Planning for a 100% independent energy system based on smart energy storage for integration of renewables and CO2 emissions reduction

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Planning for a 100% independent energy system based on smart energy storage for integration of renewables and CO_2 emissions reduction

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ABSTRACT

EU import dependence on hydrocarbons and resulting negative environmental impact related to their use led to setting of new measures and energy policy that will make, in time, a post carbon society more feasible and achievable. Energy systems of this society will be based on four pillars: Renewable Energy, Buildings as Positive Power Plants, Energy Storage and Smart grids in combination with Plug-in Vehicles. All these pillars must be supported by the use of smart energy storage. The results of previous research has shown that in order to increase security, efficiency and viability, there is need for energy storage, in primary or secondary form, in order to transfer energy surplus from period of excess to the period when there is a lack. The problem of today's storage systems is that they increase the cost of already expensive, distributed and renewable energy sources. That makes the large scale use of storage systems even less economically viable in market circumstances, despite economics of scale. The paper shows results of an energy planning methodology applied to several cases where use of smart energy storage system helps integration of energy flows, transformations and energy demand at the location of the energy end-use or close to it. Main results presented in this paper focus on planning a 100% independent energy system of Croatia. They also show the role of energy storage in a self-sustainable energy system with excess electricity production from renewable energy sources. The technical and financial analyses have been carried out for periods of one year taking into consideration demands and renewable energy production during all hours.

1. Introduction

In 2007, the primary energy import dependency of the EU-27 was 53.1%. It is expected that in the next 20–30 years it will reach or surpass 70%. The situation in Croatia is similar, where in 2008 the import dependence was 52.3%, while for 2030 it is predicted to reach 72% [1]. EU-27 imports: 41.2% of solid fuels, 82.6% of oil and 60.3% of gas [2]. Such dependence on imported hydrocarbons leads to decreased security of energy supply as the import from Russia surpassed 1/3rd of total imported fossil fuels and approximately 1/3rd of imported gas and oil come from unstable geopolitical regions. Of course, competition for those same resources from developing countries is progressively growing. Thus, the EU energy strategy and a compatible Croatian strategy are focused on policies and measures that will increase the share of renewable and distributed energy sources, increase energy savings and improve energy efficiency. All these measures will increase the security of energy supply and decrease green house gas emissions. Moreover, the latest actions of the EU energy policy makers are focused on promoting and planning of the Post Carbon Society [3] and [4]. The four pillars of energy systems of the Post Carbon Society, as they were presented by Carvalho et al. [5], are:

Abbreviations: CAES, compressed air energy storage; CEEP, critical excesses electricity production; CES, Croatian energy strategy; CHP, combined heat and power; COP, coefficient of performance; CSHP, industrial combined heat and power; DH, district heating; DHP, district heating plant; EEX, the european energy exchange AG; ENTSO-E, european network of transmission system operators for electricity; ESCO, energy service company; HEP, Croatian utility company; HPP, hydro power plant; HR, Croatia; JP, jet petrol; LPG, liquefied petroleum gas; LULUCF, (land use, land – use change and forestry); N.gas, natural gas; NPP, nuclear power plant; PHS, pumped hydro storage; PP, power plant (condensing); RES, renewable energy sources; SL, Slovenia; TSO, transmission system operator; V2G, vehicle-to-grid.

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- Renewable energy
- Buildings as positive power plants
- Energy storage
- Smart grids and plug-in vehicles

These characteristics will also be the result of strong political, public and economic support for all renewable energy technologies. In the EU political support has been reflected through European Energy Policy and primarily by its directives, the EU "climate and energy package" and The Strategic Energy Technology Plan (SET Plan). EU had an indicative target to cover 12% of the gross inland energy consumption by RES in 2010. New RES directive is setting RES target for 2020 on 20% of the gross final energy consumption, while the most recent initiatives have already begun process to convert EU Energy supply to 100% RES. On 15th April 2010 RE-thinking 2050 Campaign [6] was launched in the European Parliament. It outlines a path how the European Union can switch to a 100% renewable energy supply (for electricity, heating and cooling as well as transport), and harvest the positive effects of Europe's energy supply system and reduce CO_2 emissions. RE-thinking 2050 and similar initiatives [7–10] will help to create Post Carbon Society for the EU. As it is highlighted by Prof. Carvalho [3]: A post carbon society makes it possible to reframe the energy and climate change challenges as opportunities, not just to foster a wealthier society, but also to create a more equitable and sustainable one. The Post Carbon Society is the concept that explains a more sustainable world, independent from the use of fossil fuels. It describes the process of change and the necessary development of new technologies together with their integration in energy, environment and other systems. Aside technological change, it will require changing of society life-styles and behaviour. For more information on these issues see Refs [3,4].

In order to increase efficiency and viability of power systems, there is need for energy storage, in primary or secondary form, in order to transfer energy surplus from period of excess production (or cheaper production) to other more appropriate periods. Although storage systems have a positive effect on RES integration, their problem is that they increase the cost of already expensive distributed and renewable energy sources, making them, in market circumstances, even less economically viable.

Many energy storage technologies have been present on the market for more than a century. What is novel and smart in these technologies is their use for specific purposes and their synergies with new processes and combination with other energy sources.

Use of traditional energy storage for increasing RES integration has been tackled and proposed by many authors. Use of pumped hydro storage (PHS) is proposed in [11–13] batteries in [14–16] and compressed air energy storage (CAES) in [17]. Use of emerging technologies as flow batteries and storages connected to new energy carriers has been explained in [15,18,19]. Thermal storage and heat pumps could be used to store excess of RES production as showed in [20] or effectively combined with smaller scale applications to rise profits as modelled and explained in Ref. [21].

Some solutions based on novel principle of use of the thermal storage for electricity storage and generation in cases where PHS or CAES are not applicable are explained in [22]. A more detailed review of thermal storage, in particular thermal storage with phase change materials and their application is given in [23]. Cooling storage could also be used for the integration of renewable energy sources [24,25].

The idea behind this work was to see how smart use of energy storage could improve and guide the development of a real energy system. In addition, it was needed to investigate different approaches for addressing intermittency problems and energy independency for selected sectors. It was also important to compare the planned system without storage and an alternative with storage, thus highlighting advantages and disadvantages. Energy storage system could help with integration of energy flows, transformations and energy demand at the location of the energy end-use or close to it. The smart use of energy storage will support all four pillars of the Post Carbon Society.

2. Problem background, methods and tools implemented in the case study

This section presents the main issues that arise in using energy storage in long-term planning of energy systems. It continues by presenting tools used by the authors for modelling as well as three major scenarios/systems modelled and investigated.

By portraying three different cases, the current status and possible development of the Croatian Energy System will be given. Information used in the modelling will be presented together with the assumptions and regulation strategies applied to the technical energy system analyses of the increased penetration of RES, storage and integration technologies.

