Planiranje lokalnog energetskog sustava primjenom analize "od dna prema gore"

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MASTER'S THESIS

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Bottom-up Planning of Local Energy System

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I hereby declare that this thesis is entirely the result of my own work except otherwise indicated. I have fully cited all used sources and I have only used the ones given in the list of references.

Viktorija Dobravec

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Naslov rada na hrvatskom jeziku: Planiranje lokalnog energetskog sustava primjenom analize „od dna prema gore"

Naslov rada na engleskom jeziku: Bottom-up planning of local energy system

Opis zadatka:

The EU's territory is divided in NUTS statistical regions - Nomenclature of territorial units for statistics in order to produce regional statistics. Statistical units are structured into three levels. NUTS 3 level will be used to calculate how 100% renewable energy system of Dubrovnik - Neretva county could be developed from bottom-up analysis.
It is necessary to:

1. Give a brief overview of the bottom-up approach in comparison to the top-down approach.
2. Collect the available and needed data in order to analyse baseline year (electricity consumption and production, energy consumption of the following sectors: industry, transport, households, etc.).
3. Develop a scenario of 100% renewable energy system taking into account internal regional energy and resource balance.
4. Scenario should also take into account energy exchange with neighbouring regions as well as sustainable use of biomass.
5. The modelling of energy system should be done by LEAP software tool.
6. Finally, all results should be discussed and conclusion about work should be given.

The paper should state all used literature and eventually provided help.

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NOMENCLATURE

Symbol	Unit	Description
E_{ind}	GWh	Final energy consumption in industry sector
$x_{ind,CRO}$	-	Annual increase of energy consumption in industry sector at the country level
E_{air}	GWh	Final energy consumption of air transport
N_{DNC}	-	Number of passengers at county level
N_{CRO}	-	Number of passengers at the country level
E_{PV}	kWh	Yearly potential electrical energy generation of PV
P_k	kW	Peak power installed
r_p	-	System performance ratio
$H_{h,I}$	$\mathrm{kWh/m^2\ /day}$	Monthly or annual average of daily global radiation on the horizontal or inclined surface

Units

kWh	Kilowatt hour	Energy
MWh	Megawatt hour	Energy
GWh	Gigawatt hour	Energy
TWh	Terawatt hour	Energy
MW	Megawatt	Capacity
km	Kilometre	Length
kg	Kilogram	Mass
t	Tonne	Mass
m^2	Square metre	Area

ha	Hectare	Area
L	Litre	Volume

Abbreviations

B&H	Bosnia and Herzegovina
BAU	Business as usual
CCR	Carbon Capture & Recovery
CHP	Combined Heat and Power Plant
CO_2	Carbon dioxide
DME	Dimethyl ether
EU	European Union
GHG	Greenhouse Gas
HEP	Hydroelectric Power Plant
IRES	Intermittent Renewable Energy Sources
LAU	Local Administrative Unit
LPG	Liquefied Petroleum Gas
NUTS	Unit Nomenclature of Territorial Units for Statistics
PV	Photovoltaics
RES	Renewable Energy System
SOEC	Solid Oxid Electrolyser Cell

Economy

GDP	Gross domestic product
EUR	Euro
€	Euro

ABSTRACT

This thesis presents analysis and results of energy transition to a 100% renewable energy system of a local area by the year 2050. The transition is carried out by bottom-up approach. Local areas are considered to be initiators in building 100% renewable energy system, from the political, social, and economic point of view. Therefore, the study area has been selected according to the third level of the Nomenclature of units for territorial statistics (NUTS).

Firstly, definition of bottom-up approach in comparison to the top-down, definition of European Union territory classification for statistical purposes, and explanation of holistic approach were given.

Secondly, the general methods were defined and described. Methods were presented in a form of several steps so reapplication is possible to other systems of different size and complexity.

After establishing methods, a case study for Dubrovnik-Neretva county was made. Energy system was analysed for the baseline year. Final energy consumption in the year 2015 was 2.24 TWh out of which 1.25 TWh was in transport sector. Afterward, the potential of local renewable energy sources was investigated. The biggest potential had wind, solar and hydro where special emphasis was on biomass potential in order to keep its utilization on sustainable level. Biomass potential accounted for 510.4 GWh.

Modelling of the scenario was done for complete energy system – including transport sector. Due to transition complexity in transport sector, several alternatives were proposed. Two out of three variations follow 100% renewable energy system approach while third was made in accordance with the net zero carbon system approach.

In order to ensure system flexibility and higher penetration level of intermittent renewable energy sources (IRES) smart energy system concept was used.

As a benchmark for 100% renewable energy system business-as-usual scenario was made. Final energy consumption of all sectors in BAU scenario in comparison to the baseline represents growth of 57.8%. On the other hand, energy consumption of 100% RES scenario with electrofuel production was 1.49 TWh which was 33.3% lower than in the baseline year.

Finally, all results were discussed from both, energy and economic aspect.

Key words: Renewable energy system, Bottom-up approach, Smart energy system, Sustainable biomass, Transport sector

SAŽETAK

U ovom radu prikazana je analiza i rezultati prijelaza lokalnog energetskog sustava na 100% obnovljivi energetski sustav do 2050. godine. Prijelaz je proveden primjenom analize „od dna prema gore“ (eng. bottom-up). Smatra se da su lokalne zajednice glavni pokretači u prelasku na 100% obnovljivi energetski sustav, s političkog , društvenog i gospodarskog aspekta. Stoga je područje istraživanja određeno prema Nomenklaturi prostornih jedinica za statistiku na trećoj razini.

U uvodu je dana definicija analize „od dna prema gore“ u usporedbi s analizom „od vrha prema dolje“ (eng. top-down) , definicija sustava klasifikacije prostornih jedinica za potrebe službene statistike Europske unije kao i objašnjenje holističkog pristupa u energetskom planiranju.

Nakon uvoda razvijene su i opisane metode. Metode se sastoje od nekoliko koraka i prikazane su u obliku koji omogućava primjenjivost metoda na sustave različitih veličina i složenosti.

Nakon razvoja metoda, provedena je analiza slučaja za Dubrovačko-neretvansku županiju. Energetski sustav analiziran je za baznu, 2015. godinu. Ukupna potrošnja energije za 2015 godinu bila je 2.24 TWh od čega je potrošnja u sektoru prometa iznosila 1.25 TWh. Nakon toga ispitan je potencijal obnovljivih izvora energije u županiji. Najveći potencijal ima energija vjetra, Sunca i hidroenergija. Poseban naglasak je stavljen na određivanje potencijala biomase kako bi njeno korištenje u energetske svrhe ostalo u granicama održivosti. Potencijal biomase iznosio je 510.4 GWh.

Modeliranje scenarija provedeno je za cjelokupni energetski sustav, uključujući sektor transporta. Zbog složenosti takve tranzicije predloženo je nekoliko alternativnih rješenja. Dvije od tri varijacije baziraju se na konceptu 100% obnovljivog energetskog sustava (eng. 100% renewable energy system) dok se treći temelji na principu nulte ukupne emisije ugljičnog dioksida.

Kako bi se osigurala fleksibilnost i omogućila implementacija veće količine intermitentnih obnovljivih izvora energije prihvaćen je koncept pametnog energetskog sustava.

Za usporedbu 100% obnovljivog energetskog sustava razvijen je temeljni (eng. business as usual) scenarij. Ukupna potrošnja u temeljnom scenariju u usporedbi s baznim predstavlja porast od 57.8%. S druge strane, potrošnja energije u 100% obnovljivom scenariju s proizvodnjom elektrogoriva (eng. electrofuels) iznosila je 1.49 TWh što predstavlja 33.3% manju potrošnju nego u baznoj godini.

Na kraju je provedena diskusija o rezultatima s energetskog i ekonomskog aspekta.

Ključne riječi: Obnovljivi energetski sustav, analiza ”od dna prema gore”, Pametan energetski sustav, održivo korištenje biomase, sektor transporta

PROŠIRENI SAŽETAK (EXTENDED SUMMARY IN CROATIAN)

U uvodnom poglavlju prikazan je značaj energetskog planiranja s lokalne razine. Taj značaj se očituje u prihvaćanju i implementaciji mjera energetske učinkovitosti kao i drugih mjera koje vode prema tranziciji k održivom energetskom sustavu. Smatra se da su lokalne zajednice glavni pokretači te tranzicije s ekonomskog, političkog i društvenog aspekta. Također, dan je pregled osnovnih pristupa koji se koriste u modeliranju energetskih sustava. Postoje dva osnovna pristupa, oni se odnose na: analizu „od dna prema gore“ i analizu „od vrha prema dnu“ gdje su uvrježeniji nazivi za ove pojmove odozdo prema gore i odozgo prema dolje [1].

Analiza „od dna prema gore“ predstavlja inženjerski pristup u modeliranju energetskih sustava. Omogućuje detaljan opis tehnologija i tehnoloških procesa, modelira tehničke promjene i prikazuje tehničke potencijale. Pristup „od vrha prema dnu“ je ekonomskog karaktera te ne pruža mnogo informacija o energetskom sektoru. Model koristi skupne pokazatelje u prognoziranju budućih scenarija, temelji se na promatranom ponašanju tržišta te ne uzima u obzir tehnički najefikasnije tehnologije što može dovesti do podcjenjivanja potencijala tehnološkog razvoja. Kroz ovaj rad odabran je pristup „od dna prema gore“. Odabrani pristup u kontekstu ovog rada ne predstavlja način prikupljanja podataka već izgradnju i planiranje energetskih sustava gdje su temelj tog sustava upravo lokalne zajednice.

Sukladno primijenjenoj analizi odabir lokacije za istraživanje proveden je prema Nomenklaturi prostornih jedinica za statistiku na trećoj razini (NUTS III). To je hijerarhijski sustav za identifikaciju i klasifikaciju prostornih jedinica za potrebe službene statistike u zemljama članicama Europske unije. Zemlje su podijeljene na statističke jedinice strukturirane na tri razine:

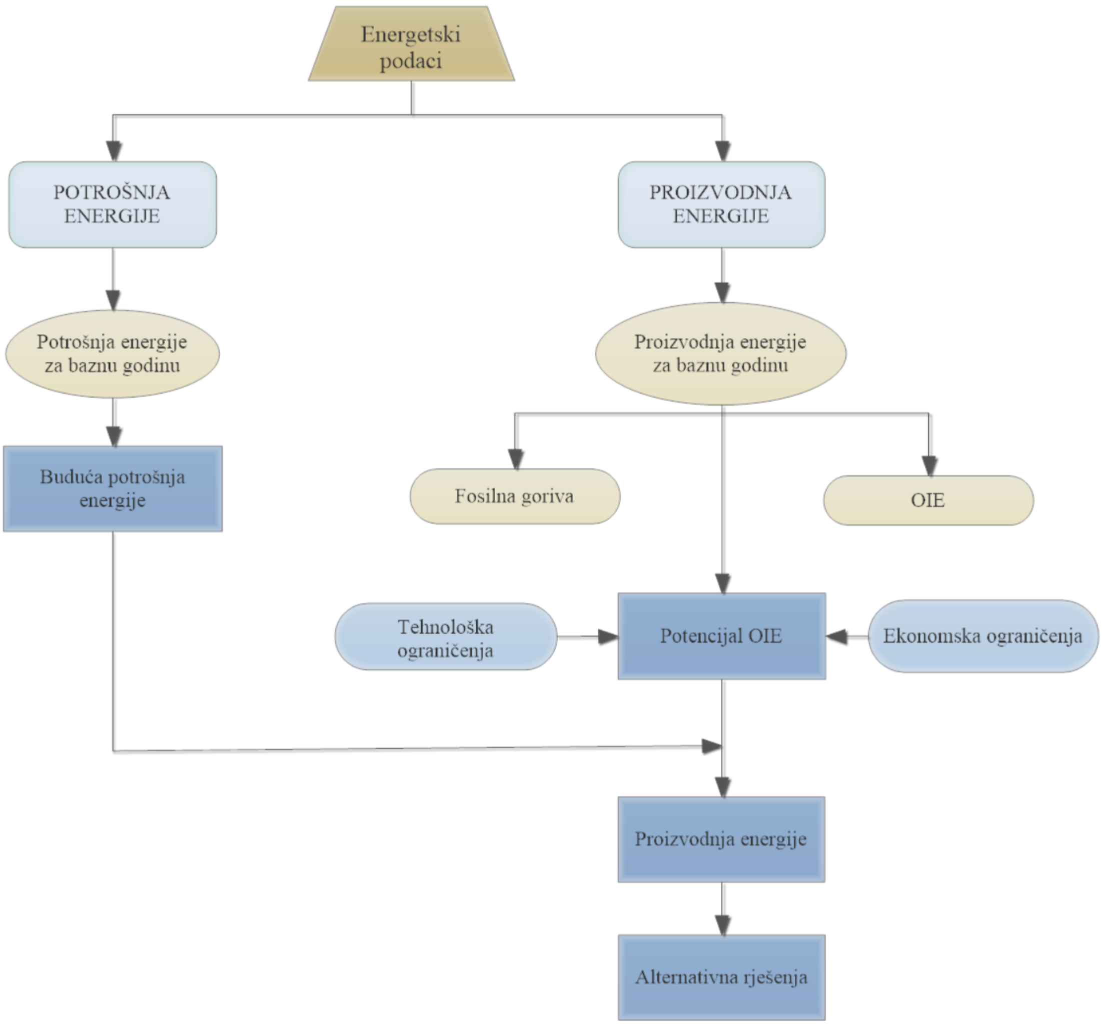
1) NUTS 1 : odgovara statističkim jedinicama u kojim živi od 3 do 7 milijuna stanovnika
2) NUTS 2 : od 800 000 do 3 000 000 stanovnika ;
3) NUTS 3 : od 150 000 do 800 000 stanovnika.

Teritorijalne jedinice definirane su za statističke svrhe i napravljene su iz praktičnog razloga lakšeg prikupljanja i obrade podataka kao i za jednostavnije provođenje političkih mjera.

U drugom poglavlju definirane su opće metode razvijene za potrebe ovog rada. Metode se baziraju na četiri osnovna koraka te su primjenjive za sustave različitih veličina i složenosti. Koraci metoda su sljedeći:

1) Mapiranje potreba
2) Mapiranje resursa
3) Modeliranje scenarija
4) Analiza scenarija

Proces modeliranja energetskog sustava shematski je prikazan Slika proširenog sažetka 1.



Slika proširenog sažetka 1. Prikaz procesa modeliranja energetskog sustava

Mapiranje potreba predstavlja potrošnju energije u baznoj godini. Potrošnja energije odnosi se na potrošnju električne energije, toplinske, odnosno rashladne energije te energije za korištene u svrhu transporta. Nadalje, potrošnja je podijeljena prema sektorima: industrija, promet, opća *potrošnja* koja obuhvaća sljedeće podsektore: kućanstva, uslužni sektor, poljoprivreda, graditeljstvo. Potrebe su prikazane u vidu baznog scenarija.

Izvori energije su obnovljivi izvori energije dostupni unutar granica odabranog područja istraživanja. Posebna pozornost je posvećena određivanju potencijala biomase jer je nužno da iskorištavanje biomase u energetske svrhe ne prelazi potencijal područja. Jedino se takvo korištenje biomase smatra održivim u 100% obnovljivom energetskom sustavu [2]. Potencijali su uspoređeni s postojećim studijama i radovima o mogućnostima i potencijalima obnovljivih izvora energije na području.

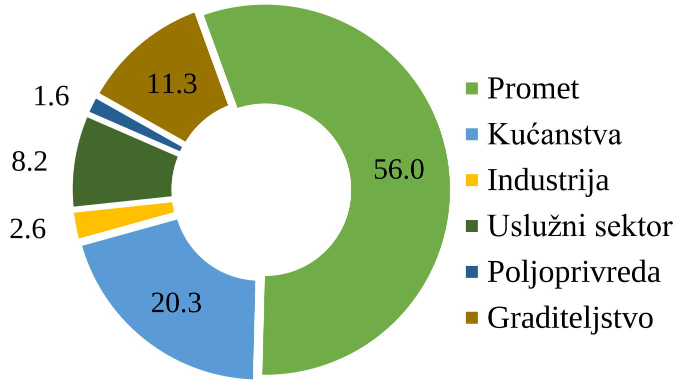
U svrhu izrade 100% obnovljivog scenarija prihvaćen je koncept pametnog energetskog sustava. Na strani potrošnje dodatno je razvijen scenarij koji prati trenutna kretanja energetske potrošnje bez sustavnog utjecaja političkih odluka ali s očekivanim poboljšanjima tehnologija, odnosno temeljni scenarij. U energetskoj tranziciji najzahtjevnija je tranzicija prometnog sektora stoga su unutar osnovnog scenarija predložena dodatna alternativna rješenja. Scenariji su izrađeni u Microsoft Excelu te su potom podaci prilagođeni za korištenje u LEAP računalnom programu. Analiza u LEAP-u je provedena na strani potrošnje energije te su rezultati integrirani u konačne rezultate prikazane u radu.

Posljednji korak u metodama je analiza rezultata s energetskog aspekta s teorijskim osvrtom na ekonomske troškove.

U trećem poglavlju prethodno opisanim metodama provedena je analiza slučaja za Dubrovačko-neretvansku županiju. Prikazan je i opisan proces te proračuni za dobivanje ulaznih podataka potrebnih za izradu scenarija za baznu godinu. Na početku je dan kratak pregled županije: analiza lokacije, stanovništva, infrastrukture, gospodarstva i energetskog sustava. Energetski sustav i neposredna potrošnja energije u županiji analizirani su za 2015. godinu koja je određena kao bazna.

Dubrovačko-neretvanska županija je najjužnija županija u Republici Hrvatskoj. Granica s Bosnom i Hercegovinom kod Neuma dijeli županiju na dvije osnovne funkcionalne i fizionomske cjeline: uzdužno obalno područje s nizom pučinskih i bližih otoka (od kojih su najznačajniji Korčula, Mljet, Lastovo i grupa Elafitskih otoka) i poluotok Pelješac te prostor Donje Neretve s gravitirajućim priobalnim dijelom. Teritorijalna podijeljenost ima i značajan utjecaj na energetski sustav.

Energetski sustav i neposredna potrošnja energije za baznu godinu analizirani su u obliku baznog scenarija kao dio koraka *Mapriranje potreba*. Proračunata neposredna potrošnja energije svih sektora iznosila je 2 240 GWh. Udjeli u neposrednoj potrošnji energije pojedinih sektora prikazani su na Slika proširenog sažetka 2.



Slika proširenog sažetka 2. Udjeli u neposrednoj potrošnji energije, 2015. [%]

Županiju karakterizira bogatstvo obnovljivih izvora energije, značajna osunčanost tijekom godine, izražen vjetropotencijal, te bogatstvo voda. Posljednji, hidropotencijal, se već koristi u značajnoj mjeri no prostor za njegovo dodatno korištenje je još uvijek izrazit. Županija ne obiluje velikim potencijalom za korištenje biomase u energetske svrhe no ovom proračunu se pridala pozornost kako nebi došlo do prekomjernog korištenja što bi narušilo koncept održivog energetskog sustava. Potencijal iznosi 510.4 GWh i uključuje drvni potencijal šuma i šikara kao i potencijal biomase dobiven od ostataka poljoprivredne proizvodnje. Izvori su mapirani u podpoglavlju *Mapping resources.*

Opća metoda primjenjiva na sve ostale slučajeve dana je u poglavlju *Methods* dok su specifičnosti karakteristične za studiju slučaja za Dubrovačko-Neretvansku županiju opisane u dijelu *Modelling scenarios.*

Temeljni scenarij rađen je prema smjernicama iz Energetske strategije Republike Hrvatske. Strategija se bavila procjenama do 2020. uz pogled na 2030. godinu stoga se za potrebe ovog rada procjena prolongirala do 2050. godine.

