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Mapping the potential for decentralized energy generation based on renewable energy sources in the Republic of Croatia

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Abstract

There are regions in the Republic of Croatia (underdeveloped, devastated by war, depopulated, as well as islands and mountainous areas) which are still disconnected from the electricity network or where the current network capacity is insufficient. In addition, these regions have good renewable energy potential. Since the decentralized energy generation (DEG) covers a broad range of technologies, including many renewable energy technologies (RET) that provide small-scale power at sites close to the users, this concept could be of interest for these locations. This paper identifies the areas in Croatia where such systems could be applied. Consideration is given to geographical locations as well as possible applications. Wind, hydro, solar photovoltaic, geothermal, and biomass conversion systems were analyzed from a technological and economic point of view. Since the renewable energy sources (RES) data for Croatia are rather scarce, the intention was to give a survey of the present situation and an estimate of future potential for DEG based on RES. The energy potential (given as capacity and energy capability) and production costs were calculated on a regional basis and per type of RET. Finally, the RES cost–supply curves for 2006 and 2010 are given.
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Keywords: Energy planning; Renewable energy sources; Decentralized energy generation

1. Introduction

The Republic of Croatia is still recovering from the past conflict that resulted from the dissolution of the former Yugoslavia and at the same time it experiences instabilities as a consequence of the transition to a market economy. As a result of restoring order and stability, business and industrial activities have been intensified. Consequently, for a decade now, Croatia has been experiencing increased electricity consumption, estimated to be growing by approximately 0.5 TW h annually [1].

As Croatia's import dependence on primary energy supply, as well as power, increases each year and available surpluses in the neighboring transition economies are decreasing, the exploitation of all available energy sources becomes a precondition for future development. The Croatian power system generation capacity is now stretched to the limit and the construction of new plants is an imperative. Although the Croatian state-owned power utility Hrvatska elektroprivreda d.d. (HEP), as the major producer of electricity, plans to build new power plants, the planned dynamics of adding new capacity is rather slow. HEP produces 83% (or 11,069 GW h) of the electricity in the country (13,321.3 GW h power produced in 2004), while the total net domestic supply is 16,986.5 GW h[1] (import of electricity in Croatia is 31.2%, export 9.6%) [2]. It plans to build five new hydro- and thermal-power plants in the next 10 years, aiming to raise its generation capacity

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[1]Official data for 2004, released in 2006.

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by 1220 MW. Presently, two power plants are being built: the 40 MW hydro power plant Lešće and a new 100 MW gas-fired unit at the CHP[2] plant TE-TO in Zagreb. On the other hand, in the process of negotiating its accession to EU, Croatia will soon have to ratify the Kyoto Protocol, bringing limitations to further addition of fossil fuel fired thermal power plants. Considerations linked to Croatia's obligations under the Kyoto Protocol, as well as its expected obligations under Directive 2001/77/EC on the promotion of the electricity produced from renewable energy sources (RES) in the internal electricity market, and techno-economic renewable energy potentials, have brought policy makers to decide to add approximately 5 percentage points to the renewable energy share of the electricity generated. That excludes large hydro power plants, but includes small hydro power plants of up to 10 MW capacities. Presently, only 1% of power produced comes from unconventional RES (53% if conventional large hydro power plants are included) [2].

Moreover, as the countries of South-East Europe stabilize politically and economically, this region will play an important role not only as a transit center for gas and electricity as well as for the oil exports from the Russian and Caspian Sea region, but may also become a part of a new decentralized energy generation (DEG) system of the wider EU. Apart from ongoing regional integration agreed on in the Athens Memorandum (2002, 2003) for the establishment of the South-East Europe Regional Electricity Market (now known as the Energy Community of SEE), the removal of geographical constraints to the delivery of power (recent reconnection of South-East Europe into a single UCTE system), the gradual liberalization of energy markets (adoption of the new EU Directives 2003/54/EC and 2003/55/EC on the Internal Market in Electricity and Natural Gas), the privatization of the utility companies and new environmental legislation, introduce new factors into the Croatian conventional power system [3–5].

The Croatian electricity market has been liberalized for customers, so called eligible customers, with the annual consumption exceeding 9 GW h. That is about 25% of the total electricity market in Croatia. It is expected that in 2007 all non-residential customers will be allowed to buy competitively, while in 2008 the same will be possible for all consumers in the country. The electricity market, once centrally regulated, is now the responsibility of a regulatory body, Croatian Energy Regulatory Agency (HERA), as well as a number of system and market operators, as Market Operator (HROTE), Transmission System Operator (OPS) and Distribution System Operator (ODS), along with the Ministry of Economy, Labor and Entrepreneurship (MINGORP).

The liberalization of the electricity market in the EU and other countries currently does not show the expected results according to which it has been initiated. It was envisaged to bring competition into the energy markets with the formation of the competitive energy prices. Instead, the experience has shown that current liberalization did not stimulate enough investments into production and transmission capacities or into the new technologies, and therefore it caused the continuation of the existing trends and resulted in the reduction of the system reserve capacity. Only bigger producers are able to withstand such environment—they engulf the smaller ones and due to their market-share they dictate the market conditions. On the other side, reduced energy supply on the market, as well as the fossil fuel price increase, raise the electricity prices. The liberalization could show its full potential only if all market conditions were completely satisfied. In other words, the market should be very well organized with the substantial number of "players" (suppliers, buyers).

The possibilities to upgrade the energy systems range from modernization and expansion of the existing facilities, construction of new thermo- and hydro-power plants, to increasing the share of renewable and distributed power plants. It is most probably not about selecting only one potential, but more about the smart utilization of all of them.

The RES technologies, whether they exploit wind, hydro- or solar-power, geothermal heat, biomass and waste materials, have many benefits like energy resource diversification, decreased fossil fuel use, and reduced per unit GHG emissions. However, construction and utilization of dispersed energy sources should not diminish the significance of the conventional sources to maintain the integrity of power system. In line with numerous advantages of decentralized production, some of DEG–RES systems (wind, solar, biomass CHP) are characterized by their limitation in providing ancillary services as well as following the daily consumption curve. Availability of wind and solar photovoltaic (PV) conversion systems production depends on the meteorological conditions, whereas electricity production in biomass cogeneration facilities is determined by the local heat requirements. As a result of the increased share of dispersed sources, an increased reserve capacity will be required.

Bearing that and other aspects in mind, such as security of energy supply (energy resources diversification, requirements for self-preservation of national power systems), climate change mitigation (CO_2 reduction, energy efficiency programs) and economic competitiveness (electricity and gas market deregulation), the authors focused precisely on the segment of decentralized energy production based on RES. Since the RES data for Croatia are rather scarce, the intention was to give a survey of the existing situation and an estimate of future potential for DEG based on RES in the Republic of Croatia.

2. Map of DEG–RES potential in Croatia

Although the Republic of Croatia is almost completely electrified, there are still regions which do not have access

[2]Combined Heat and Power (also known as Cogeneration).

to the electricity network or where the network capacity is insufficient. For the most part such areas are under special care of the state (i.e. underdeveloped, devastated by war, depopulated), on islands or in mountainous regions (Fig. 1). Due to their remoteness, these locations are prime candidates for DEG systems. Such regions can be identified by reviewing various regional indicators, such as: energy demand, population density, GDP per capita, number of rural (agricultural) dwellings, distance from the electricity network etc., of which the first four are shown in Fig. 1. Another interesting point is that these regions have high renewable energy potential, as could be seen further on in this section.

