an underestimation of the true benefits of renewable energy [31]. It is, therefore, important to be able to get a more comprehensive grasp on the possibilities and potentials of renewables through more thorough analyses. A good start might be to consider the success of the energy sector through the scope of the energy security paradigm. Energy security has traditionally been a major concern when forming national energy policies, but the concept of energy security has mostly been observed only as a measure defining how the demand is met in an effort by the policy makers to ensure an undisrupted energy supply [32] while its true value should lie in defining the true benefits and costs of the observed energy sector. There have been a whole string of studies and papers analysing the concepts of energy security, however, due to a lack of a universal definition and a methodology for its calculation, energy security has quite often been used as an umbrella term in both science and political arenas defining a much broadened area than it should cover. As the process of energy security planning is not only extremely complex and dynamic, but is also woven from a high number of varying factors, difficulties arise when trying to unify perspectives, conflate ideologies and manage the diversity of challenges associated with this activity [33]. These complexities require appreciation and management to ensure energy security planning is implemented in proper fashion [34].

2. *Energy security*

2.1.Energy security paradigm

Stirred by high oil prices during 2008 and aided with the global credit crunch, there has been a recent revival of interest in energy security [35][36]. When coupled with geopolitical supply tensions that the 2014's Ukraine-crisis brought, the concept is receiving a growing amount of attention across the globe. In the wake of the crisis, Europe may face yet another cut-off of gas supplies from Russia, as Gazprom meets more than half of Ukraine's gas demand and, in addition, supplies nearly a third of Europe's imports, of which roughly half go through Ukraine [37]. Energy security is one of the main goals of countries' energy policies around the world. As laid out by [38][39], the three pillars of EU's energy policy are energy efficiency, sustainability and security of energy supply. It should be noted that the concept of energy security was existent as far as early twentieth century when politicians and researchers focused their concerns on the perceived threats to national security due to dependence on a handful of oil producing regions and supply routes [40]. As time passed by, the meaning and focus of the energy security concept have varied, but a number of issues remained firmly on the agenda [41]. Although the tendency to symbolise multiple dimensions at the same time led to the concept being described as "polysemic" and "slippery" energy security is today ubiquitous to contemporary discussion about both energy issues and climate change [42]. Observing the available literature, a number of papers emerged in the past couple of years which offer either definitions or methodologies for calculating energy security. Observing the available literature, a number of papers emerged in the past couple of years which offer either definitions or methodologies for calculating energy security. Whether it's observed through the scope of security of supply [43][44][45][46], economic theory [47], generation mix portfolio diversity [48], energy services [49], security cost [50], long-term aspects of energy sector development policies [51], fossil fuel resource concentration [52], system reliability [53], diversity of an energy system's energy flows [54], consumer efficiency [55], energy policy [56][57] or other, there have been quite a few attempts to better describe and quantify energy security. Additionally, The Routledge Handbook of Energy Security [58] presents an overview of a string of analyses used to index and measure energy security. Apart from investigating various aspects behind energy security such as energy poverty, equity and access, development, policy, the book focuses on the demand side as well, observing energy services and politics along with technologies and infrastructure. A number of institutions have, similarly, offered their view on the concept such as UNDP [59], EC [60] and IEA [61]. Based on a careful literature review of the sources aforementioned, it might be noticed that most of the provided definitions base the concept of energy security on three main pillars: price (affordability), security of supply (whether home-based sources, whether through imports) and sustainability (which could be viewed through the scope of environmental impact).

However, despite of its high importance, there is currently no consensus on the precise interpretation on the concept of energy security nor is there a universal methodology to be used for its calculation [62]. This is due to the fact that the interdependence between industrialised countries and energy exporters has deepened, there are close links between financial and energy markets and technology has created interdependencies between electricity and oil refining as well as natural gas processing [42]. The complexity behind such issues influences on increasing risks of supply disruptions due to a number of factors such as political turbulence, war, financial market turmoil, technical failures, unfavourable weather conditions etc. [63][64][65]. If about anything, there seems to be a consensus about the association of energy security with risks [66][67][68], but the problem is in the vast number of threats that need to be considered [69]. This is the main reason why energy security concepts sometimes very distinctively differ, as researchers, quite too often, select a subset of these risks to take into account for their analyses. By categorizing and embodying the results into various levels, according to pre-selected criteria, the development of an index capable of measuring defined levels of energy security is possible [70]. Some studies have been focused on conceptualising energy security in various dimensions [42][56], whilst some focused on measuring the levels of energy security [49][52]. Having different risk sources and/or choosing different impact measures results in a considerable variation between studies.

In an effort to summarise some of the proposed definitions, Winzer reviewed 36 studies and argued that the concept of energy security should be separated from other policy goals (such as economic efficiency and sustainability) [32]. He defined the term as "the continuity of energy supplies relative to demand" therefore narrowing the concept of energy security to simply security of supply. In a way this study does not follow these footsteps and incorporates other layers into the paradigm, as security of supply depends on different factors. Whether the models used in the presented analyses fall under the umbrella of energy security or does the methodology deserve a different term to define it, is not discussed in the study. The figures gained were meant to simply better the understanding of the quality of the energy sector analysed. In this paper, we have adopted the definition that seems to be the most frequent among researchers, saying that energy security is a measure which defines three basic dimensions: price, reliability and sustainability.

2.2. Indicators of energy security

Over the recent years there have been quite some attempts to devise indicators for quantifying energy security. Whereas some deal with one aspect, others attempt to capture several relevant factors in a single aggregated indicator [62]. In this paragraph, an overview of the indicators used in this paper is presented, as well as the methodology used for calculations. In principle, the method used aggregated a number of factors influencing the three dimensions of energy security into a single figure. The three dimensions of energy security are defined as cost, import dependence and sustainability. The following (Figure 1) figure depicts the building blocks of the presented energy security index (ESI).

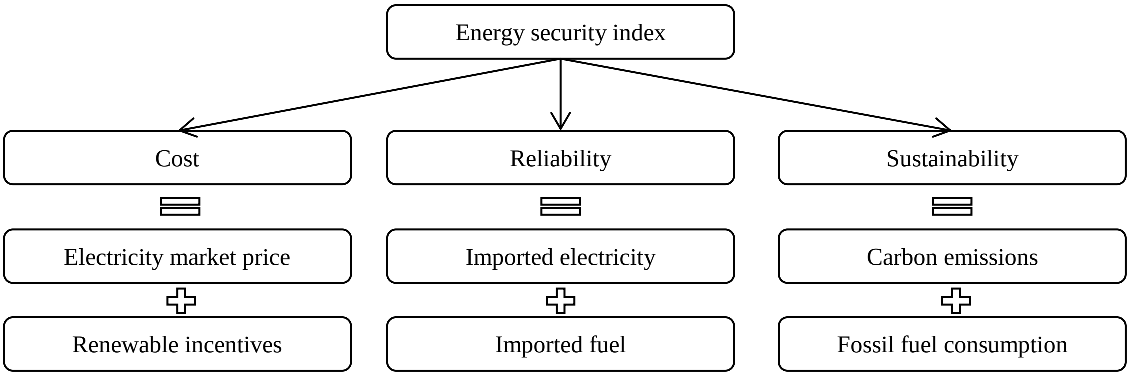

Figure 1 Main components of the energy security index

2.2.1. Cost of energy

The first dimension considered was the cost of energy. It consists of the two main components being encountered whilst covering the demand. The first component is the reported price on the power exchange, the price on the electricity market. It consists of both domestic production and foreign acquisitions. The second main component of the cost dimension is the cost of subsidizing renewables. By analysing the installed capacities being subsidized and comparing their productions with the tariffs in place, the total and specific costs can be calculated. To enable calculating this dimension, a detailed model of the electricity generating portfolio is necessary. The model used contains not only the detailed technical parameters and constrains, but also the specific costs of production per each unit of the sector. Technical aspects of the generating portfolio of SEE are given considerable focus and describe each unit in detail. However, the economic parameters were analysed in detail only for the Croatian generating set and presumed (approximated) for the rest of the units in the region. This enhanced the accuracy of optimisation between production and demand and aided in obtaining the actual costs of production of the electricity sector. The costs structure for each unit comprises of four categories [71]: investment, operation and maintenance (O&M), fuel and CO_2 costs. Naturally, only thermal power plants have fuel and CO_2 costs above the zero mark.

2.2.2. Reliability

Reliability is, in this case, interpreted as the ability of the system to rely on its domestic production. Therefore, it was observed through the scope of import dependence. Import shares are often used when assessing security of supply (SOS). Under optimal energy market operation, it might be argued that import dependence is less relevant to SOS. However, having a more regionalised world where trade barriers and a paradigm of competition prevail over cooperation, import shares prove to be both a straightforward and insightful indicator in assessing SOS. Net import of primary fuel and electricity are both taken into account. The import of electricity is pretty straightforward to calculate, but the import of fossil fuels is somewhat more complicated to take into account. The model used calculates the amount of electricity produced by imported fuels. This is achieved by taking into account the volumes of oil, gas and coal that the generation units imported during the course of the year. By comparing the amount of production to the share of imported fuel, the production achieved by foreign primary sources can be calculated. Using a weight factor, this production is then added to the existing amount of electricity acquired on the foreign market. The weight factor takes into account the percentage of the overall costs attributed to the imported fuel cost. For example, for a coal fired unit that has no more investment costs to cover and imports 100% of its fuel needs (like the Plomin 1 unit), its cost of electricity comprises of O&M and fuel costs. The percentage of the amount spent on imported fuel (compared to O&M costs) is considered to be the percentage of production imported. In this way, the construction of units importing primary energy does not improve the overall energy security as much as a unit relying on domestic sources. The two aforementioned components, electricity and fuel imports, together, form the reliability dimension.

2.2.3. Sustainability

Electricity sector's efforts to switch from carbon intensive fuel portfolios are considered an indicator for acceptability. This is done by taking into account the share of renewables in total primary energy supply and the negative effect the electricity sector has. It should be noted that acceptability concerns also exist regarding other energy options, e.g., nuclear energy. In this paper, in order to simplify the paradigm, social acceptability is equalled with environmental impact. With regards to climate change and the use of non-renewable energy sources, the most adequate way to consider the long-term sustainability of electricity generation is to take two basic things into consideration. First, the CO_2 emissions per MWh and second, the amount of mega joules of fossil fuels burned per MWh. Combining the two factors, the sustainability dimension is calculated.