Scenarij 100% obnovljivog energetskog sustava na strani potrošnje uzima u obzir mjere energetske učinkovitosti kao i druge mjere za smanjenje potrošnje energije te uvodi nove tehnologije i goriva. Zbog intermitentnih obnovljivih izvora energije kao što su vjetar i sunce bilo je potrebno ostvariti fleksibilnost sustava kako bi proizvodnja u svakom trenutku odgovarala potražnji energije. Fleksibilnost je postignuta kroz nekoliko koraka:

1) Smanjenje potreba za toplinskom energijom
2) Elektrifikacija prometa
3) Uvođenje tehnologija obnovljivih izvora energije u sustavu grijanja
4) Elektrogoriva: utječu na fleksibilnost sustava jedino ako se proizvode unutar granica sustava

Provođenje prva tri koraka omogućuje implementaciju intermitentnih izvora energije u udjelu do 55 %. Dodatna sigurnost opskrbe električne energije je postignuta na način da niti jedan od intermitentnih izvora energije ne prelazi udio od 30%. Četvrti korak ovdje nije uziman u obzir jer nije sadržan u svim varijacijama scenarija. Tranzicija u prometnom sektoru je vrlo složena i održivi prijelaz nije u potpunosti definirana kao što je to slučaj za ostale sektore. Razlog za to leži u činjenici da dio transporta, kao što je dio teških vozila, avionskog i vodenog promet nije prikladan za elektrifikaciju. Ukoliko se za taj dio prometa izuzme korištenje biogoriva potrebno je bilo predložiti nova prikladna goriva za tu primjenu. Većina takvih goriva još nije u većoj komercijalnoj upotrebi i/ili se nalazi u fazi istraživanja. Predložena goriva u ovom radu su elektrogoriva. Elektrogoriva nastaju pretvorbom električne energije elektrolizom vode u vodik koji kasnije reagira s izvorom ugljika te se u završnoj fazi pretvara u željeno gorivo [3]. Odabrani je proces proizvodnje koji ne uključuje direktno korištenje biomase. Uz složenost i neizvjesnost ove tranzicije i dodatno zbog značajnog udjela potrošnje prometnog sektora u ukupnoj potrošnji energije odlučeno je ispitati nekoliko alternativnih rješenja.

1) Proizvodnja elektrogoriva
2) Uvoz elektrogoriva
3) Uvoz/korištenje fosilnih goriva

Alternativni scenariji su dalje razvijeni na način da je kod proizvodnje goriva ispitano nekoliko mogućnosti vezanih za količinu proizvedenog goriva. Uvoz ispituje koliko je dodatno električne energije potrebno proizvesti kako bi se ostvarila energetska bilanca ukupne potrošnje energije zbog uvoza elektrogoriva. Varijacija koja uključuje fosilna goriva bavi se problematikom određivanja količine električne energije iz obnovljivih izvora koju je potrebno izvesti i time smanjiti proizvodnju električne energije okolnih regija nastalu izgaranjem fosilnih goriva. Pristup ugljičnog neutraliziranja primjenjuje se kako bi se održala ravnoteža ugljičnih emisija cjelokupnog sustava.

Na strani proizvodnje energije kreiran je scenarij koji zadovoljava potrebe potrošnje energije u slučaju 100% obnovljivog energetskog sustava s proizvodnjom elektrogoriva.

Rezultati temeljnog scenarija pokazali su porast u potrošnje energije od 57.77% te u skladu s time i porast potrošnje fosilnih goriva. Takav scenarij nije prihvatljiv u pogledu ublažavanja klimatskih promjena i smanjenja emisija stakleničkih plinova te su promjene energetskog sustava neophodne.

100% obnovljivi scenarij prikazuje korjenitu promjenu energetskog sustava i promjenu vrsta goriva. Ukupna potrošnja je 33.3 % niža u odnosu na baznu godinu i 57.8% niža u usporedbi s temeljnim scenarijem.

Analizom svih aspekata preporučeni scenarij uključuje lokalnu proizvodnju elektrogoriva kako bi se ostvarila dodatna sigurnost i fleksibilnost sustava. Scenarij zahtjeva instalirani kapacitet od 535 MW.

Izneseno istraživanje i rad predstavljaju temelj u zatvaranju jaza u energetskom planiranju održivih sustava ne samo s tehničkog nego i ekonomskog i političkog aspekta. Stoga su za kraj, dani prijedlozi i savjeti za buduća istraživanja.

1. INTRODUCTION

There is a general agreement that the energy system will need to change in the future in order to reduce greenhouse gas (GHG) emissions and fulfil climate change mitigation strategies [4, 5]. However, it is not precisely defined who will be the main driver of this change. This thesis presents energy system transition at local area level. Local areas are considered to be the main initiators of transition towards sustainable energy systems, from political, social and economic perspective.

For example, X. Zhang *et al.* [6] highlighted the important role of local policies in implementing national and regional energy policies for new energy vehicles adoption in China, while A. Kostevšek *et al.* [7] pointed out effectiveness of local communities in meeting energy objectives due to closer contact with end-users and local decision makers support.

There are many existing studies which also investigate potential transition to 100% renewable energy system. Nevertheless, many of these studies have primarily focused on large size area such as European union (EU) [4, 8], South East Europe [2] and at the country level such as Denmark [9], Ireland [10], Belgium [11], Macedonia [12]. Studies present examples and pathways of energy system transition, but it is questionable whether the main driver of sustainable transition can occur as large scale system. This is due to significant diversities among countries or even local differences within the same countries. Another important issue is the implementation of energy plans and strategies where local communities provide the best possibilities.

On the other hand, energy planning with the aim to increase the penetration of intermittent renewable energy sources or to achieve 100% RES was done for small size and/or isolated areas such as towns, cities, and islands. Examples could be found in studies for the island of Mljet [13], Porto Santo [14], Mykines [15], Samso [16], town of Frederikshavn [17] and city of Copenhagen [17]. Such areas can be seen as too separated parts of systematically integrated areas like counties.

Thus, the aim of this thesis is to focus on the local area that has not been researched yet and complete the demonstrated gap towards sustainable transition.

1.1. Bottom-up approach

There are two main approaches for modelling the interconnection between energy, the environment, and the economy [18].

Bottom-up is an engineering-based model which includes a lot of detail and describe a number of specific energy technologies with both technical and economic parameters but at the same time, it lacks interconnections with the economy in whole [18, 19]. Model includes a large number of energy technologies to define changes in the energy system such as substitution of energy carriers on the primary and final energy level, process substitution, process improvements or energy savings. Model is mostly used to calculate the least-cost method of meeting a given energy demand or demand for energy services subject to various system constraints, such as exogenous emission reduction targets [18]. It also allows estimating a wider range of policy options and includes both present and future technologies including a description of the changes in parameters based on current knowledge of new technologies development [19]. Technologies are characterized with cost and performance aspects [18]. Bottom-up tools could vary from technology databases with relatively simple implementation to models with numerous system information [20].

Top-down model is a model of a general economy with the focus on market interactions within an entire economy and does not have a lot of technological detail in the energy sector. Usually, it focuses on market processes providing the cost of production at commodity or industry level rather than providing a direct or detailed description of technologies [18, 21]. Top-down model is based on historical data and it considers historic behaviour to be relevant to the future system as well [20]. A model represents technological change as an abstract, aggregate phenomenon applicable for policy-makers to assess economy-wide price instruments such as taxes and tradable permits, but it is not suitable for combining effects of these price-based policies with technology-specific policies [21]. Disadvantage of the model is often a lack of detail on current and future technological options relevant for an appropriate estimation of energy policy proposal, also model can fail to satisfy fundamental physical restrictions such as the conservation of matter and energy [22].

Different aggregation levels exist among models, top-down model refers to aggregated while bottom-up to disaggregated models [23].

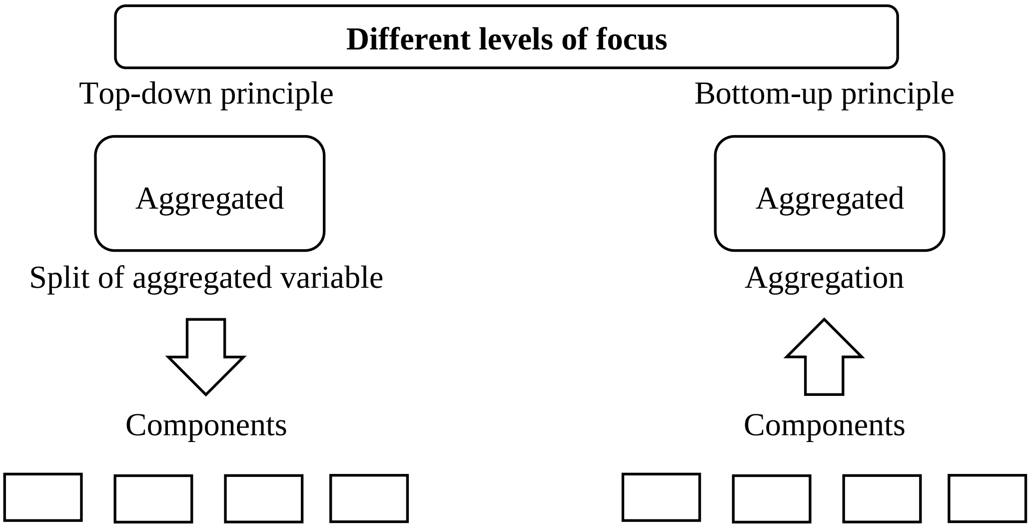


Figure 1. Aggregation level of top-down and bottom-up models [19]

Models are designed with different purposes, structure and with a different theoretical background [19]. Earlier, studies were giving very different outcomes for analysing the same issues mainly related to lower cost levels and higher reduction potentials found in bottom-up studies. Nowadays difference is less significant as confirmed in the Intergovernmental Panel on Climate Change's Fourth Assessment Report [20]. A report showed that the global emission reduction potentials from bottom-up and top-down approaches were very similar. Reduction potential calculated from various approaches is comparable in size, though differences can still be found at sectoral level [20]. The distinction between those two models, in reality, cannot be precisely defined but it is more a combination of a range of variations. Important to note is that the two approaches are not exclusive but they add different types of information while modelling energy systems [20]. Conventional bottom-up and top-down models can be characterized by three main attributes: technological explicitness, macro-economic, completeness and general micro-economic realism. Their comparison according to the listed attributes is represented using dimensions of Figure 2.

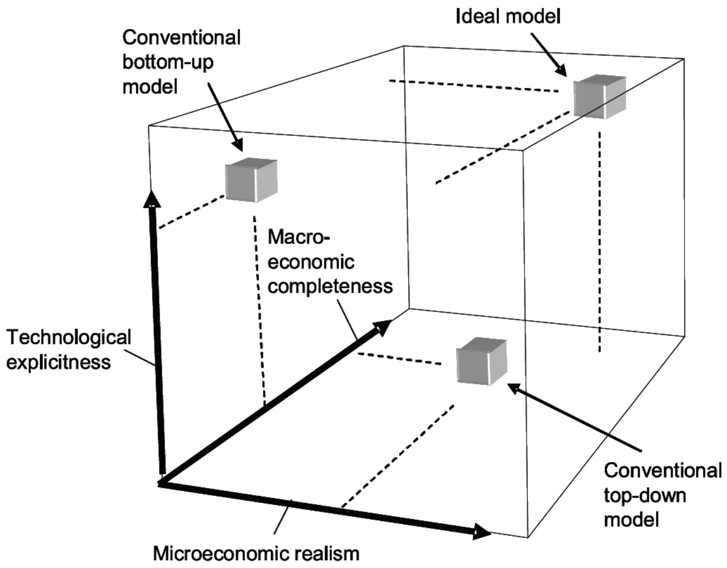


Figure 2. The three dimensions assessment of energy-economic models [21]

Conventional bottom-up models perform well in terms of technological explicitness but less well in terms of the other two attributes. On the contrary, conventional top-down models perform well in terms of macro-economic completeness and general micro-economic realism but they fail in technological explicitness. There is a tendency of creating a better model that will fulfil all three attributes. A number of researchers are working on new „hybrid“ models that will overcome limitations of existing ones [21].

In this thesis, bottom-up approach is selected. In creating a 100% renewable energy transition, bottom-up approach is considered to be the most appropriate methodology which will describe the impact of both technical and economic mechanisms. Moreover, bottom-up models are suitable to show decoupling of economic growth and energy demand [23].

However, bottom-up approach in this thesis does not refer on collecting data but it should be rather seen as a way of creating an entire energy system starting from energy system planning at local level area size. Local areas were defined according to the nomenclature of territorial units for statistics (NUTS) on NUTS III regions (Further elaborate in the *Section 1.2*).

Therefore, according to the Figure 1., components should be seen as local energy systems at NUTS III level with an aggregation path towards NUTS I, over the NUTS II whose aggregation will at the end complete energy system of EU.

1.2. Nomenclature of territorial units for statistics

The Nomenclature of territorial units for statistics is a hierarchical system for dividing up the economic territory of the European Union. The current classification is valid from 01 January 2015 and lists 98 regions at NUTS I, 276 regions at NUTS II and 1,342 regions at NUTS III level [24]. Classification was established in 1988 but, it was encoded into formal Regulation of the European Parliament and the Council in 2003 [25].

The purpose of NUTS system is to:

- Collect, develop and harmonize EU's regional statistics
- Create socio-economic analyses of the regions
- Create the framing of EU regional policies

Division of the territory is based on the three main principles:

1) Hierarchical levels

The classification is made according to the population. Three levels of NUTS system are defined with the minimum and maximum population thresholds. Each Member Country is divided into NUTS I regions, which are further divided into NUTS II and NUTS III in the previously explained way. Each of these regions is allocated a specific code and name. There are some exceptions in code names because some regions appear at more than one level. In such cases, the codes end in zero for a region with an identical territory at the next lower level.

Table 1. Minimum and maximum population thresholds for the size of the NUTS regions [25]

Level	Minimum	Maximum
NUTS I	3 million	7 million
NUTS II	800,000	3 million
NUTS III	150,000	800,000

1) Existing administrative units

NUTS classification is based on the existing administrative units within the Member states. Such classification is made for a practical reason which is the existence of administrative structures that can provide data and easier implementation of policy measures, although some exceptions can be found in cases of non-existing administrative unit for a given level. Therefore, NUTS regions are created by aggregating smaller administrative units to the higher level taking into account geographical, socio-economic, historical, cultural, and environmental circumstances.

2) Deviations of classification according to the population of regions

For non-administrative units, deviations exist for particular geographical, socio-economic, historical, cultural or environmental circumstances, especially for islands and outermost regions.

3) Lower levels of NUTS

NUTS III are divided into a more detailed level called Local Administrative Units' (LAUs) which exists in two levels LAU I and LAU II.

The NUTS nomenclature applies only on the 28 Member States of the EU, while countries that do not belong to the EU but are either:

- Candidate countries awaiting accession to the EU
- Potential candidate countries or
- Countries that are part of the European Free Trade Association

are encoded in a way which resembles the NUTS [24].

The republic of Croatia is, as a member of the EU, included in the NUTS classification. Croatia has all three levels of classifications. A country code at a NUTS I for Croatia is HR0. Croatia is further divided into two regions at NUTS II level and 21 counties at NUTS III level. Regions are created according to the geographical characteristic while counties have an administrative background. The NUTS codes are as follows:

- HR04 Continental Croatia
    - HR041 City of Zagreb
    - HR042 County of Zagreb
    - HR043 County of Krapina-Zagorje
    - HR044 County of Varaždin
    - HR045 County of Koprivnica-Križevci
    - HR046 County of Međimurje
    - HR047 County of Bjelovar-Bilogora
    - HR048 County of Virovitica-Podravina
    - HR049 County of Požega-Slavonia
    - HR04A County of Brod-Posavina
    - HR04B County of Osijek-Baranja
    - HR04C County of Vukovar-Srijem
    - HR04D County of Karlovac
    - HR04E County of Sisak-Moslavina
- HR03 Adriatic Croatia
    - HR031 County of Primorje-Gorski Kotar
    - HR032 County of Lika-Senj
    - HR033 County of Zadar
    - HR034 County of Šibenik-Knin
    - HR035 County of Split-Dalmatia
    - HR036 County of Istria
    - HR037 County of Dubrovnik-Neretva

Below the NUTS levels, there are two LAU levels:

- LAU-1: none (same as NUTS-3)
- LAU-2: Cities and municipalities [26]

Figure 3. NUTS III regions of the Republic of Croatia [24]

1.3. Holistic approach

Considering more than one renewable energy technology increases the complexity of the system in a non-linear way. Therefore, a holistic approach was used in the system modelling to show that the combination of more technologies is not a simple sum of the weights of each individual technology.

Including all sectors represents a shift in the energy system planning from sectoral to holistic approach. Holistic approach enables detection of synergies between various sectors and areas and emphasize benefits of such interconnections. Merging electricity, heating, and transport sectors allows higher penetration of IRES [2].

Considering transport sector in a transition towards 100% RES is making it even more demanding because there is no simple solution for such transition [27]. D. Connolly *et al.* [27]

in their research emphasized that electricity is not suitable for all modes of transport and therefore other, energy dense fuels are needed.

Also, they [27] highlighted that biofuels are likely to be unsustainable in the context of 100% RES. In this thesis, the selection of energy dense fuel that can be used as replacement to fossil fuels was limited on electrofuels produced with co-electrolysis. That was because they do not require any direct bioenergy input. However, there are different types and pathways of electrofuels that do include biomass input at certain extent. Production pathway combines carbon dioxide and water in the same process where the product is synthesis gas (syngas). Produced syngas can be converted to many different fuels depending on the end-use. Here, considered electrofuels are methanol and dimethyl ether (DME), both produced with co-electrolysis. Carbon dioxide can be obtained in two different ways by using either carbon capture and recovery (CCR) or air capturing [27]. CCR represents capturing CO_2 from stationary energy or industry related sources. Second technology enables capturing CO_2 emissions which are either in the motion or whose concentration is too low for using CCR. Moreover, it can even capture the accumulated CO_2 emissions from the atmosphere. Both processes are presented in Figure 4. and Figure 5.

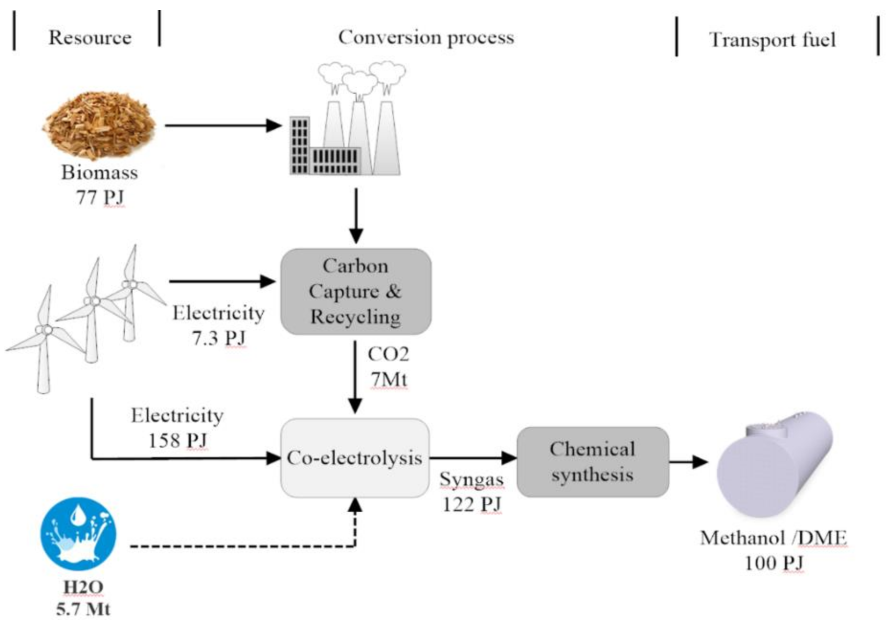


Figure 4. Co- electrolysis using CCR to methanol/DME [28]

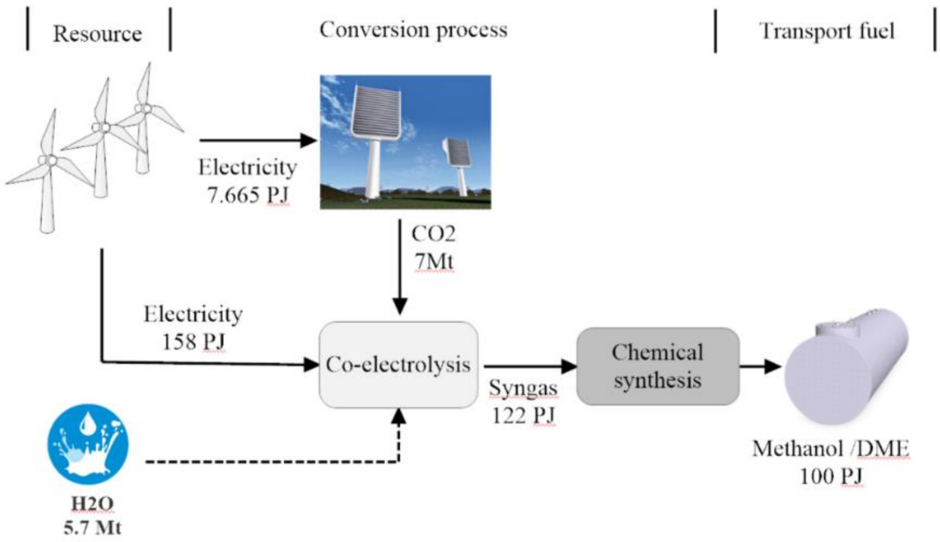


Figure 5. Co- electrolysis using air capturing to methanol/DME [28]

The CCR technology is widely investigated, even though it is not utilized on a large scale. On the other hand, air capturing, as an idea, dates back to 1940s but it is seen mostly as a future technology. Technologies for CO_2 capturing differ in price and energy demand. Air capturing requires approximately 5% more energy for extraction of carbon dioxide and this is not significant from a system perspective. In total process, electricity requirements for CO_2 capturing accounts for 4.6% and 4.9% in total electricity consumption, for CCR and air capturing respectively [28].

