University of Zagreb

FACULTY OF MECHANICAL ENGINEERING AND NAVAL ARCHITECTURE

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THE ROLE OF ENERGY STORAGE IN PLANNING OF 100% RENEWABLE ENERGY SYSTEMS

DOCTORAL THESIS

Zagreb, 2012

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Contents

Preface

What was the greatest scientific jump, crossroads or invented theory of modern society? I would say the publication of Darwin's theory of evolution in 1859. After his voyage on HMS Beagle, he made conclusions and hypotheses on natural selection, that were not proven by the experiments with calculated uncertainty and confidence levels. But at that time it was not necessary to go into such depth experiments, as the evidence was all around the world; he just observed them in a scientific way and reached the right conclusions. Society was not the same then, and neither was the scientific community. Two years later, another scientist, British physicist John Tyndall, formulated and proved another interesting hypothesis, but one that unfortunately did not cause such a drastic change in the thinking of society and scientist. His theory was that the temperature changes in the atmosphere are related to changes in the amount of carbon dioxide stored in it. 150 years later, we have much evidence in the form of, measured statistical data with calculated uncertainty levels, but still we have many scientists and educated people in the leading positions within society who are sceptical about it. Meanwhile there are still people who are sceptical about Darwin's theory of evolution. Why is this so? This thesis will certainly not answer this question.

The measured fact is that the average concentration of CO_2 in the atmosphere in January 2012 was at 393.09 ppm_v, which is about 110 ppm_v more than in the pre-industrial era and, according to ice core measurements, it represents the highest concentration in the last 400,000 years. Similarly, there has also been a large increase in the emissions of other gases that have an even bigger impact on the greenhouse mechanism. What will be the response of a nonlinear system with many positive feedbacks, and variables that have increased far beyond the normal levels? Shall we follow the market trend and its business-as-usual scenario or is there still time to change, time to minimise the damage of global warming? As we are certain that we cannot change the past, so too are we certain that we cannot exactly predict the future; we can just interpret the data, build simulation models and, according to their results, try to devise a policy that will satisfy mankind's hunger for energy in the least harmful way of entropy production while causing the least possible impact on the environment. There are many solutions or alternatives, which Prof. Lund sets out in his latest book, Renewable Energy Systems, so we need to analyse them carefully and choose one, or an appropriate mix of several alternatives. This thesis should form a part of a foundation for proving that only 100% independent energy systems based upon 100% RES supply and backed up by energy storage will make sustainable development a possible and rationale alternative for the future.

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Summary

The ultimate goals of sustainable development of modern societies are the planning and development of energy systems, so most of the developed countries have focused their energy policies on the development of sustainable energy systems. These systems should provide security of energy supply, and they should be competitive and have a minimal impact on the environment. In the long term, only renewable energy sources supported by energy storage can fulfil these requirements. There are many RES and storage technologies, so it is important to optimise their selection and integration in the energy systems. Today, there are many methods, methodologies and computer tools for solving problems of energy planning with a high share of distributed and renewable energy sources, but only a few of them successfully integrate energy storage and provide adequate results. To enhance the security of energy supply, efficiency and safety of the grid-connected energy systems, in conditions of increased penetration of distributed and renewable sources, it is necessary to increase the flexibility of the system. This also includes increasing the capacities of energy storage, both on the side of the power plants and on the end-use side. The RenewIslands/ADEG methodology for the integration of energy storage is based on mapping of local needs for electricity, heating and cooling energy, transport fuels and similar, mapping of local potentials of RES, cogeneration and polygeneration and feasibility of energy storage and demand management measures, such as reversible hydro, batteries, compressed air storage, hydrogen, production of different fuels, water desalination, etc. Combined, with IEA FAST methodology for integration of variable renewable energy sources, they qualitatively determine more a detailed way towards 100% RES systems. As a support for the methodology, two energy planning models, H_2RES and EnergyPLAN were used for analysis of scenarios for development of 100% RES systems with integrated energy storage. Presented results include 100% RES islands, 100% RES electricity production for Portugal and a 100% RES energy system for Croatia. Today the most widespread form of storage in power systems is pumped or reversible hydro storage, which has many advantages but, likes any other storage technology, can be economical only in certain conditions, and has an impact on the environment. To ensure the necessary construction and minimise the risk to investors, feed-in tariffs for storage systems have been proposed. This thesis answers the question: what is the role of energy storage in a planning of an independent energy system based on a RES energy supply? It also shows how, in a given circumstances energy storage maximises the utilisation of RES, provides security of energy supply and minimises the environmental impact of energy systems.

Sažetak

Energetskih sustavi, njihovo planiranje i razvoj su nezaobilazna komponenta u postizanju održivog razvoja modernog društva te je velika većina razvijenih zemalja fokusirala svoju politiku upravo na razvoju održivih energetskih sustava. Ti sustavi bi trebali nuditi sigurnost dobave energije, biti konkurentni te prihvatljivi za okoliš. Dugoročno gledano, jedino obnovljivi izvori energije (OIE) potpomognuti skladištenjem energije mogu zadovoljiti postavljene ciljeve. Kako postoje mnogi oblici OIE te skladištenja energije, postavlja se zahtjev za njihovo optimalno integriranje i uključivanje u energetske sustave.

Danas postoje mnoge metode, metodologije i računalni programi za rješavanje problema planiranja energetskih sustava s visokim udjelom obnovljivih i distribuiranih izvora energije, no samo nekolicina njih uspješno integrira skladištenje energije te daje zadovoljavajuća rješenja. Za povećanje sigurnosti dobave energije, te učinkovitosti i sigurnosti mrežnih energetskih sustava u uvjetima povećanja penetracije distribuiranih i obnovljivih izvora energije, potrebno je povećati fleksibilnost, a time i sposobnost skladištenja energije, kako na strani energetskih postrojenja, tako i na strani potrošača. RenewIslands/ADEG metodologija za integriranje sustava za skladištenje energije se zasniva na snimanju stanja lokalnih potreba za električnom energijom, toplinskom energijom i hlađenjem, gorivima za transport i slično, te lokalnih obnovljivih resursa, potencijala za kogeneraciju i poligeneraciju, te mogućim tehničkim rješenjima za skladištenje energije kao što su reverzibilne hidroelektrane, baterije, vodik, toplinski i rashladni spremnici, goriva u sektoru transporta.

Teza daje odgovore na pitanje koju ulogu ima skladištenje energije u potpuno nezavisnim energetskim sustavima zasnovanim na dobavi energije iz OIE te na koji način pod zadanim uvjetima skladištenje energije maksimizira iskorištavanje OIE, osigurava sigurnost dobave energije te minimizira utjecaj energetskih sustava na okoliš.

Prošireni sažetak

Ključne riječi: energetsko planiranje, skladištenje energije, obnovljivi izvori energije, potpuno obnovljivi energetski sustavi, poticajne tarife, održivi razvoj

Današnji energetski sustavi razvijenih zemalja su vrlo složeni te analiza ovih sustava i njihovo adekvatno planiranje su vrlo zahtjevni. Energetsko planiranje je još složenije zbog liberaliziranih energetskih tržišta te raznih izazova i pitanja koja se pojavljuju u društvu kao što su klimatske promjene, sigurnost dobave te razna ekonomska i politička prihvatljivost određenih energetskih postrojenja i rješenja. Kao jedan od mogućih odgovara na spomenute izazove nameću su obnovljivi izvori energije (OIE). No obnovljivi izvori energije zbog svojih karakteristika kao što su intermitentnost, nestalnost i periodičnost dodatno otežavaju planiranje postavljajući nove uvjete i zahtjeve. Danas postoje mnoge metode, metodologije i računalni programi za rješavanje problema planiranja energetskih sustava s visokim udjelom obnovljivih i distribuiranih izvora energije, no samo nekolicina njih uspješno integrira skladištenje energije te daje zadovoljavajuća rješenja. Za povećanje sigurnosti dobave energije, te učinkovitosti i sigurnosti mrežnih energetskih sustava u uvjetima povećanja penetracije distribuiranih i obnovljivih izvora energije, potrebno je povećati fleksibilnost, a time i sposobnost skladištenja energije, kako na strani energetskih postrojenja, tako i na strani potrošača. RESTEP metodologija za integriranje sustava za skladištenje energije razvijena je iz Renewisland/ADEG metodologije te FAST metode te se zasniva na snimanju stanja lokalnih potreba za električnom energijom, toplinskom energijom i hlađenjem, gorivima za transport i slično, te lokalnih obnovljivih resursa, potencijala za kogeneraciju i poligeneraciju, te mogućim tehničkim rješenjima za skladištenje energije kao što su reverzibilne hidroelektrane, baterije, vodik, toplinski i rashladni spremnici, goriva za transport. Ta metodologija, osim što upućuje na tehnološki optimalno rješenje, vodi računa i o ekonomičnosti rješenja, kao i o utjecaju primjene rješenja na smanjenje emisija u okoliš, smanjenje zagađenja voda, povećanje zapošljavanja, podršku javnosti i lokalne zajednice.

Potrebe za skladištenjem energije istaknute su od strane mnogih autora (Duić, Lund, Carvalho) kao sredstvo koje može pomoći pri uravnoteženju potražnje i dobave energije, a koje u slučaju korištenja OIE mogu biti izrazito neusklađene. Duić i Carvalho pokazuju na primjeru portugalskog otoka Porto Santo, na koji način se mogu planirati otočni sustavi s velikim udjelom energije iz intermitentnih, obnovljivih izvora, kao što su energija vjetra i energija Sunčeva zračenja, pri čemu za njihovo uspješno integriranje predlažu skladištenje

energije u elektrokemijskom obliku to jest elektrolizu vode i proizvodnju te skladištenje vodika u vrijeme niske potražnje i visokog iskoristivog potencijala OIE. Vodik se potom može koristiti u gorivnim člancima za proizvodnju električne energije u vrijeme visoke potražnje i nedostatne proizvodnje energije iz OIE.

Iz radova koji se bave sličnom tematikom može se zaključiti da se problem integracije OIE najprije počeo pojavljivati u energetskim sustavima otoka, u kojima se zbog male potrošnje i opterećenja, vrlo brzo mogla postići velika penetracija energije iz OIE na godišnjoj bazi, a što je još izrazitije u kraćim vremenskim periodima. Odnos između veličine elektroenergetskog sustava i mogućnosti prihvata energije iz vjetroelektrana navodi se u knjizi *Wind power in power systems* (Wiely & sons Ltd., 2005.) gdje autori zaključuju da veći sustavi na godišnjoj bazi mogu ostvariti znatno manju stopu penetracije energije iz vjetroelektrana bez većih posljedica na rad sustava. No za manje sustave (Duić, Krajačić) pokazuju da se integracijom energetskih tokova iz više vrsta izvora, za istu zadanu sigurnost sustava u vidu ograničavanja trenutne penetracije energije iz intermitentnih izvora, mogu postići veći udjeli OIE u zadovoljavanju predviđene godišnje potrošnje električne energije. Isti autori zaključuju da se uz zadana ograničenja u otočnim energetskim sustavima može postići 100% penetracija OIE samo uz korištenje nekog oblika skladištenja energije. Zbog kompleksnosti problema integracije OIE u energetske sustave predlaže se korištenje Renewislands metodologije, a čime se olakšava planiranje održivih energetskih sustava otoka u kojima se nastoji što više energije proizvesti iz lokalno dostupnih resursa, a što u većini slučajeva rezultira visokim udjelom OIE te integracijom energetskih tokova i skladištenja energije. Ono što je bitno za ovu metodologiju da se zbog intermitencije i varijabilnosti OIE promatrani sustavi moraju analizirati na satnoj osnovi. Upravo zbog neusklađenosti potražnje i dobave te poteškoća kod sagledavanja problema statistički, npr. pomoću sređenih krivulja opterećenja te Weibulove razdiobe za distribuciju brzina vjetra, a o kojoj ovisi proizvodnja električne energije iz vjetroelektrana, u analizi otočnog sustava Porto Santo Duić i Carvalho predlažu satnu analizu energetskih sustava kao bolji pristup sagledavanju potreba za skladištenjem te mogućnosti za integraciju različitih tokova. Renewislands metodologiju se proširuje u ADEG metodologiju kako bi se moglo što bolje ocijeniti i optimirati razmatrane scenarije.

Lund je kroz nekoliko radova također pokazao da se satni pristup analizi energetskih sustava može uspješno primijeniti i na velike umrežene energetske sustave te je dokazao da se ukupni “kritični višak proizvodnje električne energije” iz pojedinih intermitentnih izvora na godišnjoj bazi ne razlikuje s obzirom na različitu satnu distribuciju potencijala izvora kroz promatranu godinu.

Vodeći se metodologijom za regulaciju i smanjivanje "kritičnog viška proizvodnje električne energije" te korištenjem EnergyPLAN modela za satnu analizu nacionalnog energetskog sustava, Lund uspješno provodi tehničku i tržišnu optimizaciju nekoliko izvora s obzirom na različite uvjete. Dok Lund i Vad Matheisen koristeći primjer Danske pokazuju da su sustavi zasnovani na potpunoj dobavi energije iz OIE mogući, no da je rješavanje udjela pojedinih izvora te planiranje takvih sustava vrlo složeno pitanje.

Kako bi ocijenili mogućnost prihvata varijabilnih OIE u elektroenergetske sustave Međunarodna energetska agencija - IEA predlaže korištenje FAST metodologije. Ova metodologija ističe skladištenje energije kao jedan od izvora fleksibilnosti koji uvelike mogu pomoći pri uravnoteženju sustava. Skladištenje energije Carvalho ističe kao jedan od 4 temelja budućih energetskih sustava u dekarboniziranom svijetu tzv. Post Carbon Society.

Prema Strategiji energetskog razvoja Republike Hrvatske iz 2009. godine očekuje se da će instalirana snaga vjetroelektrana u Republici Hrvatskoj u 2020. godini iznositi do 1200 MW, odnosno za istu godinu postavljen je cilj da udio vjetroelektrana u ukupnoj potrošnji električne energije u RH iznosi 9 do 10%. Dinamika izgradnje vjetroelektrana određivat će se u programima provedbe Strategije, ovisno o regulacijskim sposobnostima hrvatskog elektroenergetskog sustava, mogućnosti uravnoteženja u elektroenergetskom sustavu na otvorenom domaćem elektroenergetskom tržištu, sposobnosti domaće industrije i drugih čimbenika u izgradnji vjetroelektrana te raspoloživom proračunu za poticaje. Sadašnja gornja granica mogućnosti priključenja vjetorelektrana od oko 400 MW instalirane snage značajno je manja od predviđenog cilja dok će ciljevi nakon 2020. sigurno uključivati znatno veće kvote za priključivanje vjetroelektrana i solarnih fotonaponskih elektrana. Stoga će se morati uložiti znatni napori u razvoju i izgradnji elektroenergetskog sustava, kako bi se ostvarili ciljevi zadani Strategijom te ciljevi preuzetih obveza iz europskih direktiva i europskog energetsko-klimatskog paketa 20-20-20.

Bez obzira na način: proizvodnjom i skladištenjem vodika, korištenjem reverzibilnih hidroelektrana, u obliku biomase i proizvodnjom bioplina, u baterijama, u komprimiranom zraku ili u toplinskim i rashladnim spremnicima skladištenje energije je tehnološki i ekonomski vrlo zahtjevno. Financijska isplativost ovih procesa i tehnologija može se poboljšati integracijom energetskih tokova, transformacije i potrošnje energije na mjestu potrošača, kao što su korištenje vodika za proizvodnju električne energije u gorivim člancima te njegovo korištenje kao pogonskog goriva u transportu (Duić, Lund, Krajačić, Zoulias). Primjena vodika u gorivim člancima isto tako može se koristiti za kogeneraciju, to jest, može se integrirati proizvodnja električne i toplinske energije potrebne za zagrijavanje prostora ili proizvodnja tople vode (Vad Mathiesen). Pored integracije energetskih tokova, skladištenje energije povećava fleksibilnost distribuiranih energetskih izvora jer omogućava optimizaciju proizvodnje, a isto tako pozitivno utječe na povećanje penetracije distribuiranih izvora čime se osigurava sigurnost dobave energije. Za vrijeme niske potražnje ili jeftinije proizvodnje, energija se skladišti da bi se otpuštala iz spremnika kada je potražnja za energijom najveća, a cijena najviša.

Hipoteza i opis istraživanja

Cilj istraživanja je poboljšati postupak planiranja potpuno obnovljivih energetskih sustava primjenom skladištenja energije te pokazati na koji način pod zadanim uvjetima skladištenje energije maksimizira iskorištavanje obnovljivih izvora energije, osigurava sigurnost dobave energije, i minimizira utjecaj energetskih sustava na okoliš. Rad će provjeriti hipotezu da je moguće pronaći takav sustav skladištenja energije, koji će omogućiti integraciju energetskih tokova, transformacije i potrošnje energije na mjestu potrošača, proizvođača ili dobavljača energije, a koji će biti ekonomski, ekološki i socijalno prihvatljiv te će doprinijeti i povećanju energetske učinkovitosti.

Metodologija za optimizaciju skladištenja energije i integraciju energetskih tokova se temelji na rezultatima istraživanja koja su provođena u sklopu Šestog okvirnog programa za znanost Europske komisije (FP6) na projektima Advanced decentralized energy generation in Western Balkans (ADEG) i RenewIslands. Projekt ADEG se fokusirao na decentralizirane sustave za proizvodnju toplinske i električne energije dok je projekt RenewIslands nastojao riješiti problem veće penetracije obnovljivih izvora u otočne energetske sustave pomoću vodika kao energetskog vektora. U navedenim projektima uočena je potreba za istraživanjem i optimizacijom sustava skladištenja energije, uz integraciju energetskih tokova s čime bi se pridonijelo održivosti energetike lokalnih sustava, a time i održivom razvoju u cjelini. Nadalje, pored testiranja metodologije, provedena je i detaljna analiza energetskog sustava na dva računalna programa (matematička modela) za energetsko planiranje H_2RES i EnergyPLAN te je ispitana veza između nedavno predstavljene FAST metodologije i skladištenja energije.

H_2RES model je razvijen kao pomoćni alat Renewislands metodologije, a zasniva se na satnoj analizi s jedne strane potrošnje vode, električne energije, toplinske energije i vodika, a s druge strane vjetropotencijala, sunčeva zračenja, količine oborina, biomase, geotermalne energije, valova i klasičnih fosilnih goriva kao izvora odnosno resursa. Modul za vjetar koristi satnu brzinu vjetra, najčešće uzetu s meteorološke stanice na 10 m visine, koju prilagođava na visinu kućišta vjetroagregata te za dani izbor vjetroturbina pretvara brzinu vjetra u izlaznu snagu. Slično i ostali moduli koriste satne meteorološke podatke kako bi se iz odabranih postrojenja dobila odgovarajuća satna proizvodnja. Geotermalni modul i modul za fosilna goriva bazirani su na instaliranoj snazi postrojenja te njihovom minimalnom opterećenju. Modul za biomasu omogućuje detaljan izbor izvora te tehnologija za pretvorbu biomase u korisne oblike energije. Glavni modul za opterećenje uzima u obzir sve gore navedene podatke te na osnovu danog kriterija o maksimalno dopuštenom udjelu električne energije iz obnovljivih izvora u elektroenergetskom sustavu, provodi uravnoteženje (bilanciranje) sustava na satnom nivou te rješava pitanje viška i manjka energije ovisno o prioritetima postavljenim u jednadžbama modela. Sam model može isto tako optimizirati potrošnju vode i vodika. U tezi je iznesen detaljan opis glavnih modula H_2RES modela.

EnergyPLAN je ulazno/izlazni model koji provodi godišnju analizu s jednim satom kao korakom ili osnovnim periodom za bilanciranje. Za ulaze se definiraju potrošnja i instalirana snaga postrojenja, kao i satna distribucija opterećenja i potrošnje te distribucija intermitentnih OIE. Veliki broj tehnologija je uključen u programu, što omogućuje rekonstrukciju svih elemenata energetskog sustava te omogućava analizu za integraciju tehnologija. Model je namijenjen za kreiranje scenarija s velikim udjelom intermitentnih obnovljivih izvora te analizu kogeneracijskih-CHP sustava s velikom interakcijom između dobave električne energije i topline. EnergyPLAN je korišten za simulaciju 100% obnovljivog energetskog sustava otoka Mljeta u Hrvatskoj i cijele Kraljevine Danske. Korišten je u raznim studijama za ispitivanje velikog prihvata energije vjetra u energetske sustave, optimalnu kombinaciju obnovljivih izvora energije, upravljanje "kritičnim viškom proizvodnje" električne energije, integraciju energije iz vjetroelektrana koristeći električne automobile, potencijal gorivnih ćelija i elektrolizera u energetskim sustavima, kao i ulogu skladištenja energije, skladištenje komprimiranim zrakom i toplinski spremnici. U modelu je moguće koristiti različite regulacijske strategije stavljajući naglasak na toplinu i električnu energiju, uvoz/izvoz kao i na kritični višak proizvodnje energije. Izlaz su energetske bilance, rezultirajuća godišnja proizvodnja, potrošnja goriva te uvoz/izvoz. Program omogućuje uvođenje ograničenja koja nastaju kao potreba za pomoćnim radnjama koje osiguravaju stabilnost mreže. Dakle, moguće je imati minimum opterećenja postrojenja koja trebaju biti u pogonu cijelo vrijeme ili kao postotak opterećenja koji će se namiriti iz određenog tipa postrojenja, a koja mogu održavati stabilnost napona i frekvencije.

Glavni alati metodologije su algoritam te matematički modeli H_2RES, EnergyPLAN koji se mogu primijeniti na najmanje sustave kao što su kuće i stambene zgrade, otoci ili naselja do većih regionalnih i nacionalnih energetskih sustava. U tezi se navode i najnovija saznanja i spoznaje te osnovni tehnički podaci o skladištenju energije te integraciji tih skladišta u lokalne energetske sustave, a što je ujedno i jedan od prioriteta održivog razvoja energetike na europskom nivou.

Unatoč znatnom porastu instalirane snage vjetroelektrana u EU cijena električne energije na određenim tržištima nije porasla već neki autori tvrde upravo suprotno – shodno njihovim proračunima vjetroelektrane su smanjile cijenu električne energije na tržištu. Rathmann je pokazao da je dodatna energija proizvedena iz OIE, poduprta Njemačkom regulativom-EEG, smanjila cijenu električne energije u razdoblju 2005.-2007. za 6,4 €/MWh, dok je naknada za OIE u istom periodu porasla za 3,8 €/MWh. Iz toga autori (de Miera et al.) zaključuju da bi prodajna cijena električne energije bez instaliranih vjetroelektrana bila 2,6 €/MWh viša od stvarne koja je postignuta na tržištu. Zbog istog razloga se smatra da do 2020. neće doći do znatnog porasta cijene električne energije te da će se znatan dio dodatnih troškova proizvodnje i troškova nadogradnje mreže te dodatnih troškova vođenja sustava biti nadoknađen kroz smanjivanje prodajne cijene kao direktne posljedice povećanog iskorištavanja OIE.

Uspješnu primjenu tehnologija za skladištenje energije na tržištu je moguće ostvariti definiranjem tarifnog modela, sličnog onome koji se koristi za OIE, gdje se zajamčenom otkupnom cijenom (FIT – *Feed in Tariff*) investitorima jamči racionalan povrat sredstava u određenom roku. Korištenje istog tarifnog modela pogodovalo bi se i administraciji jer je već upoznata sa svim procedurama te bi ih lako primijenila na sustave za skladištenje energije. Jedini problem kod korištenja FIT za skladištenje energije je kompleksan sustav praćenja podrijetla proizvedene električne energije, a sa svrhom omogućavanja plaćanja samo onog dijela proizvedene energije koji se proizveo uskladištenom energijom iz OIE. U slučaju da PHS za pumpanje i podizanje vode u gornje rezervoare koristi samo električnu energiju s garancijom podrijetla i da turbina radi s nekom određenom vrijednosti faktora opterećenja (ukupnog nazivnog opterećenja na godišnjoj razini odnosno ekvivalentnoj proizvodnji energije), FIT koji bi bio plaćen za električnu energiju trebao bi omogućiti povrat investicije u prihvatljivom roku uz pokrivanje svih godišnjih troškova vođenja, održavanja te troškove nabave energije traženog podrijetla iz OIE te je predložena formula za njegovo izračunavanje.

U prvom dijelu teze daje se preglede dosadašnjih spoznaja te se iznosi uvodno izlaganje vezano uz skladištenje energije, u drugom poglavlju prikazuje se RenewIslands, ADEG i FAST metodologija. Zatim se ukratko opisuju modeli za energetsko planiranje korišteni za analizu energetskih sustava otoka i država. Rezultati analiza prikazuju modeliranje nacionalnog energetskog sustava u H_2RES modelu te energetskog sustava Republike Hrvatske uz pomoć EnergyPLAN modela (osvrt na prikupljene podataka, tehnologija, proračun referentnog scenarija, dobrih i loših strana modela te tehnička i tržišna analiza). Primjenom FAST metodologije dobivene su dodatne informacije o mogućnosti integracije OIE u energetski sustav RH što ukazuje na buduće potrebe za skladištenjem energije.

Posljednja faza istraživanja uključuje detaljan opis uloge skladištenja energije u energetskim sustavima baziranim 100% na OIE te komentiranje rezultata te finalno unapređenje metodologije.

Rezultatima se pokazuje da penetracija iz vjetroelektrana, solarnih elektrana do nekoliko postotak neposredne godišnje potrošnje moguća i to bez većih ulaganja u sustav i tehničkih nadogradnji, za veću penetraciju ipak treba razmišljati o dodatnim mjerama kao što su skladištenje energije, upravljanje potrošnjom, „pametno mjerenje“ te agregirano upravljanje proizvodnjom iz intermitentnih izvora, a što može uključivati i precizno predviđanje njihove proizvodnje.

Satna analiza s jedne strane varijabilne potrošnje te s druge strane intermitentnih, varijabilnih OIE kao što su energija Sunčeva zračenja i vjetar ukazuje na potrebu za adekvatnom kontrolom sustava zbog smanjenja u proizvodnji ovih izvora, uzrokovanom slabljenjem vjetra ili oblačnog vremena. Dok se na razini dugoročnih planiranja ove oscilacije predviđaju i rješavaju postavljanjem ograničenja na satnom nivou, za detaljnije proračune vođenja samih sustava biti će potrebno razmatrati kraće vremenske razmake te prilagoditi odnosno odabrati sustave skladištenja energije koji mogu odgovoriti i na te zahtjeve.

Termoelektrane koje su već izgrađene u elektroenergetskim sustavima, a koje karakterizira tehnički minimum ne moraju biti optimalna dopuna OIE. Uz to, njihova brzina odziva, naročito kada je opterećenje nisko, može biti poprilično spora. FAST metodologija može pomoći pri sagledavanju već postojećih rješenja za fleksibilnost sustava te dati smjernice za razvoj dodatnih kapaciteta. Skladištenjem energije s danas korištenim sustavima kao što su reverzibilne hidroelektrane, baterije i vodik, rashladni i toplinski spremnici itd. moguće je eliminirati neke od tehničkih barijera koje stoje na putu razvoja potpuno obnovljivih energetskih sustava.

Doprinos rada

Istraživanjem su stvorene dodane vrijednosti i proširivanje već stečenih spoznaja o energetskom planiranju, optimizaciji planiranja energetskih sustava koji uključuju skladištenju energije. Predložena metodologija vodi računa i o regionalnim specifičnostima (lokalne potrebe za energijom i lokalni resursi ovise o području) te je provjerena i na nacionalnom energetskom sustavu. Socijalna prihvatljivost pojedinog rješenja ili scenarija provjerena je kroz mogućnost otvaranja radnih mjesta vezanih uz obnovljive izvore energije i skladištenje energije. Intermitentna priroda većine obnovljivih izvora energije predstavlja poteškoće pri usklađivanju dobave i potražnje te izaziva tehničke probleme vezane uz slabe mreže. Skladištenje energije može imati ključnu ulogu u rješavanju ovih problema, te može pridonijeti povećanju penetracija OIE u slabim mrežama, pogotovo u izoliranim zajednicama i na otocima. Uvođenje indeksa nezavisnosti energetskih sustava te njegova korelacija s prostornim i vremenskim potrebama za skladištenje energije pokazuje kako skladištenje energije podržava nezavisnost sustava i osigurava sigurnost dobave.

Teza pridonosi razvoju preporuka za integraciju tokova energije, ostalih resursa i skladištenja energije u cilju bolje optimizaciju sustava. Razvijena je i metodologija za planiranje i razvoj Energetskog sustava Republike Hrvatske kao 100% neovisnog sustava sa 100% dobavom energije iz OIE te se daje preporuka za razvoj financijskih mehanizama za potporu sustava skladištenja energije u okvirima EU klimatsko energetske politike 20-20-20 te je diskutirano kako direktiva utječe na skladištenje energije, elektrifikaciju transporta te razvoj OIE.

Tezom se pokazuje da je izgradnja elektroenergetskog sustava, koji će dobavu električne energije u potpunosti temeljiti na obnovljivim izvorima s značajnom proizvodnjom iz intermitentnih izvora, kao što su vjetar i sunčevo zračenje, realno i moguće, no da gradnja treba biti pomno planirana kako bi bila primjenjiva u praksi.

Teza ima i svoj doprinos pri uklanjanju tehničkih barijera za postizanje potpuno obnovljivih energetskih sustava jer navodi na koji način određena postrojenja i tehnologije mogu doprinijeti maksimizaciji penetracije OIE te koje daljnje korake u istraživanju treba poduzeti da bi se ostvarili potpuno obnovljivi energetski sustavi. Istraživanja navedena u tezi mogu poslužiti i uklanjanju nekih društvenih barijera uzrokovanih nedostatkom spoznaja o doprinosu OIE i skladištenja energije (smanjenje ovisnosti o uvozu, smanjenje emisija, sigurnost dobave, otvaranje novih radnih mjesta). Pretpostavlja se da bi se kao što je bio slučaj s poticanjem proizvodnje iz obnovljivih izvora energije, predlaganjem financijskih mehanizama za poticanje skladištenja energije te razvojem sustava za garanciju podrijetla preuzete, uskladištene i isporučene energije iz sustava za skladištenje, moglo utjecati na ekonomske, barijere u zakonodavnim i regulatornim okvirima te tržišne barijere koje stoje na putu razvoja novim tehnologijama. Unatoč slabom prihvaćanju novih tehnologija i tehnoloških predrasuda u ostacima monopolno uređene elektroprivrede, potrebno je kontinuirano poticati potražnju za OIE. Stoga treba utjecati na pojavu takvih tržišnih sudionika koji će koristiti OIE ili će tražiti energiju proizvedenu u OIE. Velike reverzibilne hidroelektrane su posebno zanimljive kao nezavisni proizvođači zbog svojih konkurentskih mogućnosti, bez obzira na eventualne tarifne sustave za skladištenje električne energije.

Keywords

energy planning, energy storage, renewable energy sources, 100% renewable energy systems, feed-in tariffs, sustainable development

Ključne riječi

energetsko planiranje, skladištenje energije, obnovljivi izvori energije, potpuno obnovljivi energetski sustavi, poticajne tarife, održivi razvoj

Nomenclature

Roman	**Description**	**Unit**
a	Gross final consumption of energy from renewable sources	TWh
a_e	Coefficient	-
a_s	Stored RES-E	TWh
a_t	Directly taken RES –E to the system	TWh
b	Gross final consumption of energy from all energy sources	TWh
b_{EL}	Gross final electricity consumption	TWh
b_f	Electricity from fossil fuel plants	TWh
b_{FC}	Gross final energy consumption	TWh
b_{HC}	Gross final heating and cooling energy consumption	TWh
b_s	Gross final consumption of electricity covered by storage	TWh
b_t	Gross final consumption of electricity covered by the RES	TWh
b_{TR}	Gross final energy consumption in transport sector	TWh
$\mathrm{d}_{\text{Net-Import}}$	Trade on the market	MWh
E	Energy demand	kWh
$E_{bat,in}$	Energy used for battery charging	kWh
$E_{bat,out}$	Battery electricity production	kWh
E_{bio}	Biomass electricity production	kWh
E_{el}	Energy used for water electrolysis	kWh
E_{FC}	Fuel cell electricity production	kWh
E_{ff}	Electricity production from the fossil fuel	kWh
E_G	Energy from the grid	kWh
E_{geo}	Geothermal electricity production	kWh
$E_{G,s}$	Electricity export	kWh
$E_{H2_{WGO}}$	Total delivered electricity to the network by HSS	kWh
$E_{I,pot}$	Intermittent potential electricity production	kWh
$E_{I,t}$	Intermittent renewable electricity taken by the system	kWh
E_{load}	Electricity demand at the certain hour	kWh
E_{NOGO}	Energy taken from the grid without W_{GO}	kWh
E_P	Energy used for water pumping	kWh
$E_{PHS_{NOGO}}$	Electricity produced by PHS without GO	kWh
$E_{PHS_{TGO}}$	Electricity produced by turbinating extra inflow of water	kWh
$E_{PHS_{WGO}}$	Total delivered electricity to the network by PHS with W_{GO}	kWh
$E_{PV,pot}$	Solar PV potential energy production	kWh
E_r	Rejected energy	kWh
E_T	Hydro electricity production	kWh
$E_{W,pot}$	Wind potential energy production	kWh
E_{WGO}	Energy taken from the grid with W_{GO}	kWh
$E_{WV,pot}$	Wave potential energy production	kWh
EII	Energy Independence Index	-
$EPC_{W_{GO}}$	Price of RES-E used in pumping and electrolysing water	EUR/kWh
$\mathrm{Fac}_{\text{depend}}$	Price elasticity	€/MWh/ MW
$FIT_{PHS_{WGO}}$	Feed-in tariff for PHS units with GO	EUR/kWh
$\mathrm{FIT}_{\text{YPHS}}$	Incentive price for the current calendar year	EUR/kWh

FIT_{YPHS-1}	Incentive price from the previous calendar year	EUR/kWh
i	Discount rate	-
i	Number/type of services	-
I_i	Intensity of the energy use	-
IRP_{YPHS-1}	Annual retail price index	-
N	Payback period of the investment	year
N_i	Number of customers	-
M_i	Magnitude of use of service	-
OMC_{H2}	Yearly operation and maintenance costs of HSS	EUR
OMC_{PHS}	Yearly PHS operation and maintenance costs	EUR
P	Energy price	EUR/kWh
P_i	Penetration level	-
p_i	System market price	EUR/MWh
p_o	Basic price level for price elasticity	EUR/MWh
p_X	Market price on the external market	EUR/MWh
PHS_{GO}	Guarantees of origin assigned to PHS electricity	MWh
Q_i	Quantity of energy end-use	-
R	Annuity factor	-
TIC_{H2}	Total cost of investment in HSS	EUR
TIC_{PHS}	Total investment cost in PHS	EUR
TIC_{TPS}	Total investment costs for a hydropower plant	EUR
W_{GO}	Guarantees of origin for wind electricity	MWh
WGO	Index indicating renewable origin of electricity	-
x	Share of RES	-
Y	GDP	EUR

Greek	**Description**	**Unit**
α_e	Elasticity GDP-energy	-
β	Elasticity price-energy	-
φ_I	Intermittent limit	-
η_{H2}	Total efficiency of hydrogen storage system	-
η_{ELY}	Efficiency of electrolyser	-
η_C	Efficiency of the compressor and hydrogen storage	-
η_{FC}	Efficiency of fuel cells	-
η_p	Pumping efficiency	-
η_{PHS}	Total efficiency of PHS	-
η_s	Storage efficiency	-
η_T	Turbine and generator efficiency	-

Abbreviations - Description

CAES - Compressed Air Energy Storage

CEEP - Critical Excesses Electricity Production

CES - Croatian Energy Strategy

CHP - Combined Heat and Power

COP - Coefficient of Performance

CSHP - Industrial Combined Heat and Power

DC - District Cooling

DH - District Heating

DHP - District Heating Plant

EEG - The German Renewable Energy Act

EEX - The European Energy Exchange AG

ENTSO-E - European Network of Transmission System Operators for Electricity

ESCO - Energy Service Company

HEP - Croatian Utility Company

HPP – Hydro Power Plant

HR - Croatia

HSS - Hydrogen Storage Systems

HV- high voltage

JP - Jet Petrol

LPG - Liquefied Petroleum Gas

LULUCF (Land Use, Land – Use Change and Forestry)

NREAP - National Renewable Energy Action Plan

N.gas - Natural Gas

NPP - Nuclear Power Plant

O&M - Operation & Maintenance

PHS - Pumped Hydro Storage

PP - Power Plant (condensing)

RES - Renewable Energy Sources

SI - Slovenia

TSO - Transmission System Operator

V2G - Vehicle-to-grid

List of Figures

List of Tables

1. INTRODUCTION

1.1. Background

Energy systems and their components are crucial elements that make the normal activities of a modern society possible. The way we live today and the quality of our lives are based on a sufficient and uninterruptible supply of energy. Without continuous improvement and development of technology for each link in the energy chain, it would be impossible to imagine the present world. But what is more important, without planning for future development, and without detailed mapping of our current and future needs that will have to be satisfied by available resources, utilising previously or currently installed technology, our world could come to a dead-end or a point where no further progress can be made. History has taught us, that once a civilisation reaches a certain level of development and is utilising most of its available resources, the only possible growth and future development is by means of a technological leap or progress which will either allow more efficient use of available resources or expand the boundaries for utilisation of resources. Without progress and use of new technology, there is only one option for civilisation and that is to implode, collapse and self-destruct. The proven reserves of fossil fuels, which represents 80% of current primary energy use, will last according to BP, 46.2 years for oil, 58.6 years for natural gas and 118 years for coal [**1**]. With increasing demand, they could be exhausted even sooner. Currently the main problem related to the use of fossil fuels is not the estimated quantity of reserves (deep drilling, shale gas, methane hydrates, and in general technology development could increase the proven reserves and thus delay exhaustion) and related prices, but the environmental impact they have, which is mostly related to global warming.

The ultimate goals of sustainable development of modern societies are the planning and development of energy systems, so most of the developed countries have focused their energy policies on the development of sustainable energy systems. These systems should provide security of energy supply, and they should be competitive and have minimal impact on the environment.

In the long term, only renewable energy sources supported by energy storage can fulfil these requirements. Currently, there are many available RES and storage technologies so it is important to optimise their selection and integration in the energy systems. In certain research groups at AAU, IST and CRES it is known that energy storage technologies form a central component in every energy efficient system and they are necessary for the increasing use of renewables as well as ensuring the security of energy supply. The energy systems of the future must be made as efficient as possible, while people must become aware of the energy, economic and environmental benefit of storage and RES integrated solutions.

Energy storage technologies are necessary to increase the efficiency of energy systems in the future, so it is necessary to analyse storage behaviour, its scale and costs, not only in current energy systems but also in the lights of the development of new future technologies that may have an effect not just on the technical components of the system but also on the way systems are operated and managed. This introduces another uncertainty into the planning process, so the amount of storage will be a function of the system boundaries, which must take into account the demand and production side, but also their future evolution.

Energy independent systems are those which can independently operate for a certain period of time, so there is a certain optimal capacity of energy storage in a 100% independent energy system. In this period, all energy needs are satisfied from the system's own sources, directly taken to the system or stored and utilised at times of shortage of local resources.

To measure the energy independence of an energy system, it is necessary to introduce the Energy Independence Index (EII). Currently there are also laws that prescribe the required energy independency of a country. In the EU it is necessary to cover 90 days of average fuel supply (Directive 68/414/EEC, amended by Directive 98/93/EC), and under the EU Council Directive 2004/67/EC each Member State must have stored a sufficient volume of natural gas, or have the possibility of producing it, in order to satisfy the total gas demand of the calculated area for a period of 60 days.

- The primary energy import dependence of the European Union in 2008 was 53.8%, and it is expected that in the next 20-30 years it will surpass 70%. The situation in Croatia is similar, where, in 2008, its import dependence was 52.3%, while for 2030 it is predicted to reach 72%. This level of import dependence leads to decreased security of energy supply, due to the current geopolitical situation, in which the main sources of fossil fuels are in unstable regions and in which the competition for these resources from developing countries is growing.

EU energy strategy, and a compatible Croatian strategy, is focused on policies and measures that will bring an increase in the share of renewable and distributed energy sources and energy efficiency.

The results of previous research [**2**], [**3**] and [**4**] have shown that in order to increase efficiency and viability, there is need for energy storage, in primary or secondary form, in order to transfer energy surplus from one period to the period when there is a shortage. The problem of storage systems is that they add to the cost of already expensive distributed and renewable energy sources, making them, in market circumstances, even less economically viable. Although there are numerous storage technologies, such as chemical, potential (hydro) or heat energy, not all these technologies are optimal for each energy system. Several authors [**2**], [**3**] and [**5**] have shown that by integration of energy and resource flows it is possible to decrease the costs, and that by rational energy management and financial support that takes into account externalities, it is possible to devise such a system to be environmentally, economically and socially acceptable.

This thesis answers the question: what is the role of energy storage in the planning of an independent energy system based on a 100% RES energy supply? It also shows how in given circumstances energy storage maximises the utilisation of RES, provides security of energy supply and minimises the environmental impact of energy systems.

1.2. Research motivation, questions and objectives

1.2.1. Research questions

Before posing specific questions that are related to the role of energy storage in an energy system or in a 100% RES system, the basic question should be elaborated: Is energy storage indeed crucial for energy systems or can it be avoided?

Nature provided this answer long before any "anthropogenic" energy system was created. The evolution of living creatures shows that the organisms which survive in the environment with variable and sometimes scarce sources of food, water or other necessary substances, developed the means for storage of these precious resources. This ability allows them to store as much as possible in times of abundance and then to use it later in times of deficiency, allowing them to function normally and survive.

"The assimilation, storage and use of energy from nutrients constitute a homeostatic system that is essential for life. In vertebrates, the ability to store sufficient quantities of energy-dense triglyceride in adipose tissue allows survival during the frequent periods of food deprivation encountered during evolution. However, the presence of excess adipose tissue can be maladaptive. A complex physiological system has evolved to regulate fuel stores and energy balance at an optimum level". [**6**]

An analogy with the current energy systems can be drawn only figuratively, as society and energy systems are not living organisms, but operate and evolve on other principles, by human planning, inventions and technology development, which represent very dynamic and artificial selection, rather than the negative or natural selection that is present in nature. But still, lessons from nature can sometimes lead to good solutions that are applicable in the world of technology and science**.** European energy policy and the latest documents include statements that compare the energy system and its constituent elements with the organs of living organisms: "Europe's energy infrastructure is the central nervous system of our economy", and "Energy is the life blood of our society", [**7**] or that compare the energy infrastructure with the backbone of an energy systems: "the new challenge to 2020 is to provide the backbone for electricity and gas to flow where it is needed".[**8**] Thus, anyone more familiar with the functions of organs could conclude that energy storage can act like the adipose tissue (or fat) of energy systems. This is especially so if energy systems are to be based 100% on renewable energy sources, which means they will depend on their environment, just as living species depend on their habitat. Similar to living organisms, that need enough but not too much adipose tissue, the most suitable energy system will be one that operates with the optimal size and capacities of energy storage and that will be managed by a "complex physiological system" or in more technological words a complex ICT system for storage, regulation and balancing the system's needs at an optimum level.

Looking at the energy storage as the central component of a 100% RES systems the main question in the thesis is :

What role does energy storage play in the planning of a 100% RES system?

with the sub-questions:

Which parameters should be taken into account when planning a 100% RES system?

Which storage technologies should be considered, along with their size and location, in the energy chain of the energy system?

1.2.2. Research motivation

The EU-27 imports: 41.2% of solid fuels, 82.6% of oil and 60.3% of their gas needs [**9**]. Such dependence on imported hydrocarbons leads to decreased security of energy supply, as the import from Russia surpassed one third of the total imported fossil fuels, and approximately one third of the imported gas and oil comes from unstable geopolitical regions. Meanwhile, the competition for those resources from developing countries is progressively growing. With a high share of energy imports, the sovereignty of a country or region comes into a question. Thus, EU energy strategy, and a compatible Croatian strategy, is focused on policies and measures that will bring an increased share of renewable and distributed energy sources, increased energy savings and improved energy efficiency. All these measures will increase the security of energy supply and reduce green house gas emissions. Moreover, the latest actions of the EU energy policy makers are focused on promoting and planning of the Post Carbon Society. The four pillars of energy systems of the Post Carbon Society are presented by Carvalho et al. [**10**] :

- Renewable Energy
- Building as Positive Power Plants
- Energy Storage
- Smart grids and Plug-in Vehicles

This energy system and society will also be the result of strong political, public and economic support for all renewable energy technologies. Political support has been or still is reflected through European Energy Policy and mostly through its directives such as Directive 2001/77/EC for the support of generation of electricity from renewable energy sources (RES-E), a new directive on the promotion of the use of energy from renewable sources 2009/28/EC, RES and Climate change package 20-20-20, the new European Energy strategy and Energy infrastructure plan for 2020, the Roadmap to 2050 and many other recommendations and reports. While Directive 2001/77/EC has the target to meet 12% of electricity production from RES, the new RES directive sets RES target for 2020 of 20% of the gross final energy consumption, and the most recent initiatives are already starting the process of converting the EU Energy supply to 100% RES. On 15 April 2010, the RE-thinking 2050 Campaign [**11**] was launched in the European Parliament under the patronage of Prof. Maria Da Graça Carvalho. In this campaign the European Renewable Energy Council (EREC) outlines a pathway towards a 100% renewable energy system for the EU as the only sustainable option in economic, environmental and social terms. According to their projections, the European Union can switch to a 100% renewable energy supply for electricity, heating and cooling as well as transport, and harvest the positive effects of Europe's energy supply system and reduction of CO_2 emissions. RE-thinking 2050 and similar work and initiatives [**12**], [**13**], [**14**] and [**15**] will help to create the Post Carbon

Society for the EU. As highlighted by Prof. Carvalho: A post carbon society makes it possible to reframe the energy and climate change challenges as opportunities, not just to foster a wealthier society, but also a more equitable and sustainable one.

Various technologies for energy storage are not in fact novel and they have been present on the market for more than a century. What is novel and smart in these technologies is their use for specific purposes and their synergies with new processes and energy sources.

An energy storage system can help with the integration of the energy flows, the transformations and energy demand at the location of the energy end-use or close to it. Smart energy storage will support all four pillars of the post carbon society and some of this support has been calculated by specific energy planning programs.

Decentralised energy generation (DEG) is becoming a promising solution for supplying the increasing energy demand, especially on islands and remote regions. There are several advantages of DEG: it allows use of diverse renewable energy sources (RES), it allows the heat energy normally wasted in fossil fuel-based electricity production to be captured and used [**16**]; it is also very suitable for trigeneration and polygeneration with integration of different energy flows (heating, cooling, electricity, transport fuel, etc.) and installation of various energy storage technologies. These advantages, together with the possibility of installing DEG near the place of energy consumption, represent a platform for achieving efficient energy use and thus contributing to sustainable energy development.

Although DEG was present from the beginning of modern energy utilisation, cheaper energy generation in centralized units and cheap fossil fuels held back the advanced research in technologies suitable for DEG. Islands and isolated regions were the only places where installation of DEG was essential, and that is the why research into the integration of DEG technologies in island energy systems went the furthest. A sufficient growth of energy supplies to meet human needs [**17**] is essential for achieving sustainable energy development. In isolated regions which do not possess their own fossil fuel resources, as on most islands, the only way to achieve sustainability goals is to generate energy from a growing range of clean and renewable sources; wind power, solar energy (PV and solar thermal collectors), small hydropower plants, biomass and ocean energy. The main problem with these sources, except biomass, is their intermittent nature, so in order to use them effectively and to ensure security of supply, it is essential to integrate energy storage into the energy system.

The objective of research is the improvement of a planning procedure for 100% RES systems by use of energy storage and analysis of the contribution of that energy storage to the maximisation of RES integration, security of energy supply and minimisation of the environmental impact of energy systems. The research work proves the hypothesis that it is feasible to find an energy storage system that will integrate the energy flows, the transformations and energy demand at the location of the energy end-use, generation or distribution, and that will be economically, ecologically and socially acceptable, while in addition contributing to the increase of energy efficiency.

1.2.3. Energy system

A function of every energy system is to provide enough energy in places where it is needed and at the time when it is needed. Thus energy cannot be treated like other goods or services, especially electricity, as the balance between electricity supply and demand must be kept in a short tolerance range in order to provide the required frequency and voltage. By integrating energy storage into the systems it is possible “to decouple the production from the consumption” and thus to improve the market conditions and trading.

1.2.4. Energy storage - technologies and application

Electricity Storage - The use of traditional energy storage for increasing RES penetration has been tackled and proposed by many authors. The most widespread energy storage technology in the power systems around the world is pumped hydro storage (PHS). The use of PHS for integration in the existing water supply system and increasing the wind penetration from 25% to 70% in the electricity supply of the island of Corvo is proposed in [**18**] and a similar case that also, includes sea desalination is given in [**19**]. The use of PHS for increasing wind penetration on the island of Lesbos and an algorithm for sizing the PHS units are described in [**20**] and [**21**]. In both papers the authors showed that PHS can have excellent technical and economic performance while doubling the RES penetration. Their proposal for reducing the installation costs considers the use of an existing water tank on the island as the lower reservoir of the PHS. Similar studies for the use of PHS in the several Greek islands are provided in [**22**] and [**23**], where PHS is described as the optimum energy storage system for bigger islands. The use of batteries to secure a grid with a high penetration of RES and other distributed energy resources is proposed in [**24**]. In the same paper, the authors compared lead–acid batteries for stationary applications with eight other storage technologies. The storage systems are addressed and evaluated on a technical and economic basis and at three different levels of storage application (production, transmission and end-user level). The main conclusion is that improvements need to be made in energy management and reliability to allow widespread deployments of lead–acid batteries in grid markets. The economic viability of batteries and their impact on power system operation is investigated in [**25**] and [**26**], where the authors addressed several case studies and proposed the sizing of batteries. They concluded that the implementation cost of battery storage can be justified by voltage enhancement, load capacity release, loss reduction and fuel saving. The evaluation of compressed air energy storage (CAES) plants in future sustainable energy systems with a high share of fluctuating renewable energy is explained in [**27**]. The authors proved that CAES cannot alone solve the problems of excess electricity production, while the feasibility of plants is possible if they operate on both the spot market and the regulating power market. The use of emerging technologies, such as flow batteries and storage connected to new energy carriers has been explained in [**25**], [**28**] and [**29**]. A recently conducted study in the frame of the HAWE project at the Faculty of Mechanical Engineering and Naval Architecture – University of Zagreb provides a detailed review and comparison of flywheels, compressed air, batteries and ultracapacitors in terms of efficiency, capital costs, energy/power capacity, and reliability [**30**]. In a similar description of state of the art of storage technologies in the power sector, detailed mapping of the available technology, its maturity stage and application are provided [**31**]. Some novel principles for the use of thermal storage as possible electricity storage in power systems in cases where PHS or CAES are not applicable are explained in detail by the authors in [**32**].