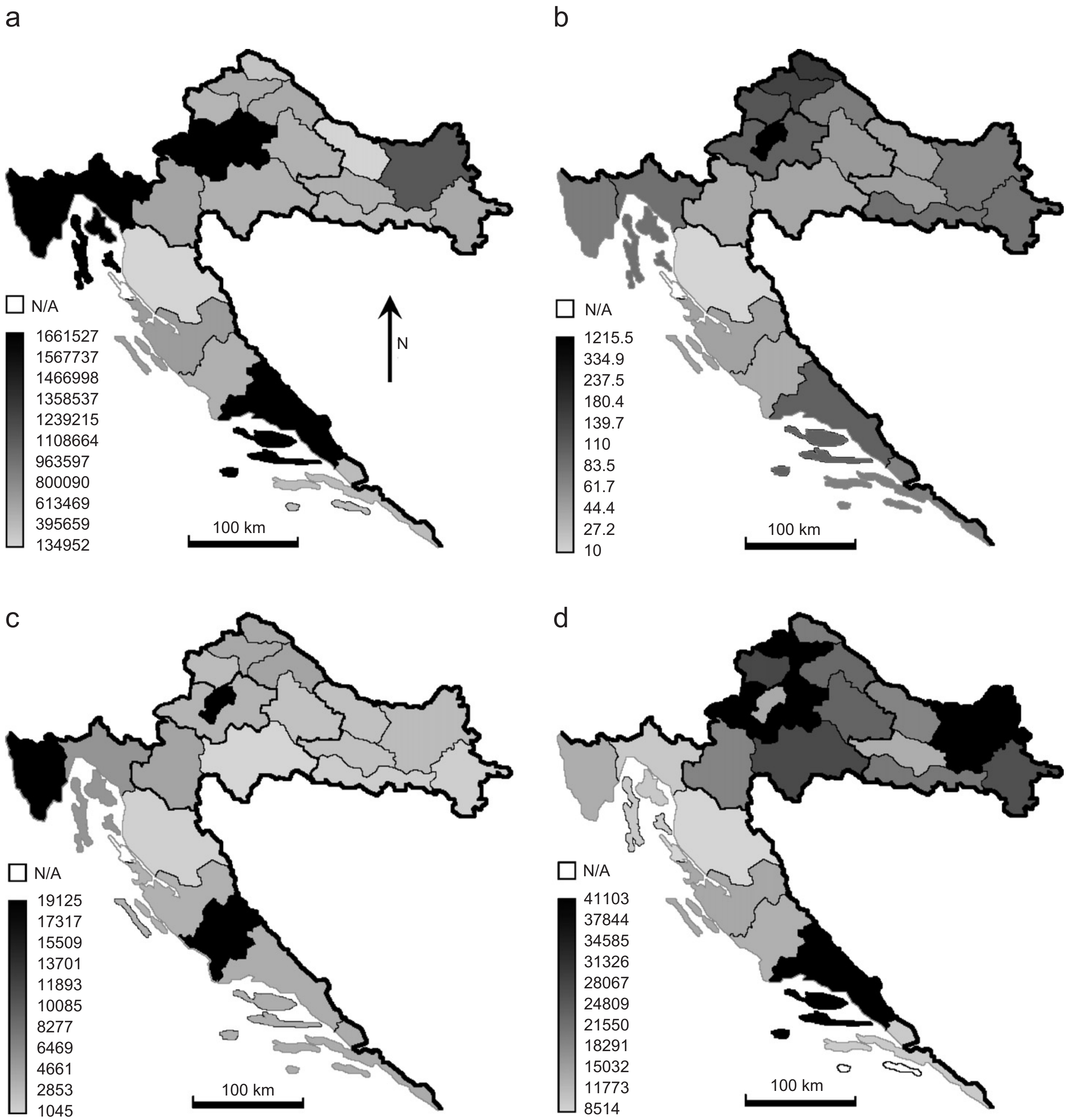

Fig. 1. (a) Total electricity demand (MW h) [6], (b) population density (people/km^2), (c) nominal GDP per capita ($US) in 2003, and (d) total number of rural (agricultural) dwellings [7].

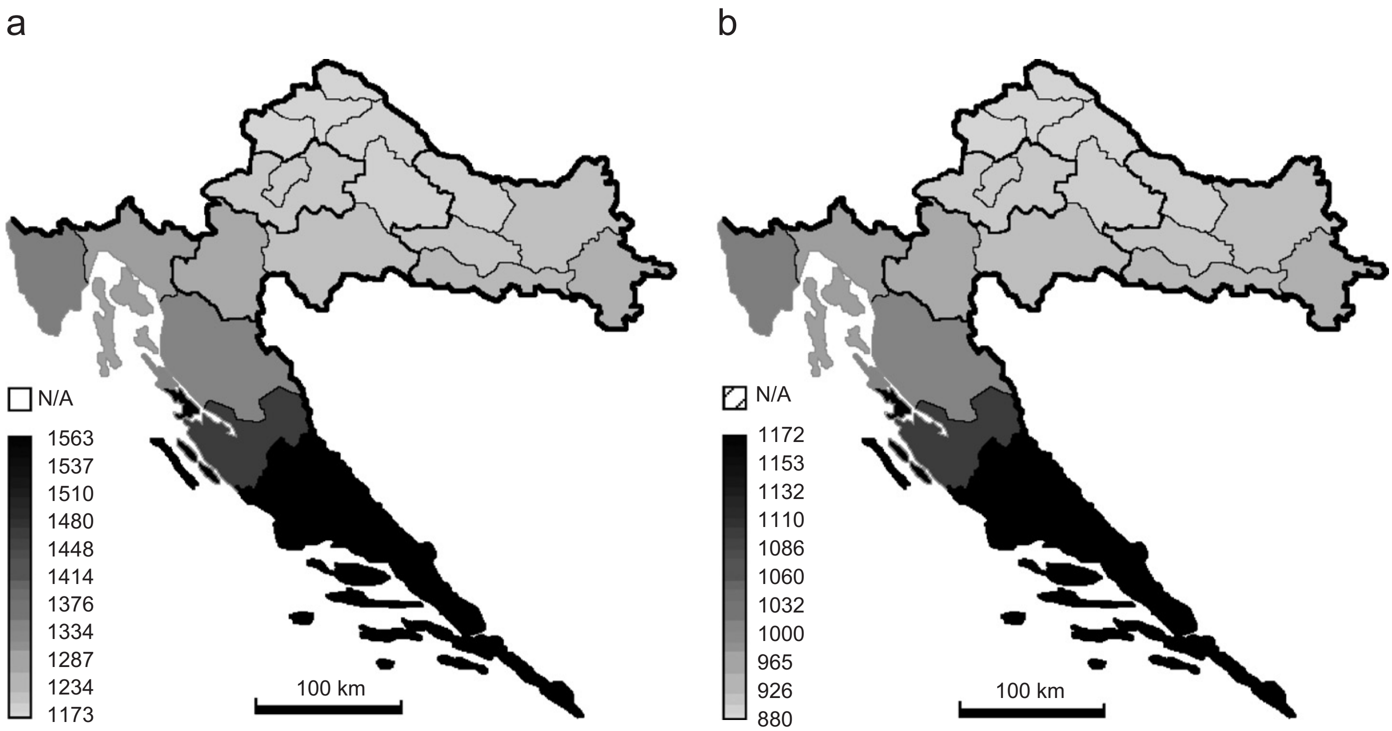

Fig. 2. (a) Global horizontal irradiation (kW h/m^2/year) and (b) PV power (horizontal) (kW h/year for 1 kW p).

DEG is intended to provide small-scale power close to users, using a broad range of technologies, many of which are renewable. Wind, hydro, solar PV, geothermal, and biomass conversion systems were examined from a technological and economic point of view. Only those technically feasible are included in the analysis. Their capacities and energy capabilities on the regional basis (NUTS[3] 2 and 3 statistical classifications) are calculated for the present situation and with future estimates. Apart from the identification of the geographical areas in Croatia where DEG–RES technologies could be applied, their potential applications were also investigated (the list of potential users and applications is given at the end, in the Conclusion).