2.3. Calculation methodology

In order to be able to express the level of energy security and still account for the various dimensions of it, a vector mathematical structure is used. The vector is placed in a Cartesian coordinate system where each reference line represents one of the aforementioned dimensions. The energy security index is quantified by a single number by calculating the distance of the situation point from the origin. In this model, the theoretically optimal situation would be found in the origin. The formula used to calculate ESI consists of three main elements:

$$ESI^2 = {I_c}^2 + {I_R}^2 + {I_S}^2$$

where ESI – energy security index; I_c – cost dimension of the index; I_R – reliability dimension of the index; I_S – sustainability dimension of the index. The following text shows how these fragments are calculated. Firstly, the costs index is calculated by using:

$$I_c = \sigma_{C1} C_M + \sigma_{C2} C_S$$

where σ_{C1}, σ_{C2} – vectors of weights; C_M – specific market costs of electricity in €/MWh; C_S – specific costs of subsidising energy production calculated by adding total costs of the subsidised electricity production and dividing it by the overall demand in €/MWh.

$$C_M = \frac{c_P + c_I}{D}$$

where C_P – specific production costs component (calculated by adding total production costs of the sector and dividing it by the overall demand covered) in €; C_I – specific market costs component refers to the costs of electricity obtained on the market (imports) in €; D – demand covered (MWh). In this case, σ_{C1} and σ_{C2} are of the same weight in order to equally value both the components of the cost dimension. Second component of the ESI is the reliability index calculated as follows:

$$I_R = \sigma_{R1} R_E + \sigma_{R2} R_P$$

where σ_{R1}, σ_{R2} – vectors of weights; R_E – amount of electricity being imported compared to the overall demand ratio; R_P – amount of imported fuel used for production compared to the overall demand ratio. Dependency on imported fuel is explained in more detail in previous paragraphs.

$$R_P = \sum_{i=1}^{N} \frac{r_{FIi} * r_{FCi} * P_i}{D}$$

where N – the overall number of units observed; r_{FIi} – ratio of fuel import dependency; r_{FCi} – ratio of fuel costs in overall cost of the *i* unit; P_i – production of the *i* unit in MWh. The third component regards the sustainability of the sector and is calculated as follows:

$$I_S = \sigma_{S1} S_C + \sigma_{S2} S_F$$

where σ_{S1}, σ_{S2} – vectors of weights; S_C – specific CO_2 emissions of the sector (overall CO_2 emissions divided by overall production) in tCO_2/MWh; S_F – specific fossil fuel consumption in MJ/MWh. Combining all the aforementioned components the ESI can be derived:

$$ESI^2 = (\sigma_{C1} C_M + \sigma_{C2} C_S)^2 + (\sigma_{R1} R_E + \sigma_{R2} R_P)^2 + (\sigma_{S1} S_C + \sigma_{S2} S_F)^2$$

$$\therefore$$

$$ESI = \sqrt{(\sigma_{C1} C_M + \sigma_{C2} C_S)^2 + (\sigma_{R1} R_E + \sigma_{R2} R_P)^2 + (\sigma_{S1} S_C + \sigma_{S2} S_F)^2}$$

The index presented in the paper is conceptually envisaged as an indicator of the energy sector's quality and a measure of probability. The index implicitly states the robustness of the observed energy sector, its ability to face shocks. In other words, if a component of the index (cost/reliability/sustainability) is higher than average it indicates an exposure, a vulnerability of the sector, therefore, it can be observed as a risk factor as well. For example, if an energy sector imports a greater volume of fuel, the reliability dimension will be notably higher. In such conditions, the index would be high, indicating higher dependence, higher exposure and, naturally lower security. The mathematical algorithm presented uses only twelve main parameters that considerably simplify the calculation of the ESI and provide a useful insight into the quality of the energy sector. The lower the index, the lower the exposure and risks, the better the quality and higher the security.

2.4. Some of the aspects of the proposed index

The goal is to create an aggregated index that is able to take into account a number of different indicators and present them in a simple manner. In addition, the weight factors used by the model might allow a unique ability to form the index in the way best suited for the participants needs. The weights presented in the paper are in equilibrium, where all the three dimensions have equal contributions. However, if generating companies/policy makers prefer certain policies, the index can be altered to better match their needs. For example, if there is a need to reduce imports even at higher costs, the alteration to the weight factors would ultimately change the breakeven point at which it is no longer viable to lower imports in order to favour domestic production. This could be done by changing the weights from 1/3 each to result in 1/2 weight on reliability, 1/4 affordability and 1/4 sustainability. The model presented in the paper should prove to be a flexible tool in determining not only the current status, but, even more importantly, the future prospects of the observed sector. The referent case can serve as a benchmark upon which a portfolio's trajectory can be calculated. The index can be calculated real-time and as such determine the quality of an electricity sector for a given hour/day/week/month. The figures presented in the paper are all based on a yearly performance average. Croatia was taken as a practical example, however, the methodology of obtaining the aggregated index is universal and with a sufficient data base, different portfolios could be evaluated. The index considers RES's impact on the sector not only through the scope of environmental protection benefits, but also the reliability and cost dimensions. Looking at the impact of renewables on costs, the model takes into account not only their influence on the market price, but, additionally, the money being spent on incentivising their production. Although social acceptability plays a growingly more important role in determining energy sector's development, it is not directly considered, but is absorbed by the sustainability dimension of the index. It is assumed that a more sustainable system is likely to be more accepted both socially, as it is more acceptable for the environment.

3. Computational method

Evaluating the characteristics of energy sector quality and analysing the different implementation approaches to the optimal portfolio selection is closely related to a number of influencing factors and several problem areas. This is why without specialised optimization algorithms it would not be possible to fully account for the amount of data that needs to be taken into consideration whilst constituting a suitable solution for solving the complex problems in hand. In mathematics, optimization is considered to be a discipline dedicated to calculating inputs of a function that minimize or maximize its value, which may be subjected to constraints [72]. Combinatorial optimization is a branch of optimization dedicated to optimizing functions with discrete variables [73]. When it comes to computational optimization, it might be defined as the process of designing and implementing algorithms suitable for solving a large variety of optimization problems. It should be noted that the optimisation in this paper merely offers a foundation on which further analyses are built, not necessarily the optimum solution to a problem. When it comes to evaluating the performance of a country's portfolio, one should take into account quite a considerable amount of data – various external influences require the evaluation utilization factors to consider the context of a network where generating plants must meet a specified (time-dependent) electricity demand [74]. As the energy sector consists of a number of integrated systems, the entire composition surrounding the country in study is also considered. This is one of the main reasons why a software tool was used to gain results needed for further analyses. As presented in [75], there are a considerable amount of computer tools available to help with the optimisation processes calculation. Optimisation-based synthesis approaches allow considering a virtually unlimited number of factors and alternative scenarios thus enabling to search for the optimal solution among all possible alternatives [76][77] in order to define tailor-made solutions for the level required, whether for distributed energy systems [78][79] or for a specific unit [80].The software in this study used was the market simulator designed by the Milan based institute Centro Elettrotecnico Sperimentale Italiano (CESI), an independent centre of expertise and a global provider of technical and engineering services to customers throughout the energy value chain, including business and technical consultancy, engineering and operational support [81], called Programmazione a mediotermine (PROMED) GRID. After collecting the necessary data of the electricity sectors across the SEE region, we built the simulator's database to match the needs of our study and designed an additional extension to the existing software in order to provide for the analyses and results presented in this paper. PROMED GRID is designed to carry out an optimal coordinated scheduling of the modelled electric system generation sets during the course of the simulated year, with an hourly time discretisation. The liberalized electricity market is simulated as a competition of generation companies which sign physical bilateral contracts and by bid on the power exchange. The day-ahead hourly energy market is characterized by a system marginal price and by a congestion management based on market-splitting per zones. The model consists of three modules: input data base, market simulation and output data. As far as the input data is concerned, it is divided into eight groups already described in our previous works [1][82][83], so they are only listed here: network model, hourly load and reserve margin of each considered market zone, energy exchanges with neighbouring systems, thermal generation set, fuel and EUA prices, hydro generation set, RES generation and bidding strategies. In addition to the previous version of the software, the new one has a stronger focus on renewable generation taking into account the increasing penetration of RES in the generation mix. The connections between the SEE regional electricity market (SEE REM) and its surroundings were considered through the scope of imports based on historical data. In addition, in line with recent trends [84] three modes of handling transmission network constraints were implemented in PROMED GRID: a pure flow-based (FB) approach, a pure Available Transfer Capacity (ATC) based approach and a hybrid one. By explicitly modeling the transmission constraints, hourly power flows and network congestions among interconnected market zones are calculated. Different sale prices determined in each market zone are directly correlated with the attainment of the inter-area transmission constraints following the market splitting principle [85].

As electricity price forecasts have become a fundamental input to both energy companies' decision-making mechanisms [86][87][88] and regulatory bodies, the main findings of the simulations presented in this study are not only the aforementioned utilisation factors (dispatch results) of the units considered, but also the electricity prices for simulated situations on the market. During the years, a variety of methods and ideas have been used to find the solution to the complex problem of electricity price forecasting (EPF) [89]. Although taking into account the bidding strategies during market simulation is often considered to be a distortive element due the biased decisions that it necessary entails in the market scenarios, PROMED GRID incorporates strategies per each generating unit based on units' presumed production costs thus determining the price of bids submitted by the company to the power exchange. Understanding all the possibilities and constraints that the market is bound to, thus becomes imperative in order to be able to form a coherent framework for simulation. To determine the market outcomes, the solution of a very large quadratic programming (QP) optimization problem is required. The optimization problem is solved implementing Kuhn-Tucker optimality conditions by means of a particular technique called Geometric ENgine (GEN). The market analysis presented in this study is based on a forecast of wholesale energy prices and power units' productions in 2015 and characterized by the most likely assumptions about the evolution of the SEE electric system. As far as the rest of the rest of the data is concerned, it was obtained through further analyses and, for the most part, conducted via an extension to the software made by the authors of the study.

4. *Surrounding peculiarity*

SEE is a specific region and determining an optimal generation portfolio in these surroundings requires considering all the specifics it brings. The SEE electricity sector has gone through a number of fundamental changes in the past few decades. It has witnessed the collapse of the socialist system as well as several wars, which deeply affected the social and economic life of people in the region. With regard to the electricity sector, extensive reforms being implemented were primarily aimed at changing the centralized organization of monopolistic utilities and introducing market-oriented structures and public regulation [90]. It is presumed that privately owned companies are able to move faster toward the efficiency frontier [91] as competition and a stronger desire for higher profits are expected to drive changes resulting in a more efficient system [92]. An important factor facilitating these changes was the EU initiative to establish the regional electricity market compatible with the internal electricity market of the EU [93]. Diversifying energy sources and developing alternative supply routes are considered to be some of the potential advantages that the establishment of the electricity market should enable [94]. A key factor driving a successful reform process will be the institutional and administrative capacity of the established national energy and regulatory authorities [95]. It should be noted, that the quality of the governance across the region substantially varies and in most cases falls behind that of other members of the EU [94]. However, as far as countries in SEE are concerned, the driving factors in the process of adoption of the EU acquis communautaire are related to both the aspirations to a membership in the EU and a realization that without major investments in generation and transmission capacities, consumers might suffer from future supply shortages [96]. The countries in the region inclined to the EU are required to follow the recommendations of the EU Energy Policy pursuing its three main objectives: competitiveness, security of supply and sustainability. In this context, integrating smaller systems into larger should prove to be beneficial to power trade and market competitiveness especially when resource endowments vary across countries. Creating a wholesale market is, in the long term, statistically positive for prices within the market [97]. Although when observing past experiences one might draw a conclusion that reforms have encountered significant difficulties during their projected paths in a number of countries [98], the reforms in SEE represent an important experiment for the entire World. It represents a test of the transferability of the EU reform model to a set of developing countries in general. The two main difficulties are the need for real time balancing of supply and demand which requires better design and regulation than most other deregulated sectors and rebalancing tariffs to cost-recovering levels as it is an important precondition to an effective market. The rebalancing of tariffs raises the issues of political sensitivity through social aspect of reform as reform which raises tariffs will have significant effects and may cause political difficulty in a region where incomes are generally low and have a wide dispersion [99].