Heat storage - Thermal storage and heat pumps could be used to store excess from RES production, as shown in [**3**], or effectively combined with smaller scale applications to raise profits, as modelled and explained in [**33**]. A more detailed review of thermal storage, and in particular, thermal storage with the phase change materials and their application is given in [**34**]. In recent studies and a demonstration project, seasonal heat storage on the demand side has been proposed.

Cooling thermal energy storage – CTES cooling storage can also be used for the integration of renewable energy sources [**35**] and [**36**]. In general, CTES systems can be divided into two main types, those using sensible heat (water) and those using latent heat (water/ice and eutectic salt hydrates). The selection of the storage type will depend on the application and desired temperatures. A review of CTES and its application for air conditioning was presented a decade ago by Hasnian in [**37**]. A more recent review has been given by [**38**] with a tabular presentation of the most important characteristics of CTES. The first of the main types of CTES systems, as mentioned previously, is sensible CTES, which stores energy by changing the temperature of a storage medium such as water, so the predetermined temperature range, quantity of media and its heat capacity usually determine the available storage capacity. The second type of CTES uses latent heat. Latent thermal energy storage is most obviously perceived in the conversion of water into ice. The principle is used in cooling systems incorporating ice storage. When the storage material melts or vaporises, it absorbs heat, and when the opposite, crystallisation or condensation, occurs, which releases heat. This change is used for storing heat in phase change materials (PCMs), the most typical being water, salt hydrates, and some polymers. Today, glycol ice-storage systems enjoy a great deal of market popularity, because of their simplicity and low installation cost. Various subsets of CTES processes have been investigated and developed for cooling in buildings, industrial applications, and utility and space power systems.

CTES provides a high degree of flexibility since it can be integrated with a variety of energy technologies, for example, solar collectors, biofuel combustors, heat pumps, and off-peak electricity generators.

Hydrogen storage – The possibility of using hydrogen as an energy vector in islands energy supply is not a novel idea. In the 1990s the authors of [**39**] and [**40**] calculated the size of the necessary hydrogen equipment for the energy supply of the island of Lastvo in the Adriatic Sea, and also made an optimization of hydrogen storage. Ten years later, the authors in [**2**] presented similar solutions and proposed hydrogen produced by electrolysis as a tool for increasing penetration of intermittent sources. The authors also tackled the problem of energy storage which it is necessary to use in combination with intermittent renewable sources for their better integration in energy systems and to achieve security of supply. Today fuel cells and hydrogen are widely used in demonstration projects by automotive industry, small mobile applications, the power sector and stand alone power supplies. Even though there is a wide range of commercial fuel cells and hydrogen production products on the market, full commercialisation and application of hydrogen technology has still not happened and it is expected in the range of 10-20 years. In 2010 there were in total 90 MW of shipments of fuel cells [**31**] and compared to, for example, PV, this was almost the same yearly production as in 1996. Since then annual PV production has grown to 24,000 MW in 2010 but with much higher growth rates than those for fuel cell technology.

Biomass storage - In general, raw biomass has lower energy density than other fuels such as coal, oil, etc. The heating value is in the range of 10-20 MJ/kg compared to fossil fuels 25-45 MJ/kg, so power plants or other conversion facilities (biorefineries, pellets factories) need to store huge amounts of biomass on site in order to ensure uninterrupted operation. This calls for the optimisation of supply transport and storage processes as biomass can be stored on either the production site, or the utilisation site or the optimal location of the transport logistic centre. Similar problems are faced also by individual users, which tend to store as much as possible in order to avoid price increases during peak periods. From the planning process onwards, there are many issues to solve with sustainable production, transport and utilisation, which also require the use of other resources such as water, growing land, fertilizers, etc. The best characteristic of biomass as a renewable energy source is that it can be quite easily stored, and can act as seasonal storage or a reserve. It can also be converted to biofuels and biogas and stored in already built storage infrastructure.

Gas storage – This is a widely used technology in the gas grids and the total amount of storage capacity in Europe was 85,380 x 10^6 m^3 in August 2011. Storage facilities are located in sites ranging from caverns and cavities in salt formations to depleted gas fields and aquifers. They are used for various purposes, from market arbitrage, to balancing the system and ensuring the security of supply, but also to comply with various durations of gas import contracts that require constant imports during the whole year so that the storage is filled in the summer when consumption is low and discharged during the winter when consumption is at peak.

Even though not directly linked to 100% RES systems, gas storage and gas infrastructure could be filled by biogas or syngas or, in specific circumstances, even hydrogen.

Storage of liquid fuels - Oil tanks, near refineries and power plants or oil terminals in the ports, are the most widespread examples of the storage of liquid fuels. The necessary storage of liquid fuels in Europe and methodology for its calculation are prescribed by the previously mentioned Directive 68/414/EEC, amended by Directive 98/93/EC. The key element of the directive is that each country must store oil sufficient for at least 90 days of operation. Similar to the use of gas storage for storing biogas, liquid fuels storage could also be utilised for biofuels or synthetic fuels.

Alternative storage technologies - New developments in energy storage technology are emerging very rapidly as there is an increased need for storage in the integration of renewables, for the greening of the transport sector, in mobile applications and stand alone power systems. Synthetic fuels could become an interesting option as they can use existing infrastructure, especially in the transport sector. The transport sector's transition to renewable energy presents significant challenges since it is historically dependent on liquid fuels and it is characterised by a wide variety of modes and needs [**41**]. Recycling CO_2, using electrolysers and wind energy, into synthetic fuels provides lower CO_2 emissions, storage options, and geographical independence, and solves supply related issues of conventional fuels and biofuels while electrolysers provide an option for regulating the energy system [**41**].

1.2.5. Basics of energy system planning and modelling

The planning of energy systems and components of the energy chain with a centralised energy supply, taking a macro-economic and top-down approach as well as a micro-economic and bottom-up analysis, was much simpler than the current planning of systems with a decentralised and distributed energy supply. In centralised systems, the energy/power flows from centralised production to decentralised demand, with very rare back (return) flows, which is not the case with decentralised and distributed production, when it is frequently possible for power to flow in both directions. Electricity demand is variable, so the planning and operation of a centralised system is ensured through the adoption and control of a supply side that was made flexible enough to follow variable demand. In new decentralised and distributed systems with RES supply, the supply side also becomes variable and, in some circumstances, uncontrollable.

Regarding energy planning there are several terms: short-term energy planning 5-10 years, medium-term for 10-20 years, long-term planning for over 20 years (20-40) years, etc. From the power system point of view, short-term planning of system operation is one day ahead, medium-term plans for a week to several weeks, and long-term, for up to a year. In liberalised markets scheduling is mostly done according to the market rules.

Bottom-up analysis of energy supply consists of a quantitative description of energy conversion, use and related technologies. Bottom-up analysis can give better predictions, but collecting detailed data on the current status of the demand and technology in the system and predicting future developments with reasonable uncertainty is very time consuming and heavy on resource.

In the bottom-up approach, demand is predicted by end-use models that are characterized by the equation:

$$E = \sum_{i=1}^{n} Q_i I_i \quad (1)$$

where E is demand, Q_i is quantity of energy end-use (for some commodity or service), I_i is intensity of the energy use for the service i (i =1..n) number/type of services.

$$Q_i = N_i \cdot P_i \cdot M_i \quad (2)$$

where N_i is the number of customers, P_i is penetration level, M_i is magnitude of use of the service.

The top-down approach is based on econometric models. The biggest advantage but also a disadvantage of this approach is that it is easy to determine in business-as-usual scenarios from historic development and historical trends. A the same time, however, the factors that are determined by a regression analysis are mostly valid in the range of regression, while further developments are usually unknown and depend on many factors that are not included in regression, e.g., policy development, market saturation rate, consumer behaviour, etc. Hopefully, if a developing country is pursuing a policy similar to that of a developed country and has a similar climate and other conditions, then it can compare its own calculated and predicted factors with those calculated for the similar country.

$$E = a_e Y^{\alpha_e} P^{-\beta} \quad (3)$$

where E is demand, a_e is the coefficient, Y is GDP, α_e is GDP-energy elasticity, β is price-energy elasticity.

Elasticity is calculated by formulas 4 and 5:

$$\alpha_e = \frac{\frac{\Delta E}{E}}{\frac{\Delta Y}{Y}} \quad (4)$$

$$\beta = \frac{\frac{\Delta E}{E}}{\frac{\Delta P}{P}} \quad (5)$$

1.2.6. Uncertainties in forecasting of demand, supply, market prices and energy policy impacts

There are many uncertainties in the energy planning process, mostly related to the assumptions and constraints made in planning, and to the time-span covered by the planning process [**42**]. The longer the planning period is, the greater is uncertainty. From the supply side, the uncertainty has been increased by application of intermittent RES that could be forecast only until a certain level. Uncertainty in forecasting will require greater flexibility of the system and reserves. In the hypothetical case of 100% accurate forecasts, flexibility just needs to cover a net load [**43**], but this is not the case in practice. As an illustrative example, the typical values for wind power forecast in Germany are given in Table 1. Similar to wind production forecast, forecasting of energy production was also conducted from 12.3 MW of solar PV plant in Spain. The inaccuracy in the daily production forecast over the period August 2009 to September 2010 was around 50% on average, the lowest value being 25.4% [**43**].

There is also great uncertainty in the demand-side planning, as this is correlated with population increase or decrease, GDP, industrial development, policy measures, etc. Technology development and learning curves (explained further in section 1.2.8) also introduce another level of uncertainty into the calculations.

Table 1. Mean errors in wind power forecasts (% of installed wind capacity).

Uncertainty	Part of Germany (≈350 km)	All of Germany (≈ 1 000 km)
Day-ahead	6.8%	5.7%
4 hours ahead	4.7%	3.6%
2 hours ahead	3.5%	2.6%

1.2.7. Energy policy and energy planning – A closed loop process

Energy planning and energy policy are two interactive processes. One depends on the other and one is also the cause of the other.

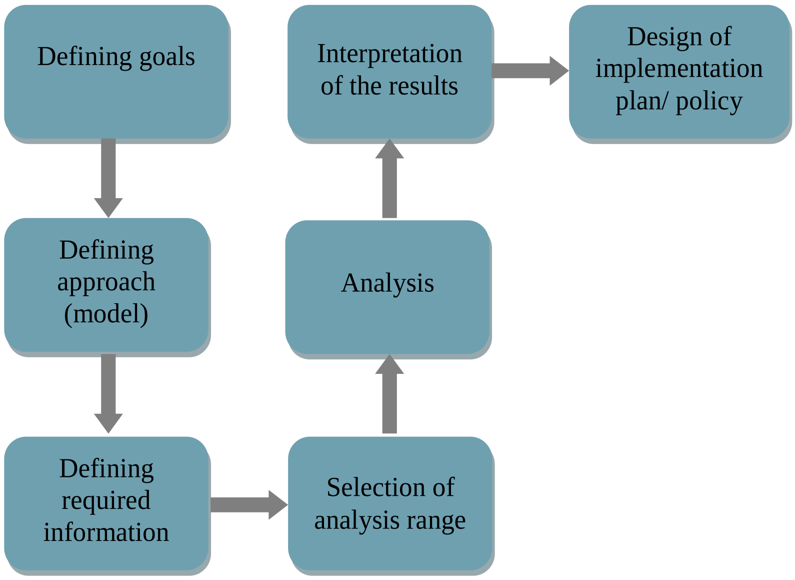


Figure 1. A process of energy planning as described by Zeljko [**42**].

As described by Zeljko in [**42**], energy planning should be a continuous process whose clear goals should be stated and presented to energy planners. The planners must then define and calculate several alternatives, define all details and prepare them for presentation to policy and decision makers. The results of analysis should be constantly updated with new data so that the planners will be able to show the most realistic and sometimes optimal solution, calculated under certain constraints and assumptions. In the light of EU policy, the goals that were put energy planners included mandatory targets for the share of renewable energy sources in the gross final energy consumption. The planners then evaluated several scenarios and as their final plan or policy, together with policy makers, proposed NREAPs to the Commission (delivery of NREAP was mandatory for each member state). As the goals and NREAPs have now been agreed, all stakeholders can track their fulfilment while the energy planners, according to developments on the ground and developments of new technologies and price changes, will constantly update the models and propose new alternatives to interested parties, or will show what opportunities or threats lie behind certain solutions/decisions. As this thesis has defined the goal of energy planning as the achievement of a 100% RES system, the models used are H_2RES and EnergyPLAN while the required information came from the application of the Renewislands/ADEG, FAST and RESTEP methodologies. The range and data vary from case to case, and the most interesting results are interpreted, including some policy proposals in the form of feed-in tariffs for support of energy storage technologies.

1.2.8. 100% RES systems - past, present and future of RES technologies

Many agencies (IEA, Danish Energy Agency, Austrian Energy Agency), research centres and institutes (JRC, RISO, EIHP etc.), government, non-government and industrial organizations are analysing and describing the historical development, current status and future progress of technologies for the utilisation of renewable energy sources. The Joint Research Centre of the European Union publishes a regular review of low carbon energy conversion technologies, in its so called Technology Map [**31**] which is also a reference document of the SET-Plan and SETIS technology calculator.

The development of RES technologies can be explained with a learning curve which says what is or will be the cost reduction of a certain technology when its market capacity is doubled. So it can be concluded that the learning effect is measured in terms of the reduction in the unit cost (or price) of a product as a function of experience gained from an increase in its cumulative capacity or output. The average PV price in the period 2009-2010 fell from 4.5 to 3.5 EUR/W while installed production capacity almost doubled, with annual production growing from 12 to 25 GW of yearly capacity. In this case, the learning rate based on production capacity (not cumulative installed capacity) is higher than 22% which is in line with other energy technologies that have learnig rates between 20-35%. Solar PV is also becoming more efficent, which will certainly reduce the costs of material, and with a high level of automation processes, learning rates could be increased. In the period 2000-2011 most of the new generation capacity was in gas power plants (116 GW), followed by wind power plants, which showed the most progressive growth of installed capacity (84 GW) and solar PV (47 GW) [**44**].

1.2.9. Intermittent RES and energy system planning and security of supply

Before planning and achieving the 100% RES systems there are two other characteristic phases in the introduction of RES technologies in such systems (as explained by Lund [**45**]). First is the introduction phase, when few or no RES are introduced to the system. In this phase there is no need for change the system planning and behaviour, as any type of RES can be easily integrated into the system. In the second phase, a large-scale integration is envisaged, where detailed planning is required as intermittent RES will influence the system operation. The last phase is achieving a 100% RES system, which includes very detailed planning and modelling of the necessary capacities, uncertainty levels and the need to integrate the old technology with the new.

1.2.10. Planning of 100% RES system (from an island to the entire continents)

Due to the small size of their energy systems, islands were the first places where it was possible to go through all the phases of development of 100% RES systems. Technical and economic planning of small systems was not so demanding. Also it was possible to show the effectiveness of energy storage options when transforming fossil fuels based systems (usually diesel blocks that have certain amount of flexibility) to systems based on hydrogen. Currently, several islands have managed to achieve 100% RES electricity supply and a large share of RES in heat supply, including Samsoe and Aro in Denmark. Today there are many studies that have analysed how far is possible for countries, regions, and the entire world, to meet 80–100% of end-use energy demand from renewable energy by 2050 or even sooner. National scenarios exist for Australia [**46**], Denmark [**12**], Germany [**47**], Ireland [**48**], Japan [**49**], New Zealand [**50**], Portugal [**15**], the United Kingdom [**51**]; there are several regional studies, for northern Europe [**52**], south east Europe [**53**], the whole of Europe [**11**], and there are also studies that have analysed the entire world [**54**], [**55**], [**56**] and [**57**].

1.3. Novelty and significance of the research

The novelty of this research is in its holistic approach to the planning of a 100% renewable energy systems with particular emphasis on integrated energy storage.

Other key areas of significance are: 1) The introduction of an energy independence index and its correlation with time and space needs for energy storage. 2) Recommendations on the integration of energy, other resources flows and energy storage for better system optimisation. 3) Development of methodology for planning and analysis of the energy system of the Republic of Croatia as a 100% independent system with a 100% RES supply. 4) Development of the financial mechanisms for energy storage in the framework of the EU climate energy policy 20-20-20.

1.4. Hypothesis

It is feasible to find such an energy storage system that will integrate the energy flows, the transformations and energy demand at the location of the energy end-use, or close to it, and that will be economically, environmentally and socially acceptable, while additionally contributing to the increase of energy efficiency.

To enhance the security of energy supply, and the efficiency and safety of the grid energy system in conditions of increased distributed and renewable energy sources (RES) penetration, it is necessary to enhance the energy storage capacities on the side of the power plants, transmission and distribution networks as well as on the end-use side.

It is necessary to define a methodology for optimising the energy storage system; based on mapping the local needs for electricity, heating and cooling energy, transport fuels and similar, local renewable resources, cogeneration and polygeneration potentials, and possible energy storage scenarios such as pumped storage hydro, batteries, hydrogen, CAES, etc. The proposed methodology will, apart from addressing the technically optimal solution and taking its efficiency into account, integrate the solutions for reducing emissions to the environment, enhance employment, gain public support, and involve local communities. The methodology can play a significant role in island development and the development of sustainable tourism, given that local energy systems are a huge burden for the environment. Besides, the methodology can contribute to the sustainable development of cities, where the consumption density enables the greatest advances in rational and efficient energy utilisation, and significantly contributes to the energy supply level.

1.5. Methodology and models

The methodology for energy storage and the energy flows integration is based on the research results of the European Commission Framework Programme projects ADEG: Advanced Decentralised Energy Generation in the Western Balkans (FP-6) and RenewIslands: Renewable Energy Solutions for Islands, Target action A (FP-5). The ADEG project was focused on decentralised systems for heat and electricity production, while the RenewIslands project aimed to manage the increased problem of RES penetration into the islands' energy systems with hydrogen having the role as the energy vector. The results of these two projects have shown the necessity for research and optimisation in energy storage systems, followed by energy flow integration, in order to support the sustainability of local energy systems and overall sustainability. Besides the testing of the methodology a detailed energy system analysis is performed on the two energy planning tools (mathematical models) H_2RES [**2**], [**5**] [**18**], [**28**] and [**58**] and EnergyPLAN [**3**], [**13**], [**59**], [**60**] and [**61**] together with analysis of the relation between energy storage and the recently published FAST methodology [**43**]. The H_2RES model is designed in support of the RenewIslands methodology [**18**] and it is primarily used for balancing between hourly time series of water, electricity, heat and hydrogen demand, appropriate storage facilities and supply from wind, solar, geothermal, biomass, wave, and hydro or fossil fuel resources. The wind module uses the hourly wind velocity data mostly obtained from the nearest meteorological station at 10 metres height, adjusts them to the wind turbines hub level and, for a given choice of wind turbines, converts the velocities into the output. Other similar modules use meteorological data to get an hourly production output from selected technologies. A more detailed description of the model is given in section 2.2 and in the papers [**2**], [**5**], [**18**], [**28**] and [**58**]. The H_2RES model is adopted for the case of Portugal by a wave module. The EnergyPLAN model is an input/output model that performs annual analyses in steps of one hour. Inputs are demands and capacities of the technologies included, as well as demand distributions and fluctuating renewable energy distributions. A number of technologies can be included, enabling the reconstruction of all the elements of an energy system and allowing analysis of the integration technologies. The model is specialised in making scenarios with large amounts of fluctuating renewable energy and analysing CHP systems with a large interaction between the heat and electricity supply. EnergyPLAN was used to simulate a 100% renewable energy-system for the island of Mljet in Croatia and the entire country of Denmark [**12**]. It was also used in various studies to investigate the large-scale integration of wind energy [**3**], optimal combinations of renewable energy sources, management of surplus electricity, the integration of wind power using electric vehicles, the potential of fuel cells and electrolysers in future energy systems [**62**] and the effect of energy storage, compressed-air energy storage and thermal energy storage. The model can be used with different regulation strategies, putting emphasis on heat and power supply, import/export, and excess electricity production and using the different components included in the energy system being analysed. Outputs are energy balances, resulting annual productions, fuel consumption, and import/exports. It provides the possibility of including restrictions caused by the delivery of ancillary services to secure the grid's stability. Hence, it is possible to have a minimum capacity running during all hours and/or a percentage running from a certain type of plants required to secure voltage and frequency in the electricity supply. The main tools of the methodology are the mathematical models H_2RES and EnergyPLAN, which are applied in analysis from the smallest systems such as houses and residential buildings to bigger systems such as islands or countries. Moreover, the most recent findings and technical data are collected in the fields of energy storage and integration of the storage in local energy systems, which is one of the priorities of sustainable development of energy systems on the European level.

1.6. Data and constraints

Publicly available data were used for most of the case studies in order to allow replication of the methodology to other regions, countries and case studies. Another important issue related to the use of publicly available data is to avoid any publication of commercially confidential data that could harm companies such as HEP, REN etc., and cause financial loss due to their publication or the publication of results coming from these data that might influence the market.

ENTSO-E - The European Network of Transmission System Operators for Electricity represents 41 transmission system operators (TSOs) from 34 European countries. ENTSO-E publishes most of the statistical data relevant to the power system operation, as well as production, consumption and exchange of electricity between power systems, net generating capacities and hourly loads. Statistical errors are not published with the data, but anyone interested can calculate these from the range of the historical data provided.

REN - is a Portuguese utility company acting as transmission system operator for electricity and gas networks as well as LNG terminals. Most of the data for the case study of Portugal were obtained from REN’s webpage and publications.

HEP - is a Croatian utility company in charge off transmission, distribution and production of electricity and production and distribution of heat to district heating systems. Data from their official publications and web pages were used for the Croatian case study.

MINGORP – the Croatian Ministry of Economy, Labour and Entrepreneurship publishes detailed yearly energy statistics [**63**] and [**64**]. It is also in charge off the registry of RES projects in Croatia. Data from both sources have been used in the Croatian case study.

METEONORM - is commercial software that provides a wide range of meteorological data taken from a large number of the locations around the world. Available data includes wind speeds, temperatures, solar radiation, etc. Meteonorm is able to interpolate hourly data between measured locations according to its own developed methodology.

PV-GIS - is an on-line application developed by JRC which provides a vast range of GIS services related to solar irradiation, production of PV plants, optimal angles, etc. [**65**]. PV-GIS was mainly used to adapt global solar irradiation from a horizontal surface to an inclined surface for the purpose of calculations in the H_2RES model.

DHMZ – the Meteorological and Hydrological Institute of Croatia is the main institution for meteorology and hydrology in Croatia. Data provided have been adapted and used for calculation of the case studies of the Croatian islands (Mljet, Losinj and Unije).

More accurate wind measurements for the Croatian region of Dalmatia were acquired from site measurements at ten locations. AWSERCRO, Assessment of Wind and Solar Energy Resources in Croatian Pilot Region, was a project financed by the European Commission as part of its technical assistance under the CARDS program. A major component of this project was a measurement campaign and acquisition of wind and solar data. On-site wind measurements were taken from June 2007 until March 2009 by the Energy Institute Hrvoje Pozar. The measurement locations are on well-exposed and remote sites located in the region of Southern Dalmatia to achieve a high spatial density of measured data [**66**].

1.7. Results

The presented results include findings related to energy planning of 100% RES systems for islands and two national energy systems. They also include necessary changes in methodologies for energy planning in order to have a better view off storage possibilities. The differences between methodology application for the islands and the country have been solved by introducing new levels for qualitative mapping. By a simple procedure, Croatian energy and other needs have been mapped, resources have been identified and more accurate wind energy production has been calculated. This resulted in the planning of a Croatian energy system with several types of energy storage for the year 2020, period 2030-2050 and finally for a 100% RES system in 2050. The results show that Croatia may have problems in reaching the RES targets for 2020 if the final energy consumption is equal to one assumed in the calculations. The islands case studies have been additionally evaluated for social acceptance through the possibility of creating new jobs in the energy sector. An energy independence index has been proposed as a measure of the sustainability of a certain plan that includes storage technologies.

The influence of feed-in tariffs for storage technologies in the lights of EU Directive 2009/28/EC has been investigated, as well as the impact of the Directive on the development of pumped storage hydro capacities and the achievements of the Croatian goals set by the EU climate and energy package 20-20-20.

1.8. Structure of the thesis

A main purpose of the proposed research was to create added value and to expand the existing acquired knowledge of energy planning, and the optimisation and energy storage fields, by developing new knowledge that will enhance the development of the planning of smart energy networks and the integration of energy flows. The developed methodology takes into account a regional approach (local energy needs and the local resources differ according to the area) and it is tested on the national energy system. Social acceptance of the given solution or scenario is tested through its ability to create new jobs related to the RES and energy storage. The first part includes elaboration of the methodology that is based on the verified steps of the Renewislands, ADEG and FAST methodologies. The next phase includes analysis of the national energy system using the H_2RES model, and is followed by analysis of the Croatian energy system using the EnergyPLAN model. Analysis includes: data collection, technologies, calculation of referent scenarios, selection of good and weak points of the model and technical and market analysis. New information regarding the integration of RES into the energy system of the Republic of Croatia is obtained by application of the FAST methodology and by more detailed calculation of hourly production of wind power plants. This also leads to easier planning of future needs for energy storage. The last phase includes detailed description of the role of energy storage in the energy systems based on 100% RES supply, and the influence of current EU legislation on energy storage and on the proposal for an alternative financial mechanism for storage technologies. It also includes a description of the results, final improvements to the methodology, and conclusions.

2. METHODOLOGY

2.1. RenewIslands/ADEG Methodology

The RenewIslands methodology [**18**] was developed in order to enable assessment of the technical feasibility of various options for integrated energy and resource planning of the islands. The proposed methodology is presented in Annex A. The Renewislands methodology consists of four basic steps that were further expanded to form the ADEG methodology [**58**]**.**

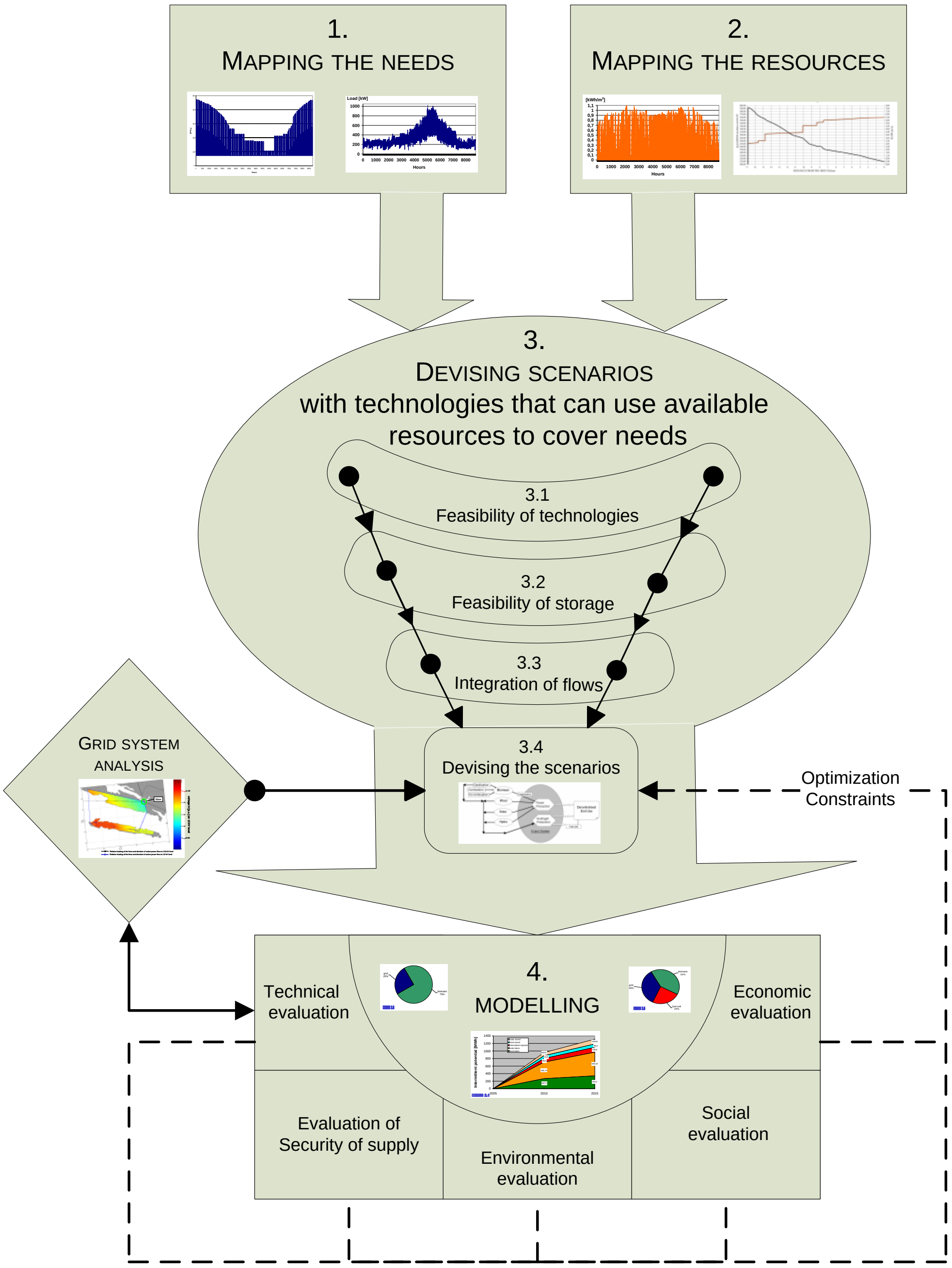


Figure 1. ADEG methodology flow diagram.

The four basic steps of the Renewislands/ADEG Methodology are:

1. Mapping the needs
2. Mapping the resources
3. Devising scenarios with technologies that can use available resources to cover needs
4. Modelling the scenarios and their evaluation

The needs are commodities that the local community demands, not only energy (electricity, heat, cold, fuel for transport, etc.), but also all other types of commodities (or utilities in the old jargon) like water, waste treatment, wastewater treatment, etc., that depend on the energy supply [**18**].

The resources are locally available ones, like wind, sun, geothermal energy, ocean energy, hydro potential, water resources, but also imported ones like grid electricity, piped or shipped natural gas, oil derivatives or oil, water shipped, the potential to dump waste and wastewater, etc.

The technologies can be commercial energy conversion technologies, like thermal, hydro and wind electricity generation or solar thermal water heating, commercial water, waste and wastewater treatment technologies including desalination, or emerging technologies, like geothermal energy usage, solar electricity conversion systems, or technologies in development, like fuel cells, wave energy, etc.

The scenarios should try to satisfy one or several needs, by using available resources, and satisfying present criteria. Due to global warming and falling reserves, and sometimes security of supply problems, fossil fuels should generally be used as the option of last resort in setting scenarios, even though they will often provide the most economically viable solution at the current price levels, and the advantage should be given to locally available renewable resources.

Differences between the two methodologies RenewIslands and ADEG can be found in the third step, where different optimisation constraints have been added, and in the fourth step, which has been expanded with a different evaluation of scenarios.

Since complicated strongly coupled flows depend on the timing of resources, demands, etc, the only practical way to check the viability of the scenarios is to model them in detail. After the technical viability of scenarios is thus checked, and many of the potential scenarios are dropped due to not being acceptable or viable, the economic viability should then be checked, even when it is clearly a demonstration activity [**18**]. The scenarios have to be evaluated after the modelling, but to obtain specific results which may depend on local particularities and to save modelling time, some technical, economic, security of supply, social and environmental parameters can also be included in the process of the development of scenarios. These parameters can therefore be used as optimisation constraints which will be used in modelling. If no changes in the power system are predicted according to the results of grid analysis, such constraints could directly lead to exclusion of some scenarios or DEG configurations which are not technically feasible.

The economic evaluation will show which scenarios are the most attractive and which are not economically feasible, while the environmental study can show environmental benefits such as reduction of CO_2 emissions, or improved land use.

2.1.1. RESTEP (Renewable Energy and Storage Technology Energy Planning) methodology

The RenewIslands/ADEG methodology has been designed for the assessment of smaller systems such as islands or systems with units for decentralised energy generation. In order to widen its application to larger systems that may include countries, or several different regions, islands, etc., and to give a better overview of the integration of flows and storage technologies, new modifications are proposed in the RESTEP methodology.

In the first place, three levels are introduced for the areas assessed: Global (G), Regional (R) and Local (L). These levels could represent geographical size, administrative or statistical areas, but in general they will depend on the planning purpose and goals. If possible, choice of the area size should be adapted to available and known data in order to simplify the modelling procedure in step 3. The second novelty is the proposed diversification of typical human use of space, mostly related to the regional and local levels. Highlighted are three characteristic areas: Urban (U), Suburban (SU) and Rural (RU), that will have specific concentrations of different needs and resources which could be effectively integrated and coupled by different types of related storage.

Urban areas can be characterized as city blocks with different purposes, e.g. residential apartments, different services, commercial, educational, health, etc. They can include some form of industry if urbanization is organized around an industrial complex or if it has moved towards it by the typical process of expansion of urban parts. Urban areas are characterized by a large number of people concentrated at some space at a certain time, so all their needs, such as transport, electricity, heat, cold, water, waste and wastewater collection and treatment, will be reflected through concentrations of population.

Suburban areas typically include suburbs for living purposes, e.g., family houses, smaller buildings, buildings for different services, small and large industrial complexes, as well as agricultural or other similar land uses at their edges. The concentration of needs in suburban parts will not be as high as in urban areas, but will still be concentrated enough to allow integration of flows, especially in the case of energy-intensive industry.

Rural areas are characterised by isolated settlements such as villages, industrial and agricultural complexes, and the concentrations of some needs will depend on the purpose of the objects or activities.

The assessment of flexibility has been introduced as an indicator of the possible repercussions of some need, resource, conversion and storage technology on their integration in the system. As explained by the FAST method in Chapter 2.4, flexibility in the power system is necessary due to variability on both the demand side and the supply side required by the introduction of intermittent sources and uncertainties in their forecasts. So, increased use of intermittent sources will have a negative impact on the system integration as it will require more flexibility, while the introduction of a stable and controllable source such as hydro or biomass could have a positive impact on the system and its flexibility. Although not as so strict as in the power system, flexibility is required in district heating and cooling systems, as well as in the gas supply and water system. In all of these systems demand and supply need to be balanced. Storage in the power system increases the available flexibility and, similar to all other systems, storage has positive impact on flexibility. Due to cycle losses, use of storage in the same system or energy carrier eventually leads to decreased efficiency, as it is not possible to return all the energy stored; on the other hand, if the storage is combined with the integration of different energy flows or other resources flows, it can increase the overall system flexibility and efficiency and reduce the size of the required installed components.

Thus it is important to identify all the possible sources and needs of flexibility while during mapping community needs and available resources; what is even more important is to assess the flexibility during the selection of conversion and storage technologies and the feasibility of integration of flows.

RESTEP (Renewable Energy and Storage Technology Energy Planning) methodology:

1. Mapping the needs (Global level/ Regional level/ Local level) (Urban/Suburban/Rural) flexibility +/-

2. Mapping the resources (Global level/ Regional level / Local level) flexibility +/-

3. Devising Scenarios Local (flexibility +/-) → Regional (flexibility +/-) → Global (flexibility +/-)

- feasibility of technology, Urban/Suburban/Rural, control system flexibility +/-
- feasibility of storage, Urban/Suburban/Rural, control system flexibility +/-
- feasibility of integration of flows, Urban/Suburban/Rural, impact on system flexibility +/-

4. Modelling and Evaluation of the Scenarios

- Technical evaluation a) grid study, storage deployment
  b) flexibility needs/resources
- Energy Independence Index (Global, Regional, Local) – Security of supply
- Economic evaluation
- Evaluation of social impact (jobs created, surveys and public debates)
- Environmental evaluation

2.2. H_2RES model

The part of the work presented in this sub-chapter has already been published in papers [**58**] and [**28**]. Several other papers describe the H_2RES model with details of its operation [**2**] and [**4**].

The main characteristic of the H_2RES model is that it uses basic technical data of equipment, hourly meteorological data for intermittent sources and, according to the description in [**2**], energy balancing is regulated by equations. The main load module of the H_2RES model, based on a given hourly wind limit, accounts for the renewable electricity taken by the grid, and the excess is available for storage, desalination or some other kind of dump load.

The H_2RES model is designed for balancing between hourly time series of water, electricity, heat and hydrogen demand, appropriate storages (hydrogen, reversible hydro, batteries) and supply (wind, solar, waves, hydro, geothermal, biomass, fossil fuels or mainland grid). The model has been designed as support for the simulation of different scenarios devised by the

RenewIslands methodology [**18**], with the specific purpose of increasing the integration of renewable sources and hydrogen into island energy systems. The main purpose of the model is energy planning for islands and isolated regions which operate as stand-alone systems, but it can also serve as a planning tool for single wind, hydro or solar power producers connected to bigger power systems.

Wind velocity, solar radiation and precipitation data obtained from the nearest meteorological station are used in the H_2RES model. The wind module uses the wind velocity data at 10 metres height, adjusts them to the wind turbines hub level and, for a given choice of wind turbines, converts the velocities into the output.

The solar module converts the total radiation on the horizontal surface into the inclined surface, and then into the output.

The hydro module takes into account precipitation data, typically from the nearest meteorological station, and water collection area and evaporation data based on the reservoir free surface to predict the water net inflow into the reservoir.

The biomass module takes into account the feedstock information, the desired mix of feedstocks, conversion processes (combustion, gasification and digestion) and desired output production (power, heat or combined heat and power). The biomass module is set to follow the heat load and it generates electricity as a by-product. This module has the ability to calculate the minimum and maximum potential energy output in order to optimise production according to unwanted shutdowns. The minimum is a factor between the installed capacity and the minimum load factor. This assures that the unit never goes below the minimum design. If the available energy is below this, it shuts off. The maximum also depends on the available energy but it is reduced based on the guaranteed production days. It foresees that the available energy of the same hour is enough to guaranty production for the desired amount of days. If there is not enough available, the maximum is reduced to meet these requirements. This is to lessen the frequency of shutdowns. It is programmed not to go below the minimum but does not foresee deliveries; it considers only what is in storage at that time. This is a major factor when dealing with isolated systems which cannot afford to run out of fuel constantly and which is why it is highlighted here.

The geothermal module functions in continuous mode, where the installed power generates electricity for the system continuously, except when it is in maintenance. The system primarily uses the electricity produced from a geothermal source in detriment of the other power sources, because this is a safe source, not intermittent. The H_2RES allows management of the amount of electricity produced from the geothermal source that enters the grid and satisfies electricity demand and storage demand, which becomes very useful when intending to use the geothermal potential for hydrogen production for transports.

The wave module consists of a wave data file in which the hourly distribution of significant wave heights and wave power periods are located, together with the power matrix of wave energy converters and wave output sheets. In the input module, the number of wave convertors units is set for the specific location and, by use of bipolar interpolation in the wave power matrix, H_2RES calculates the potential wave electricity production.

The desalination module uses the electricity produced from excess wind to supply the desalination units that produce drinkable water and put it on the lower reservoir, which is then used to supply the population. This module takes into account the total capacity of these units (m^3 of water produced per hour) and their electricity consumption per unit of water produced. At each hour, the desalination module verifies if the lower reservoir has at least 1 day of water demand; if it does not, and if the user allows this option the desalination units are supplied with electricity from the fossil fuel blocks [**67**].

The load module, based on a given criteria for the maximum acceptable renewable electricity in the power system, integrates a part or all of the available renewables output into the system and discards the rest of the renewable output. The excess of renewable electricity is then stored either as hydrogen, pumped water or electricity in batteries, or for some non-time critical use. The energy that is stored can be retrieved later and supplied to the system as electricity or hydrogen for transport purpose. If there is still unsatisfied electricity load it is covered by fossil fuels blocks or by the mainland grid where such connection exists. The model can also optimise the supply of water and hydrogen demand.

The order of sources in supplying of demand can easily be set up according to specific criteria. In most cases, the system will first take geothermal energy, then biomass that operates in CHP mode and then the rest of the renewables. Currently the model does not support automatic optimisation either according to the minimal or marginal cost of electricity or according to minimal environmental pollution, thus the scenarios must be evaluated afterwards.

The wind module of the H_2RES system is designed to accept up to four types of wind turbines which may be located in two different wind parks. The conversion from wind velocities to electrical output is done using wind turbine characteristics obtained from the producer. The solar module can either use data for solar radiation on a horizontal surface, which then has to be adjusted for the inclination of the PV array, or it can directly use radiation on a tilted surface. The adjustment of solar radiation to the inclination angle is done by monthly conversion factors which are calculated by the RETScreen or the PV-GIS programme. Efficiency data for PV modules and other components (inverter, line losses, etc.) can be obtained from the producer and they serve for calculation of the hourly PV output. The hourly precipitation data of the hydro module can be either obtained from the nearest meteorological station, or estimated by using daily, weekly or monthly averages. Generally, the necessary resolution of the precipitation data should depend on the storage size. Similarly, the evaporation per unit free surface of the reservoir should be estimated. The difference will then produce net water inflow into the storage system [**2**]. The load module of the H_2RES model, based on a given hourly renewable and intermittent limit, accounts for the renewable electricity taken by the grid, and the excess is available for storage, desalination or some other kind of dump load. The excess electricity can be exported if the island has a connection with the mainland grid. The storage module can be based either on an electrolysing unit, a hydrogen storage unit, and a fuel cell, or a hydro pumping storage, a reversible fuel cell or batteries. The input into the storage system is limited by the chosen power of the electrolyser, the pumps or the charging capacity of the batteries, so the renewable excess power which is superfluous to the storing facility or cannot be taken to the storage system because the storage is full has to be dumped or rejected [**2**]. On islands, there is often also a need for the desalination of seawater, which might be a good destination for dumped load, water pumps, or refrigeration units.

The basic version of H_2RES 2.0 has been constantly upgraded, by a i) grid module (version 2.1) which in the case of the island of Mljet enabled import and export of electricity, ii) fossil fuel module (version 2.2) which allowed the use of 6 different types of fossil fuel blocks in the case of Malta, iii) geothermal module (version 2.3) which has been used for the Terceira island case study, iv) biomass module (version 2.4), v) heat load (version 2.5) and heat storage (version 2.6) used in the case studies of the island of Losinj and the island Unije, vi) wave module (version 2.7) and vii) desalination module (version 2.8). All modules have been tested on various case studies, but mostly on islands.

The intermittent renewable electricity taken by the system in each hour, $E_{I,t}$, is defined by the intermittent limit φ_I, and the intermittent potential, $E_{I,pot}$:

$$E_{I,t} = \mathrm{MIN}(\varphi_I E_{load}, E_{I,pot}) \tag{6}$$

where intermittent potential is a sum of wind, solar PV and wave potentials:

$$E_{I,pot} = E_{W,pot} + E_{PV,pot} + E_{WV,pot} \tag{7}$$

The main equation for energy demand end balancing at a specific hour is:

$$E_{load} = E_{I,t} + E_{geo} + E_{bio} + E_T + E_{FC} + E_{bat,out} - E_P - E_{el} - E_{bat,in} + E_G + E_{ff} \tag{8}$$

where E_{geo} represents geothermal energy, E_{bio} biomass energy, E_T, E_{FC} and $E_{bat,out}$ hydro energy, fuel cell and battery energy. E_P, E_{el}, $E_{bat,in}$ energy used for pumping of water into higher reservoirs, water electrolysis and battery charging. E_G energy from the grid (mainland or neighbouring power systems). E_{ff} energy from the fossil fuel blocks. $E_{I,t}$ is the intermittent renewable electricity taken by the system.

The total intermittent $E_{I,pot}$, potential will be either taken by the system or used for deferrable load, in pumps, by electrolyser or stored in batteries, sent to the grid if there is possibility for export $E_{G,s}$ and the rest will be rejected E_r:

$$E_{I,pot} = E_{I,t} + E_{D,load} + E_P + E_{el} + E_{bat,in} + E_{G,s} + E_r \tag{9}$$

2.3. EnergyPLAN methodology

The EnergyPLAN methodology has been used to analyse national or regional energy planning strategies through assessment of technical and economic parameters for implementation of different energy systems, related investment and other costs. The basic tool of the methodology is the EnergyPLAN model. This is a mathematical model programmed in Delphi Pascal with a very user-friendly interface organized in a series of tab sheets. The model has been developed and constantly updated by Prof. Henrik Lund since 1999. A description of the model and its comparison to other models has been given in [**59**], [**61**], [**4**].

The basic characteristics of the EnergyPLAN model are as follows: it is an input/output deterministic energy system analysis model. It analyses the system for one year on an hourly level, which means that hourly distribution curves for different demands and production should be provided. Moreover, it works with aggregated values of the system description, as opposed to models which describes each single component. The model optimises the operation of the system rather than direct investments in the system, which can be assessed later by analysing different options or scenarios. The model is based on analytic programming to increase the speed of calculations.

EnergyPLAN is used for analysis of scenarios with large amounts of intermittent renewable energy production and for analysing CHP systems with large interaction between heat and electricity supply. EnergyPLAN was used to simulate a 100% renewable energy-system for the island of Mljet in Croatia [**4**] and the entire country of Denmark [**12**]. It was also used in various studies to investigate large-scale integration of wind energy in power systems [**3**], optimal combinations of renewable energy sources [**68**], management of surplus electricity [**61**], the integration of wind power using electric vehicles (EVs) [**60**], the investigation of fuel cells' and electrolysers' potential in future energy-systems [**62**], the effect of energy storage [**36**] and compressed-air energy storage [**27**].

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

Four step approach to energy system analysis in the EnergyPLAN model [45]:

Step 1: Defining reference energy demands
Step 2: Defining a reference energy supply system
Step 3: Defining the regulation of the energy supply system
Step 4: Defining alternatives

2.4. FAST methodology (IEA approach to harness variable renewables)

The FAST methodology has been developed by the IEA in order to assess the integration of variable renewable into the power systems of several countries and power market areas [**43**]. The methodology is similar to the RenewIslands/ADEG methodology, as in the first two steps it has identification or mapping of flexible resources, and in the third step it tries to identify needs for flexibility. Finally, in the last step it compares the needs for flexibility with the flexible resources and it proposes optimisation/development of additional flexible resources.

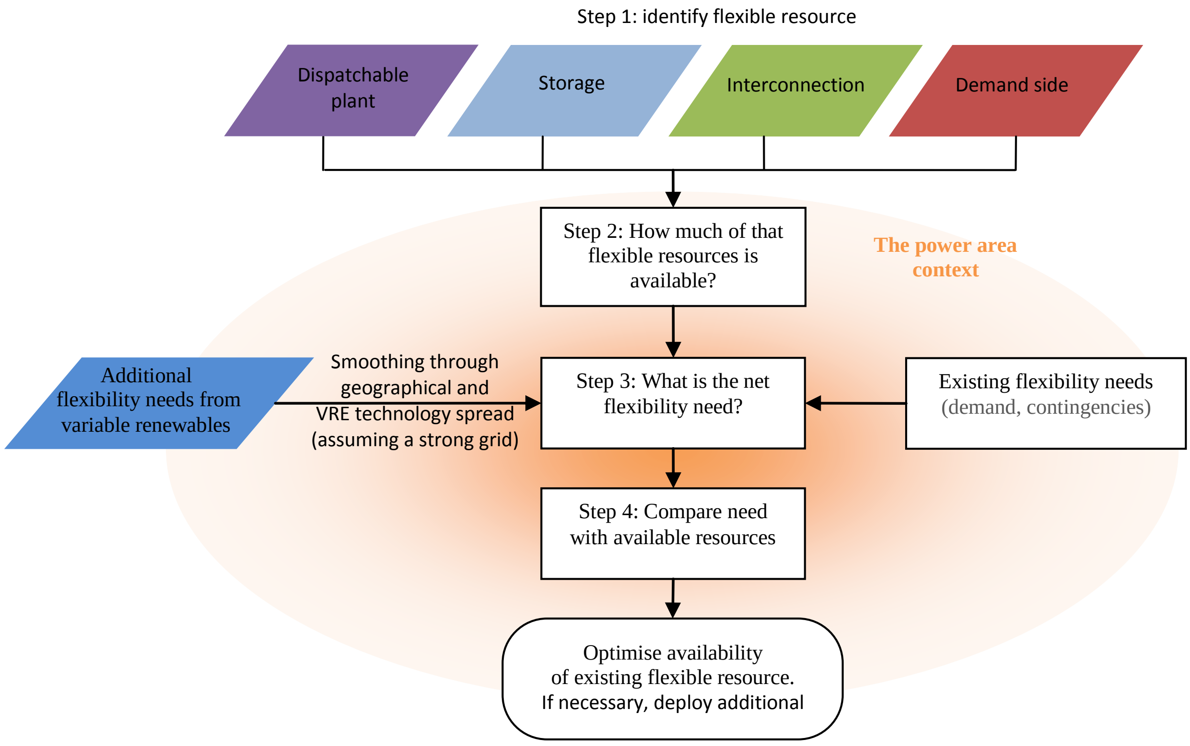


Figure 2. Flow chart of FAST Methodology [43]**.**

As explained and discussed in [**43**] the four basic steps of the FAST method are as follows:

Step 1: Identification of flexible resources in the power system.