2.1. Renewable energy, its intermittency problem and energy storage

The intermittency of renewable sources like wind, solar and waves prohibits their exclusive use for power production as in many cases it is very hard to match intermittent production with demand. Technical and economic problems of variable production could be decreased by introducing different types of energy storages. Typically, as RES penetration gets higher for autonomous or weakly interconnected areas (i.e. islands), operators give instructions for shedding RES production. Similar problems appear in large power systems when RES penetration reaches certain levels [26]. As previously indicated, potential use of this excess electricity can be utilized by heat pumps and thermal energy storage for later use. However, introducing storage systems further increases the cost of an already expensive system using renewable energy sources. Consequently, this makes the large scale integration of storage less economically viable in market circumstances. So an appropriate approach is need for achieving a system based on high RES penetration (a highly independent system). For the case of hydrogen it has been shown in [27] that electricity price should be in range of 43 euro cents/kWh to 171 euro cents/kWh.

Analysis for storage requirements that will respond to intermittency problems and critical excesses electricity production (CEEP) has been carried out based on the Croatian energy Strategy after 2020 and the premise of a 100% independent energy system.

2.2. Tools used for analyses

A detailed energy system analysis is performed by the use of the freeware model EnergyPLAN [28] and H_2RES [27]. Both models are input/output models that perform annual analyses in steps of 1 h. Inputs are power demands and capacities of different technologies included as well as demand distributions, and fluctuating renewable energy distributions. Different options can be included enabling the reconstruction of all elements of an energy system and allowing the analyses of used technologies.

H_2RES model was used to determine hourly production of wind turbines in Southern Croatia from the wind speed measurements obtained within the AWSERCRO project [29]. The same model was used to create the distribution curve of PV production. The EnergyPLAN is used for analysis of scenarios with large amounts of intermittent renewable energy production and for analysing CHP systems with large interaction between heat and electricity supply.

EnergyPLAN was used to simulate a 100% renewable energy system for the island of Mljet in Croatia [30] the entire country of Denmark [7]. It was also used in various studies to investigate large scale integration of wind energy in power systems [20], optimal combinations of renewable energy sources [31], management of surplus electricity [32], the integration of wind power using electric vehicles (EVs) [33], the investigation of fuel cells' and electrolysers' potential in future energy systems [34], the effect of energy storage [25] and compressed-air energy storage [17].

The EnergyPLAN identifies CEEP as the export which exceeds the transmission line capacity. This production can damage system and electricity supply so it is not allowed in real system operation. However, it is calculated in order to see the system behaviour under different operational and optimization conditions. Also, EnergyPLAN can use different regulation/policy strategies, putting emphasis on heat and power supply, import/export of electricity, excess electricity production and use of different components in the analysed energy system. Outputs include energy balances, annual productions, fuel consumptions, and import/exports.

2.3. The reference energy system

The Croatian energy system for 2008 has been modelled in EnergyPLAN. Energy consumption and supply data have been taken from [1], while hourly load data for Croatian power system have been provided by ENTSO-E [35]. Basic data on generators has been obtained from the Croatian electricity company (HEP) [36] and from [1]. Data for hourly production of hydro power plants has been reconstructed from monthly values provided in [35] while capacities of hydro storage have been calculated by data provided in [37]. Load curves for the hourly district heating demand were calculated according to yearly heat consumption in Croatia [1] and using patterns of hourly heat demand in Denmark that are available in EnergyPLAN. Heat production from large cogeneration plants and district heating systems have been added as district heating demand, while all industry heat and process steam demand was treated separately, through energy consumption of the industry sector. EnergyPLAN has the ability to model hourly heat production from industry and this heat is modelled using its own distribution under which it supplies heat to the district heating systems. In EnergyPLAN, there is no possibility to treat separately heat demand in the industry sector from the other sectors, since all district heating demands are aggregated and represented by the one hourly demand curve.

A total cross border transmission capacity for electricity exchange is set to 3200 MW as published in Ref. [38]. The author in Ref. [39] provides a value of 3040 MW for the total import capacity for Croatia and 2400 MW for the export capacity to neighbouring countries. For the same capacities, the Slovenian TSO calculates interconnection capacities from SL to HR to be 1200 MW, instead of 1000 MW that has been published in [39] so 3200 MW was taken as final value for 2008.

Croatian import of electricity varies from 25% to 40% of yearly end-consumption and is fairly dependent on hydro power production and fossil fuel prices. Final import quantities and prices are mostly set by bilateral contracts. As there are no obligations to publish these contracts there is no data regarding the price of the imported electricity. To replicate similar conditions as in 2008, hourly changes of market prices from the German spot market published at EEX have been adopted by the elasticity, that is explained in the EnergyPLAN manual [40].

The market price on the external market, p_X, is calculated by formula:

$$p_X = pi + (p_i/p_o) \times Fac_{depend} \times d_{Net\text{-}Import} \quad (1)$$

where p_i is the system market price (as used by EnergyPLAN [40]),

Fac_{depend} is the price elasticity (€/MWh/MW)

p_o is the basic price level for price elasticity (input),

$d_{Net\text{-}Import}$ the trade on the market.

The Nuclear Power Plant (NPP) Krsko in Slovenia, which is under 50% ownership of HEP, is modelled as fixed import under the constant hourly distribution taking into account the real outages from 2008. It resulted in an almost constant power of 344 MW supplied by NPP. In all calculated cases, the import was 2986 GWh.

Reference case calculated by the EnergyPLAN model has been compared to statistical data for Croatia [1] in order to see how well it represents the situation in 2008.

2.4. The case of Croatian energy strategy scenario until 2020

The idea behind this scenario was to analyse the Croatian energy system if it will follow the development plans laid down in the current Croatian Energy Strategy (CES). According to the CES, the share of RES in the gross final consumption will be 20% in 2020. This share is divided between three energy vectors and it is planned to have 35% of RES share in electricity consumption, 10% of RES share in transport fuel and 20% RES share in heating and cooling. The 20% goal in terms of final energy consumption is given in the Table 1.

As it is mentioned above, one of the goals of the strategy is to satisfy 35% of electricity consumption by renewable energy sources including big hydro power plants in 2020. To fulfill this goal it is expected to add 300 MW of new large hydro power plants, 1.200 MW of wind turbines, 85 MW of biomass power plants and 100 MW of small hydro power plants. These RES installation have been inserted in the EnergyPLAN model in a way that one half of the planned capacity of new big hydro power was added as the run-off river hydro and the other half as storage hydro. Small hydro has been treated separately but with the same hourly distribution curve as run-of river.

For 2020, the CES envisages use of 26 PJ of biomass and 9 PJ of biofules while planned production of biogas from agriculture is 2.6 PJ. Another 6 PJ will come from waste as a result of better waste management. This will lead to a reduction of GHG emission for 1.069 Gg CO_2-eq [41]. Additionally, CES sets a goal to install 0.225 m^2 of solar thermal collectors per each Croatian resident (0.225 m^2/per capita).