Structural changes in the SEE electricity sector were primarily imposed by the EU and driven by two electricity directives in 1996 and 2003 [100]. There are currently a number of issues still to be addressed if the experiment of a regional energy market is to lead to further regional integration. It’s worth noting that the Balkans conflict also had a significant detrimental effect on the energy infrastructure in parts of the region from which some of the countries are only recently emerging [101]. Analysing the main concerns of an independent power producer (IPP) in the SEE REM we have identified the issue of different views on regulation and further development in terms of legislation as a driving force of insecurity of the investors in the region. Having unstable, someway unpredictable, regulatory framework results in competitors on the market facing disloyal competition. Two of the main difficulties regarding successful integration into a regional electricity market are the EU emission trading scheme (EU ETS) and the low competitiveness throughout the countries of the region. As shown by Figure 2, countries in the region are divided when it comes to the EU ETS affiliation. This causes a significant imbalance between competitors on the market and results in considerable additional risk for investors as thoroughly discussed in [82].

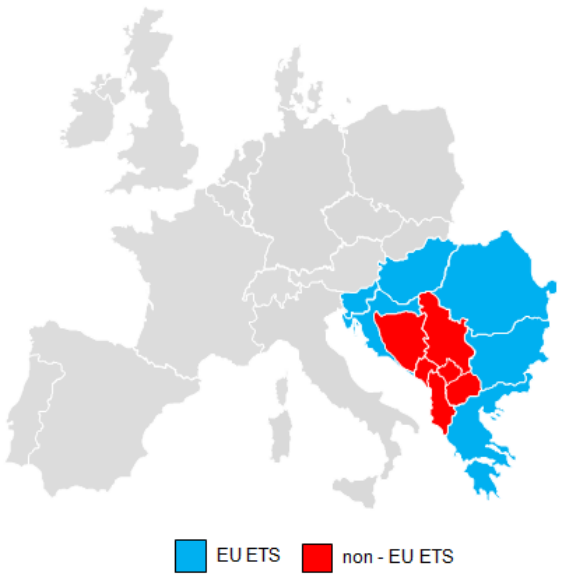

Figure 2 South East Europe countries ETS affiliation

In addition to the EU ETS affiliation, the following figure (Figure 3) offers an insight into the competitiveness of the electricity markets within the SEE region through the scope of the results obtained by Datamonitor's MCI index competition intensity analysis [102]. MCI is the index which measures the development of the electricity markets competitiveness, comparing between each other 34 European markets. As it might be noticed, the countries in SEE mostly face significant difficulties and have low market competitiveness. The best placed SEE country in this analysis is Romania, while the worst is Macedonia.

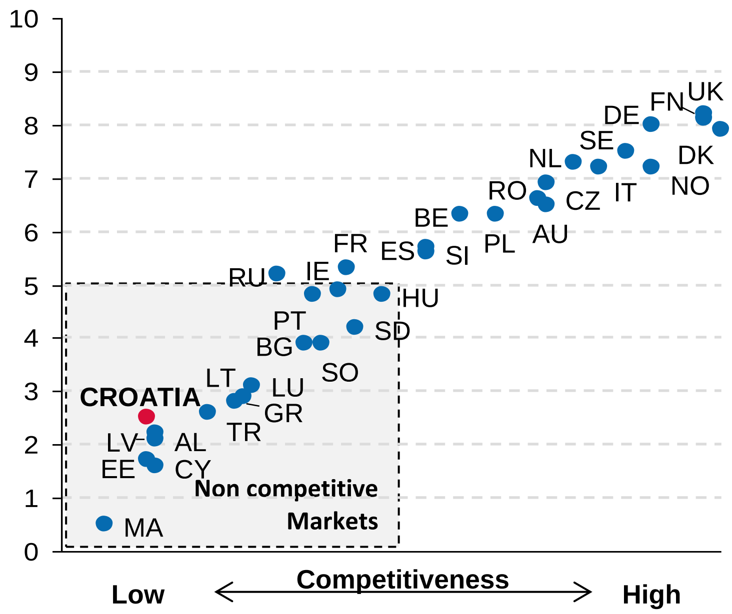

Figure 3 MCI score 2013 (source: Datamonitor [102])

4.1.Overview on the Croatian electricity sector

For the purposes of this study, a model of the electricity sector has been built, representing the assumed state of the SEE REM in the year of 2015. This paragraph describes the electricity sector of the case study country – Croatia. The overall installed capacity is set at 4551 MW. It consists of the groups of generating sources as listed in Table 1.

Table 1 Installed generation capacity in Croatia (2015)

Power plant types by source		Installed capacity (MW)			
RES		438			
	Wastewater gas	2.99			
	Municipal waste	2.43			
	Wind	355.19			
	Solar	36.25			
	Small hydro	1.73			
	Biomass	9.19			
	Biogas	14.49			
	Cogeneration	15.89			
Industrial		212			
Thermal		1789	Gas	Oil	Coal
	TE Sisak	420		420	
	TE Rijeka	320		320	
	TE Plomin 1	120			120
	TE Plomin 2	210			210
	KTE Jertovec	76	55	21	
	TE-TO Zagreb	440	320	120	
	TE-TO Osijek	95	50	45	
	EL-TO Zagreb	89	89		
	Other small units	19			
Hydro		2112			

It should be noted that a 50% share of the nuclear power plant (NPP) Krško is also a part of the generation set belonging to the Croatian leading utility HEP. With a nameplate generating capacity of 696 MW, it generates over five TWh of electrical energy per year. However, as the power plant is not based in Croatia, we did not include it in our considerations of the energy mix. Each of the units listed is described with the constraints and technical characteristics in our model used in the optimisation software. The energy mix used for calculations corresponds to the situation in the Croatian electricity sector and is a result of observing available literature [103][104] and team analysis. Figure 4 shows the shares of installed generating capacities of the four main sources of electricity. As it can be seen, hydroelectric generation accounts for the largest share at 47%, but closely followed by the thermal sector's 40% stake. Currently, there are two large projects foreseen that might alter the shares in the thermal sector's favour. It should be noted, however, that most of the thermal units have been present for quite a number of years and now due to low efficiencies have high fuel consumptions making them considerably less competitive on the electricity market. In addition, there are a number of oil fired units too expensive to be used electricity generation. Despite ambitious plans, looking at the past few years, the biggest increase is recorded by the renewable sector which now holds 10% of the total generating capacity.

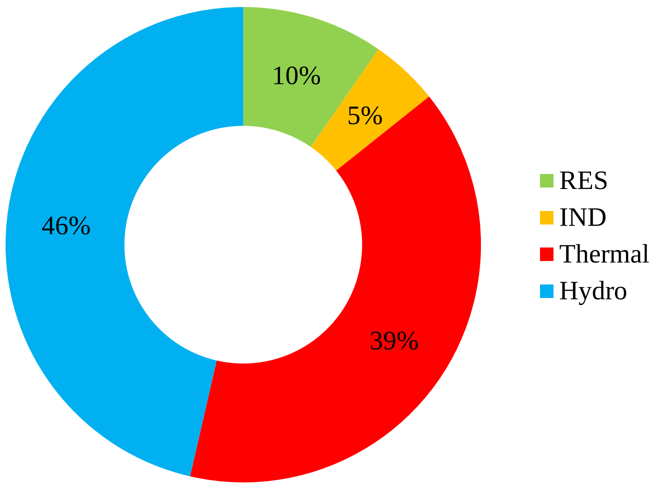

Figure 4 Croatian energy mix

Building on the basis of an elaboration of the historical data of the national electricity consumption published by ENTSO-E [105], the forecast of the national energy demand is defined on an hourly basis. For a predetermined year of 2015, we presumed the annual demand to total 17.83 TWh. This procedure of identifying the generation mix, constraints, demand and other relevant data resulted in the collection of a considerable database used to update the data compiled by CESI. The modifications implemented into the SEE REM database were further used for the purpose of simulating the SEE REM with the optimisation software. Figure 5 presents the presumed annual demand on an hourly basis for Croatia and the same data was used for each country of the SEE region. The optimum solution of energy trades between countries of the region and between the region and its neighbours, respecting technical constraints of power flows is expressed by Net Transfer Capacity (NTC) on all interconnection corridors.

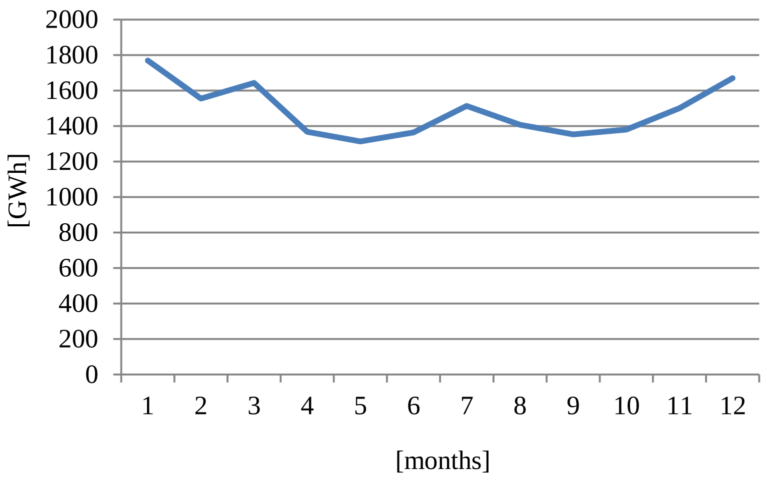

Figure 5 Croatian annual electricity demand (2015)

5. Results & further analysis

After constructing a model of the SEE electricity sector and taking the assumptions regarding fuel costs, hydrological conditions, RES production and electricity demand, a number of simulations of the SEE REM were made. Aided with an extension of the software made by the authors of the paper, the quality of the Croatian energy sector is assessed and the most relevant data presented in the text below. The main sources of information used is the data provided by ENTSO-E (demand, interconnections, exchanges)[105], HEP (generation portfolio, units' production, Croatian demand) [106], CESI (electricity sector settings, generating portfolios) [81], , HROTE (RES capacities, RES incentives, future development possibilities of the RES sector), HERA (tariff prices for RES)[107][108], EEX (fuel prices, electricity prices)[109], HUPX (fuel prices, electricity prices)[110] and team research.