This step is related to the identification of the technical flexible resource among four groups of flexible resources, which are: Dispatchable power plants, Energy storage, Interconnection, Demand side management. The flexibility is measured as the capability of source to ramp up or ramp down in a certain time interval (e.g. MW/min, MW/15min, MW/hour, MW/ 6 hours, etc.). When flexibility is summarized it represents the total technical flexible resource in the assessed area, expressed in MW over the desired time interval. The identified source can be used to balance the net load.

Step 2: Assessment of the available flexible resource.

When technical resources are identified it is necessary to see how much of these resources could be available at a certain moment, so all constraints in the system should be introduced. Constraints will be related to the operation of the power market, contingencies in power lines, forecasting uncertainties, use of power plants for other purposes, etc. The final number will show the actual flexible resources that can ramp-up or down as required.

Step 3: The need for flexibility.

This step will show the needs for flexibility which may come from the demand side or supply side and related forecast uncertainty, unpredicted outages, etc. The different renewable energy sources available and utilised as well as the size of area under assessment will have a big influence on the flexibility needs. Finally, the maximal needs for flexibility will be known and will be expressed as megawatts over the desired period of time.

Step 4: Identifying the possibility of integration of new variable RES

This step should identify what the possible installed capacity of variable RES in a certain area is in order to have a reliably balanced system. As it takes into account how the system is presently designed and operated it will also point out what new flexible resources could be deployed in order to increase the variable RES.

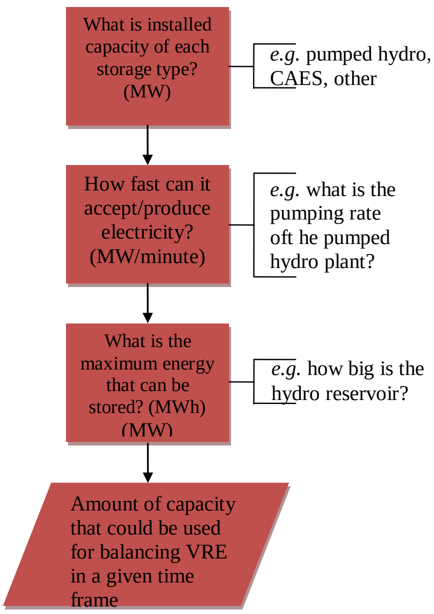


Figure 3. Assessing the energy storage issue in the FAST methodology [43].

2.5. Case studies

2.5.1. 100% RES islands

Today, islands represent excellent places for the demonstration of new clean technologies and new pathways for sustainable development. Islands are, in their nature, isolated systems so to organize life on them they usually have all the elements of a big system but just operated on a smaller scale. The advantage of islands is that they have favourable potential for renewable energy sources and they are not as rich in fossil fuels, so many of them are 100% dependent on imports. Small islands' markets and large imports of fuels that cannot be stored locally, due to the restricted space and capacity of local storage, make fossil fuels even more expensive. Here RES and storage technologies are competitive with fossil fuels, even without subsidies. Of course, that competitiveness in the first place depends on the RES potential and the cost of selected conversion and storage technologies, but, as stated in the introduction, there are some islands that have managed to find financial models that allowed them to achieve 100% RES electricity supply and almost 100% of their heat supply. The discussed case studies are assessed by the RenewIslands methodology, while the scenarios are modelled by the H_2RES model. Among others, the scenarios includes plans for 100% RES electricity supply with a certain level of transport fuel and hot water supply. With some assumptions on grid stability, it is proved that 100% RES islands are technically feasible solutions. Scenarios without an hourly penetration limit on electricity from RES were modelled in a such way that rejected potential is kept below 30% of yearly potential, while the size of the installed components is minimised. Evaluation of the costs, environmental impact and possible creation of jobs is assessed separately for each evaluated scenario.

2.5.2. 100% RES electricity supply for Portugal

The case showed the behaviour of the H_2RES model when calculating a national energy system. Portugal was chosen as a representative case as there was no official policy to have a 100% RES electricity supply, while on the other hand there is strong support for RES and the country has among the highest shares of RES electricity coming from wind, while there is also a large share of hydropower production and some solar, wave and biomass power plants. As RenewIslands/ADEG methodology firstly proposes pumped storage hydro as the most mature storage technology in the power systems, this technology was also favoured in the calculations until a certain amount of installations was reached, when batteries and fuel cells were introduced. The 100% scenario was not made for a particular year, as it was more oriented for testing of the H_2RES model and to get rough overall estimation of the necessary capacities for achieving 100% RES system.

2.5.3. Towards 100% RES Croatia

The Croatian case study has been assessed with the EnergyPLAN model and several methodologies described in Chapter 2.1. EnergyPLAN was more suitable for calculations than H_2RES as it has better integrated financial analysis and it has been designed for calculation of national systems, so it better covers demand and supply in all sectors. Still, EnergyPLAN is working with aggregated curves which should be based on real production or calculated from meteorological data and the help of other models, as was the case with Croatia. By calculating this case, several steps of new RESTEP methodology have been tested.

3. RESULTS

The part of the work presented in this chapter has already been published in papers [**2**], [**18**] and [**28**] so only the most interesting findings will be presented here.

3.1. 100% RES Islands

As mentioned in Chapter 2, the Renewislands methodology has been primarily developed in order to assess the technical feasibility of various options for integrated energy and resource planning of islands, and not necessarily to support development of 100% RES systems. Only options that come out from locally present resources for the analysed islands have been the renewable energy sources, soathough not designed for it, the Renewislands methodology guided the development of solutions for 100% RES systems.

The methodology has been applied by various authors to the islands of Malta, Porto Santo, Mljet and Corvo [**18**], Losinj [**69**] and Unije [**70**].

Through the use of the methodology, several islands have been approached. Implementation of the methodology for each island produced bigger differences in the first two steps, which was due more to local conditions, while the third and fourth steps brought more similar results. It was shown that electricity and hydrogen are good solutions for energy carriers or energy vectors on the islands.

In general, the focus was mainly on the electricity supply for the power system and transport. Heating and cooling needs were identified as dispersed and not high, so it was proposed that the design should be at unit level, not island level. However, the results of the H_2RES calculations for the island of Losinj showed that 80% of the heat energy for hot water could be satisfied by the solar thermal collectors and thus decrease the future peak load end electricity demand. In most of the analysed cases, hydrogen has been used as energy vector, allowing the storage of energy and provision of fuel for transport. In the case of the Unije [**70**], which is very small island with very low road transport needs, electricity was proposed as the energy carrier and a 100% RES system was calculated with batteries as the storage technology. Additionally, heat in individual heat storage facilities (hot water boilers linked to the solar thermal collectors) was introduced. The results for Corvo have been published in [**5**] and [**71**] but there were no scenarios for calculation of a 100% RES island. In the cases of the islands of Mljet and Porto Santo, the predicted electricity supply and simulated consumption of transport fuel were satisfied 100% from local RES, wind and solar. For Porto Santo, the plan was to reach a 100% RES system in 2010 and for Mljet that should be achieved in 2015. With similar planning for a 100% RES system on the island of Losinj that will include electricity supply, transport and 80% of hot water consumption, the simulation showed that it can be achieved by 2025. In the case of the island Unije, a 100% RES island including hot water consumption was planned for 2030. Finally, social acceptance of 100% RES scenarios has been assessed through calculation of possible work places related to manufacturing, installation, operation and maintenance of installed technologies. The number of work places has been calculated by multiplication of the installed capacities of the generating and storage technologies by average employment coefficients given by the authors in [**72**], [**73**] and [**74**].

For the island of Mljet and planned installations in the scenario with 100% RES electricity supply and hydrogen transport fuel, 216 person-years are necessary for the production and installation of equipment, while 11 people could be employed on O&M on the island. For Losinj, which has almost ten times more people, it will require 3987 person-years to produce and install the equipment and 520 people could work in O&M. This large number is the result of 74,000 m^2 of solar thermal collectors and big hydrogen installations that should also cover the needs of the transport sector. The island of Unije is the smallest, with only 47 residents, but to achieve “100% RES island” in 2030 it will still require 95 person-years for equipment production and 6 people in full employment to work on maintenance of the equipment.

3.1.1. Conclusion on 100% RES islands

The conclusion drawn from all these case studies is that the Renewislands/ADEG methodology qualitatively presented possible solutions for RES utilisation, integration of energy and resources flows, and guided the calculations towards 100% RES electricity supply that covers specific heat demand and transport fuel consumption on the analysed islands. The constraints in the calculations and goals of the optimisation were to achieve a 100% RES island with a minimal size of installed equipment and 30% of the maximal allowed curtailed intermittent potential. Technical evaluation [**75**] conducted for the grid stability for the island of Mljet showed that with the grid status from 2004 it is possible to connect a maximum 2 MW of capacity which cannot provide the reactive power and means that a 100% RES island can be achieved only if additional power electronics for support of voltage stability are installed. Financial evaluation of some case studies (Mljet and Unije) showed that energy storage such as hydrogen and batteries necessary for 100% RES solutions still imply for much higher electricity costs than those that could be supplied by the grid, even with the decreased costs of installations that are planned for the future. Pure financial evaluation does not give the whole picture on the social cost and benefits. Moreover, energy planning models use simplified methods for calculation of costs related to installations that usually cover periods of 5 years (as a time step). In this way, a certain error is introduced into calculations related to the net present values of some technologies. For example, building integrated PV, solar collectors, and batteries but also some smaller decentralised fuel cells and hydrogen installations are scalable, or they are installed throughout the whole period (not necessarily in the first year). For these systems it will be correct to redistribute the costs so that, for example the price of installed PV over a period of 5 years could be decreased by a half or similar. Another problem is on the earning side, as large power plants such as coal or gas are installed over period of 3-5 years, while PV, wind, batteries, and fuel cells can be installed in a month or a few months and immediately start to produce energy. So models that have year by year calculations could better reflect the cost analysis. Environmental assessment for the island of Mljet included only emissions saving related to the electricity from the grid and land occupation for planned installations, and a similar analysis was done for the island of Lošinj and Unije. The main conclusion is that just a small part of the island’s land surface is enough to achieve the 100% RES supply. The desalination on the Mljet and Unije represented good integration of energy and water production and desalination could be further used as demand side management measure. The conclusions related to social acceptance is that for all the islands combined 4299 person-years are necessary to produce and install equipment. This will represent jobs that will be created on the islands but, more importantly 537 work places could be established on the islands. These are full-time work places so they are even more important as they can serve for populate the islands with younger experts and thus support sustainable development.

Also interesting is that a survey conducted for the study in [**70**] showed that 50% of the population is ready to produce its own energy and even more, 75%, if the energy facilities are in the ownership of all the residents from the island.

Currently, of all the analysed islands only Porto Santo has installed hydrogen demonstration plant similar to one that has been installed on Utsira island in Norway. The facility on Utsira was able to work 50% of the time in a standalone mode but severe problems with fuel cell and hydrogen engine operation were experienced. The expected commercialisation of hydrogen technology could happen in the next 15-20 years, as current shipments of technology are in amounts equal to those seen for solar technology had 1996. An alternative scenario to hydrogen is to promote the use of batteries and electric vehicles provided that battery recycling is ensured within the waste management system on the islands.

3.2. 100% RES electricity supply for Portugal

3.2.1. H_2RES and its application to the power system of Portugal (mapping the power needs and resources)

Portugal's power system is based on thermal power units, which mostly use fossil fuels as primary energy sources. The total installed capacity amounting to 13.6 GW in 2006 comprises 5.8 GW from thermal power plants with an additional capacity of 1.3 GW from thermal power plants classified as producers with special status (P.R.E.), such as CHP and in smaller amounts waste, biomass, and biogas facilities [**76**]. In total, 53% of the installed capacity comes from thermal units. The installed power in hydro power was also high, i.e. 4.6 GW with an additional 365 MW from hydro power plants acting as special producers (smaller plants) totalling 36% of the installed power capacity. The remaining installed power generating capacity amounting to 11% or 1.6 GW, is derived from wind power plants, whereas a very small amount, 3.4 MW, relates to installed solar photovoltaics [**77**] .

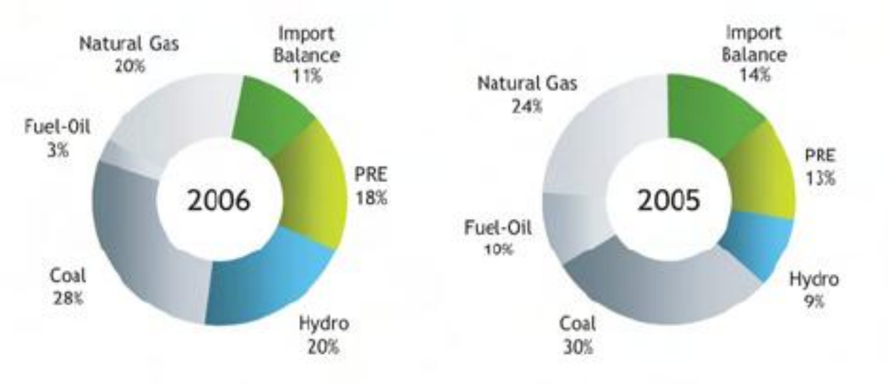


Figure 4. Portugal's power supply in 2006 and 2005 per type of fuel and production technology [21].

Total power demand in 2006 was 49,176 GWh, an increase of 2.6% with respect to 2005 [**76**]. Yearly power production according to type of technology and fuel is presented on Figure 4 while Figure 5 presents the same data on a weekly basis for 2006. PRE represents Special Status Generation, producers such as wind, biomass, CHP, small hydro, etc.

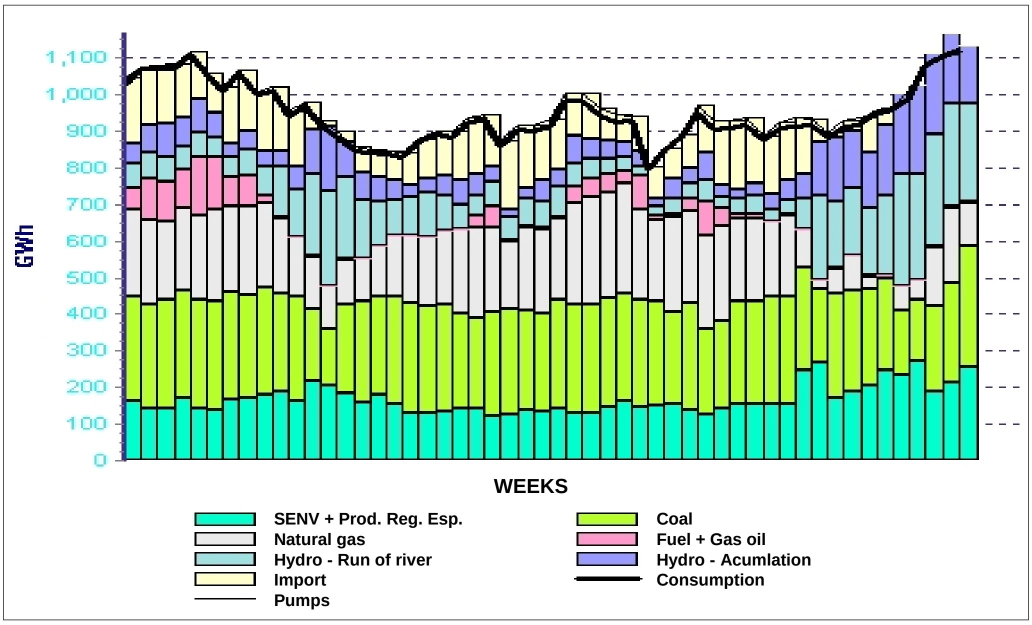


Figure 5. Portugal's weekly power consumption and supply in 2006 per type of fuel and production technology [21].

- **Power load:** Real hourly data from 2006 has been used (see Figure 6 [**78**]) for hourly balancing of the power system in Portugal. The peak load in 2006 was 8,777 MW with the lowest off-peak value at 3,171 MW.

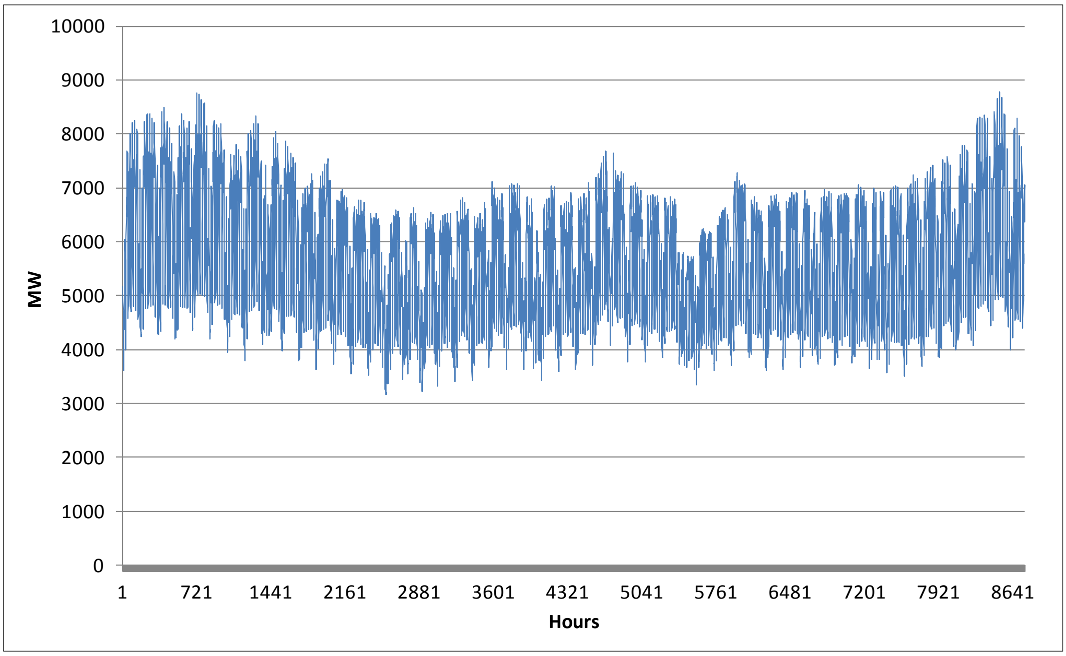


Figure 6. Hourly power load for Portugal in 2006 [23]. Data provided by ENTSO-E.

- **Thermal power plants:** Installed power from thermal power plants has been inserted into H_2RES according to [**76**]. Based on the type of fuel used, power plants according to the type of fuel used produced the following installed power: 1,776 MW for coa1, 1,476 MW for fuel oil, 236 MW for fuel oil and natural gas, 197 MW for gas oil and 2,166 MW for natural gas. Installed capacity produced from waste, biomass and biogas power plants was removed from the installed capacity from PRE producers [**77**] and was treated in the H_2RES model separately using the biomass module.

- **Wind power:** The wind data, used in the H_2RES model, is mostly collected from the reports [**77**] and [**79**]. Total installed power in 2005 amounted to 1,047 MW compared to 1,681 MW in 2006. Portugal has been divided into six continental (onshore) areas called Faro, Lisbon, Coimbra, Viseu, Braga, and Bragamca, and two offshore areas, Sagres and Peniche. For these locations, the hourly wind speed necessary for the calculations has been obtained from the METEONORM program [**80**]. Since this program uses wind speeds that are measured at meteorological stations which are mainly installed in urban or hidden places and not at the wind turbine sites, the necessary wind speed adjustment has been applied using monthly correction factors defined to match production in 2006 with the data presented in [22]. The adjustment has been carried out using simple monthly correction factors.

Two models of wind turbines, the 2MW Vestas V90 and 5MW Re-Power, with their associated power curves have been incorporated into the calculations. The smaller turbine represents current installations and those that will be built by 2020, while the 5MW model is used for new installations in the 100% RES scenario. There are unavoidable uncertainties in assessing wind energy potential at a site. To quantify these uncertainties, the author in [**81**] presents a numerical procedure for evaluating the uncertainty caused by the variability of natural wind and power performance. These uncertainties increase when all turbines in a certain region are represented by one measurement and one type of turbine.

- **Solar power:** In 2006, there were around 3.4 MW of installed solar power plants in Portugal [**77**]. Since then, there has been much progress in the construction of other solar PV power plants. The Amareleja plant is located near the southern town of Moura (Alentejo), with approximately 262,080 solar panels spread over more than 250 hectares and with 46 MW of installed power. Another completed solar PV plant is the Parque Fotovoltaico Hércules at Brinches, Serpa, with an installed capacity of 11 MW and annual electricity generation of more than 18 GWh. Another interesting project, the Tavria thermal solar power station, is currently under construction and will have installed capacity of 6.5 $MW_{e,}$ generating approximately 12 GWh of electricity per year [**82**]. In the H_2RES model, all power plants have been treated as solar PV plants installed in a single location in southern Portugal. Hourly solar radiation for the location has been obtained using the METEONORM program. All PV modules have been treated as fixed modules under an optimal radiation angle. Total efficiency of the solar PV plant was set to 15%.

- **Wave power:** There are several demonstrational wave power plants currently installed or under construction in Portugal. Parque Aguçadoura with 2.25 MW consisting of 3x750 kW Pelamis machines and the 2 MW the plant Archimedes Wave Swing, with both installations located at Póvoa de Varzim, the CEO Douro, a 1 MW installation at Porto do Douro, AQUABUOY with 2 MW located at Figueira da Foz. As explained in the second chapter, all the wave power plants in the calculations are represented by the Pelamis machines [**83**]. The hourly wave data used in calculations has been obtained from forecasting models described in [**84**] and [**85**].

- **Biomass:** According to [**77**], in 2006 the total installed capacity of power plants using biomass was 477.2 MW, of which 357 MW was from CHP plants, 24 MW from plants without CHP, 88 MW from waste incineration and 8.2 MW from biogas facilities. The total bioenergy electric power potential in Portugal from forest biomass was estimated to be 6 %. Forest biomass potential consists mainly of eucalyptus and pine thinning and cleanings, representing 55% of the total forest biomass production in Portugal [**86**]. Additional potential could lie in production from *Miscanthus*, a giant perennial rhizomatous grass. In study [**87**], the authors estimated electricity production from *Miscanthus* in Portugal to be 2.8 TWh annually which represents 5.7% of the current demand. In [**88**], the estimated bioenergy potential in Portugal is 26,366 GWh/year, of which 8,378 GWh/yearly comes from energy crops used in biofuel production. The use of biomass should be maximised in local plants due to expensive transport costs. To get a better overview of the local potential, it would be desirable to follow the methodology stated in [**89**], where a detailed analysis of the whole region has been conducted. The authors carried out an analysis of the potential from the biomass residues using the Geographical Information Systems (GIS) database and statistical analysis. The authors concluded that the annual biomass residue potential for the Marvão region is about 10,600 tonnes, corresponding to an energy production potential of about 106,000 GJ. The Marvão region covers an area of 154.9 km^2 (less than 0.2% of Portugal) and with an average forest cover rate of about 49%. Although the H_2RES model accepts up to five different types of units for biomass energy conversion, and since there was no specific data on biomass collection for the whole of Portugal, an equal distribution of biomass throughout the year was assumed. This was represented by a group of biomass source with a lower heating value of 14 GJ/t and a biomass to electricity conversion efficiency amounting to 25%. In 2010, the installed biomass capacity will amount to 250 MW [**90**]. It will also be possible in Portugal to utilize energy from municipal waste incineration. According to RES technology roadmap, a 100 MW target of installed capacity for anaerobic waste treatment units has been established [**90**].

- **Hydropower:** Portugal is one of the European Union countries with the highest exploitable hydropower potential. It is also one of the countries with the lowest hydro capacity growths over the last 30 years, remaining at around 54% of its exploitable potential. As has already been mentioned, Portugal in 2006 had in its hydropower plants 4,582 MW of installed power with an additional 365 MW from P.R.E producers. According to [**91**], storage hydropower plants possessed an installed capacity of 2,287 MW and a maximum storage capacity of 3,082 GWh, with the ability to store up to 7,716 mil. m^3 of water. The installed hydropower plants accounting for 2,295 MW and 365 MW from P.R.E are treated in the H_2RES calculations as run-of-river. Portugal also has a large installed capacity in pumped hydro storage power plants and according to [**92**], their capacity in 2006 was 1048 MW. The water data for the hydropower production has been simulated in accordance with rainfall measurements in Bragamca (the northeast of Portugal) and obtained from the METENORM program. The data also included weekly power production from hydropower plants and obtained from the REN website. The hydro module in H_2RES accepts only one reversible or storage hydropower plant with upper and lower reservoirs, which means that all storage hydro is combined with the storage capacities aggregated and treated as a single power plant. This assumption could lead to certain errors if hydropower plants are required to work at a full load capacity for longer than two days in a period without natural or pumped water inflow into the upper reservoir, as illustrated in Figure 7. The possibility of the module including evaporation from the reservoirs has not been incorporated in the calculations, as it requires additional detailed data concerning reservoir surfaces. Hydropower is clearly a priority and one of the principal commitments in the national energy policy. The High Potential Hydroelectric Dams National Program (PNBEPH) identifies the viability and development of hydroelectric plants and aims to identify and prioritise investments in hydroelectric power plants due for completions by 2020. The program seeks to achieve a hydroelectric power installed capacity exceeding 7000 MW by 2020 in Portugal, providing an additional capacity of 2000 MW [**93**].

- The Grid-Import/Export capacity in 2006 was 1,200 MW [**94**] and there are also plans for increasing the capacity to over 3000 MW by 2014 [**95**].

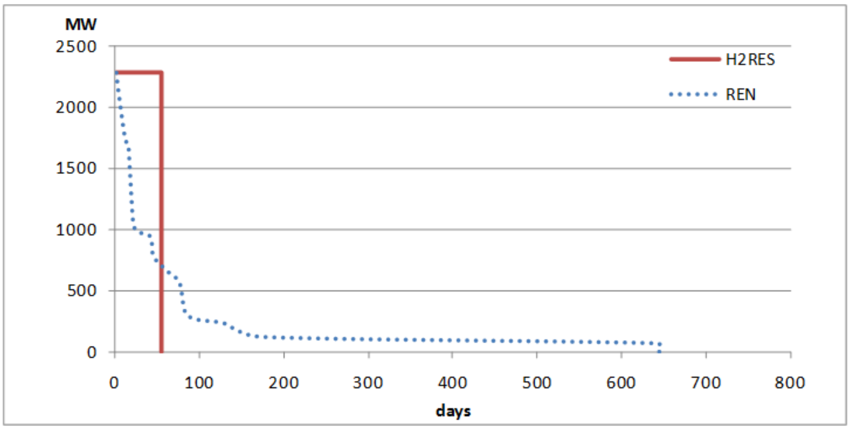


Figure 7. Operation of the hydro storage power plants from full storages and maximal load in the period without inflow of water in the upper reservoirs.

3.2.2. The H_2RES reference scenario for Portugal in 2006

A reference scenario has been used for testing the H_2RES model and its preparation for 100% RES simulation in Portugal. Figure 6 shows the results of the H_2RES calculation for the reference scenario. A comparison of H_2RES results and data from the literature in the bibliography is given in Table 2.

Table 2. Comparison of electricity production in 2006 for H_2RES results and data from literature [91] and [76].

Supplying demand [GWh]	H_2RES		Literature	
Wind	2811	5.7%	2892	5.8%
Solar	4.6	0.0%	3.4	0.0%
Wave	0	0.0%	0	0.0%
Run-of-river	6911	14.1%	6866	13.8%
Biomass	1998	4.1%	1945	3.9%
Hydro	4360	8.9%	4319	8.7%
Fuel cell	0	0.0%	0	0.0%
Batteries	0	0.0%	0	0.0%
Grid-Import	51	0.1%	5441	10.9%
Fossil Fuel	32964	67.1%	28399	57.0%
Total	49099	100%	49865	100%

As the model does not support hourly financial analysis, there is also no possibility of optimising the operation of the power plants with respect to marginal costs, and hence this was the main reason why importing electricity was replaced with fossil fuel generation. Due to the amount of installed power from wind turbines increasing in 2006 at an almost linear rate, and an additional 634 MW since the start of the same year, in order to obtain similar results in achieved production, installed wind power in 2006 in H_2RES was reduced to one half of the new installations.

3.2.3. H_2RES Portugal 2020 – open system calculation

In this scenario, the power from renewable units has been increased until reaching the goals set for 2020 [**96**]. Once the power was increased, the grid was expanded to allow the export of all power that would otherwise be rejected. The intermittent limit was set to 80%. Primary generation is presented on Figure 8. The scenario where demand is met in Portugal in the year 2020 is presented in Figure 9. In this case, new biomass production is increased to 793 GWh.

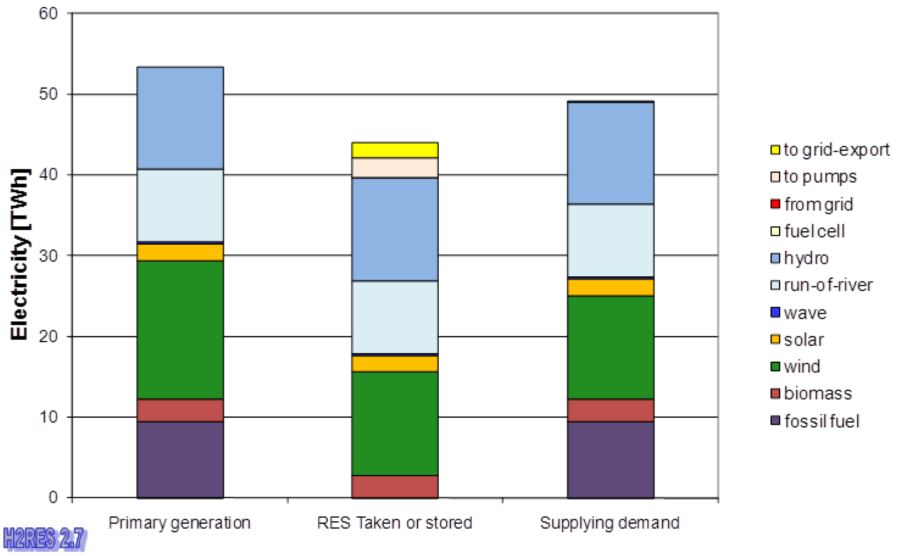


Figure 8. Primary generation of electricity in Portugal 2020.

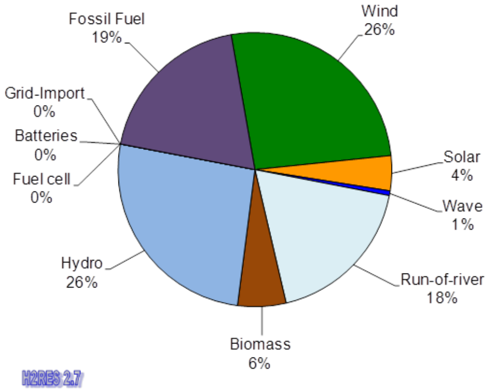


Figure 9. Supplying the demand in Portugal for 2020.

The results for weekly energy balancing and power production, pump consumption and RES export are given in Figure 10.

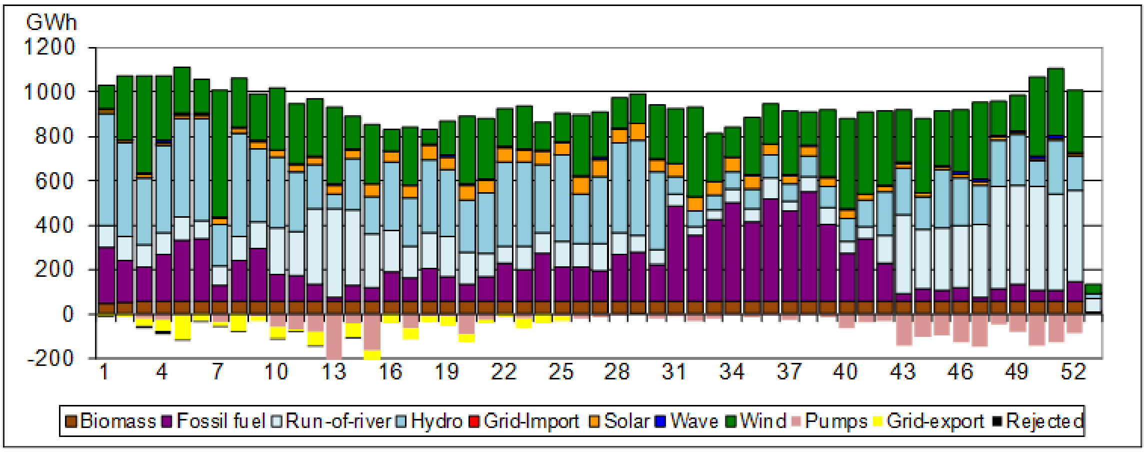


Figure 10. Calculated weekly power production, pump consumption and RES export in Portugal 2020 scenario.

According to data provided in [**93**], the turbine power of storage and reversible hydropower plants was expanded to 2,779 MW, while pump power was increased to 1,889 MW. The remaining hydropower increase of 794.25 MW in order to reach strategy goals was added to run-of-river. Additional energy production in 2006 amounted to 4,034 GWh for storage hydro systems and 2,063 GWh or 30% for run-of-river production. Storage and reversible hydropower plants operated in turbine mode for 4,816 hours at a total capacity factor of only 28%, whereas in pumping mode the plants operated for only 1,356 hours accounting for a total capacity factor of 10%. Without expanding the grid export capacity, exported electricity totalled 1.8 TWh with the rejected intermittent potential at 156 GWh. With the additional 2,510 MW of grid export capacity, the system was able to export all intermittent potential. It is interesting to note that with the additional new grid capacity, the system could operate without fossil fuel production by importing 9.43 TWh of electricity, resulting in a total import-export balance of 7.47 TWh. If the guarantees of renewable origin could be obtained for imported electricity, on the assumption that the system could also import ancillary services and with the same consumption as in 2006, Portugal achieve a 100 % renewable electricity supply by 2020.

3.2.4. An H_2RES 100% RES scenario – closed system calculation

Similar to the open system calculation, another analysis of the 100% RES scenario has been conducted with the main assumption in energy balance being that the Portuguese power system is a closed system, implying no connections for electricity import/exports with Spain.

In this scenario, planned installations in the Portuguese energy strategy for 2020 have been further expanded to achieve a 100% RES scenario. There are no intermittent limits in the calculations as it was assumed that units such as hydropower plants, biomass facilities and large 5MW wind turbines would possess some degree of frequency and voltage control. Results for weekly and daily energy balancing for a 100% RES scenario are shown in Figure 11 and Figure 12.

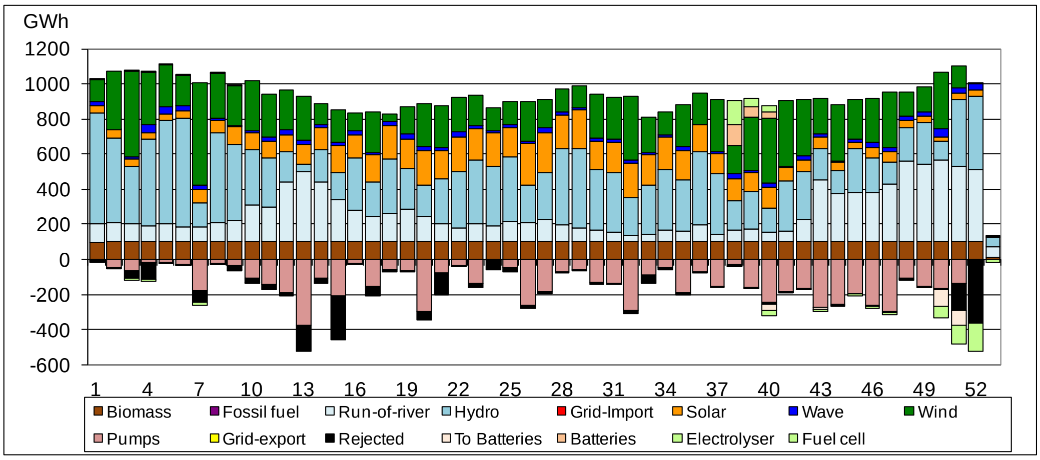


Figure 11. Calculated weekly power production, storage consumption and rejected RES potential in 100% RES scenario.

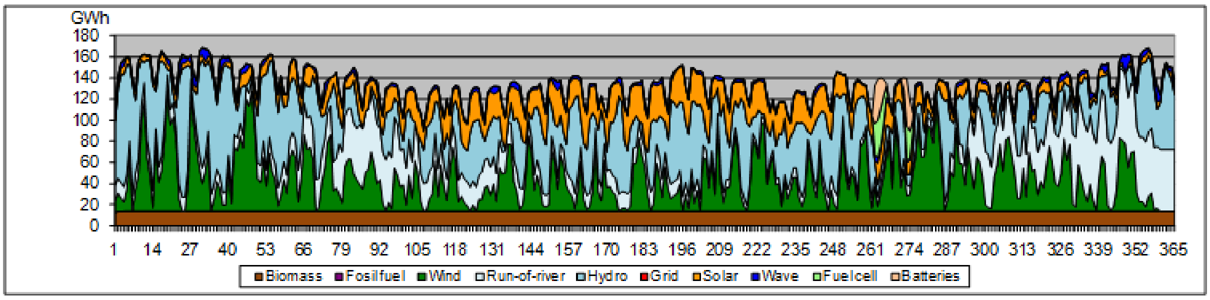


Figure 12. Calculated daily power production in 100% RES scenario.

Energy from biomass and waste is constant on the assumption that collection during the year remains the same. The power of installed components for 100% renewable electricity production is 9,970 MW wind, 4,500 MW solar, 6,289 MW hydro power plants (turbine mode of operation), 5,600 MW (pump mode of operation), a planned 1,200 MW of electrolysers, 1,500 MW fuel cell, 3,850 MW of battery connections, 3,454 MW Run-of-river hydropower plants, 750 MW of biomass, and 1005 MW of Pelamis Wave machines. Interestingly is that Portugal is planning to install 3266 MW of PHS by 2020 (Table 29).

The installed power from wind turbines reached almost 10 GW and is only 1.5 GW more than that planned by the new energy strategy. A total of 640 MW of new installations were added as off-shore units. The rest were added to current locations, by replacing old and small turbines with 5-6 MW units. Consequently, a lot of space could be saved at good windy locations. The second largest installations, are the turbines and pumps in storage systems and reversible hydropower plants. In the closed system, calculations resulted in a biomass potential of 20.75 TWh, producing 5.18 TWh of electricity or around 11% of total demand (see Figure 13).

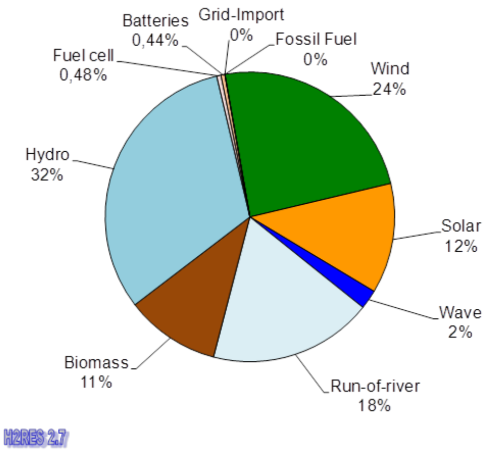


Figure 13. Supplying demand in 100% RES scenario- closed system calculation.

Furthermore, pumped hydro, batteries and fuel cells (hydrogen loop) have been used in calculations as possible energy storage technologies. Battery storage and retrieval efficiencies have been set to 92% in the calculations, with electrolysis efficiency set at 78% and fuel cells at 60%. The aggregated capacities of storage units were 4456 GWh of PHS, 360 GWh of hydrogen storage and 235 GWh of the batteries.

3.2.5. Discussion on modelling 100% RES national energy system in H_2RES

In the H_2RES model, only one unit was used to simulate reversible hydro storage, which is usually enough in simulating islands or particular units connected to larger systems. However, when used for simulation of large power systems with different types of hydropower plants and respective reservoir capacities, it would be desirable to optimise the system at a more detailed level using as much of the available technical details for existing and planned power plants as possible. In this way, PHS systems will achieve improved total capacity factors and certain errors due to the aggregation of installed power and storage capacities will be avoided. Moreover, as energy planning is carried out by simulating power systems at an hourly rate, it will be desirable to try to optimize the operation of systems according to market behaviour, which is already done by models such as EnergyPLAN or by the market-equilibrium model explained in [**97**]. This model has been used to analyse the Iberian market and the different conditions faced by generation companies: the scenarios for CO2-emission prices, hydro conditions, demand, fuel prices and renewable generation. According to the model in [**97**], the authors have calculated 33% of RES electricity in the Iberian market by 2012. Therefore, it will be interesting to see the results of their model for a 100% RES system for the Iberian market, since the authors are looking at the whole issue of sustainability.

In both stated future scenarios, system stability was addressed using intermittent limits or the assumption that current and new RES units acting as biomass and hydro power plants will provide adequate ancillary services. Ancillary services, rendered in order to maintain voltage and frequency stability by controlling active and reactive power, are normally supplied from large dispatched central stations. Alternatives to these stations are required as production share decreases in systems with high RES shares, which are mostly represented by smaller decentralised units [**98**]. In the same paper, the author has demonstrated the possibility of integrating large quantities of wind power into an electrical power system, on condition that certain requirements are fulfilled. Wind power and small-scale CHP plants must be able to supply ancillary services units [**98**]. There is also the possibility that new wind turbines may supply all types of ancillary services by the use of power electronics, as explained in [**99**] for the Doubly Fed Induction Generator (DFIG) wind turbine. In addition to the ancillary services issue, there are also other localised (e.g. grid congestion) problems since most of the RES sources are not distributed evenly in the area.

Portugal already has a large quantity of reversible hydro in its system. As a proven technology, the new storage installations in 100% RES should be mostly reversible power plants that can be used as extensions to already existing storage power plants, and this is addressed in [**93**]. Pumped hydro storage plants could also be built near existing lakes or reservoirs where a suitable height elevation exists. A possibly interesting approach for identifying potential PHS locations is explained in [**100**]. Other storage technologies exist such as compressed air and hydrogen production, but at their current cost and level of technological development, they could only be used to a smaller extent.

A 100% RES scenario relies heavily on hydro energy, which can vary significantly between wet and dry years. As presented in [**82**], large hydropower plants possess capacity factors ranging from 11.8% to 43.2% in period of 1997-2009. The capacity factor in large hydropower plants in 2006 was 26.3%, making it the most average year with regards to hydropower production in the mentioned period. In order to have a stable supply and due to the large variability of hydro, planning should also be conducted for the worst case scenarios in dry years. This will lead to increased reserve capacities installed by other technologies, but which will then have low usage during the wet years. Another approach for a secure supply could be the optimisation of system operation at hourly and seasonal levels, where some controllable sources could be saved for a longer period of time.

From the 17 identified locations for wave power plants examined in H_2RES, only ten were selected for large installations (50 or more units). The capacity factors for these locations range from 10% to 13%, meaning that Pelamis wave energy converters will work with very low load factors, at a smaller percentage than described in [**101**]. This means that wave data and power matrices should be additionally checked or the Pelamis machines will need to be fitted in Portugal for operation. Meteorological data from METEONORM and H_2RES results should be compared to actual measured wind speeds and solar radiation at the selected sites or compared with real production when available for certain installations in operation. Biomass and waste potential should also be verified if new detailed studies are published.

With the current renewable energy policy and strategy for the expansion of RES installations by 2020, and taking into account a RES share in electricity consumption amounting to 35.1% in 2009, comprising 40% wind energy and 46% hydro energy, Portugal provides a good example of an experimental region targeting a 100% RES electricity supply by applying pumped hydro and other storage technologies.

3.2.6. Conclusion on the 100% RES electricity supply for Portugal

The modelling results are presented for three electricity production scenarios in Portugal's power system, a reference scenario for 2006, a Portugal 2020 scenario drawn up according to the new energy strategy for 2020 and the 100% RES scenario. All the scenarios are modelled using H_2RES software and they will need further, more detailed elaboration. In both future scenarios, electricity demand was the same as in 2006; hence an additional forecast should be made to include increases or decreases in demand. Possible energy efficiency measures may significantly decrease demand; for instance, improved building insulation resulting in reducing electricity requirements for air conditioning during the summer or heating during the winter. The use of solar thermal collectors for hot water heating or absorption cooling could also decrease electricity consumption.

Closed system calculations enabled a better overview of accessible energy technologies but also identify certain limitations of the H_2RES program that have restricted development of more detailed and optimised results. The model used accepts only a single reversible hydro installation, and this should be reprogrammed in order to gain higher quality results that will enable modelling of larger energy systems with more geographically dispersed units. There is no automatic optimization of the model based on cost, and the environmental and social parameters arising from each technology. By optimising these parameters, the model will provide more sustainable solutions that should now be calculated separately.

Without cost optimisation, the order of generation and priority of storages is set deterministically by the limitation equations in the model. Consequently, if there is no penetration limit, the model forces a certain technology to its maximum or to the maximum available potential, without giving priority to lower costing technology or production during certain hours.

The current 100% RES solution favours hydro and wind power. Wind power should be implemented using installations with big reversible or pumped hydropower plants and could be achieved by installing bigger wind turbines and storage systems. Hydrogen and batteries could become a storage solution for large future systems once the technology progresses further, and once it become possible to combine these storage systems into a transport system.

If Portugal is to fulfil all the goals set out by the new energy strategy and if it undertakes additional grid expansion, which will allow it to exchange (export-import) only RES electricity, theoretically it will then be possible to achieve a 100% RES supply within 10 years. Energy efficiency measures could be speed up and make the conversion to 100% RES system even easier. Achieving a 100% RES electricity supply in a closed system will take more effort and certainly be more financially demanding as there are additional installations on the production and storage side that will be in operation for a small number of hours. In order to calculate optimal solution models for energy planning that carry out energy balancing on an hourly basis, it will be necessary to include more detailed operational planning amongst the system units. This will result in a full exploration of existing and planned assets without the necessary erroneous estimations of required installed power and the size of RES units and energy storage systems.

Covering 100% of electricity demand from renewable energy sources is just one big step in achieving a 100% renewable energy system. The effects of energy production from renewable energy sources could be multiplied if a whole energy system is calculated and if energy and other resources flows are integrated. Hydro storage and pumping could be easily and effectively integrated with fire protection and irrigation. This can be further integrated with biomass and biofuel production. Integrating power heat and cold generation provides maximal efficiencies. Finally, energy demands in the transport sector could be easily coupled with power production using hydrogen or batteries in electric vehicles.

3.3. 100% RES Croatia

3.3.1. STEP-1 Mapping the needs

The mapping of needs from the country level is not the same as from the island level, as the system is not as homogeneous as for the islands. Several new factors in geographic distribution are introduced. The level for assessment may be Global, code G, which may represent national or EU level; Regional, code R, which corresponds to statistical or any other area that is recognized as having several similar characteristics (e.g towns governed from one place, geographical regions such as Dalmatia, or Slavonia, counties with in the states, etc.) and finally Local level, code L, which represents the smallest level for assessment. Moreover, needs at the local level are divided into three groups for better recognition of the integration of flows: Urban-U/ Suburban - SU/ Rural – RU.

Table 3. Mapping the needs.

Needs	Level	Geographic distribution			
Electricity	High	Concentrated	G/R/L	U/SU/RU	ElectHC
Heat	High	Concentrated	L*	U/SU/RU	HeatHC
Cold	High	Concentrated	L*	U/SU/RU	ColdHC
Transport fuel	High	Long	G/R/L	U/SU/RU	TranHL
Water	High	Concentrated	R/L	U/SU/RU	WaterHC
Waste treatment	High	Concentrated	R/L	U/SU/RU	WasteHC
Wastewater treatment	High	Concentrated	L	U/SU	WWTHC

* industrial and agricultural heat or cold needs could also have a regional character (food processing factories or big refrigerators for preserving fruit and vegetables but usually concentrated at one or two locations).

Electricity and all other commodity needs have been marked on the high level in order to have sustainable development, although the gross electricity consumption per capita in Croatia was 33.7% below the European Union (EU27) average in 2010. The current and historical quantity of demand for each commodity is determined from statistical publications and future needs can be calculated by the models that use methods described by the formulas given in the introduction section 1.2.5 (formulas 1-5). The need for electricity in Croatia can also be seen from the power system load in 2008 (Figure 14) or monthly consumption (Figure 15). From both figures it is evident that higher peak loads and consumption are achieved during winter months, which can be correlated to colder weather, lower temperatures and increased heating demand. Similarly, there is also an increase during the summer months that can be correlated to higher air temperatures and great cooling demand, but it must also be correlated with the arrivals of tourists who increase the population in Croatia by at least 10% during July and August.

The same figures also show the possibility of daily and seasonal load levelling by energy storage technologies that are further discussed in the third step of the methodology application.

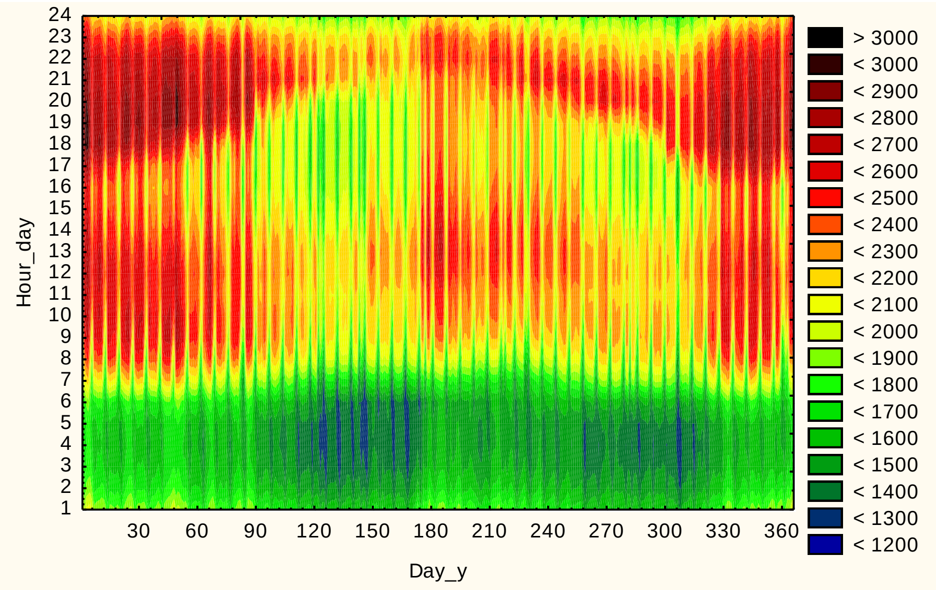


Figure 14. Hourly load of Croatian power systems in 2008 (load in MW plotted against hour of day and day of year).