Process of co-electrolysis is performed by using the solid oxide electrolysers cell (SOEC). The SOEC, compared to the other electrolysers, alkaline and polymer membrane, has higher efficiency and it is the only electrolyser that is capable of electrolysing carbon dioxide and conducting a combined water and CO_2 electrolysis [28].

2. METHODS

This section presents the key principles of the methods for the bottom-up energy planning of the local area used in this thesis. Basic concept for the methods can be found in the paper [29] where three components of bottom-up models, energy demand forecasting, renewable energy resource assessments and whole energy system optimization are presented. Due to the size of the area that was assessed in the thesis methods were made as a combination of primary energy planning and secondary energy planning models. Primary energy planning models are used for national, regional and urban level, while secondary energy planning models are used for community, village and neighbourhood buildings [29]. Methods proposed for this thesis consist of four main steps. General approach can be applied to systems of different size and complexity. Steps of the methods are following:

1) Mapping the needs
2) Mapping the resources
3) Modelling scenarios
4) Analysing scenarios

Energy demand, available energy resources and energy conversion technologies are linked by the first and second laws of thermodynamics to meet the thermodynamic balance. Additionally, economic and environmental constraints were taken into consideration. A framework of the modelling process is illustrated in Figure 6.

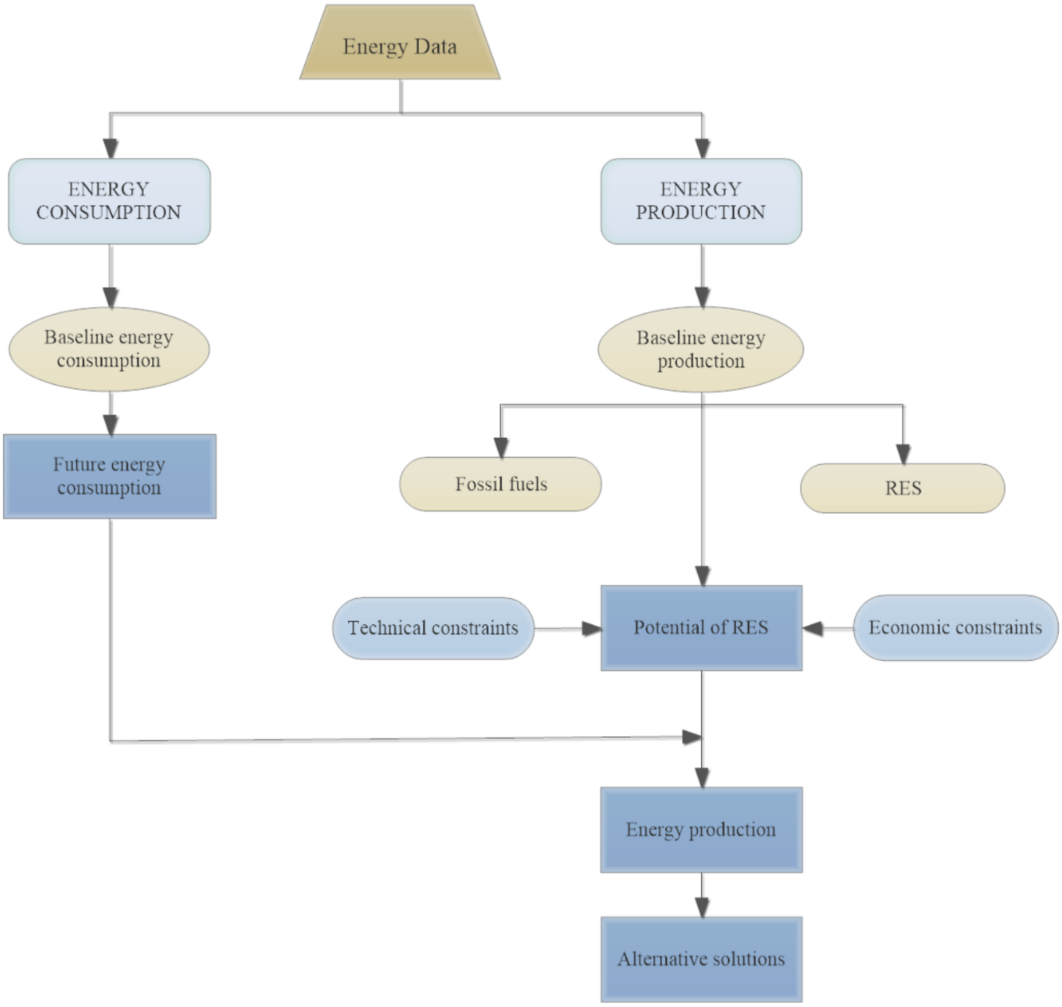


Figure 6. Framework of the process for energy system modelling

2.1. Mapping the needs

The needs are commodities that the local community demands. For the purpose of this thesis, needs represent exclusively energy consumption. Energy consumption consists of electricity, heating, cooling and the fuel load. Other commodities which are also dependent on energy supply, such as a need for drinking water, waste treatment, wastewater treatment and similar were not taken into consideration due to their low share in final energy consumption. Energy consumption was divided among sectors: industry, transport, and *other sectors* – which consist of households, services, agriculture, and construction. The needs are presented in a way of baseline scenario.

2.2. Mapping the resources

The resources taken into consideration for mapping the potential were only resources available at the local area, where only renewable energy resources were assessed. The main criterion for calculating an energy resource potential was an available amount of specific resource but also technological maturity and availability of technical and economic data for their evaluation. A special emphasize was given to the analysis of biomass potential and later of biomass production. It was important to keep biomass utilization on the sustainable level to achieve sustainability of the entire system. Potential of renewable energy sources was compared with existing studies and already created plans for renewable energy source implementation. A comparison was carried out in order to estimate the maximum possible quantities of energy from renewable energy sources that can be produced in the studied area considering constraints and factors specific to the area. Such constraints were environmental, socio-economic or technical.

2.3. Modelling scenarios

The concept of the smart energy system was adopted for this thesis. Starting point in scenario modelling was the analysis of the energy consumption for baseline year. Baseline scenario was calculated as a part of Mapping the needs step. On the demand, side two scenarios were calculated. Besides 100% RES, business-as-usual scenario was also developed. The BAU scenario was used as a benchmark to assess the impact of the measures in the 100% RES scenario. It assumes an increase in energy consumption in line with market trends and consumer habits without the systematic implementation of energy efficiency measures but with expected improvements in technologies for energy production, conversion, and storage. On the other hand, the 100% RES scenario is a scenario with implemented all possible efficiency measures, improvements in technologies as well as a decrease in energy demand due to sectoral interconnection (industry, transport, *other sectors* – where possible) and interconnection between different energy forms (electricity, heat, cold, transport fuel). Long-range energy planning brings many uncertainties of energy demand. Many external factors that are difficult to predict have an effect on energy demand. Such as population, building area, building performance, and weather conditions. In order to make planning schemes and targets effective it is vital to calculate reliable energy demand scenario [29]. Scenarios represented energy balances on annual time steps.

Within the 100% RES scenario along with the main solution for sustainable transition in transport sector, other alternatives were proposed. They were proposed for the part of the transport that could not be electrified or shifted to different transportation modes. One alternative solution had not follow a principle of 100% RES but therefore it fulfilled a principle of net zero carbon energy system. Proposed solutions were:

1) Electrofuels production
2) Electrofuels import
3) Fossil fuels import/consumption

Net zero carbon energy system or shorter carbon neutrality refers to achieving net zero carbon emission of the specific system or organization by balancing their CO_2 release with reduction of CO_2 emission elsewhere [30, 31].

The first step in scenario modelling is logical analysation of wide range of possibilities, both from resources and technologies, in order to come out with the best possible solution. Scenarios were firstly created in the Microsoft Excel spreadsheet. Afterwards, results were modified for the use in the LEAP software tool. Both results were combined and presented in integrated way as total amounts or in a way of either graphs or pie charts.

2.4. Analysing scenarios

Analysis of the scenario was done in the last step as a part of *Results and discussion* section. On the demand side scenario of 100% RES was compared with both, baseline and a BAU scenario. Economic costs were discussed from theoretical point of view showing the prices of specific technologies.

2.5. LEAP software tool

The Long-range Energy Alternatives Planning system is a scenario-based software tool for energy-environmental modelling developed at the Stockholm Environment Institute. Software can be used to track energy consumption, production and resource extraction in all sectors of an economy. It can also track greenhouse gas emission sources and sinks for both; energy and non-energy sectors. Flexible data structure, ease-of-use and possibility of presenting complex energy analysis concepts in a transparent way makes software used worldwide. LEAP is used in more than 190 countries in thousands of organizations [32]. Its users range from a different level of expertise: from leading global experts, consulting companies, energy utilities, government agencies, to academics and non-governmental organization. Furthermore, it is applicable at many different scales ranging from cities and states to national, regional and global applications.

LEAP is a tool used to create different energy systems with a variety of modelling methodologies on both demand and supply side. On the demand side, methodologies can range from bottom-up, end-use accounting techniques to top-down macroeconomic modelling while on the supply side, they range from accounting, and simulation to optimization methodologies.

As its name suggests, LEAP is a long-term modelling tool but it can be also used for medium time horizon. Usually, it is used for a period of 20 to 50 years. Calculations occur mostly on an annual time-step and some results can be split into finer „time-slices“ such as seasons, types of days or even times of day [32].

LEAP uses the concept of scenario analysis for evaluating and comparing energy systems. Scenarios represent modes of how an energy system might evolve over time. A comparison can be done for energy requirements, social costs and environmental impacts of different scenarios. Unlike macroeconomic models, the LEAP does not attempt to estimate the impact of energy policies on employment or gross domestic product (GDP). However, it is possible to integrate such models into LEAP. It can identify least-cost scenarios but it cannot generate an optimum or market-equilibrium scenario. An advantage of the LEAP is that it can assess interconnection among multiple policies and measures. Benefits of a combination of policies and measures might be different than a simple sum of the benefits considered separately. With the LEAP, it is possible to examine a different project, programs, technologies and other energy initiatives in order to find the best strategies for solving energy and environmental problems [33]. Another benefit is low initial data requirements. A user can decide on the complexity of the particular system or part of the system, based on the available data and an aim of the research. [32].

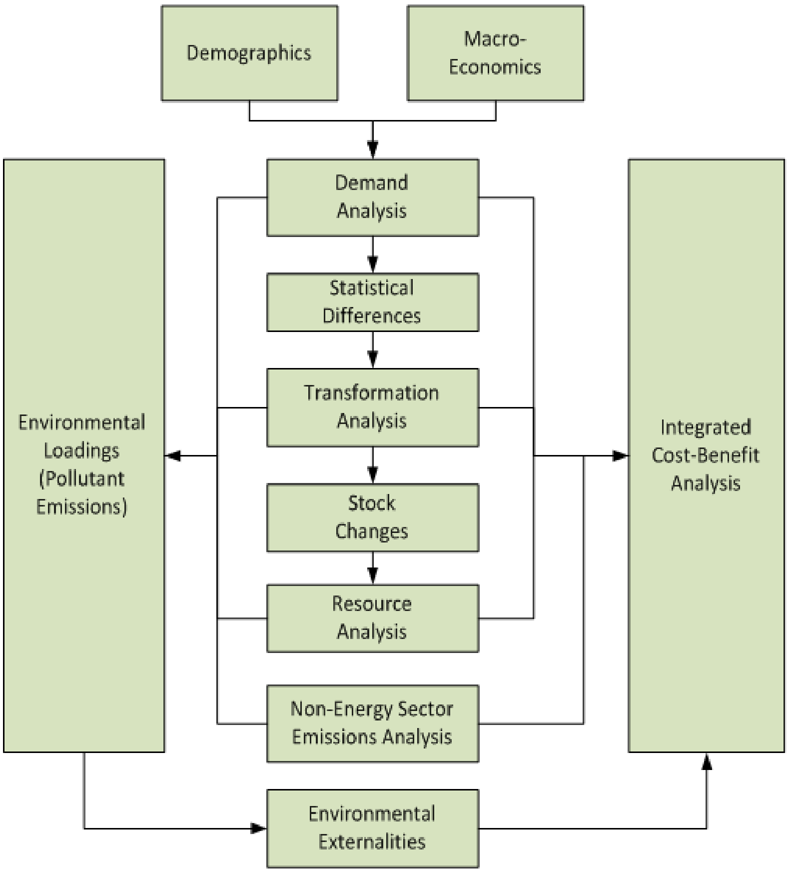


Figure 7. The Structure of LEAP's Calculations [25]

LEAP has been selected for this thesis because it is using the bottom-up approach for energy system modelling and it is appropriate for use on the local area level.

3. COLLECTING AND ANALYSING INPUT DATA

Bottom-up analysis of local energy system was presented as an example of case study for Dubrovnik-Neretva county. Following section presents Dubrovnik-Neretva region and describes in detail the process of collecting and calculating initial data needed for creating scenarios. Initial data were baseline energy consumption and amount of the available resources at the local area. Procedure of calculating, both, resources and baseline energy consumption was not elaborated as a part of methods since it is specific for the local area. Even though it can be applied for areas with the same or similar conditions and availability of data. In order to create representative and repeatable method general steps, presented in *Section 2 Methods,* were separated from specific ones presented in the following section (*Section 3 Collecting and analysing input data)*

3.1. Description and overview of Dubrovnik-Neretva county

3.1.1. General information

The Dubrovnik-Neretva county is the southernmost county of the Republic of Croatia. The total area accounts for 9,272.37 km^2 of which only 20% represents a land area with a surface of 1,782.49 km^2 while the remaining 80% or 7,489. 88 km^2 belongs to the sea area. The land represents only 3.15 % of the overall land territory of the Republic of Croatia. The length of the regional coastline is 1,024.63 km. The County consists of two basic geographic and functional regions: southern Dubrovnik part with closer islands (most notably Korčula, Mljet, Lastovo and the Elaphiti Island group) and the Pelješac peninsula and the northern Neretva region with its gravitating coastal zone. The Region is divided by the state border line with Bosnia and Herzegovina (B&H). The county has border lines with three neighbouring countries and one other Croatian county Split-Dalmatia. With countries Bosnia and Herzegovina and, Montenegro the county is sharing land border whilst with Italy, it is connected exclusively with sea border. The total length of the border is 561.66 km, out of which189.56 km belongs to the land border. County is territorially organized into 22 units of local government and self-government with 5 cities and 17 municipalities [34]. The regional centre is the City of Dubrovnik. Dubrovnik-Neretva county and its city and municipal centres are presented in Figure 8.

In NUTS classification system Dubrovnik-Neretva County belongs to the NUTS III classification level. It is coded as HR037 and is part of bigger NUTS II region Adriatic Croatia. As the previously stated county has land borders with three different territories. In terms of NUTS classification these are:

1) Split-Dalmatia County at North-West. Region belongs to the NUTS III classification of Croatia and it is also part of NUTS II Adriatic Croatia region
2) Bosnia and Herzegovina at North-East. potential candidate country for the EU
3) Montenegro, at South-East: candidate country for the EU

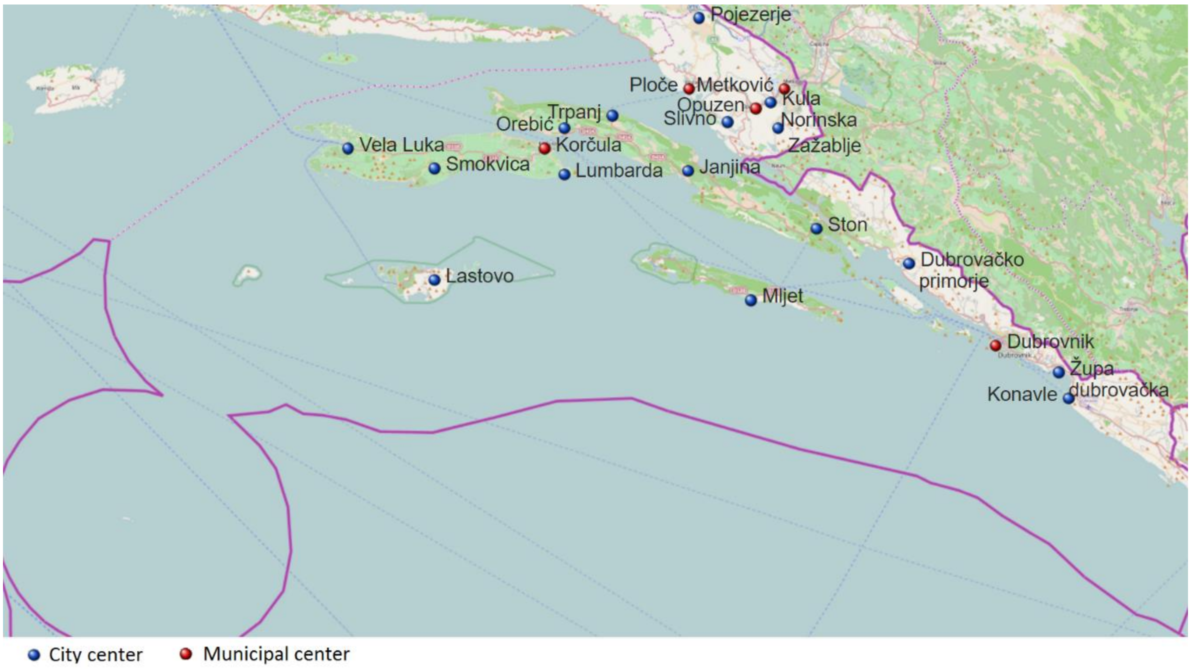


Figure 8. City and municipal centres of Dubrovnik-Neretva county [35]

3.1.2. Demographic data

According to the last population census from 2011, the county has a total population of 122,568 inhabitants. The average population density is 68.82 inhabitants per km2 and it is lower than the country average which is 75.71 inhabitants per km2 [36]. Compared to the 2001 census, the county recorded a population decline of 0.2%. There are many causes of negative population movements. The most significant one is emigration [34]. Huge differences in population density exists within the county. According to the 2011 census more than half of the population, or

78,455 inhabitants lived in only five cities (64.0% of total population of the county) while the remaining 17 municipalities had 44,113 inhabitants (36% of total population of the county). A number of permanently occupied dwellings in the county is 40,605 and the average number of residents per household is 3.02, which is slightly above the national average of 2.86 residents per household [36].

3.1.3. Economy

Economic development is based on tertiary sector, while primary and secondary sector has lower significance in the overall economic growth. The main sectors of the economy of the region are hospitality industry, tourism, agriculture and maritime transport. Similarly, to the population, economic activity is unevenly distributed over the county. The main economic centres are cities led by the City of Dubrovnik. Microregion of the Neretva valley is mainly oriented to the agricultural activities, trade, and transport. The most important economic activities of Dubrovnik microregion are hospitality industry and tourism. Island of Korčula is oriented towards industry, namely agriculture, fisheries, transport and communication with highly represented shipbuilding industry.

Agricultural production is concentrated around the valley of Neretva river and the island of Korčula. County has significant opportunities for agriculture due to the variety of soil types, microclimates, and geographical location. It is possible to grow the most sensitive species of fruit trees such as citrus fruit, vegetables, and flowers in the open fields, top quality grape types, olives as well and special sorts of fish and shellfish.

Lately, investments in the field of renewable energy sources started to have a bigger impact on the overall economy. County has a potential for hydro, the sun, the wind, and biomass utilization. The increasing share of renewable energy sources is improving economy's competitiveness on the market, increasing energy system's sustainability and reducing the dependence on the import of energy.

Total gross domestic product in the year 2013 was 1.22 billion EUR, while GDP per capita was 9,969 EUR which is slightly below state average of 10,228 EUR [37].