The current power plants in Croatian Energy systems are older (in average) than 35 years and it is envisaged by the CES that 1100 MW will be decommissioned until 2020. In order to have enough production capacities to satisfy peak loads and to provide adequate security of supply, the strategy set a goal to install 1200 MW of new gas power plants and 1200 MW of coal power plants until 2020. An additional 300 MW of new power plants will be installed as CHP units which will partly replace existing ones. After 2020 it is not planned to use oil in power plants. This was the main reason for separating new units and existing units that will not be decommissioned in two groups in EnergyPLAN. One group represented by CHP plants, modelled as a combination of back pressure and condensing plants and another group with the condensing plants using coal.

Table 1
The share of RES in the gross final consumption of energy.

Gross final consumption	Share of RES %
Electricity	9.2
Transport fuel	2.2
Heating and cooling	8.6

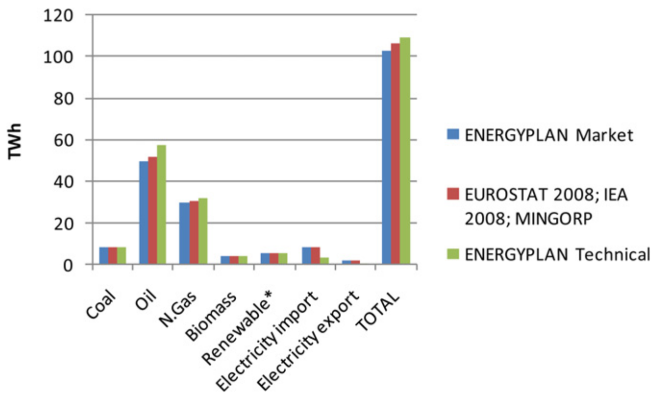

Fig. 1. Gross energy consumption by fuel and electricity export in the reference case (*geothermal heat for hot water and space heating not included).

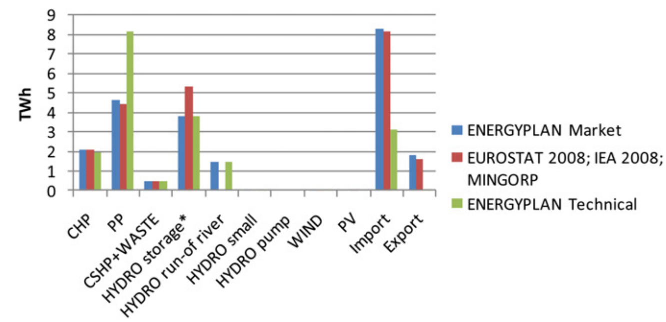

Fig. 3. Electricity production by source in Reference case (*data from statistics are not divided according type of HPP).

Until 2020 it is planned to construct several new natural gas pipelines. One cross border line with Hungary with transport capacity of 860,000 m^3/h and new LNG terminal in Omisalj, on the island of Krk, with the capacity of 10–15 Gm^3/year. By successful realization of at least one of these two projects, Croatia will ensure enough import capacity for gas that will be supplied to new power plants. Without new import capacity it will be hard to satisfy predicted demand.

According to sustainable scenario presented in the CES, projected final energy consumption in 2020 is 386.84 PJ including energy efficiency measures foreseen to save 22.76 PJ. For the period 2006–2020 the predicted increase in electricity consumption is 2.7% yearly. The CES did not take into account recent economical crisis which has also decreased energy consumption. Based on this fact the gross electricity consumption (without heat pumps, pumping and electric vehicles) used in the model has been set to 22.5 TWh. This value gives the same increase in the period 2012–2020 as it was in the period 2000–2008. Similar, the growth in the transport sector and for individual households is set to lower rates than those assumed by the Strategy.

2.5. 100% independent (self-sufficient) Croatian energy system

Current Croatian natural gas reserves are estimated at 36.4361 Gm^3 and with a yearly production at 2.8472 Gm^3, theoretically they may be exhausted in less than 13 years. Similar lifetime can be predicted for Croatian domestic oil reserves that are estimated at 11.4725 Mm^3 and depleted with a yearly production of 815,000 tonnes. However, this is just a hypothetical prediction as in a real system the production will fall together with the reserves which means that domestic reserves will last longer but with a lower yearly production rates. Without significant domestic hard coal reserves, it seems that even in the near future the Croatian energy system could become 100% independent only if its energy supply will rely 100% on local renewable energy sources. With this in mind, a scenario has been defined that uses energy storage and RES and will enable energy independency.

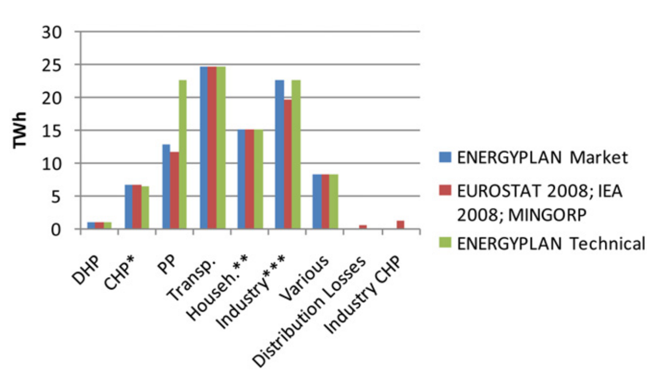

Fig. 2. Gross fuel consumption by sector, 2008 (**Includes boiler consumption within CHP plant; **Consumption of households plus services without electricity consumption and heat from DH; ***Consumption of Industry plus Agriculture plus losses in refineries and gas production facilities).

According to Croatian Green Paper [42] the total estimated potential of wood biomass from forestry, industry and agriculture in Croatia is 26 TWh with an additional potential of 4 TWh for biofuels production using standard crops. A larger estimation of the potential for biofuels production of 14.15 TWh with a special type of biomass and using second generation of biofuels is given by authors in Ref. [43]. While above numbers are related to the total technical potential of biomass in Croatia, more realistic and economically feasible numbers are provided in Ref. [44]. The authors estimated 6 TWh/year as the average energy potential of forestry residues, wheat straw and corn stover. In the period after 2020, most of technical potential for large hydro power plants will be exploited. Only options that may be built would have to be pumped storage and small hydro power plants. Locations have been already identified for 200 MW in small hydro power plants and registered in the national registry of RES projects. Therefore, an additional 100 MW capacity has been envisaged (in addition to the CES) and taken into consideration. There is also potential for geothermal power plants and a total of 40 MW was added to the model. Aside from hydro power, biomass is renewable energy source with the highest potential in the continental part of Croatia while wind and solar represent the highest potential for electricity production along the coastline and in southern Croatia. For low temperature heat generation, besides traditionally used biomass, solar and geothermal have the highest potential. The economic potential of solar energy for heat production is estimated to be around 50% of the total low temperature heat production in 2000 in Croatia, or nearly 12 TWh/year [42].

For the period after 2020, the transport sector is modelled in the way that regular cars on gasoline and diesel will phase out while the share of electric and biodiesel vehicles will progressively grow. In case of the 100% independent system it is assumed that a share of 25% of diesel consumption in the transport sector is used by trucks,

Table 2
Fuel prices used in calculations.