Since this work is a part of the wider project for Western Balkans—ADEG [8,29], a system of administrative division of countries similar to that of the NUTS, established by Eurostat, is used for the purpose of uniform representation of data given on the regional basis. The counties of the Republic of Croatia (Cro. *županije*) rank as the NUTS 3 regions. Although the Energy Strategy of the Republic of Croatia [9] defines the counties as the basic units of energy planning, the NUTS 3 level is often inadequate for energy planning in a wider region (e.g. Western Balkans), so it was necessary to present data at the NUTS 2 level. The first proposal to divide Croatia in five NUTS 2 regions (Eastern, Northern, Central, Western and Southern Croatia) was rejected by the European Commission because population in some regions was insufficient. One of the conditions for the NUTS 2 region is to have more than 800,000 inhabitants (the total population of Croatia is around 4.5 million). However, a new division of Croatia into four regions (Central, Eastern, Adriatic Croatia and Zagreb region) is currently under consideration [10]. Consequently, the energy potential presented here is given at the NUTS 2 level.[4]

The Republic of Croatia is endowed with a long coast and many islands in the Adriatic Sea. These areas have very good solar and wind potential [11–15]. A great number of sunny hours with irradiation that exceeds 1,450 kW h/m^2 annually [11] and average wind speed velocities above 4–5 m/s represent energy potential that should not be ignored (Figs. 2a and 3a).

Systematic measurements of solar irradiation and wind speed have been conducted in Croatia only recently. Although collected for many decades, the data obtained from meteorological stations are incomplete for the investment purposes (e.g. they lack data like vertical wind speed profiles).[5] The situation slightly improved with the publication of the first solar radiation atlas of the Republic of Croatia [15]. The analysis in this report however, was done before this atlas was published. Therefore, the horizontal irradiation in Fig. 2a was compiled using the data from the Joint Research Center of European Commission [16] for the region of Croatia.

[3]Nomenclature of territorial units for statistics (NUTS).

[4]Thick black lines on the maps of the Republic of Croatia represent borders of NUTS 2 regions, while the thin lines represent borders of NUTS 3 regions (counties).

[5]Wind velocity at different heights.

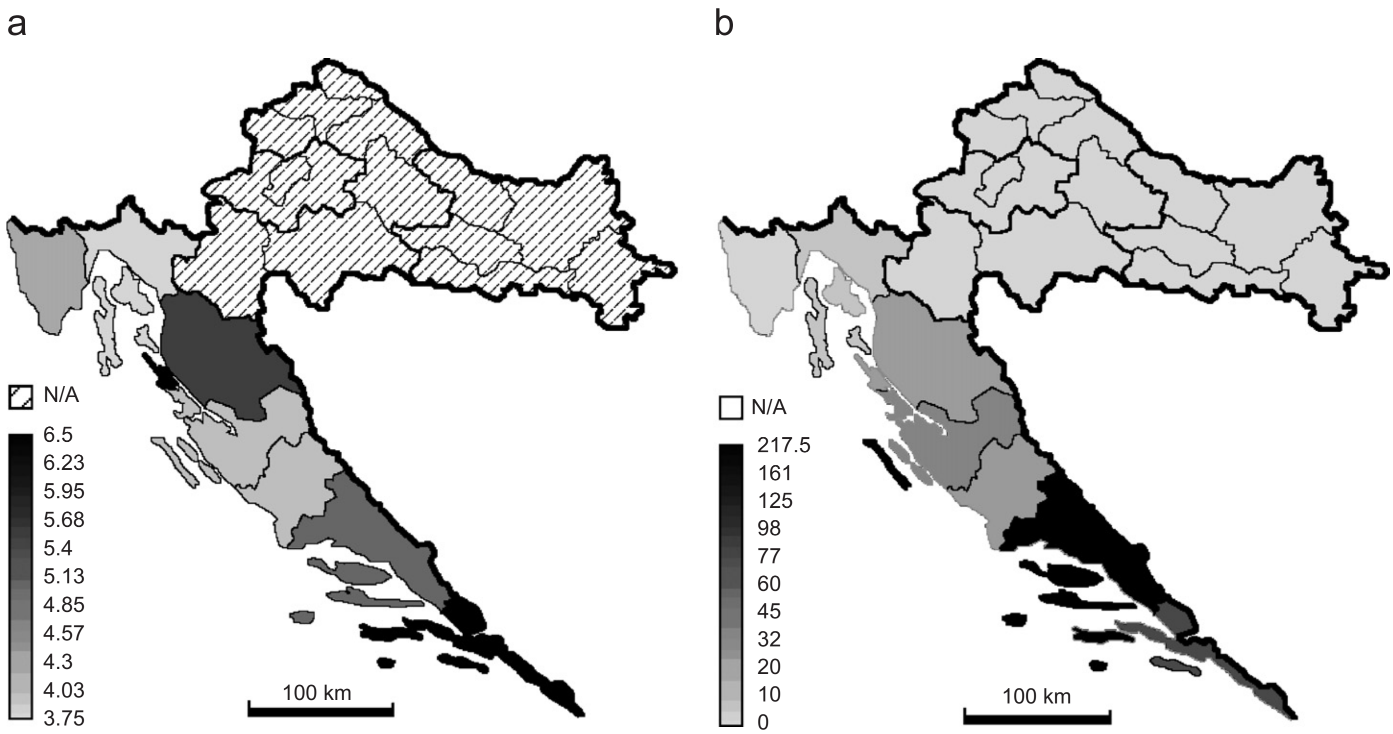

Fig. 3. (a) Average annual wind velocity (m/s) and (b) maximum load capacity of proposed wind facilities (MW).

While a similar wind atlas does not exist yet, measurements are presently being conducted in several coastal counties. Fig. 3a shows regions of Central and Eastern Croatia for which average annual wind speeds have not yet been measured (N/A—not available). Knowing wind speed at the macro-level (wind atlas) is not sufficient for potential developers of wind power plants since the on-site data (micro-level) are required. Except for a dozen locations, there is no continuous measurement of wind speed over several years. Therefore, various companies willing to invest in this sector have difficulties to assess the feasibility of the projects. Despite this, there is strong interest in building wind farms especially on locations along the Adriatic Sea, which can be observed from the map in Fig. 3b. The map shows proposed future wind power plant projects, with their capacities totaled per NUTS 3 regions. Main developments in wind energy, in expectance of feed-in tariffs, are located in four counties of Dalmatia: Zadar county, Šibenik-Knin county, Split-Dalmatia county and Dubrovnik-Neretva county. There is some interest in other counties along the coast, with more than 50 projects in total in different phases of preparation. There are two wind power plants already built: 6 MW VE "Ravne 1" on the island of Pag, at the end of 2004, and 11 MW VE Trtar Krtolin near Šibenik, which was finished in mid 2006.

The load capacity given in Fig. 3b (and in all other corresponding figures) represents the maximum capacity, assumed to be solely active power, that could be produced continuously throughout a prolonged period of operation under representative climatic conditions. Similarly, the energy capability (e.g. Fig. 7a) is the maximum quantity of electrical energy produced under the most favorable conditions. It should be noted here that the resource availability takes no account of electricity transmission and distribution constraints, which will be considered in the next stage of the above-mentioned ADEG project. The maximum load capacity and the maximum potential energy produced (energy capability) were calculated using the information considering all planned and potential RES projects. The data used were obtained from different sources: published literature (e.g. national energy programs [11–14,17–19]), MINGORP, HEP, Environmental Protection and Energy Efficiency Fund of the Republic of Croatia (FZOEU), and where relevant data were not available or obsolete, experts were consulted. These parameters (load capacity and energy capability) consider all possible resources, even the projects of low confidence (10–20%) that could be developed but difficulties are expected in terms of permission and access. In comparison to the RES cost–supply curves (Figs. 8 and 9) that consider only medium confidence resources, the maps representing the maximum load capacity and energy capability take into account all levels cumulatively (available resource of low confidence includes both the high and medium confidence bands).