3.1.4. Climate

The climate of the Dubrovnik-Neretva County has all the characteristics of the Mediterranean climate with climate variations that are the result of a high mountain barrier in the vicinity of the coast, an array of islands and the occasional continental influences. It has hot and dry summer with rainy and mild winter. Average annual temperature is 16.5 °C. During July and August temperatures can reach 34 °C while winter temperature rarely falls below 0°C, with the exception in the area exposed to strong wind – called bura. Annual mean precipitation has character of subtropical climate, with the most rainfall in late autumn and early winter with 200 mm/m^2 on an average for December. An average number of sunny days is 106-111 per year and cloudy 87 -101. The most frequent winds are:

- Jugo, south east: up to 30%
- Bura, north-east: up to 29%
- Maestral, north-west: up to 24%
- Levant, east: up to 15% [36]

3.1.5. Infrastructure

The county is located at the end of the Trans-European highway Central Europe-Slavonia-Bosnia and Herzegovina-Ploče, at the end of the international transport corridor VC (5C).

It is connected with the rest of the Croatia by the Adriatic tourist road D8. Highway connection ends in the City of Ploče. There are several approaches on how to finish the highway to the city of Dubrovnik. Road infrastructure is at an unsatisfactory state at some parts of the county. Besides that, the transport connection of the municipalities by the means of bus lines represents another problem that has to be solved [39].

In addition, to the possibilities in the road infrastructure, a maritime transport provides a great potential for further development and improvement of transport connections with the rest of the country but also within the county. County has two sea ports of international importance: Port Ploče and Port Gruž in Dubrovnik, 6 ports which are significant at the regional level, as well as 74 ports of local level relevance [38]. Railway lines connect county via Pan-European VC (5C) corridor with the rest of the Europe, while the Dubrovnik part of the county has no more railway connections [40, 41]. Railway line Metković-Ploče is exclusively used for cargo transport.

Air transport is the most important form of the transportation according to the number of the passengers travelled and due to the specific territorial isolation of the County. Airport is located in Čilipi and it accounts for over 60% of tourist arrivals to Dubrovnik with a significant annual increase in a number of passengers travelled per year [42].

3.1.6. Energy system

Territorial division affects the integrity of the power system. Dubrovnik-Neretva county is supplied from two distribution areas. Southern part of Dubrovnik, including peninsula Pelješac and all islands of the county belongs to the distribution area of Elektrojug Dubrovnik while smaller northern part of Neretva valley belongs to the distribution area of Elektrodalmacija Split [43].

Common for the both distribution area is that they use renewable energy sources for the electricity production. Furthermore, the main energy source is hydropower. Hydropower plants that belong to the distribution area of Elektrojug Dalmacija are hydroelectric power plant Dubrovnik and Zavrelje [44]. (Further elaborated in *Section 3.5.4 Hydro*). Currently, there is neither gas nor oil pipeline in the area even though, there is a proposal for building Ionian-Adriatic Pipeline that would go from Fier in Albania through Montenegro, and Bosnia and Herzegovina, to Split in Croatia. In Split, the pipeline would be connected with the existing gas transmission system of Croatia [45, 46]. Luka Ploče includes several terminals one of which is the liquid cargo terminal which includes an oil terminal [47].

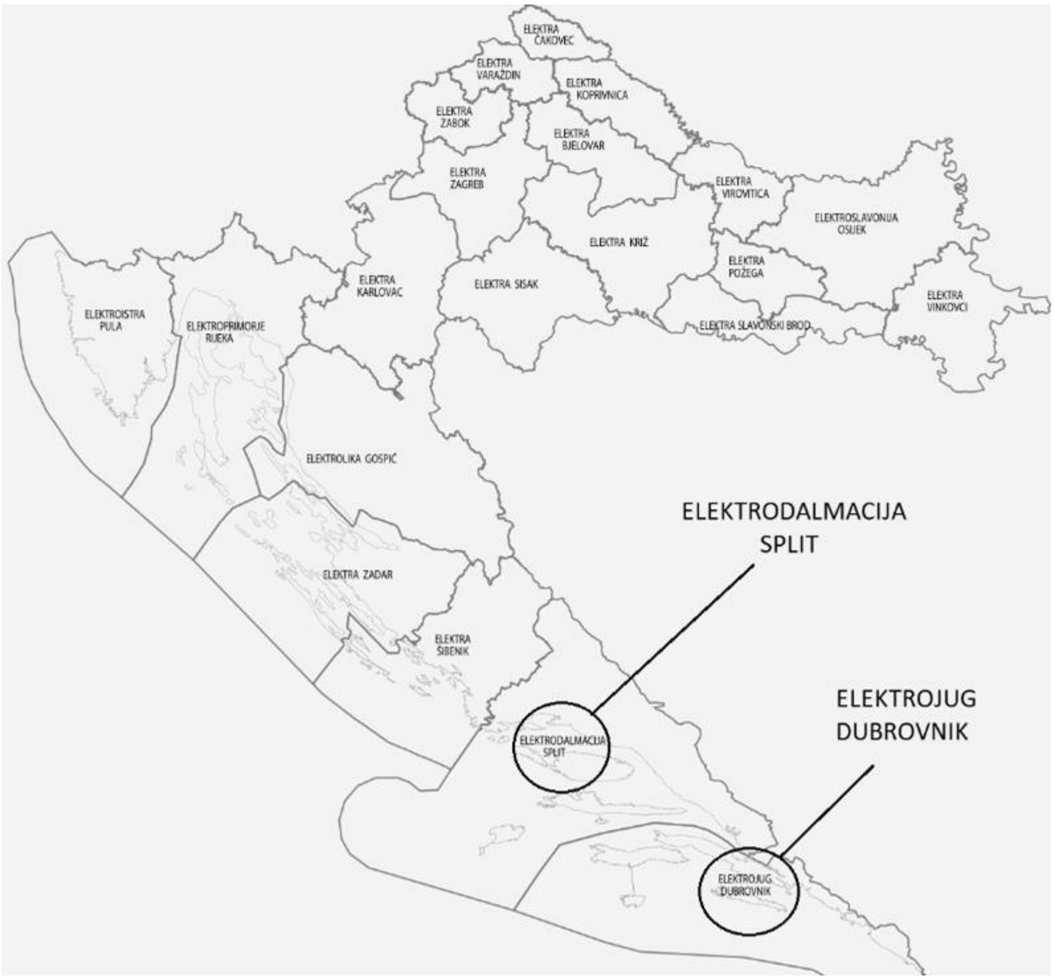


Figure 9. Distribution system regions of the Republic of Croatia [37]

3.2. Mapping the needs: Baseline scenario

Calculating energy consumption for baseline year was the initial step in the methods implementation. For the assessed area, there is no systematic database of energy consumption data. Availability of data was unsatisfactory to carry out classic bottom-up approach for data collection. Therefore, a various combination of references and methods were used for calculation. Baseline year was set to 2015 in order to capture the latest movements and trends in energy consumption. In the most of the cases data originated from the same year. Data that were not available for the year 2015 were either recalculated for 2015 or the value that originated from earlier years was accepted if there was no significant change in energy consumption over the years. Time range of energy consumption data for baseline year was from 2012 to 2015.

The main source used for calculating energy consumption in the baseline year was the Plan of the energy efficiency for energy consumption of Dubrovnik-Neretva county (later in the text: Plan of the energy efficiency) [38]. The plan is using sectors classification according to the report Energy in the Croatia. Consumption balance is made for industry, transport and *other sectors* where transport is further subdivided into road, rail, sea, and air transport while sector named *other sectors* is subdivided into households, services, construction, and agriculture [39]. Same division of sector was accepted in this thesis. In order to validate data from county level, several other publications were used. Those are Sustainable energy action plans made for following municipalities and cities: Municipality of Blato [40], Lastovo [41], Konavle [42], Mljet [43], Smokvica [44], Ston [45], Vela Luka [46], Župa dubrovačka [47] and City of Korčula [48] and Dubrovnik [49].

Final calculated energy consumption of Dubrovnik-Neretva county for the baseline year was 2,240.3 GWh. Comparing to the consumption of entire country that was 3.1% of total final energy consumption [39]. A sector that accounted for the highest share in the energy consumption was the transport sector with a share of 56.0%. Other shares in final energy consumption are presented in Figure 10.

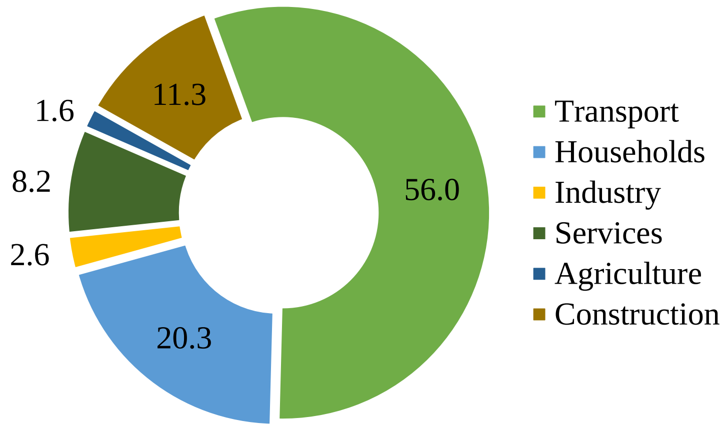


Figure 10. Shares in final energy consumption of all sectors [%]

On the country level, minor differences in shares of energy consumption exists. Sector that consumed the most energy was households, followed by transport. None of the sectors consumed more than 50% of energy, unless households, services, agriculture, and construction would be considered as a part of one sector - *other sectors*. According to the report [39] share of energy consumption was as follows: households 35.9%, transport 32.4%, industry 15.6%, services 10.8%, agriculture 3.7% and construction 1.6 %. A difference can appear because of several specificities of the area, especially when considering transport sector. Some of these specificities are large energy consumption from air transport in comparison to the area size, dispersed settlements (and cities) without sufficiently developed public transportation, seasonal tourist influx, transport of goods. Apart from transport there was a small influence of industry sector and a big influence of services sector, especially tourism. Energy consumption per subsector in *other sectors* and type of fuel is given in the Table 2. and Table 3**.**

Table 2. Calculated final energy consumption per subsector in *other sectors* for the year 2015

Sector	Final energy consumption [GWh]	Share [%]
Households	454.4	49.0
Services	184.1	19.8
Agriculture	36.4	3.9
Construction	252.9	27.3
TOTAL	927.8	100.0

Table 3. Calculated final energy consumption per type of energy in *other sectors* for the year 2015

Type of energy	Final energy consumption [GWh]	Share [%]
Electricity	487.0	52.5
Fuel oil	87.8	9.5
LPG	46.4	5.0
Biomass	148.3	16.0
Solar thermal	0.6	0.1
Diesel	151.7	16.3
Gasoline	6.1	0.7
TOTAL	927.8	100.0

3.2.1. Industry

Data for energy consumption in industry sector were obtained from Plan of the energy efficiency [38] for the year 2012 and therefore needed to be recalculated for the year 2015. Energy consumption was extrapolated according to the annual increase of energy consumption on the country level [50]. Final energy consumption is:

$$E_{ind,2015} = \sum_{i=1}^{n} E_{ind,i,2015} \tag{1}$$

$$E_{ind,i,2015} = E_{ind,i,2012} \cdot \left(1 + x_{ind,CRO}\right)^{2015-2012} \tag{2}$$

Where i represents specific type of energy in the county and $x_{ind,CRO}$ is annual increase of energy consumption in the industry sector at the Croatian level [50].

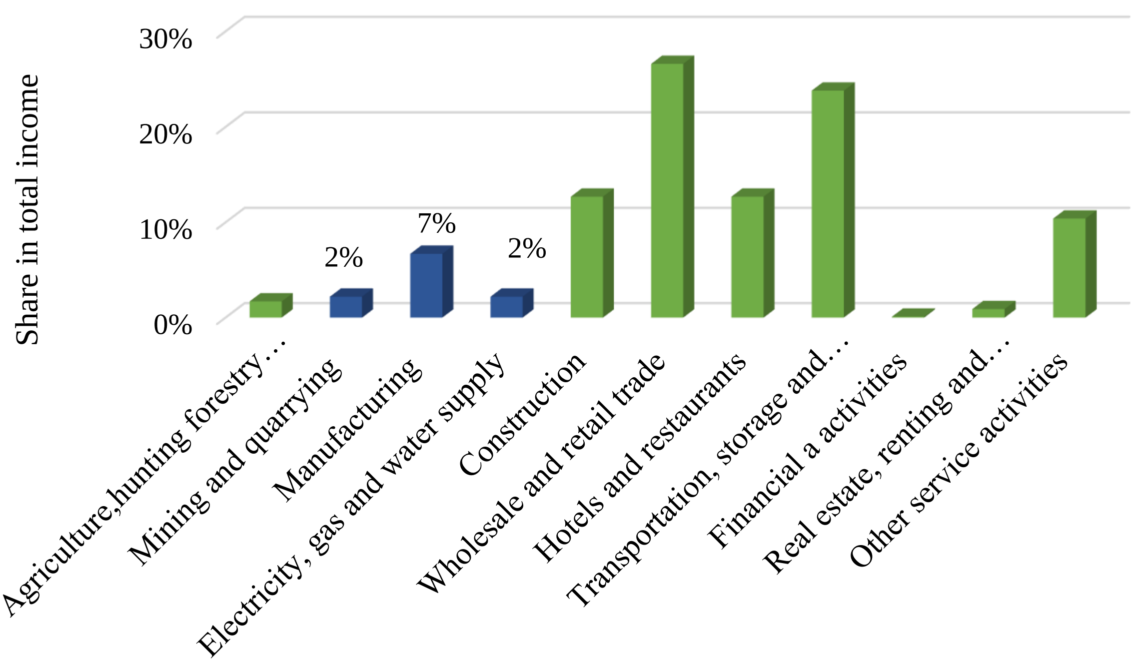


Figure 11. Shares per sectors in total income of Dubrovnik-Neretva county [50]

In general, industry has no significant impact in Dubrovnik-Neretva county neither from an economic point of view nor from an aspect of energy consumption. If mining and quarrying, manufacturing, electricity, gas, and water supply are considered to be part of industry sector, then their share in total income is approximately 11% [36].

Energy consumption in the industry sector was 58.6 GWh. An industry is based on fossil fuel consumption with share of 69.07%. Fossil fuels used in the industry sector are fuel oil, diesel and liquefied petroleum gas (LPG).

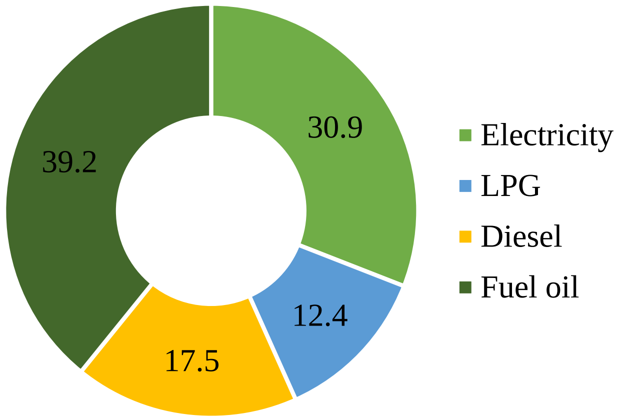
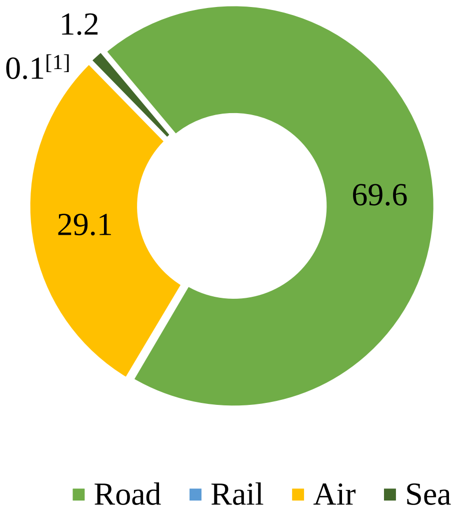


Figure 12. Shares in final energy consumption per type of energy in industry sector; 2015 [%]

3.3. Transport

Transport sector is subdivided into road, rail, sea, and air transport where road transport accounts for the highest consumption rate. Except for the rail, the transport sector is highly dependent on intensive use of fossil fuels. Final energy consumption of transport sector was 1,253.9 GWh. Share of energy consumption per type of fuel and mean of transport can be seen in Figure 13.



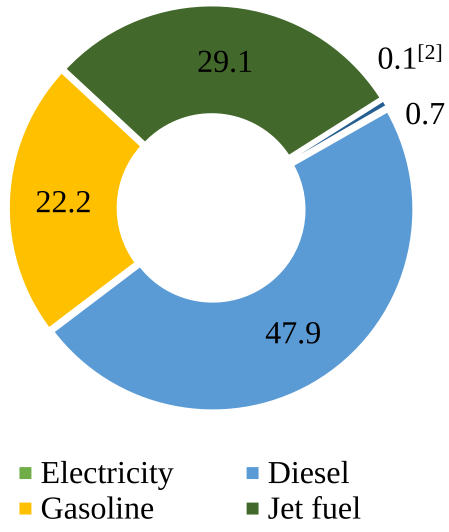


Figure 13. Share in final energy consumption per type of transport (left) and share per type of fuel (right) [%]

3.3.1. Road transport

Road transport of Dubrovnik-Neretva county includes public transportation and private and commercial vehicles. Public transport connections with bus lines are not satisfactory developed. Main reasons for such undeveloped public transportation are specificities of the area that are characterised mainly by dispersed settlements, lack of funding but also the habits of local population. Public transportation consists of busses and minibuses driven by diesel fuel. Public transport accounted for only 5.25% share of the final energy consumption in the road transport.

Private and commercial vehicles were subdivided into two-wheelers, passenger cars, light vehicles, heavy vehicles and private buses. Total number of registered vehicles for the year 2015 was 61,930, while number of vehicles by type of vehicle was [51, 52]:

- Two-wheelers: 8,795
- Passenger cars: 47,801
- Buses: 106 (buses for public transportation are excluded);

[1] *very low share in energy consumption for the rail transport (left) reduced transparency in the pie chart in Figure 13*
[2] *very low share in energy for electricity consumption(right) reduced transparency in the pie chart in Figure 13*

- Light vehicles: 4,251
- Heavy vehicles: 977

Data for the energy consumption of road transport originate from the year 2012 but are recalculated for 2015 in line with the increase of vehicle fleet by 5.51% [61].

3.3.2. Air transport

Dubrovnik airport is the third largest and the third most important airport in the Republic of Croatia, right after Zagreb and Split. The whole country has 9 airports where more than 70% of traffic takes place in the three largest ones [63]. Airport recorded for the continuous growth in the passenger traffic over the last years. The number of passengers who passed through the airport in the year 2015 was 1,679,176 [42]. There is a significant seasonal difference in the number of passengers, where summer season is very busy due to tourist arrivals. Statistics can be seen in Figure 15.

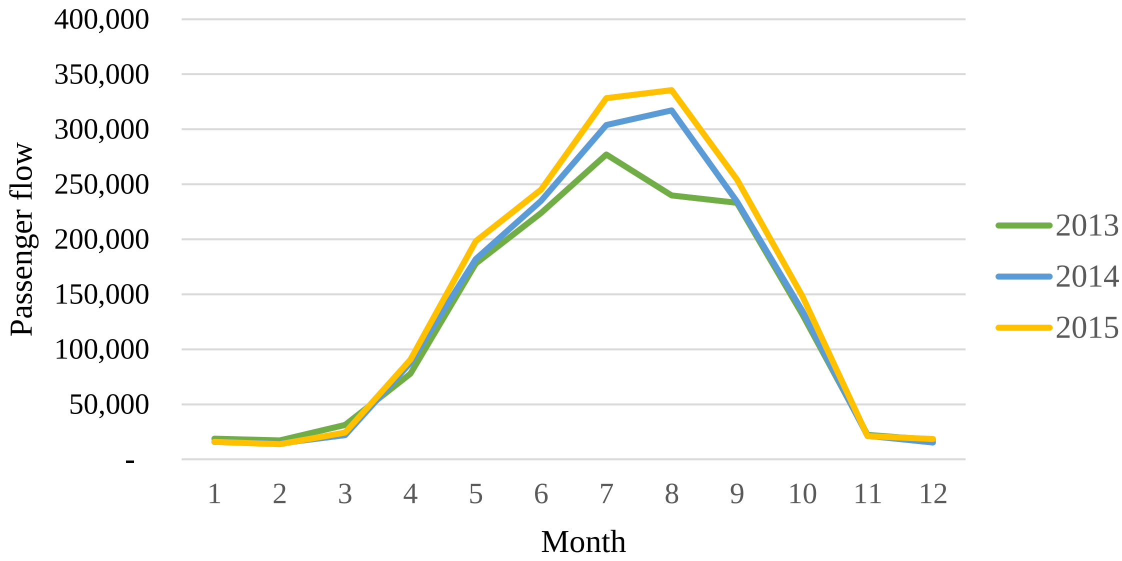


Figure 14. Passenger flow of Dubrovnik airport [53]

There are no any statistical data for energy consumption of air transport in the county, therefore a method for calculating energy consumption was defined. Data were scaled from the country level to the county level with the factor of the passenger number.

$$E_{air,DNC} = \frac{N_{DNC}}{N_{CRO}} \cdot E_{air,CRO} \quad (3)$$

Where $E_{air,DNC}$ is energy consumption of air transport at county level, N_{DNC} is number of passengers at county level, N_{CRO} is total number of passengers for the country and $E_{air,CRO}$ is energy consumption of air transport at country level.