	Fuel prices [€/GJ]						
Year	Coal	Fuel oil	Diesel	Petrol/JP	N.gas	LPG	Biomass
2008	2.1	10.76	14.8	16.2	4.87	11.27	2.66
2020	3.76	12.93	17.78	19.5	10.18	13.54	3.26
2030	4.53	17.78	22.02	25.04	12.25	17.60	3.8

Table 3
Gross final energy consumption, CO_2 and fuel costs.

	Market.	MINGORP [1]	Technical
Total energy: EnergyPLAN [TWh]	96.63	106.09	106.37
Total energy: EnergyPLAN corrected [TWh]	106.38	106.09	106.44
CO_2 [Mt]	22.14	20.30*	24.57
CO_2 corrected [Mt]	25.19		24.77
Total fuel costs [M€]	3075		3383
Coal [M€]	62		62
FuelOil [M€]	849		1104
Diesel [M€]	959		959
Petrol/JP [M€]	571		571
N.gas [M€]	597		650
Biomass [M€]	36		36
Marginal operation costs [M€]	43		52
Import [M€]	219		6
Export [M€]	−96		−4
Total (Marginal (imp./Exp.) [M€]	3241		3437

busses and other vehicles or 4.75 TWh and an additional 5.4 TWh is used by trucks and other heavy vehicles from industry and agriculture. In this case diesel consumption is modelled as it was totally covered by biofuels. All other road transport or 30 billion/km per year, is assumed to be switched to electric vehicles making in average 10,000 km per year. Batteries are integrated part of electric vehicles and way of their operation (grid charging and eventual discharging) could have large impact on future energy systems. Jet fuel consumption in this case is increased for 50% to 3 TWh and has not been replaced by any other fuel.

Due to a large potential in energy efficiency and a dubious demographic growth it has been assumed that yearly energy consumption will not increase significantly from the level planed in the CES for 2020. To demonstrate the potential for energy savings and energy efficiency, a good example is electricity consumption for a public lighting (440.16 GWh in 2008). Only one ESCO project aimed at public lighting of the town of Karlovac [45] realized savings of 25%. If similar measures were to be applied across the whole country, approximate savings only for public lightning could reach 110 GWh annually, which is figuratively speaking the annual electricity production of a medium size power plant. In the same year households' electricity consumption was 6711 GWh. In the EU, in average 20% of electricity consumption in households is spent on lighting so if the same share is applicable to Croatia it accounts for 1342 GWh in electricity consumption. New efficient lightning could reduce this consumption to 1/5 of its original value. In relation to energy efficiency in buildings, with proper insulation achievable savings in Croatia for households and buildings is around 50 PJ (or almost equal to all heat consumption in the household sector) [46].

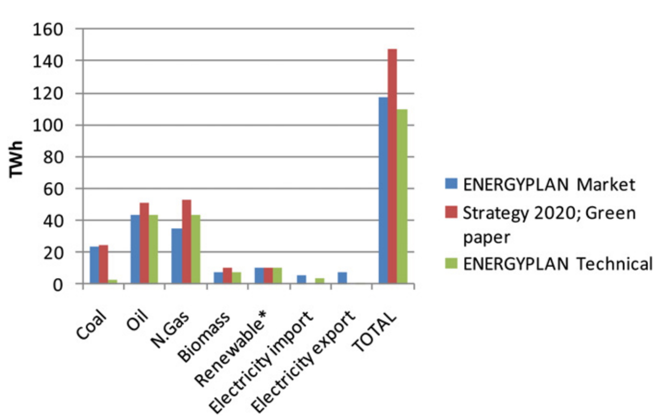

Fig. 4. Gross energy consumption by fuel and electricity export in the case of CES 2020 (*geothermal heat for hot water and space heating not included).

Table 4
Gross energy consumption and CO_2 emissions in 2020. (*gross final energy consumption in sustainable scenario).

	EP_Market	Strategy	EP_Tech
Total energy [TWh]	118.86	108.10*	106.78
Total energy corrected [TWh]	109.96	n/a	106.76
CO_2 [Mt]	26.51	n/a	21.14
CO_2 corrected [Mt]	24.91	n/a	21.34

3. Results of modelling in EnergyPLAN

3.1. Analysis of the reference case for 2008

Despite difficulties in obtaining some data that represents real hourly consumption in 2008, the final numbers have showed that EnergyPLAN model could represent the Croatian energy system adequately. Comparison of the gross energy consumption by fuel and electricity exports for two different calculations (market and technical optimization) and data from the literature have been presented in the Fig. 1.

Gross fuel consumption by sector is given in Fig. 2. It shows big differences in energy sector between results of market optimization regulation strategy and literature data on the one side and the technical optimization on the other. This difference is caused by the preference of technical optimization to supply demand with local production instead of importing. Thus the market optimization provides a more realistic simulation. In EnergyPLAN, consumption of the energy sector has been divided between heat and power producers. The energy losses at refineries, gas production facilities and energy consumption of all other production facilities have been added to the energy consumption of the industry sector. Energy consumption in agriculture has been also added to the industry sector. The Household sector, in EnergyPLAN, has been used to represent the consumption of households and the services sector, although consumption of different types of energy has been treated separately.

Electricity production by source and import of electricity are given in Fig. 3. Since no published data exists related to production of hydro power plants according to their type, hourly production distribution curves have not been compared to real data. As previously mentioned, technical optimization tries to avoid imports or exports and minimizes the use of fossil fuels in observed power plants whereas energy from all other sources is calculated before estimation of the PP share.

Analyses were conducted with the following restrictions in order to ensure the delivery of ancillary services and achieve grid stability (voltage and frequency). At least 30% of the produced electric power (at any hour) must come from power production units capable of supplying ancillary services, such as central PP, CHP, HPP. The distributed generation from RES and small CHP units is not capable of supplying ancillary services necessary for grid stability. Additionally, large CHPs are not able to operate below their minimum

Table 5
Cost of CES 2020 case for different model optimizations.

	Market opt.	Technical opt.
Total CO_2 emission costs [M€]	530	423
Total variable costs [M€]	4516	4629
Fixed operation costs [M€]	223	223
Annual Investment costs [M€]	573	573
Total annual costs [M€]	5312	5425

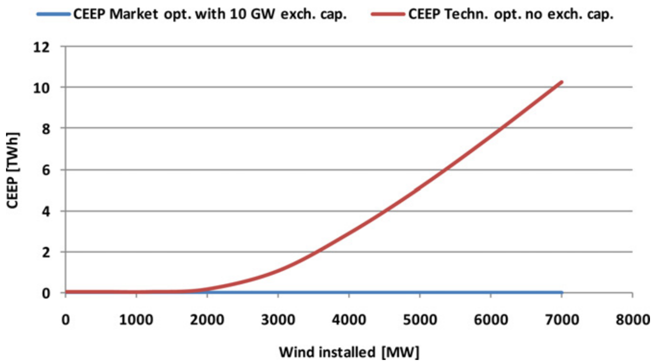

Fig. 5. Critical excess electricity production for increased wind capacity (the case of interconnected and independent energy system).