The RES electricity cost–supply curves were also calculated based on all planned/potential projects available.[6] These histograms combine the cost of electricity (€/kW h) with the energy produced (annual GW h) from a

[6]Previous expressions of interest/commitment (e.g. consent applications) by potential developers were also taken into account.

Table 1
Average costs per type of RES per NUTS 2 region

Type of RES	Region (NUTS 2)	Capital cost (€/kW)	Fuel cost (€/kW h/year)	O&M (€kW/year)	Insurance €/kW/year)	Energy supply costs (c€/kW h)
Large hydro	Central Croatia	1827	—	13.15	10.96	5.73
	Zagreb region	2268	—	16.33	13.61	4.87
	Eastern Croatia	—	—	—	—	—
	Adriatic Croatia	1866	—	13.44	11.20	7.73
Small hydro	Central Croatia	11718	—	84.37	70.30	28.80
	Zagreb region	7141	—	51.41	42.84	16.51
	Eastern Croatia	4038	—	29.07	24.23	10.80
	Adriatic Croatia	2051	—	14.77	12.31	5.82
Wind power	Central Croatia	—	—	—	—	—
	Zagreb region	—	—	—	—	—
	Eastern Croatia	—	—	—	—	—
	Adriatic Croatia	994	—	24.84	7.95	7.86
Small PV	Central Croatia	—	—	—	—	—
	Zagreb region	—	—	—	—	—
	Eastern Croatia	4202	—	14.71	21.01	53.26
	Adriatic Croatia	—	—	—	—	—
Biomass	Central Croatia	1931	0.02	15.60	19.31	8.40
	Zagreb region	1907	0.02	11.46	19.07	8.06
	Eastern Croatia	1943	0.01	15.14	19.43	7.04
	Adriatic Croatia	1722	0.01	13.22	17.22	6.95
Geothermal	Central Croatia	2925	—	102.37	23.40	7.24
	Zagreb region	—	—	—	—	—
	Eastern Croatia	2084	—	72.93	16.67	5.15
	Adriatic Croatia	—	—	—	—	—

specific energy source (wind, biomass, geothermal and hydro). The technologies included in the analysis were considered as proven or commercial. The plant costs used are levelized unit costs for each project life. For every particular project the unit cost was derived by taking the present value of costs, i.e. capital, operation and maintenance (O&M), depreciation (including tax benefits of depreciation), fuel (where applicable), and was divided by the present value of the kW h generated over the lifetime of the project. No revenue stream was included in this calculation. Various discount rates were used depending on the project and investor (e.g. the discount rate for the projects where investors are big companies like HEP and INA (Croatian Oil and Gas Industry) that have access to favorable financial instruments is 8%, while the discount rate for projects financed with the loans given by commercial banks is almost 12%). First, the disaggregated costs were given per NUTS 2 region and type of RES in Table 1. Then the aggregated costs were arranged in tight bands to be used in energy modeling that will be part of the next phase of the ADEG project.

Calculated potential of wind units for electricity generation is technical and it does not take into consideration recent decree of the Croatian government (Ministry of Environmental Protection, Physical Planning and Construction) to ban construction and planning of all new wind power plants (together with quarries, warehouses, factories etc.) on locations that are on islands and less than 1000 m from the sea. The projects that had already obtained the location permits prior to that decree are excluded. The act was explained as a measure to protect the Croatian coastal area. That, unfortunately, includes some of the best wind potential locations on Croatian islands and along the Adriatic coast (NUTS 2 region Adriatic Croatia). Time will tell if this decree will be removed or altered, because many investors have already complained. Presently, the ban is still in force and there has been no sign of revoking it.

Large offshore wind farms in Croatia are technically viable at only three to four locations in the southern part of the Adriatic Sea (the best wind potential) [20]. Problem is high depths near the coast and islands as well as environmental constraints. Currently, there are no plans for building offshore wind farms in Croatia.

Energy production from large wind power plants (wind farms) by definition belong to centralized energy generation [21]. Due to their great significance for the Croatian power system and high degree of readiness for implementation, they are included here into the total viable (technical) wind potential as the DEG systems.

Wind turbines can provide the landowner with a source of income through land rentals. One of the problems with land ownership in Croatia is that one plot (where the turbine is to be built) could be sometimes owned by tens of owners. It is less complicated to build the wind turbine on state land.

Apart from electricity production from the large wind farms, there are also other possible applications, e.g. the small wind turbines for irrigation in river deltas and on lakes (e.g. delta of the river Neretva). One good example of a proposed hybrid facility is the wind farm Stupišće on the island of Vis (planned in the National energy program ENWIND [13]), which was forethought to supply energy for pumps for irrigation and water desalination.

Despite good solar potential it is not likely that large solar power plants will be built in the following years in Croatia due to high cost of these facilities. The graphs representing the RES cost–supply curves for 2006 and 2010 in Figs. 8 and 9, respectively, do not include data for large solar thermal or PV power plants since the costs of such facilities exceed the chosen upper cost limit of 20 c€/kW h. The energy supply costs and some other influential factors are given in Table 1.

Table 1 shows how the energy supply costs vary according to the geographical location. For each of the existing or planned RES plants the categorization per type of RES per NUTS 2 region was derived using the information regarding capital costs (€/kW), operational and maintenance costs (€/kW/year), and other costs like insurance costs, fuel cost, etc. All these costs were combined to form the total energy supply cost (€/kW) for a particular type of RES plant.

With the exception of a certain number of households and other buildings, solar PV systems will be reserved for isolated areas and specific purposes. Potential applications could be: telecommunication base stations, meteorological stations, lighthouses, road signs, public lighting, different autonomous monitoring systems (pollutant emission monitoring, forest fire protection, technical protection of individual facilities etc.). It is difficult to estimate the maximum load capacity of potential PV systems because there are no official statistics of their use. The PV potential could be given approximately by the PV power shown in Fig. 2b. Their future implementation will probably include a large number of units of smaller outputs, up to 1 MW on grid applications and up to 2 MW off grid applications.

On the other hand, thermal solar systems for hot water production will be used extensively due to their reasonable economy. At the moment however, the main obstacle preventing wider usage of such systems is the lack of legislation that promotes and subsidizes the use of renewable energy systems, contrary to other European countries. The newly established Environmental Protection and Energy Efficiency Fund periodically announces public invitations for RES projects, including solar thermal collectors. This mechanism though, is mainly reserved for companies and units of local self-government.

Use of biomass is favorable in the low plains of the Pannonia Basin, Slavonia region in north-eastern Croatia. Here agricultural residues [17] such as, sunflower, soybean, rapeseed and beans (shown in Fig. 4) are plentiful.[7] Fruit residues are available all over Croatia, while olive residues could be found in Adriatic Croatia. Also, in the mountainous forested regions (and partially in plains) of counties of Primorje-Gorski Kotar, Lika-Senj, Karlovac, and some other eastern and central counties, forest residues and wood waste from wood processing industry (Fig. 5) could be recovered in large quantities. This biomass could be used for the purpose of district heating and, on a smaller scale, electricity production. Energy potential from biomass is considerable and it is expressed as the energy capability given in Fig. 6a. This represents the maximum electricity that could be produced from the planned and potential biomass cogenerations and biogas units.

Biomass cogeneration facilities have relatively low energy production costs, comparable to those of wind power plants (Table 1, Figs. 8 and 9). But unlike the wind farms, power production from the biomass has higher social benefits in terms of increased employment of local workforce and additional activities for farmers that will produce raw material.