Method may show an unrealistic picture of energy consumption of air transport at the county level but it is assumed that with their decision of choosing airplanes as a way of transport passengers are „carrying“ a part of fossil fuel emissions with themselves to the destination place. Cargo transport is not included in the modelling of consumption factor because of its very small share in total air traffic [53]. Energy consumption of air transport for the year 2015 was 365.1 GWh.

3.3.3. Sea transport

Energy consumption of the sea transport included company for local and international ferries Jadrolinija. Jadrolinija is operating at three local and one international line for which it is using seven ships [54]. Other means of sea transport were not taken into account in this thesis due to lack of data and general complexity of tracking energy consumption for entire sea transport. Nevertheless, it is recommended that the future research includes other means of sea transport especially cruise transport of Dubrovnik port and cargo transport of port Ploče. In the year 2014, the port of Dubrovnik was the second largest port according to the number of passengers while the port of Ploče was fifth according to the total traffic of goods [55, 56]. Fuel used in the sea transport is diesel fuel and its consumption for the year 2015 was 15.2 GWh. Consumption is overtaken from the report Plan of the energy efficiency where consumption was calculated for the year 2012. It is assumed that the consumption did not grow over the years due to the fact that number of passenger remained almost the same [54].

3.3.4. Rail transport

Although rail transport has a small impact on energy consumption, it is still important for the cargo transport because it connects Ploče harbour with international rail traffic route 5C [65].

Total length of the railway is 21.9 km and it operates only for cargo transport. A railway is entirely electrified at 25 kV, 50 Hz therefore, it consumes electrical energy except in special situations such as breakdown. Furthermore, switching operations at the railway station and the port rails of the port Ploče are performed by locomotives, which use exclusively diesel fuel. Data on fuel consumption was not available therefore that consumption is not taken into account. Consumption of electrical energy in the rail transport for the year 2015 was 1.2 GWh [66].

3.4. Other sectors

Sector named as *other sectors* consists of four subsectors: households, services, agriculture, and construction. The same classification is used in the report Plan of energy efficiency [38] and it is anticipated for this thesis. Final energy consumption of entire sector was 927.8 GWh. Shares of the calculated final energy consumption of certain sectors are presented in Figure 15.

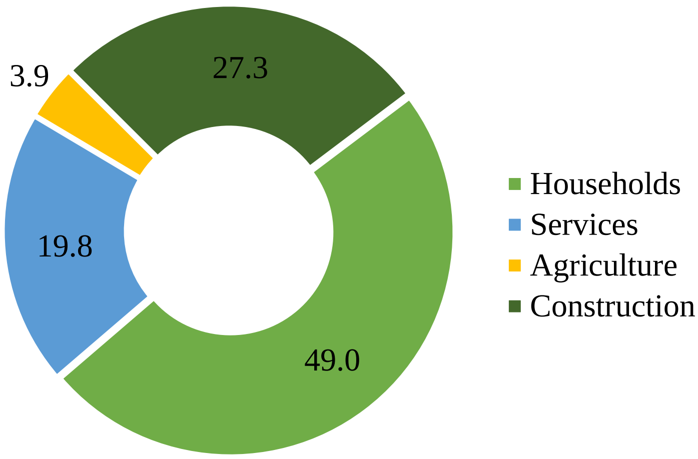


Figure 15. Shares in final energy consumption of *other sectors*; 2015 [%]

For the comparison, the shares of energy consumption in 2014 at country level for households was 69.03%, services 20.73%, agriculture 7.17% and construction 3.07%. The largest difference between county and country level is in the share of energy consumption for construction. This appeared because of the method used for calculating energy consumption in particular sector (Further elaborated in the following *Sections*: *3.4.1 Households, 3.4.2 Services, 3.4.3 Agriculture 3.4.4 Construction*).

3.4.1. Households

Final energy consumption of households in 2015 was 454.4 GWh where electrical energy had more than 50% share. Electrical energy is the most used energy source for several reasons, due to climate characteristic heat demand of the area is not very high and a lot of heat demand is met by electrical appliances. Furthermore, cooling demand is intense especially during summer season. Households sector provides many possibilities for improvements in the transition to a renewable energy system in particular when the transition takes place at the local level.

3.4.2. Services

Services sector has big contribution on the county's economy. In the overall service sector, tourism is the most important and it recorded a significant increase over the last years. In the baseline year number of tourist arrivals was 1,443,103 which is almost 12 times more than population of the whole county. More than 60% of tourist arrivals were in Dubrovnik. Tourist arrivals and overnight stay in period from 2004 to 2015 are presented in Figure 16 and Figure 17, respectively [63]. It is assumed that tourism will continue to grow in the following years, therefore new capacities will be built. Tourist arrivals had impact on the unevenly distribution of energy consumption during tourist-summer season and winter.

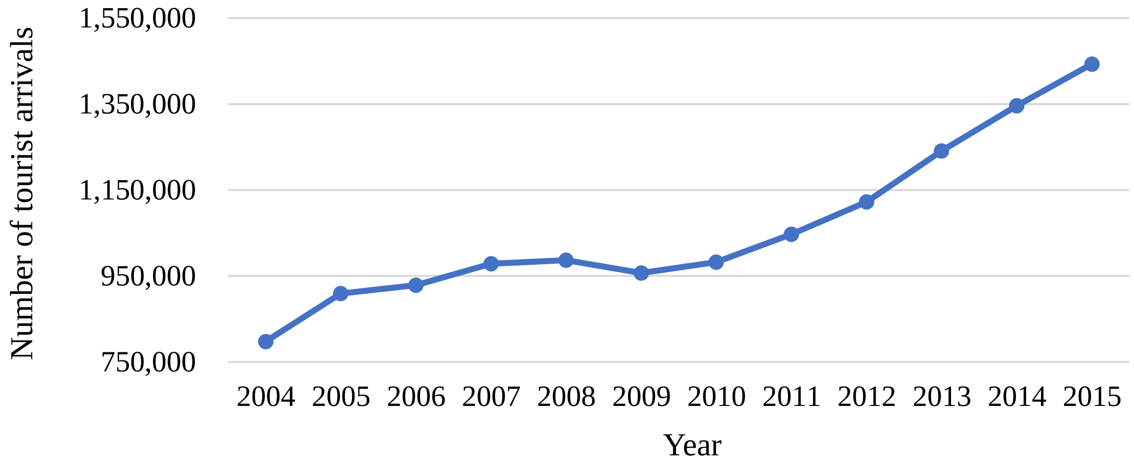


Figure 16. Tourist arrivals over the years [63]

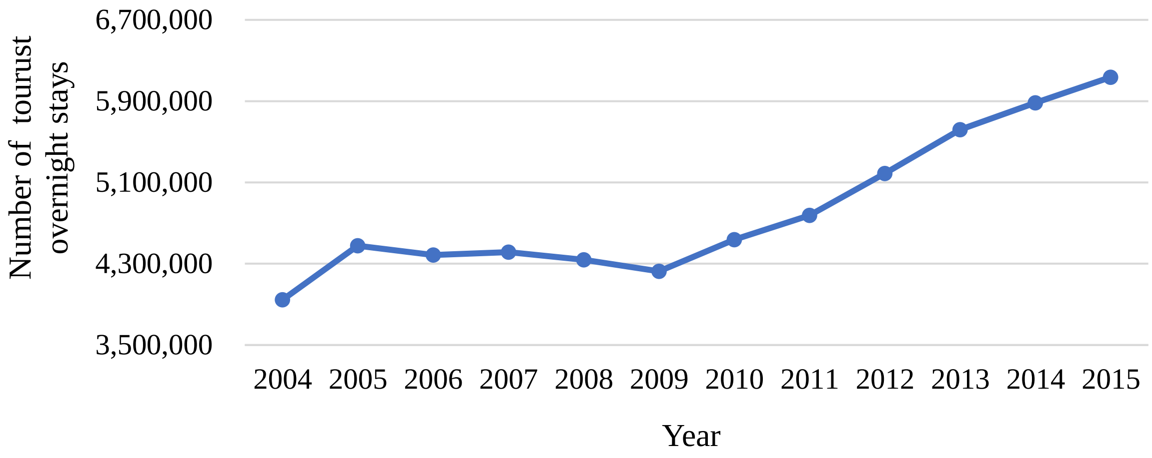


Figure 17. Tourist overnight stays over the years [63]

It is important to consider large and ever increasing number of tourist arrivals since they have an impact on peak consumptions, especially during summer. Energy consumption of sector was 184.1 GWh which is 19.84% of the final energy consumption of *other sectors*. This energy consumption may not seem correspondent with sector activity. The reason for that lies in the fact that tourism makes a significant part of a private rental accommodation. Therefore, such accommodations might be recorded as household rather than services because of lack of control in performing these activities.

3.4.3. Agriculture

According to the source of data [48] it is very interesting to note that 100% of the energy consumption in the agriculture sector was from fossil fuels, diesel, and LPG. Energy consumption in 2015 was 36.4 GWh. Even though, observing the entire agriculture sector and all consumer that can appear within the sector and comparing final energy consumption in the other counties it is likely to expect consumption of electricity [67].

3.4.4. Construction

It is observed that minor deficiency exists in data provided in the Plan of energy efficiency if they are compared with the energy consumption on the country level [39]. Therefore, energy consumption was calculated scaling from country level. In the Plan consumption of fossil fuel was not included. Energy consumption in the construction sector is not just limited to the energy used for the operation but at substantial amount is also used in construction activities, including manufacturing and operating construction vehicles and machines. Production of materials for construction was not taken into consideration here but energy consumption does include operating vehicles on construction sites. Energy consumption in 2015 was 252.9 GWh.

3.5. Mapping the resources

The main renewable energy resources in Dubrovnik-Neretva county are the wind, solar and hydro but there is also potential for installation of heat pumps with either sea or ground as a source. In addition to the above, there is a potential for biomass utilization and ground source heat pumps. Particular emphasis was put on analysis of available biomass potential and use of biomass in the selected territory in order to keep it on the sustainable level. Hydro potential of local and neighbouring regions for the energy production of Dubrovnik-Neretva county was already in use to a very high extent, although there is still potential for further exploitation.

3.5.1. Wind

Wind potential in Dubrovnik-Neretva county was estimated according to the existing studies [45, 46].

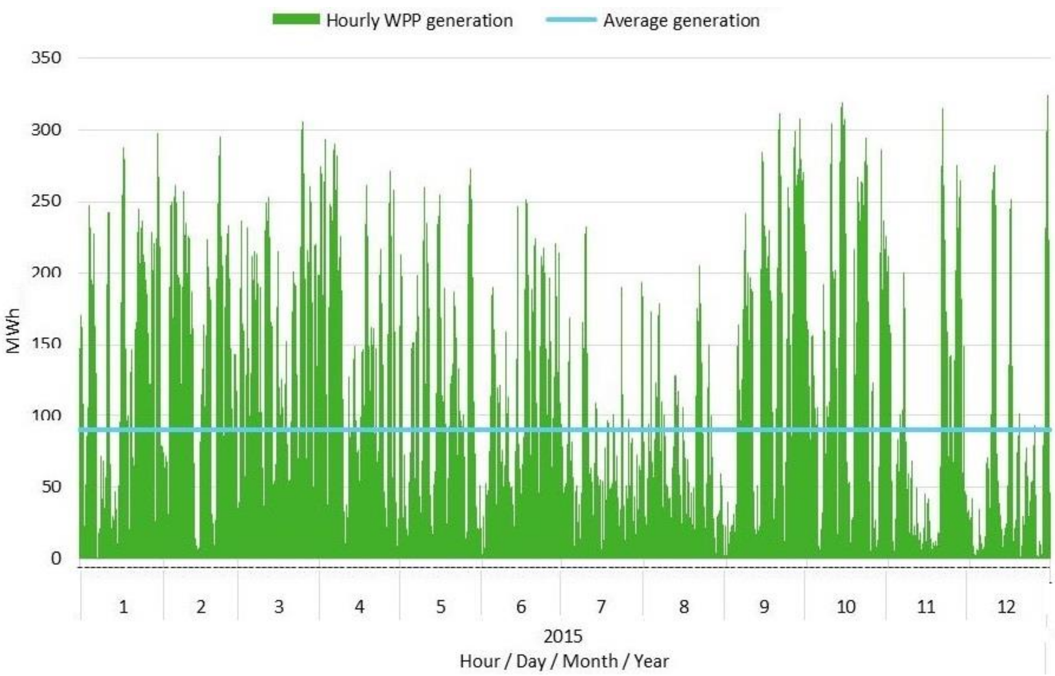


Figure 18. Hourly generation of all wind power plants [58]

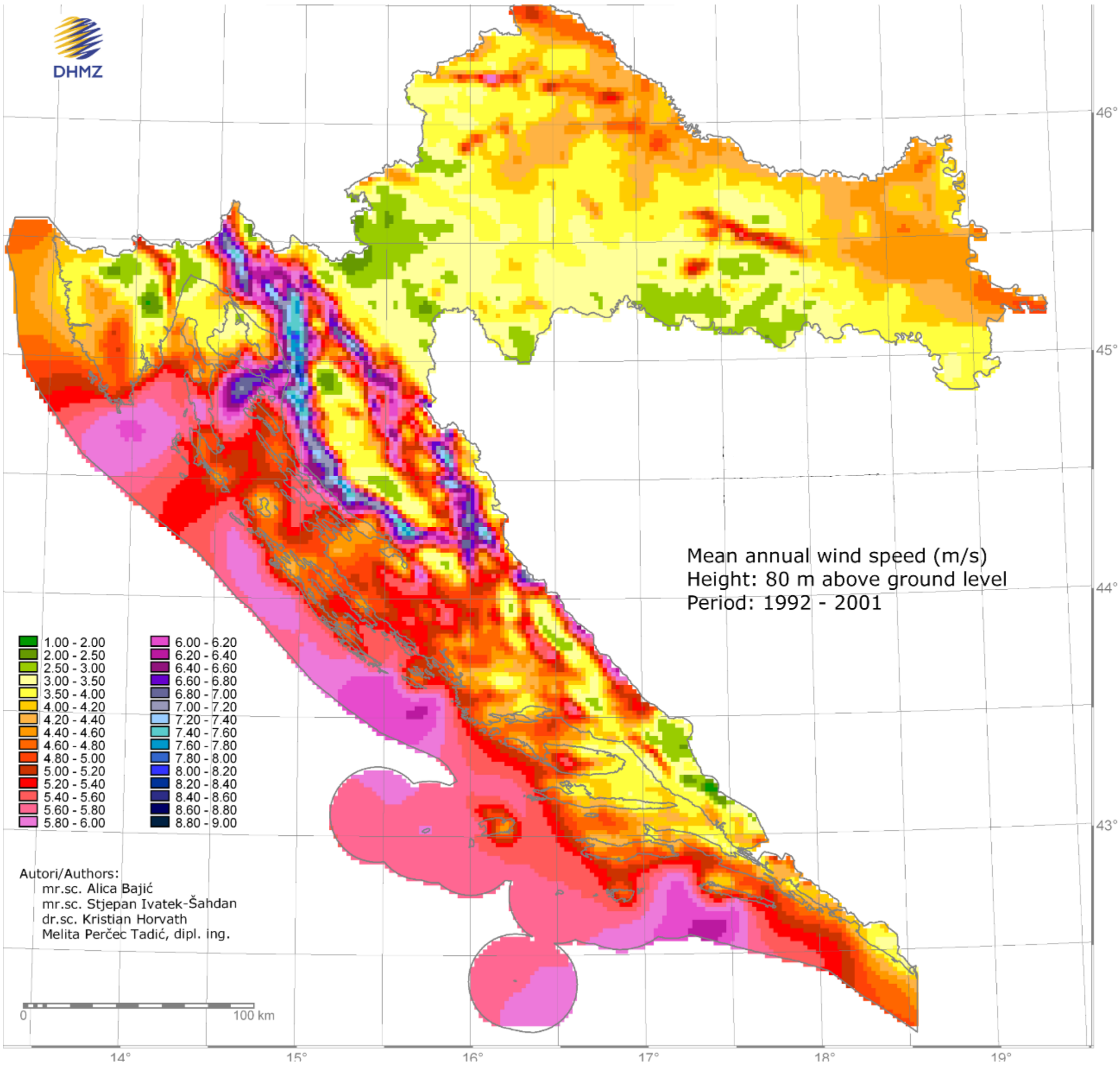


Figure 19. Distribution of mean wind speed in the Republic of Croatia [57]

Figure 19. shows the distribution of mean wind speed in the Republic of Croatia, it can be seen that location of area has favourable position regarding wind energy potential with mean annual speed of 4.5 m/s at 80 meters above sea level.

Hourly generation of all wind power plants in Croatia for year 2015 can be seen in Figure 18. [58].

In order to get the real potential and not just the theoretical values availability of sites were assessed using different criteria. Such assessment was possible due to already existing plans for the wind turbine installation [59, 60] and more detailed research on the sites [59].

Table 4. Locations, installed capacity and estimated yearly production of wind turbines [59]

Number	Location	Electrical capacity [MW]	Net AEP [GWh]
1	Dubrovačko primorje - Slano	70	190.76
2	Dubrovačko primorje - Slano	125	304.583
3	Konavle - Cavtat	120	345.488
4	Orebić	33	94.032
5	Ston	34	111.397
6	Dubrovačko primorje - Slano	57	196.072
7	Orebić	30	116.798
8	Kula Norinska	22	83.229
9	Pozla gora	20	68.558
10	Istočna plina	10	32.473
11	Čukovica	10	29.072
12	Vrtlog	20	63.297
13	Grabova gruda	20	55.323
14	Trštenovo	10	25.364
15	Štrbina	20	70.358
16	Trnova	10	33.45
17	Korčula	50	202.518
18	Lastovo	10	40.434
19	Mljet	20	83.74
TOTAL		691	2146.946
Wake losses - average [%]			4.4
Other losses (min 5% - max 10%) [%]			7.5
TOTAL (all losses included) [GWh]			1985.925

Calculated production of electricity from the wind for Dubrovnik-Neretva county was 1985.9 GWh including the capacity at islands where construction of wind turbines is currently prohibited [61]. Total area suitable for installation of wind power plants accounted 9.32% of the total land area of Dubrovnik-Neretva county. An area was estimated as a sum of total area evaluated as the most suitable and very suitable and 60% of area evaluated as relatively suitable [60].

Table 5. Suitability of area for wind turbine installation in Dubrovnik-Neretva county [60]

Range of suitability	Area size [*1000 m2]	Percentage of total area [%]
0 - not suitable	1,054,400	56.87
1 - the lowest range of suitability	304,260	16.41
2 - low suitability	315,980	17.04
3 - relatively suitable	112,530	6.07
4 - very suitable	50,260	2.71
5 - the most suitable area	16,570	0.89
TOTAL	1,854,000	100.00
Potentially suitable area	172,732	9.32

Dubrovnik-Neretva county has no promising offshore wind potential. An area with mean annual wind speed higher than 6 m/s is at the centre of offshore county area. It has a good wind potential but most of the area does not satisfy a condition of sufficiently small depth for wind farms with columns based on the seabed which are more commercialized at the moment. Only a small area between islands Lastovo and Mljet can be taken into consideration. Though that area is highly protected by Natura 2000 [62] and due to the small size considered, it is not feasible in comparison with onshore wind power plants.