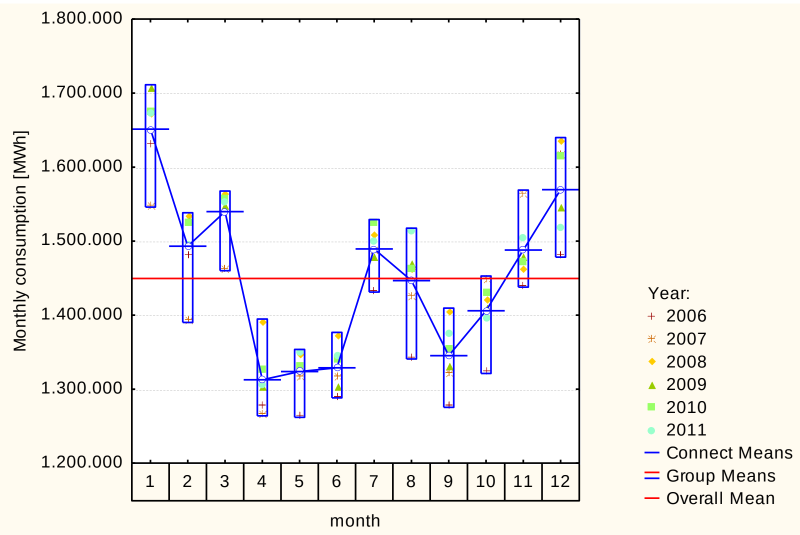


Figure 15. Monthly electricity consumption in Croatia for the period 2006-2011.

3.3.2. STEP-2 Mapping the resources

As for the needs, the geographical distribution of resources is extended to three levels, Global/Regional/Local, the potential of resources on these levels can be estimated as High/Medium/Low, or in the case of electricity connection Strong/Weak/No, and there is a code for existing infrastructure Yes/No.

Table 4. Mapping the resources for Croatia.

Resource	Level		Code
Global-Regional-Local primary energy			
Wind	Medium	GM/RH/LH	**WindM**
Solar	Medium	GM/RM/LH	**SolarM**
Hydro (height)	High	GM/RH/LH	**HydroHH**
Hydro (river flow)	High	GM/RH/LH	**HydroRfH**
Biomass	High	GH/RH/LH	**BiomH**
Geothermal	Medium	GM/RM/LH	**GeothM**
Wave	Low	GL/RL/LL	**WaveL**
Sea current	Low	GL/RL/LL	**SeaCurrL**
Tidal	Low	GL/RL/LL	**TidalL**
Energy import infrastructure			
Grid connection	Strong	GS/RS/LM	**GridS**
Natural gas pipeline	Yes	GY/RY/LN	**NGplY**
LNG terminal	No		**LNGtN**
Oil pipeline	Yes	GY/RY/LN	**OilPY**
Oil terminal/refinery	Yes	GY/RY/LN	**OilRY**
Oil derivatives terminal	Yes	GY/RY/LN	**OilDY**
Water			
Precipitation	High	GH/RH/LM	**H2OPH**
Ground water	High	GH/RM/LM	**H2OGH**
Water pipeline	Yes	GY/RN/LN	**AquaY**
Sea water	Yes	GY/RN/LN	**H2OSY**

3.3.3. Wind resources

At the end of 2010 there were 89 MW of installed wind power plants in Croatia and in the next ten years more than 1100 MW should be installed to fulfil the goals of the current Croatian energy strategy. In the registry of RES projects, investors applied for over 6540 MW of new wind installations, of which 4800 MW are located in the Southern Croatian region of Dalmatia, which reflects the fact that it has a very favourable wind conditions.

Together with the development of wind turbines and wind power plants, there has also been much higher progress in the development of wind power meteorology. According to the authors of [**102**] wind power meteorology does not belong wholly within the fields of meteorology, climatology or geography, and they claim that it is more their combination, so it represents an applied science whose methods are meteorological, but whose aims and results are geographical. To assess the wind potential and prediction of possible production, three main areas are important: micro-siting of wind turbines, estimation of regional wind energy resources, and short-term prediction of the wind power potential, hours and days ahead. The installation of wind turbines in large areas on many projects can significantly reduce the 10-minute fluctuations as a fraction of the total installed output, which could also have a positive impact on the integration of wind power [**103**]. As measurements on most of the potential sites for wind farms are conducted by private companies and investors, their data are not publicly available. This is a major obstacle for energy planners with in different sectors, as without a good and precise wind atlas they are unable to predict and calculate the benefits of wind energy utilisation. This will be a major issue if energy systems are try to become more independent [**104**] and sustainable [**15**] or when special financial mechanisms for support of RES integration need to be calculated [**105**]. The problems for the people in charge of the planning, operation and safety of power systems is that having fewer stations than potential project sites implies that much of the "diversity benefit" due to geographical dispersion of the sites may be lost in simulated data on a small time-scale. The size of the appropriate area for impact studies and time-scale has been described in [**103**]. In general, time-scales from milliseconds to minutes and all areas are related to system stability and primary reserves. A minutes to hours time-scale is relevant for system balancing, while a scale from months to years is related to the system adequacy. The seasonal changes of the mean monthly wind speeds measured at 46m height for three locations are presented in Figure 16. Measurements were taken as a part of the AWSERCRO [**66**] project and they are elaborated in detail in Annex D where the methodology for determination of possible hourly wind power electricity production for Croatia is described.

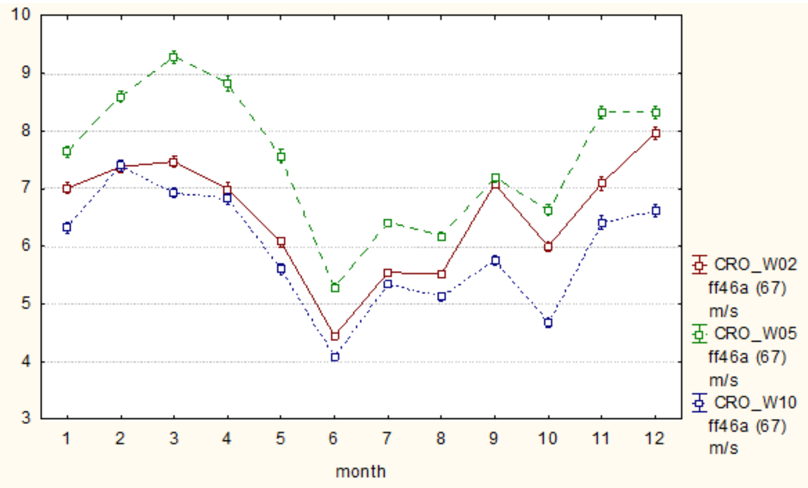


Figure 16. Seasonal changes of the mean monthly wind speeds for the locations W02, W05 and W10 at 46m height - AWSERCRO.

There are some measurements for the Dalmatia region; some of the results are available as well as meteorological data and data on the with historical production of wind turbines from a few operating sites. Moreover, wind turbine power curves are given by their producers and there is also detailed information regarding proposed wind farms in the region, so estimations of the energy production from wind farms and hourly production are possible and have already been done by the authors in [**106**] and [**107**]. The question that will always arise with these calculations is what was the uncertainty of the calculated wind turbine power production? For the Croatian case study, there are also three potential technologies that could be interesting for further development. The harnessing of off-shore wind is currently not an option due to law that forbids construction of these kinds of machines, but interest in their constriction exists as the foundations and installations of wind turbines in deeper sea is more demanding, so this could be an opportunity for local shipyards. The second option is installation of small and micro wind turbines with vertical and horizontal axes integrated in buildings or near them, and the third option is utilisation of high altitude winds as explained by Ban, Perkovic and Duic.

3.3.4. Solar resources

It is preferable to have long-term measurements when solar resources are assessed, as variation in annual irradiation for one year measurements could go as high as +/- 15%, compared to the long-term mean; for ten year measurements it could be around +/- 9%, while for 20 year measurements +/- 2.5%. For Croatia several sources are available (Solar Atlas EIHP, METEONORM, PV-GIS, DHMZ measurements, AWSERCRO). In all of them, the yearly sum of global irradiation on horizontal surfaces is 1100-1600 kWh/m^2, but as is evident from Figure 17 and Figure 18, the stated regional and local irradiation could vary for different models and different measurement periods.

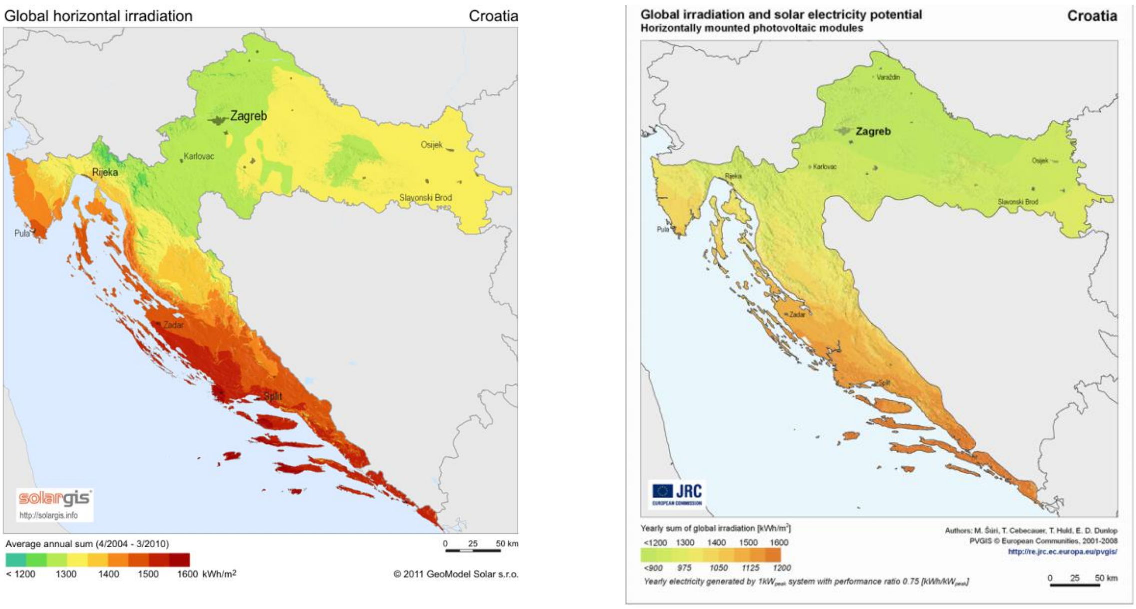


Figure 17. Solar global irradiation on horizontal surface calculated by two different GIS models for two different time periods solargis (2004-2010) and PV-GIS (1981-1990) [65]**.**

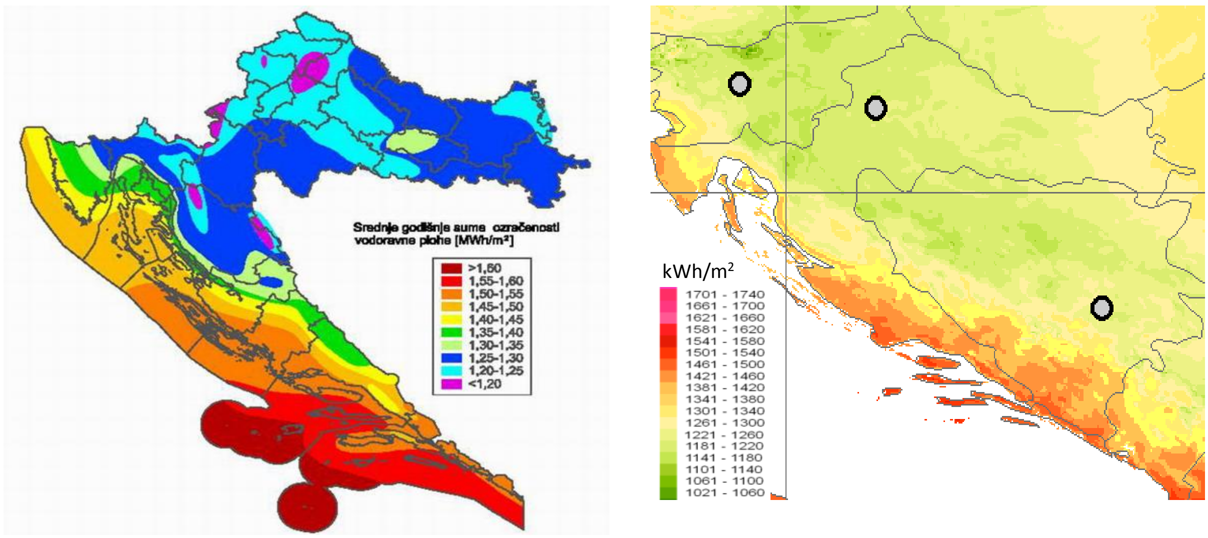


Figure 18. Solar global irradiation on horizontal surface from two different sources Croatian Solar Atlas [108] **and METEONORM software** [80]**.**

3.3.5. Hydropower resources

The Croatian power system is characterized by a large production share from hydropower plants. In the period 1998-2010 they had a mean monthly production of 505 GWh with a maximum production of 1056 GWh in December 2010 and minimum production of 166 GWh in September 2003. The seasonal production is evident, as the mean monthly production in the period November-February was 608 GWh, while the mean monthly production in the period June-September was 337 GWh. On average, hydropower plants covered 38% of electricity consumption on a monthly basis, or from 14% in the summer months to 70% in the winter months (Figure 19).

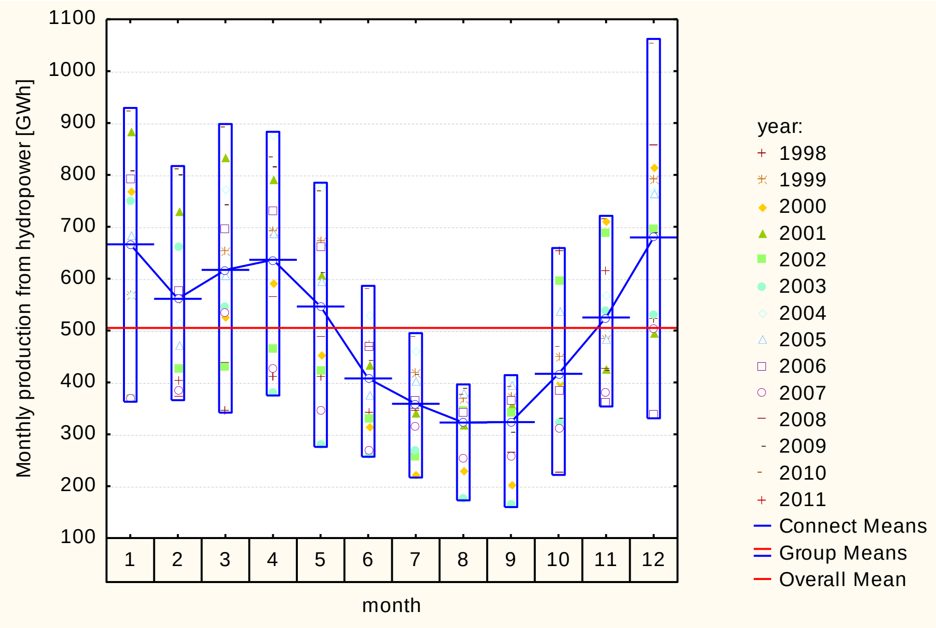


Figure 19. Monthly production of hydropower plants in Croatian power system for the period (1998-2011).

3.3.6. Biomass resources

According to [**109**] the total estimated potential of wood biomass from forestry, industry and agriculture in Croatia is 26 TWh with additional potential of 4 TWh for biofuels production from standard crops. A high estimation of the potential for biofuels production of 14.15 TWh with special types of biomass and using the second generation of biofuels is given by authors in [**110**]. While the above numbers are related to the total technical potential of biomass in Croatia, more realistic and economically feasible numbers are provided in the paper [**111**]. The authors estimated 6 TWh/year as the average energy potential of forestry residues, wheat straw and corn stover.

3.3.7. Geothermal resources

Publication [**109**] states that the potential for power production from geothermal power plants in Croatia is 48 MW with a complete utilisation of the basin, while the potential for providing low temperature heat is 840 MW (providing media at 50°C) or 1170 MW (providing media at 25 °C) [**109**].

Croatia has a long history of the utilisation of geothermal springs, so it is evident that potential for geothermal energy exists at the local level. For the purpose of modelling the energy system, the only power production will be directly linked to geothermal, while most of the potential will be utilised in the form of heat pumps.

3.3.8. Wave, tidal, sea currents

The Adriatic Sea is a closed sea and part of the Mediterranean Sea, which has tidal differences and waves that are much lower than those present in the oceans. Tides in the Adriatic Sea are even smaller, and the normal tidal difference is below 30 cm, and there is to date no known technology or prospects for its development, that will be able to effectively utilise low tides. Similarly, the wave heights and power periods compared to the Portugal case study are smaller, and according to the values reported in [**112**], only 22.41% of the time waves will be suitable for production by Pelamis wave energy converters (in Portugal it was 75% of the time), while for only 1% of the time could they produce full power. Calculated load factors for Pelamis machines in Portugal were in the range 10%-13%, so for Croatia the figure is even lower and thus not comparable to the other technologies for power production.

The speed of the sea currents in the Adriatic Sea is on average around 0.25 m/s, but in some places it can reach 2 m/s so it is recommended to make a local assessment with a special type of energy converters that fits specific current speeds once a detailed map of local sea currents is available.

In general, the potential for power production from sea energy in the Adriatic using existing and planned feasible technologies is very low, so energy from the sea will only be assessed as potential for heat pumps in heating and cooling systems.

Due the fact that there is large inflow of fresh water to the Adriatic Sea, a large potential for energy production may lie in the utilisation of pressure-retarded osmosis. This is the salinity gradient energy retrieved from the difference in the salt concentration of seawater and river water. However the technology is still in its research phase without predictions for commercialisation and currently only one 4 kW power plant exists in the world, so for now the technology will not be considered in the planning of the Croatian power system.

Once needs and resources are mapped, the potential energy carriers have to be selected according to Table 5. Electricity is one of the most suitable and most needed energy carriers. If an electricity grid exists at a certain level, then even a geographically distributed need for electricity can be treated as concentrated around the existing grid infrastructure. On the global level, it could be treated as concentrated on the high voltage grid (related substations and other infrastructure), and then distributed to the medium voltage and low voltage grids. Similarly, a regional concentration of electricity needs can be linked to existing infrastructure concentrated on high and medium voltage levels, and then distributed on the low voltage level. Local needs will be concentrated around low voltage substations and grids in other cases where there is no grid and the electricity need should be treated as distributed (mostly rural areas, urban and suburban areas will have all needs concentrated).

District heating and cooling as energy carriers should be assessed from the local level in the areas with urban and suburban characteristics; otherwise, in rural areas or on the regional and global level, the energy losses in their distribution will be too high.

Hydrogen is envisaged as possible energy carrier if there is a need for transport or electricity.

Natural gas, like electricity, is a networked energy carrier with a good possibility for grid distribution. It could be chosen as the energy carrier if suitable grid infrastructure exists or is planned to be built.

Other energy carriers can be chosen provided that the available infrastructure or resources needed for their production are present on some level.

Table 5. Potential energy carriers.

Potential energy carriers	Condition	Code
Electricity	IF ElectC AND G OR R OR L	**ECEl**
District heating	IF HeatHC AND L–U OR L-SU	**ECDH**
District cooling	IF ColdHC AND L–U OR L-SU	**ECDC**
Hydrogen	IF (Tran OR ElectC) AND G OR R OR L	**ECH2**
Natural gas	IF (NGplY OR LNGtY) AND G or R or L	**ECNG**
Biogas	IF (BiomH OR WasteHC OR WWTHC) AND R OR L	**ECBG**
Petrol/Diesel	IF (OilRY OR OilDY) AND G OR R OR L	**ECPD**
Bioethanol	IF (BiomH OR WasteHC) AND G OR R OR L	**ECEt**
LPG	IF (OilRY OR OilDY) AND G OR R OR L	**ECLPG**
Biodiesel	IF (BiomH OR WasteHC) AND G OR R OR L	**ECBD**

3.3.9. STEP-3 Devising scenarios

The third step of the RenewIsland/ADEG methodology has four sub-steps:

1. Feasibility of technologies (energy conversion, water supply, waste treatment, wastewater technology treatment)
2. Feasibility of technologies for energy, water, waste and wastewater storage
3. Feasibility of integration of flows (cogeneration, trigeneration, polygeneration, etc.)
4. Devising potential scenarios and their evaluation

Table 6. Potential delivering technologies.

Technology	Condition	Code
Electricity conversion system		
WECS (Wind)	IF (ElectM OR ElectH) AND (WindM OR WindH)	**WECS**
SECS-PV (Solar PV)	IF (ElectL OR ElectM) AND (SolarM OR SolarH)	**PV**
SECS-Thermal (Solar thermal electricity)	IF (Elect) AND (SolarH)	**SECS**
HECS (Hydro)	IF (Elect) AND (HydroM OR HydroH)	**HECS**
GECS (Geothermal)	IF (ElectM OR ElectH) AND (GeothH)	**GECS**
BECS (Biomass)	IF (ElectM OR ElectH) AND (BiomH)	**BECS**
DEGS (Diesel engine)	IF (Elect) AND (NGplY OR LNGtY OR OilRY OR OilDY)	**DEGS**
CCGT (Combined cycle gas turbine)	IF (ElectH) AND (NGplY OR LNGtY OR OilRY OR OilDY)	**CCGT**
FC (Fuel cell)	IF (Elect) AND (H2Fuel)	**FC**
Heating system		
Solar collectors	IF (Heat) AND (SolarM OR SolarH)	**STCo**
Geothermal	IF (HeatH) AND (GeothM OR GeothH)	**GeTH**
Heat pumps	IF (HeatH AND ECEl)	**HPHe**
Biomass boilers	IF (HeatH) AND (BiomM OR BiomH)	**BMBo**
Gas boilers	IF (Heat) AND (NGplY OR LNGtY OR OilRY or OilDY or WasteG or WWG)	**GSBo**
Cooling		
Solar absorbers	IF (Cold) AND (SolarH)	**SAbs**
Heat pumps	IF (ColdH AND ECEl)	**HPCo**
Gas coolers	IF (ColdH) AND (NGplY OR LNGtY OR OilRY or OilDY or WasG or WWtG)	**GSCo**
Electricity coolers	IF (ColdH AND ECEl)	**ELCo**
Fuel		
Hydrogen	IF (Tran) AND (ECH2)	**H2Fuel**
Electricity	IF (Tran) AND (ECEl)	**ElFuel**
Bioethanol	IF (Tran) AND (ECEt)	**EthanolFuel**
Biodiesel	IF (Tran) AND (ECBD)	**BDFuel**
LPG	IF (Tran) AND (ECLPG)	**LPGFuel**
Natural Gas	IF (Tran) AND (ECNG)	**NGFuel**
Biogas	IF (Tran) AND (ECBG)	**BGFuel**
Petrol/Diesel	IF (Tran) AND (ECPD)	**PDFuel**
Water supply		
Water collection	IF (Water) AND (H2OPM OR H2OPH)	**WaterC**
Water wells	IF (Water) AND (H2OGM OR H2OGH)	**WaterW**
Desalination	IF (Water) AND (H2OSY)	**WaterD**
Waste		
Incineration	IF (WasteHC)	**WasteI**
Gasification	IF (WasteHC)	**WasteG**
Wastewater treatment		
Gasification	IF (WWTHC)	**WWG**

3.3.10. Feasibility of technologies - wind energy - WECS production

The main problem facing power system operators, investors in wind power, banks and energy planners is how to determine and predict, with acceptable uncertainty or error, the yearly, monthly, hourly and instantaneous wind power production from the field measurements. The power system operators are interested in the impacts of wind power on the reliability and efficiency of the power system, while investors and owners in wind power plants and banks are more interested in production at a certain location or site. The interest of energy planners will be somewhere in between, as they usually need to take care of planning from local to regional and global levels.

This chapter presents results for the vertical wind profile determined by multiple regression and related energy production at measured locations which has been conducted in order to obtain an hourly curve of wind production in Croatia. The hourly distribution curve is used in the analysis of scenarios. Detail methodology and measurement data is provided in Annex D.

The wind in the boundary layer of the atmosphere is very turbulent and not stationary so wind speed is variable on all time-scales from short periods such as milliseconds to longer terms such as months, days and years. If the energy planning of the system with integrated energy storage is conducted with longer time steps, the hourly distribution of wind speed and possible average hourly electricity production provide enough information, while from the perspective of the secure operation of the power system, shorter time intervals must be assessed before connecting the wind power plant to the grid.

For each wind turbine type there are detailed wind power curves, so it is easy to determine the expected production under a given operating regimes. The biggest problem is how to determine the relevant wind speed at a certain location and height for each wind turbine and to calculate the uncertainty attached to it. Southern Croatia is very complex terrain with the characteristic north wind Bora that makes analysis even more complex. When wind turbines are installed in complex terrain, other parameters influence the power output to a greater or lesser degree - some to a degree that cannot be neglected [**102**].

Calculation of the type of wind height profile and turbulences is very important for many reasons. It also influence the turbine hazard framework, their availability and fallout, so it is desirable to measure the turbulent intensity, turbulence spectrum, turbulence coherence and wind speed distribution (vertical and horizontal wind profiles).

Some important external parameters that influence hourly production of a wind turbine are as follows:

- Turbulence intensity
- Variability of wind direction

- Scale/spectral content of turbulence
- Vertical shear
- Horizontal shear
- Atmospheric stability
- Precipitation rate
- Yaw error

The energy production is much more sensitive to errors and uncertainties in the wind study than to deviations in the power curve, which is why it is so important to focus on correct measurements and follow standard procedures. Typical uncertainties of a (good) wind study are in the range of 8-12% on the derived energy production, which makes the wind the number one parameter of importance for a project. The uncertainty of power curve measurements, even for flat terrain, is of the order of 6-8% while the statistical variation (the standard deviation) of the power curves for a given type of wind turbine generator is in the range of 2-3%. In other words, the uncertainty in verification of the power curve is several times higher than the variations looked for! [**102**] Another issue is the relation between the energy production and the power curve (1:1), while the energy production changes with the mean wind speed raised to the 3rd power. Therefore, the energy production is much more sensitive to errors and uncertainties in the wind study than to deviations in the power curve [**102**]**.** The same authors concluded that uncertainty in the wind power curve is in the order 2-3% and almost certainly does not exceed 5% in any case, and since the uncertainty in power curve measurements for ideal test sites is of the order of 6-8%, and more for complex sites, it is important to assess the wind flows over the rotor if the turbine shows significant deviations in power curves.

As explained in Annex D, a five step procedure enabled acceptable prediction of power production by wind power plants in Croatia. The calculation has been conducted in order to have better insight into available wind resources and to produce more accurate distribution curves. To calculate the hourly production of wind turbines from wind speeds it is necessary to obtain accurate wind turbine power curves. The Ecotecnica 100 has been selected as representative wind turbine that will be installed at all sites as detailed power curves were provided by its producer Alstom. The turbine may come with different tower heights and a 110 m tower has been selected for calculations. The height of the tower is site specific and it depends on wind site class, turbulences, wind share and vertical wind profiles, access roads, and economy, but in all the calculations it was assumed that the same type of turbine will be installed.

The geographical distribution of planned wind farms in Croatia is given in the registry of wind projects at the MINGORP. It shows that the majority of the proposed sites fit the area of measurement locations, so the results of the power production prediction could very well represent the production of all wind turbines in Dalmatia and most probably the whole of Croatia.

To calculate the energy production of a wind turbine from the probability distribution function of the wind speed is explained by [**113**].

Instead of using the probability distribution function explained in Annex D, which will not provide the necessary information for the storage needs, as explained in [**2**], the same principle of the H_2RES model has been used to calculate the energy production of wind turbines at a 10 minute level and then mean hourly production. Applying a similar methodology, the calculated production from 10 min or hourly intervals could additionally be validated.

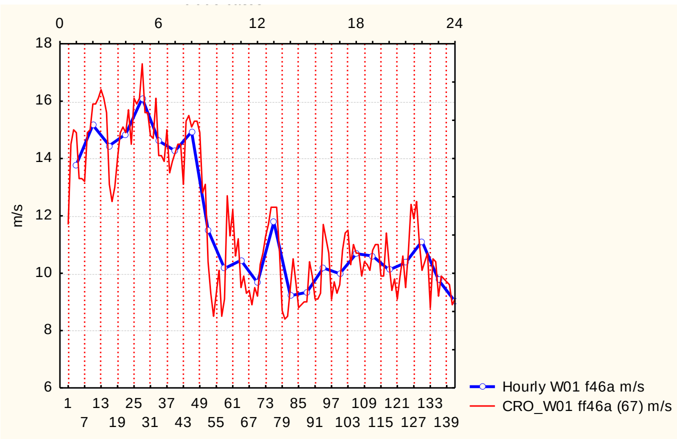


Figure 20. Mean wind speed measured for 10min intervals and calculated speed for average hourly intervals. Data represents the first day in 2008.

The variability of predicted wind production and the mean monthly wind power calculated from hourly values are presented in Figure 21. The results show that November-April energy production (or the average power in a 10 min period) will be much higher than summer and autumn, which could also help the integration of wind energy in the power system, as most of the heating in households during winter in the Dalmatia region is based on thermo-accumulation electric furnaces and heat pumps.

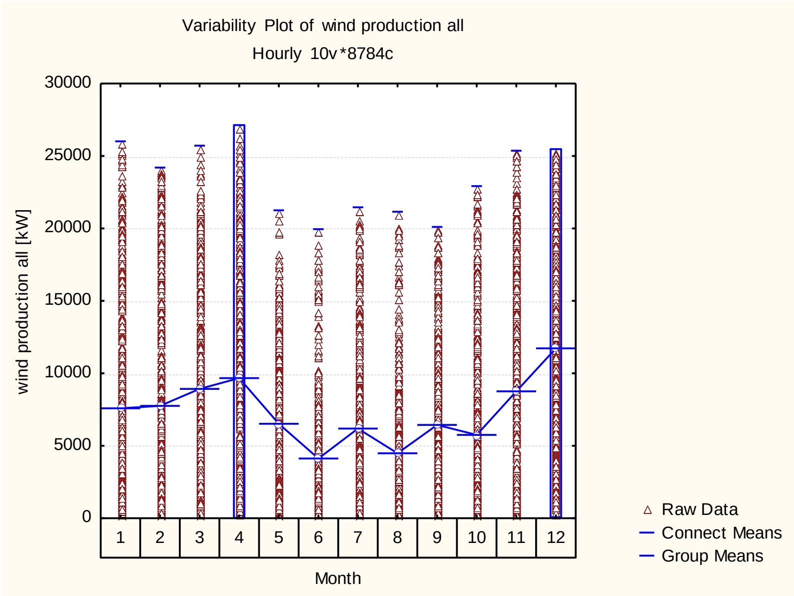


Figure 21. Mean monthly wind power calculated from hourly values.

To validate the prediction of the hourly power production of wind power plants from the field measurements in Southern Croatia, the results have been compared with two other analyses, real production of all wind power plants in Denmark in 2008 and wind production for Croatia [**58**] calculated by the H_2RES model and METEONORM data as shown in Figure 22.

Due to their similarity to real production, it can also be concluded that, by using the prediction of wind speed from measured data and the regression formula from Annex D and by using precise power curves for different air density, it is possible to predict production of wind power plants to better reflects possible real production, which automatically influences the uncertainty of further analysis.

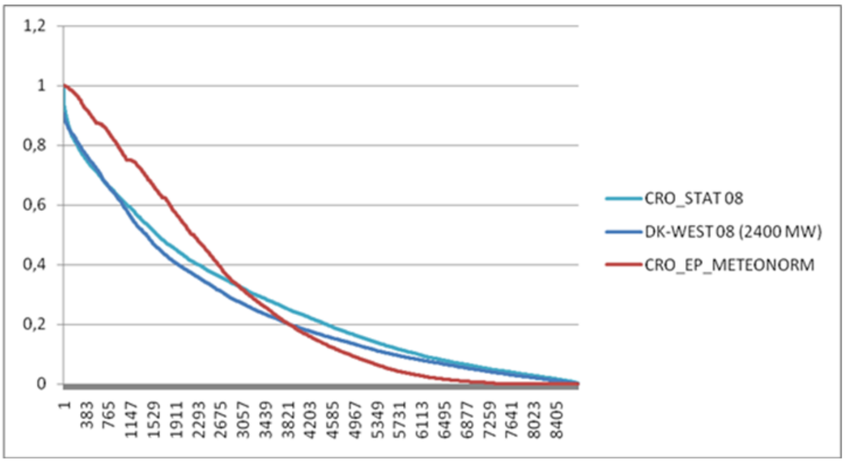


Figure 22. Comparison of sorted hourly energy production from all wind turbines as share of total installed capacity.

3.3.11. Conclusion on WECS production

This chapter addressed the problem how to determine and predict, with acceptable uncertainty or error, the yearly, monthly, hourly and instantaneous power production of wind power plants from field measurements in Southern Croatia which is the main problem faced by the power system operators, investors in wind power, banks and energy planners. Fortunately, there are many sources of various data on energy potential in the region, but many of them have not been properly analysed and evaluated and thus projects that can ensure publicly available data for use by professionals should be widely supported.

Current commercial onshore wind turbines with installed capacity from 1.5 to 3 MW have hub heights from 80-120 meters so to calculate power production from these turbines it is also necessary to have wind speeds at their hub heights. Until now wind measurements were mostly conducted at lower heights and for different heights are calculated by use of the power formula or by logarithmic formulas that includes terrain roughness.

As explained in Annex D, by the use of multiple regression several formulas have been tested and the formula that had the best fit for calculation of wind speed at different heights has been selected and tested on several sites. The results show very good potential at a few sites with load factors above 34%, so additional measurements and validations are required, if it is proved that the vertical wind profile in complex terrain such as that in Croatia can be calculated at greater heights from the power law that includes measurement at lower heights. For site assessment and wind turbine construction the rule is that wind should be measured at least at 2/3 of hub height.

The results of measurements and calculated wind production from the island of Brac (location W10 –Annex D) show very good wind potential even on measured heights. In 2004 the Croatian government prohibited the installation of wind turbines on islands and thus, as has been shown by current calculations, jeopardised the sustainable development and security of energy supply on the islands. Utilisation of a local source of energy that is coupled with some form of energy storage [**28**] could lead to 100% RES communities. It will be good to reconsider the government decision as new measurements have just proved the old hypothesis that the wind potential on Croatian islands is very favourable for utilisation.

The authors of [**114**] used wind velocities measured at 32 sites in Croatia, statistically processed it and made calculations for the Weibull distribution parameters at an elevation of 10 m. They concluded that, at time of their calculations, wind generators at the best sites in

Croatia were close to becoming marginally competitive with fossil-fuel technologies. Similar results, but with more detailed costs calculations, are provided in [**115**], where the authors calculated the RES cost–supply curve for 2010 and predicted generation of 755 GWh of electricity by wind with the costs in the range of 4-10 c€/kWh.

Compared to the results of study [**103**], the correlation results for wind speeds and wind production between wind measurements sites showed that wind speeds are less similar than in Finland, which could lead to easier integration in the system, but also brings greater uncertainty in forecasting and power predictions.

3.3.12. Feasibility of storage technologies

Table 7. Feasibility of storage technologies.

Storage technology	Condition	Code
Electricity storage system		
Reversible hydro	IF (WECS AND HECS)	**RHECS**
Electrolyser + Hydrogen	IF (WECS OR SECS OR PV) AND NOT HECS	**ELYH2**
Reformer + Hydrogen	IF (ECNG OR ECBG OR ECPD OR ECEt OR ECLPG OR ECBD) AND NOT HECS	**REFH2**
Batteries	IF (WCES OR SECS OR PV) AND NOT HECS AND NOT ECH2 OR REFH2	**BAT**
Electric vehicle to grid	IF (WCES OR SECS OR PV) AND ElFuel	**V2G**
Heat storage		
Heat storage	IF (HeatH)	**HeatS**
Cold bank	IF (ColdH)	**ColdS**
Fuel		
Hydrogen	IF H2Fuel	**H2stor**
Bioethanol	IF EthanolFuel	**Ethanolstor**
Biodiesel	IF BDFuel	**BDstor**
LPG	IF LPGFuel	**LPGstor**
NG	IF NGFuel	**NGstor**
BG	IF BGFuel	**BGstor**
Petrol/Diesel	IF PDFuel	**PDstor**
Synthetic fuel	IF SYNF	**SYNFstor**
Water, Waste and Wastewater		
Water	IF Water	**WaterS**
Waste fill	IF Waste	**WasteF**
Wastewater tanks	IF WWT	**WWstor**

3.3.13. Devising scenarios - The reference energy system for Croatia

To model possible scenarios, the Croatian energy system for 2008 has been reconstructed in the EnergyPLAN model. Energy consumption and supply data have been taken from [**63**], while hourly load data for the Croatian power system have been provided by ENTSO-E [**78**]. Basic data about power production units have been obtained from the Croatian utility company (HEP) [**116**] and from [**63**]. Water distribution data for hourly production of hydro power plants have been reconstructed from the monthly values provided in [**78**], while the capacities of hydro storage have been calculated by the data in [**117**]. The load curve for the hourly district heating demand was calculated according to the yearly heat consumption in Croatia [**63**] and according to the patterns of hourly heat demand in Denmark that are provided by the EnergyPLAN model. Heat production from a large cogeneration plants and district heating system has been added as a district heating demand, while all industry heat and process steam demand was treated separately, through the energy consumption in industry. EnergyPLAN has the ability to provide hourly heat production from industry. Usually this heat is represented according its own distribution, under which it supplies excess heat to district heating systems. In the EnergyPLAN, there is no possibility to treat heat demand in the industrial sector separately, as all district heating demands are aggregated and represented by the one hourly distribution curve.

Total cross-border transmission capacity for electricity exchange is set to 3200 MW, as published in [**118**]. The author of [**119**] provides a value of 3040 MW for the total import capacity for Croatia and 2400 MW for the export capacity to neighbouring countries. For the same capacity, the Slovenian TSO calculates interconnections from SI to HR to be 1200 MW, instead of the 1000 MW that has been published in [**119**], so 3200 MW was taken as the final value for 2008.

Croatian import of electricity varies from 25%-40% of yearly consumption and it is dependent on hydropower production and import prices. Final import quantities and prices are mostly set by bilateral contracts. As there is no obligation to publish these contracts, there were no data regarding the price of the imported electricity. To replicate a similar amount of imported electricity for 2008, under market optimisation calculations, the hourly distribution of market prices from the German spot market published at (EEX) has been adopted by the elasticity given in the EnergyPLAN model and its manual [**59**].

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

$p_X = pi + (p_i / p_o)* Fac_{depend} * d_{Net\text{-}Import}$ (10)

where p_i is the system market price,

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

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

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

In all the calculated cases, the import of 2,986 GWh of electricity from the Krsko Nuclear Power Plant (NPP) in Slovenia, which is under 50% ownership of HEP, is modelled as fixed import/export under the constant distribution taking into account the real outages from 2008. It resulted in almost constant power of 344 MW supplied by NPP.

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

3.3.14. The case of the Croatian energy strategy scenario until 2020

The idea behind this scenario was to calculate the behaviour of the Croatian energy system if it follows the development plans laid down in the current Croatian Energy Strategy (CES). According to the CES, the share of RES in the gross final consumption will be 20% in 2020. This share is divided between three energy vectors and it is planned to have 35% of RES share in electricity consumption, 10% of RES share in transport fuel and 20% RES share in heating and cooling. The 20% goal in terms of final energy consumption is set as 9.2% electricity, 2.2% transport fuel and 8.6% heating and cooling.

As mentioned above, one of the goals of the strategy is to satisfy 35% of electricity consumption by renewable energy sources including big hydro power plants by 2020. To fulfil this goal it is expected to add 300 MW of new large hydro power plants, 1200 MW of wind turbines, 85 MW of biomass power plants and 100 MW of small hydro power plants. These RES installation have been inserted in the EnergyPLAN model in such a way that one half of the planned capacity of new big hydro power was added as the run-of- river hydro and other half as storage hydro. Small hydro has been treated separately but with the same hourly distribution as run-of-river.

In 2020 the CES envisages use of 26 PJ of biomass and 9 PJ of biofuels while planned production of biogas from agriculture is 2.6 PJ. Another 6 PJ may come from waste as a result of better waste management, which could lead to reduction of GHG emission for 1.069 Gg

CO_2-eq [**120**]. Additionally, the CES sets the goal of installing 0.225 m^2 of solar thermal collector per each Croatian resident (0.225 m^2/per capita).

The current power plants in the Croatian energy system are older (on average) than 35 years and it is envisaged by the CES that 1100 MW will be decommissioned by 2020. In order to have enough production capacity to satisfy the peak load and to provide the necessary reserves, the strategy sets the goal of installing 1200 MW of new gas power plants and 1200 MW of coal power plants by 2020. An additional 300 MW of new power plants will be installed as CHP units, which will partly replace existing ones. After 2020 it is not planned to use oil in power plants. This was the main reason for separating new units and existing units that will not be decommissioned into two groups in the EnergyPLAN model: one group represented by CHP extraction plants, modelled as a combination of back pressure and condensing plants, and another group with condensing plants using coal.

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

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

3.3.15. 100% independent (self-sufficient) Croatian energy system

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

According to [**109**], the total estimated potential of wood biomass from forestry, industry and agriculture in Croatia is 26 TWh with additional potential of 4 TWh for biofuels production from standard crops. A higher estimation of the potential for biofuels production of 14.15 TWh with a special type of biomass and using the second generation of biofuels is given by the authors in [**110**]. While the above numbers are related to the total technical potential of biomass in Croatia, more realistic and economically feasible numbers are provided in [**111**]. The authors estimated 6 TWh/year as the average energy potential of forestry residues, wheat straw and corn stover. In the period after 2020, most of the technical potential for large hydro power plants will be exploited. The only options that may be built are pumped storage and small hydro power plants. Locations are already identified for 200 MW of small hydro power plants in the current national registry of RES projects so, additional to the capacity envisaged by the CES, an extra 100 MW has been taken into consideration. There is also some potential for geothermal power plants and 40 MWe was added in the model as power generating units. Beside hydro power, biomass is a renewable energy source with the highest potential in the continental part, while wind and solar represent the highest potential for electricity production on the coastline and southern part of Croatia. For low temperature heat generation, besides the traditionally used biomass, solar and geothermal have the highest potential. The economic potential of solar energy for heat production is estimated to be around 50% of the total low temperature heat in 2000 in Croatia, or nearly 12 TWh/year [**109**].

After 2020, the transport sector is modelled in such a way that regular cars on gasoline and diesel will be phased out while the share of electric and biodiesel vehicles will progressively grow. In the case of a 100% independent system, it is assumed that a share of 25% of transport sector diesel consumption is used by trucks, buses and other vehicles, or that 4.75 TWh and an additional 5.4 TWh is used by trucks and other heavy vehicles in industry and agriculture. Total diesel consumption is modelled as if it is supplied by biofuels. All other road transport, or 30 billion/km per year, is assumed to be switched to electric vehicles making on average 10,000 km per year. Batteries are integrated parts of electric vehicles and their mode of operation (grid charging and eventual discharging) could have a large impact on future energy systems. Jet fuel consumption in this case is increased by 50% to 3 TWh and has not been replaced by any other fuel.

Due to the large potential in energy efficiency and the not very promising demographic growth, it was assumed that energy consumption will not increase significantly from the level planned in the CES for 2020. The potential for energy savings and energy efficiency is large and the best illustrative example may be electricity consumption for public lighting, which was at 440.16 GWh in 2008. Just one ESCO project, in the public lighting of the town of Karlovac [**121**], realised savings of 25%, which means that if similar measures are going to be applied across the whole country, the approximate savings only for public lighting could reach 110 GWh annually, which is figuratively speaking 10 GWh more than the total production of 36.8 MW hydropower plant HE Rijeka in 2008. In the same year household electricity consumption was 6,711 GWh. In the EU, on average 20% of electricity consumption in households is spent on the lighting so if the same share is applicable to Croatia this accounts for 1,342 GWh. New efficient lighting could reduce this consumption to 1/5 of its original value. Besides the electricity consumption for lighting, households and buildings in general makes these the largest consumers of heat energy. With proper insulation, achievable savings in Croatia in these sectors are calculated to be at 50 PJ (or almost equal to all the heat consumption of the household sector) [**122**].

3.3.16. Results for the reference case for 2008

Although there were some difficulties in obtaining data that could represent real hourly consumption in 2008, the final numbers have shown that the EnergyPLAN model could very well represent the Croatian energy system. Comparison of the gross energy consumption by fuel and electricity export for two different calculations (market and technical optimisation) and data from the literature is presented in Figure 23.

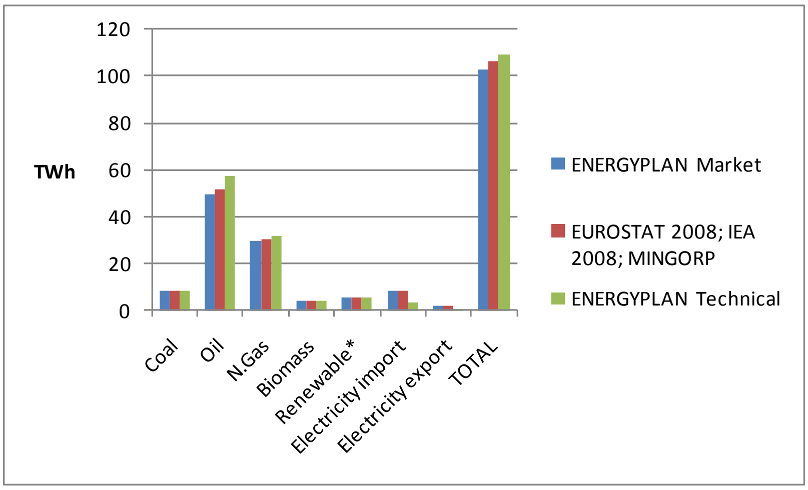


Figure 23. Gross energy consumption by fuel and electricity export in the reference case. (*geothermal heat for hot water and space heating not included).

Gross fuel consumption by sector is given in Figure 24. This shows big differences in the energy sector between the results of a market optimisation regulation strategy and data from the literature on the one hand and the technical optimisation on the other. This difference is caused by the preference in the technical optimisation to supply demand with local production and not take imports. Thus the market optimisation provides a more realistic simulation. In the EnergyPLAN, the consumption of the energy sector has been divided between the heat and power producers. The energy losses at refineries and gas production facilities and energy consumption of all other industrial energy own producers have been added to the consumption of the industry sector. Energy consumption in agriculture has also been added to the industry sector. The household sector represents the energy consumption of households and the services sector without their consumption of electricity and district heating, which have been treated separately.

Electricity production by source and import of electricity is given in Figure 25. There were no data in the literature for the production of hydro power plants according to their type, so the estimated distribution curves have not been compared to real data. As previously mentioned, the technical optimisation seeks to avoid import or export and to minimise use of the fossil fuels in condensing power plants, as energy from all other sources is calculated before estimation of the PP share.

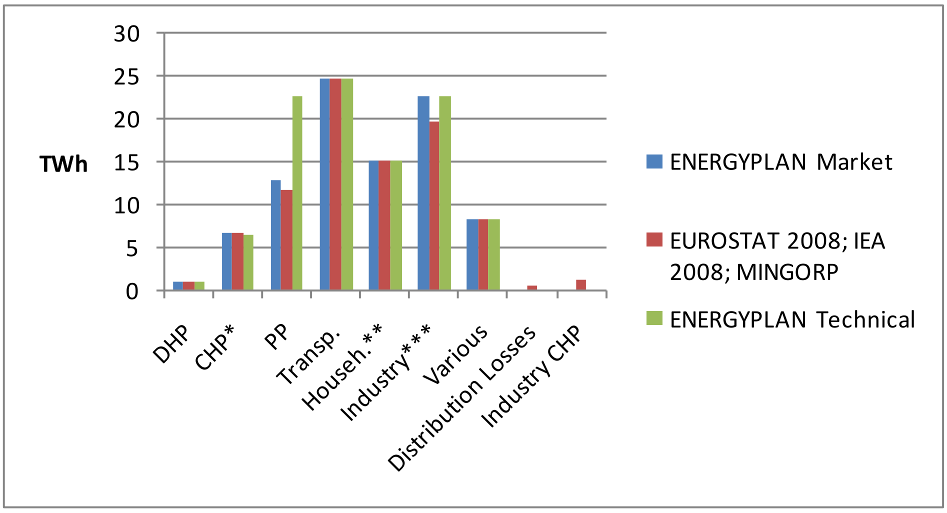


Figure 24. Gross fuel consumption by sector, 2008.((Includes boiler consumption within CHP plant; **Consumption of households plus services without electricity consumption and heat from DH; ***Consumption of industry plus agriculture plus loses in refineries and gas production facilities)**

The analyses are conducted with the following restrictions in order to secure the delivery of ancillary services and achieve grid stability (voltage and frequency). At least 30% of the power (at any hour) must come from power production units capable of supplying ancillary services, such as central PP, CHP, and HPP. The distributed generation from RES and small CHP units is not capable of supplying ancillary services necessary for grid stability. Additionally, large CHPs are not able to operate below their minimum load of 110MW, while the minimum load for condensing power plants is set to 516 MW. In the analyses here, the Croatian energy system is treated as a one-point system, i.e., no internal bottlenecks are assumed.