While talking about biomass, the significant energy potential of waste should be mentioned. Waste considered here includes: municipal solid waste, sewer sludge, landfill gas, solid and liquid manures from livestock farms and abattoirs. Generally, waste recovery has been neglected in Croatia and hence waste was unused as an energy source. The Republic of Croatia is currently making efforts to establish its waste management system. Among other things, it anticipates the energy recovery of waste (that part of the waste that cannot be recycled or used in other ways). It can be expected that the importance of this sector will grow in the near future. The total biomass (plus waste) technical energy potential is estimated to be between 50 and 80 PJ in 2030.

Certainly, some negative externalities of biomass and waste combustion, such as air pollution, should be kept in mind. Biomass, although considered as renewable fuel and CO_2 neutral, can cause local air pollution if the products of combustion are not treated adequately. Therefore, a basic requirement when burning biomass and solid waste is to ensure appropriate flue gas cleaning and control systems, which will satisfy limiting values of emissions prescribed by law. An especially sensitive issue in solid waste combustion is the emission of toxic organic substances like dioxins and furans that should be monitored very carefully.

Hydro potential is traditionally the most exploited renewable energy resource. The share of hydro power generation capacity is 51% of total installed capacity [6,22]. The energy capability of potential large and small hydro power plants is shown in Fig. 7. The small hydro power plants are of sizes less than 10 MW. Croatia still has a certain number of undeveloped sites where large projects

[7]The figures showing usable biomass are calculated based on existing (at the time of evaluation) agricultural land and do not take into account potential agricultural land, which is not yet developed.

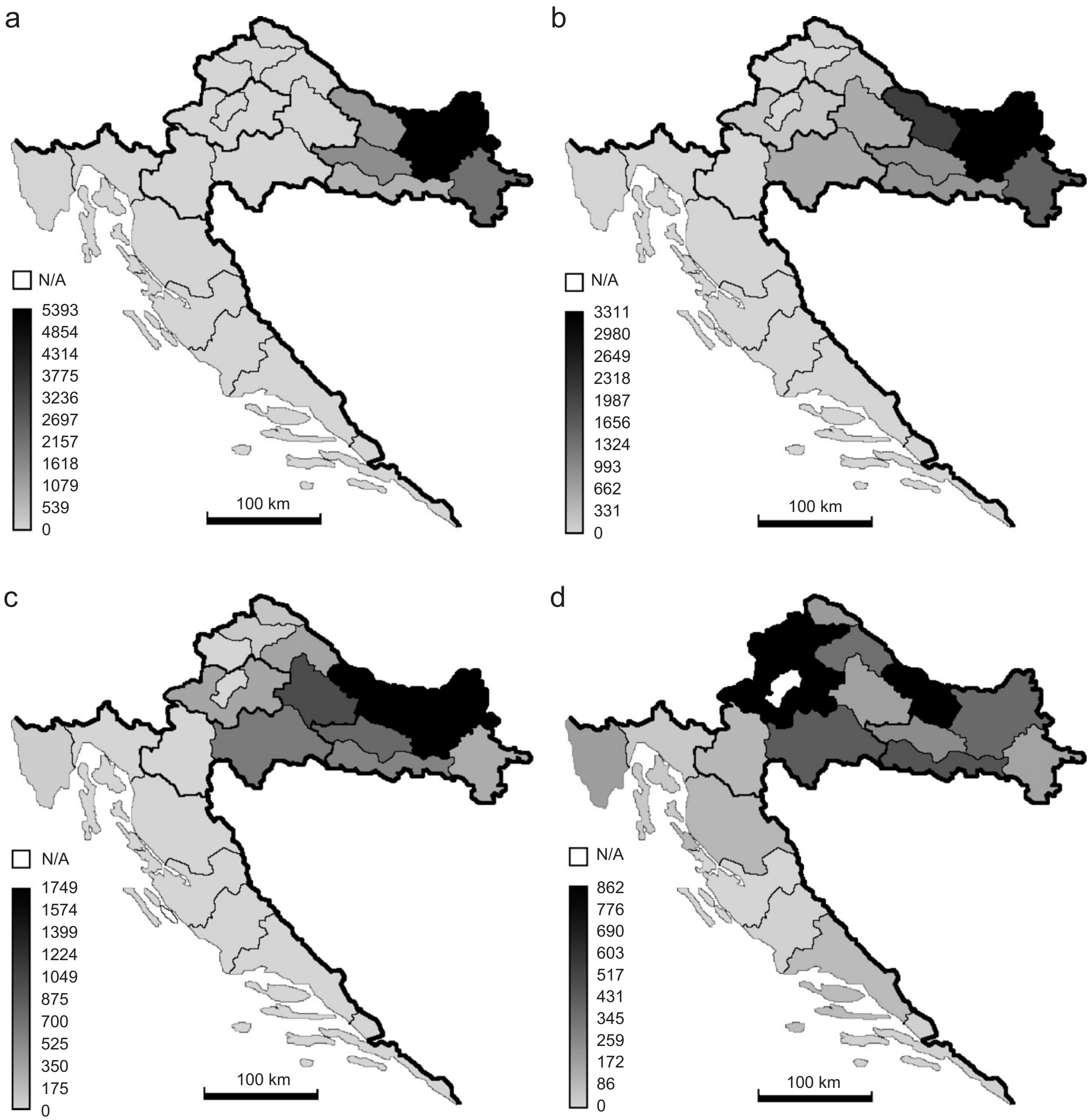

Fig. 4. Agricultural biomass potential (t): (a) sunflower, (b) soybean, (c) rapeseed, and (d) beans.

could fit in. In most cases the energy capability of potential (large) hydro power plants refers to an increase of capacity/capability of already existing facilities (additional or improved units) and only at few locations completely new large hydro power plants could be built. In 2006 HEP started construction of a new hydro power plant Lešće with the net energy output of 94 GW h. Next two hydro power plants planned by HEP, Podsused and Drenje, of 215 and 185 GW h, respectively, are scheduled to be finished by 2010.

The large hydro power plants, although belonging to centralized power generation, are included in this analysis for the purpose of cost comparison. It is not surprising that the cost of electricity produced from the big hydro power plants is the lowest of all RES (Table 1). The same however, does not stand for the small hydro power plants.