5.1.Referent case

The two basic results of the simulation are the hourly productions of the units and the electricity prices. Figure 6 shows the productions of domestic units' during the course of the simulated year. It can be seen that hydrological conditions (which are based on the elaboration of historical data regarding inflow capacities) significantly vary even during shorter periods of time thus having a significant influence on the Croatian sector.

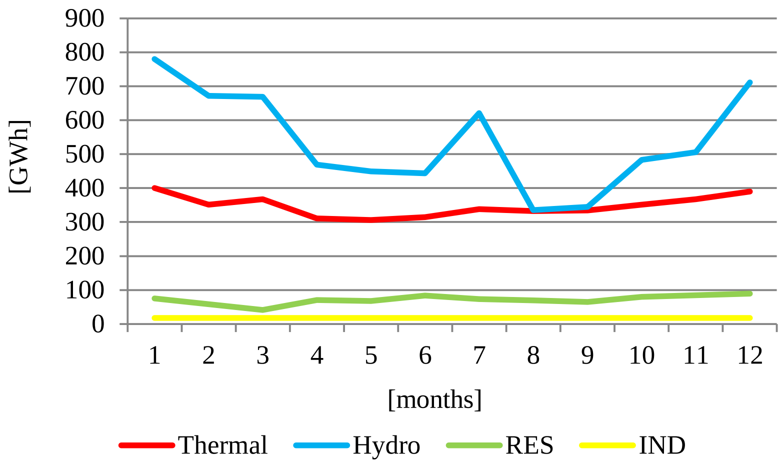

Figure 6 Domestic units' productions

When these productions are considered along with the production of NPP Krško (NPPK) and the Croatian demand, the following figure can be built (Figure 7). Having a stable production, the NPPK improves the overall status of the sector lowering the gap between production and demand. However, as it can be seen from Figure 7, the Croatian electricity sector faces significant difficulties when covering its demand and has to strongly rely on foreign imports. Paired with high dependence on hydrological conditions and fuel imports, these electricity imports represent the main downfalls of the sector.

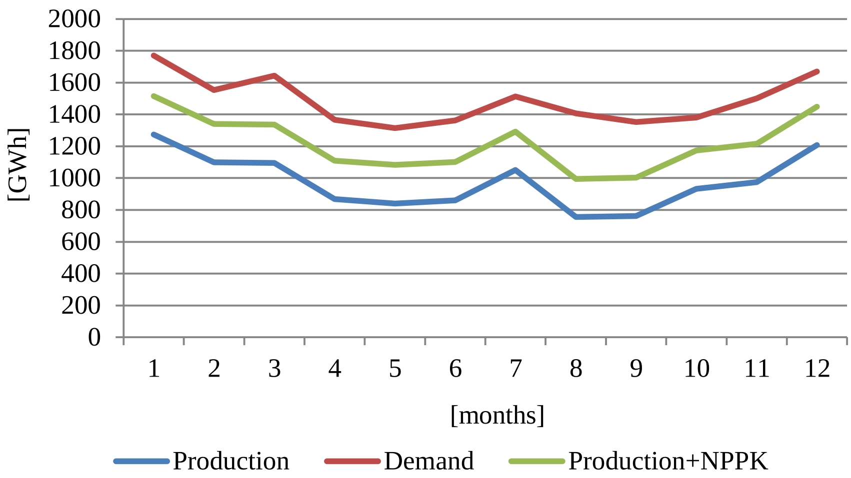

Figure 7 Demand and production comparison

Setting up the electricity market allows for the prediction of electricity prices under presumed market conditions. This allowed the formation of the following analysis regarding the dependence of electricity prices on demand. One of the general rules of supply and demand dictates lower prices at lower demand and higher prices at higher demand. Price of electricity in the simulation derives from the bid-up strategy modelling: an hourly bid-up proportional to the demand level has been superimposed on the marginal cost curve of each thermal unit. This results in price having a trend of following the demand being higher in peak load hours and lower off peak hours. It is important to note a distinction between two electricity prices reported in the paper. First, there is the electricity market price and second, the cost of electricity as reported in the earlier text. The cost of electricity represents the specific cost needed to cover the costs of producing or importing the necessary amount of electricity.

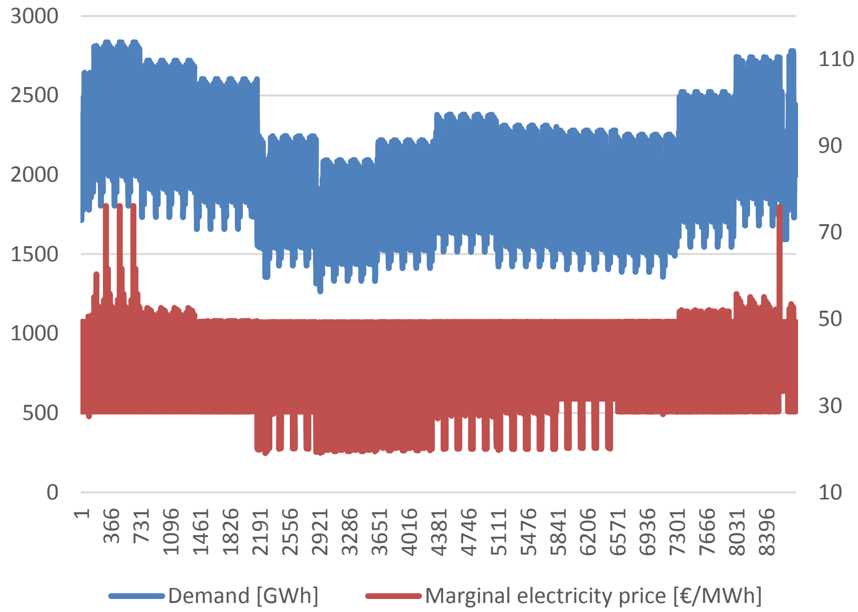

Figure 8 Electricity price demand dependence

The total production of domestic units of the Croatian electricity sector equals 11.69 TWh. Without the production of NPPK, 34.4% of the 17.83 TWh demand needs to be imported. If the 50% share of NPKK is added, import lowers to 18.2%. These figures correspond to 261

M€ and 138 M€ respectively. When this is added to the imported fuel costs, the expenses rise to 379 M€ and 261 M€ respectively, representing a significant burden on the energy sector. CO_2 emissions amount to 2.96 Mt or 0.166 tCO_2/MWh. The average marginal price of electricity on the SEE market equals 42.57 €/MWh, whilst the specific cost of electricity for Croatia equals 44.55 €/MWh (this figure includes both market costs and costs of subsidising RES). The overall cost of covering the 17.83 TWh demand equals 794.54 M€, 79.4 of which is regulated by the tariff system. Figure 9 can be used to compare these prices with the average marginal costs of production of the domestic units belonging to the Croatian thermal sector.

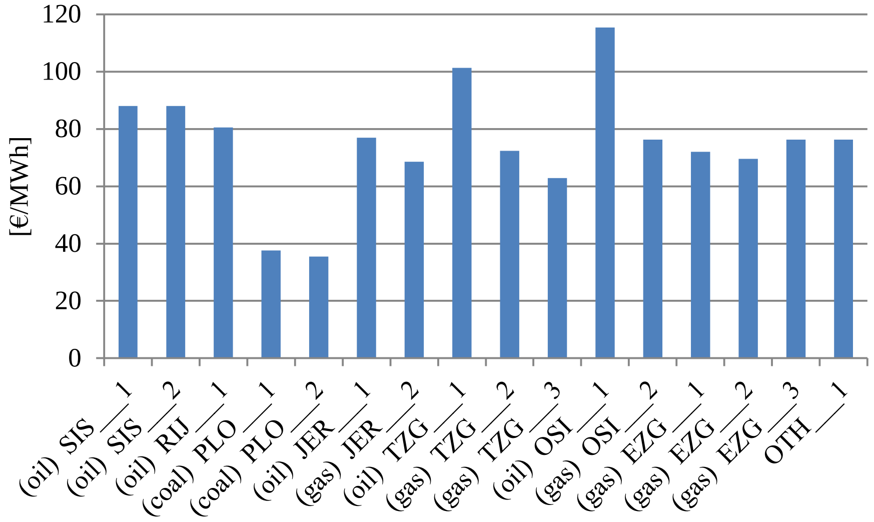

Figure 9 Croatia thermal sector's specific production costs

5.2.Energy security index

The successful collection of data provided the possibility of calculating the energy security index (ESI) for Croatia. The cost of energy is determined by summing the overall costs of covering the annual demand. Costs consist of three categories: production, imports and tariffs. Production costs, in this case, present the overall costs needed to produce electricity by domestic sources. They are a value expressed in euros per megawatt hour and refer to the average marginal price of electricity that the Croatian power exchange would achieve for the selected period. These costs are obtained with the help of the optimisation software and further team analysis. Adding to the production costs are the imports with their specific costs and volume. Last, but not least, are costs of tariffs. They refer to the money spent on subsidizing the renewable energy sector. As the optimisation software only deals with simulating the electricity market, the costs of subsidies are calculated strictly through team analysis. First, the data provided by the Croatian energy market operator – HROTE was taken into account describing the progress made when installed renewable capacities are in question. For the year 2015, as mentioned earlier, the presumed installed capacity is presumed at 438 MW. Considering the mix in hand, this correlates to an annual production of 859 GWh as shown in Table 2.

Table 2 Renewable sector's production in 2015

Power plant types by source	Installed capacity (MW)	Annual production (GWh)
Wastewater gas	2.99	10.04
Municipal waste	2.43	13.97

Wind	355.19	651.51
Solar	36.25	21.00
Small hydro	1.73	10.25
Biomass	9.19	65.56
Biogas	14.49	82.57
Cogeneration	15.89	4.23
Total	438	859

In addition, according to the tariff system in place [108] defined by the Croatian energy regulatory agency – HERA, we calculated the annual costs of the renewable sector to reach 79.4 M€ (609 M Kuna) compared to the 72.1 M€ (553 M Kuna) in year 2013 [104] report. This corresponds to a 7.3 M€ increase or, in other terms, a 19% production increase. The 79.4 M€ are added to the existing 715.14 M€ spent on the aforementioned production and import costs resulting in a total of 794.54 M€ needed for covering the overall demand of 17.83 TWh. Taking subsidies into consideration increases the overall marginal price by 4.45 €/MWh adding to the overall 44.55 €/MWh price tag for producing electricity in Croatia. This price reflects the situation on the electricity market in which all the production costs of the dispatched units are covered. The simulated bidding strategies of the production units' aim at covering investment, O&M, fuel and CO_2 costs. However, as the current situation in Croatia is somewhat different (almost all of the trade within the sector is done via bilateral agreements), an additional scenario has been developed. This involves setting a system of bilateral agreements between the electricity market and the power producers. These contracts allow the compensation of the dispatched units to equal only the variable production costs disregarding the producers' need to achieve profits at the end of the year. Furthermore, a few units (cogeneration) were on a must-run basis during the winter hours (to best depict the situation present in Croatia).