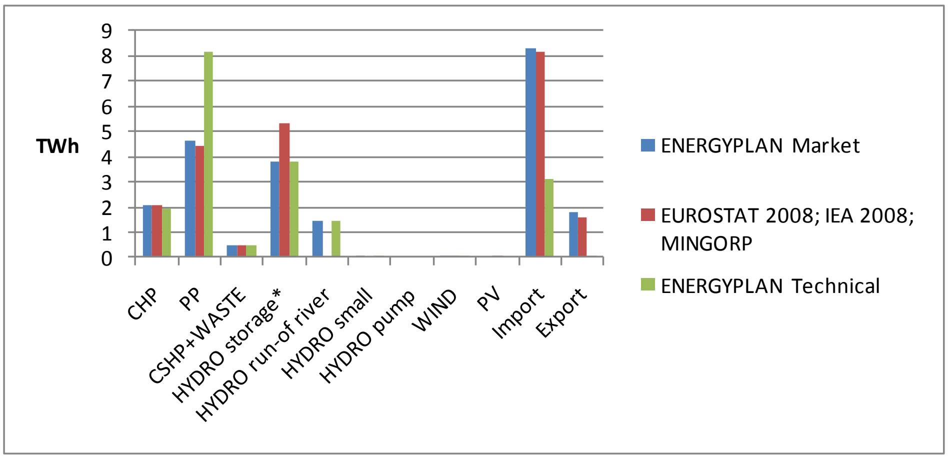


Figure 25. Electricity production by source in the reference case.

In the EnergyPLAN, it is not possible to automatically calculate uncertainty or estimate error for the use of aggregating distribution curves, storage and production capacities. One should calculate these values according to the developed methodology and check the possible error in a treatment of the whole energy system as one point.

In general Croatia can be divided into three climatic regions, continental, coastline or Mediterranean and mountain. Besides the distribution of population within a region, the hourly distribution of energy consumption is also highly dependent on the air temperature. It can be concluded that there are significant differences between the stated climatic regions and their hourly distribution curves of heat and electricity consumption.

The applied market optimisation regulation strategy was conducted with the real fuel prices published in [**63**] for 2008. All future prices of fuel and investment costs in new technologies have been taken from EnergyPLAN data used in [**12**], data from [**123**] and data obtained from the Strategic Energy Technology Information System (SETIS) web calculator. Table 8 presents the fuel prices used in calculations for different years.

Table 8. Fuel prices used in calculations.

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

Gross final energy consumption, CO_2 and fuel costs for different optimization strategies and literature data are presented in Table 9. The value of CO_2 emissions taken from [**63**] only represents preliminary data. Official statistics for emissions from the energy sector in 2008 have never been published. In 2007, CO_2 emissions in the energy sector were 24.7 Mt CO_2 according to [**9**], while the EUROSTAT value for 2008 is 22.14 Mt CO_2. This value includes all sectors and excludes international bunkers and LULUCF (Land Use, Land – Use Change and Forestry) emissions. As data for CO_2 emissions obtained by the EnergyPLAN calculations fall within the range of published data, they are considered acceptable.

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

Table 9. Gross final energy consumption, CO_2 and fuel costs.

	Market.	MINGORP [**63**]	Technical
TOTAL ENERGY: ENERGYPLAN [TWh]	96.63	106.09	106.37
TOTAL ENERGY: ENERGYPLAN corrected [TWh]	106.38	106.09	106.44
CO_2 [Mt]	22.14	20.30*	24.57
CO_2 corrected [Mt]	25.19		24.77
Total Fuel Costs [M€]	3075		3383
Coal [M€]	62		62
FuelOil [M€]	849		1104
Diesel [M€]	959		959
Petrol/JP [M€]	571		571
N.gas [M€]	597		650
Biomass [M€]	36		36
Marginal operation costs [M€]	43		52
Import [M€]	219		6
Export [M€]	-96		-4
TOTAL (Marginal (imp./Exp.) [M€]	3241		3437

3.3.17. Modelling of scenarios results for the case of 2020 Croatian Energy Strategy

The results for gross energy consumption by fuel and electricity export in the case of CES 2020 for different system optimisations and CES data are presented in Figure 26. The strategy values include data according to the baseline scenario. The big difference is mostly the result of different estimations of energy consumption growth rates, as explained in the previous chapters.

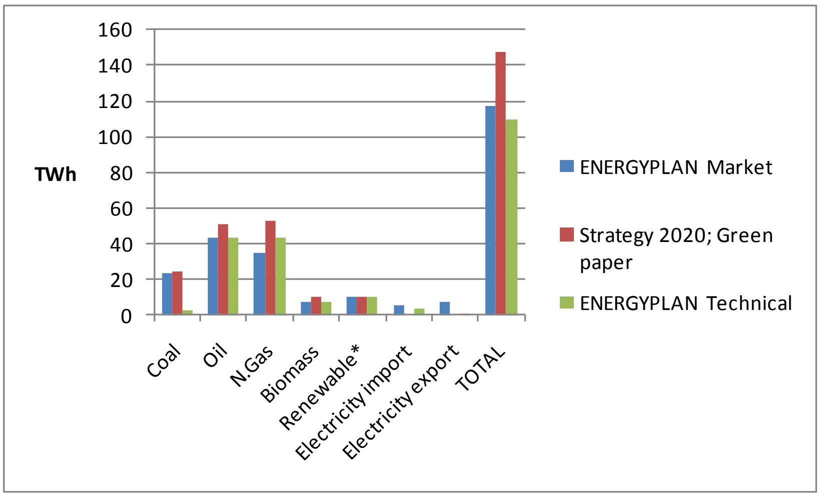


Figure 26. Gross energy consumption by fuel and electricity export in the case of CES 2020. (*geothermal heat for hot water and space heating not included).

In the Green paper [**109**], the estimated use of heat pumps for heating is 18% of the useful surface in services and households for 2020. The value used in the EnergyPLAN calculations is 2.7 TWh supplied by heat pumps with COP 3. The related electricity consumption was 0.86 TWh, as it was estimated that 0.25 TWh of the heat needs in households with heat pumps will also be supplied by solar thermal. These installations also included heat storage with capacity equal to two days of average heat demand. Assuming large grid extensions with the neighbouring countries, the maximum import export has been increased to 10,000 MW. Modernization of power plants should allow better flexibility of their operation, so the minimal load of CHP plants was set to 50 MW, while the minimal load for the power plants that operate in condensing mode was set to 400 MW. An additional 10 GWh of thermal storage has been added to large CHP facilities in order to increase their flexibility, while existing pumped storage facilities of 257/282 MW pump/turbine capacity have been put in the function of RES integration. The grid stabilisation share was kept at 30% of the hourly load.

The estimated averaged increase in the fuel prices for 2020 (Table 8) from 2008 is 52%. Consequently the assumed electricity market prices of EEX have also been also increased by 50%. Elasticity was the same as in 2008. The price of CO_2 emission allowances has been set to 20€/tCO_2 and discount rate used for the investment calculation was at 5%.

Gross energy consumption and CO_2 emissions for 2020 are presented in Table 10. By comparing this with the results for 2008, it can be concluded that CO_2 will be reduced only in the case of a technical optimisation which minimises the use of coal, which makes investment in 1200 MW of new coal power plants questionable.

Table 10. Gross energy consumption and CO_2 emissions in 2020 (*gross final energy consumption in sustainable scenario).

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

Table 11 shows the difference in costs between market and technical optimisation in the case of CES 2020. Market optimisation increases the load of coal power plants, but even in the market optimisation, they operate with a low load factor of 29%. Total gross inland electricity consumption calculated by the EnergyPLAN that takes into account pumping, electric vehicles, heat pumps and extra electric heating was 23.68 TWh for the case of the market optimization for 2020. With the export of 6.77 TWh, this could represent total inland electricity production of 30.45 TWh. The gross inland consumption according to CES 2020 is assumed to be 29.94 TWh. As there is fixed yearly import of 2.99 TWh from NPP Krsko which will probably continue for the next three decades, there is only an additional 3.78 TWh that could be produced by coal power plants. Even if the load increases by double the growth rates seen in the period 2003-2008 and by neglecting all additional import, the planned coal power plants could reach load factors of 70%. This will certainly not ensure an adequate return on invested capital to investors, so construction of 1200 MW of coal power plants as foreseen in the strategy should definitely be reconsidered before making the final investment decision.

Table 11. Cost of CES 2020 case for different model optimizations.

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

The need to of introduce the integration technologies necessary to achieve a 100% independent energy system after 2020 has been analysed by varying the amount of wind energy in the electricity system. In this study, installed wind power generation is varied from 17 MW to 7000 MW, which corresponds to electricity generation from 0.04 TWh to 16.69 TWh.

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

3.3.18. The way towards 100% independent energy system

The goal behind calculating a 100% independent energy system is not to finally operate it as standalone mode but to make it more sustainable and to ensure some security of energy supply and independence. A system that does not depend on energy import/export can achieve better deals on the market. As energy systems are planned for the period 20-40 years ahead, the most important step is to determine future energy needs and demands, which, in the case of the independent and sustainable energy system should be satisfied by locally available resources. This will also require detailed analysis of available resources and their potential. It is mentioned in Chapter 2.5 that the biomass and biofuel potential for Croatia are estimated to at 30 TWh but to fully exploit this potential, in the optimal way, its exploitation has to be properly managed. Management of biomass resources could be done as explained by [**124**], in which the authors used a regional energy clustering algorithm for analysing the energy surpluses and deficits from well-defined zones in a region in order to form energy supply chain clusters and optimise the use of biomass according to a minimum total carbon footprint and reduced waste of energy. Similarly, the other resources should be managed using proper modelling tools and following proper methodologies. When the needs and potentials are known, one of the most challenging tasks is to see what technologies could match demand by utilisation of available resources. This analysis should cover the current status of foreseen technologies, but also their status in the future. Here, all alternatives should be stated and compared by objective technical, economic, environmental and social parameters. Finally, according to the evaluation results, decision makers could choose the most sustainable and acceptable alternatives and consequently propose appropriate strategies to realise the plans. This means that the case of a 100% independent Croatian energy system, as calculated by the EnergyPLAN model, represents only a part of the possible alternatives, as it mostly takes into account the current and market mature, technologies (except electric vehicles). These technologies can be used immediately and their price will not significantly decrease over time due to learning effects (except maybe the PV technology).

To achieve an independent energy system, firstly all hydropower technical potential has been utilised, then all biomass potential has been allocated for consumption in different sectors, and an adequate share of solar thermal heating has been introduced together with proper heat storages. Similarly, heat pumps with appropriate heat storage have been added to replace traditional boiler heating. Then after the introduction of electric cars is assumed and related electricity demand wind capacity has been increased up to 7,000 MW, while related CEEP has been reduced by installation of PHS systems or additional heat pumps and heat storage. The additional need for extra energy has been satisfied by increasing the PV installations.

When the reduction of CEEP by adding new storage capacity became inefficient, the CEEP reduction was achieved by operational regulation: by reducing RES production, by reducing CHP and replacing it by boiler systems, and by replacing boiler heat production with electric heating.

Electricity production by source in the case of a 100% independent system is presented in Figure 27. What is notable that under technical optimisation the load of the condensing power plants is almost zero. This was possible on the assumption that PP and CHP will allow full operational flexibility or, put differently, that they could frequently be switched off and on, which means they can operate without minimal load.

Table 12. Gross energy consumption and CO_2 emissions in 100% RES scenario.

	EP_Market	EP_Tech
TOTAL ENERGY [TWh]	89.91	80.22
TOTAL ENERGY corrected [TWh]	73.23	80.22
CO_2 [Mt]	5.45	4.372
CO_2 corrected [Mt]	3.41	4.372

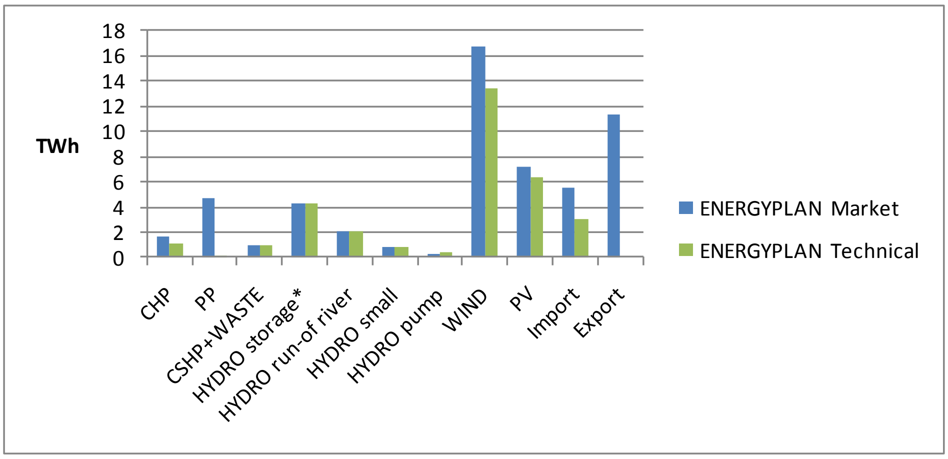


Figure 27. Electricity production by source in the case of 100% independent system.

Table 12 and Table 13 present gross energy consumption, CO_2 emissions and costs of different optimisation strategies in the scenario towards a 100% RES system. Technical optimisation gives lower costs, as in market optimisation electricity is also produced for trade on external market.

Table 13. Cost of 100% independent energy system for different model optimizations.

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

3.3.19. Role of smart storage in increase of RES penetration in Croatia

Due to smart use of energy storage as a source of flexibility in the system that can help the integration of renewable but also demand-side management, Croatia could achieve high penetration of RES or 78.4% in the gross final energy consumption and decrease its energy dependence from a predicted 70% to almost 20%.

The most widespread storage technology used in the power system is pumped storage hydro, with more than 127 GW of installed capacity worldwide [**125**]. As presented in Figure 28, Figure 29 and Figure 30, after the installed 2000 MW and 350 GWh, its contribution to further integration of wind energy is rather small. Figure 31 represents calculated total yearly costs for different PHS capacities. These costs include annual CO_2 emission costs, total variable and fixed operation costs, and annual investment costs.

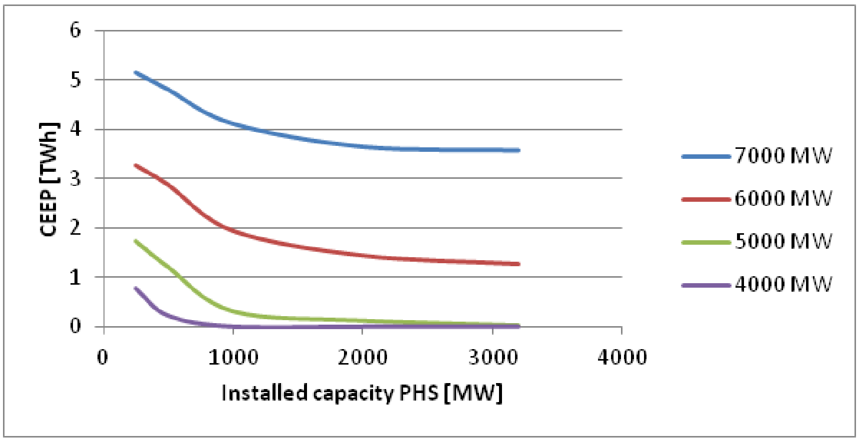


Figure 28. Reduction of critical excess electricity production for different installed wind power capacities and pumped storage capacities (legend shows installed wind capacity).

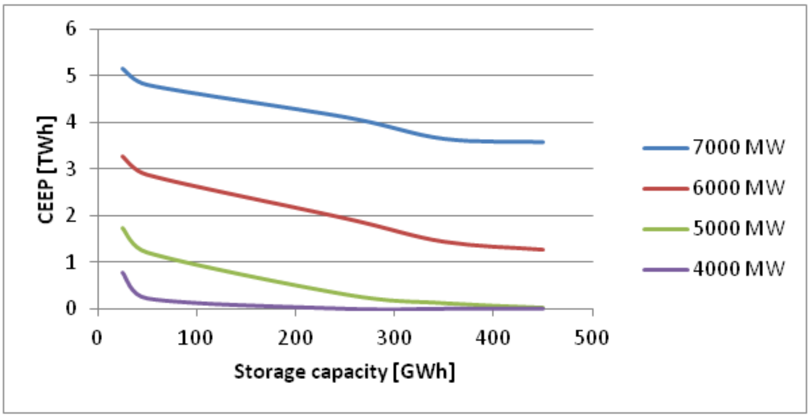


Figure 29. Reduction of critical excess electricity production for different installed wind power capacities and storage capacities of PHS (legend shows installed wind capacity).

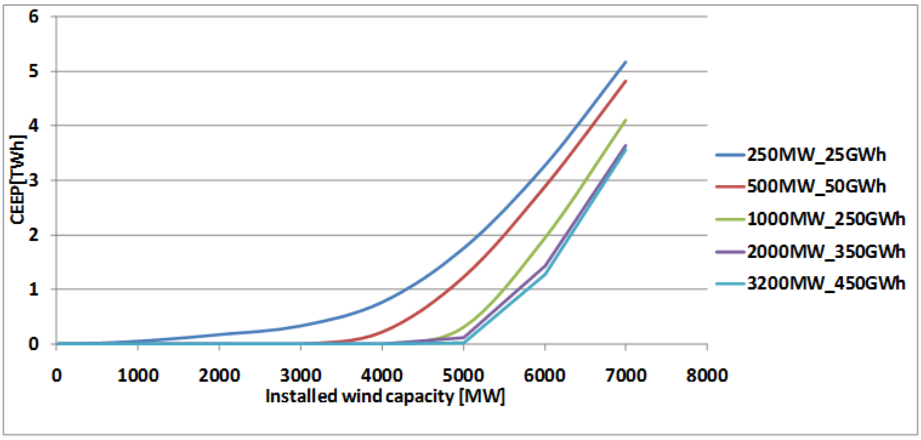


Figure 30. Increasing wind integration by different PHS capacities (legend shows installed capacity of pumps/turbines and PHS related storage).

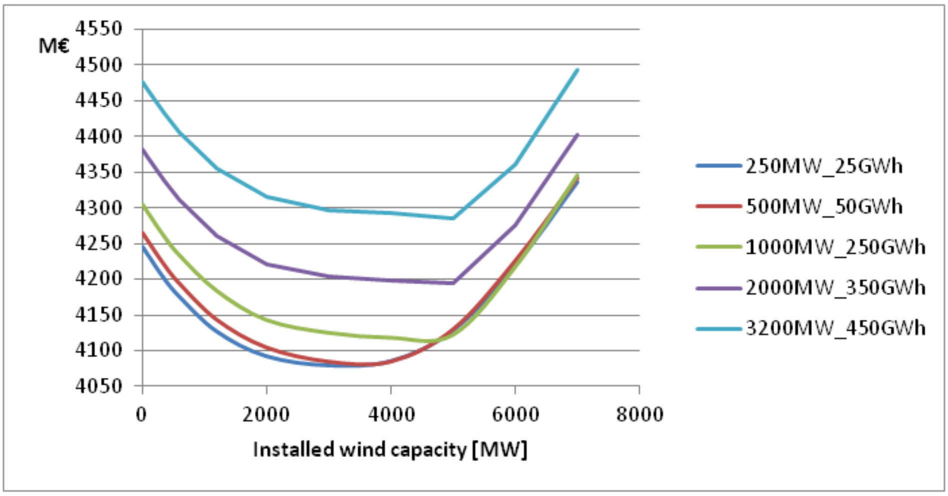


Figure 31. Calculated total yearly costs for different PHS capacities (legend shows installed capacity of pumps/turbines and PHS related storage).

Figure 32 shows results for the reduction of critical excess electricity production under different consumption of heat pumps in the household and services sector and Figure 33 presents total yearly costs for the same case.

Energy storage technologies such as PHS, decrease CEEP and at the same time increase RES penetration, and similar is achieved by V2G. Heat storage and heat pumps represent technologies that could be integrated with other energy flows, so they decrease the CEEP but in some other circumstances they also increase peak load which may require the installation of new production capacities. The construction of new capacities is not desirable in the systems with limited resources. Additional reduction of peak power could be achieved by the application of different operation strategies for charging and discharging the batteries in V2G (Figure 34 and Figure 35) or by larger thermal storages whose operation is optimised to reduce the peak power load.

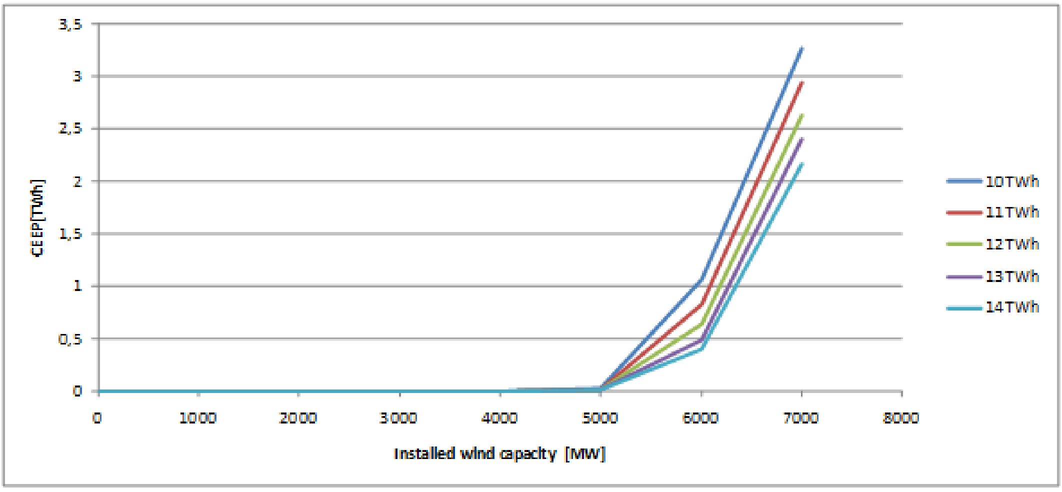


Figure 32. Reduction of CEEP for different consumption of heat pumps in household and services sector.

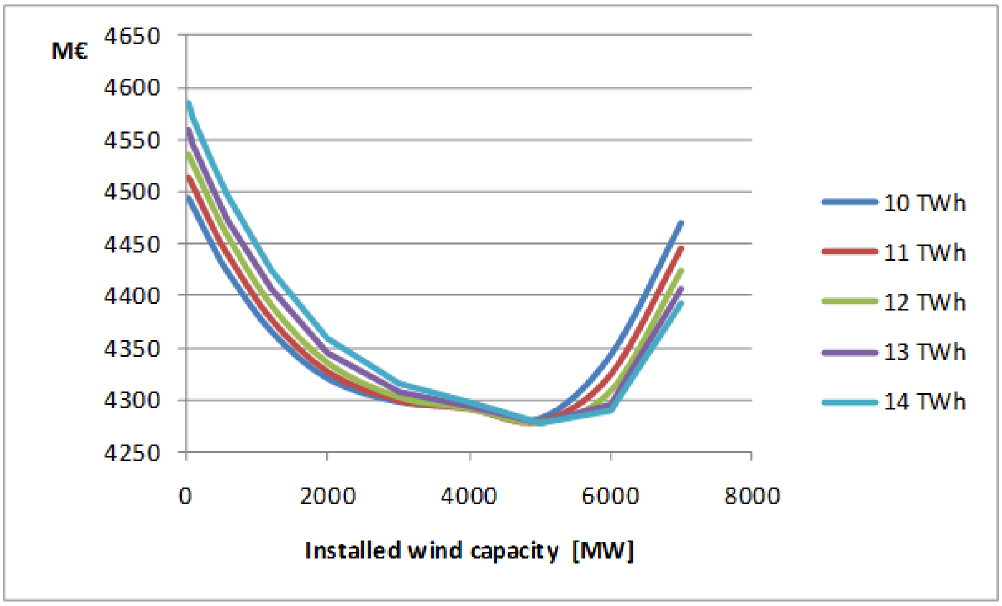


Figure 33. Calculated total costs for different consumption of heat pumps in household and services sector.

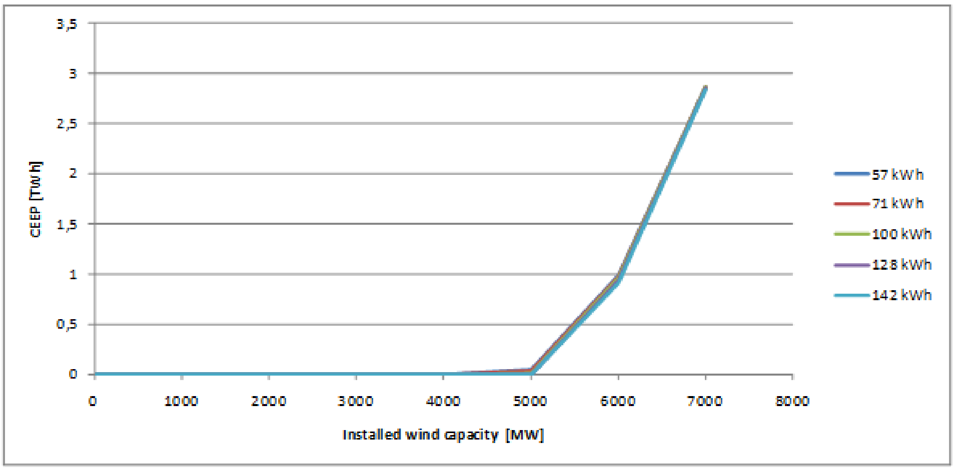


Figure 34. Reduction of CEEP for different sizes of batteries in electric vehicles.

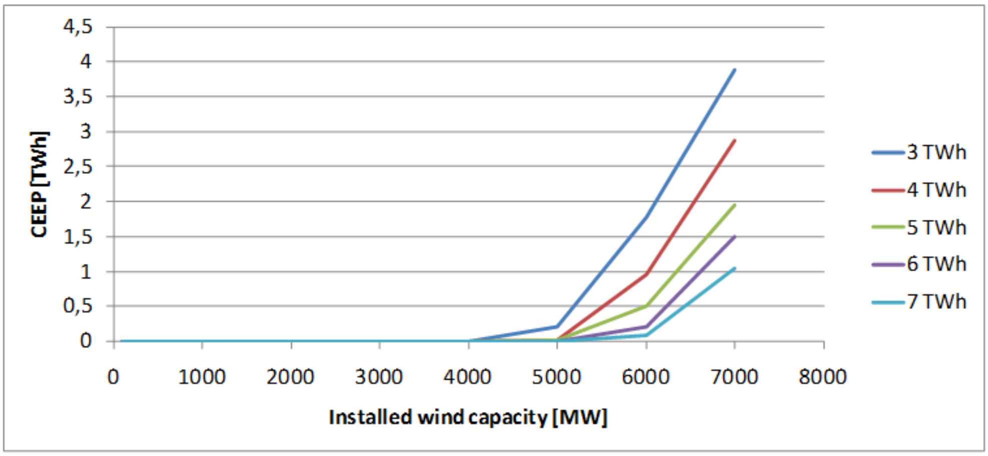


Figure 35. Reduction of CEEP for different electricity consumption of electric vehicles (in TWh).

3.3.20. Role of smart storage in reduction of CO_2 emissions

The use of RES in combination with energy storage can reduce CO_2 emissions in Croatia by 82% or 20 Mt of CO_2 (Figure 36). According to CES 2020, reduction of emissions after 2020 is planned through the development and installation of additional nuclear power plant. However, this option will need further clarifications before the final decision for its construction is made. It should be also recognised that nuclear power plants represent the most inflexible power source, used to supply only base load. If it is planned to significantly increase RES penetration in combination with nuclear power plant, this will be very difficult without large interconnection capacities and extensive application of energy storage technologies. Thus energy storage could be promoted and installed before any other option, RES or nuclear, as storage supports all options and brings additional benefits, regardless of the installed power source.

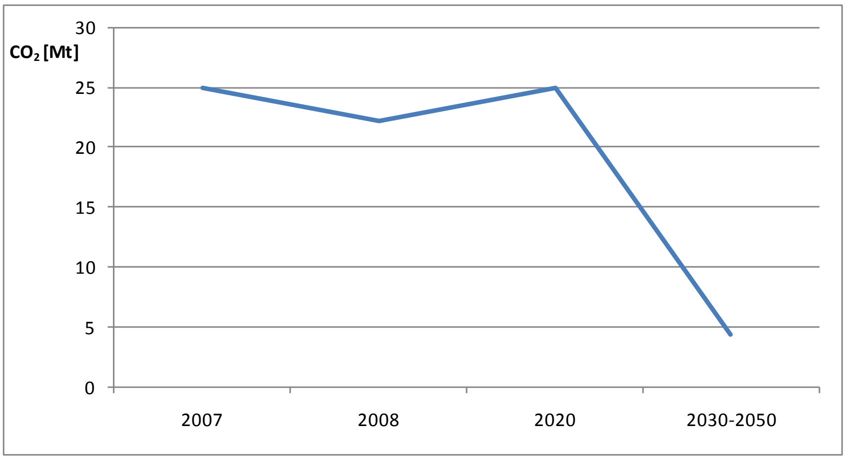


Figure 36. Estimated CO_2 emissions in Croatia (2007 data from [2] , 2008, 2020, 2030-2050 EnergyPLAN calculations).

3.3.21. Modelling and evaluation of 100% RES system scenario for Croatia

The calculations in the scenario towards a 100% independent system showed that a high share of energy independency can be reached by the use of the currently available technology, but to achieve 100% energy independent system based on 100% RES supply it is necessary to introduce assumptions on the development of future technology and its costs, as well as system operation. (Of course, it is possible to use the constraints of current systems and technologies for the system calculated for 2050, but not taking into account the learning curves and progress in the development of technology could become more misleading than when certain assumptions are introduced).

In the analysis of the 100% RES scenario, the Croatian power system has been treated as closed, without any possibility to exchange electricity with neighbouring countries. (This will certainly not be the case in 2050, but it was necessary to limit the export in order to assess the independent operation of the system). By this assumption, 10 GW of import/export capacity were removed, so 11.35 TWh of exported excess and import of 2.51 TWh from the nuclear power plant should be regulated and replaced by other sources. Most probably Croatia will run out of its own resources of natural gas by 2050, so it is necessary to find replacement for the 5.29 TWh of natural gas as a fuel in PP. 15.52 TWh of fossil fuels consumption in the industry sector as well as the consumption of 3 TWh of transport JET fuel should be replaced by non-fossil fuels that could be produced locally. Every branch of the industry sector has its own needs for heating and cooling at different temperature levels and uses fossil fuels for different purposes. To supply these needs with available or future technologies, detailed assessment of demand should be made. In 100% RES calculations it is assumed that by 2050 energy for the industry sector and JET fuels will use synthetic fuels or hydrogen.

According to the mapped resources (Table 4) and converting technologies (Table 6), the hydropower resource has high potential at the regional and local levels and medium at the global level due its seasonal character, and, in general, where flows are high the height differences are less and vice versa. Until 2000, around 50% of the technical hydro potential in Croatia was utilised, but technical potential does not mean that a particular location is economically or environmentally suitable for utilisation. Assuming that all hydropower with acceptable environmental impact has been utilised by 2050, no new installations except for PHS units will be envisaged in this scenario. Looking at yearly, and monthly production, hydropower is the most variable RES source in Croatia, as its production varied in the period 1998-2011 from -27% to +40% from the average yearly production in that period. On the other hand, hydropower plants are the most flexible and controllable source, with the possibility to store large amounts of energy. Thus they can ensure a certain amount of system stability and security of supply. The flexibility of resources and related technologies is assessed in Chapter 3.6.

Biomass has been marked as high on all levels and in the scenario towards a 100% energy independent system 30.66 TWh of biomass (including biofuels) has been utilised on a yearly basis, which is 1.36 TWh more than the technical potential of biomass and biofuels production stated in the Green Book [**109**]. Biomass is a very labour-intensive sector and with the current status of urbanization and unemployment rate in Croatia, biomass and biofuels seem a good option, but the sustainability of their production, the land occupation and available working force, together with urbanization and depopulation by 2050 could lead to decreased use of biomass. Thus wind and solar are stressed as the most important sources of electricity production in the 100% RES scenario for 2050. This assumption is based on the estimation that the wind turbine size for on-shore and off-shore applications will keep increasing at current rates, so the capacity of planned current projects applied in the RES registry is doubled or set to 13,350 MW. This results in the production of 31.82 TWh of electricity. For solar PV installations, further improvement in efficiency is expected, as well as a price reduction. The installed capacity has been increased to 12,000 MW, with a corresponding production of 19.2 TWh yearly, which is close to the current gross electricity consumption in Croatia. The capacity of geothermal power plants has not been increased, while the use of geothermal energy is envisaged in combination with heat pumps. Biomass use has been reduced to 23.56 TWh, of which 10.90 TWh is in biofuels for use in heavy transport trucks, 6.74 TWh will be used in industry and only 0.95 TWh in households. The electricity from waste incineration has been left at 1.67 TWh. A large share of heating has been satisfied by solar thermal energy, in total 9.29 TWh. If it is assumed that the average efficiency of solar thermal collectors is 50%, with average solar radiation at global level and decrease of population, the installed surface of solar thermal collectors will correspond to 3.76 m^2 per capita, which is 3.5-4 times bigger than the current per capita installations in the most suitable countries. The other part of heating and cooling energy will be satisfied in greater measure by heat pumps, with 2.15 TWh in district heating and 9.04 TWh of final heat consumption in households. The COP of heat pumps is set to 3.5 and it is possible to satisfy 70% of hourly heat demand from HP as a proxy for restriction of HP to supply high temperature heat demand. Heat storage systems in district heating CHP units have size of 15 GWh and 30 GWh, and they are located in group 2 (small CHP) and group 3 (large CHP). To produce fuels for the needs of industry (synthetic or H_2), it was necessary to introduce large amounts of electrolysers, or 2650 MW. The system was still not in balance, so the additional power of the PHS system has been increased to ensure system stability. As total electricity consumption crosses over the 60 TWh, this means that if the system is operated with current technology, high losses in transmission and distribution can be expected, so it will be better to manage the system locally (consumption and production), using electric vehicles, batteries or H_2.

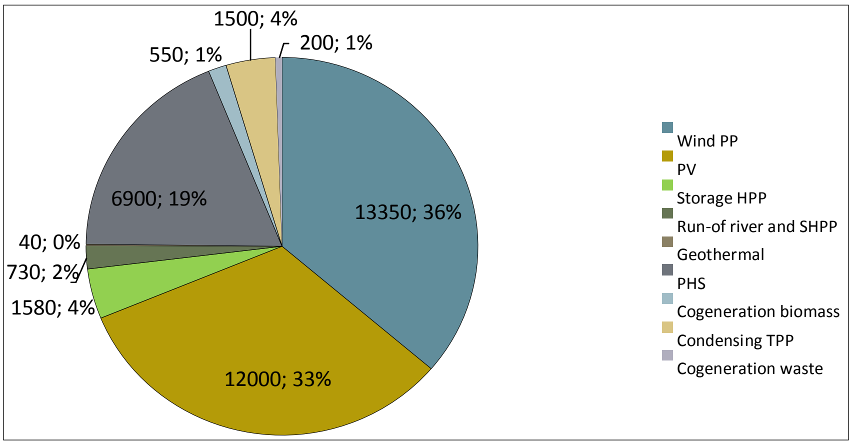


Figure 37. Installed capacity in MW and their share of total installed capacity in the case 100% RES Croatia.

3.3.22. Conclusion on 100% RES Croatia

The new approach to the planning of the Croatian energy system places significant emphasis on the integration of RES energy by the use of different energy storage technologies and system regulation strategies. It presents the results of planning of a 100% independent energy system as just one of the possible alternatives for the development of the Croatian energy system. By 2050, total energy independency has not been achieved due to different needs for fossil fuels in various sectors, but the results are still very promising as concerns CO_2 emission reduction and utilisation of RES.

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

From the calculations in the EnergyPLAN model it was proved that it will be hard to reach total energy independence, but the RES share still reached 78.4% in gross final energy consumption and CO_2 emissions were reduced significantly by 20 Mt. A 100% RES system for 2050 was calculated by making severe assumptions on the future development of energy systems and RES and storage technology. It was not the aim in this case to recommend precise optimal solutions for the integration of RES. Instead, the aim was to provide information on which technologies are fuel-efficient and able to integrate with RES and which approximate capacities of storages and other energy technologies are relevant and could serve as alternatives for further energy planning.

Croatia could reach a significant level of energy independence by the application of commercial technologies that are already present on the market. To achieve a 100% independent or 100% RES system, detailed planning of all economy sectors should be conducted in order to limit the uncertainties introduced by assumptions about technology and system development.

Before any new big installation, one must consider possible energy savings in current systems, as they are the most cost-efficient way to decrease consumption and thus avoid the needs for extra capacity. Energy efficiency can restrain consumption and decouple economic growth from the growth of energy consumption, as it basically creates growth through the reduction of energy consumption. It is important in energy system planning to consider all suitable technologies and to plan their behaviour not just in current conditions but also in future energy systems. Thus storage technologies could also play an important role in the development of smart grids and virtual power plants.

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

3.4. Energy Independence Index - EII

Energy independent systems are those which can independently operate for a certain period of time. In this period all energy needs are satisfied by their own sources (resources). Another interpretation of the Energy Independence Index EII can be done through analysis of the primary energy demand and its supply from own resources (usually stated and measured as energy dependency). In 100% RES systems, the EII is directly linked to RES and storage and thus Directive 2009/28/EC could be the basis on which to determine the EII. Since the Directive does not recognize the full role of energy storage, as discussed in Chapter 3.8, the EII will be based on the physical balancing of the system in order to provide a better picture of the role and possibilities for energy storage.

The EII can be defined as RES production divided by the gross final energy consumption

$$EII_{A,FC}^{\mathrm{T}} = \frac{a_{RE}}{b_{FC}} \tag{11}$$

where index T is the period of time for measuring independency: this could be a year, month, day or hour, and could be written as (year.mm.dd.hh or 2050.12.31.24) if the index is describing the energy independence of an hour from 23:00-24:00 on 31 December 2050, or it could just be written as 2050 if it describes a whole year. Index A is the area or level under examination (G-global, R-regional, L-local), FC is the gross final energy consumption (EL-electricity, HC-heating and cooling and TR–transport) and can be calculated as

$$b_{FC} = b_{EL} + b_{HC} + b_{TR} \tag{12}$$

The EII for the electricity sector for Portugal for 2020 according to Figure 9, if it is assumed that there were no exports of RES, can be written as:

$$EII_{\mathrm{G},EL}^{2020} = 0.808 \tag{13}$$

The Energy Independence Index will also allow a better statistical overview of the energy system's sustainability and needs for energy storage. So, to measure it, detailed balance sheets are required, as well as distribution curves and energy system modelling results. In most cases, it will have two values, forecast and achieved. An energy independent system with the optimal size of energy storage will have an EII equal to 1 (or above 1 for the level required for security of supply) on all levels, from global to local and through the whole measured duration time. For example, if the global EII is on a yearly basis (measured by yearly energy balances) and the global level is greater than 1, but for some shorter time interval (e.g. a month) it is less than 1, this means that the system is exporting, and so is not truly independent, even though it produces more than needed on a yearly basis (the export will depend on the capability of the importing side to take over the excess production), which means it needs to transfer the export to times when there is a shortage of local RES production. The time of excess and shortage will define the type of storage which will similarly be defined by the level or sector.

3.5. Integration of energy and resources flows

The Renewislands/ADEG methodologies covered the large amount of flow integration. New findings and codes are added to the table.

Table 14. Integration of energy and resources flows.

Integration technology	**Condition**	**Code**
Combined heat and power	IF (Elect PROPORTIONAL Heat) AND (DEGS OR CCGT OR FC OR BECS OR SECS OR GECS) AND L-U or L-SU	**CHP**
Combined heat and cold	IF (Heat PROPORTIONAL Cold) AND L-U or L-SU	**CHC**
Trigeneration	IF (Elect PROPORTIONAL (Heat + Cold)) AND (DEGS OR CCGT OR FC OR BECS OR SECS OR GECS) AND L-U or L-SU	**3G-HPC**
Combined water and power	IF (HydroM OR HydroH) AND Water AND R OR L	**CWP**
Combined waste treatment and heat generation	IF (WasteI AND (HeatM OR HeatH)) AND L-U or L-SU	**CWTH**
Combined waste treatment and power generation	IF (WasteI AND (ElectM OR ElectH)) R OR L	**CWTP**
Combined waste treatment and heat and power generation	IF (WasteI AND (ElectM OR ElectH) AND Elect PROPORTIONAL Heat) AND R OR L	**3G-WTHP**
Combined waste treatment and heat, power and cold generation	IF (WasteI AND (ElectM OR ElectH) AND Elect PROPORTIONAL (Heat + Cold)) AND R OR L	**4G-WTHPC**
Combined waste treatment and bioethanol production	IF (WasteG AND ECEt) AND R OR L	**CWTC2H5OH**
Combined waste treatment and gas production	IF (WasteG AND ECBG) AND R OR L	**CWTGas**
Combined wastewater treatment and gas production	IF (WWG AND ECBG)	**CWWTGas**
Combined power and hydrogen production	IF (WECS OR PV) AND ECH2	**CPH2**
Combined heat, power and hydrogen production	IF (SECS OR BECS OR GECS) AND ECH2	**3G-HPH2**
Combined heat, power, cold and hydrogen production	IF (SECS OR BECS OR GECS) AND ECH2	**4G-HPCH2**
Synthetic fuel	IF (WECS OR PV) AND ELY	**SYNF**

3.6. Flexibility of Croatian power system

As mentioned in the description of the FAST method, flexible resources exists in four parts of the power system: the dispatchable power plants, the installed storage facilities, the interconnections with other power systems, and the possibility to control and manage demand. The second source is directly linked to storage of electricity while the fourth source can be examined in the lights of Chapter 3.3 on the integration of flows and especially storage technologies on the demand side, such as cooling thermal energy storage and, heat storage, but also through the production of water by desalination, the production of hydrogen or other synthetic fuels. So, the integration of energy flows and storage technologies could significantly help in integration of RES by increasing controllable flexibility on the demand side.

The first step of the FAST methodology is to identify this existing flexibility in the current system. Due to data limitations, the investigation will mostly focus on the one-hour base which is important as the balancing period in the EnergyPLAN and H_2RES models, so the results should be comparable with analyses of these systems. Trading of electricity is usually done in hourly blocks, so this period is very interesting for the market and organization of dispatching. Other interesting periods for flexibility are from 36 hours to 15 min before electricity consumption.

3.6.1. STEP 1 - Identification of flexible resources in the Croatian power system

Each generation unit in the power system has its own dynamics, so it can be calculated or assessed from the operational data. Average values for broad technology types are used to assess the flexibility of the Croatian power system.

Dispatchable plants in the Croatian power system: the Croatian power system is characterized by a large amount of hydro power plants that should be able to ramp up or ramp down power very quickly (Table 15).

The share of installed capacity in coal power plants (steam turbines) forms only 18% of the total installed power and the rest of the capacity is fuelled by either oil or natural gas. As mentioned before, the majority of the installed capacity is very old and should be replaced by 2020, so new power plants can drastically increase the flexibility of the current system if the required flexibility is prescribed by the TSO.

Table 15. Hydropower plants owned by HEP [64].

Hydro power plants			
	Available power (MW)		**Available power (MW)**
Storage plants		**Run-of-river**	
HPP Zakučac	486	HPP Varaždin	92.5
PHS* Velebit	276/(-240)	HPP Čakovec	77.44
HPP Orlovac	237	HPP Dubrava	77.78
HPP Senj	216	HPP Gojak	55.5
HPP Dubrovnik	216	HPP Rijeka	36
HPP Vinodol	90	HPP Miljacka	24
HPP Kraljevac	46.4	HPP Lešće	42.3
HPP Peruća	60	**Small run-of-river**	
HPP Đale	40.8	HPP Jaruga	7.2
HPP Sklope	22.5	HPP Golubić	6.54
PHS* Buško Blato	11.7/(-10.2)	HPP Ozalj	5.5
Small storage plants		HPP Krčić	0.3
PHS* Fužina	4.6/(-5.7)		
HPP Zavrelje	2		
PHS* Lepenica	0.8/(-1.2)		
HPP Zeleni Vir	1.7		
Total storage HPP	**1,711.50**		
Total small HPP	**28.64**		
Total run-of-river	**425.06**		
TOTAL HPP	**2,136.56**		

*PHS – pumped hydro storage

In 2010 in the Croatian power system, beside the capacities stated in Table 15 and

Table 16, there were also installed 4.113 MW of a small run-of-river power plants producing 17.02 GWh yearly, industrial power plants with installed power of 210.15 MW and 1.92 GWh delivered to the grid, small biogas and natural gas CHP 9.399 MW with symbolic production of 17.07 GWh delivered to the grid. All sources possess, in some degree, technical flexibility but their operation will be scheduled by the needs of industrial operations or by maximising the generation in the case of privileged producers.

By proposing the market incentives, some of the flexibility will be unlocked as it is in the case of Denmark, where small CHP and other small producers with certain dispatching capabilities are participating in the system regulation market.

As mentioned earlier, storage hydro power plants should be dispatchable and they should be able to ramp up or ramp down -0-100% of installed capacity in a 15 min range. Even run-of-river hydro plants have a small retention/accumulation that can allow some flexibility if natural inflow of water is lower than the projected turbine discharge (as it is desirable to avoid overflow, but in the events of security reasons, overflow can be acceptable, so due to their scheduling run-of-river power plants will usually have downward ramping capability). The total discharge of water from accumulation for big run-of-river plants, if full discharge is assumed, takes from 4 to 58 hours. Altogether there are 2,140.663 MW of hydropower plants which could be dispatched. Even making conservative assumptions stated in Table 16 regarding flexibility (the assumption is based on the minimum stable load), and without industrial and other privileged producers (except the hydropower plants), the total technical flexibility of current power plants could be rounded at 2,908 MW. The net available flexibility depends on other factors and is assessed in STEP 2.

Table 16. Thermal power plants owned by HEP [64] and assumed flexibility.

Thermal power plants	Available net capacity (MW)	Fuel	assumed 1 hour flexibility of installed capacity
TE Sisak	396	fuel oil / natural gas	40%
TE-TO Zagreb	422	natural gas / fuel oil	40%
TE Rijeka	303	fuel oil	40%
TE Plomin (A)	110	coal	30%
EL-TO Zagreb	90	natural gas / fuel oil	50%
KTE Jertovec	78	natural gas / extra light oil	90%
PTE Osijek	48	natural gas / extra light oil	90%
TE-TO Osijek	42	fuel oil / natural gas	75%
TE Plomin (B)	192	coal	50%
TOTAL	**1681**		767.3 MW

Storage: The installed capacity of pumped storage hydropower plants in the Croatian system is 293.1 MW (including PHS Buško Blato which is in fact located in Bosnia and Herzegovina) for operating in turbine mode, and 255.9 MW for operation in pump mode. The PHS facilities in the Croatian power system have a big natural inflow of water so they also work as storage hydropower plants and they are included in the capacity of HPP.

Interconnection: According to HEP-OPS, the following interconnection lines are available with neighbouring countries: 10 x 400 kV connections, 8x 220 kV connections and 18 x 110kV connections [**126**]. In 2008 the power of the interconnection was 3,200 MW, which was more than the yearly peak load of the Croatian power system. Since then, the exchange capacity has been improved so, according to the same study [**126**], the total rated power of 400 kV transformers is 4,100 MVA, 220kV transformers 2,120 MVA and 110 kV 4,961

MVA. Taking into account that all the 400 kV substations, and most of the 220 kV are connected to other power systems, the import/export capacity should be 5500-6500 MW. This value is twice the peak load, and most probably the thermal limits of the cables will allow even higher transports. Very good connection capacities with neighbouring power systems allow significant import, export and transit-transport of electricity through HV grids, which also make RH an important interconnector in the region.

Demand side: According to another analysis, the possible demand measures have a value of 5-10% of peak load, which means, if the upper border is assumed, that the flexibility of demand side is around 320 MW. Croatia currently has a two tariff model for electricity, day and night, so consumers may take opportunity to move the load to periods with a lower tariff. Thermo-accumulation furnaces, washing machines and electric hot water boilers are such examples.

3.6.2. STEP 2 - How much of the source is available and how much will be needed

There are three basic levels of flexibility connected to the market and its value. Maximal technical flexibility in the system could be reached by cycling baseload and midmerit plants, but this is hardly economically efficient, so it will usually not happen. Flexible resources available with incentives, financial mechanisms or other fees could stimulate and unlock flexible potential that lies in the system, but are usually not used due to their different operational conditions. If properly designed, incentives can enhance the building of new storage or promote deployment of smart grids and demand management.

Taking into account scheduling of thermal power plants, their age and efficiency in a very conservative approach, their flexibility is assumed to be 50% of the available load. Taking a similar approach for hydropower plants that do not have enough water during the summer while during the winter they must operate at full capacity in order to avoid overflows, it will be assumed that only 50% of HPP potential is available, including PHS. The available flexibility in power plants is 1,454 MW for down and up ramping. Due to specific market conditions, exchange capacity is constrained by bilateral contracts, security codes and n-1 rules, so flexibility of interconnection is assumed to 3,200 MW (which was the existing installed exchange capacity in 2008) and, with 320 MW on the demand side, the assumed total net available flexibility is 4,794 MW.

3.6.3. STEP 3 - Flexibility needs

Flexibility requirements come in the first place from the load side and uncertainty in the load forecast, and they have been successfully tackled by the system operators. An additional need for flexibility comes from the variable renewable energy sources and forecasting of the output, so the net flexibility will be a combination of these two. The needs for flexibility have been presented on Figure 38 and Figure 39. The blue line in Figure 38 represents positive or negative change in the system load between two adjacent hours, so it could be presented as the hourly need for flexibility for a change of average load in the hour t and t-1. The maximal positive difference was 442 MW, while the maximal negative difference was -353 MW. Taking into account the peak load of 3008 MW and the minimal system load of 1182 MW in 2008, the flexibility represented 14.7% of peak load for upward change and 11.7% for downward change, or 37.4% and 29.9% of minimal load. The red line represents the same flexibility, but calculated for the net load with installed 2,400 MW of wind power plants (in this calculation, system stability has been disregarded as the maximal flexibility from the difference between load and wind production has been assessed). If the need for flexibility in the wind production alone is assessed then it is in the range of 339 MW (almost equal for the upward and downward change) or 14.2% of the total installed wind capacity. Compared to the peak load, this is almost the same need, but when the net load is assessed then the total flexibility requirements are much higher, 685 MW for upward regulation or 572 MW for downward regulation, or 28.6% and 23.9% regarding installed wind capacity. The percentage of the flexibility need of net load as a percentage of the installed wind capacity decreases with increasing wind capacity.