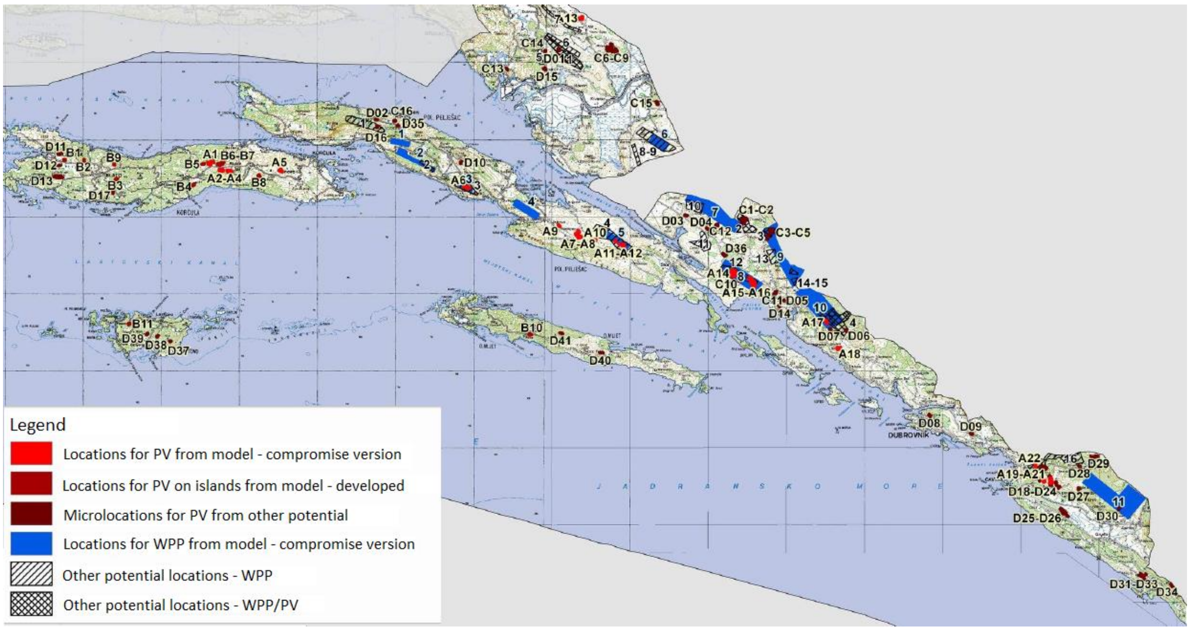


Figure 20. Potential locations for wind turbines installation [60]

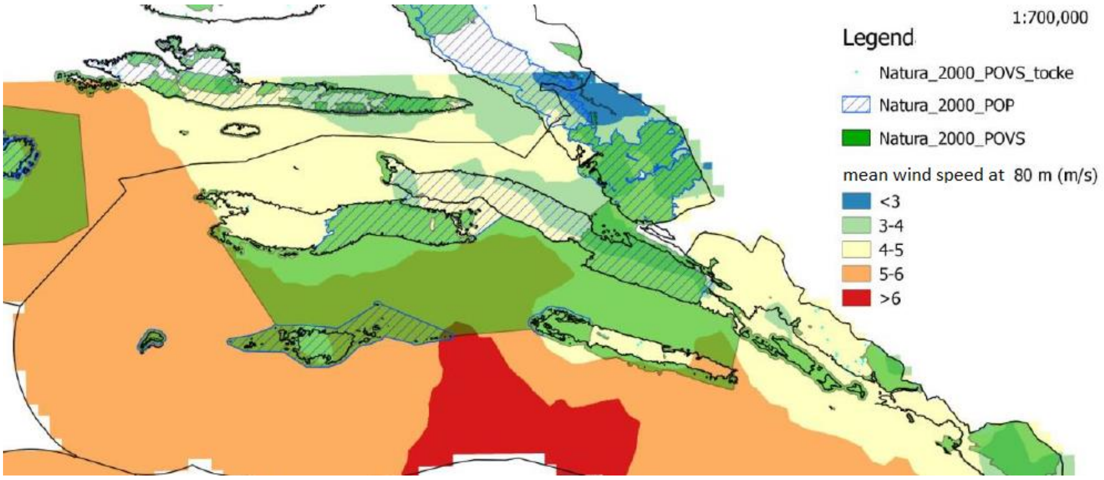


Figure 21. Mean wind speed and protected area by Natura 2000 in Dubrovnik-Neretva county [62]

3.5.2. Solar

Dubrovnik-Neretva county has one of the highest solar potentials in the republic of Croatia with annual mean solar insolation of the horizontal plane of more than 1,500 kWh/m2 [74].

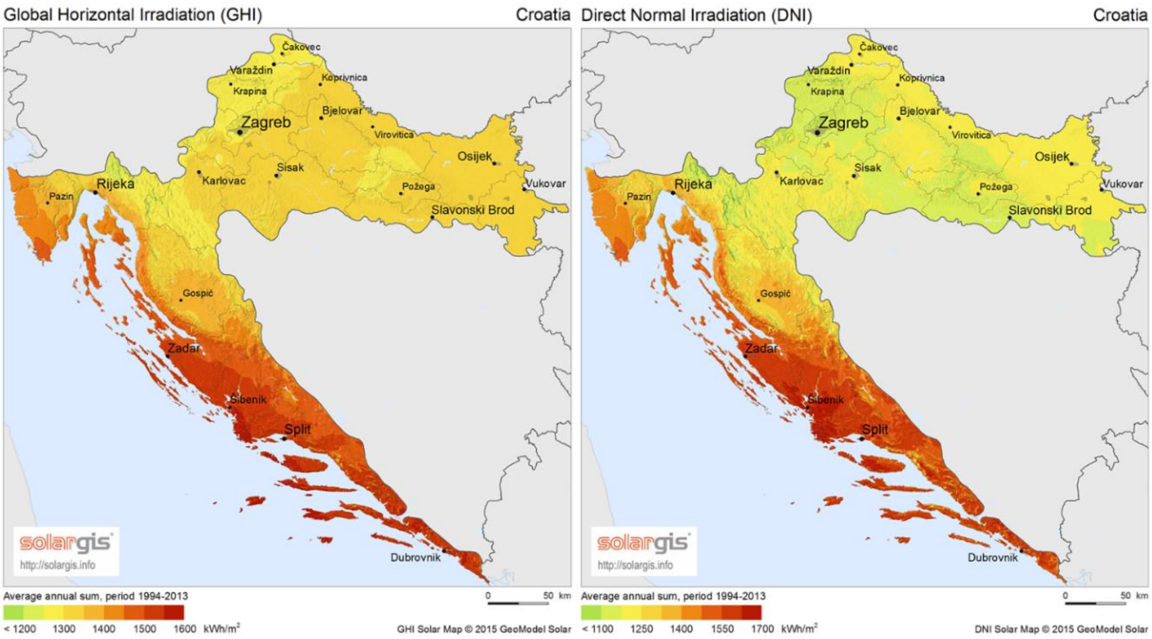


Figure 22. Annual mean solar insolation of the horizontal plane [63]

Solar radiation curves for photovoltaic (PV) modules and Solar Thermal systems are obtained from [64]. Curves are made based on the data obtained from Meteonorm simulation software for three locations Metković, Gorica and Čilipi situated in the Dubrovnik-Neretva county. The curve for energy production from PV modules represents mean solar radiation on the horizontal surface and solar radiation at fixed angle for all three cities which are then summarized. Solar thermal radiation curve is made by using a similar approach but instead of the mean solar radiation, it takes 40% of solar radiation on the horizontal surface and 60% of radiation at the fixed (optimal) angle. The data obtained are presented on the Figure 23. and Figure 24.

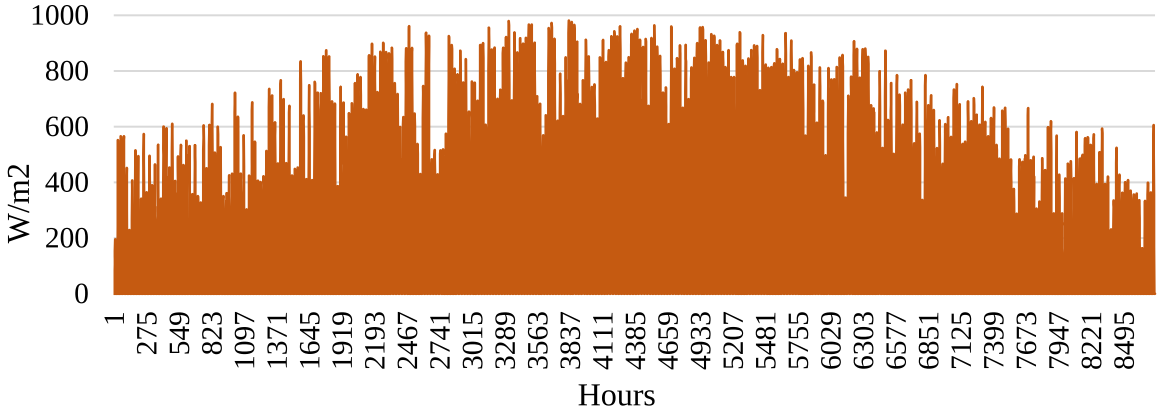


Figure 23. PV hourly global distribution curve [65]

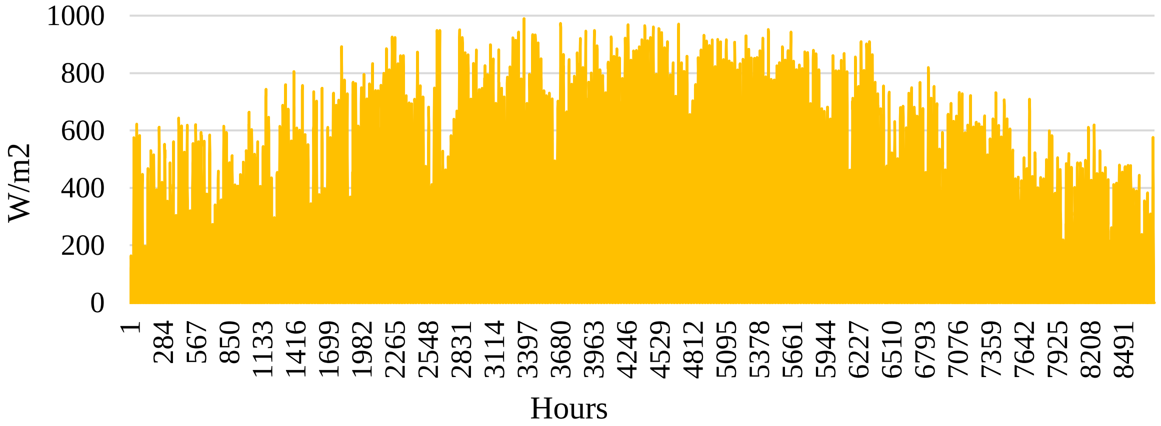


Figure 24. Solar thermal hourly global distribution curve [65]

Figures show, as expected, that the peak radiation occurs in the summer months. Total annual solar irradiance for PV is 1.733 MWh/m2 and for solar thermal is 1.92 MWh/m2.

The institute for environmental and sustainability together with the European commission, Directorate-General, and Joint Research centre have launched a web site aiming to provide more information about solar potential [66]. The available obtainable data on the site vary from solar radiation and irradiance data which provides monthly and annual averages of global radiation at horizontal and inclined surfaces, as well as other climatic and PV-related data. The site also provides solar electricity production. This application calculates the monthly and annual potential electricity generation E [kWh] of an installed PV system with defined modules inclination and orientation using a formula:

$$E_{PV} = 365 \cdot P_k \cdot r_p \cdot H_{h,I} \quad (4)$$

Where P_k [kW] is the peak power of the equipment installed, r_p is the system performance ratio and $H_{h,I}$, is the monthly or annual average of daily global radiation on the horizontal or inclined surface. The calculator can suggest the optimum inclination/orientation of the PV modules to harvest maximum electricity within a year [67]. According to the data from PV-GIS for installed peak PV power of 1 kWp crystalline silicon system integrated into building total annual electricity production of PV module is 1,296 kWh.

While calculating solar potential of the specific area for PV module installation several things have to be considered. Those are the available area for installation of PV panels as well as the tilt and azimuth angle in order to optimize the output of PV panel and panel efficiency [68]. The optimal inclination angle for PV modules in Dubrovnik-Neretva County varies from 32°to 35° depending on the specific location.

The main potential categories for PV installation are building rooftops of domestic houses, industrial estates, commercial sector and public buildings but also individual systems that are not integrated into the building. The major potential lies in the domestic sector for which total available area has been calculated. Calculations were made according to the total number of all dwellings including dwellings for permanent residence, dwellings used occasionally and ones for business activity only [56] and the average size of rooftops [41,54] taking into consideration some factors that can reduce available space. Those are:

1) Orientation of rooftop,
2) Available side of rooftop,
3) Spacing between the different rows of solar modules to avoid shading [68].

All dwellings were considered as available to use for PV and solar thermal system installation. Priority was given to solar thermal systems primarily for covering the need for domestic hot water production. Households rooftops in the year 2015 provided an available area of 3,104,592 m^2 for PV and solar thermal installation. If only PV systems are considered that amount of area is sufficient for installation of 443.5 MW PV panels that can produce 607.7 GWh on annual basis [69]. It was considered that part of the available rooftop area is used for solar thermal installation. The total amount of household rooftop area available for PV was in that case reduced. But there is a great possibility for installation of building integrated PV and solar thermal at other previously mentioned buildings: industrial estates, commercial sector, and public buildings where beside rooftop area vertical integration is also possible6383. There was no sufficient data to calculate available area but it was assumed that the potential area accounts for at least one third of rooftops of domestic houses.

In addition to the building integrated system, there is a large potential for installation of a free standing solar system or solar farms. It was already investigated that 3,629,000 m^2 of land area in Dubrovnik-Neretva county is suitable for solar farms [60]. There is 58 [60] more locations that could also be used for solar farms but further research is needed in order to investigate their size and feasibility. Locations are given in Table 6.

Table 6. Suitable and additional locations for free-standing PV installation [60]

Suitable locations for free-standing PV			Additional locations		
Number	Location	Area size [m2]	Number	Location	Area size [m2]
1	Puovo	180,000	1	Velika Rashoatica	60,000
2	Dubovo1	40,000	2	Gornji Zanarat	30,000
3	Dubovo2	60,000	3	Petrov Vrh	40,000
4	Vela Žukovica	190,000	4	Lampolje	50,000
5	Ošišće	100,000	5	Sločaja	50,000
6	Zabrada	136,000	6	Puovo	70,000
7	Zabrđe1	211,000	7	Doca	70,000
8	Zabrđe2	100,000	8	Pod Zakosirica	50,000
9	Grude	45,000	9	Mala Krtinja	40,000
10	Gradac	50,000	10	Nerezini dol	75,000
11	Golo Brdo	175,000	11	Velji pod	50,000
12	Butkov dolac	40,000		TOTAL	585,000
13	Grabovina	140,000			
14	Pišnja	640,000			
15	Monjine	120,000			
16	Pješi	380,000			
17	Zadubravica	83,000			
18	Ravne glavice	110,000			
19	Mokri	80,000			
20	Dubok	50,000			
21	Dugažica	60,000			
22	Čulev	54,000			
	TOTAL	3,044,000			
Number of locations:		33			
Total area size [m2]		3,629,000			

3.5.3. Biomas

The classification of solid biomass is based on their origin and source. The solid biomass is divided into following four sub-categories for classification in EN 14961-1 [56,57]:

1) Woody biomass
   a) Forest, plantation and other virgin wood

   b) By-products and residues from wood processing industry
   c) Used wood
2) Herbaceous biomass
   a) Herbaceous biomass from agriculture and horticulture
   b) By-products and residues from herbaceous processing industry
   c) Fruit biomass
3) Orchard and horticulture fruit
   a) By-products and residues from fruit processing industry
   b) Blends and mixtures

Approximately 70% of the total county land area is covered by forest. Though structurally, 55% of forest areas are degraded forests -maquis, garrigue, and scrub, 16.8% are infertile forest and only 12.6% of high forests with annual increment from 1.3 to 6.0 m^3/ha [72].

Forest potential was calculated as the sum of the potential for which official data on the forest are available and potential of forest area that is not recorded [60]. Latter one represents a significant amount of forest and therefore such potential is estimated. The evaluation was carried out using satellite images and data on the management of private forests from the previous periods. The possibility of using woody biomass for energy purposes was estimated. First the amount of wood from logging is calculated as an 80% of the forest increase. In addition to forest biomass, the potential of the scrub and bushes for use in the energy purposes has been counted. This is taken into consideration because in the area it is common to use wood from the scrub and bushes for space heating. Increase of the scrub and bushes was estimated as an 80% of increase of the forest in the surrounding area. For shrubs and underbrush, the potential volume of wood for logging was also calculated as 80% of their growth. Entire wood available for logging is not equal to the available amount of woody biomass for energy purposes. According to the type and size of wood only specific amount is available for energy purposes where wood residues from forest work was also taken into consideration. Detailed description of the process how technical potential was calculated can be found in the [60]. Energy potential [Wh] was calculated according to the technical potential [m3] and structure of forest trees available for energy needs in the county.

Figure 25. Forest are from for energy production [60]

An entire technical potential of forest biomass and biomass from degraded forests was 170,125 m3 [60] while energy potential was 432.6 GWh. Currently, annual consumption of biomass is approximately 13,050 m3 which is much less than total technical potential. Huge disproportion exists due to the existing restrictions on exploitation of wood on the one hand and on the other, the fact that there is no tradition of exploitation of wood from local forests in the county [60].

In addition, biomass from agriculture in the area can be used at a certain level as an energy source. Biomass from the production of grape and olives as well as by-products and residues from vineyards, olive groves, and husk can be used for energy purposes while the husk can be used in power plants directly -as fuel, but also in biogas plants. The technical potential was calculated to be 14,211 t and energy potential 77.8 GWh [60].

County has no sufficient energy potential of biomass for biofuel production [73]. For purpose of this thesis, biomass was used only for space heating and/or hot water production for households and at some level for small size cogeneration power plants for heat and power production for industry sector.

Dubrovnik-Neretva county has a low potential of an available area that can be used for short-rotation forests, so this potential is not taken into consideration [74].

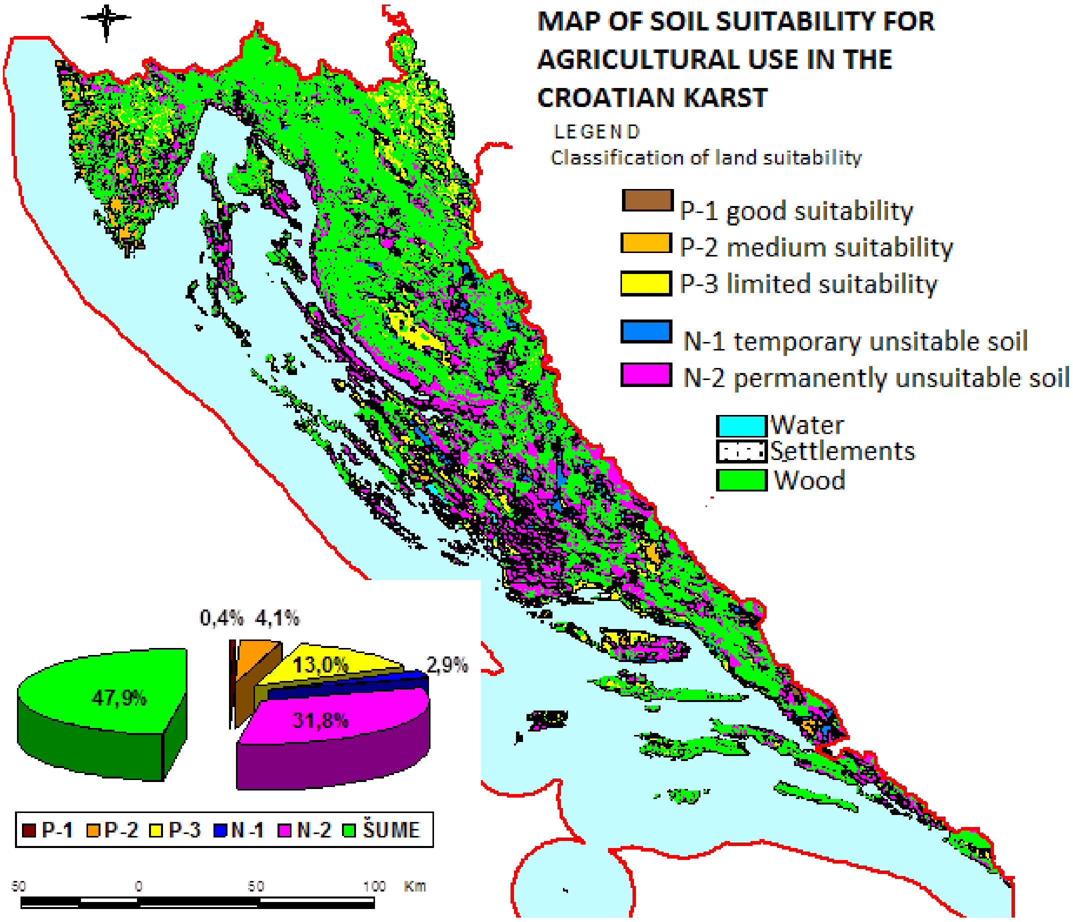


Figure 26. Map of soil suitability for agricultural use in the Croatian karst [74]

Most of the area is permanently unsuitable for agricultural use due to the variety of factors. Part of the area is covered with rocks; other parts have high inclination while remaining area that is unsuitable for agriculture is either covered by wood or abandoned and unused. Although area of the Neretva valley has a good quality of soil, it is already being used for agriculture and there is not enough soil left for a feasible production of short rotation forests.