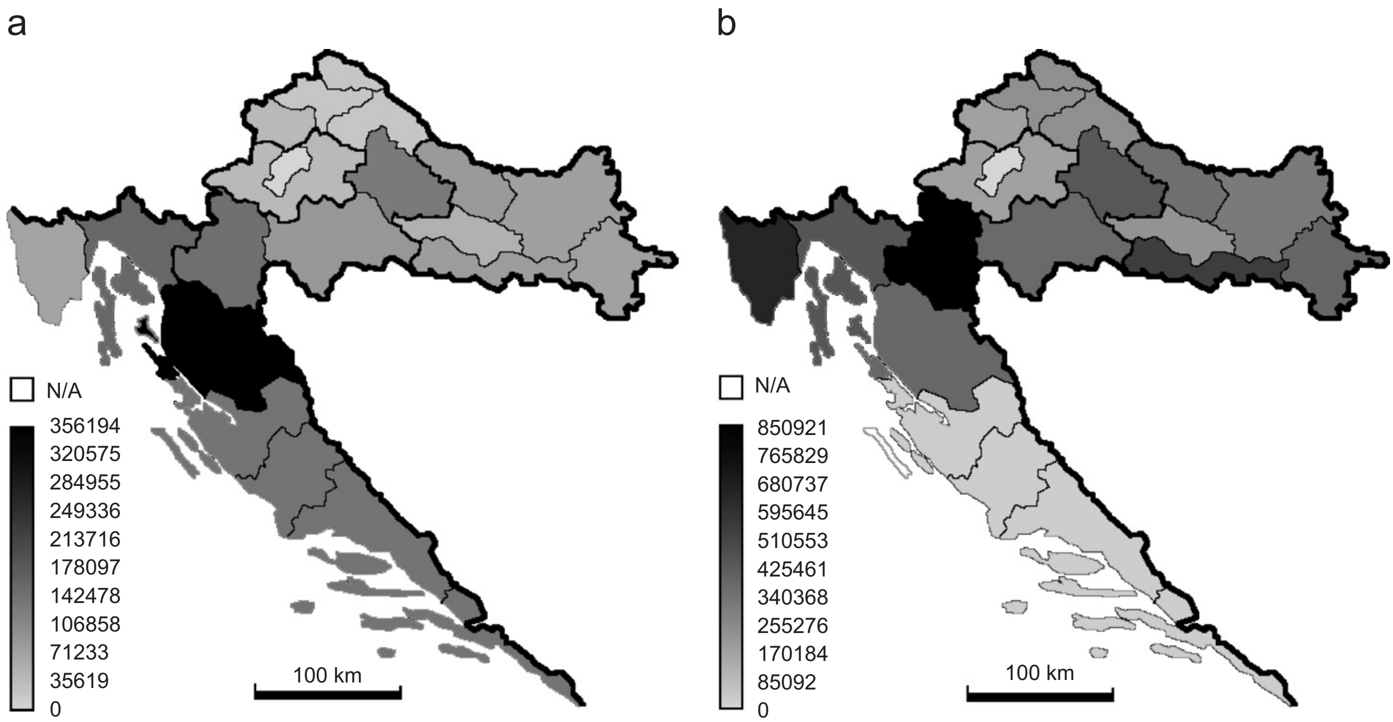

Fig. 5. Woody biomass potential: (a) forest area (ha) and (b) annual production of wood assortment (logs, firewood, wood residue) (m^3).

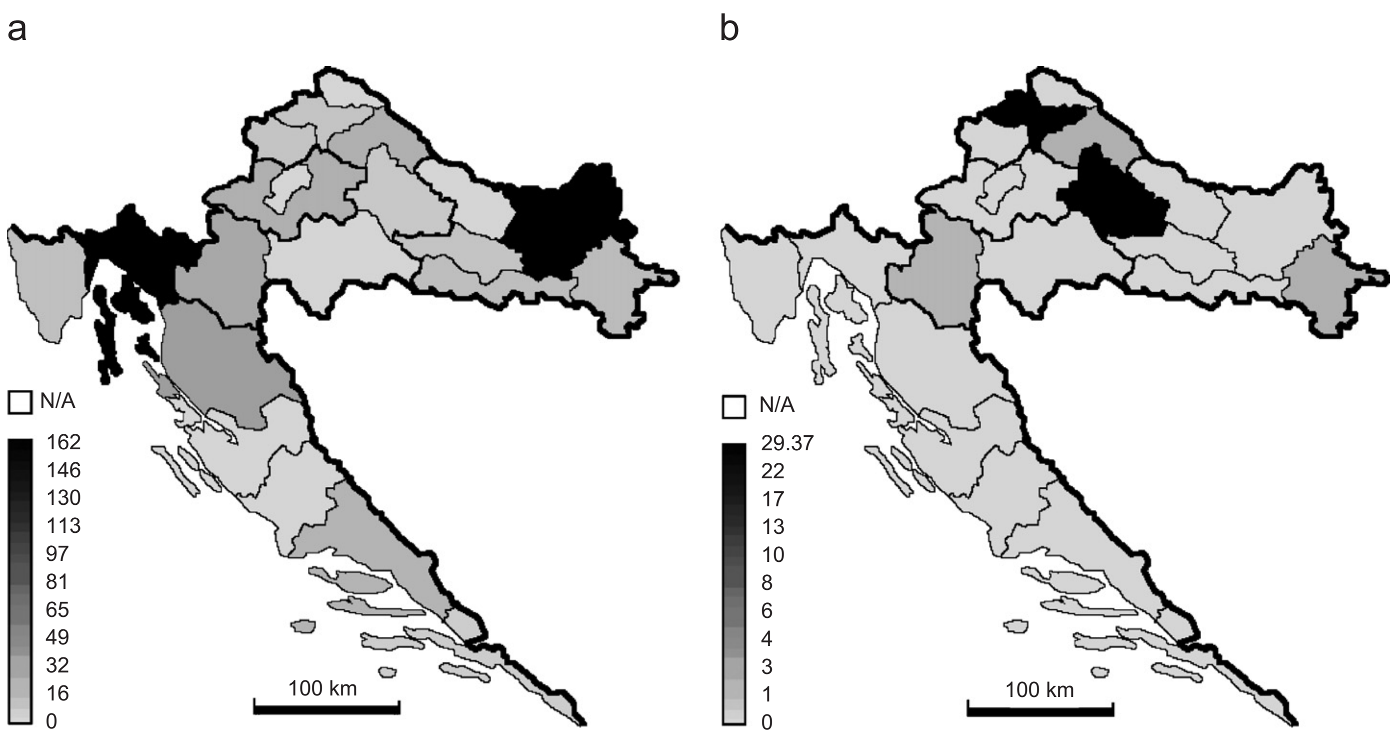

Fig. 6. (a) Energy capability of potential biomass facilities (GW h) and (b) maximum load capacity of potential geothermal facilities (MW).

Depending on the specific case they could exhibit substantial costs.

One part of hydro potential suitable for large hydro power plants is permanently lost due to urban, environmental and economic limits, or due to significant tourist potential of Croatian rivers. For example, the construction of the before mentioned hydro power plant Lešće is meeting fierce opposition of a number of the environmental