The real flexibility needs will be higher by 4-5% due to forecast uncertainties, but could be further decreased by geographical distribution of wind power plants.

Figure 39 presents the maximal downward and upward ramping of net load in the Croatian power system with the installed 3600 MW of wind capacity in the time period 1 - 47 hours. The change in the load has been calculated similar to hourly flexibility, as the maximal value of change is looked for in the period t-n, where n is the range of hours from 1-47. As expected, the maximal flexibility is reached in the period 32 – 39 hours with the values of -4,160 MW for downward and 4,180 MW for upward change.

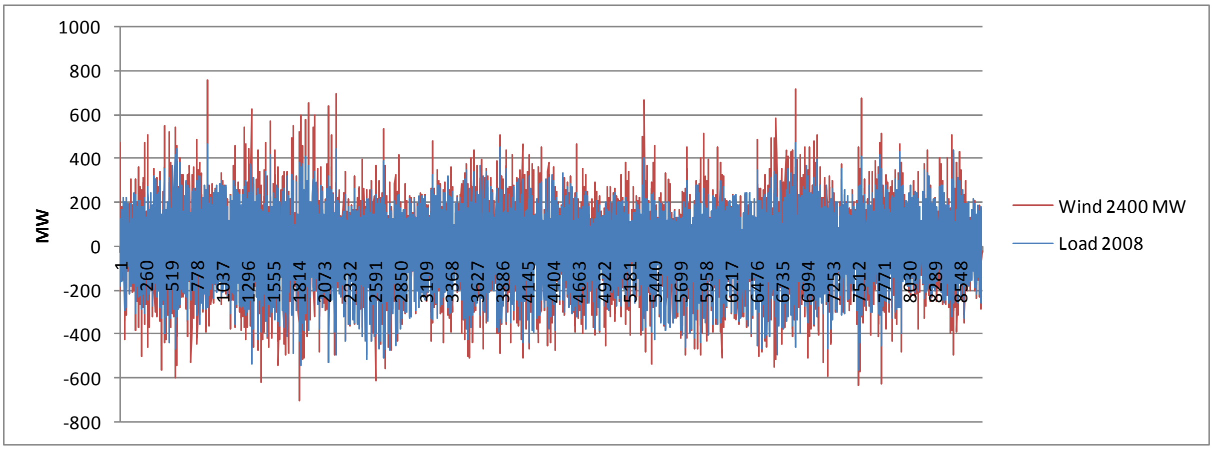


Figure 38. Ramping needs of Croatian power system according to the system load from 2008 and calculated wind power production with 2400 MW of installed wind capacity.

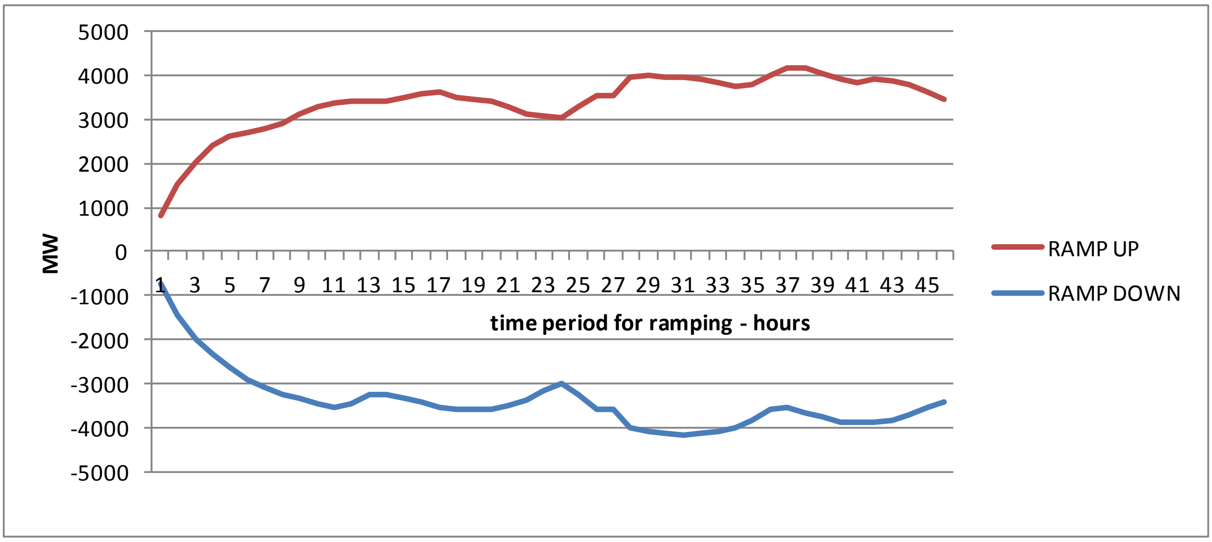


Figure 39. Maximal downward and upward ramping of net load in Croatian power system with installed 3600 MW of wind capacity in the time period 1 - 47 hours.

3.6.4. STEP 4 - Compare needs with available resources

Even working as a one point system, the geographical spread of resources is included in the aggregating curves of hourly wind production, solar production, heat production and different distribution of loads. By analysing hourly distribution curves, the H_2RES model and EnergyPLAN provide a comparison of flexibility needs on an hourly level that is in some ways more detailed than those explained in the FAST method. The models are also capable of calculating the system behaviour over longer time periods, so when the flexibility of the system will not be satisfied, for example, when calculating closed systems, the models will indicate critical excess of electricity production, problems with grid stabilisation or, in the open system, import/export bottlenecks. Comparing the flexibility needs from STEP-3 with the assumed available flexible resources from STEP-2, it can be concluded that, according to the FAST method, it is possible to integrate double or triple of the wind power capacity compared with what is planned in the current energy strategy. Of course, the FAST method should be seen as a screening method for flexibility assessment, so detailed modelling of the system with its real dynamics and in real market environment should be assessed.

3.7. Methodology for planning of 100% RES systems

On the global level, Croatia has been assessed by the Renewislands/ADEG methodology with some parts adapted to form the RESTEP methodology, to show the benefits of using EII as a measure of energy independency and, the EU 2020 goals, and as an indicator for better assessment of the RESTEP processes and the role of energy storage. The EII could be calculated from the EnergyPLAN calculations for 2008-2050 and taken from the mandatory target for the share of RES in the gross final consumption in 2020 set by the Croatian energy strategy and Directive 2009/28/EC.

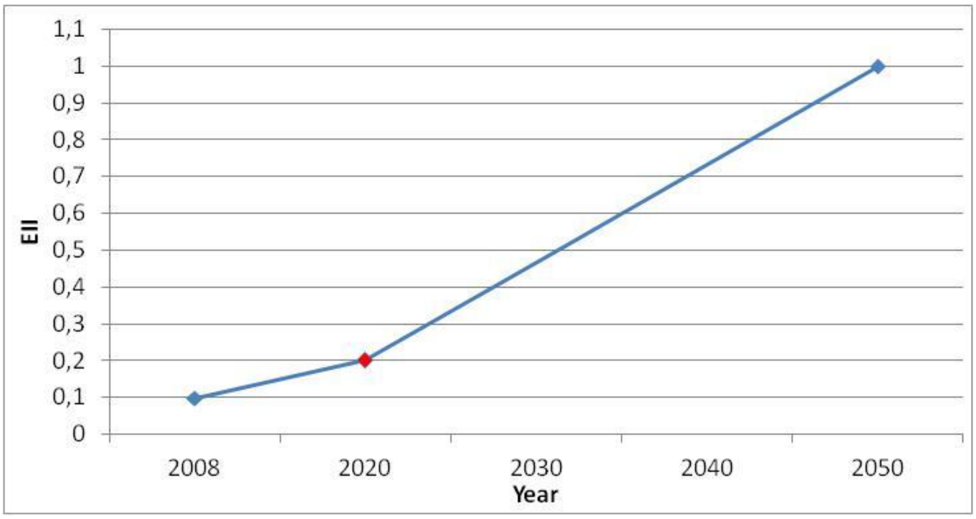


Figure 40. Global EII for Croatia 2008-2050.

The lines connecting points in the diagram in Figure 40 could represent trajectories which a country or energy system will need to follow to reach the goal of 2020 or of any other year in the future in order eventually to reach energy independence. (If it bases all of its supply on the locally available RES so no imports/exports are included -though if necessary they can be indicated-, export will raise the curve so it will be above the EII number, while import will pull down the curve to below the EII). As said before, the future EII is calculated from the results of models that are based on the physical characteristics of planned technology or simulation, optimisation and balancing models for energy planning, so it describes the contribution of energy storage and electric vehicles to energy independency more realistically than it is prescribed by the Directive. The EII can also be calculated according to the rules of the Directive, so for electricity consumption the line of EII will fall below the realistic one (due to the problem discussed in Chapter 3.8) and the EII trajectory for reaching a 10% RES share in the transport sector's fuel consumption, will be above the realistic one as it includes a multiplication of the RES electricity consumed by transport by factor of 2.5, and only road and rail transport consumption are taken into account (similar to the previous explanation). The index based on the Directive may indicate import and export, so the benefits gained by the use of electricity in transport regarding independency could be lost due to the import of fossil fuel. Presenting the EII index for any year in the future and linking it by trajectories is just another way of presenting the goals and obligation to the policy makers. The calculation of trajectories to 2020, as well as the NREAP, should lead to fulfilment of the overall national targets for the share of energy from renewable sources in the gross final consumption of energy in 2020 (as prescribed by the Directive).

The EII is an indicative measure and system optimisation should be done using suitable models but the EII diagram could still provide information on the system behaviour in fulfilment of the goals, as well as possible improvements in achieving them. If the planned future consumption is effectively decreased by some energy efficiency measure or by the deployment of new technology and the planned RES and storage technologies are built, then the EII curve will increase slope more steeply and move to the left, so energy independency will be achieved sooner. Similarly, if the consumption increases more than planned, the slope of the curve will decrease and move down and achievement of the goal will be prolonged. The achieved values of EII above 1 indicate excess or storage larger than necessary (as mentioned earlier this may be necessary for security of supply reasons) and if the EII is above 1 on all levels and in all final consumption sectors, this means that system is able to export RES and contribute to increasing the RES share in other countries (consequently reducing GHG emissions if imported energy from RES in these countries replaces energy from fossil fuels). The amounts of RES above trajectories calculated according to the Directive are allowed to be statistically transferred to the other countries, which will mean that even statistically exporting, the real EII of the country will stay the same, without jeopardising the way towards achievement of an energy independent system.

Going back to the RESTEP methodology that has been applied in Croatia on the global level, a more detailed explanation will be given here of its application on regional and local levels.

As explained in Chapter 2, the Renewislands/ADEG and RESTEP methodologies are in general qualitative not quantitative; they point out better solutions, opportunities for energy storage and integration of flows that should first be investigated and then further processed by the energy planning models, so the time spent on planning can be saved as less optimal solutions can be automatically disregarded. The FAST method and the calculation of EII rely on technical data and, results of analysis, but they can still be indicative measures in fulfilment of policy goals and can indicate future opportunities.

On the example of Dubrovnik region, which includes the island of Mljet, that has been assessed by the Renewislands methodology, a comparison of regional and past findings will be presented and combined.

Global level needs: -electricity, as it is grid-connected and can be easily transferred among the levels and between sectors and stored in many ways (electricity is very a favourable energy vector regarding integration of different flows).

Heating and cooling needs may be mapped in just general way on the global level as a consequence of the climate conditions, while their assessment should be done on the regional and local levels.

Transport can be assessed from the global level, as transport fuels are distributed by all means of transportation (sea, road, train, pipelines) to the final customers but a regional/local assessment of distribution can be notified.

From the local point of view, Dubrovnik County has only 5 cities (Dubrovnik with a population of 43,770, Korčula 5,889, Metković 15,384, Opuzen 3,242 and Ploče 10,834). These could be defined as urban/suburban areas, there are also 17 municipalities that could be defined as suburban/rural areas, and 227 settlements, villages and small places that could be mostly defined as rural areas.

In 2010 Dubrovnik region had a gross electricity consumption of 435,618,219 kWh (area operated by local ODS Elektrojug Dubrovnik, excluding the towns Opuzen, Metković and Ploče) with a peak load of almost 90 MW and losses in the electricity distribution equal to 27,418,096 kWh or 6.29%.

The consumption could represent a regional level, as the amount is taken from the transmission grid, while distribution losses could indicate concentration of consumption, and in the case of dispersed settlements the losses will be much higher.

Table 17. Mapping the needs in Dubrovnik region.

Needs	Level	Geographic distribution			Code
Electricity	High	Concentrated	R/L	U/SU/RU	**ElectHC**
Heat	High	Concentrated	LM*	U/SU/RU	**HeatHC**
Cold	High	Concentrated	LH**	U/SU/RU	**ColdHC**
Transport fuel	High	Short	R/L	U/SU/RU	**TranHL**
Water	High	Concentrated	R/L	U/SU/RU	**WaterHC**
Waste treatment	High	Concentrated	R/L	U/SU/RU	**WasteHC**
Wastewater treatment	High	Concentrated	L	U/SU	**WWTHC**

*hot water heating

**summer period

Heating needs for space heating are low, but there are still several days with a peak demand that are reflected through increased loads in the power system (since most of the heating is supplied by heat pumps or electric heating). The needs for hot water are certainly above average, as Dubrovnik region has a highly developed tourist sector. During the summer, cooling needs and hot water needs are both high, so integration of these two flows could lead to better efficiencies and will be discussed in Step 3. This mapping applies for all local levels, but only urban areas and some more concentrated suburban areas with a specific service sector (hotels, hospitals, food processing industry) will have concentrated demand suitable for integration from a central point, while in the remaining suburban and rural areas heating and cooling needs should be assessed from the single object, as due to thermal losses it will not be cost-effective to install central heating or cooling units. However, this does not mean that there are no possibilities for integration of flows or integration of energy storage in the single object.

Most of the road transport in the region is for short distance travel, so its distribution is ensured through regular supply, although fuel demand in Dubrovnik comes not just from road transport, as there are significant shares of sea and air transport. Water needs are high especially in the summer months due to tourism but also due to low precipitation which creates increased needs for irrigation. Wastewater treatment is concentrated in urban and suburban areas and provides opportunities for energy utilisation but since the sea is the biggest bioreactor most of the wastewater is disposed to the sea. If not properly designed, this treatment can cause severe problems in the tourist season, so collection and wastewater treatment is desirable. Similarly, waste has been landfilled without any treatment, although there is large organic component in the waste produced by the domestic and service sector that could be utilised for biofuels or biogas production.

Looking at the flexibility needs, the nature of demand will allow some flexibility. Washing and irrigation as demand-side measures in the domestic, service and agriculture sectors, and space and hot water heating as well as cooling could be made flexible by the introduction of energy storage and at the same time they could provide the integration of flows. Due to the large impact of tourism, certain activities will be closely related to standardized behaviour of tourists, so it will be hard to reschedule the needs related to them, which means that extra flexibility will be provided by storage.

Table 18. Mapping the resources of Dubrovnik region.

Resource	Level		Code
Global-Regional-Local primary energy			
Wind	High	RH/LH	**WindH**
Solar	Medium	RM/LH	**SolarM**
Hydro (height)	High	RH/LH	**HydroHH**
Hydro (river flow)	High	RL/LH	**HydroRfH**
Biomass	Medium	RM/LH	**BiomM**
Energy import infrastructure			
Grid connection	Weak	RW/LS	**GridS**
Oil derivatives terminal	Yes	GY/RY/LN	**OilDY**
Water			
Precipitation	Medium	RM/LM	**H2OPH**
Ground water	High	RM/LH	**H2OGH**
Water pipeline	Yes	RY/LY	**AquaY**
Sea water	Yes	RY/LY	**H2OSY**

Hydropower is currently the most utilised power source in the Dubrovnik region and it has good height differences, but flows are concentrated only on a few points. HPP Dubrovnik has installed capacity of 216 MW and average yearly production of 1,321 GWh which is shared between HEP and a company in Bosnia and Herzegovina which operates the hydro reservoirs. In 2009 HEP's share of electricity was 685.7 GWh, while in 2010 it was 786 GWh. As mentioned before, the reservoirs of HPP Dubrovnik are located in Bosnia and Herzegovina and their capacity is 756 GWh but, being located in the another country, these will not be taken into account as possible storage technology for Dubrovnik region (in this example only the energy independence of the administrative region is assessed). The SHPP Zavrelje is located near HPP Dubrovnik and it has average production of 4 GWh, but in 2009 the production was above average or 5.9 GWh while in 2010 it reached 9 GWh.

Although a storage type, HPP Dubrovnik operates almost as a baseload plant in order to utilise the maximal potential of water and avoid overflow, so its upward flexibility is restrained, as well as downward. There are plans to extend it with two additional turbine and generator sets with a total additional capacity of 200-350 MW, which will increase yearly production for 300-400 GWh, but more importantly this will increase the flexibility of the power plant, giving it a much better position for trade in the market. At the same time, additional flexibility for integration of intermittent RES sources will become available. There are also plans to build another hydropower plant in Dubrovnik region - HPP Ombla. With the installed capacity of 68.5 MW and planned yearly production of 223.1 GWh, HPP Ombla will act as the water reservoir for Dubrovnik's water supply and thus it represents a good integration of energy and water supply. Construction of an additional 13.02 MW of SHPP has been applied for.

Despite having one of the biggest irradiation values, the solar resources have been regionally assessed as medium level due to possible shadowing, so high values are achieved on the local levels, which means that each location should be separately assessed. Currently there are 2 solar PV installations in the region, with total power of 20 kW, although one is still under construction. Similarly, there is a wind power plant at Ponikve, still under construction, although once finished it should have installed capacity of 34 MW, and 664 MW of new wind power has been applied for in the registry of OiERKK. Biomass is locally present and traditionally used in rural regions, but the biggest problem is its collection in the very harsh environment, so it has been marked medium with locally high values.

Despite having a large hydropower plant, Dubrovnik region has weak connections to other parts of Croatia, but there is still a strong connection with Bosnia and Herzegovina.

The region has an oil derivates terminal located in the sea port of Ploče.

Water precipitation is on a medium level but Dubrovnik region is very close to the region with the highest precipitation value in Europe, so large amounts of ground water exists and they have been utilised. Dubrovnik region is a basically coastline region, so almost all of it is connected to the Adriatic Sea.

Table 19. Potential energy carriers.

Potential energy carriers	**Condition**	**Code**
Electricity	IF ElectC AND G OR R OR L	**ECEl**
District heating	IF HeatHC AND L –U OR L-SU	**ECDH**
District cooling	IF ColdHC AND L –U OR L-SU	**ECDC**
Hydrogen	IF (Tran OR ElectC) AND G or R or L	**ECH2**
Petrol/Diesel	IF (OilRY OR OilDY)	**ECPD**

Electricity is selected as the main energy carrier that is present on all levels. As discussed before, district heating and district cooling will be applicable in urban and suburban parts that have identified needs. Hydrogen as an energy carrier is suitable for remote parts such as the island of Mljet while petrol/diesel will be used in the transport sector.

The most feasible technologies for utilization of local resources have already been used in the region and there are plans to build more capacity. By building HPP Ombla, extending HPP Dubrovnik and building of the SHPP envisaged by the registry of RES almost all the identified hydro potential will be utilised.

Having 500 MW in very flexible source such as storage hydropower, the regional power system will also be able to accept production of WECS and SECS-PV. The latter could be building integrated but also deployed on large unused non-agricultural land surfaces.

FC as conversion system is applicable locally where hydrogen is selected as energy carrier (e.g. the Island of Mljet).

Table 20. Potential Energy conversion technologies in Dubrovnik region.

Technology	Condition	Code
Electricity conversion system		
WECS (Wind)	IF (ElectM OR ElectH) AND (WindM OR WindH)	**WECS**
SECS-PV (Solar PV)	IF (ElectL OR ElectM) AND (SolarM OR SolarH)	**PV**
HECS (Hydro)	IF (Elect) AND (HydroM OR HydroH)	**HECS**
FC (Fuel cell)	IF (Elect) AND (H2Fuel)	**FC**
Heating system		
Solar collectors	IF (Heat) AND (SolarM OR SolarH)	**STCo**
Heat pumps	IF (HeatH AND ECEl)	**HPHe**
Biomass boilers	IF (HeatH) AND (BiomM OR BiomH)	**BMBo**
Cooling		
Heat pumps	IF (ColdH AND ECEl)	**HPCo**
Electricity coolers	IF (ColdH AND ECEl)	**ELCo**
Fuel		
Hydrogen	IF (Tran) AND (ECH2)	**H2Fuel**
Electricity	IF (Tran) AND (ECEl)	**ElFuel**
Petrol/Diesel	IF (Tran) AND (ECPD)	**PDFuel**
Water supply		
Water collection	IF (Water) AND (H2OPM OR H2OPH)	**WaterC**
Water wells	IF (Water) AND (H2OGM OR H2OGH)	**WaterW**
Desalination	IF (Water) AND (H2OSY)	**WaterD**
Waste		
Incineration	IF (WasteHC)	**WasteI**
Gasification	IF (WasteHC)	**WasteG**
Wastewater treatment		
Gasification	IF (WWTHC)	**WWG**

Heat pumps are proposed solutions for both heating and cooling and thus they represent technology that can integrate these two different energy flows. This situation can be described with the simple example of households where a space is cooled during the summer by an air conditioner (heat is evacuated to the open air) while at the same time the water is heated by an electric boiler or similar. By heating water with the evacuated heat from the room, a more efficient cooling process can be achieved and overall energy consumption can be reduced. This simple example also indicates that in some systems it may be more beneficial to install SECS-PV on the roof in combination with a heat pump for heating and cooling than to install a separate solar thermal for hot water and heat pump for cooling. These issues are discussed further in the Table 21. With the rapid development of electric vehicles, electricity is selected as the fuel for the transport sector on the regional level, as well as petrol and diesel for use in sea and heavy road transport. The water supply depends on the local character of available resources and installation of water pipelines. Desalination is suitable for remote islands as in the case of Mljet and Lastovo. Concentrated waste collection with a high share of biodegradable waste and waste oil could be an interesting option for installation of a smaller biodiesel production facility, as given by Ćosić.

Table 21. Potential integration of flows in Dubrovnik region.

Integration technology	Condition	Code
Combined heat and power	IF (Elect PROPORTIONAL Heat) AND (DEGS OR CCGT OR FC OR BECS OR SECS OR GECS) AND L-U or L-SU	**CHP**
Combined heat and cold	IF (Heat PROPORTIONAL Cold) AND L-U or L-SU	**CHC**
Trigeneration	IF (Elect PROPORTIONAL (Heat + Cold)) AND (DEGS OR CCGT OR FC OR BECS OR SECS OR GECS) AND L-U or L-SU	**3G-HPC**
Combined water and power	IF (HydroM OR HydroH) AND Water AND R OR L	**CWP**
Combined waste treatment and heat generation	IF (WasteI AND (HeatM OR HeatH)) AND L-U or L-SU	**CWTH**
Combined waste treatment and power generation	IF (WasteI AND (ElectM OR ElectH)) R OR L	**CWTP**
Combined waste treatment and gas production	IF (WasteG AND ECBG) AND R OR L	**CWTGas**
Combined power and hydrogen production	IF (WECS OR PV) AND ECH2	**CPH2**
Combined heat, power and hydrogen production	IF (SECS OR BECS OR GECS) AND ECH2	**3G-HPH2**
Combined heat, power, cold and hydrogen production	IF (SECS OR BECS OR GECS) AND ECH2	**4G-HPCH2**
Synthetic fuel	IF (WECS OR PV) AND ELY	**SYNF**

As EII for electricity sector is high above one so it necessary to transfer the surplus to other sectors. Electric vehicles in transport and heat pumps in combination with heat storage could provide good flexibility. Even PHS systems are feasible, due to restrictions in land use but also lower amount of available surface most probably will exclude it from the list of possible storages. Another issue for choosing batteries or eventually electric cars as they will help in integration of present variable RES but they can decrease the losses in the system if electricity will be produced locally eg. building integrated SECS-PV.

After mapping the needs and resources and assessing the feasibility of technologies, as well as the integration of flows and storage the scenarios should be devised and modelled with some of the available modelling tools.

Table 22. Feasibility of storage technologies.

Storage technology	Condition	Code
Electricity storage system		
Reversible hydro	IF (WECS AND HECS)	**RHECS**
Electrolyser + Hydrogen	IF (WECS OR SECS OR PV) AND NOT HECS	**ELYH2**
Batteries	IF (WCES OR SECS OR PV) AND NOT HECS AND NOT ECH2 OR REFH2	**BAT**
Electric vehicle to grid	IF (WCES OR SECS OR PV) AND ElFuel	**V2G**
Heat storage		
Heat storage	IF (HeatH)	**HeatS**
Cold bank	IF (ColdH)	**ColdS**
Fuel		
Hydrogen	IF H2Fuel	**H2stor**
Biodiesel	IF BDFuel	**BDstor**
Petrol/Diesel	IF PDFuel	**PDstor**
Synthetic fuel	IF SYNF	**SYNFstor**
Water, Waste and Wastewater		
Water	IF Water	**WaterS**
Waste fill	IF Waste	**WasteF**
Wastewater tanks	IF WWT	**WWstor**

In Croatia, regions, counties, etc., are not obliged to produce energy balance sheets so there are no detailed data for the gross final consumption of energy for heating and cooling or for transport, and future discussion and evaluation will be made based on available data and according to certain assumptions. As gross final electricity consumption for 2010 is known, as well as average production of hydropower plants, the value of EII for electricity can be easily calculated:

$$EII_{\mathrm{R},EL}^{2010} = \frac{a_{RE}}{b_{EL}} = \frac{1325}{435.618} = 3.041$$

As discussed before, this indicates the large potential of hydropower in the region and electricity production is 3 times higher than currently needed, which means that electricity should be used in other sectors in order to become 100% independent region based 100% on RES supply.

The calculated EII index will be accepted by the EU, but it does not give the real picture, as half of the electricity belongs to Bosnia and Herzegovina, so a more correct value regarding only the Dubrovnik region for 2010 will be:

$$EII_{\mathrm{R},EL}^{2010} = \frac{a_{RE}}{b_{EL}} = \frac{786 + 9}{435.618} = 1.825$$

This still indicates the high value of RES electricity production, and if the production of planned hydro, wind and solar are taken into account, all the heating and cooling needs, as well as transport fuel needs, could be satisfied from local RES. Thus Dubrovnik region could become a 100% RES region through use of storage in electric cars, batteries, DH and DC and, as shown in the example of the island of Mljet, by using hydrogen for remote areas.

3.8. FIT for storage technologies in the light of European energy and climate 20-20-20 goals by 2020

3.8.1. Feed-in tariffs application and design

The problem of storage systems is that they increase the cost of already expensive distributed and renewable energy sources, making most of them, in market terms, even less economically viable. For the case of hydrogen, the additional price has been estimated within the range of 43 c€/kWh to 171 c€/kWh, as shown in [**127**] and [**58**]. However, some exceptions for battery systems and hydrogen for the island of Corvo [**74**] suggest that, in certain circumstances, storage can be a viable option.

To overcome financial barriers and create favourable market conditions for energy storage technologies, support schemes and policies must be developed. Feed-in tariffs, Green Certificates, tendering procedures, tax initiatives, and investment initiatives are examples of schemes that have been accepted by different governments and energy regulatory bodies.

As explained in [**128**], due to the relatively high costs of production, wind power and other renewable sources of electricity cannot in a free commercial market compete against mature technologies such as large hydro, combined cycle plants based on natural gas, efficient coal-fired combined heat and power plants, or nuclear power plants. Therefore, special support systems are needed for RES-E until such technologies become commercially competitive. Recent experience from around the world suggests that feed-in tariffs (FIT) are the most effective policy in encouraging rapid and sustained deployment of renewable energy [**129**]. Also, as explained by [**130**], FIT has made Spain and Germany two of the most successful countries in the public promotion of electricity from renewable energy sources. FIT has led to the emergence of an RES-E techno-institutional complex made up of learning networks between RES-E producers, RES-E equipment suppliers, local communities, policy makers and NGOs [**131**].

Currently, only Greece has a policy that supports installation of hybrid systems that include energy storage. Greek law [**132**] regulates the policy, which is currently under revision. The main characteristic is that one tariff is set for electricity from an intermittent RES source, which is directly fed to the grid, while another is set for electricity produced by storage units. There is also a restriction on the amount of energy from the grid that can be used for filling of storage. [**133**] proposed FIT systems for the hybrid systems in Ecuador. The use of thermal energy storage in Denmark was indirectly supported through a triple tariff system used for CHP generation, since excess capacities in CHP units can be used to relocate hours of electricity production if thermal energy storage is added to the CHP plant [**134**].

There are several different ways to structure a FIT policy, each containing its own strengths and weaknesses. [**129**] presented an overview of seven different ways to structure the remuneration of a FIT policy. In general, they divided FIT into two broad categories: those in which remuneration is dependent on the electricity market price, and those that remain independent of it. In the same paper, the advantages and disadvantages of different FIT models were examined, and an analysis of design options was made focusing on the implications for both investors and society. The fixed-price model is very simple to calculate and it offers the same price through the whole contracting period so the price is always known as it is not related to inflation. The disadvantage is that FIT at the beginning of the contracting period should be high enough to make investment attractive, as inflation is unknown and it could decrease the real value of the project revenues. The second feed-in tariff policy option is the fixed-price model with full or partial inflation adjustment. This option is further discussed in the thesis under the proposal of FIT for PHS. The advantage is on the side of RES developers, as their investment and their revenues are ensured and the project can bring larger profits at the end of its life-time, when the majority of capital costs will be paid-off while revenues are mostly the profit. The advantage is that the tariff could be designed closer to the market price, while the disadvantage is that the electricity ratepayer could be under an extra burden until the project is paid off and eventually pay a higher price than for those on the market. In relation to the first two, the third option described by [**129**] is a front-end model where higher rates are paid at the beginning than at the end of the project so related cash flow is higher on the beginning then on the end. This type of tariff could also be designed according to the production rate of the facility, which will depend on the available resources, so facilities with lower production rates will get higher payments than those with higher available resources. In the first period, the rate is determined through a benchmarking and after a certain period it could be determined by the historical production of the plant. The advantage of this model is that the best sites, that have a high rate of full load hours, will not be overpaid while sites with low full load hours will still be built, allowing geographical diversification and the possible deployment of RES in regions with lower potential. The fourth FIT model is the spot gap model, where the FIT has a fixed value and the premium is paid regarding the market price. This model from the producer's perspective does not depend on the market price, while the premium gap could be paid by ratepayers or tax payers, so in the case of increased marginal costs of other technologies, the burden for support is decreased. The model provides a good option for integration of RES into the electricity market. The first market-dependent feed-in tariff policy option examined by the authors in [**129**] is the premium price model. This model offers a constant premium or bonus over and above the average retail price. It does not offer security like the fixed FIT, as the remuneration will be overpaid or underpaid, but its advantage is that RES could compete on the spot market at times when electricity is most needed. The variable premium FIT policy design is applied in Spain and it allows the FIT to go from minimum to maximum values (floor and top) according to the spot market price. At the minimum spot price the premium will be maximal, while if the spot market price is equal to or higher than the market price, the premium will drop to zero. The advantage is that RES investment is secured while overpaying is avoided so this provides security to investors while protecting the ratepayers from unnecessary payments. The last FIT model discussed by [**129**] is the percentage of retail price model, where the FIT tariff is set as a fixed percentage of the retail price. The model was abandoned by all the countries that had implemented it. The authors of [**135**] and [**130**] conclude that the specific design elements of support schemes, rather than the type of support scheme chosen, are the major factor for their success. Political commitment and other factors including the granting of administrative authorisations are also important as they may cause delays in investments and render RES-E investments unattractive. This means that, besides the finances, there are many other barriers for RES-E installations, as identified by [**136**] and [**137**], and in their work they also propose methodologies for overcoming the identified barriers for RES-E installations. As presented by [**138**], utilities have been accused in the past of using third-party grid access as an obstacle to RES-E deployment as they had control over the application procedure and any delays in the approval procedure caused extra costs. This and similar barriers should be addressed before implementing a FIT application for energy storage development.

By providing different support levels for various types of technologies, FIT are more likely to promote different types of technologies than, say, other instruments which prioritise the cheapest technologies [**131**]. This is an important characteristic of FIT, as there are many storage options on the market in various development stages.

A stepped FIT is characterised by a lower tariff for technologies, locations and plant sizes possessing a greater efficiency [**130**]. A stepped FIT is a tool for reducing the surplus produced and, consequently, the societal burden [**139**]. Reducing support as the initial investment provides a return that can also be justified in order to reduce a windfall in profits for investors. In contrast, support is not adjusted according to the RES-E potentials of different locations, which is another positive element of a stepped FIT [**140**]. Reductions in support levels for new plants are linked to cost reductions due to economies of scale and learning effects [**130**]. A similar reduction of over profit for producers due to FIT application could lead to de-escalation of FIT over time. The de-escalating of the feed-in tariff alleviates the burden on consumers, who have to provide the funds for the subsidy through a specially designed RES-E tax. However, if the technological progress envisaged in the policy design is not as rapid as expected, the penetration of RES might abruptly cease when the feed-in tariffs fall below the technology's levelised cost [**141**] .

[**142**] explains the main difficulty with the development of FIT compared to other schemes. The FIT requires policymakers to define administratively the FIT attributes, specifically payment amounts for individual technologies (e.g., wind, solar, geothermal), payment structures (e.g., fixed or declining), and payment durations. All three attributes can require significant 'guesswork' on the part of policy makers regarding future market conditions and the pace of technological improvements. On the other hand, [**143**] concludes that the advantage of the FIT is that it differentiates between various renewable energy technologies at

different stages of development that have different generation costs. Moreover, FITs do not narrow competition, because in the interest of keeping construction costs low, developers try to buy the cheapest and best technologies and thus drive the cost of technology down [**143**]. It could then be concluded that FITs for storage technologies (hydrogen and batteries) will help such technologies to "move up" on the learning curves. As presented by [**143**], in some countries FITs have a long history and a adequate administration to handle its procedures. In these countries, the use of FITs in storage systems could easily be accepted and would not affect the market greatly.

[**143**] explains specific benefits that countries plan to gain using a FIT application. Most countries support the development of RES for the following reasons:

- Ensuring security of supply (reducing dependence on fossil fuels and creating diversity of supply). Reducing greenhouse gas emissions (and other environmental effects of the energy sector).
- Fostering innovation and broadening industrial capabilities (e.g., to improve export potential, skills and enhance competitiveness).
- Increasing local and regional benefits (e.g., through job creation, manufacturing, economic development).

It is desirable to meet these objectives in the most cost-effective manner and this is therefore the main reason for conducting a detailed cost benefit analysis before the application of storage systems [**74**].

As shown by [**144**], extensive public support for electricity from renewable energy sources (RES-E), in addition to environmental and socio-economic benefits, has also resulted in RES-E decreasing the total price of electricity. The additional amount of RES-E, supported by the German RES-E policy (EEG), has reduced the wholesale price of electricity in 2005–2007 by 6.4 €/MWh [**145**], while increasing the RES-E fee by 3.8 €/MWh. Thus, [**144**] concludes that without the support of RES-E, the retail price of electricity would have been 2.6 €/MWh higher than it actually has been. Economic benefits have been reported in the operation of the Cretan power system [**71**] due to the FIT scheme for wind turbines.

The design of FIT for application in the storage system is quite simple and could be easily performed by Energy Regulatory Agencies or Electricity Market Operators and assisted by

TSO and DSO experts. The calculations necessary for evaluating a FIT design could be carried out using energy planning models as described in [**45**] and [**146**].

3.8.2. Feed-in Tariffs for energy storage systems

In general, there exist two basic installations for storage systems, i.e., storage installed as a separate unit (Figure 41) or as part of a hybrid system (Figure 42). The installation in a hybrid system does not necessarily mean that the producing RES units (wind or photovoltaic or any other power plant) is physically installed in the same location as the storage unit. It could be just a conceptual combination of these two plants where each unit has its own grid connection but they are operated as a single hybrid system.

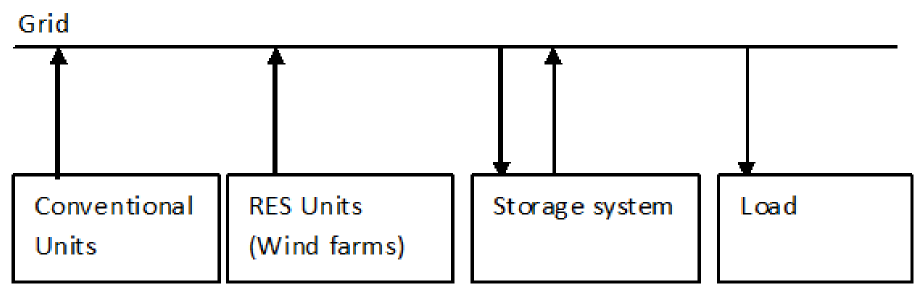


Figure 41. Storage system as separate unit.

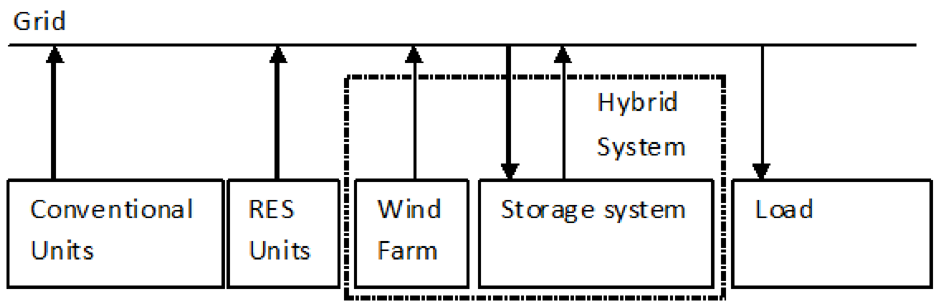


Figure 42. Storage system as part of a hybrid system.

Each of the presented concepts has its own advantages and field of application. Storage systems as separate units are mostly used in big power systems with numerous production units; hence the size of the units is larger. The best such representative installations currently operating worldwide are large pumped hydropower plants. Hybrid systems are more common on islands and in standalone applications.

3.8.3. Feed-in Tariffs for Pumped Hydro Storage - PHS

Pumped or reversible hydropower stations (PHS), not installed as hybrid systems, use energy from the grid to raise water to an upper reservoir. This energy may come from all the power plants in the system. In order to avoid harnessing power from conventional stations used for pumping and increasing emissions of pollutants, these kinds of PHS units should be supported only in systems with an established certification of the renewable origin of electricity ("guarantees of origin" - GO). As mentioned in the introduction, FIT should be different with respect to project size, application, location or resource intensity and the same factors should be applied in supporting PHS.

$FIT_{PHS_{WGO}}$ represents the FIT paid for electricity produced by PHS with the amount equal to the electricity used for pumping and decreased by the total efficiency of the PHS system. This means in theory that electricity produced by PHS could also gets amount of guarantees of origin for RES-E, only decreased by the PHS system efficiency. This is illustrated by the equation below:

$$PHS_{GO} = \eta_{PHS} \cdot W_{GO} \tag{14}$$

where PHS_{GO} are guarantees of origin assigned to electricity produced by PHS and W_{GO} are guarantees of origin for wind electricity supplied from the network. η_{PHS} is the total efficiency of PHS calculated by

$$\eta_{PHS} = \eta_T \cdot \eta_p \tag{15}$$

where η_T is the turbine and generator efficiency and η_p is the pumping efficiency. η_{PHS} is an important factor and must be determined from technical documentation for the proposed PHS or typical groups of PHS .

If η_{PHS} is 70% and if guarantees of origin are standardised at 1 MWh, then for 1 MWh of $E_{PHS_{WGO}}$ (RES-E coming from PHS with provable renewable origin of electricity) or 1 PHS_{GO} will need to supply 1.4285 MWh of E_{WGO} or 1.4285 W_{GO} (RES-E coming from wind power plants with provable renewable origin of electricity). Complex accounting of GO requires a central registry which should be located at the energy market system operator and supported by power system operators (TSOs or DSOs). The importance of the given GO is explained by [**140**] who states that, EU-wide trading of RES-E is most likely to take the form of an exchange of guarantees of origin (GOs).

Although there is obvious support for storage technology in the new EU energy policy, according to the new RES directive (The European Parliament and the Council of the European Union, 2009), the production of electricity in pumped storage units from water previously pumped uphill is not treated as renewable electricity (RES-E). Consequently, it cannot receive guarantees of origin that are recognized at an EU level or accepted by the European Commission. The aim here is to avoid twofold counting of produced renewable electricity. In the scenario that PHS uses only electricity with W_{GO} for pumping, and the turbine has a load factor <=20%, FIT should cover the total costs of electricity production which will be paid for the electricity possessing PHS_{GO}. This is calculated by the formula:

$$FIT_{PHS_{WGO}} = \left(\left(\frac{TIC_{PHS} \cdot R + OMC_{PHS}}{E_{PHS_{WGO}}}\right)_{WGO} + \left(\frac{EPC_{WGO}}{\eta_{PHS}}\right)_{WGO}\right)_{E_{PHS_{WGO}}} \quad (16)$$

where TIC_{PHS} is the total investment cost in PHS, OMC_{PHS} is yearly PHS operation and maintenance costs , $E_{PHS_{WGO}}$ is the total electricity delivered to the network by PHS. $EPC_{W_{GO}}$ represents the market price of RES-E used in pumping. WGO indexes only indicate to which renewable origin of electricity the terms in brackets are related.

The annuity factor R is defined as:

$$R = \frac{i}{1-(1+i)^{-N}} \quad (17)$$

where *i* is the discount rate and *N* the payback period of the investment.

The size of Hydro Power Plants and Pumped Hydro Storage plants varies from a few hundred kW to hundreds of MW, leading consequently to a big span in installation costs. Another characteristic of PHS is that it can be built by adapting existing structures, by adding a pump station and pumping penstock to existing hydropower plants which already have both reservoirs, or by adding an upper or lower reservoir, penstock, reversible turbines or turbines and pumps to an existing water reservoir, as described in the case studies of STORIES project Deliverable 2.1 [**71**]. In the same deliverable, total costs of Hybrid Wind Pumped Hydro Storage (WPHS) and PHS are given by the formulas shown in Table 23. New developments of PHS and the respective installation costs and details are described by [**22**] and [**92**].

FIT suggestions for PHS systems should take into account the local particularities of possibly developing PHS and, accordingly, the suggestions should propose one or several levels of FIT_{PHS}. For a specific energy system, the limit on the turbine load factor in PHS, supported by a different level of FIT, can be optimised. This can be carried out according to desired levels of excess production from RES units or according to the needs of supply security or the energy autonomy of the system as described by [**23**], or the wind capacity index and the reservoir's capacity index as used by [**22**].

Table 23. Overview of the formulas and assumptions for the PHS and WPHS cost estimation [105].

Equipment – Cost symbol	Data/Formula for Cost Estimation (€)
Wind Farms (C_W)	1200 €/kW
Pumps (C_P)	$C_P = N_P \cdot C_{0,P} \cdot \left(\frac{P_{P,rated}}{H_P^{0,3}} \right)^{0,82}$, $C_{0,P} = 1814$
Hydro-turbine (C_T)	$C_T = C_{0,T} \cdot \left(\frac{P_{T,rated}}{H_T^{0,3}} \right)^{0,82}$, $C_{0,T} = 4687$
Reservoir (C_R)	$C_R = 420 \cdot V^{0,7}$
Penstock ($C_{Penstock}$)	$1.25 \cdot \sum_I \left\{ \left[\underbrace{(W_M \cdot \pi D_I \cdot e_I \cdot L) \cdot C_M}_{Material\ Cost} + \underbrace{(\pi\pi_I \cdot L) \cdot C_I}_{Insulation\ Cost} + \underbrace{\left(1.5 \cdot \frac{\pi D_I^2}{4} \cdot L \right) \cdot C_E}_{Excavation\ Cost} \right] \right\}$
Grid connection (C_{GC})	4%*(C_P+C_T+C_R+$C_{Penstock}$)
Control system (C_{CS})	1.6%*(C_P+C_T+C_R+$C_{Penstock}$)
Transportation of equipment (C_T)	2.4%*(C_P+C_T+C_R+$C_{Penstock}$)
Personal (C_P)	30%*(C_P+C_T+C_R+$C_{Penstock}$)
Others (C_O)	2%*(C_P+C_T+C_R+$C_{Penstock}$)
Operation and Maintenance (OMC_{PHS})	2%*(C_P+C_T+C_R+$C_{Penstock}$+C_W)

If the PHS system turbines have a capacity factor greater than 20%, meaning they operate in excess of 1750 full load hours, the PHS system should then receive one FIT until it fulfils the quota of 1750 full load hours (or the energy equivalent). The FIT covering this production will allow PHS owners to make a return on investment at a set discount rate and within an expected time period. Another tariff between 1750 and 2750 full load hours is directly linked to the price of electricity used for pumping. Its purpose is to stimulate additional use of PHS in storing excess intermittent energy and thus reduce curtailment. The third tariff allows minimal earnings in storing excess and is set when PHS operates in excess of 2750 hours. In systems with one penstock, similar pump and turbine power, and no extra inflow of water in the upper reservoir, it can hardly be expected that turbines will operate in excess of 2750 full load hours. However, operation hours will be directly linked to system design and for the purpose of the PHS system.

Table 24. FIT according to capacity factor.

Working hours at full load (or energy equivalent),	**FIT**
<1750 h	$FIT_{PHS_{WGO}}$
1750-2750	$1.055 \cdot \frac{EPC_{WGO}}{\eta_{PHS}}$ (18)
>2750	$1.005 \cdot \frac{EPC_{WGO}}{\eta_{PHS}}$ (19)

Table 24 presents just one example of calculating a stepped FIT and, as mentioned before, these limits will most probably be case related. Therefore, the recommendation is to calculate a stepped tariff for the group of similar case studies through system optimisation of the following parameters: security of energy supply or energy autonomy, reduction of RES-E excess rejection, desired RES-E targets/penetration levels, system regulation, costs and benefits of PHS installation.

Wind potential and hydraulic head are site-dependent features, which strongly affect the attractiveness and profitability of the investment, but do not affect the hybrid wind and PHS energy contribution. In achieving the desired hybrid wind and PHS energy contribution or a peak demand supply for a turbine, a specific wind energy amount combined with a specific storage capacity is required [**19**].

When contracted, $\mathrm{FIT}_{\mathrm{PHS}_{\mathrm{WGO}}}$ should last for a specified period. A period of 12 years seems reasonable from an investor's point of view and contracting should cover a 5 year period after the FIT is ensured (this provides some security to investors and system planners). Following this 5 year period, a revision of the FIT is recommended.

Including 100% of the tariffs for protection against inflation is the best way to ensure stability for investors. The amount of the FIT for electricity produced in plants using renewable energy sources during the validity of the electricity purchase contract is adjusted annually with respect to the retail price index. This is carried out by taking the FIT from the previous calendar year and multiplying it with the annual retail price index from the previous calendar year, i.e.

$$FIT_{YPHS} = FIT_{YPHS-1} \cdot IRP_{YPHS-1} \tag{20}$$

where $\mathrm{FIT}_{\mathrm{YPHS}}$ is the incentive price for the current calendar year. $\mathrm{FIT}_{\mathrm{YPHS-1}}$ is the incentive price from the previous calendar year. For the first year, it represents the amount of the tariff item $\mathrm{FIT}_{\mathrm{YPHS}}$, referred to in paragraph 1 of this Tariff System. $\mathrm{IRP}_{\mathrm{YPHS-1}}$ is the annual retail price index according to official data from the Central Bureau of Statistics for the previous calendar year. YPHS is the yearly index.

A system where the feed-in tariff schedule is updated each year, while taking into consideration the inflation, rate is described in [**141**]. However, the compensation is not complete, but amounts to only 25% of inflation. The reason is that anything less than full compensation provides incentives for constantly improving the efficiency of the subsidised unit through innovation, learning, and so on.

Another criticism against the FIT has been that favourable tariffs have typically not been reduced in step with technological development [**128**]. A supplementary solution would be to adjust the tariff for new installations at regular intervals, taking into account the best technology on the market (bench marking principle).

When additional inflow of water in the upper reservoir exists, enabling a load factor of turbines >=20% (or higher than any other calculated desired limit), the FIT for electricity produced in this way is calculated according to equation 21:

$$FIT_{PHS_{TGO}} = \left(\left(\frac{TIC_{TPS} \cdot R + OMC_{TPS}}{E_{PHS_{TGO}}}\right)_{TGO}\right)_{E_{PHS}-E_{PHS_{WGO}}-E_{PHS_{NOGO}}} \tag{21}$$

$$E_{PHS_{TGO}} = E_{PHS} - E_{PHS_{WGO}} - E_{PHS_{NOGO}} \tag{22}$$

$$E_{PHS_{WGO}} = \eta_{PHS} \cdot E_{WGO} \tag{23}$$

$$E_{PHS_{NOGO}} = \eta_{PHS} \cdot E_{NOGO} \tag{24}$$

where $E_{PHS_{TGO}}$ is electricity produced by turbinating extra inflow of water, $E_{PHS_{WGO}}$is electricity produced by the PHS with GO (by E_{WGO} energy taken from the grid with W_{GO} is used for pumping) and $E_{PHS_{NOGO}}$ is electricity produced by the PHS without GO (by E_{NOGO} energy taken from the grid without W_{GO} is used for pumping). TIC_{TPS} represents total investment costs for a hydropower plant (turbines, generators, penstock and eventually upper reservoir without pumping part). The $\mathrm{FIT_{PHS_{TGO}}}$ should only cover the cost of the PHS when operating as a hydropower plant using extra inflow of, water which means that $\mathrm{TIC_{TPS}}$ should be determined from the ratio $\frac{\mathrm{E_{PHS_{TGO}}}}{\mathrm{E_{PHS}}}$. Extra inflow of water in the upper reservoirs can be easily determined, as pumped volume will always be known. The FIT for electricity produced from PHS, if there are no guarantees of origin for electricity used for pumping, is calculated using:

$$FIT_{PHS_{NOGO}} = 0 \tag{25}$$

meaning that the operator of the PHS is buying electricity and selling back $E_{PHS_{NOGO}}$ at market price. This mode of PHS work should be allowed only if there are no scheduled requests for pumping of RES-E from the system operator, in order to avoid curtailment of RES-E.