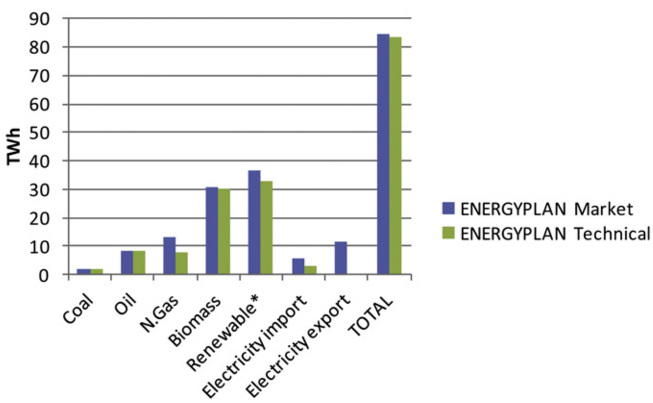

Fig. 6. Gross energy consumption by fuel and electricity export in the case of 100% independent system (*geothermal heat for hot water and space heating not included).

load that can be set within EnergyPLAN (in this case 110 MW), while the minimum load for condensing power plants is set to 516 MW. In the analyses here, the Croatian energy system was treated as a one point system, i.e. no internal bottlenecks are assumed.

EnergyPLAN does not offer the possibility to automatically calculate uncertainty or an error estimate for the use of aggregating distribution curves, installed storage and production capacities. One should calculate these values according to one's own methodology and check if it is wrong to treat the whole system as a point.

However, Croatia can be roughly divided in three climate regions: continental, coastline or Mediterranean and mountain. Hourly distributions of energy consumption are highly dependent on the air temperature and population density. It can be concluded that there are significant differences between the indicated climate regions and their hourly distribution curves of heat and electricity consumption.

Applied market optimization regulation strategy was conducted with the real fuel prices published in Ref. [1] for 2008. All future prices of fuel and investment costs for new technologies and units have been taken from EnergyPLAN data used in Ref. [7], data from Ref. [47] data obtained from Strategic Energy Technology Information System (SETIS) web calculator. Table 2 presents fuel prices used in calculations for different years.

Gross final energy consumption, CO_2 and fuel costs for different optimization strategies and literature data are presented in Table 3. Values of CO_2 taken from Ref. [1] just represent preliminary data since official statistics for emissions from the energy sector in 2008 have never been published. In 2007, CO_2 emissions in energy sector were 24.7 Mt CO_2 according to Ref. [2], while the EUROSTAT value for 2008 is 22.14 Mt CO_2. This value includes all sectors and excludes international bunkers and LULUCF (Land Use, Land – Use Change and Forestry) emissions. As data for CO_2 emissions obtained by EnergyPLAN calculations falls in the range of published data they are considered acceptable.

The CO_2 corrected emissions take into account imported electricity and they have been adjusted according inland production. This means that imported electricity produced the same amount of GHG emissions as if it was produced in Croatia. Looking at a whole picture, importing electricity is not a solution for reducing the GHG emission, as CO_2 is a global problem, so import sometimes just moves the problem across the borders.

3.2. Analysis of the case Croatian Energy Strategy 2020

Results for the gross energy consumption by fuel and electricity exports in the case of CES 2020 for different system optimizations and CES data are presented in Fig. 4. The values from CES include data according to the baseline scenario. The difference is mostly result of the used estimation of energy consumption growth rates as explained in chapter 2.

In the Green paper [42], the estimated use of heat pumps for heating is 18% of useful surfaces in services sector and households for 2020. The value used in EnergyPLAN calculations is 2.7 TWh supplied by heat pumps with COP 3. The related electricity consumption was 0.86 TWh where 0.25 TWh of heat needs in households with heat pumps was assumed to be supplied by solar thermal. It is also presumed that those installations also include heat storage with a capacity sufficient for providing two days of

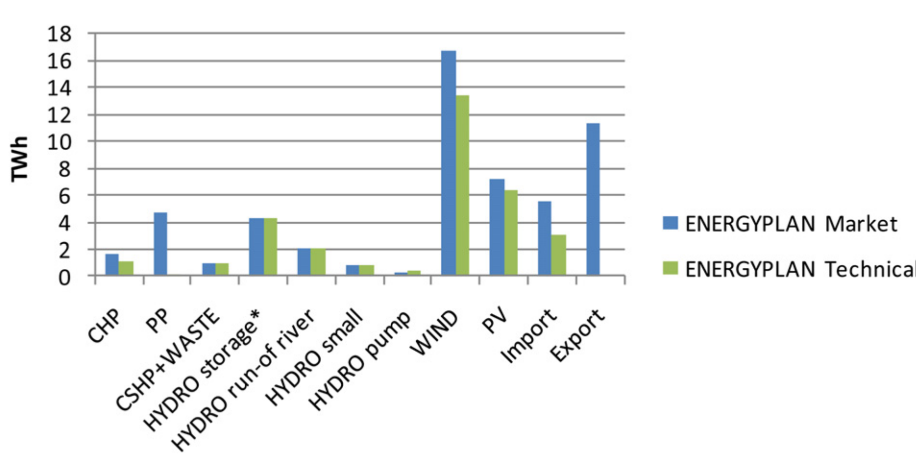

Fig. 7. Electricity production by source in the case of 100% independent system (*data from statistics are not divided according type of HPP).

Table 6
Gross energy consumption and CO_2 emissions in 2020.

	EP_Market	EP_Tech
Total energy [TWh]	89.91	80.22
Total energy corrected [TWh]	73.23	80.22
CO_2 [Mt]	5.45	4.372
CO_2 corrected [Mt]	3.41	4.372

average heat demand. Based on plans for large grid extensions with the neighbouring countries, maximum import and export has been increased to 10000 MW. Modernization of power plants was set to allow better flexibility of their operation so the minimal load of CHP plants was set to 50 MW while minimal load for power plants that operate in condensing mode was set to 400 MW. Additional 10 GWh thermal storages have been added to large CHP facilities in order to increase their flexibility, while existing pumped storage facilities of 257/282 MW turbine/pump capacity have been put in the function of RES integration. Grid stabilization share was kept at 30% of the hourly load.

Estimated averaged increase in fuel prices for 2020 (Table 2) from 2008 is 52%. It is consequently assumed electricity market prices of EEX will also increase by 50%. The electricity price elasticity was the same as in 2008. The price of CO_2 emission allowances has been set to 20€/tCO_2 and the discount rate used for the investment calculation was 5%.

Gross energy consumption and CO_2 emissions for this case are presented in Table 4. By comparing it with the results for the reference case it can be concluded that CO_2 will be reduced only in the alternative provided by the technical optimization which minimizes use of coal and thus makes investment in 1200 MW of new coal power plants questionable.