In general, it can be concluded that in the area of Dubrovnik-Neretva County utilization of biomass resources for energy production is limited. The most suitable areas for the use of biomass are the island of Korčula, the western part of Pelješac, Konavli, and Lastovo. In these areas, it is possible to build smaller cogeneration power plants with recommended capacity between 5 and 10 MW [60].

3.5.4. Hydro

Hydro potential of the area is already being significantly utilized. It consists of a storage, and a small hydroelectric plant (HEP). Hydroelectric HEP Dubrovnik has total installed capacity of 252 MW and it is shared between Croatia and Bosnia and Herzegovina where one turbine generates electricity for Croatia while the other for B&H. Small hydro has installed capacity of 2 MW. Current and examined future capacities are shown in Table 7 [75, 76, 64]. Distribution curves for electricity production were obtained from country level for both dam and run-of-the-river hydro [64].

Table 7. Hydroelectric plan capacities – current and future [75, 76, 64]

Year	Power plant	Location	Type	Installed capacity [MW]
2015	HEP Dubrovnik	Župa dubrovačka (Srebreno)	Dam	126 (252)[3]
	Zavrelje	Mlini	Small hydro	2
Future possible capacity	MHE Ljuta 1	Konavle	Small hydro	2.206
	MHE Ljuta 2	Konavle	Small hydro	3.3
	HEP Ombla	Dubrovnik	Dam	68.5
	HEP Dubrovnik	Župa dubrovačka (Srebreno)	Dam	100 (200)[4]
	Run-of-the-river	Not specified	Run-of-the-river	3.3
TOTAL				305.306

[3] *Total installed capacity is 252 MW where one turbine generates electricity for Croatia while the other for B&H*
[4] *Upgrade of HEP Dubrovnik will be done with the same principle like existing HEP Dubrovnik – total installed capacity of 200 MW will be shared between Croatia 100 MW and B&H 100 MW*

4. MODELLING SCENARIOS

The basic idea of modelling scenarios was given in the *Section 2.3 Modelling scenarios.* Here, more detailed information on the specific procedures applied for the case of Dubrovnik-Neretva county are described.

4.1. Scenario 1: Business as usual scenario

Business as usual scenario was developed according to the guidelines of the Energy Strategy of the Republic of Croatia (later in the text: Strategy) [50]. Strategy estimates energy development of the entire country until the year 2020 with the view to 2030. For the purpose of this thesis, estimations were extrapolated until the year 2050. In the strategy, sectors are divided in the same way like they are in this thesis, into industry, transport and *other sectors*. Projected energy growth rates for each sector for the energy growth until 2020 and 2030 were directly applied from the strategy while growth from the year 2030 to 2050 was modelled for the purpose of this thesis. Estimation was based on the growth from the Strategy but with an assumption that growth will slow down with the factor of 0,5 after the year 2030. Therefore, energy growth from 2030 to 2050 was calculated as a product of energy growth from 2015 to 2030 and factor 0,5. Annual growth was then linearly distributed until the year 2050. The average growth rate of energy consumption between 2015 and 2020 applied in the scenario is 2.2% for the industry, 1.7% for the transport and 3.2% for the *other sectors*. The average growth rate in energy consumption between 2020 and 2030 is 2.0% for the industry, 1.2% for the transport and 2.6% for the *other sectors*.

4.2. Scenario 2: 100% renewable energy system scenario

The first step in building a 100% RES scenario was predicting energy consumption of all sectors. In order to achieve a reduction in energy consumption, despite expected economic and lifestyle growth, an increase in the energy efficiency, and synergies between different sectors and energy forms were introduced. The following sections describe various measures, technology, and fuel changes implemented on the demand side in transport, industry, and *other sectors*.

Industry

In the industry sector, it is assumed that increased efficiency of 2% per year [2, 77] is greater than an increase in industrial activity of 1,5 %. Therefore, energy consumption for 2050 is lower than baseline year energy consumption. Measures are adopted from the reference [77] with modification in the growth of the activity level. A great amount of energy demand of fossil fuels in the industry is replaced with electricity due to new efficient induction furnaces that are coming to the market. As shown in the reference, induction furnaces can replace conventional gas od oil-fired furnaces [78, 2]. The rest of energy demand in the industry is met by solar thermal energy and CHP. According to the reference share of solar thermal energy in the industry could reach up to 33% [79]. A more conservative approach of 18% was assumed in this thesis.

Transport

A transition of the energy system in the transport sector was done in several steps:

1) Improvements in the public transportation
2) Electrification
3) Changes for the heavy-duty vehicles, sea and air transport
    a) Electrofuels - introducing new fuel types
    b) Fossil fuels - net zero carbon system

The first step was a reduction of energy consumption due to improvements in the public transportation. It was assumed that 8% of energy savings could be achieved by improved public transportation system and replacement of one part of individual vehicles with public transportation. According to the reference [47], energy savings by improved public transportation could reach up to 20 %. A more conservative approach of 8% of energy savings, was assumed in this thesis because of the specific situation that currently exists in the county. That situation refers to undeveloped public transportation, a habit of people to use personal vehicles rather than public transportation, and the size of the investigated area.

The transport sector was designed with the maximum utilisation of electricity for the part of transport sector where this was possible. Electrification was done for a great part of the road transport, including entire public transportation and a part of sea transport while railway transport was already completely electrified in the baseline year. Impact on the electrical system for part of the county is already envisaged and several issues are stated [80]. Electrical vehicles are more efficient than fossil fuels. They have an efficiency of 0.139 kWh/km, while diesel and petrol vehicles have an average efficiency of 0.417 kWh/km and 0.528 kWh/km respectively [81]. Higher efficiency causes a decrease in energy consumption. The growth of the road transportation is predicted according to the growth on the country level for the year 2050 [51].

The third step in a transition of the energy system in the transport sector, was further developed as stated in the Methods, on:

1) Electrofuels production
2) Electrofuels import
3) Fossil fuels import/consumption

Electrofuel production examined several combinations based on the amount of electrofuels produced in the area. They refer to the production of: 100%, 130%, 150%, and 170% of total fuel demand. Combinations are presented to investigate if there is enough potential in the area for production of additional amounts of electro fuels available for export.

The second solution was electro fuel import where the main idea was to keep energy balance of the entire system, compensating energy needed for the electrofuel production in other areas. To maintain that energy balance additional energy had to be produced in the local area and exported.

The third alternative scenario where fossil fuels are imported and consumed in the local area can be considered as a collision with the climate mitigation strategies [5]. However, it was examined as an extreme case where technologies for electrofuel production would have not developed as expected by the year 2050. Even though fossil fuels are consumed CO_2 emission reduction on a global level is possible if a concept of carbon neutrality is properly applied. Balancing CO_2 released into the atmosphere from burning fossil fuels can be done with renewable energy that produces a similar amount of useful energy so that the carbon emissions are compensated. Emissions produced in the local area are balanced with the emissions produced in the neighbouring regions. Selected regions are neighbouring countries Bosnia and

Herzegovina and Montenegro. Countries have electricity production from fossil fuels therefore, CO_2 balance is possible if exported renewable electricity from local area replaces electricity produced from fossil fuels in the other area. Electricity is exported as 70% to B&H and 30% to Montenegro. Proportions are chosen according to the current situation on electricity production within the countries. It is also assumed that electricity production mix in countries will remain the same as today.

It was expected that railway system would not be used anymore just for cargo but also for the passenger transport. That would reduce the use of both individual vehicles and buses at the route. Already existing railway structure for implementing electric trains for passenger transport was more feasible than total replacement of current road public transport. It was also expected that intensity of railway system will increase and thus provide a larger amount of cargo transport carried with an electric train instead of using heavy vehicles. The increase in the intensity of use will give less energy savings despite the improvement of energy efficiency of trains that could be expected in the future. Therefore, final energy savings were 5%.

Sea transport that was investigated in this thesis included exclusively ferries. It was expected that intensity of ferry transport will grow while final energy consumption will decline. This is due to the replacement of all local ferries with electric ones [82]. On the other hand, the ferry used for international transport will depending on the scenario, use either electrofuels or fossil fuels.

In air transportation, domestic flights were reduced to 5% of the current demand while no changes were implemented in international aviation but more efficient planes were expected to lower the fuel demand [9]. Measures for air transport were adopted from reference without any alternations.

<u>Other sectors</u>

It is assumed that energy consumption from agriculture and services sector is remaining the same like in the year 2015. An increase of energy efficiency is levelled out with the same increase of energy activity in each of these sectors. After implementing energy efficiency measures, new more efficient technologies and change in fuel mix decrease in final energy consumption of households was 18.8% and construction 51.3%.

A study [83] showed that it is possible to replace fossil fuels from agriculture. That requires more efficient use of energy and mineral resources as well as higher level of water and soil preservation. Electricity has an important role in changing fuel mix in agriculture. Electricity can power agricultural machinery, including vehicles for transportation and field work and it could be used for electric heating and cooling purposes.

Fossil fuels used for vehicles in the construction sector were replaced partly with electrical vehicles and partly with electrofuels (100% RES scenario – variation with electrofuels) or fossil fuels (100% RES scenario – variation with fossil fuels).

For the household sector, it is assumed that population size will remain constant until 2050 but the number of households will increase because of increased lifestyle, more comfort, and privacy. Energy consumption will decrease due to the high increase of energy efficiency in individual houses. According to the study [77], energy efficiency can increase up to 72%. For this thesis, more conservative approach was assumed and 50% of increased energy efficiency was accepted. In smart energy systems district heating, and more recently district cooling coupled with a thermal (cooling) storage play significant role. Also, a combination of an individual heating system with district heating is recommended for achieving a low-carbon energy system [81]. Such solutions were not applicable for studied area. Heat demand of the area is lower than minimum heat demand required for feasible application of district heating [84]. Heat demand was met exclusively by individual heating systems such as heat pumps (24%), electric heating (36%), and solar thermal (27%). In the case where none of the above technologies were suitable, individual biomass boiler technology was proposed (12%). However, individual heat pumps are very often proposed as a solution for the future heating sector in Europe [85, 86].

In the overall service sector, tourism is the most important and it records a significant increase over the last years. It is assumed that tourism will still grow in the following years, therefore new capacities will be built. Tourist arrivals have a special impact on the uneven distribution of energy consumption during tourist – summer season and winter. But also tourism provides a lot of potential for implementation of different types of renewable resources [60] and technologies as well as large increase in the energy efficiency e.g. in buildings, appliances, heating and cooling systems.

4.3. Installed capacity

Installed capacity was predicted for the 100% RES scenario. Therefore, it was very important to create flexible energy system to ensure that demand and supply would always match. The scenario consists of three different modifications due to different subsectors of heavy-duty transport. The scenario was made in several steps and it follows several rules. Each step represents a specific technological change in order to allow a higher penetration of IRES in the energy system. Steps do not reflect the order in which transition should be carried out, but instead, they are a transparent representation of an amount of intermittent energy that can be integrated into the system by each step.

1) Heat savings: reducing the heat demand
2) Electric vehicles: electrification of all possible vehicles
3) Individual heating: fuel and technology switch for heating purposes, heat pumps are prioritized, followed by other renewable energy sources such as electricity, solar thermal and biomass
4) Electrofuels: they can have influence on the flexibility of the energy system only if electrofules are produced in the area

After implementing the first three changes, the share of IRES in the total electricity consumption can reach up to 55% [81]. The fourth step was not considered since it is not common for all modifications inside the scenario. Modifications are created due to the previously explained complexity and uncertainty of energy transition in the transport sector. Moreover, to increase the security of supply it was set that none of the IRES had more than a 30% share [2]. Electricity production was set for wind to 25% and from solar 20% share of total electricity production. It was assumed that all HEP are storage HEP A majority of the electrical energy production was utilized from hydro. Therefore, it had more than 30% share. Such approach was accepted since storage hydro is not considered as IRES and current experience shows that high penetration of storage hydro energy in the energy system is completely reliable. Nowadays, almost 100% of electricity for the local area is being produced from storage HEP.

5. RESULTS AND DISCUSSION

5.1. Scenario 1: Business as usual

Data for energy consumption in the BAU scenario were calculated as described in the *Section 4.1*. Results are shown in the Table.

Table 8. Calculated final energy consumption in BAU scenario; 2050

Sector	Fenergy consumption [GWh]	Share [%]
Transport	1725.2	48.8
Households	840.3	23.8
Industry	93.8	2.7
Services	340.4	9.6
Agriculture	67.3	1.9
Construction	467.6	13.2
TOTAL	3534.5	100.0

Final energy consumption of all sectors for the year 2050 was 3.53 TWh. In comparison to the baseline year it represents growth of 57.77%

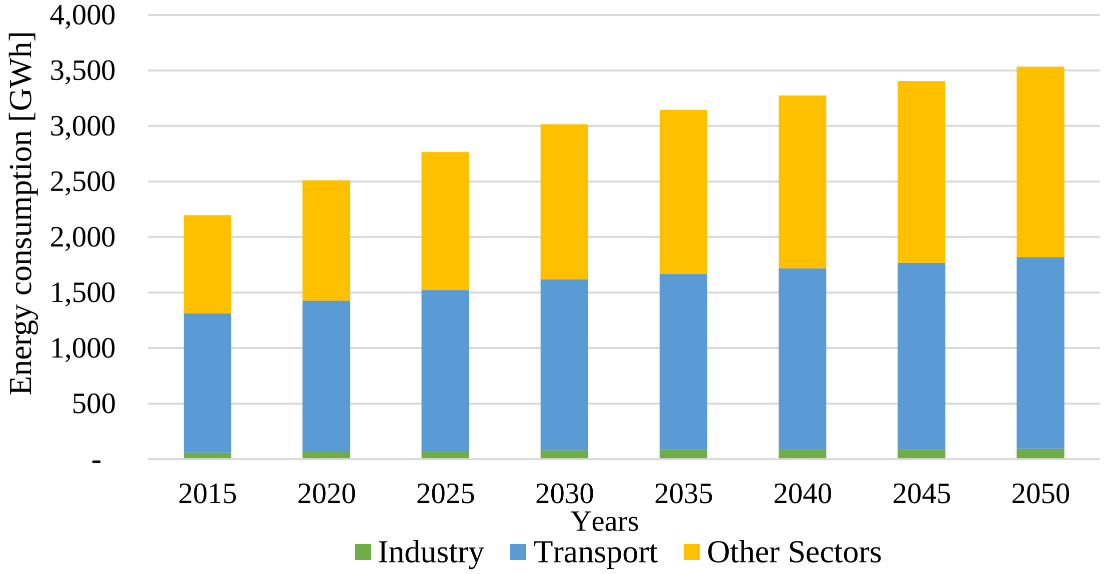


Figure 27. Final energy consumption in BAU scenario over the years

It is evident that the energy consumption will grow if systematic political measures followed by social acceptance will not be taken. Even if considered that entire production of electricity will come from renewable energy sources and penetration of electrical vehicles will appear, it can be seen that consumption of fossil fuels will significantly grow. Production of electricity from RES can be assumed due to a huge unused potential for HEP. Taking into consideration that changes in fuel mix in BAU scenario will not happen and shares of specific energy type per sector remained like in the baseline year, electricity consumption in the BAU 2050 accounted for 931.2 GWh and could be easily met only from an unused potential for new HEP. Growth in fossil fuel consumption cannot be an option if considering climate change mitigation and inevitable greenhouse gas reduction. According to the report from the United Nations Intergovernmental Panel on Climate Change from 2014, IPCC Fifth Assessment Report: Climate Change 2014, GHG emissions in 2050, comparing to 2010 must be 40% to 70% lower globally to keep temperature change below 2°C relative to pre-industrial levels [5]. Therefore, any further increase of fossil fuels consumption on a local level should not happen. That requires GHG mitigation strategies to be carried out. Strategies are based on carefully made energy planning but also, they require political acceptance and support.

5.2. Scenario 2: 100% renewable energy system

The scenario is considering a variety of different measures and radical turnover in the fuel mix. Proposed measures were adapted directly or with modifications from several different sources where the main was paper [2]. Changes in measures were done in order to get more achievable solutions for a specific area. It is already discussed in [2] that improvements in energy efficiency play the most important role in decreasing energy consumption. In [2] authors evaluated the cost of implementing energy efficiency measures on a case study of South East Europe. Costs regarding measures implementation caused high initial costs but in a long term they shown measures will have a positive impact due to the energy savings. Results of final energy consumption for main sectors are presented in Table 9.

Table 9. Calculated energy consumption in the 100% RES scenario for year 2050

Sector	Final energy consumption [GWh]	Share [%]
Transport	597.9	40.0
Households	381.4	25.5
Industry	49.2	3.3
Services	201.0	13.5
Agriculture	36.4	2.4
Construction	227.6	15.2
TOTAL	1493.5	100.0

It is clear that CO_2 emissions in 2050 were equal to zero. The comparison with baseline scenario and business as usual is shown in the Table 10.

Table 10. Comparison of CO_2 emissions for different scenarios

CO2 emissions [tCO2e]		
2015	2050 - 100%RES	2050 - BAU
420,423	0[5]	610,428

Considering CO_2 emission price of 46.6 €/ton in the year 2050 [87] implies an additional cost of 28.45 MEUR for internalization of costs due to fossil fuel consumption.

Scenario showed that energy consumption was 33.3% lower than in the baseline year and 57.8% lower if compared to the business as usual scenario for 2050. Final energy consumption for the year 2015 and 2050 can be seen in Figure 28. Scenario for the year 2050 presented here refers to variation with electrofuel production as a replacement for high dense fuels. As the main objective was to develop a scenario of 100% RES, this is the highly-advised solution. Moreover, it can be considered that this is the only solution that entirely fulfil the main objective. Also, it is important to note that total consumption included electrofuels in a form of fuels while if we consider electrofuels from production stage that will imply higher total consumption of electricity from RES. Variations with electrofuel import, fossil fuel import/consumption, and electrofuels from production stage are elaborated in the following sections.

[5] *Total CO_2 emissions were equal to zero in the 100% RES scenario with electrofuel production and electrofuel import, in the 100% RES scenario with fossil fuel consumption/import this referred to net zero carbon balance*

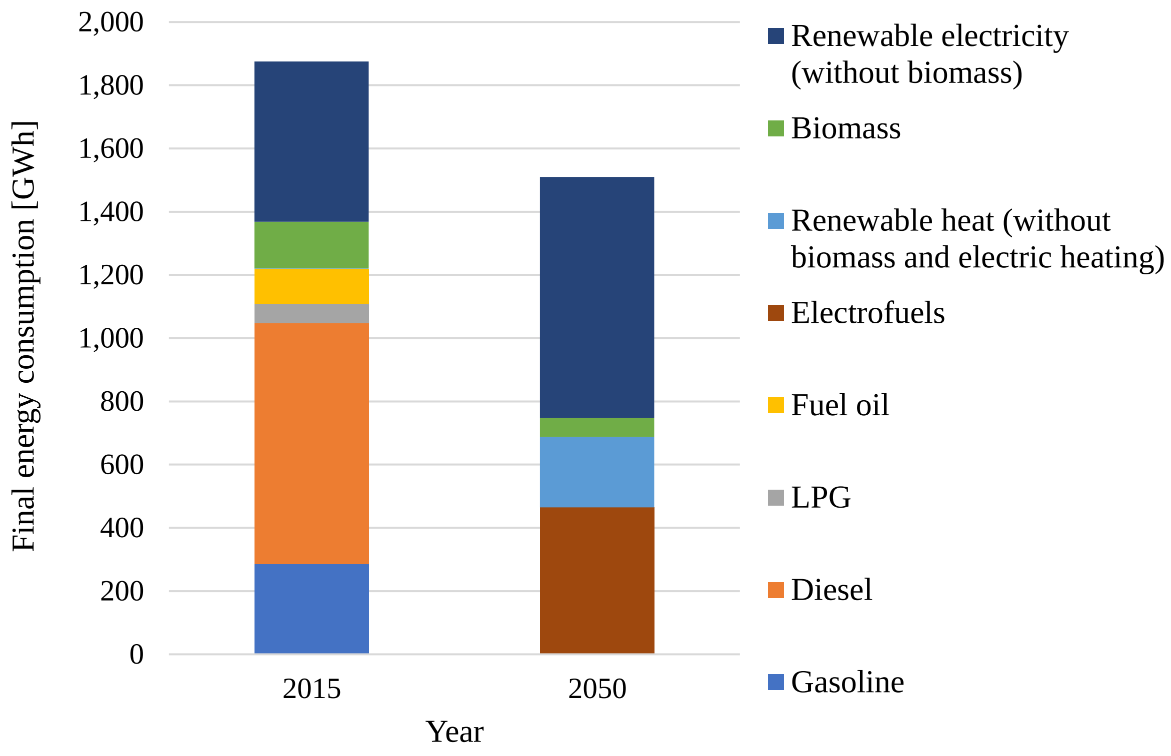


Figure 28. Final energy consumption in the year 2015 and 2050

Share of each sector in the final energy consumption did not change significantly. The notable change of share in energy demand can be observed in the transport sector. The transport sector recorded a lower share in 100% RES than in baseline scenario. Share of energy consumption in base year was 55.97% while in 100% RES it is 44.0%. A significant decrease occurred because electric engines are more efficient than fossil fuel engines. Considering the efficiency of DME and methanol engine it is very much the same as diesel in current state of engine development. These studies are made for personal vehicles, though DME trucks are showing the same performance as diesel truck and very similar to buses [28].