If the TSO or DSO for some reason requests the PHS operator to pump and fill the upper storage, and if they cannot provide GO, the PHS owner should receive compensation for carrying out this operation (usually done in accordance with rules for balancing energy and prescribed in network operation codes).

A proposal for organising the market in terms of invoicing, payments, insuring GO and fees for the FIT is shown in Figure 43. In organising such systems, it will be desirable to have Wind Power Dispatch Centres supporting the DSO and TSO [**147**]. This would enable a precise decision to be made on the amount of electricity to be sourced from wind power plants and fed directly to the system, and the amount to be used for pumping. This is important if the GO is also to be determined for the PHS system, meaning the RES privileged producer will only get the amount of GO for its electricity directly absorbed by the system, while part of the GO will be passed to the PHS, decreased by its efficiency. In this way, twofold counting of produced RES-E is avoided and it is then possible to track RES-E, thus organising payments according to the FIT. Market operators at the end of each month or any other agreed payment period could easily calculate the amount of money, according to the prescribed FIT, to be given to the RES and PHS producers. As is also shown in Figure 43, it is then possible to show final consumers the amount of GO and RES consumed, therefore validating their payments.

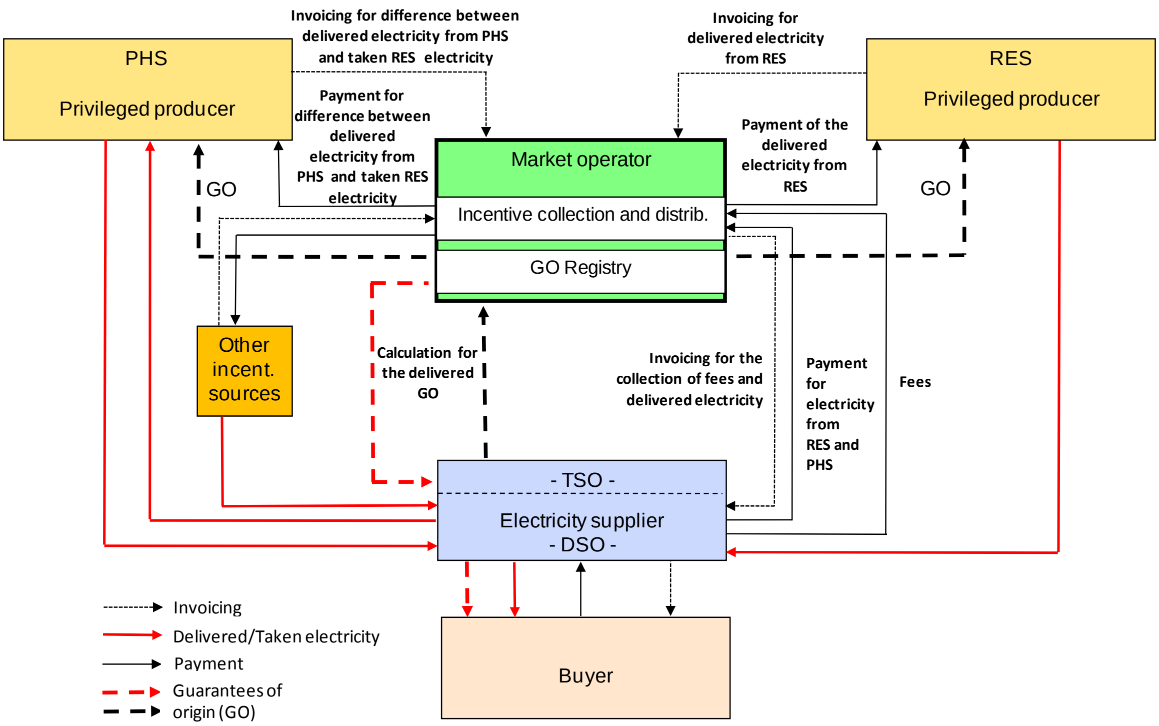


Figure 43. Invoicing, payments and GO flows for FIT.

3.8.4. Feed-in Tariffs for PHS in the Ios island case study

The Ios case study will be used as an example to show how the proposed formulas for the FIT work. Ios is an island in the Cyclades Complex and its electrical supply is part of the autonomous Paro-Naxia system, which includes five main islands (Paros, Naxos, Ios, Sikinos, Folegandros) and some smaller islands.

The only local power station is located in Paros with 10 internal combustion (IC) power units at a cumulative capacity of 61.4 MW. All the islands are interconnected but this system is considered vulnerable and centralised with high energy transportation losses and stability problems. The annual energy demand in the Paros power system is estimated at 189.56 GWh, and the peak demand is 61.2MW with a load factor of 37.6%. Estimations for Ios refer to 12.6 GWh with a peak demand of 3.9 MW. Ios has high wind potential and several existing water reservoirs, which are currently used for irrigation and may be cumulatively exploited for a PHS [**71**].

The energy planning model H_2RES described in Chapter 2 has been used for modelling the system behaviour with installed PHS, a reduction of curtailed energy and operating hours of a PHS station. As explained, the main characteristic of the H_2RES model is that it uses technical data from equipment specifications (efficiencies, installed power, etc.), hourly meteorological data for intermittent sources and, according to the description in Chapter 2 and in [**2**] and [**4**], energy balancing is regulated by the equations.

Table 25. Ios case study data[71**].**

Rated power of the turbine – MW	8.0
Rated power of pumps – MW	6.5
Capacity of the reservoir - m3	120000
Installed power of WT – MW	18.3
Additional installed power of WT - MW	13.5
EPC_{WGO} - €/MWh	87.42
η_{PHS}	0.696
I	15%
N – payback years	8

In 2010, annual energy demand in the Paros power system was estimated at 246.3 GWh and peak demand at 74.8 MW. The estimated hourly data for 2010 has been used in H_2RES. It was also assumed in the calculations that 18 MW of wind was already installed in the system with an additional 13.5 MW following installation of the PHS system. With the limit on hourly wind penetration at 30% and without PHS and new wind installations, it was possible to satisfy 19% of yearly electricity demand while rejecting 30% of total wind potential. With the installation of PHS used for peak shaving at 82.5% of the dynamic weekly peak, it was possible to store 19% of all wind potential. In this case, PHS turbines supplied 3.5% of the total demand and the capacity factor equalling 12%. Under the same conditions and with 13.5 MW of extra wind installed, the capacity factor of the turbines in the PHS was increased to 20%, accounting for a supply of 6% of total electricity demand. Wind share in the total demand was 23% with 34% representing the rejected potential. Figure 44 presents a H_2RES simulation of the power system on Paros in January. The high rejected potential is caused by low demand and favourable wind conditions.

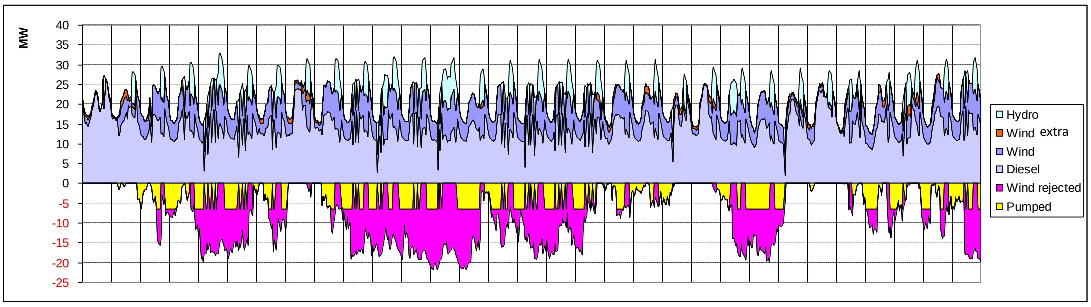


Figure 44. H_2RES Simulation of the power system on Paros in January (development of PHS in IOS) – dynamic weekly peak.

The equipment cost for TIC_{PHS} is calculated according to Table 23 and does not take into account the cost of a lower reservoir, in its current state. The calculated TIC_{PHS} is 6.8 mil. € and $\mathrm{OMC_{PHS}}$ is 97,226 €. Table 26 and Figure 45 present the calculated stepped FIT in the Ios island case. Possible extra earnings for the PHS owners if working in excess of 1750 hours are marked in yellow.

Table 26. Proposed $\mathrm{FIT_{PHS_{WGO}}}$ for PHS on Ios with the existing lower reservoir and 20% turbine load factor.

Working hours at full load (or energy equivalent)	$\mathrm{FIT_{PHS_{WGO}}}$ [€/MWh]
<1750 h	240
1750-2750	132.5
>2750	126.2

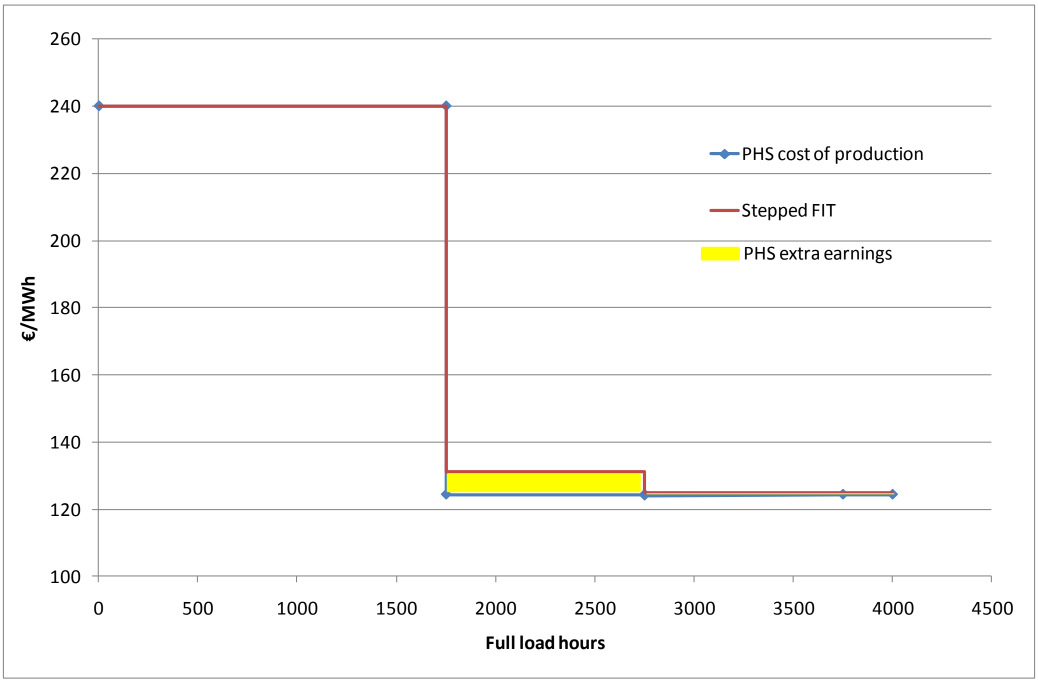


Figure 45. Stepped FIT.

This $FIT_{PHS_{WGO}}$ should be valid for the PHS with 1 MW to 10 MW of installed power turbines and for installations that already have lower reservoirs. Bigger systems and different configurations of PHS installations require additional calculations made using equations 1-6 and Table 23 .

For example, if the system on the Ios island requires the installation of a lower reservoir of the same size as the upper, the FIT for a load factor <1750 h (or energy equivalent) should be at least 263 €/MWh.

If the same principle for designing a FIT is applied to case studies calculated by [**22**], the average FIT for all islands will be 422 €/MWh, in the cases where it was assumed that hydro-turbines' peak demand supplies 50% and 43% energy contribution. The high FIT is due to different conditions for system design but also to large differences in the islands sizes. Therefore, the FIT for Crete would be 269 €/MWh while for Megisti it is 1065 €/MWh. It is interesting to note that if the discount rate in the design of the FIT is set to i=5% and the payback period set to 20 years, as used by [**22**], the average FIT calculated for their case studies is 240 €/MWh for a turbine size of PHS ranging from 1 MW to 10 MW.

3.8.5. Feed-in Tariffs for Hydrogen Storage Systems - HSS

A typical hydrogen storage system includes a water electrolysis unit, a hydrogen storage tank and a fuel cell. Electrolytic hydrogen is produced when excess energy is generated by renewable electricity-generating technologies. Hydrogen is then stored in a gaseous form and can be used as a feedstock for the fuel cell in order to produce electricity when needed. Additionally, hydrogen can be used for transport purposes. In this case, the calculation of feed in tariffs could be more complicated, since part of the payback should come from transport fuel prices. Installation costs of the electrolyser, hydrogen storage, control system and compressor should be divided between electricity and transport costs.

The FIT for hydrogen storage could be calculated in a similar manner to equation 16 for PHS:

$$FIT_{H2_{WGO}} = \left(\left(\frac{TIC_{H2} \cdot R + OMC_{H2}}{E_{H2_{WGO}}}\right)_{WGO} + \left(\frac{EPC_{WGO}}{\eta_{H2}}\right)_{WGO}\right)_{E_{H2_{WGO}}} \tag{26}$$

where TIC_{H2} is total cost of investment in HSS, OMC_{H2} is yearly operation and maintenance costs of HSS, and $E_{H2_{WGO}}$ is total electricity delivered to the network by HSS from electrolysed water. $EPC_{W_{GO}}$ represents the price of RES electricity used in electrolysing water. η_{H2} is the total efficiency of HSS and is calculated by

$$\eta_{H2} = \eta_{ELY} \cdot \eta_C \cdot \eta_{FC} \tag{27}$$

where η_{ELY} is the efficiency of the electrolyser, η_C is the efficiency of the compressor and hydrogen storage and η_{FC} is the efficiency of fuel cells. η_{H2} is an important factor and must be determined from technical documentation relating to the proposed hydrogen system or taken as an average of values for η_{H2}.

Similar to the several levels of FIT for a PHS, $FIT_{H2_{WGO}}$ should also have several levels so that a single price is paid until the fuel cell reaches full load capacity. Subsequently, the load factor FIT is calculated from the equation:

$$FIT_{H2_{WGO}} = 1.02 \cdot \frac{EPC_{WGO}}{\eta_{H2}} \tag{28}$$

3.8.6. Feed-in Tariffs for HSS – Milos case study

Milos is a Greek island situated in the south-western part of the country, in the group of islands called Cyclades. Combining and introducing wind energy and hydrogen storage into the Milos power system has shown that a reduction in fossil fuel dependency, an improvement in supply security and a decrease in the production of harmful fossil fuel emissions are feasible and can be undertaken at a lower cost than current power generation [**74**]. For Milos, the thermal units' capacity can also be reduced. Annual electricity demand for the Milos island is approximately 39,729 MWh with peak demand equal to 8.5 MW. In order to meet this demand, the existing power system includes 8 thermal generator sets with a total capacity of around 11.25 MW and a small wind park comprising 3 wind turbines with a total installed capacity of 2.05 MW and a 13.9% share in demand [**74**].

Table 27. Milos case study equipment and O&M costs [105**].**

Equipment	**O&M**	**Installation**
Fuel Cell -1 MW	4,418 €/year	1,500,000 €
Electrolyser – 2MW	50,000 €/year	2,000,000 €
Hydrogen storage tank – 4000 kg	4,000 €/year	1,600,000 €
Other data		
EPC_{WGO} - €/MWh		87.42
$E_{H2_{WGO}}$ -kWh		2,353,161
η_{H2}		0.3575
I		15%
N – payback years		8

In this case, $FIT_{H2_{WGO}}$ should be equal to or greater than 50 c€/kWh and should be paid until fuel cells reach a full load capacity factor of 27%. Subsequently, the following load factor equation should be used to determine the feed-in tariff:

$$FIT_{H2_{WGO}} = 1.02 \cdot \frac{EPC_{WGO}}{\eta_{H2}} \tag{29}$$

When not taking into account other benefits like fuel savings, avoid emissions, etc., as described in detail in [**74**], the additional fee that should be collected in Milos in order to cover $FIT_{H2_{WGO}}$ is 3 c€/kWh. Furthermore, if all benefits are taken into account, the total price of electricity could be less by 0.1 c€ [**74**], meaning that there is no need for an extra fee. In the report provided by [**74**], a detailed description of CBA analysis and subsidies required for hydrogen storage technologies is given.

3.8.7. Size and location of the PHS system

In general there are no restrictions on the size of the system, which mostly depends on the technology of the turbines and pumps used, which are in turn related to the available height and reservoir capacity. The most promising option for new installations is the transformation of current reservoir hydropower plants by adding a lower or upper reservoir and by constructing pumping stations if turbines are not suited for reversible operations. Additionally no-hydropower dams could be transformed to PHS by building a second reservoir and the necessary hydropower facilities. Another possibility is the construction of completely new pumped hydro storage plants in the most suitable locations.

This study gives an overview of the Croatian potential for the best locations of the PHS installations, which in general could be divided into:

- Mainland – typical locations where there is a possibility to extend current installations (e.g. building of RHE Vinodol);
- Islands – in larger islands such as Krk, where pumped storage could be combined with a water irrigation service and water supply provision; the potential combination with a PV facility could represent a reliable source of energy.

3.8.8. Regulatory frame within EU in support of storage

The variable nature of renewable energy sources (RES) like wind, solar and waves is one of the limiting factors for their penetration in the network. This problem has been recognized in autonomous networks, as RES penetration in those systems easily reached technical limits. Now, similar problems are facing integrated power systems when RES penetration exceeds certain levels (Table 28).

Table 28. EU countries with highest wind share in the gross electricity consumption in 2010.

Country	**Wind penetration 2009**	**Wind penetration 2010**
Denmark	24.9%	22%
Portugal	14.6%	17.1%
Spain	13.9%	16.6%
Ireland	---	10%
Germany	7.2%	6.2%

As explained before, one of the solutions for increasing the intermittent RES-E penetration is to add energy storage to the power system. In addition to helping increase the RES penetration, energy storage can also serve for load management, power quality management and system services[1], security of energy supply, profitable trade of energy, etc. Balancing energy flows via electricity storage can improve the capacity factors of power plants, facilitate the valuation and integration of variable electricity production, avoiding power curtailment, and provide flexibility and support to electricity grid capacities through asset deferral and

[1] System services are all services provided by a system operator to all users connected to the system. Some users provide some system services that are ancillary to their production or consumption of energy. These system services are called ancillary services (Eurelectric, 2004).

reduced grid congestion issues [**148**]. These benefits of storage are of significant interest for renewable energy sources, as they offer a technological solution that maximises the usage and benefits of renewable energy production by reducing for instance, the recourse to fossil fuel-based back-up capacity and power curtailment measures.

In the study on energy storage technologies delivered to the European Parliament [**149**], it is stated that energy storage technologies could contribute to European energy security if they could enable the increased penetration of intermittent renewables. The development of a range of cost-effective, flexible energy storage systems is likely to allow the delivery of the RES targets at a reduced overall cost and with enhanced network flexibility (COM(2007) 723 final).

The means by which the European electricity market is regulated and the nature of the electricity markets are key policy issues determining the scope for energy storage to contribute effectively to energy security and emissions reduction. Currently the European electricity market remains fragmented, resulting in inconsistent operational and regulatory approaches with variable consequences for energy storage, as explained in the discussions in the following chapters. In particular, there is little incentive for energy storage to be introduced in many European electricity markets that do not yet have full liberalisation and transparency, and in those that do have this, there is a small space for market arbitrage and gain profitability only on the spot market.

In the EU there is strong political, public and economic support for renewable energy technologies. Political support is reflected through the European Energy Policy and mostly through directives such as Directive 2001/77/EC for support of generation of electricity from Renewable energy sources (RES-E), superseded by Directive 2009/28/EC on the promotion of the use of energy from renewable sources; the RES and Climate Change package 20-20-20 and many other recommendations and reports. While Directive 2001/77/EC had a target to meet 12% of electricity production from RES, Directive 2009/28/EC sets a RES target for 2020 of 20% of final energy consumption. The Strategic European Technology Plan (SET-Plan), as the technology pillar of the EU Climate and Energy Policy, identifies storage as the key technology priority in the development of the European power system, in line with the 2020 and 2050 EU energy targets (EC 2007, 2009, 2010). The main fields where storage could be of benefit to the power system are identified through support for renewable energy integration, the green building concept, thermal and power storage, smart grids and electrical vehicle transport [**104**] and [**150**].

The Commission has proposed (COM(2007) 723 final) a European electricity grid industrial initiative and recommends that this should encourage integration of energy storage into electricity networks. However storage development faces uncertainties surrounding the power sector evolution, such as the level of variable renewables, the carbon price, the level of base-load technology deployment, and the level of demand side measure effectiveness in curbing and peak shaving energy consumption. Therefore, SET-Plan recommends advancing the analytical framework by building scenarios on the future requirements for electricity storage.

There are significant market and regulatory barriers to assessing the full value of an electrical energy storage device embedded within an electricity network. Work should be conducted to assess the impact of electricity network management and regulation requirements on the future prospects for energy storage.

Naish et al. in [**149**] recommend assessing the effects of renewable energy support mechanisms on electricity energy storage in order to develop measures that could provide confidence in market opportunities for storage investors, on the one hand, and to make policy makers in renewable energy aware of the issues surrounding electricity energy storage, on the other hand.

The main barriers facing electricity storage are market related, with regard to, for example the development of the future energy mix and interconnections, and related regulation such as the definition of the assets between the generation, transmission and distribution utilities to help storage operators address their projects' specificities and to define a clear business case [**123**].

The capacity of electricity storage to provide multiple services to the power system is at the origin of the difficulty in assessing its economics. In particular, this is due to the fact that there is an overlap created between the levels to which storage contributes, i.e., generation, grid, end-user. For storage to be profitable, all the multiple value streams need to be cumulated, and regulatory barriers must be removed. Establishing a framework to assess the economic potential of storage would enable the industry to take investment decisions and public authorities to support the development of electricity storage.

Only Greece had a policy that supports installation of hybrid systems that included large energy storage, while Germany supported PV + batteries hybrid systems. In Greece this policy was set by law [**132**] and it was revised in 2010. The main characteristic of this law was that one tariff is set for electricity from an intermittent RES source that directly fed to the grid, while another was set for electricity produced by storage units. There was a restriction on the amount of energy from the grid that can be used for filling of storage. A more detailed explanation of the hybrid system and possible charging of electricity production is provided in [**105**].

3.8.9. Techno-economic features of PHS storage technologies

Today the most widespread storage in power systems is pumped or reversible hydro storage, which has many advantages. Current pumps/turbines have the capability to work in all possible modes of operation, under full automatic control with automatic operation of all transient states (pumping-stopping-generating) and quick change between them (1-5 minutes). They are easily remotely controlled, have high start/stop frequency and the highest availability and capability to support black starts. In an integrated system, storage and pumped storage hydropower can also help to reduce the challenges of integrating variable renewable resources [**151**].

As stated above, forecasting the future needs for storage capacity is dependent on the future electricity mix, e.g. the level of variable energy and the capacity of the EU grid to accommodate variable power generation, flexibility needs and resources, togheter with production and consumption forecast uncertainties. To date, there are no agreed scenarios on the requirement for additional storage capacities in Europe; however, to some extent National Renewable Allocation Plans provide targets for increasing the PHS installed capacities[2]. In Europe, there are many proposed PHS facilities, mostly in countries with a high wind share or with good conditions for PHS as shown in Table 29. The current hydropower system, with its regional diversity, can be further operated in a more flexible way and provide additional storage capacity to the European system as a whole. Proposed PHS in Spain and Portugal with published costs are presented in Table 30. The costs are estimated in the range from 486 to 2,170 €/kW. The total capital cost for nominal capacities stated in [**148**] for PHS between 200 MW to 500 MW is in the range of 1,000 to 3,600 €/kW.

[2] http://www.ecn.nl/units/ps/themes/renewable-energy/projects/nreap/

Table 29. Proposed PHS in Europe from [92] and projected increase 2020/2010 from the National Renewable Energy Action Plans [152].

Country	Proposed PHS (MW)	NREAPs-declared increase by 2020
Switzerland (CH)	2140	N/A
Portugal (PT)	1956	3266
Austria (AT)	1430	0
Germany (DE)	1000	1406
Spain (ES)	720	3154
Slovenia (SL)	180	0
France	-	2000
Italy	-	200
Total	7426	10026

Table 30. Proposed PHS in Spain and Portugal with estimated costs [92].

Facility	Size	Published cost	Developer	Operational date
Alto Támega Complex	1200 MW turbines, 900 MW pumps	1700 M€	Iberdrola	2018
Baixo Sabor	170 MW	369 M€	EDP	2013
Foz Tua	324 MW	340 M€	EDP	2018
Fridão Alvito	256 MW + 136 MW	510 M€	EDP	2016
Alqeueva II (expansion)	240 MW	150 M€	EDP	2012
La Muela II (expansion)	720 MW	350 M€	Iberdrola	2012

3.8.10. Energy storage and EU Directive 2009/28/EC on promotion of the use of energy from RES

According to Article 5 of the Directive 2009/28/EC of the European Parliament and of the Council of 23 April 2009 on the promotion of the use of energy from renewable sources and amending and subsequently repealing Directives 2001/77/EC and 2003/30/EC, production of electricity in pumped storage units from water that has previously been pumped uphill is not treated as renewable electricity (RES-E), since the power used while pumping is not necessarily wind, solar or of any other renewable origin. In order to frame the discharge with PHS within the RES accounts, a guarantee of resource origin would be useful in order to be recognized in statistics accepted within RES targets, as explained in Chapter 3.8.10.

For further discussion on this issue, the following definitions from Article 2 of the directive are important:

(a) ‘energy from renewable sources’ means energy from renewable non-fossil sources, namely wind, solar, aerothermal, geothermal, hydrothermal and ocean energy, hydropower, biomass, landfill gas, sewage treatment plant gas and biogases;

(f) ‘gross final consumption of energy’ means the energy commodities delivered for energy purposes to industry, transport, households, services including public services, agriculture, forestry and fisheries, including the consumption of electricity and heat by the energy branch for electricity and heat production and including losses of electricity and heat in distribution and transmission;

(j) ‘guarantee of origin’ means an electronic document which has the sole function of providing proof to a final customer that a given share or quantity of energy was produced from renewable sources as required by Article 3(6) of Directive 2003/54/EC;

(k) ‘support scheme’ means any instrument, scheme or mechanism applied by a Member State or a group of Member States, that promotes the use of energy from renewable sources by reducing the cost of that energy, increasing the price at which it can be sold, or increasing, by means of a renewable energy obligation or otherwise, the volume of such energy purchased. This includes, but is not restricted to, investment aid, tax exemptions or reductions, tax refunds, renewable energy obligation support schemes including those using green certificates, and direct price support schemes including feed-in tariffs and premium payments;

(l) ‘renewable energy obligation’ means a national support scheme requiring energy producers to include a given proportion of energy from renewable sources in their production, requiring energy suppliers to include a given proportion of energy from renewable sources in their supply, or requiring energy consumers to include a given proportion of energy from renewable sources in their consumption. This includes schemes under which such requirements may be fulfilled by using green certificates;

The following issues from the Article 16, paragraph 2 point (c) and paragraph (3) of the Directive are also important:

2. Subject to requirements relating to the maintenance of the reliability and safety of the grid, based on transparent and non-discriminatory criteria defined by the competent national authorities:

(c) Member States shall ensure that when dispatching electricity generating installations, transmission system operators shall give priority to generating installations using renewable energy sources in so far as the secure operation of the national electricity system permits and based on transparent and non-discriminatory criteria. Member States shall ensure that appropriate grid and market-related operational measures are taken in order to minimise the curtailment of electricity produced from renewable energy sources. If significant measures are taken to curtail the renewable energy sources in order to guarantee the security of the national electricity system and security of energy supply, Members States shall ensure that the responsible system operators report to the competent regulatory authority on those measures and indicate which corrective measures they intend to take in order to prevent inappropriate curtailments.

3. Member States shall require transmission system operators and distribution system operators to set up and make public their standard rules relating to the bearing and sharing of costs of technical adaptations, such as grid connections and grid reinforcements, improved operation of the grid and rules on the non-discriminatory implementation of the grid codes, which are necessary in order to integrate new producers feeding electricity produced from renewable energy sources into the interconnected grid.

And finally the explanation given in paragraphs (1), (3) and (6) of the Article 5:

Calculation of the share of energy from renewable sources

1. The gross final consumption of energy from renewable sources in each Member State shall be calculated as the sum of:

(a) gross final consumption of electricity from renewable energy sources;

(b) gross final consumption of energy from renewable sources for heating and cooling; and

(c) final consumption of energy from renewable sources in transport.

Gas, electricity and hydrogen from renewable energy sources shall be considered only once in points (a), (b), or (c) of the first subparagraph, for calculating the share of gross final consumption of energy from renewable sources.

3. For the purposes of paragraph 1(a), gross final consumption of electricity from renewable energy sources shall be calculated as the quantity of electricity produced in a Member State from renewable energy sources, excluding the production of electricity in pumped storage units from water that has previously been pumped uphill.

6. The share of energy from renewable sources shall be calculated as the gross final consumption of energy from renewable sources divided by the gross final consumption of energy from all energy sources, expressed as a percentage

Taking into account paragraphs 1, 3, and 6 of Article 5, the following equation for RES share can be written (for simplification of explanation, only electricity will be considered so points b and c from paragraph 6 will be disregarded assuming that those sectors do not exist. Moreover, the system will be observed as a closed one, without exchange of RES-E between the member states):

$$\frac{a}{b} = x \tag{30}$$

where a is the gross final consumption of energy from renewable sources in TWh, b is the gross final consumption of energy from all energy sources in TWh, and x is the share of RES.

If we further assume that only intermittent sources, wind, wave and solar are in the system, which means x=1, then $a = b$, or the examined system is 100% renewable. 100% RES systems without energy storage need several times bigger RES capacities than otherwise necessary, which could cause large curtailments and rejections of potential and, more importantly, the security of supply will be drastically reduced, from an adequacy as well as a system stability point of view. Thus it is necessary to introduce energy storage in the system, so equation (30) can be written as

$$\frac{a}{b} = \frac{a_t + a_s}{b_t + b_s + a_s} = x \tag{31}$$

where a_t is RES-E directly taken into the system, a_s is stored RES-E, b_t is consumption covered by the RES-E, b_s is consumption covered by the storage. The stored RES-E a_s has to be present in the numerator according to Article 2 and Article 5 paragraph 6, as well as it has also to be present in the denominator, as required by definition (f) in Article 2 and paragraphs 3 and 6 in Article 5.

Physically, in 100% RES a_t must be equal to b_t or

$$a_t = b_t \tag{32}$$

and if all stored energy is consumed with in the year (so called closed storage balance),

$$b_s = \eta_s \cdot a_s \tag{33}$$

so Eq. 31 becomes

$$\frac{a_t + a_s}{a_t + \eta_s \cdot a_s + a_s} = x \tag{34}$$

or after solving

$$\frac{1}{1 + \frac{\eta_s \cdot a_s}{a}} = x \tag{35}$$

for 100% RES x=1 so

$$1 = 1 + \frac{\eta_s \cdot a_s}{a} \tag{36}$$

or

$$\frac{\eta_{s} \cdot a_s}{a} = 0 \tag{37}$$

the expression (37) is true only if a_s is 0, which is known from before (a system without storage), and the same is if η_s is 0, which is maximally inefficient storage and the third option is if a is infinite but since $a = a_t + a_s$ and a_t for Europe or any member state will have real value and efficiency of storage $\eta_s < 1$, then the storage should be infinite.

Although this is only a theoretical discussion because there is very little chance that any member state will reach a 100% RES system by 2020, it still has real implications on for the member states and their obligations. This will be shown by the examples of calculations for Portugal and Croatia (assuming that RES excess should be disregarded for the simplicity of explanations).

According to Figure 9, 19.2% of the consumption was satisfied by fossil fuel and, as there was no import, the rest of the consumption was satisfied by RES. This means that the real share of RES was 80.8%, but according to the rules of the Directive the share that will be accepted is 78.36%.

This is calculated by the gross final consumption of energy from all energy sources b, which in this case was only electricity, so

$$b = b_f + b_t \tag{38}$$

electricity from fossil fuel plants b_f=9.438 TWh and RES electricity directly taken by the system b_t which is equal to a_t or in the calculated case 37.931 TWh.

Other important factors are stored RES-E a_s or 2.522 TWh and total efficiency of storage η_s which was set to 0.6864 so calculated RES share according to the Directive is:

$$\frac{a}{b} = \frac{a_t + a_s}{b_f + b_t + b_s + a_s} = \frac{a_t + a_s}{b_f + a_t + \eta_s . a_s + a_s} = \frac{37.931 + 2.522}{9.438 + 37.931 + 0.6864 \cdot 2.522 + 2.522}$$
$$= 0.7836$$

or 78.36% .

Even though theoretical, this result proves that member states could be impaired in their achievements of RES 2020 targets. Hypothetically, country's real achieved share in 2020 could be 20% of RES in the gross final energy consumption, but according the rules of Directive 2009/28/EC and the treatment of stored RES, it will be admitted only 18%. This conclusion also has several other implications, as the policy of the European Union is to promote use of the storage technologies in order to increase the integration of renewable sources, as explained in previous sub-chapters, while at the same time it has large barriers in its own Directive 2009/28/EC. It can also be concluded that the Directive is discriminatory towards storage technologies and automatically guides member states towards increasing grid capacities (in order to exchange and trade RES electricity) instead of storage to promote the use of electric vehicles which can then act as storage (which is explained in further paragraphs).

Using the simplified models as explained by Eq. (6), in H_2RES it is possible to constrain the share of intermittent sources that can be taken by the system in order to have safe operation. In other words, if no other resources that can ensure grid stability are available (hydro, biomass, geothermal), fossil fuel blocks will provide 20% of the regulating power or reserve necessary to keep the system on the safe side. Going below this limit will jeopardise, system operation and is forbidden and excluded as an option. If this situation occurs, the system operator has only three options: to export, if there are available export capacities, to fill storage if there is available storage capacity or to curtail and reject the RES production. Export will be possible only if regulation can be provided from the exported side (this is part of grid dynamics) or if the fossil fuel production is increased, which automatically causes an increase of green house gas emissions, as explained by the results of the EnergyPLAN calculations. Taking into account Article 6 on the Statistical transfers between Member States, each member state should calculate what is more beneficial to it, jointly work on the development of RES and maximise the reduction of greenhouse gas emissions or to meet its goals with its own resources. The optimal deployment of RES, emissions trading, electricity trading and statistical exchange of RES between countries until 2020 is out of the scope of this thesis, but in order to show the possible role and deployment of energy storage, the hypothetical example of Slovenia and Croatia will be examined.

Assuming that Slovenia has installed 1000 MW of coal power plant emitting 820 tCO_2/GWh and if Croatia has installed 1000 MW of combined cycle gas power plants emitting 420 tCO_2/GWh, and an additional 1000 MW of wind power plants, and if both countries have the same load of 1000 MW for one hour with 50% RES penetration limit in the Croatian system, or the same value if both systems are regulated together, five cases are discussed.

- Case A where Slovenia is producing all its needs by coal PP and Croatia is curtailing 500 MW of wind
- Case B where Slovenia has reduced its production of coal and is importing 500 MW from Croatia and providing a reserve for the system stabilisation
- Case C where coal power plant has been shut down in Slovenia and all electricity is imported from Croatia
- Case D where Slovenia is producing all its needs from coal while Croatia is operating 500 MW PHS in a pumping mode
- Case E where Slovenia is producing all its needs from coal while Croatia is charging electric cars with connected power of 500 MW

The results of the analysis of these five cases are given in Table 31. As expected, the best scenario for both countries, in which the highest RES share and lowest CO_2 emissions are achieved, is case C, when the coal power plant in Slovenia is shut down and the system is stabilised by CC in Croatia, while all wind energy is exported. In this way, Slovenia could save 820 tCO_2 per hour while Croatia has increased emissions but has achieved a 100% RES share (calculated according to The Directive). The best case for Croatia is case D, when all the wind is taken while half of the load is met by CC power plant, which means that the coal plant in Slovenia reduced power by 50% and the rest is covered by wind production from Croatia. As there will certainly be trading of RES share and CO_2 allowances in the next decade, it is for both countries to agree on the optimal scenario. Cases D and E represent the use of storage to increasing the RES share. As discussed before, even a simple model makes clear that, according to the current Directive, exchange of RES excess will have priority over the storage technologies, and the conclusion can be drawn that member states should first upgrade their grid connections, work to maximise exchange capacities, conduct joint integration and stability studies and projects, and after that try to deploy storage capacities. This conclusion is made on the basis of the best way to satisfy the Directive on RES and CO_2 reduction goals from the point of view of the EU goals, and not the security of supply of each country, its market development or the profitability of the national and local utilities.

Table 31. Share of RES and CO_2 emissions for examined cases of SI-HR.

	A		B		C		D		E	
	RES	CO_2 [t]	RES	CO_2 [t]	RES	CO_2 [t]	RES	CO_2 [t]	RES	CO_2 [t]
SI	0	820	0	410	0	0	0	820	0	820
HR	0.5	210	1	210	1	420	0.67	210	0.67	210
SI-HR	0.25	1030	0.5	620	0.5	420	0.40	1030	0.40	1030

There are also two other implications that come from the simple example and which are related to the charging of electric vehicles. According to the Directive, electricity from renewable energy sources could also be included in the final consumption of energy from renewable sources in transport, but then it shall be deducted from the calculations for gross final consumption of electricity from renewable energy sources. Furthermore, when calculating the share of renewable energy sources in transport, the Member States may choose to use either the average share of electricity from renewable energy sources in the Community or the share of electricity from renewable energy sources in their own country as measured two years before the year in question. Another important issue is that, for the calculation of the electricity from renewable energy sources consumed by electric road vehicles, that consumption shall be considered to be 2.5 times the energy content of the input of electricity from renewable energy sources (Directive 2009/28/EC).

This means that if a member state plans to achieve part of its 10% share of energy from renewable sources in all forms of transport in 2020 it needs to maximise the production of RES-E in 2018, if by doing so it will manage to reach the RES share above the average share in the Community. If the country is going to satisfy the 2020 goal by RES electricity from wind energy, then it should build most of the capacity by 2017 or, due to logistics problems, even 2-3 years before. Of course, the timing of installations should be optimised if wind installations are to be supported through feed-in tariffs or other mechanisms (taking into account fuel and emission savings on the one side and the present value of social costs on the other side). There is also a possibility of creating a bottleneck in the supply of the wind turbines if countries realise that they will not be able to reach their goals with the planned installations and if industry does not have the capacity to produce the market needs 2-3 years before 2020. Furthermore, as explained in Table 31, the member state could increase its own RES share by forcing RES export to other member states, so by doing this in 2018 it can achieve a higher RES share, while at the same time reducing CO_2 emissions in the importing countries (as presented in Table 31). So if the electrification of transport is the selected goal of the member state for supplying the 10% of RES share in all modes of transport, and the member state will in 2018 have a higher RES share in the gross final consumption of electricity than the average RES share in gross final consumption of electricity of the EU, then it is desirable for the member state not to promote the buying of electric vehicles until 2018, as this will increase the country’s electricity consumption and automatically decrease the achieved RES share. This member state must have massive electrification and support for electric vehicles in 2019, which will then allow the transfer of as much RES-E as possible to the transport sector, which will be calculated with the share of RES-E in the gross final consumption of electricity from 2018. This amount will be deducted from the nominator of Eq. (32) for calculating the RES share in the gross final consumption of electricity, but it will be automatically added to the same place (nominator) in the similar equation for calculation of the gross final consumption of energy in transport, but with a factor of 2.5 and the RES-E share from 2018, thus automatically increasing the total RES share.

This can be shown in the example of the Croatian case study for 2020 calculated by the EnergyPLAN model. According to the rules for calculation of the gross final consumption of energy (GFCE) from RES set in the Directive, the RES shares that will be achieved are calculated as follows; total RES share in the gross final consumption of energy 18.2%, and share of RES in gross final consumption of energy in transport 9.69%. Both numbers indicate that Croatia will not reach the targets of the Directive, but if the RES electricity is transferred to the transport sector and if the share of RES-E in 2018 is the same as calculated RES-E share in 2020, then the achieved share of RES gross final consumption of energy in transport will be 10.8%, while the total share in the GFEC will be reduced to 17.9%. Even reduced total RES share in gross final consumption of energy, by transferring RES-E to transport sector Croatia will be able to fulfil at least one goal set by the directive.

But if it is assumed that all installations for 2020 will be installed in 2018 and that wind power will be increased to 2000 MW, then an additional 1.91 TWh of wind energy will be produced, with additional export of 0.83TWh. In this case, the share of RES in gross final consumption of energy will rise to 20.1% and the share of RES-E will be 47.6% (with assumed normalised hydropower production according to the rules of the Directive and data for period 1998-2011 and calculated production in 2020, the wind energy has not been normalised). This will give a much better position in 2020, and with strong support for changing old petrol-driven cars into EV, which will cover exported 0.83 TWh and at the same time replace 3 TWh of petrol, the RES share in the gross final consumption of energy is achieved is 19.6% while the share of RES in the gross final consumption of energy in transport will be 16.7%. Moreover, as the Croatian 20% target is still not reached because there was consumption of 0.3 TWh, by electric vehicles in transport in 2018 (as observed with data from 2020), if this consumption is removed the share of RES in the gross final consumption of energy rises to 20%, which fulfils the Croatian target for the share of RES in the gross final consumption of energy in 2020. This action reduces the RES in the gross final consumption of energy for transport to 15.3%, which is still 5.3% above the mandatory target, and which also means that the amount of biofuels on the market could be reduced by 1.2 TWh, or 131 million litres of biodiesel, and still fulfil the mandatory target of 10%. These examples are just theoretical, and it will be hard in practice for Croatia to increase the number of EV in one year to 300-500 thousands, or to related numbers that will cover the assumed consumption. However, some other bigger countries as Germany or France that have a strong car industry may exploit this opportunity, while the Croatian tourism sector can also be a promoter of transport electrification in 2019 and 2020. The examples indicate additional opportunities regarding EV and some understatements in the Directive regarding the treatment of energy storage so if the Directive is not changed during the revision in 2015, it will mean that storage (such as PHS or CAES as the only current large storage facility) for many countries is not an option as it will not contribute to increasing the RES share in the gross final consumption of energy, as can be done with export or EV.

As proven by the examples, according to the RES Directive, electricity that is used by the pumped storage is counted in the gross final consumption of energy, which means that, if used, it will increase the amount of energy from renewable sources that should be satisfied in 2020. On the other hand, all the electricity that is produced by wind power plants (directly taken from the grid or used to pump water uphill or for any other dump load) will be counted in the gross final consumption of electricity from renewable energy sources.

However, despite supporting the uptake of RES by prescribing a mandatory target for each member state and providing literary support to installation of storage facilities, it is impossible to achieve a 100% RES independent system using the energy storage in the power sector in the line with the explanation and prescribed accounting of the current Directive. This means that 100% RES systems (from the point of yearly balancing and roles set in the Directive) can only be achieved by export of RES or in small local systems that will not be included in the statistics as consumers.

The support of wind power integration by means of a pumped hydro facility could be beneficial for islands but also for constrained power systems.

To be able to recognize the benefits of the PHS framework, it is proposed to formalise the share of the RES power generation which is used to pump the water in order to assess, on the level of a country, the way the pumped hydro could increase RES-E penetration and its contribution to the national RES targets. Increasing the RES-E penetration by the use of pumped hydro is still possible due to the large difference between gross electricity consumption and RES production. When this difference is small, the benefits of pumped storage regarding increasing the RES share under the current Directive are neglected. However, the Directive stresses the need to take into account the holistic cost of generating electricity and also that the main policy objectives are not simply economic but also environmental and health related.

Financial compensation ought to be paid if renewable energy generators are curtailed where the curtailment is necessary for safety and reliability reasons. Strong support for the storage technologies has been given in the preamble of the RES Directive, which states that there is a need to support the integration of energy from renewable sources into the transmission and distribution grid and the use of energy storage systems for integration of intermittent production of energy from renewable sources. The same support is also reflected in Article 16 of the Directive dealing with the Access to and operation of the grids: “Member States shall take the appropriate steps to develop transmission and distribution grid infrastructure, intelligent networks, storage facilities and the electricity system, in order to allow the secure operation of the electricity system as it accommodates the further development of electricity production from renewable energy sources, including interconnection between Member States and between Member States and third countries. Member States shall also take appropriate steps to accelerate authorisation procedures for grid infrastructure and to coordinate approval of grid infrastructure with administrative and planning procedures.”

3.8.11. Potentials for the PHS in the Croatian energy system

Croatian Transmission System Operator HEP-OPS has regulated the installation of wind capacities at 360 MW, due to technical limits and specificities of the Croatian power system. However, the perspectives for installing more wind power capacity show a wide emerging wind energy market at around 6900 MW of potential installations [**153**], given the high wind potential and good site locations which the country possesses.

With plans for an increasing amount of variable electricity production in order to meet the 2020 targets, it is generally acknowledged that Europe needs to move towards a fully integrated and flexible European electricity network and market [**148**]. Increased spatial diversity: improved forecasting, market-based approaches, such as adjustment of the power market designs, time-of-use, demand control, real-time pricing; and grid technology options: cross-border interconnections, high-voltage direct current (HVDC) lines, power flow control technologies, smart meters, etc. are among the main enabling options for the technologies and techniques to accommodate and mitigate variability. There is a consensus within the electricity sector that electricity storage has the potential to play a complementary role alongside those options for improving the manageability, controllability, predictability and flexibility of supply and demand power flows of the European power system [**154**].

If the Croatian wind power potential is exploited accordingly, the fluctuations generated could increase, especially for a relatively correlated wind power generation along the Croatian coast. However, the operation of new PHS units could reduce this intermittency if their operation is oriented towards an active regulation and control of the Croatian power system in order to allow for greater system flexibility and reliability. PHS units could easily utilise a critical excess of electricity production from wind or other intermittent sources. Meanwhile, the existing hydropower plants could be included in system regulation (currently only three are included in P/f regulation) and contribute to grid support. This would enable more wind and other non-firm renewables into the system.

Wind excess or curtailment, and the capacities of pumps and turbines are not the only factors relevant for construction of a PHS system. Other important factors are the capacities of reservoirs, differences in their elevations and water availability, evaporation and the geology of the terrain. In order to optimise all important factors regarding technical and economic aspects of the PHS system and to determine their capacity, detailed hourly analysis of the power system should be conducted with detailed grid data and historical time series of power loads, hydrological and meteorological data.

The part of investment costs in PHS systems could be avoided if the potential sites for their installation are located near current reservoirs of hydropower plants or near other natural and artificial lakes. As Croatia has few natural lakes, which are mostly in nature protected areas, potential sites could be located near artificial lakes. Table 32 shows the potential locations of PHS systems near artificial lakes in Croatia. The lakes and reservoirs listed in Table 32 are located in the southern and western parts of Croatia. There are also lakes in the northern and eastern parts such as the lakes on the river Drava or the Lake Borovik on the river Vuka with a capacity of $8x10^6$ m^3, but there are no significant height differences in the terrain around these lakes, so they have not been taken into account. Nevertheless, if combined with irrigation, flood protection and even soil drainage, some lower heads or specific locations could be utilised, and therefore integration of flows in storage assessment is important.

Table 32. Larger artificial lakes in Croatia [117].

Lake	**Max. volume [10^6 m^3]**	**Surface [km^2]**	**Basic use**
Peruća	570.9	20	HPP Peruća, HPP Zakučac, HPP Đale, HPP Kraljevac
Kruščica	142.0	8.6	HPP Sklope, HPP Senj
Lokvarka	35.2	1.79	PHS Fužine, HPP Vinodol
Štikada	13.6	2.71	PHS Velebit
Prančevići	6.8	0.65	HPP Zakučac
Lepenica	4.5	0.73	HPP Lepenica, HPP Vinodol
Sabljaci	4.1	1.35	HPP Gojak
Đale	3.7	0.46	HPP Đale
Opsenica	4.3	3	PHS Velebit
Gusić	1.6	0.4	HPP Senj
Bajer	1.5	0.36	HPP Vinodol
Botonega	22.1	2.42	flood protection, water supply
Ričice	35.2	-	flood protection, irrigation
Letaj	8.3	0.74	flood protection, irrigation

The detailed search for available sites for PHS systems could be carried out with the use of computer programs. The authors of [**155**] presented a computer program that scans a terrain and identifies if there are any feasible PHS sites on it. A brief description of the program is provided in [**100**], including the limitations identified during the initial development. The program was used to evaluate a 20 km x 40 km area in the south west of Ireland and the results obtained from this study are discussed in the same publication.

3.8.12. FIT recommendations for PHS in Croatia

The most promising solution in the construction of PHS for Croatia will be the extension of current storage hydropower plants. This could be done by adding lower or upper reservoirs and constructing pumping stations where turbines and penstocks are not suited for reversible operations. A possible development of feed-in tariffs (FIT) for PHS on the mainland is applied to the case of the hydropower plant HE Vinodol and its reservoirs.

HE Vinodol is a part of a complex hydrological and hydropower system constituted from several lakes (reservoirs), hydropower plants, pumping stations and penstocks [**156**]. The water collecting area is not particularly large (about 80 km^2), but its key benefit is that most of the upper reservoirs are located at a height above 700 m, which gives 658 m of gross head at HE Vinodol. The dimensions and use of lakes/reservoirs for HE Vinodol are presented in Table 33.