Table 5 shows difference in costs between market and technical optimizations in the case of CES 2020. Market optimization increases load of coal power plants but even in the market optimization, they operate with a low load factor of 29%. Total gross inland electricity consumption calculated by EnergyPLAN (taking into account pumping, electric vehicles, heat pumps and extra electric heating) was 23.68 TWh for the case of the market optimization for the 2020 case. With the export of 6.77 TWh it could represent total inland electricity consumption of 30.45 TWh. The gross inland consumption according to the CES 2020 is assumed to be 29.94 TWh. Since there is a fixed yearly import of 2.99 TWh from NPP Krsko that will certainly continue for the next three decades, only 3.78 TWh could be additionally produced by coal power plants. Even if the load will increase by the double growth rates than in period 2003–2008 and by neglecting all additional import beside existing NPP, planned coal power plants could reach load factors of 70%. This will certainly not ensure adequate return on invested capital to investors so construction of 1200 MW of coal power plants as foreseen in the Strategy should be definitely reconsidered before making the final investment decision.

The needs for introducing integration technologies necessary to achieve 100% independent energy system after the 2020 has been analysed by varying the amount of wind energy in the electricity system. In this study, installed wind power generation is varied

Table 7
Cost of 100% independent energy system for different model optimizations.

	Market opt.	Technical opt.
Total CO_2 emission costs [M€]	109	87
Total variable costs [M€]	1522	1355
Fixed operation costs [M€]	556	568
Annual Investment costs [M€]	2577	2605
Total annual costs [M€]	4655	4528

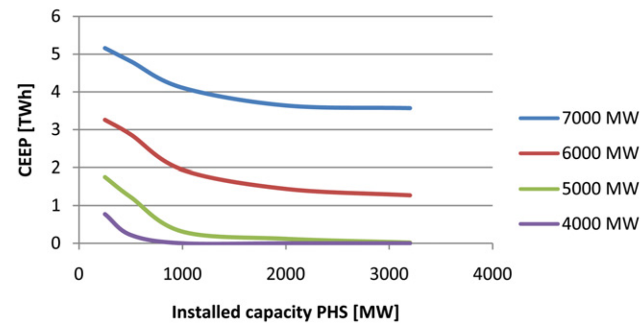

Fig. 8. Reduction of critical excess electricity production for different installed wind power capacities and pumped storage capacities.

from 17 MW to 7000 MW with corresponding electricity generation from 0.04 TWh to 16.69 TWh.

Fig. 5 shows just rough requirements for allocation options for increased wind production in the case of the market optimization in an interconnected system and the technical optimization in an independent (closed) system without interconnections with neighbouring countries. It could be concluded that in an open system, with an organized spot market, there would be no problems for installing 2000 MW of wind turbines, under the condition that new condensing power plants envisaged by the Strategy will allow flexible operation with minimal load at 400 MW while CHP units should be allowed minimum operation at 50 MW with 10 GWh of thermal storage capacity. Detailed analysis for the independent (closed) system is provided in the following two chapters.

3.3. *Analysis of the case of a 100% independent energy system*

The goal of modelling and analysing a 100% independent energy system is not to finally operate it in standalone mode but to make it more sustainable and to insure adequate security of energy supply and independency. A system that does not depend on energy import/exports can achieve better opportunities on the market. As energy systems are planned for periods of 20–40 years, an important step is to determine future energy needs and demands, which in this case should be satisfied by locally available resources. In terms of this study, this required a detailed analysis of available resources and their potential. As mentioned in Chapter 2.5, biomass and biofuels potential for Croatia are estimated to 30 TWh - but to fully exploit this potential, its exploitation has to be properly managed. Management of biomass resource could be done as explained by [48]. Similarly, other resources should be managed by using proper modelling tools and methodologies. When needs and potentials are known, one of the most challenging tasks is to see what technologies could match demands by using available resources. Analyses should

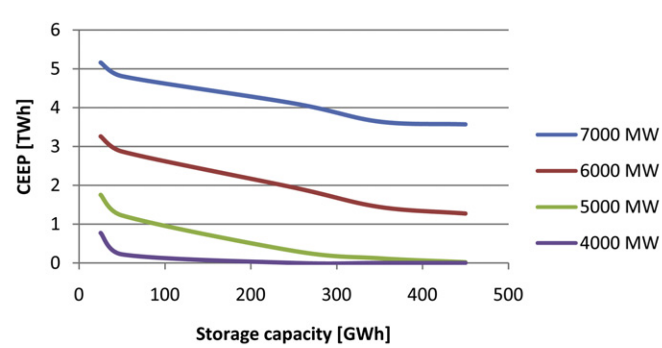

Fig. 9. Reduction of critical excess electricity production for different installed wind power capacities and storage capacities of PHS.

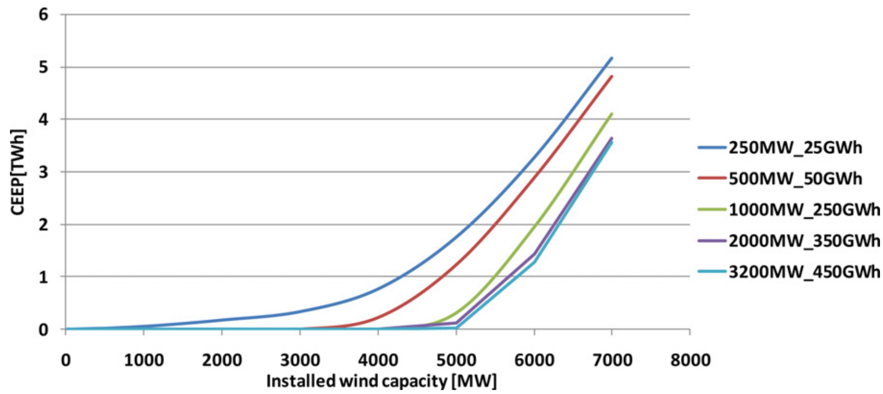

Fig. 10. Increasing wind integration by different PHS capacities.

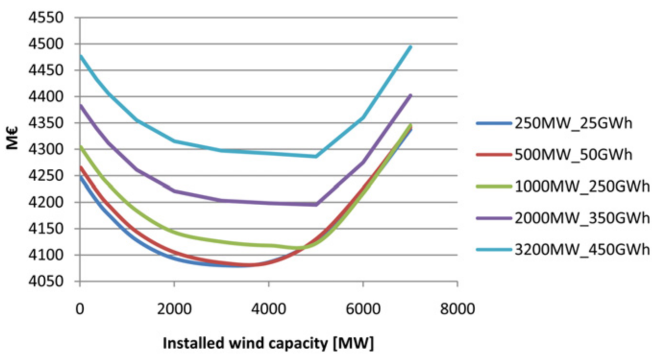

Fig. 11. Calculated total yearly costs for different PHS capacities.

cover the current status of available technologies but also their status in the future. Here, all alternatives are stated and compared by objective technical, economic, environmental and social parameters. As a general rule, decision makers could choose the most sustainable and acceptable alternatives and consequently propose appropriate strategies to realize the plans based on evaluation results. This means that the case of 100% independent Croatian energy system, calculated by the EnergyPLAN model, represents only a part of possible alternatives as it mostly takes into account current and market mature, technologies (except electric vehicles). These technologies can be used immediately although their price will not significantly decrease over the time due to learning effects (except PV technology).