The reliability/security depends on the volume of imports. To calculate this index component, we took into consideration the percentage of electricity imported for covering the total demand – 18.21% and, in addition, the volume of imported primary resources. By analysing the data given by the Croatian Ministry of Economy [111], we were able to gather the average imports of the Croatian energy sector which are listed as follows: 100% of coal is imported, 79.48% of crude oil and 35.1% of natural gas. When compared to the annual productions by each of the thermal units, this results in a total cost of 133.29 M€ for electricity production by using imported fuels.

The third component of energy security is sustainability. It corresponds to both the environmental impact and the usage of fossil fuels in the electricity generation process. The environmental impact is considered through the scope of CO_2 emissions per MWh of produced electricity. By analysing the emission coefficients of the thermal units in the Croatian energy sector and observing the productions of these units (via optimisation software), their total emissions were calculated. In total, the Croatian energy sector, when considering referent conditions, emits 2.95 $MtCO_2$. When compared to the annual demand, this results in emissions equal to 0.166 tCO_2/MWh. As fossils fuels are considered to be expendable, the second main factor of the sustainability component is the mentioned fossil fuel consumption. This was calculated in a way similar to calculating emissions. The result was a total of 36.846 TJ of fossil fuels burnt to satisfy the need of the thermal sector in Croatia. This corresponds to 8.9 MJ/MWh when considering only the thermal sector and 2.06 MJ/MWh when compared to the overall energy sector (the number in mostly reduced because of the use of hydro generation).

Taking all these into account and using the mathematical model presented in the paper, the ESI of Croatia is calculated to equal 0.723, with the cost, reliability and sustainability components contributing with 0.445, 0.331 and 0.455 respectively. Figure 10 depicts how far Croatia currently is on the path of having an energy sector that is more reliable, sustainable and cost effective.

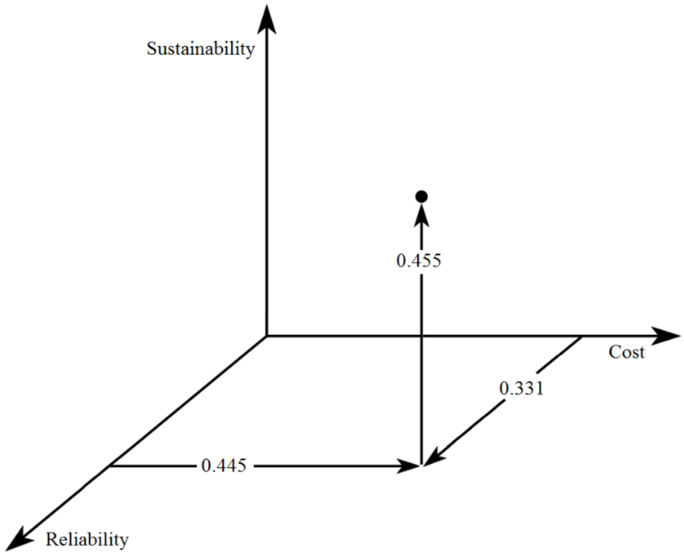

Figure 10 Referent case ESI for Croatia

5.3.Sensitivity market analysis

Quite a while ago Markowitz demonstrated that in order to optimise an investment it must be diversified in more financial assets, maximising the expected return while, at the same time, minimising associated risks [112][113]. In other words, every asset taken into consideration during portfolio analyses must be characterised not solemnly by its expected return, but additionally by the variability it holds. A number of sensitivity cases have been analysed in order to take into account the uncertainty regarding some of the parameters in the market analysis conducted. This offers a more detailed perspective on the possible changes that directly reflect the performance of the electricity sector in study. We have focused on four major factors: demand, hydrological conditions, fuel and carbon prices and observed the strength of their impact on the performance of the sector. It should be pointed out that the analysis of the variations of factors focused on the boundaries of optimal and pessimal possible scenarios. It is, therefore, unlikely that the parameters considered in the sensitivity analysis would remain such for a prolonged period of time, but the results obtained represent a valuable insight on the robustness of the electricity sector. Demand is presumed at -5% (pessimal) and +5% (optimal). Pessimal and optimal hydrological conditions are based on historical conditions. Fuel prices range from +20% to -20%. Carbon prices are set at 0 €/tCO_2 and 20 €/tCO_2. The changes are applied to Croatia and the rest of the SEE region (EU ETS affiliation is taken into consideration).

Table 3 Main sensitivity cases differences compared to referent scenario

No.	Abbreviation	Scenario
1.	REF	Referent
2.	DP	Demand lowered by 5%
3.	DO	Demand raised by 5%
4.	HP	Hydrological conditions presumed pessimal for electricity generation (based on historical data)

5.	HO	Hydrological conditions presumed pessimal for electricity generation (based on historical data)
6.	FP	Fuel costs raised by 20% (coal, gas and oil)
7.	FO	Fuel costs lowered by 20% (coal, gas and oil)
8.	CP	Carbon costs set at 0 €/tCO_2
9.	CO	Carbon costs set at 20 €/tCO_2

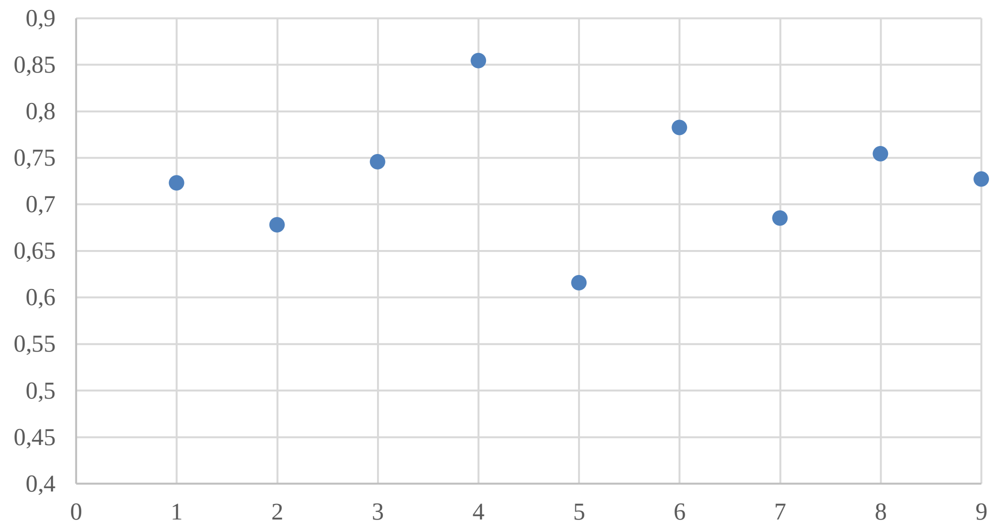

Figure 11 Sensitivity cases ESI

As it can be seen, although staying within certain boundaries, the index varies as the conditions regarding the sector change. The variations of the index represent the maximum volatility that the Croatian sector can face within the year. The referent index, along with its three dimensions, represents the exposure of the sector to certain types of external influences and can be regarded as a risk factor. High values of index components (with values towards 1) therefore mean higher risks. What the sensitivity analysis reveals is the great significance of hydrological conditions to the Croatian electricity sector. There is a difference of 300 M€ in obtaining (producing and acquiring) electricity between optimal and pessimal conditions. Because of the high share of hydro-power plants, the Croatian electricity sector is more affected by hydro conditions than variations of ±5% demand and ±20% fuel costs.

5.4.Possible development scenarios

In this section, the variation of the energy mix is analysed. This section applies the portfolio choice model depicted above to analyse the impact of renewables in energy security. Three main paths are analysed and involve incorporating RES, TPP Sisak (cogeneration, 230 MWe + 50 MWt) and TPP Plomin (coal, 500 MW) in the generating portfolio. TPP Sisak is currently in the final stages of construction whilst Plomin is on tender. The main additions to the scenarios are shown in Table 3.

Table 4 Main differences compared to referent scenario

No.	Abbreviation	Scenario
1.	REF	Referent
2.	R2	Installed RES capacity set to match 2 TWh annual production
3.	R4	Installed RES capacity set to match 4 TWh annual

		production
4.	TS	TPP Sisak (cogeneration, 230 MW)
5.	TP	TPP Sisak and TPP Plomin (coal, 500 MW)
6.	TR2	TPP Sisak, TPP Plomin and RES production of 2 TWh
7.	TR4	TPP Sisak, TPP Plomin and RES production of 4 TWh

Each scenario has benefits and drawbacks. Out of the six development scenarios analysed, four are able to improve the ESI defined in this paper. ESI indices are shown in Figure 12.

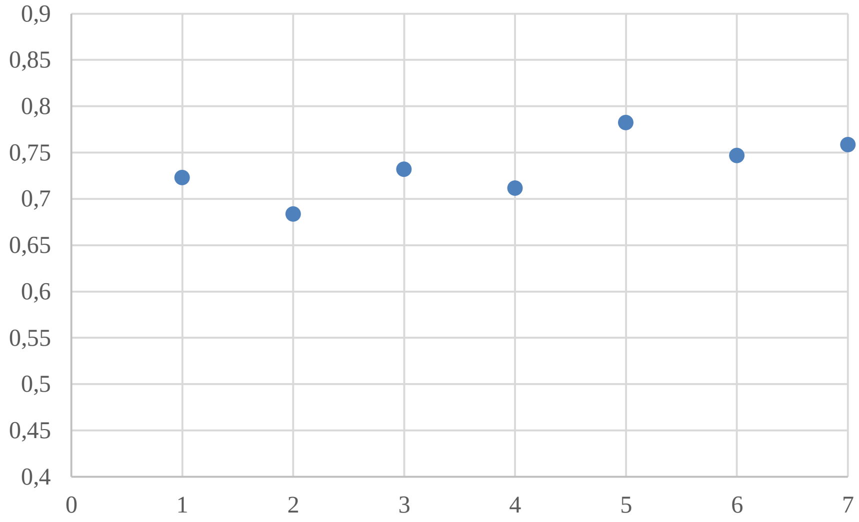

Figure 12 Development scenarios ESI

Comparing present costs of RES in Croatia (79.4 M€) and their production along with assumptions regarding the development of the RES sector in Croatia, the costs for producing 2 TWh and 4 TWh of electricity on a yearly basis were calculated at 183.9 M€ and 370 M€ respectively. The analysis revealed that incorporating RES into the portfolio would increase cost, but improve reliability and sustainability dimensions of the index resulting in the overall improvement of the ESI. Apart from the two scenarios with presumed increase in RES penetration, other scenarios do not offer significant improvement. Comparing scenarios R4 and TP, the biggest difference can be observed. Despite adding significant generating capacities, it seems that TPP Sisak might be rendered uncompetitive on the market. Acting as an IPP on the SEE REM, without having a power purchase agreement (PPA), it will find current market conditions rather difficult. The coal fired unit, on the other hand, will find its place in the dispatch. It will, however, have an overall detrimental effect on the ESI raising the negative environmental impact without properly compensating it through cost and reliability (the unit would have to import fuel). As far as the RES scenarios is concerned, we have, additionally, identified the breakeven point at which the instalment of further RES would cause a degradation of the ESI. For Croatia, this would be the mentioned 4 TWh per annum. Beyond that point, under current circumstances, the cost of renewables would have too strong of an impact on the cost to be fully compensated through increased reliability and sustainability. Additionally, although not fully considered under the scope of this paper, technical feasibility of fostering such increased renewables portfolio should be analysed. Due to the great variability of RES production, it is fundamental to know the territory in which the portfolio choice must be done, so to address the analysis coherently to the territorial contest during energy planning [114].