Table 11. Energy efficiency for personal vehicles [28]

Efficiency for personal vehicles		
Fuel	Type of engine	[kWh/km]
Diesel	Compression ignition	0.42
Petrol	Spark ignition	0.53
Methanol	Fuel cell	0.41
DME	Compression ignition	0.43

Table 12. Energy efficiency for buses and trucks [28]

Efficiency for buses and trucks			
	Type of vehicle	Truck	Bus
Fuel	Type of engine	[kWh/km]	[kWh/km]
Diesel	Compression ignition	3.02	4.56
Methanol	Compression ignition	3.02	4.33
DME	Compression ignition	3.02	4.33

The main difference among those fuels that should be stated is in their properties. Methanol and DME fuels have lower energy density so they require bigger volume storages or tanks for the same amount of energy stored. Detailed results are presented in the following section.

Table 13. Comparison of methanol, DME, Diesel and Petrol properties [28, 88]

Energy density	Methanol	DME	Diesel	Petrol
LHV[6][kWh/kg]	5.47	7.95	12.08	11.57
LHV[7] [kWh/L]	4.39	5.26	8.90	9.91

<u>Transport</u>

Transport sector faced the biggest change. Electrification of a majority of road vehicles, including the entire public transport and local ferries was introduced. Calculations were made to examine the probability of implementing electrical vehicles until the year 2050. If penetration of electrical vehicles in total vehicle fleet will follow a current increase of purchasing new vehicles electrification can be done before 2035 (Figure 29.). In case of electrification of entire vehicle fleet until the year 2050 penetration of EV per year should be 3% (Figure 30.). In reality, most likely that electrification will not follow linear increase and will probably happen as a combination of those two scenarios where mix of fossil, hybrid and pure electrical vehicles can be expected [81].

[6] *LHV – Lower heating value*
[7] *LHV – Lower heating value*

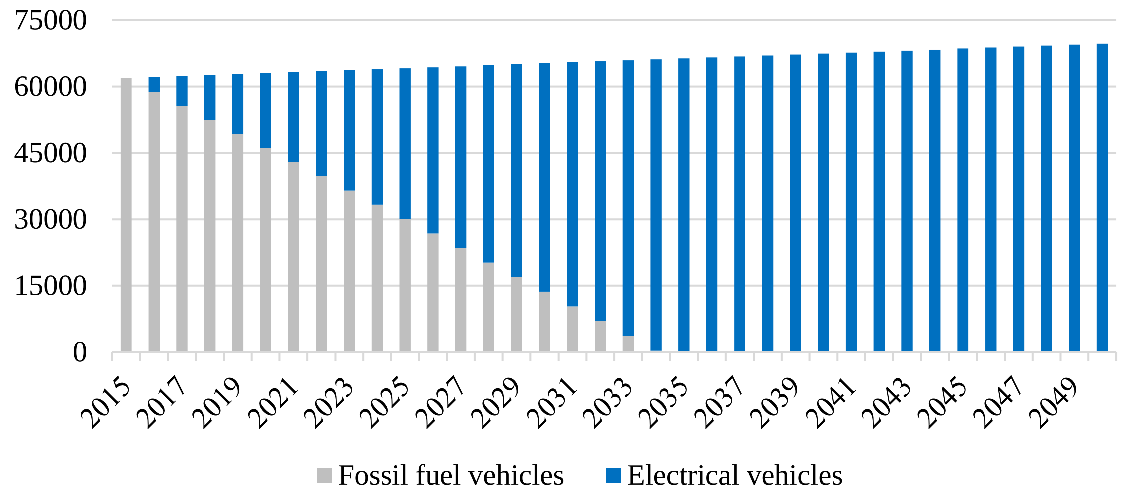


Figure 29. Penetration of electrical vehicles, 5.4%

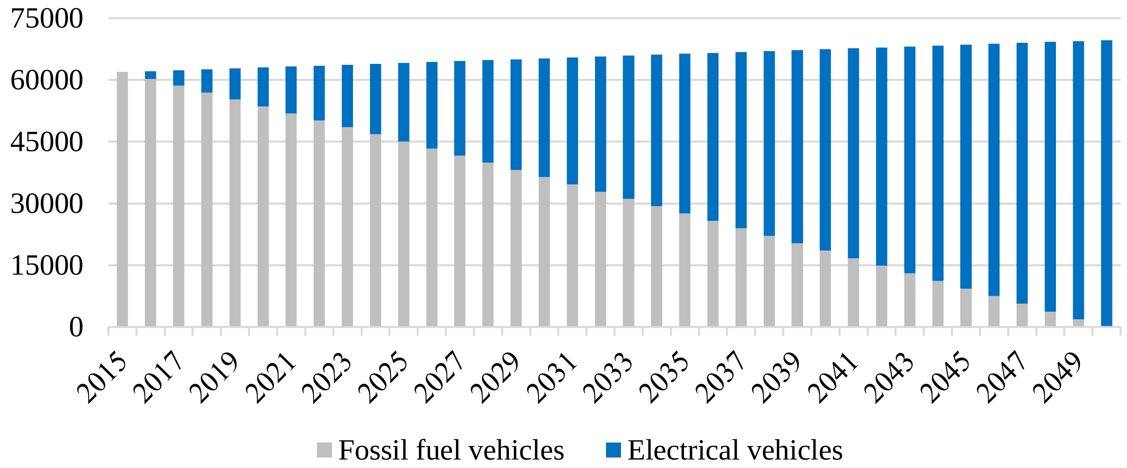


Figure 30. Penetration of electrical vehicles, 3%

Implementation of electrical vehicles in transport requires adequate infrastructure.The scenario was considering that most of the electrical vehicles will be using smart charge system. Smart charge system is important for balancing power system, especially when intermittent energy sources are implemented. Energy consumption of electrical vehicles, including electrical buses, was 199.9 GWh and total consumption of electricity in transport sector was 206.3 GWh. Remaining energy demand was met like it was mentioned before either from electofuels or fossil fuels. To meet 100% demand for electrofuels additional electricity was needed for their production. Results for all three scenarios are given below where some variations within these solutions were introduced.

To examine the possibility for implementation of EV and electrofuel vehicles from socio-economic perspective current and future prices were investigated. In their report from 2016, Bromberg et al. [89] predicted that the total cost of ownership of EV will be lower than for fossil fuel cars in 2022. This is possible due to a significant price drop of batteries for EV. N. Björn *et al*. [90] gave a systematic review, analysing over 80 different estimates reported from 2007 to 2014. They showed that the costs of battery packs are notably coming down. Reducing the price of electric vehicles is decisive factor for their penetration on the higher level.

Research [28] gave a concise overview of the historical development and current status of methanol and DME vehicles. Methanol vehicles are already in use for many years and conversion from petrol vehicles to methanol is possible. The conversion costs range from €90 to 260€. Interest in DME as a transport fuel has been growing in recent years and more research has been carried out to examine their performance and feasibility [28].

1) Electrofuel production

The production process was described earlier. The main difference from an energy point of view is a different amount of energy needed for capturing carbon dioxide using CCR or air capturing. The one selected for further research on energy consumption is CCR technology as more reliable data on technology and costs nowadays exist [28]. Air capturing technology is more expensive at the current stage but from a system perspective it requires a negligible higher amount of electricity, so will not significantly affect results on total energy demand. The final, choice, in reality will be determined by the maturity of technology as well as costs. However, air capturing is recommended technology for electrofuel production. In future when all fossil fuels will phase out the only carbon source appropriate for CCR will come from the heat and power sectors or industry based on biomass. Therefore, lack of CO_2 emission from stationary sources may occur and air capturing could possibly become the essential technology for producing electrofuels [28].

Results of electricity demand for the whole energy system including electrofuel production are presented in Table 14.

Table 14. Electricity demand for 100% RES scenario variation 1: Electrofuel production

Variations	Production	Export	Electricity demand [TWh]
1.1	100%	0	1.64
1.2	130%	30%	1.89
1.3	150%	50%	2.05
1.4	170%	70%	2.22

Electricity demand in all sectors including electrofuels production accounts for 1.64 TWh where total installed capacity to meet demand is 535 MW and consists of wind, PV, HEP, and CHP. Detailed renewable energy production by source is presented in Figure 31. The largest share in electricity production has hydro. A large share of hydro was possible due to the capacity in the county and stability of electricity production in comparison to IRES.

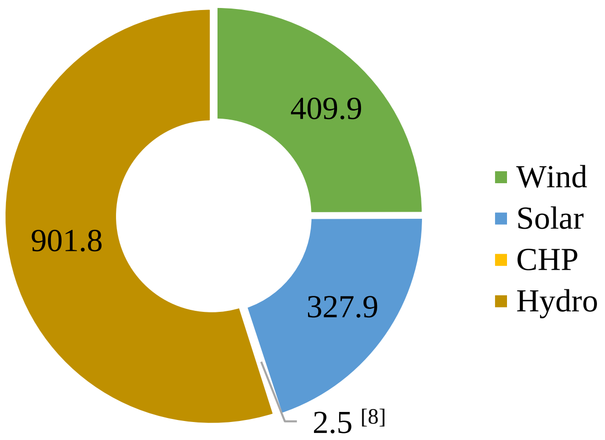


Figure 31. Mix of renewable electricity generation in the year 2050 [GWh]

Other variations (Electrofuel import and Fossil fuel import/consumption) are presented to investigate if there is enough potential in the area for production of additional amounts of electrofuels. Results confirmed that potential of the region is fairly sufficient. The idea of production of additional amounts of electrofuels is to use those fuel as an electricity storage.

[8] *very low share in electricity production from CHP due to limited biomass capacity reduced transparency in the pie chart at Figure 31*

This increases the security of supply and allows even higher penetration of IRES in the energy system.

2) Electrofuel import

The idea for this scenario is keeping energy balance of the entire system considering investigated local region where electrofuls are imported and consumed and place where electroufuels are produced. To maintain the balance, energy used for electrofuel production in other regions had to be compensated with additional energy produced in the studied area and exported. Electricity demand for that case, in theory, is the same like as for production of electrofuels in the studied area. In reality that will not be the case because it is necessary to consider additional losses of transmission and distribution. Moreover, import of electrofuels is imposing the question of security of supply due to high dependency on other regions and also reducing the possibility of having additional system flexibility.

3) Fossil fuel import/consumption

Results that present applied concept of carbon neutrality are presented in Table 15. To compensate 124,973 tCO_{2e} emissions from diesel and jet fuels it was necessary to export 353.6 GWh electricity from RES, in order to replace electricity that would otherwise be produced from burning fossil fuels in neighbouring regions.

Table 15. CO_2 emissions and electricity for balancing the system

CO_2 emissions [tCO_2e]		Export of electricity [GWh]	
Diesel	Jet Fuel	B&H	Montenegro
34,157	89,816	247.6	105.9

Results showed that this principle requires lower additional electricity production. Requirements would grow if additional transmission and distribution losses apply as well if emissions are extended to include other GHG. Currently, electricity imported from Dubrovnik-Neretva county has a small share in total electricity production from fossil fuels in both countries.

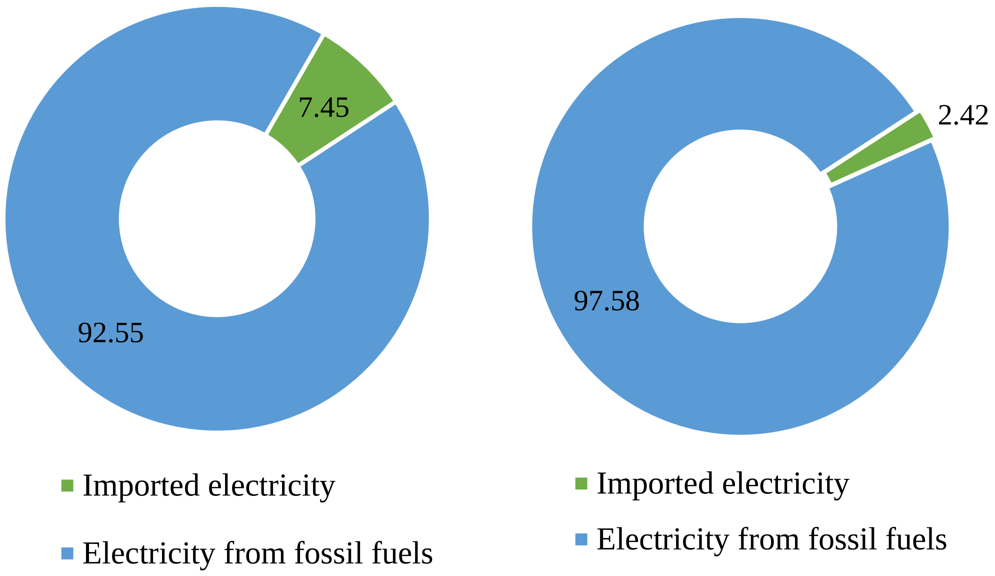


Figure 32. Share of imported electricity from Dubrovnik-Neretva county in the production of electricity from burning fossil fuels in Montenegro (left) and in B&H (right)

Electricity export, in that case, is not considered as a problem and is not affecting power system of mentioned countries. Taking into account that energy systems of other regions and countries will develop towards 100% RES will cause difficulties or even the inability of maintaining the carbon neutrality concept of the local area. Furthermore, similarly to the case for the electrofuels import, same disadvantages appear if fossil fuels are imported. Security of supply is disrupted and the possibility of additional flexibility is lost.

Heat production

Heat demand is met by heat pumps, solar thermal, biomass CHP, individual biomass furnaces and electrical heating. Excluding electrical heating to cover the heat demand, 220.8 MW of installed capacity is needed. Heat capacity was calculated to cover peak heat demand and therefore system could be oversized. Optimization of the whole system was out of the scope of this work. In order to calculate optimal capacity in further research, it is recommended to carry out the hourly analysis. Further decrease in capacity for heat production can be achieved by implementing thermal storages. Thermal storages can increase efficiency and security of entire the system. Heat excess during the day or even season can be stored and used when it is needed.

6. FURTHER RESEARCH

The research carried out in this thesis has investigated how local energy system might evolve over the years toward 100% renewable energy system including various technologies and measures to achieve that goal. The scenario proposed here should not be viewed as a final solution. It represents a foundation for future work in closing the gap into the transition to 100% RES from energy, economic, social and political point of view. Therefore, some key elements were pointed out to be researched in more detail in further work:

- Biomass and waste utilization

In the further research, it is recommended to investigate in more details potential for utilization of biomass from production of grape and olives as well as by-products and residues from vineyards, olive groves, and husk. Potential of biodegradable waste should be examined with special emphasis on biofuel production. Furthermore, it is recommended to investigate a local potential for cultivation of algae for biofuel production.

- Account hourly fluctuations in energy production

It is highly recommended to carry out the system optimization on the hourly basis. Such analysis will resolve problems of intermittent nature of RES such as wind and solar that could not be tackled with analysis carried out on the yearly basis. Electricity excess and losses might happen at certain hours; therefore, it is important to create energy balance on the hourly level.

- Optimal combination of technologies

In further research, it is advised to find the optimal combination of technologies taking into account energy, environmental and economic aspects.

- Electricity and thermal storages

In this thesis batteries of electrical vehicles are seen as a way of electricity storages. Detailed investigation on other possible storages for electricity and heating/cooling will ensure even more stability of the energy system and will provide a higher level of synergies between sectors and energy forms. Moreover, additional storages can increase penetration of IRES.

- Energy exchange with neighbouring countries

Taking into account energy exchange increases the complexity of energy system but it provides many benefits for total energy system stability. Possibilities of energy exchange with neighbouring countries are recommended to examine in more detail along with the rules for that exchange.

- Infrastructure

Implementation of specific renewable energy technologies requires a wide variety of initial work related to their infrastructure. For example, charging stations for EV or electrical ships, filling stations for electrofuel vehicles, aeroplanes and ships and many others. It is recommended to examine this additional work and infrastructure according to the type of renewable energy technology used from technical and economic perspective.

- Socio-economic analysis

The data on costs for specific fuels and technologies proposed for this thesis is very difficult to obtain as it is not widely reported in the literature. It is recommended to combine system optimization from technical and energy perspective with economic analysis to develop the best possible solution.

- Alternatives for high density fuels

Fuels selected for this substitution were electrofuels since they do not require any biomass input. There are a lot of other fuels that might also be used for this substitution. The constraint that should be considered is to choose fuel in the context of a 100% RES considering sustainable use of biomass.

- Analysis and development of electrofuels for aircrafts

Electrofuels were assumed as a suitable replacement for jet fuels but further research has to be carried out on their properties and performance of aircraft propulsion systems running on this fuel.

7. CONCLUSION

In this thesis, bottom-up planning of local energy system was carried out. The main aim of this energy planning was to build a scenario for 100% renewable energy system of a local area by the year 2050. In sustainable energy transition, local areas are considered to be the main drivers of this change from the political, social and economic point of view. First of all, an overview of the main principles and approaches was presented. The overview pointed out their importance in performing the transition.

Bottom-up approach in the context of this thesis referred to the way of building up the energy system from the “bottom” – local areas, to the entire integrated energy system of European Union. Therefore, a local area was selected from the Nomenclature of territorial units for statistics on the third level. That provided statistical data and socio-economic analysis of the local area. The importance of holistic approach was reflected in the possibility to detect synergies between different sector and areas. Special emphasis was on transport sector as it is one of the greatest challenges in the sustainable development.

The next task was to develop methods that can be replicated on other systems of different size and complexity. Bearing in mind that all local system will be merged to form one integrated and complete energy system four basic steps were established.

In order to examine methods, case study for Dubrovnik-Neretva county was performed. The first step was the analysis of a local potential of renewable energy sources. The results demonstrated that the county has a large potential for wind, solar and hydropower, where special emphasise was given to account biomass potential. Only the exploitation of biomass resources that is in line with potential can be considered as sustainable. Biomass potential of the area was equal to 510.4 GW and the limit was not crossed in the 100% RES scenario.

Secondly, baseline energy system for the year 2015 was calculated which confirmed the great need of sustainable transformation of transport sector. Consumption of a transport sector accounted for more than 55% of final energy consumption of the area. Nearly entire consumption came from burning the fossil fuels.

Thirdly, two substantially different future scenarios were built for the year 2050. First, business as usual scenario revealed that development of energy system which follows current market trends and customer habits without the systematic implementation of energy efficiency measures but with expected improvements in technologies for energy production, conversion, and storage cannot be considered as a solution in climate mitigation strategies. Moreover, it will bring additional expenses to internalize the costs of fossil fuel emissions of 28.45 MEUR. Considering holistic approach, 100% RES scenario was built with several variations to tackle the difficulties and uncertainties in the transport sector. Highly advised solution included the production of electrofuels highlighting the benefits such as security and flexibility of energy system.

Lastly, 100% renewable scenario with electrofuels showed that implementing energy efficiency measures and performing radical turnover in the fuel and technology mix, especially in the transport sector will give 33.3% lower energy consumption than in the baseline year.

Performing the task revealed many additional opportunities for further research. Placing focus on the field that has not been fully examined yet created the foundation in closing the gap towards sustainable energy transition.

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