An independent energy system was designed as following – firstly, all hydro power technical potential has been utilized, then all biomass potential has been allocated for consumption in different sectors, adequate share of solar thermal heating has been introduced together with proper heat storages. Similarly, heat pumps with appropriate heat storages have been added to replace traditional boiler heating. After the introduction of electric cars and related electricity demand, wind capacity has been increased as showed in Fig. 5 where the related CEEP has been reduced by installation of PHS systems or additional heat pumps and heat storage. The additional need for extra energy has been satisfied by increasing of PV installations.

When the reduction of CEEP (by adding of new storage capacity) became inefficient, further reduction has been made by operational regulation: by reducing RES production, by reducing CHP production and replacing it by boiler, and by replacing boiler heat production with electric heating.

Final calculations for the gross energy consumption by fuel and electricity export are given in Fig. 6. Data shown in the figure represents results of two optimizations: a market optimization done in an open system with 10 GW of interconnection and a technical optimization based on a closed system with no interconnections. Unsurprisingly, the demand in the market system is greater since it is possible to trade electricity on external markets. Electricity production by source in the case of a 100% independent system is presented in Fig. 7. It should be emphasized that under the conditions of the technical optimization, load of condensing power plants has been almost 0. This was possible under the assumption that PP and CHP will be allowed full operational

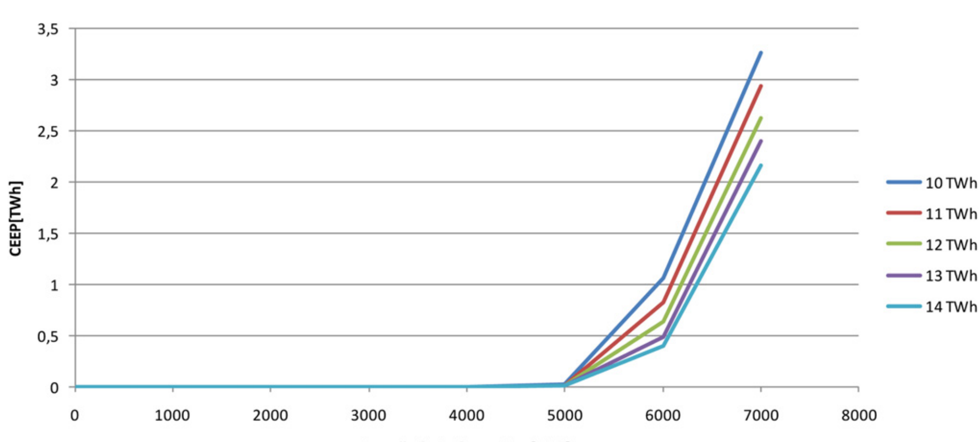

Fig. 12. Reduction of CEEP for different consumption of heat pumps in household and services sector.

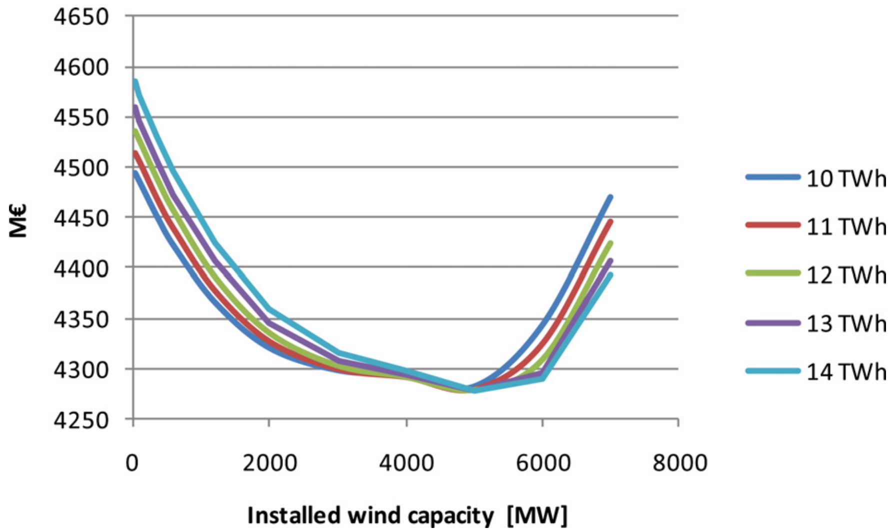

Fig. 13. Calculated total costs for different consumption of heat pumps in household and services sector.

flexibility or, put it differently, they could be frequently switched off and on (which means they can operate without minimal load).

Table 6 and Table 7 present gross energy consumption, CO_2 emissions and costs of options provided by different optimization strategies in the 2020 case. Technical optimization gives lower costs as in market optimization electricity is also produced for trade on external markets.

3.4. Role of smart storage in increase of RES penetration

Due to smart use of energy storage Croatia could reach high penetration of RES or 78.4% in the gross final energy consumption and decrease energy dependence from predicted 70% to almost 20% in the period after 2020.

Currently, the PHS technology is the most widespread storage technology used in the power systems around the world. As it is presented in Figs. 8–10 after installed 2000 MW and its 350 GWh, PHS contribution to further integration of wind energy into Croatian power system is rather small. Fig. 11 shows calculated total yearly costs for different PHS capacities. By increasing only of installed wind capacity it is possible to decreases total system costs, but only up to certain number if CEEP is not acceptable. Thus, Fig. 11 and Fig. 10 should be analysed at the same context.

Fig. 12 shows results for the reduction of critical excess electricity production with different consumption of heat pumps in household and services sector and Fig. 13 presents total yearly costs for the same calculations. The results for additional CEEP reduction by electric vehicles are presented in Figs. 14,15. It could be concluded that by only increasing of battery capacity per vehicle from 57 kWh to 142 kWh will not make significant effect on CEEP redaction. Larger effects can be achieved by increasing electricity consumption in the transport sector.

Energy storage technologies as PHS, decrease CEEP and in the same time increase RES penetration, similar is achieved by V2G. Heat storage and heat pumps represent technologies that could integrated heat with other energy flows so they decreases the CEEP, although under some other circumstances they could also increase peak load and eventually require new production capacities. The construction of new capacities that might use same limited resources is not desirable as it could lead to decreased load factors and interruption of production.

Additional reduction of peak power could be achieved by the application of different operation strategies used for charging and discharging the batteries in V2G or by using larger thermal storages where operation is optimized to reduce peak load.