6. *Discussion*

In order to provide for an affordable and reliable source of electricity, support the increase of domestic industry development, reduce greenhouse gas (GHG) emissions and achieve a secure and diversified supply of energy – renewable energy sources such as biomass, solar, hydro and wind play an important role in reaching these goals in the industrial countries as shown by numerous studies [7][18], some facing their attention to biomass [115][116], cogeneration [117], hydro [118] or distributed sources [119]. Other GHG reduction measures might, also, prove to be efficient and economical, such as the potential of municipal solid waste (MSW) [120][121][122]. Diversification among RES is necessary in order to reduce the short-term variability of the main renewable energy sources (solar and wind) and technological exposure in the long run [27]. Interestingly enough, as pointed out by [123], systematic risk might be considered as a group of climbers roped together. Each prefers to be roped as it reduces his chances of falling, yet if one climber does slip, he threatens the stability of his neighbours and the whole group. In similar terms, portfolio diversification does make investors safer regarding individual investments, but on the other hand, creates connections between them through common asset holdings causing endogenous covariances between both assets and investors enhancing systematic risk and thus propagating shocks through the entire system [123]. This was a common model up until the 2008 credit crunch, when the swiftness with which risk spread through the market led to re-examining existing methodologies for assessing risk.

Although the conventional mind-set might dictate that RES increase costs and risks of the energy system, as proved by this paper, from a portfolio choice perspective, domestically produced renewables improve the energy security reducing the risk-cost trade-off. Modern RES such as wind and solar are the so-called zero marginal-cost technologies. In other words, they have no fuel costs and thus lessen the exposure of the energy sector to fuel price volatility. In addition, considering their favourable environmental impact, it is easy to deduct why the use of RES is confirmed to improve the ESI presented in the paper. Croatia's energy sector reforms have objectives that are similar to other national policies [124][125][126][127][128]. Hopefully, new development strategies will continue to follow the successful examples set fourth [25][26] and precipitate a move towards environmentally acceptable and sustainable electricity sector of the future.

7. *Conclusion*

In recent years, due to increased geopolitical instability and a realisation that energy sources are crucial for economic growth, the topic of energy security raises global concerns. In this study, we suggest an approach to quantitatively measure and compare the quality of an energy sector observing three different dimensions of energy security: cost, reliability and sustainability. The paper proposes a new calculation model able to provide a mathematical tool for energy planning decisions that incorporates environmental concerns and is able to recognise the possible benefits of the renewable sources in the optimal energy mix. The conceptual framing is described and it is ensured that the right metrics are used. A set of conceptual boundaries that improve the distinction between the policy goals of security, sustainability and economic efficiency is proposed. The resulting concept, should prove to be the core of energy security concerns.

As mentioned, there have been quite a few of energy security indices published in literature during past years. However, these aggregated indicators do not record performance during time bands and are, therefore, unable to show trends in energy security performance.

In addition, and perhaps even more importantly, these indices do not help in assessing future performance with regard to energy policy and/or development strategy. In order to be able to consider current, but also future movements across the sector, we developed an alternative methodology for calculating an aggregated energy security indicator sensitive to dynamic market circumstances. The methodology consists of three phases: data collection and modelling, simulation through the optimisation software and results analyses. There are a few advantages of the ESI being proposed. It can be used as a useful tool in determining past and current energy security status, but also help in assessing the future status considering energy policies and development strategies. Therefore, paired with the optimisation tool and as shown in the paper, it can enable monitoring of the impacts of different policies and strategies on the three pillars of energy security. Second, the aggregated indicator presented in this paper represents holistic performance at the selected level, whether it's local, country or region. Third, it can provide a benchmark or baseline scenario of energy security, while at the same time simplifying the representation of the performance/trend among observed energy sectors. Finally, it could be applied as a tool for monitoring the progress and analysis of the barriers in the energy sector.

The results obtained in the analysis confirm that, following the new framework for energy planning, the suggestion would be to invest in technologies based on renewable sources. Although this solution might prove more costly investment wise, in this way, an improvement in the overall quality of an energy sector is possible. A detailed evaluation of the criticalities deriving from the surroundings should allow the reduction of negative impacts both on the environment and the community due to the better, more informed choices of plant engineering. Pursuing new solutions that take into account the reality and a wider set of interests of the community is a necessary step towards achieving an objective of choosing a generation portfolio best suited for the potentialities and the constraints of the surrounding environment.

Looking at the changes in the energy sector towards a more sustainable system, economically, technically and environmentally, the analysis conducted in this paper revealed that further research might be directed into observing the status of other SEE countries compared to Croatia to record their efforts in reaching EU goals of energy security. In addition, when talking about different generating portfolios, it might prove to be useful to take into account the existing literature from financial markets. Although, not easily applicable to solving the issues of selecting the optimal solution for the energy sector, in their heart, these methodologies might hold one of the keys able to help better the understanding of problems being encountered during policy and/or strategic planning.

Appendix

Table A1. Sensitivity cases main results

	REF	DP	DO	HP	HO	FP	FO	CP	CO
TPP [GWh]	4138	3801	4532	4874	3793	4276	4146	4105	4163
HPP [GWh]	6482	6317	6428	4636	8022	6474	6476	6286	6436
RES [GWh]	859	859	859	859	859	859	859	859	859
IND [GWh]	212	212	212	212	212	212	212	212	212
Production (P) [GWh]	11692	11189	12031	10581	12886	11821	11693	11462	11670
P+NPPK [GWh]	14585	14083	14924	13474	15779	14715	14586	14356	14563
Import w/o NPKK [GWh]	6141	5752	6694	7252	4947	6012	6140	6371	6163
%	34.4%	34.0%	35.7%	40.7%	27.7%	33.7%	34.4%	35.7%	34.6%
Import w NEK [GWh]	3248	2859	3800	4359	2054	3118	3247	3477	3270
%	18.2%	16.9%	20.3%	24.4%	11.5%	17.5%	18.2%	19.5%	18.3%
Overall cost [M€]	794.5	599.2	845.5	937.5	636.9	925.4	660.6	876.5	777.3
€/MWh [€/MWh]	42.6	32.7	43.3	51.2	33.2	50.3	34.6	47.5	41.4
Consumption [GJ/MWh]	36.8	34.8	39.2	41.3	34.7	38.6	36.9	36.5	37.1
Fuel costs [M€]	204.4	190.4	222.8	240.1	190.2	252.4	172.1	203.6	204.4
CO_2 costs [M€]	20.7	19.7	21.8	22.6	19.6	21.5	21.6	59.4	0.0
Imported electricity [M€]	138.3	93.4	164.7	223.1	68.2	156.7	112.3	165.1	135.4
Imported fuel [M€]	133.3	127.0	140.5	146.6	126.7	166.1	113.1	132.0	133.9
CO_2 emissions [Mt]	2.96	2.81	3.11	3.22	2.80	3.07	3.09	2.97	3.10
tCO_2/MWh	0.166	0.166	0.166	0.181	0.157	0.172	0.173	0.166	0.174
Cost	0.446	0.354	0.452	0.526	0.357	0.519	0.370	0.491	0.436
Reliability	0.342	0.368	0.361	0.394	0.306	0.349	0.341	0.339	0.346
Sustainability	0.455	0.447	0.471	0.546	0.397	0.471	0.464	0.461	0.468
ESI	0.723	0.678	0.746	0.854	0.616	0.783	0.685	0.754	0.727

Table A1. Development scenarios main results

	REF	R2	R4	TS	TP	TR2	TR4
TPP [GWh]	4138	4106	4012	4124	7771	7622	7424
HPP [GWh]	6482	6487	6493	6480	6490	6472	6369
RES [GWh]	859	1990	4004	859	859	1990	4004
IND [GWh]	212	212	212	212	212	212	212
Production (P) [GWh]	11692	12795	14721	11675	15332	16296	18009
P+NPPK [GWh]	14585	15688	17615	14569	18225	19189	20903
Import w/o NPKK [GWh]	6141	5038	3112	6158	2501	1537	-176
%	34.4%	28.3%	17.5%	34.5%	14.0%	8.6%	-1.0%
Import w NEK [GWh]	3248	2145	218	3264	-392	-1356	-3070
%	18.2%	12.0%	1.2%	18.3%	-2.2%	-7.6%	-17.2%
Overall cost [M€]	794.5	834.5	933.7	785.9	772.2	807.6	854.2

€/MWh [€/MWh]	42.6	46.8	52.4	44.1	43.3	45.3	47.9
Consumption [TJ]	36.8	36.7	36.1	36.0	64.9	64.0	62.5
Fuel costs [M€]	204.4	202.9	198.7	210.7	302.4	295.9	289.1
CO_2 costs [M€]	20.7	20.6	20.4	20.0	30.0	29.7	29.0
Imported electricity [M€]	138.3	88.9	8.9	137.0	-16.1	-53.9	-108.4
Imported fuel [M€]	133.3	132.7	131.1	130.4	227.5	225.1	220.4
CO_2 emissions [Mt]	2.96	2.95	2.91	2.86	4.29	4.24	4.14
tCO_2/MWh	0.166	0.165	0.163	0.160	0.240	0.238	0.232
Cost	0.446	0.468	0.524	0.441	0.433	0.453	0.479
Reliability	0.342	0.266	0.150	0.340	0.274	0.212	0.131
Sustainability	0.455	0.422	0.371	0.443	0.591	0.555	0.497
ESI	0.723	0.684	0.659	0.712	0.782	0.747	0.703