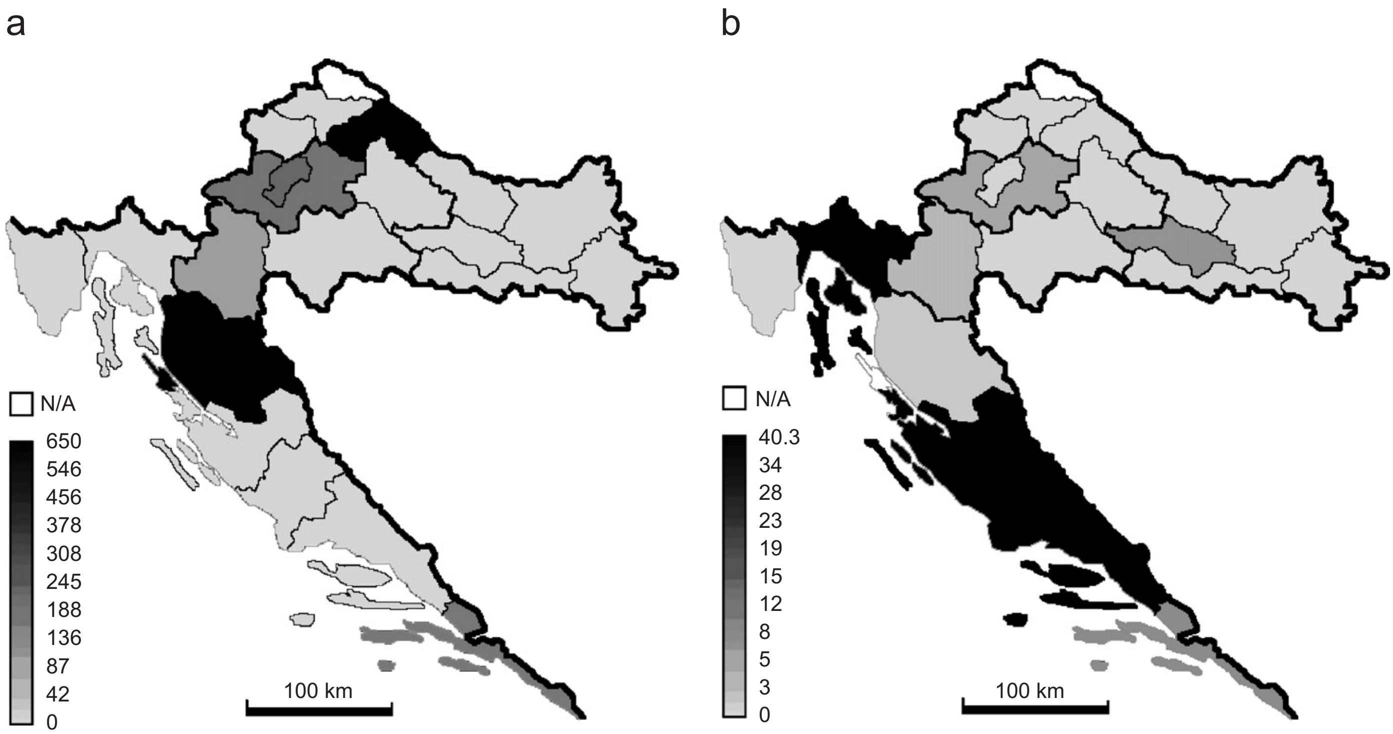

Fig. 7. Energy capability (GW h) of potential: (a) large and (b) small hydro power plants.

non-governmental organizations. Even small hydro power plant projects in Croatia are confronted with strong public resistance due to increased environmental consciousness. Therefore, the list that defines the quite significant hydro potential of small hydro power plants, shown in Fig. 7b, will have to be revised.

The Republic of Croatia has a geothermal gradient of 0.049 °C/m (in the Pannonia Basin), which is greater than the European average (0.03 °C/m) [19]. The potential for electricity production would be profitable at only five (up to now) discovered locations with the temperature of hot water/steam above 120 °C. Fig. 6b shows these locations along with their potential capacities. Heat energy from other wells (with lower temperatures) could be used for heating purposes or in horticulture and agriculture industries (heating of greenhouses, drying and pasteurization of agricultural products). Low temperature geothermal energy could also be used for balneological and recreational purposes (spas and sport centers), which it has been traditionally exploited for. On the other hand, the potential for low temperature geothermal heat by using heat pumps is significant and unused.

3. RES electricity cost–supply curves

The resources availabilities and plant cost projections were combined to form electricity cost–supply curves (Figs. 8 and 9). For the cost projections, the existing estimates of electricity costs were used, while for the resource availability, the technological status, existing commitments on RES development and bearable fuel costs were considered. The costs were estimated based on different publicly available sources. Published data were used, and additional analyses were undertaken where the published information is considered no longer applicable. Also, consultations with a number of experts were conducted when information was unpublished. Nevertheless, the uncertainty in estimates is probably high (medium confidence level is declared). Medium confidence represents an intermediate resource estimate, for the most part a median estimate of uptake. High confidence resources are well proven resources, assessed as readily able to be authorized and developed. Here, achievable development rate was considered.

The current use of RES power generation systems was subtracted from the total assessed resource to obtain potential uptake by 2006 and 2010 over and above the current usage (in 2005). These two curves represent a cumulative uptake of all feasible RES technologies in Croatia, based purely on the potential electricity supply, which does not address network constraints. The total annual energy supply (excluding large hydro power plants) coming from RES in 2006 could be 325 GW h, while in 2010 it could be 1367 GW h.

The facilities having costs above given specific threshold of 20 c€/kW h were omitted from the curves. That includes solar PV and some of the small hydro power plants. Then the potential projects were put in narrow bands (of 2 c€/kW h) in the histograms depending on their energy supply costs, from the least to the most expensive one. The length of a particular horizontal bar corresponds to the availability of specific RES on a different cost level (e.g. in 2006, the small hydro power plants can provide 2.37 GW h of

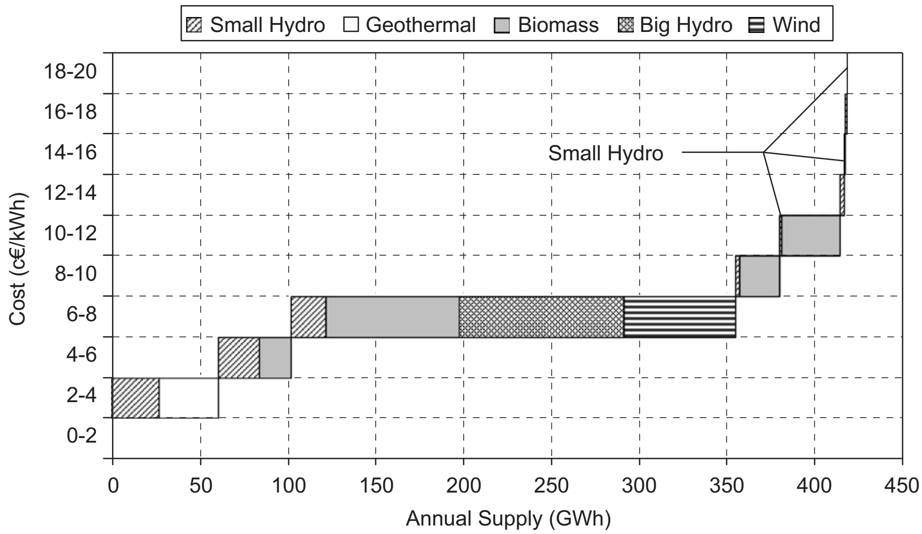

Fig. 8. RES cost–supply curve for 2006 (GW h).

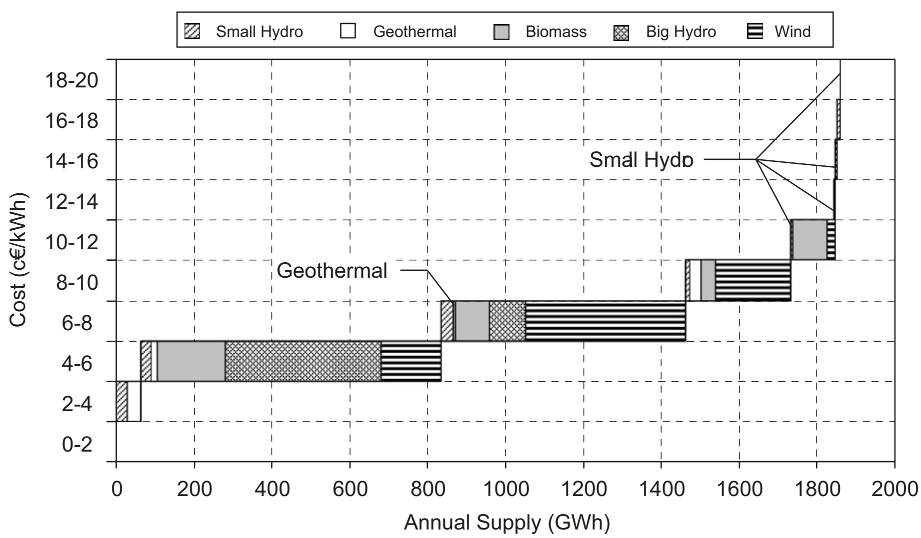

Fig. 9. RES cost–supply curve for 2010 (GW h).

energy, available at cost of 12–14 c€/kW h, while the same technology can provide 27.14 GW h of power in the 2–4 c€/kW h band). This is explicitly given in Tables 2 and 3.

A comparison of the RES cost–supply curves for 2006 and 2010 shows that more wind resource will be available in 2010 in the 6–8 c€/kW h cost band. As this technology is maturing resulting in progressive decrease of costs, other resources will be also available in the cost band of 4–6 c€/kW h.