3.5. Role of smart storage in reduction of CO_2 emissions

Use of RES in combination with energy storage may reduce CO_2 emissions in Croatia by 82% or 20 Mt of CO_2 (Fig. 16). According to

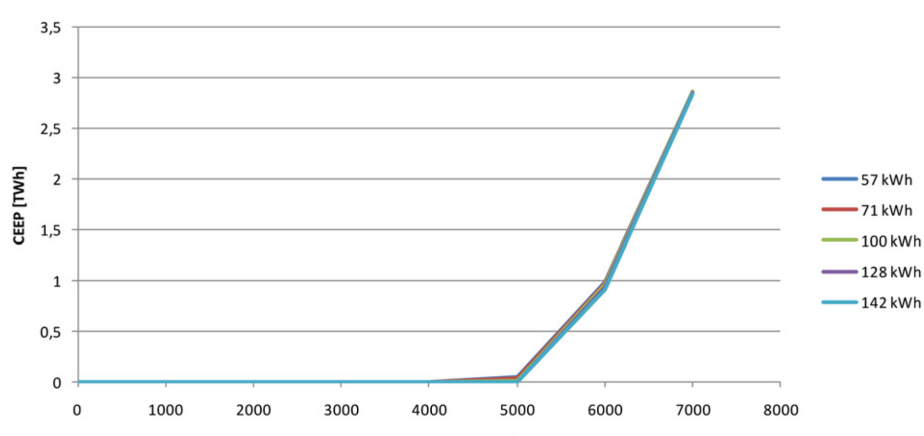

Fig. 14. Reduction of CEEP for different sizes of batteries in electric vehicles.

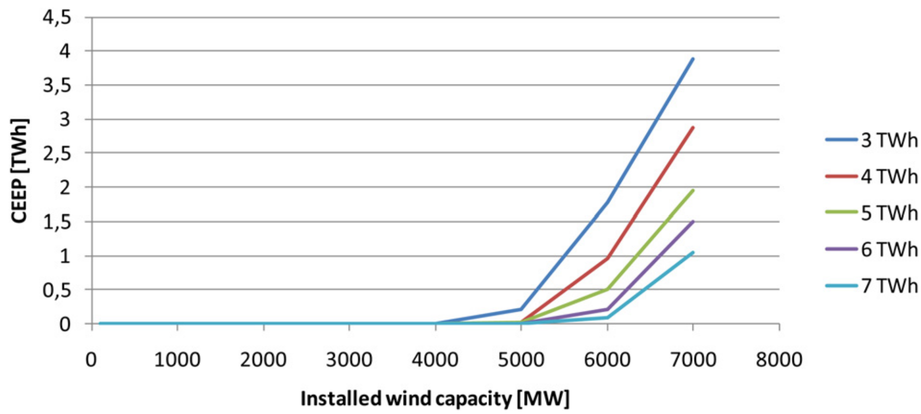

Fig. 15. Reduction of CEEP for different electricity consumption of electric vehicles (in TWh).

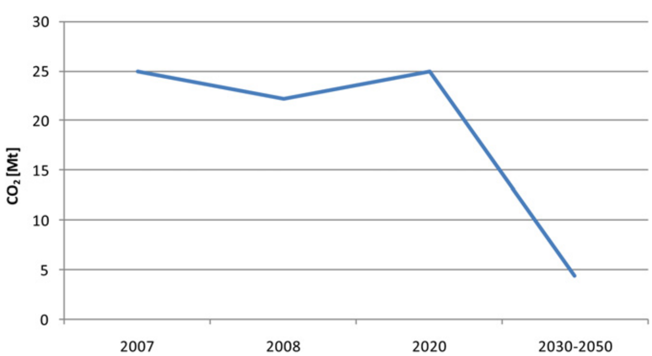

Fig. 16. Estimated CO_2 emissions in Croatia (2007 data from [2], 2008, 2020, 2030–2050 Energy PLAN calculations).

the CES, reduction of emissions after 2020 is planned through the development and installation of a nuclear power plant. This option will need further clarification, before the final decision for its construction will be made. It should be also known that nuclear power plants represent the most inflexible power source, used only to supply base load. If it is planned to significantly increase RES penetration in combination with a new nuclear power plant, it will be very difficult without substantial interconnection capacities and large scale application of energy storage systems. Therefore, energy storages could be promoted and installed before any other option (RES or nuclear) as they support all options and bring additional benefits.

4. Conclusion

This paper presents a new approach in planning of the Croatian energy system with significant emphasis on integration of RES energy by use of different energy storage technologies and system regulation strategies. It presents results of planning for a 100% independent energy system as just one possible alternative for the development of the Croatian energy system. Even though total independency has not been achieved in a planning sense, due to different needs for fossil fuels in various sectors, the results are very promising regarding CO_2 emission reduction and utilization of RES.

Pumped storage hydro, heat storage and heat pumps, batteries and electrical vehicles are not the most advanced technologies, but they have been used almost for a century. What makes them smart is their use as support for a post carbon society or, more precisely, their use for RES integration and support for distributed energy production and management. As current trends in R&D show, storage technologies will play an important role in future energy systems. For that reason, their use and installation, as well as further R&D, must be supported by all stakeholders involved in planning and operation of an energy system.

Calculations in EnergyPLAN proved that it will be hard to reach total energy independence. Still, the RES share reached 78.4% in gross final energy consumption and CO_2 emissions was reduced significantly by 20 Mt.

The aim of this paper was not exactly to recommend the precise optimal solution for integration of RES. The aim was to provide information on technologies that are fuel efficient and able to integrate RES. Also, the aim was to provide insight into approximate capacities of energy storage systems and other energy technologies that are relevant and could present valuable means for further energy planning.

Croatia could reach a significant level of energy independence by application of commercial technologies for energy storage that are now present on the market. To achieve a 100% independent or a 100% RES system, detailed planning of all economy sectors should be conducted.

Before any new big installation, one must consider possible energy savings in current systems as they are the most cost efficient way for decreasing consumption and thus avoid or postpone needs for extra capacities. Energy efficiency can restrain consumption and decouple economic growth from growth of energy consumption as it basically creates added value by reducing energy consumption. It is important in energy system planning to consider all adequate technologies and to plan their behaviour not just under current conditions but also in future energy systems. Storage technologies could also play an important role in developing of Smart grids and Virtual power plants.

Another important issue to consider in the planning of sustainable and independent energy systems is flexible operation of new power plants. From conducted calculations in EnergyPLAN, it could be concluded that, if Croatian power system will operate as an open system, with organized spot market, there would be no problems for installing and operating 2000 MW of wind turbines under the condition that new power plants envisaged by the Croatian Energy Strategy will allow flexible operation with minimal load at 400 MW while CHP units should allow minimum operation at 50 MW with 10 GWh of thermal storage capacity. PHS can also contribute to RES integration but it was showed that after installed 2000 MW and 350 GWh its contribution to further integration of wind energy is rather small. Results also shows that 10% of total electricity demand could be covered by wind energy without any significant change in current system.

Acknowledgements

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