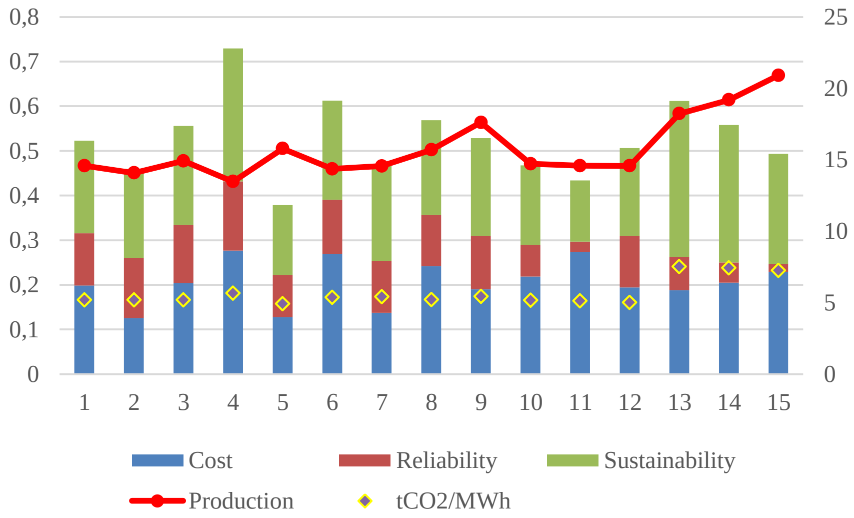

Figure A1. Main findings of the ESI analysis for Croatia (ESI^2=$Cost^2$+$Reliability^2$+$Sustainability^2$)

References

[1] Višković, A., Franki, V., Valentić, V., 2014. CCS (carbon capture and storage) investment possibility in South East Europe: A case study for Croatia. Energy 70, 325-337

[2] Berger, A., 2002. "The Effect of Greenhouse Gases on Climate", Proceedings of the Conference on the Future Energy Systems and Technology for CO_2 Abatement, Antwerp, Belgium, November, 3-10

[3] Intergovernmental Panel on Climate Change (IPCC), 1990. Policymaker's summary of the scientific assessment of climate change; report to IPCC from working group. Meteorological Office: Branknell, United Kingdom

[4] Intergovernmental Panel on Climate Change (IPCC), 2007. Summary for policymakers. In: climate change 2007: the physical science basis, contribution of working group i to the fourth assessment report of the intergovernmental panel on climate change. Geneva: World Meteorological Organization/United Nations Environment Program

[5] Grubb, M., Jamasb, T., Pollit, M., 2008. Delivering a Low Carbon Electricity System: Technologies, Economics and Policy. Cambridge University Press

[6] Sevilgen, S.H., Erdem, H.H., Ali Volkan, B.C., Dagdas, A., 2005. Effect of economic parameters on power generation expansion planning. Energy Conversion and Management 46, 1780–1789

[7] Lior, N., 2012. Sustainable energy development (May 2011) with some game-changers. Energy 40, 3-18

[8] Lior, N., 2010. Sustainable energy development: the present (2009) situation and possible paths to the future. Energy 35, 3976-3994

[9] Lund, H. 2007. Renewable energy strategies for sustainable development. Energy, volume 32, 912-919

[10] Clark, W., Lund, H., 2007. Sustainable development in practice. Journal of Cleaner Production 15, 253–258

[11] Lund, H., Hveplund, F., 2012. The economic crisis and sustainable development: The design of job creation strategies by use of concrete institutional economics. Energy 43, 192-200

[12] Esseghir, A., Haouaoui Khouni, L., 2014. Economic growth, energy consumption and sustainable development: The case of the Union for the Mediterranean countries. Energy, in press

[13] Hennicke, P., 2004. Scenarios for a robust policy mix: the final report of the German study commission on sustainable energy supply. Energy Policy 32, 1673–1678

[14] Liu, W., Lund, H., Mathiesen, B.V., Zhang, X. 2011. Potential of renewable energy systems in China. Applied Energy 88, 518-525

[15] Safian, F. 2014. Modelling the Hungarian system – The first step towards sustainable energy planning. Energy 69, 58-66

[16] Ayres, R.U., Turton, H., Casten, T. 2007. Energy efficiency, sustainability and economic growth. Energy 2007, Volume 32, 634-648

[17] Duic, N., Graca Carvalho, M., 2004. Increasing renewable energy sources in island energy supply: case study Porto Santo. Renewable Sustainable Energy Review 8, 383–399

[18] Perry, S., Klemeš, J., Bulatov, I. 2008. Integrating waste and renewable energy to reduce the carbon footprint of locally integrated energy sectors. Energy 33, 1489-1497

[19] Hvelplund, F., Lund, H., 1998. Rebuilding without restructuring the energy system in east Germany. Energy Policy 26, 535–546

[20] Kang, C.A., Brandt, A.R., Durlofsky, L.J. 2011. Renewable energy is closing the technological and economic gap compared with CCS technologies. Energy 36, 6806-6820
[21] Lund, H. 1999. A green energy plan for Denmark – job creation as a strategy to implement both economic growth and a CO2 reduction. Environmental Resource Economics 14, 431–439
[22] Fernandes L, Ferreira P. 2014. Renewable energy scenarios in the Portuguese electricity system. Energy 69, 51-57.
[23] Alberg Østergaard, P., Mathiesen, B.V., Möller B, Lund, H., 2010. A renewable energy scenario for Aalborg municipality based on low-temperature geothermal heat, wind power and biomass. Energy 35, 4892-4901
[24] Østergaard PA, Lund H. A renewable energy system in Frederikshavn using low-temperature geothermal energy for district heating. Applied Energy 88, 479-487.
[25] Mahiesen, B.V., Lund, H., Karlsson, K. 2011. 100% Renewable energy systems, climate mitigation and economic growth. Applied Energy 88, 488-501
[26] Lund, H., Mahiesen, B.V., 2011. Energy system analysis of 100% renewable energy systems – The case of Denmark in years 2030 and 2050. Energy 34, 524-531
[27] Francés, G.E., Marín-Quemada, J.M., González, E.S.M., 2013. RES and risk: Renewable energy's contribution to energy security. A portfolio-based approach. Renewable and Sustainable Energy Reviews 26, 549–559
[28] Sensfuss, F., Ragwitz, M., Genoese, M., 2008. The merit-order effect: A detailed analysis of the price effect of renewable electricity generation on spot market prices in Germany. Energy Policy 36, 3086–3094
[29] Valentine, S.V., 2011. Emerging symbiosis: renewable energy and energy security. Renewable and Sustainable Energy Reviews 15, 4572–4578
[30] Johansson, B. 2013. A broadened typology on energy and security. Energy 53, 199-205
[31] Wu, J.H., Huang, Y.H., 2014. Electricity portfolio planning model incorporating renewable energy characteristics. Applied Energy 119, 278–287
[32] Winzer, C., 2012. Conceptualizing energy security. Energy Policy 46, 36–48
[33] Rafey, W., Sovacool, B.K. 2011. Competing discourses of Energy development: the implications of the Medupi coal-fired power plant in South Africa. Global Environmental Change 21(3), 1141-1151
[34] Sovacool, B.K., Saunders, H., 2013. Competing policy packages and the complexity of energy security. Energy 67, 641-651
[35] European Commission (EC), 2006. GREEN PAPER A European Strategy for Sustainable, Competitive and Secure Energy, SEC(2006) 317
[36] International Energy Agency (IEA), 2007. Energy Security and Climate Change; assessing interactions. International Energy Agency. Paris
[37] NATO review magazine, 2014. http://www.nato.int/docu/review/index_EN.htm, last accessed 24th October 2014
[38] European Commission (EC), 2008. Communication from the commission. 20 20 20 by 2020: Europe’s climate change opportunity. Brussels, Belgium: COM 30 final
[39] European Commission (EC), 2010. Communication from the commission to the European Parliament, the Council, the European Economic and Social Committee and the Committee of the Regions of 10 November 2010 – Energy 2020 A Strategy for competitive, sustainable and secure energy. Brussels, Belgium: COM 639 final
[40] Yergin, D., 2006. Ensuring energy security. Foreign Affairs 85, 69-82.
[41] Månsson, A., Johansson, B., Nilsson, L.J., 2014. Assessing energy security: An overview of commonly used methodologies. Energy 73, 1-14

[42] Chester, L., 2010. Conceptualising energy security and making explicit its polysemic nature. Energy Policy 38, 887-895
[43] Creti, A., Fabra, N., 2007. Supply security and short-run capacity markets for electricity. Energy Economics 29, 259–276.
[44] Jamasb, T., Pollitt, M., 2008. Security of supply and regulation of energy networks. Energy Policy 36, 4584–4589
[45] Le Coq, Chloe, Paltseva, Elena, 2009. Measuring the security of external energy supply in the European union. Energy Policy, 37, 4474–4481
[46] Turton, H., Barreto, L., 2006. Long-term security of energy supply and climate change. Energy Policy 34, 2232–2250
[47] Bielecki J., 2002. Energy security: is the wolf on the door? The Quarterly Review of Economy and Finance 42, 235–250
[48] Grubb, M., Butler, L., Twomey, P., 2006. Diversity and security in UK electricity generation: the influence of low-carbon objectives. Energy Policy 34, 4050–4062
[49] Jansen, J.C., Seebregts, A.J., 2010. Long-term energy services security: what is it and how can it be measured and valued? Energy Policy 38, 1654–1664.
[50] Jun, E., Kim,W., Chang, S.H., 2009. The analysis of security cost for different energy sources. Applied Energy 86, 1894–1901
[51] Johansson, B. 2013. Security aspects of future renewable energy systems – A short overview. Energy 61, 598-605
[52] Lefèvre, N., 2010. Measuring the energy security implications of fossil fuel resource concentration. Energy Policy 38, 1635–1644
[53] McCarthy, R.W., Ogden, J.M., Sperling, D., 2007. Assessing reliability in energy supply systems. Energy Policy 35, 2151–2162
[54] Ranjan, A. Huges, L. 2014. Energy security and the diversity of energy flows in an energy system. Energy 73, 137-144
[55] Rutherford, J.P., Scharpf, E.W., Carrington, C.G., 2007. Linking consumer energy efficiency with security of supply. Energy Policy 35, 3025–3035
[56] Sovacool, B.K., Mukherjee, I. 2011. Conceptualizing and measuring energy security: A synthesized approach. Energy 36, 5343-5355
[57] Ren, J., Sovacool, B.K. 2014. Quantifying, measuring, and strategizing energy security: Determining the most meaningful dimensions and metrics. Energy 76, 838-849
[58] Sovacool, B.K., ed. 2011. The Routledge Handbook of Energy Security. Oxford and New York: Routledge
[59] UNDP – United Nations Development Fund (UNDP), 2000. World energy assessment: Energy and the challenge of sustainability. New York: United Nations Development Programme, United Nations Department of Economic and Social Affairs, World Energy Council; 508
[60] European Commission (EC), 2000. Green paper: towards a European strategy for the security of energy supply. European Commission, 2000. Luxembourg: Office for Official Publications of the European Communities; 105 COM(2000) 769 final
[61] International Energy Agency (IEA). World Energy Outlook 2007. China and India insights. Paris:IEA/OECDf[55
[62] Kruyt, B., van Vuuren, D.P., de Vries, H.J.M., Groenenberg, H., 2009. Indicators for energy security. Energy Policy 37, 2166–2181.
[63] Birol, F., 2006. Policy forum: the future of energy markets – world energy prospects and challenges. The Australian Economic Review 39,190–195.
[64] Yergin, D., 2005. Energy security and markets. In: Kalicki, J.H., Goldwyn, D.L. (Eds.), Energy and Security: Toward a New Foreign Policy Strategy. Washington, Woodrow Wilson Press, 51–64