Not taking into account the large hydro power plants (which are the most profitable RES with 494 GW h at 4–8 c€/kW h costs), the second most attractive renewable resource in 2010 will be biomass, with 173 GW h electricity supply in the 4–6 c€/kW h cost band and 210 GW h in higher bands. For biomass plants, as for all other renewable technologies, energy production costs depend more on capital costs than it is the case for fossil fuel plants (one exception are coal-fired power plants with appropriate pollution control technology), where fuel has the greatest importance. However, these costs were partially estimated since the biomass fuel market in Croatia has not yet been established. In this case the prices of biomass in Slovenia and Austria were used to foresee the price in Croatia.

Some of the small hydro power plant projects exhibit the energy supply costs comparable (and even lower) to those of wind and biomass plants (88 GW h in 2–8 c€/kW h cost bands) but their availability is very limited since most hydro potential is already exploited while other available potential is subject to strong environmental constraints. There are also 11 small hydro power plant projects that are not taken into account due to their substantial costs, which are higher than the threshold value of 20 c€/kW h.

The power production costs of geothermal power plants are relatively low, compared with other renewable sources. But their potential energy supply is not substantial due to the low temperature energy of the considered geothermal

Table 2
RES Cost–supply curve for 2006 (GW h)

Cost (c€/kW h)	Small hydro	Geothermal	Biomass	Large hydro	Wind
0–2	—	—	—	—	—
2–4	27.14	34.32	—	—	—
4–6	23.30	—	18.00	—	—
6–8	19.50	—	76.00	94.00	63.24
8–10	2.13	—	22.90	—	—
10–12	1.39	—	33.25	—	—
12–14	2.37	—	—	—	—
14–16	0.40	—	—	—	—
16–18	1.14	—	—	—	—
18–20	0.21	—	—	—	—
Total (GW h)	77.59	34.32	150.15	94.00	63.24

Table 3
RES Cost–supply curve for 2010 (GW h)

Cost (c€/kW h)	Small hydro	Geothermal	Biomass	Large hydro	Wind
0–2	—	—	—	—	—
2–4	28.00	34.32	—	—	—
4–6	28.78	14.84	173.50	400.00	153.70
6–8	30.92	7.42	86.00	94.00	409.53
8–10	9.64	29.75	36.90	—	191.99
10–12	5.60	—	87.50	—	21.46
12–14	2.37	—	—	—	—
14–16	0.40	—	—	—	6.13
16–18	8.13	—	—	—	—
18–20	0.21	—	—	—	—
Total (GW h)	114.04	86.33	383.90	494.00	782.81

wells. The first geothermal power plant in Croatia will be built on Lunjkovec-Kutnjak site (2.5 MW_e/14.64 GW h). Another similar project in preparation is the geothermal power plant. Velika Ciglena (4.36 MW_e/34.32 GW h that could be increased to 13.1 MW_e/102.97 GW h in 2016), which has a peak temperature of 170 °C. However, the measured temperature at the surface is significantly lower. On the other hand, it should not be forgotten that some of these potential projects could be converted to heat generation facilities that will serve for space heating and in balneological/recreational purposes in spas, rather than for power production.

4. Conclusion

The DEG based on RES in the Republic of Croatia will find its niche easier for the users that will produce electricity for their own needs and for the users located in remote rural areas where there is no electricity network or the network capacity is insufficient (off-grid applications). The users (most likely small companies) that produce heat and/or power for their own use (like agriculture, wood and food processing industry) could thus control and reduce their costs for energy and achieve some sort of energy independence (e.g. applying cogeneration plant that uses biomass). They could also be grid-connected, islanded (off-grid) or embedded (in which case the extra generation could be sold to retailer).

Examples of potential application of DEG based on RES in Croatia could include:

- Hotels and apartment houses, restaurants, auto-camps, nautical marinas, sports and entertainment centers, chalets, also some facilities in rural and hunting tourism—in general all tourist facilities that are situated in remote isolated areas on islands and in mountains where there is no possibility of network connection or it would be too expensive to connect or is not permitted by environmental laws (e.g. in national parks and nature reserves).
- Cooling facilities for temporary storage of fish, meat etc., field ambulances (for electrical medical appliances and cooling of medicines), electrical fences for livestock ranching, autonomous electrical livestock/game feeders and water-troughs, for lighting and operation of agricultural facilities, hatcheries.
- Irrigation in deltas of rivers, water desalination on islands.
- Telecommunication (base) stations, meteorological stations, lighthouses, road signs, public lighting, different autonomous monitoring systems (pollutant emission monitoring, forest fire protection, technical protection of individual facilities etc.).
- Households (permanent and weekend settlements) in isolated and rural areas (mountainous and coastal/island regions).
- Saw mills situated near small rivers, in which power from the small hydro power plants could be used.
- Hybrid combination of solar systems or wind turbines with LPG or diesel aggregates could help solve the problem of energy infrastructure on islands and other remote locations (region of Adriatic Croatia). Furthermore, that could start development of traditional island activities with the engagement of local resources and workforce in accordance with the strategic development of Croatian islands [23–25], which could, in turn, reduce depopulation of islands.

An intermittent nature of renewable sources can be partially mitigated by applying different energy storage systems or energy carriers such as high capacity batteries (new technologies and electrolytes, flow batteries) up to several tens of MW h, capacitors, flywheels, compressed air systems, reversible hydro systems and hydrogen (fuel cells), which could provide power when it is needed.

Among all DEG systems based on RES that were analyzed, the most profitable ones (Table 1) are technologically mature wind power systems. Particularly, the large wind farms, with new feed-in tariffs, are becoming commercially profitable in Croatia. The second are the CHP plants that use biomass. Comparison of the RES cost-supply curves for 2006 and 2010 (Figs. 8 and 9, respectively) shows that in 2010 more energy capability will be available at lower costs. Excluding large centralized hydro power plants and based on cost, the prevailing RES type in 2006 would be biomass, while in 2010 it would be wind power. Although the biomass plants have higher initial (capital) costs than the wind power plants (Table 1), they exhibit the energy supply costs comparable to those of wind farms. Furthermore, the power production from biomass should be examined in a wider social context of encouraging local employment and development of local business activities, particularly in rural areas, which finally contributes to their sustainable development.

If external costs connected with global climate change and local pollution are included in the cost of electricity from conventional sources, which could reach up to 10 c€/kW h (for coal power plants, externalities included [26,27]), then the production of electricity from renewable sources becomes quite attractive. The utilization of these resources could also help Croatia meet its Kyoto Protocol requirements, with the condition that the adequate incentives are provided. The annual energy supply of 1367 GW h from RES in 2010 (excluding the electricity produced by large hydro power plants) is also in concordance with the energy strategy of the Republic of Croatia [9,28], where it is suggested that the minimal share of the total electricity consumption coming from non-large hydro RES in 2010 should be at least 5.8% (or 1100 GW h/year). This target, supported by feed-in tariffs, is set based on RES electricity cost of supply and economic and external costs of conventional electricity.

Nevertheless, Croatia, aware of the shortcomings of existing RES data, has plans to acquire the data and studies necessary for planning and development of RES sector. The recent grant of the Global Environment Facility Trust Fund (GEF) and the World Bank: "Croatia—Renewable Energy Resources Project" in the amount of US$5.5 million, for developing a rational policy framework for renewable energy [29], is in line with those efforts. This project has two main objectives: to support the market framework and other market conditions for renewable energy and to ensure an adequate and sustainable supply of potential projects through investment in the early stage of renewable energy project development. The GEF grant and other EU funds will certainly help Croatia fulfill the national goals for implementation of renewable energy, based on a clear understanding of the costs and technical issues related to financing and installing projects.

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