[65] United Nations Development Program (UNDP), 2004. World Energy Assessment: Overview 2004 Update. UNDP, New York.
[66] *Ö*lz, S., Sims, R., Kirchner, N., 2007. Contribution of Renewables to Energy Security. International Energy Agency (IEA), 2007.
[67] Rutherford, J.P., Scharpf, E.W., Carrington, C.G., 2007. Linking consumer energy efficiency with security of supply. Energy Policy 35, 3025–3035
[68] Wright, Philip, 2005. Liberalisation and the security of gas supply in the UK. Energy Policy 33, 2272–2290
[69] Gnansounou, E., 2008. Assessing the energy vulnerability: case of industrialised countries. Energy Policy 36, 3734–3744
[70] Ryu, H., Dorjragchaa, S., Kim, Y., Kim, K., 2014. Electricity-generation mix considering energy security and carbon emission mitigation: Case of Korea and Mongolia. Energy 64, 1071-1079
[71] Višković, A., Franki, 2015. Coal Based Electricity Generation in South East Europe: A Case Study for Croatia. International Journal of Energy Economics and Policy 5, 206-230
[72] Pardalos, P.M., 2002. Resende MGC. Handbook of applied optimization. Oxford University Press
[73] Du, D.-H., 2005. Pardalos PM. Handbook of combinatorial optimization: supplement volume B. Springer
[74] Rubin, E.S., Chen, C., Rao, A.B., 2007. Cost and performance of fossil fuel power plants with CO2 capture and storage, Energy Policy, Vol. 35, 4444-4454
[75] Connloy, D., Lund, H., Mathiesen, B.V., Leahy, M. 2010. A review of computer tools for analysing the integration of renewable energy into various energy systems. Applied Energy 87, 1059–1082
[76] Baños, R., Manzano-Agugliaro, F., Montoya, F.G., Gil, C., Alcayde, A., Gómez., J., 2011. Optimization methods applied to renewable and sustainable energy: A review. Renewable and Sustainable Energy Reviews 15, 1753–1766
[77] Bazmi, A.A., Zahedi, G., 2011. Sustainable energy systems: role of optimization modeling techniques in power generation and supply – a review. Renewable and Sustainable Energy Reviews 15, 3480–3500
[78] Ren, H., Gao, W., 2010. A MILP model for integrated plan and evaluation of distributed energy systems. Applied Energy 87, 1001–1014
[79] Mehleri, E.D., Sarimveis, H., Markatos, N.C., Papageorgiou, L.G., 2013. Optimal design and operation of distributed energy systems: application to Greek residential sector. Renewable Energy 51, 331–342
[80] Rubio-Maya, C., Uche-Marcuello, J., Martinez-Gracia, A., Bayod-Rujula, A.A., 2011. Design optimization of a polygeneration plant fuelled by natural gas and renewable energy sources. Applied Energy 88, 449–457
[81] CESI, www.cesi.it/Pages/default.aspx, last accessed 7th December 2014
[82] Višković, A., Franki, V., Valentić, V., 2014. Effect of regulation on power-plant operation and investment in the South East Europe market: an analysis of two cases. Utilities policy 30, 8 – 17
[83] Višković, A., Valentić, V., Franki, V., 2013. The impact of carbon prices on CCS investment in South East Europe. Economics and Policy of Energy and the Environment, Volume 2013/3
[84] CWE Market Coupling algorithm, June 2010, www.apxendex.com, last accessed 7th December 2014
[85] Capurso, P., Cova, B., Elia, E., Portoghese, P., Stabile, M., Vedovelli, F., Venturini, A., 2012. Market integration in Europe: a market simulator taking into account different

market zones and the increasing penetration of RES generation. CIGRE 2012, Paris session
[86] Eydeland, A., & Wolyniec, K. (2003). Energy and power risk management. Hoboken, NJ: Wiley
[87] Bunn, D. W., 2004. Modelling prices in competitive electricity markets. Chichester: Wiley
[88] Weron, R., 2006. Modeling and forecasting electricity loads and prices: a statistical approach. Chichester: Wiley
[89] Weron, R. 2014. Electricity price forecasting: A review of the state-of-the-art with a look into the future. International Journal of Forecasting 30, 1030–1081
[90] Višković, A., Franki, V., 2015. Status of Croatia's energy sector framework: progress, potential, challenges and recommendations. Thermal Science, accepted for publication
[91] Jamasb, T., 2002. Reform and Regulation of the Electricity Sectors in Developing Countries. DAE Working Paper No. 226. University of Cambridge
[92] Arocena, P., Waddams, C., 2002. Generating efficiency: economic and environmental regulation of public and private electricity generators in Spain. International Journal of Industrial Organization 20, 41–69
[93] Memorandum of Understanding on the Regional Electricity Market in South East Europe and its Integration into the European Union Internal Electricity Market – "The Athens Memorandum – 2002", Athens, 15 November 2002
[94] Deitz, L., Stirton, L., Wright, K., 2009. South East Europe's electricity sector: Attractions, obstacles and challenges of Europeanization. Utilities Policy, volume 17, 4-12
[95] Pollitt, M., 2009. Evaluating the evidence on electricity reform: Lessons for the South East Europe (SEE) market. Utilities Policy 17 (2009), 13 – 23
[96] Hooper, E., Medvedev, A., 2009. Electrifying integration: Electricity production and the South East Europe regional energy market, Utilities Policy, volume 17, 24-33
[97] Hattori, T., Tsutsui, M. 2003. Economic Impact of Regulatory Reforms in the Electricity Supply Industry: A Panel Data Analysis for OECD Countries. Energy Policy, volume 32, 823-832
[98] World Bank, 2003. Private Sector Development in the Electric Power Sector: A Joint OED/OEG/OEU Review of the World Bank Group's Assistance in the 1990s, Operations Evaluation Department, Operations Evaluation Group, Operations Evaluation Unit, OED, July 21, World Bank, Washington, D.C.
[99] Waddams Price, C., Pham, K., 2009. The impact of electricity market reform on consumers. Utilities Policy, volume 17, 43–48
[100] Jamasb, T., Pollitt, M., 2005. Electricity market reform in the European Union: review of progress toward liberalization and integration. Energy Journal, 11–41
[101] Scholl, B., 2009. Electricity Reform in Bosnia-Herzegovina. Utilities Policy, volume 17, 49–64
[102] Datamonitor. Energy, Market Landscape: Croatia, https://www.datamonitor.com, last accessed 29th October 2014
[103] HOPS website,www.hops.hr/wps/portal/hr/web, last accessed 21st April 2014
[104] HROTE. Annual report 2013. www.hrote.hr/, last accessed 21st April 2014
[105] ENTSO-E website, www.entsoe.eu/, last accessed 21st April 2014
[106] HEP, www.hep.hr/hep/en/news/default.aspx, last accessed 21st April 2014
[107] HERA website, www.hera.hr/en/html/index.html, last accessed 21st April 2014
[108] Croatia's Official Gazette (133/2013, 151/2013)
[109] EEX website, www.eex.com/en/, last accessed 21st April 2014
[110] HUPX website, www.hupx.hu/en/Pages/hupx.aspx?remsession=1, last accessed 21st April 2014

[111] Croatian Ministry of Economy, 2014. Annual energy report: Energy in Croatia 2013
[112] Markowitz, H.M. 1952. Portfolio selection. The Journal of Finance 7, 77-91
[113] Markowitz, H.M. 1959. Portfolio selection: Efficient diversification of investment. Cowles Foundation for Research in Economics at Yale University; Library of Congress. Catalog Card Number: 59-6771
[114] Arnesano, M., Carlucci, A.P., Laforgia, D., 2012. Extension of portfolio theory to energy planning problem: The Italian case. Energy 39, 112-124
[115] Gustavsson, L., Holmberg, J., Dornburg, V., Sathre, R., Eggers, T., Mahapatra, K., et al. 2007. Using biomass for climate change mitigation and oil use reduction. Energy Policy, Volume 35, 5671-5691
[116] Demirbas, M.F., Balat, M., Balat, H. 2009. Potential contribution of biomass to the sustainable energy development. Energy Conversion and Management, Volume 50, 1746-1760
[117] Lončar, D., Duić, N., Bogdan, Ž. 2009. An analysis of the legal and market framework for the cogeneration sector in Croatia. Energy, Volume 34, 134-143
[118] Jaramillo, O.A., Borja, M.A., Huacuz, J.M. 2004. Using hydropower to complement wind energy: a hybrid system to provide firm power. Renewable Energy, Volume 29, 1887-1909
[119] Lund, H., Ostergaard, P.A. 2000. Electric grid and heat planning scenarios with centralized and distributed sources of conventional, CHP and wind generation. Energy, Volume 25, 299 – 312
[120] Schneider, D.R., Kirac, M., Hublin, A. 2012. Cost-effectiveness of GHG emission reduction measures and energy recovery from municipal waste in Croatia. Energy, Volume 48, 203-211
[121] Münster, M., Meibom, P. 2011. Optimization of use of waste in the future energy system. Energy, Volume 36, 1612-1622
[122] Schneider, D.R., Duić, N., Bogdan, Ž. 2007. Mapping the potential for decentralized energy generation based on renewable energy sources in the Republic of Croatia. Energy, Volume 32, 1731-1744
[123] Raffestin, L. 2014. Diversification and systemic risk. Journal of Banking and Finance 46, 85-106
[124] Lund, H., Hvelplund, F., Kass, I., Dukalskis, E., Blumberga, D. 1999. District heating and market economy in Latvia. Energy, volume 24, 549-559
[125] Lund, H., Hvelplund, F., Ingermann, K., Kask, U. 2000. Estonian energy system – proposals for the implementation of a cogeneration strategy. Energy Policy, volume 28, 729–736
[126] Szklo, A.S.,Tolmasquim, M.T. 2003. Analysis of Brazil's cogeneration legal framework. Energy Conversion and Management, Volume 44, 369-380
[127] Lund, H., Hvelplund, F., Nunthavorakarn, S. 2003. Feasibility of a 1400MW coal-fired power-plant in Thailand. Applied Energy, Volume 76, 55-64.
[128] Lund, H., Münster, E. 2006. Integrated energy systems and local energy markets. Energy Policy, Volume 34, 1152-1160