The system has been in operation since 1952 and in 1985 it was expanded to include the pump storage power plant Lepenica. The main parts of HE Vinodol are explained in [**156**]. These are Lokvarka dam and reservoir, Fužine pump storage power plant and Bajer reservoir, Lepenica dam and reservoir, Lepenica pump storage plant, Križ pumping station, Lič pumping station, Lokvarka-Ličanka tunnel, Križ connecting tunnel, Lič pipeline, Kobljak-Razromir tunnel, and the penstock and powerhouse of Vinodol power plant.

The total installed capacity of HE Vinodol is 94.5 MW (3 generating sets x 2 turbines x 15.75 MW) with maximum annual production achieved in the period 1976-2006 of 197 GWh and average yearly production of 139 GWh.

Table 33. Dimensions and use of lakes/reservoirs for HE Vinodol.

Lake	**Max. volume [10^6 m^3]**	**Surface [km^2]**	**Hydropower plant**
Lepenica	4.5	0.73	HE Lepenica, HE Vinodol
Lokvarka	35.2	1.79	CHE Fužine, HE Vinodol
Bajer	1.5	0.36	HE Vinodol
Tribalj	1.5	0.46	HE Vinodol, lower reservoir

If the volumes of all the upper reservoirs are combined, the maximal potential energy stored in the upper reservoirs for HE Vinodol alone is around 70 GWh. Annual capacity factors are in the range of 16.8% for an average year, while a factor of 23.8% was achieved in the year with the maximum annual production. There have been plans to build PHS Vinodol II which will consist of a pump and turbine station, penstocks and an additional upper reservoir, as described in [**156**].

It is assumed for the purposes of this study that the new upper lake for PHS Vinodol will have a total volume of 5.491.235 m3, which is more than double the size of the planned upper Razromir reservoir given in [**156**], while the assumed height will be lower than those assumed in the same publication, i.e. around 770-780 metres above sea level. The assumed roundtrip efficiency of the PHS calculated by equation 15 is 0.7832.

In order to present a general overview of the possibilities for PHS construction and FIT recommendations, the following calculations have been made:

a) FIT for adding a pump station, penstock and upper reservoir to the existing hydropower plant
b) FIT for adding a pump station and upper reservoir while partly using the old penstock of the existing hydropower plant
c) FIT for construction of the new PHS, including pump station, new turbines, penstocks and upper or lower reservoir
d) FIT for construction of the new PHS, including new pumps and turbines, penstocks, upper and lower reservoir

In all calculations it is assumed that four new pumps will be installed, each with a rated power of 34 MW. This reference scenario, called Case a), is analysed in parallel with a scenario called Case b) where only 300 m of additional penstocks result in lower investment costs than in Case a). Alternatively, two cases – Case c) and Case d) – are tested where 4 new PHTs are installed (30 MW each), with a parallel penstock and additional lower reservoir respectively, with the same capacity as the upper reservoir.

The costs for all cases are estimated according to the formulas and assumptions for the PHS and WHPS cost estimation explained in [**157**] and they are discussed in the Chapter 3.8.2. while for the case of PHS Vinodol they are presented in Annex E.

The only difference from the recommended values in [**105**] is the C0,p factor which has been increased to 2000 due to the use of the large pumps with variable speed drive, which are not as common on the market and it is assumed that new penstocks will be constructed without insulation.

Estimation of the costs of the PHS system according, to the formulas given can be used only for the first evaluation and grading of similar projects, as a more detailed analysis should be employed for each proposed PHS system in the same group of used technology. The disadvantage of using the empirical formulas proposed for new installations of overall PHS systems for calculation of different options within one particular system can be seen in Annex E, where the costs of the grid connection have been calculated differently for units with the same size of pumps and PHTs. Similar results will be achieved only if the reservoir size is varied, as the costs of grid connection, control systems, personnel, etc. are considered as a percentage of the basic equipment cost (PHTs, pumps, penstocks and reservoirs).

FIT are analysed for three sets of capacity factors of turbines/generators corresponding to 10%, 20% and 30% full load hours or energy equivalent. Results for 10% and for 20% and 30% are presented in Annex E.

As stepped tariff is easily calculated using the equations given in Table 34. The tariff stimulates PHS to operate in the pumping mode for even more hours than contracted and as the investment is returned by 1750 hours the tariff beyond that only depends on the price of the wind electricity and variable operation costs that are covered by the increase. Instead of stepped FIT, the PHS could also operate on the free market. This operation is described at the end of the chapter.

Table 34. FIT according to different capacity factors for contracted 1750 full load hours.

Working hours at full load (or energy equivalent),	**FIT**
<1750 h	selected value Table48 – Annex E
1750-2750	131.3 €/MWh
>2750	125.1 €/MWh

If the PHS in Case a) is used to pump water uphill when guarantees of origin for the used electricity cannot be ensured, for example, if electricity is bought on the spot market, in order to cover the investment and operation costs and ensure the desired payback, the lowest selling price of electricity from PHS should be calculated by adding the O&M costs of the turbine part and the spot market price of the electricity taken for pumping divided by PHS efficiency, to the costs of the electricity production without the cost of the wind electricity for pumping (stated in Annex E). The costs in Case d) are equal to the costs of installing a complete new PHS system.

The formalised approach used in this study enabled an order of magnitude to be calculated for the supporting schemes of PHS contributing directly to the wind power integration in the

Croatian power system. This level varies with the cost of the excess electricity sold to the PHS operator, with the technical parameters of the PHS system to operate during one year, with the number of pumps and penstocks installed which could lower the investment cost, and finallywith the pre-determined contractual conditions such as the number of years to pay back the capital cost and the rate of return agreed by both the regulator and the PHS investor.

As a synthesis of the results presented in our calculus, when the electricity from wind excess is charged for free, the FIT-GO varies in the range of 42-141 €/MWh for an average capacity factor of 20% (1750 FLH). This range is wider for a lower number of operating hours (84-283 €/MWh for 870 FLH) and is lower for higher generation rates (28-94 €/MWh at 2630 FLH).

When the electricity charged is at fixed tariff, 97.5 €/MWh, the level of FIT_GO naturally increases and attains margins of 166-265 €/MWh for 1750 FLH, 209-408 €/MWh for 870 FLH and 152-218 €/MWh at 2630 FLH.

These levels are to be analysed by both the regulator and the investor when setting the profitability of a PHS project. A reasonable range for both agents is the average number of FLH of 20% yearly, which could enable the PHS operator, where it is technically possible, to improve the business prospects by operating in other market segments and diversifying the risks and the benefits. This would provide an opportunity for the PHS operator to cumulate all possible benefits it can obtain on the market and to benefit from the market price volatility which is the main business driver of the storage. From a system perspective, it could also benefit from wind power support from all the services that PHS can provide, given its technically proven characteristics, such as rapid response time, high seasonal storage capacity, fast switching of charging-discharging operations and an unlimited number of cycles.

Since market opportunities are hampered by reduced connection capacities in the Croatian islands, another business case applies to entire or partial remote areas. Therefore, this study analyses the level of FIT_GO for those investors who might choose island locations for their projects.

3.8.13. Feed in Tariffs for PHS in the Croatian islands

In general, PHS systems are not geologically suited for Croatian islands, as most of them do not have natural or artificial lakes with potable or fresh water; moreover, lower precipitation in such schemes on the islands will require a large water collecting area which will be hard to implement on porous ground and with significant evaporation during summer months. All the populated islands of Croatia are connected to a mainland grid, so it is easy to export/import electricity and most of them have water pipelines that are also connected to the mainland in order to satisfy their water needs. PHS systems will only make sense if the islands want to become more independent from the import of resources from the mainland and if they would like to integrate PHS systems with water supply network and irrigation for agriculture.

The most interesting island for PHS systems is the island of Cres, as it has the natural lake Vransko Jezero with a surface area of 5.745 km^2 and a volume of potable water of 220 x 10^6 m^3; it also has possibilities for the construction of an upper reservoir at promising heights of 200-400 metres above sea level. Also of interest is the island of Krk with two artificial lakes, Jezero and Ponikve, and scope for reservoirs at lower levels.

Vransko Jezero on the island of Cres is a specific protected area, so the case study for the Croatian Islands will be based on the case of the Ponikve artificial lake on the island of Krk. The maximum volume of water in Lake Ponikve is 2.65 x 10^6 m^3 with a water level at +19.01 meters above sea level. It would be possible to construct an upper reservoir approximately 2000 metres from the lake at a height of approximately 200 m above sea level.

For the calculated case, it was assumed that an upper reservoir of 1 x 10^6 m^3, pump and PHT station with two pumps/turbines of 5 MW each and two penstocks would be constructed. Water management and evaporation have not been included in the pre-feasibility study but they are important factors and must be assessed for each PHS system separately.

The costs for the case of the PHS on the island of Krk are estimated as similar to the costs of PHS on the mainland, according to the methodology presented in chapter 3.8.1 and they are presented in the table of Annex E. The assumed FIT for solar photovoltaic electricity that will be used for pumping is at is 0.15 €/kWh.

$FIT_{PHS_{WGO}}$ for the PHS on the island of Krk is calculated according to Eq.5 and presented in Annex E, as well as the cost of electricity production from the PHS without the price of energy. The capacity factor of the turbines in the PHS is 20% or 1750 of full load hours. FIT according to capacity factor is also presented in Annex E.

3.8.14. Conclusion on FIT for storage technologies

The European electricity market is still fragmented. The different operational and regulatory approaches, and different market structures, have variable consequences for energy storage. In particular there is little incentive for energy storage to be introduced in many European electricity markets that do not yet have full liberalisation and transparency.

The case study in this thesis analysed the conditions under which a PHS project could be integrated in the supporting mechanism developed in Croatia for the integration of wind power generation. At EU level, this regulatory framework set by Directive 2009/28/EC provides conditions for the integration of renewables and member states decide on the supporting financial level for those generators which allow the target to be attained. Since the PHS has the same outcome, namely it increases the RES generation by avoiding the power curtailment by storing the excess or by providing ancillary services, the financing of the PHS through a tariff system could be considered through regulation combined with market financial mechanisms (public-private partnerships, tax incentives, etc.)

A clear regulatory framework which guarantees the payment of the capital cost and a reasonable rate of return would make clearer the business environment for investors, for both storage and RES operators. The link with the market by power prices and a periodical revision would allow the risk to be split between consumers and investors and would further create conditions for a competitive market operation.

As indicated by the FAST method and calculations for a 100% RES Croatia, the flexibility of the system and related RES integration could be increased with several technologies, so it is not necessary to support just one storage technology through FIT, as funds for the support of RES are usually limited, so the optimal support may be in their combination. The regulatory authority may then choose what to support and by which mechanisms. The PHS in the islands could be part of a hybrid system integrated with a desalination and water supply network or an irrigation and fire protection system. In this case, the burden for investment could also be passed to the water consumers or any other users of services.

4. CONCLUSIONS AND RECOMMENDATIONS

4.1. The role of energy storage in planning of 100% Renewable Energy Systems

4.1.1. Energy storage and 100% RES systems

As assumed at the beginning of this research on the role of energy storage in planning of 100% RES systems, storage forms an essential part of these systems, as without it the installed capacities of all the components in the system, due to the seasonal variability of primary sources (wind, solar, hydro, wave), the less variable but still limited biomass resources, and less accessible geothermal potential, will need to be several times greater than required and they will still not provide the ideal level of security of supply. On the other hand, connections with other power areas may smooth the supply curves and enable 100% RES systems without storage, but then the problem of intermittency should be assessed along with other constraints and parameters of flexibility, storage and interconnections which will then just represent a larger area. Thus, energy storage plays an important role in both, the production side as shown by large PHS systems and, heat storages in large CHP plants, or on the demand and distribution size, as shown by electric vehicles and most the of demand side measures that include heat storage, cold storage, and other demand side measures such as desalination, or in future production of hydrogen and synthetic fuels.

From the global point of view, the advantage of electricity storage, comes mostly from the advantage of electricity as an energy vector, as it is most widespread and electrification has reached even rural areas. Meanwhile, on the global level large storage capacities such as PHS or hydrogen production facilities could help in congestion management of big power lines. Storage at the local level, for example, at the distribution sub-station or even in each house, will help reduce distribution losses.

The results of the analysis of the Croatian islands showed that they could become 100% RES systems as they have very favourable wind and solar potential that just needs to be coupled by appropriate energy storage [**28**], such as hydrogen and heat storage for the islands of Losinj or Mljet and batteries for the island of Unije. Moreover, the calculated integration of RES and a storage system could have a positive effect on the employment in the islands. The results of the measurements and calculated wind production from the island of Brac (location W10 in the Annex) show very good wind potential even on the measured heights. In 2004 the

Croatian government prohibited installation of wind turbines on the islands and thus, as has been shown by the current calculations, jeopardised sustainable development and the security of energy supply on the islands. It would be good to reconsider that government decision as the new measurements have proved the old hypothesis that the wind potential on the Croatian islands is very favourable for utilisation.

4.1.2. Energy storage and strategic planning of energy systems

To begin creating a 100% RES system, it is good to start with smaller systems such as individual houses, city blocks or islands while at the same time start to deploy renewable energy sources on a large scale in the energy and transport sector. As the results have shown, after a certain level of RES penetration in the closed and independent system, taking into account current constraints, technological development and decentralisation introduced in the case studies, further development towards a 100% RES system is only possible by introducing energy storage technology or interconnection with the adjacent regions.

The Renewislands/ADEG methodology and, FAST methodology were coupled to form the RESTEP methodology, which represents a new view on the planning of 100% RES systems, as it points out the benefits of energy storage not just to bridge the gap in production and demand but also to increase system flexibility and help system stability.

4.2. Recommendation for integration of energy and resources flows

Integration of different flows has been proposed with several functions. Increasing of efficiency of the system, as in the example of CHP plants for the Croatian power system, has previously been discussed in many works in Denmark, while the connection of intermittent resources such as PV with cold storage has not been previously discussed at a regional and national level.

Energy storage supports the integration of several energy vectors (carriers), electricity, heat, cold and transport fuels, thus not just making the system more efficient but reducing the costs of a 100% RES system that relies on intermittent sources. In normal systems, storage adds to the total cost of the system and it can be only profitable in market circumstances by doing market arbitrage, buying low and selling high, or, in other words, when the marginal prices of producing energy from storage are lower than the market selling prices, which will be hard to achieve in future systems as renewable sources will most probably reduce the price difference between peak hours and off-peak low load. The pumped storage can be integrated with water consumption, desalination plants, water irrigation, or flood and fire protection. Batteries are integrated with electric cars and the transport sector, and heat pumps with heat and cold storage.

4.3. Recommendations for the development of models

As energy systems become more and more complex due to decentralisation, distributed generation and the variability of primary sources, as well as variability caused by further market liberalisation and expansion, the models for energy planning must become more sophisticated and adapted to different user needs. They need to serve spatial planning offices, government institutions, investors and energy traders. The RenewIslands/ADEG/RESTEP and FAST methodology are qualitative and can provide general answers and areas worth further investigation and thus save time and resources for general planning, but they also point to benefits that may come from integration of energy storage, energy and resources flows.

Closed system calculations of the national system of Portugal enabled a better overview of accessible energy technologies but also indicated certain limitations of the H_2RES program, which has restricted development of more detailed and optimised results. The model used accepts only a single reversible hydro installation (similar to EnergyPLAN), and this should be reprogrammed in order to gain high quality results that will enable modelling of larger energy systems with more geographically dispersed units. The aggregation of production and storage capacities can provide valid results, as both models were able to reproduce the system behaviour in referent years, but the needs of markets, the behaviour of a single player or a group of them and thus power plants dispatching will certainly need more attention in future planning, and models should be able to provide optimisation on dispatching not based only on the marginal costs of production or fuel and emissions savings.

There is no automatic optimisation in H_2RES based on cost, and the environmental and social parameters arising from each technology. By optimising these parameters, the model will provide more sustainable solutions that should now be calculated separately.

Without cost optimisation, the order of generation and priority of storage systems is set deterministically by the limitation equations in the model. Consequently, if there is no penetration limit, the model forces a certain technology to its maximum or to the maximum available potential, without giving priority to lower cost technology or production during certain hours. This was one of the main reasons for switching the modelling of the Croatian energy system to EnergyPLAN, which provides both technical and market optimisation.

However, both models cover only one year's calculations, so longer scenarios with time periods of, for example 20-40 years and time steps of 5 years require manual work that is mostly related to setting up new parameters on supply and demand and checking the financial analysis. The automation of scenario calculations could save a lot of time and certainly provide a better overview of the results. It could also lead to better financial analysis without discrimination of RES and storage technologies as discussed in the conclusion of the Chapter 3.1.1. The evaluation of possible jobs created or lost in the energy industry should become essential part of any model.

The H_2RES and EnergyPLAN models, if used for calculations on national energy systems, should be adapted to provide results according to the statistical publications. Energy storage will play a major role in the development of future energy systems and it should be integrated in the models in such a way that all the benefits of storage can be recognized, as storage allows greater system flexibility, helps with the utilisation of RES, and can provide ancillary services and participate in the market arbitrage.

4.4. Further analysis of modelling results

The core of any element of the energy system, it is related to energy use or energy needs of a community or a certain customer. Even more generally, the needs are related to a certain space (or simplified and projected to the Earth), land surface; thus every space or volume on Earth's surface will have the possibility of energy production and supply, which, in the case of renewable energy systems, will be directly linked to the potential of renewable energy sources on that surface or related volume above and below the surface. Similar to the physical characteristics of matter confined within certain borders, a given space from the energy system point of view, in a given time-frame, could have the following five basic states/processes: consumption (consuming-transforming), production-generation (generating-transforming), storage (storing-charging-discharging), import and export. The system could function in all these states at the same time, individually or in their combination. If the convention is set as represented in Figure 46, that production, import and storage discharge are treated as sources (they make positive balance) while consumption, export and storage charging are treated as energy sinks, then the following energy equation can be assumed:

$$P+C+S+I+E=0 \quad (39)$$

Taking into account limitations and constraints on available capacities in a given space and within a predefined time step, the programs will be required to solve a relatively simple balancing equation.

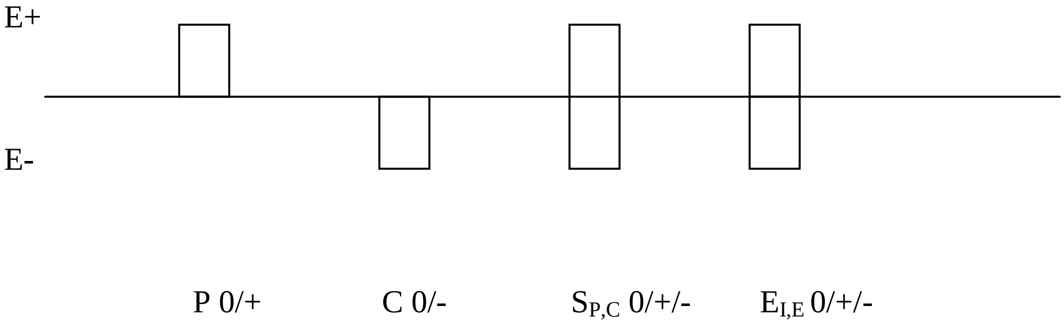


Figure 46. Basic structure for development of energy planning programs.

5. LITERATURE

[1] BP, "BP Statistical Review of World Energy June 2011," BP p.l.c., London, Annual report 2011.

[2] N. Duić and M. G. Carvalho, "Increasing renewable energy sources in island energy supply: case study Porto Santo," *Renewable and Sustainable Energy Reviews*, vol. 8, no. 4, pp. 383–399, August 2004.

[3] H. Lund, "Large-scale integration of wind power into different energy systems," *Energy*, vol. 30, no. 13, pp. 2402-2412, 2005.

[4] H. Lund, N. Duic, G. Krajacic, and M.G. Carvalho, "Two energy system analysis models: a comparison of methodologies and results," *Energy*, vol. 32, no. 6, pp. 948–54, 2007.

[5] N. Duić, M. Lerer, and M.G. Carvalho, "Increasing the supply of renewable energy sources in island energy systems," *International Journal of Sustainable Energy*, vol. 23, no. 4, pp. 177-18, 2003.

[6] J. M. Friedman and Halaas J. L., "Leptin and the regulation of body weight in mammals," *Nature*, vol. 395, pp. 763-770, October 1998.

[7] European Commission, "Energy infrastructure priorities for 2020 and beyond — A Blueprint for an integrated European energy network' ," EC, Blueprint COM(2010) 677 final , 2010.

[8] European Commission, "Energy 2020 - A strategy for competitive, sustainable and secure energy ," Strategy

[9] European Commission, "EU energy and transport in Figures," Luxembourg, Statistical pocketbook 2010 ISBN 978-92-79-13815-7, 2010.

[10] Maria da Graça Carvalho, Matteo Bonifacio, and Pierre. Dechamps, "Building a Low Carbon Society. ," 5th Dubrovnik Conference on Sustainable Development of Energy Water And Environment Systems., SDEWES Invited Lecture on the 2nd October 2009 2009.

[11] Arthouros Zervos, Christine Lins, Josche Muth, and Eleanor Smith, "RE-thinking 2050: A 100% Renewable Energy Vision for the European Union," EREC - European Renewable Energy Council, 2010.

[12] H. Lund and BV. Mathiesen, "Energy system analysis of 100% renewable energy systems--The case of Denmark in years 2030 and 2050.," *Energy*, vol. 34, no. 5, pp. 524-531, 2009.

[13] H Lund, "Renewable energy strategies for sustainable development," *Energy*, vol. 32, pp. 912–919, 2007.

[14] INFORSE. The International Network for Sustainable Energy. [Online]. http://www.inforse.org/europe/Vision2050.htm

[15] G. Krajačić, N. Duić, and M. G. Carvalho, "How to achieve a 100% RES electricity supply for Portugal?," *Applied Energy* , vol. 88 , pp. 508–517, 2011.

[16] WADE, "Decentralising UK Energy: Cleaner, Cheaper, More Secure Energy for the 21st Century. Application of the WADE Economic Model to the UK.," Greenpeace, London, Strategy March 2006.

[17] M. Jefferson, "Sustainable energy development: performance and prospects," *Renewable Energy*, vol. 31, no. 5, pp. 571-582, April 2006.

[18] N. Duić, G. Krajačić, and M. G. Carvalho, "RenewIslands methodology for sustainable energy and resource planning for islands," *Renewable and Sustainable Energy Reviews*, vol. 12, no. 4, pp. 1032-1062, May 2008.

[19] Raquel Segurado, Goran Krajačić, Neven Duić, and Luís Alves, "Increasing the penetration of renewable energy resources in S. Vicente, Cape Verde," *Applied Energy*, vol. 88, pp. 466-472, 2011.

[20] J.K. Kaldellis, M. Kapsali, and K.A. Kavadias, "Energy balance analysis of wind-based pumped hydro storage systems in remote island electrical networks," *Applied Energy*, vol. 87 , pp. 2427–2437, 2010.

[21] M. Kapsali and J.K. Kaldellis, "Combining hydro and variable wind power generation by means of pumped-storage under economically viable terms," *Applied Energy*, vol. 87, pp. 3475–3485, 2010.

[22] G. Caralis, K. Rados, and A. Zervos, "On the market of wind with hydro-pumped storage systems in autonomous Greek islands," *Renewable and Sustainable Energy Reviews* , vol. 14 , pp. 2221–2226, 2010.

[23] J.K. Kaldellis, D. Zafirakis, and K. Kavadias, "Techno-economic comparison of energy storage systems for island autonomous electrical networks," *Renewable and*

Sustainable Energy Reviews, vol. 13, no. 2, pp. 378-392, February 2009.

[24] M. Perrin, Y.M. Saint-Drenan, F. Mattera, and P. Malbranche, "Lead–acid batteries in stationary applications: competitors and new markets for large penetration of renewable energies," *Journal of Power Sources*, vol. 144, pp. 402–410, 2005.

[25] K.C. Divya and Jacob Østergaard, "Battery energy storage technology for power systems—An overview," *Electric Power Systems Research*, vol. 79, pp. 511–520, 2009.

[26] M.A. Kashem and Ledwich G., "Energy requirement for distributed energy resources with battery energy storage for voltage support in three-phase distribution lines," *Electric Power Systems Research*, vol. 77 , pp. 10–23, 2007.

[27] H. Lund and G. Salgi, "The role of compressed air energy storage (CAES) in future sustainable energy systems.," *Energy Conversion and Management*, vol. 50, no. 5, pp. 1172-1179, 2009.

[28] G. Krajačić, R. Martins, A. Busuttil, N. Duić, and M.G. Carvalho, "Hydrogen as an energy vector in the islands' energy supply," *International Journal of Hydrogen Energy*, vol. 33, no. 4, pp. 1091-1103, February 2008.

[29] Yongliang Li, Haisheng Chen, Xinjing Zhang, Chunqing Tan, and Yulong Ding, "Renewable energy carriers: Hydrogen or liquid air/nitrogen?," *Applied Thermal Engineering*, vol. 30 , pp. 1985-1990, 2010.

[30] Danijel Pavković, Matija Hoić, Joško Petrić, Zvonko Herold, and Joško Deur, "An Overview of Energy Storage Systems Considering Renewable Energy Applications," in *6th Dubrovnik Conference on Sustainable Development of Energy, Water and Environment Systems*, Dubrovnik, 2011, pp. 1-24.

[31] European Commission, "TECHNOLOGY MAP of the European Strategic Energy Technology Plan (SET-Plan). ," Joint Research Centre - European Commission, Luxembourg, ISBN 978-92-79-21630-5 2011, 2011.

[32] T. T. Desrues, J. Ruer, P. Marty, and J.F. Fourmigué, "A thermal energy storage process for large scale electric applications," *Applied Thermal Engineering*, vol. 30 , pp. 425–432, 2010.

[33] Giorgio Pagliarini and Sara Rainieri, "Modelling of a thermal energy storage system coupled with combined heat and power generation for the heating requirements of a

University Campus," *Applied Thermal Engineering*, vol. 30, pp. 1255–1261, 2010.

[34] Belen Zalba, Jose M. Marın, Luisa F. Cabeza, and Harald Mehling, "Review on thermal energy storage with phase change: materials, heat transfer analysis and applications," *Applied Thermal Engineering*, vol. 23 , pp. 251–283, 2003.

[35] Yanshun Yu, Zuiliang Ma, and Xianting Li, "A new integrated system with cooling storage in soil and ground-coupled heat pump," *Applied Thermal Engineering* , vol. 28, pp. 1450–1462, 2008.

[36] MB. Blarke and H. Lund, "The effectiveness of storage and relocation options in renewable energy systems.," *Renewable Energy*, vol. 33, no. 7, pp. 1499-1507, 2008.

[37] S.M. Hasnain, "Review on sustainable thermal energy storage technologies. Part II: cool thermal storage. ," *Energy Conversation and Management*, vol. 39, no. 11, pp. 1139–1153, 1998.

[38] Marino Grozdek, "Load Shifting and Storage of Cooling Energy through Ice Bank or Ice Slurry Systems," Department of Energy Technology, Royal Institute of Technology, Stockholm, PhD Thesis ISBN 978-91-7415-434-4, 2009.

[39] R., Barbir, F. Vujčić, "Pilot postrojenje: Prvi korak u uvođenju vodikovog energetskog sustava," in *XIV Znanstveni skup o energiji i zaštiti okoliša, Energija i zaštita okoliša I* , Opatija, 1994, pp. 511-518.

[40] R. Vujčić, Ž. Josipović, F. Matejčić, and F. Barbir, "The Role of Hydrogen in Energy Supply of the County of Split and Dalmatian Islands," in *Proceedings of XII World Hydrogen Energy Conference*, Buenos Aires, 1998, pp. 483-494.

[41] I Ridjan, BV Mathiesen, D Connolly, and N Duić, "The feasibility of synthetic fuels in renewable energy systems," in *Austrian-Croatian-Hungarian Combustion Meeting* , Zagreb, 2012, p. Poster presentation.

[42] Mladen Zeljko, "Planiranje izgradnje elektrana u okružju otvorenog tržišta električnom energijom," Faculty of Electtrical Engineering and Computing , Zagreb, PhD Thesis 2003.

[43] International Energy Agency, *Harnessing Variable Renewables - A Guide to the Balancing Challenge*, Hugo Chandler, Ed. Paris: IEA, 2011.

[44] EWEA, "Wind in power, 2011 European statistics," The European Wind energy association, Statistical report 2012.

[45] Henrik Lund, *Renewable Energy Systems - The Choice and Modeling of 100% Renewable Solutions*. London, UK: Academic Press - Elsevier, 2010.

[46] Ben Elliston, Mark Diesendorf, and Iain MacGill, "Simulations of scenarios with 100% renewable electricity in the Australian National Electricity Market," *Energy Policy*, vol. 45, pp. 606–613, 2012.

[47] German Advisory Council on the Environment, "Pathways Towards a 100% Renewable Electricity System," German Advisory Council on the Environment, Berlin, Germany, Technical report 2011.

[48] D. Connolly, H Lund, B. Mathiesen, and M. Leahy, "The first step towards a 100% renewable energy-system for Ireland," *Applied Energy*, vol. 88, pp. 502-507, 2011.

[49] H. Lehmann, "Energy Rich Japan," Institute for Sustainable Solutions and Innovations, Technical Report 2003.

[50] I. Mason, S. Page, and A. Williamson, "A 100% renewable electricity generation system for New Zealand utilising hydro, wind, geothermal and biomass resources," *Energy Policy*, vol. 38, pp. 3973–3984, 2010.

[51] M. Kemp and J. Wexler, "Zero Carbon Britain 2030: A New Energy Strategy," Centre for Alternative Technology, Technical Report 2011.

[52] B. Sørensen, "A renewable energy and hydrogen scenario for northern Europe," *International Journal of Energy Research*, vol. 32, pp. 471–500, 2008.

[53] B. Ćosić, G. Krajačić, N. Markovska, G. Giannakidis, and N. Duić, "A 100% Renewable Energy System in the Year 2050: the Case of South East Europe Energy Community," in *6th Dubrovnik Conference on Sustainable Development of Energy, Water and Environment Systems*, Dubrovnik, 2011, p. Poster presentation.

[54] B. Sørensen and P Meibom, "A global renewable energy scenario," *International Journal of Global Energy Issues*, vol. 13, pp. 196-276, 2000.

[55] M.Z. Jacobson and M.A. Delucchi, "Providing all global energy with wind, water, and solar power. Part I: technologies, energy resources, quantities and areas of infrastructure, and materials," *Energy Policy*, vol. 39, pp. 1154–1169, 2011.

[56] M.A. Delucchi and M.Z. Jacobson, "Providing all global energy with wind, water, and solar power. Part II: reliability, system and transmission costs, and policies," *Energy Policy*, vol. 39, pp. 1170-1190, 2011.

[57] WWF, "The Energy Report: 100% Renewable Energy by 2050.," World Wide Fund for Nature, Technical Report 2011.

[58] G. Krajačić, N. Duić, and M. G. Carvalho, "H2RES, Energy planning tool for island energy systems – The case of the Island of Mljet," *International Journal of Hydrogen Energy*, vol. 34, no. 16, pp. 7015-7026, August 2009.

[59] H. Lund, "EnergyPLAN - Advanced Energy Systems Analysis Computer Model," Aalborg University, Users manual Documentation Version 8.0, 2010.

[60] H. Lund and W. Kempton, "Integration of renewable energy into the transport and electricity sectors through V2G," *Energy Policy*, vol. 36, no. 9, pp. 3578-3587, 2008.

[61] H. Lund and E. Munster, "Management of surplus electricity-production from a fluctuating renewable-energy source," *Applied Energy*, vol. 76, no. 1-3, pp. 65-74, 2003.

[62] BV Mathiesen and H Lund, "Comparative analyses of seven technologies to facilitate the integration of fluctuating renewable energy sources," *Renewable Power Generation IET*, vol. 3, no. 2, pp. 190-204, 2009.

[63] MINGORP, "Energy in Croatia - Annual Energy Report - 2008," Ministry of Economy Labour and Entrepreneurship Ministry of Economy Labour and Entrepreneurship., Zagreb, Annual Report 2009.

[64] MINISTRY OF ECONOMY, LABOUR AND ENTREPRENEURSHIP , "ENERGY IN CROATIA - ANNUAL ENERGY REPORT," MINISTRY OF ECONOMY, LABOUR AND ENTREPRENEURSHIP, REPUBLIC OF CROATIA , Zagreb, Statistical report 2011.

[65] JRC. GIS Assessment of Solar Energy Resource in Europe. [Online]. http://re.jrc.cec.eu.int/pvgis/pv/index.htmd

[66] Nikola Karadža, László Horváth, and Zdeslav Matić, "Progress of wind resource assessment program in Croatia," in *European Wind Energy Conference & Exhibition*, Brussels Expo, Belgium, 31 March - 3 April 2008.

[67] Raquel Segurado, Goran Krajačić, Neven Duić, and Luís Alves, "Increasing the penetration of renewable energy resources in S. Vicente, Cape Verde," *Applied Energy*, pp. doi:10.1016/j.apenergy.2010.07.005, 2010.

[68] H. Lund, "Large-scale integration of optimal combinations of PV, wind and wave

power into the electricity supply.," *Renewable Energy*, vol. 31, no. 4, pp. 503-515, 2006.

[69] Boris Hemetek, "Planiranje energetskog sustava otoka Lošinja primjenom RenewIslands metodologije," FSB, Zagreb, Master Thesis 2007.

[70] Darko Jardas, Andrej Čotar, Silvio Bratić, Goran Krajačić, and Neven Duić, "Scenariji energetskog razvoja otoka Unije," REA Kvarner; FSB, Rijeka; Zagreb, Development study 2011.

[71] Antonios G. Tsikalakis et al., "Market applications for energy storage methods and RES," STORIES project, 2009.

[72] Daniel M. Kammen, Kamal Kapadia, and Matthias Fripp, "Putting Renewables to Work: How Many Jobs Can the Clean Energy Industry Generate?," University of California, Berkeley, RAEL Report 2004.

[73] REN21 Renewable Energy Policy Network, "Renewables 2005 Global Status Report," Worldwatch Institute, Washington, DC, 2005.

[74] O Parissis et al. (2009) COST-BENEFIT ANALYSIS. [Online]. www.storiesproject.eu

[75] Joachim Lehner and Tobias Weißbach, "Global and local effects of decentralised electric power generation on the grid in the Western Balkan Countries (WBC)," *Energy*, vol. 34, no. 5, pp. 555–563, 2009.

[76] REN - Redes Energéticas Nacionais SGPS, S.A., "Technical Data Provisional Values 2006," REN, Lisbon, Technical data 2007.

[77] Direcção Geral de Energia e Geologia, "Renováveis estatísticas rápidas Novembro/Dezembro 2009," Direcção Geral de Energia e Geologia, Report Nº 57/58, 2010.

[78] ENTSO-E. ENTSO-E. [Online]. https://www.entsoe.eu/

[79] IEA, "IEA Wind Energy Annual Report 2006," International Energy Agency, Boulder, Colorado, Annual Report ISBN 0-9786383-1-x, 2006. [Online]. http://www.ieawind.org/

[80] METEOTEST. Global Meteorological Database for Engineers, Planners and Education. [Online]. http://www.meteonorm.com/pages/en/meteonorm.php

[81] Soon-Duck Kwon, "Uncertainty analysis of wind energy potential assessment ,"

Applied Energy, vol. 87, no. 3, pp. 856-865, 2010.

[82] Direcção Geral de Energia e Geologia, "Renewable Energy in Portugal," Portugeese Ministry of Economy and Innovation, 2007.

[83] Pelamis Wave Power Ltd. Pelamis Wave Power Ltd. [Online]. http://www.pelamiswave.com

[84] M.T. Pontes, R. Aguiar, and H.O. Pires, "A nearshore wave energy atlas for Portugal," *J Offshore Mechanics and Articarctic Engineering-transactions of the ASME* , vol. 127, no. 3, pp. 249-255, 2005.

[85] M. Gomez Lahoz and J. C. Carretero Albiach, "Wave forecasting at the Spanish coasts," *Journal of Atmospheric and Ocean Science*, vol. 10, no. 4, pp. 389–405, December 2005.

[86] K. Väätäinen, Y Nuutinen, and 22. 13 p.., "Forest biomass use for energy in Portugal.," Finnish Forest, Research Institute, Joensuu, Project Report 22. 5 EURES (EIE/04/086/S07.38582), 2007.

[87] John et al. Clifton-Brown, "Miscanthus biomass production for energy in Europe and its potential contribution to decreasing fossil fuel carbon emissions," *Global Change Biology*, vol. 10, pp. 509–518, 2004.

[88] Sergio Ferreira, Nuno Afonso Moreira, and Eliseu Monteiro, "Bioenergy overview for Portugal," *Biomass and Bioenergy*, vol. 33, pp. 1567 – 1576, 2009.

[89] U. Fernandes and M. Costa, "Potential of biomass residues for energy production and utilization in a region of Portugal," *Biomass and Bioenergy*, vol. 34, pp. 661-666, 2010.

[90] EREC, "RES 2020: Monitoring and Evaluation of the RES Directives implementation in EU27 and policy recommendations to 2020," March 2008.

[91] REN - Redes Energéticas Nacionais SGPS, S.A. REN. [Online]. http://www.centrodeinformacao.ren.pt/PT/InformacaoTecnica/Paginas/CentraisHidroelectricas.aspx

[92] J.P. Deane, B.P. O'Gallachoir, and E.J. McKeogh, "Techno-economic review of existing and new pumped hydro energy storage plant," *Renewable and Sustainable Energy Reviews*, vol. 14, pp. 1293–1302, 2010.

[93] COBA, SA; PROCESL, LDA, "Programa Nacional de Barragens com Elevado

Potencial Hidroeléctrico (PNBEPH)," Instituto da Água, I.P.; REN - Redes Energéticas Nacionais SGPS, S.A.; Direcção Geral de Energia e Geologia, Report 2007.

[94] European Commission, "Prospects for the internal gas and electricity market," Brussels, Implementation report SEC(2006) 1709, 2007.

[95] REN - Redes Energéticas Nacionais SGPS, S.A., "Report and Accounts for the REN Group 2009," REN, Lisbon, Report and Accounts 2010.

[96] Governo de Portugal, "Estratégia Nacional para a Energia 2020 (ENE2020)," Diário da República, 1.ª série N.º 73, 15th April 2010.

[97] Javier Reneses and Centeno Efraim, "Impact of the Kyoto Protocol on the Iberian Electricity Market: A scenario analysis," *Energy Policy*, vol. 36, no. 7, pp. 2376-2384, 2008.

[98] Poul Alberg Østergaard, "Ancillary services and the integration of substantial quantities of wind power," *Applied Energy*, vol. 83, no. 5, pp. 451-463, 2006.

[99] Ioannis D. Margaris, Anca D. Hansen, Poul Sørensen, and Nikolaos D. Hatziargyriou, "Illustration of Modern Wind Turbine Ancillary Services," *Energies*, vol. 3, pp. 1290-1302, 2010.

[100] D. Connolly, S. MacLaughlin, and Leahy M., "Development of a computer program to locate potential sites for pumped hydroelectric energy storage," *Energy*, vol. 32, pp. 375-381, 2010.

[101] G.J. Dalton, R. Alcorn, and T. Lewis, "Case study feasibility analysis of the Pelamis wave energy convertor in Ireland, Portugal and North America," *Renewable Energy* , vol. 35, pp. 443–455, 2010.

[102] Troels Friis Pedersen et al., "Wind Turbine Power Performance Verification in Complex Terrain and Wind Farms," Risø National Laboratory, Roskilde, Report Risø-R-1330(EN), April 2002.

[103] Hannele Holttinen et al., "Design and operation of power systems with large amounts of wind power State-of-the-art report," VTT, Finland, IEA WIND Task 25 Report 2007.

[104] Goran Krajačić et al., "Planning for a 100% independent energy system based on smart energy storage for integration of renewables and CO2 emissions reduction,"

Applied thermal engineering, vol. 31, pp. 2073-2083, 2011.

[105] G. Krajačić et al., "Feed-in tariffs for promotion of energy storage technologies," *Energy Policy*, pp. doi:10.1016/j.enpol.2010.12.013, 2011.

[106] D. Bajs and G., Majstrović, "The Feasibility of the Integration of Wind Power Plants into the Electric Power System of Republic of Croatia," *Energija*, vol. 57, no. 2, pp. 124-155, 2008.

[107] G. Krajačić, V.B. Mathiesen, N. Duić, and M. G. Carvalho, "Increasing RES Penetration and Scurity of Energy Supply by Use of Energy Storages and Heat Pumps in Croatian Energy System," in *Energy Options Impact on Regional Security*, NATO Science for Peace and Security Series ed., F. Barbir and Ulgiati S., Eds.: Springer, 2010, pp. 159-171.

[108] Zdeslav Matić, *Solar Radiation Atlas of the Republic of Croatia*, Zdeslav Matić, Ed. Zagreb, Croatia: Energetski institut Hrvoje Požar, 2007.

[109] MINGORP; UNDP, "Green paper- UPDATE/UPGRADE OF THE ENERGY STRATEGY AND OF THE IMPLEMENTATION PROGRAMME OF THE REPUBLIC OF CROATIA," Ministry of Economy, Labour and Entrepreneurship and United Nations Development Programme, Zagreb, 2008.

[110] Mislav Kirac, Goran Krajačić, and Neven Duić, "Planning energy sector development in Croatian agricultural sector following guidelines of the European Energy Policy "20-20-20" ," in *18th FORUM: ENERGY DAY IN CROATIA*, Zagreb, 2009.

[111] Boris Ćosić, Zoran Stanić, and Neven Duić, "Geographic distribution of economic potential of agricultural and forest biomass residual for energy use: Case study Croatia," *Energy*, pp. doi:10.1016/j.energy.2010.10.009, 2010.

[112] Dinko Zorović, Robert Mohović, and Đani Mohović, "Towards Determining the Length of the Wind Waves of the Adriatic Sea," *Naše more*, vol. 50, no. 3-4, pp. 145-150, 2003.

[113] D. Villanueva and A. Feijoo, "Wind power distributions: A review of their applications," *Renewable and Sustainable Energy Reviews*, vol. 14, pp. 1490–1495, 2010.

[114] Danilo Feretić, Željko Tomšić, and Nikola Čavlina, "Feasibility analysis of wind-energy utilization in Croatia," *Energy* , vol. 24 , pp. 239–246, 1999.

[115] Daniel Rolph Schneider, Neven Duić, and Željko Bogdan, "Mapping the potential for decentralized energy generation based on renewable energy sources in the Republic of Croatia ," *Energy*, vol. 32, no. 9, pp. 1731-1744, 2007.

[116] HEP. [Online]. http://www.hep.hr/proizvodnja

[117] Dragutin Gereš, "Water resources and irrigation systems in coastal and karstic regions of Croatia," in *Manual for the hydro-irrigation: Aspects of water management in development of irrigation in the coastal and inland Croatian karst*, Nevenka Ožanić et al., Eds. Rijeka, Croatia: Faculty of Civil Engineering, University of Rijeka, 2007, pp. 23-68 (in Croatian).

[118] International Energy Agency (IEA), *Energy in the Western Balkans - The Path to Reform and Reconstruction*. Paris: International Energy Agency (IEA), 2008.

[119] Riccardo Vailati, "Electricity transmission in the energy community of South East Europe," *Utilities Policy* , vol. 17, pp. 34–42, 2009.

[120] Aleksandra Anić Vučinić, Andrea Hublin, Ružinski, and Nikola, "Greenhouse Gases Reduction Through Waste Management in Croatia," *Thermal Science*, vol. 14, no. 3, pp. 681-691, 2010.

[121] HEP ESCO d.o.o. (2010, September) References. [Online]. http://www.hep.hr/esco/en/references/karlovac/default.aspx

[122] Goran Granić, Helena Božić, and Damir Pešut, "How to Address the Challenges of the Climate Preservation," in *18th FORUM: ENERGY DAY IN CROATIA*, Zagreb, 2009.

[123] JRC - European Commission, "2009 TECHNOLOGY MAP of the European Strategic Energy Technology Plan (SET-Plan)," JRC-IE, JRC-IES, JRC-IPTS , Joint Research Centre - European Commission, Luxembourg, Plan ISBN 978-92-79-14587-2, 2009.

[124] H.L. Lam, P.S. Varbanov, and J.J. Klemeš, "Regional renewable energy and resource planning," *Applied energy*, vol. 88, no. 2, pp. 545–550, 2011.

[125] ALSTOM, "Hydro Pumped Storage Power Plant," Levallois- Perret Cedex / Paris, Brochure PWER/BPROB/HDPSTR09/eng/HYD/12.09/FR/7033, 2010.

[126] HEP - TSO, "Indicative Medium-term Development Plan of Croatian Transmission System," HEP, Zagreb, Study 2011.

[127] Jose L. Bernal Agustin and Rodolfo Dufo Lopez, "Hourly energy management for grid-connected wind–hydrogen systems," *International Journal for Hydrogen Energy*, vol. 33, no. 22, pp. 6401 – 6413, 2008.

[128] Niels I. Meyer, "European schemes for promoting renewables in liberalised markets," *Energy Policy*, vol. 31, pp. 665–676, 2003.

[129] T. Couture and Y. Gagnon, "An analysis of feed-in tariff remuneration models: Implications for renewable energy investment," *Energy Policy*, vol. 38, pp. 955–965, 2010.

[130] P. del Rio Gonzalez, "Ten years of renewable electricity policies in Spain: An analysis of successive feed-in tariff reforms," *Energy Policy*, vol. 36, pp. 2917–2929, 2008.

[131] P. del Rio Gonzalez and Miguel A Gual, "An integrated assessment of the feed-in tariff system in Spain," *Energy Policy* , vol. 35, pp. 994–1012, 2007.

[132] Hellenic Republic; Ministry of Development , "Law 3468/2006 - Generation of Electricity using Renewable Energy Sources and High-Efficiency Cogeneration of Electricity and Heat and Miscellaneous Provisions; (Official Gazette A' 129/27.06.2006) ATHENS, OCTOBER 2006," Renewable Energy Sources and Energy Saving Directorate, Directorate General For Energy, Athens, Law 2006.

[133] M. Solano-Peralta et al., "“Tropicalisation” of Feed-in Tariffs: A custom-made support scheme for hybrid PV/diesel systems in isolated regions," *Renewable and Sustainable Energy Reviews*, vol. 13, pp. 2279–2294, 2009.

[134] H. Lund and A.N. Andersen, "Optimal designs of small CHP plants in a market with fluctuating electricity prices," *Energy Conversion and Management* , vol. 46, pp. 893–904, 2005.

[135] R., Haas et al., "How to promote renewable energy systems successfully and effectively," *Energy Policy* , vol. 32, no. 6, pp. 833–839, 2004.

[136] E.K. Oikonomou et al., "Renewable energy sources (RES) projects and their barriers on a regional scale: The case study of wind parks in the Dodecanese islands, Greece," *Energy Policy*, vol. 37, pp. 4874–4883, 2009.

[137] S Suarez et al. (2009) Barriers assessment and recommendations to overcome them. [Online]. www.storiesproject.eu

[138] J.L. Garcia and E. Menendez, "Spanish renewable energy: successes and untapped potential," in *Renewable Energy Policy and Politics: a Guide for Decision Making*, K. Mallon, Ed. London: Earthscan, 2006, pp. 215–227.

[139] C Huber et al., "Green-X. Deriving optimal promotion strategies for increasing the share of RES-E in a dynamic European electricity market.," Vienna University of Technology, Austria, Final report of the EU-funded project GREEN-X 2004.

[140] M. Ragwitz et al., "Assessment and optimisation of renewable energy support schemes in the European electricity market," Supported by the European Commission , Brussels, Final Report of the project OPTRES 2007.

[141] Svetoslav Danchev, George Maniatis, and Aggelos Tsakanikas, "Returns on investment in electricity producing photovoltaic systems under de-escalating feed-in tariffs: The case of Greece," *Renewable and Sustainable Energy Reviews*, vol. 14, pp. 500–505, 2010.

[142] J.A. Lesser and X. Su, "Design of an economically efficient feed-in tariff structure for renewable energy development," *Energy Policy* , vol. 36, pp. 981–990, 2008.

[143] J. Lipp, "Lessons for effective renewable electricity policy from Denmark, Germany and the United Kingdom," *Energy Policy*, vol. 35, pp. 5481–5495, 2007.

[144] Gonzalo Saenz de Miera, Pablo del Rio Gonzalez, and Ignacio Vizcaino, "Analysing the impact of renewable electricity support schemes on power prices: The case of wind electricity in Spain. ," *Energy Policy* , vol. 34, no. 9, pp. 3345-3359, 2008.

[145] M. Rathmann, "Do support systems for RES-E reduce EU-ETS-driven electricity prices?," *Energy Policy*, vol. 35, no. 1, pp. 342–349, 2007.

[146] D. Connolly, H. Lund, B.V. Mathiesen, and M. Leahy, "A review of computer tools for analysing the integration of renewable energy into various energy systems ," *Applied Energy*, vol. 87, no. 4, pp. 1059-1082, April 2010.

[147] Ana Estanqueiro et al., "How to Prepare a Power System for 15% Wind Energy Penetration: the Portuguese Case Study," *Wind Energy*, vol. 11, pp. 75–84, 2008.

[148] European Commission, "2009 Technology Map of the European Strategic Energy Technology Plan (SET-Plan)," JRC-IE, JRC-IES, JRC-IPTS , Joint Research Centre - European Commission, Luxembourg, EU, Plan ISBN 978-92-79-14587-2, 2009.

[149] Chris Naish, Ian McCubbin, Oliver Edberg, and Michael Harfoot, "OUTLOOK OF

ENERGY STORAGE TECHNOLOGIES," Policy Department Economy and Science, DG Internal Policies, European Parliament, Brussels, Study IP/A/ITRE/FWC/2006-087/Lot 4/C1/SC2, 2008.

[150] Maria da Graça Carvalho, Matteo Bonifacio, and Pierre Dechamps, "Building a low carbon society," *Energy*, vol. 36, no. 4, pp. 1842-1847, 2010.

[151] Emmanuel Branche. (2011) Eurelectric Conference Hydropower in Europe:Powering Renewables. [Online]. http://www.eurelectric.org/download/download.aspx?UserID=26196&DocumentFileID=70438

[152] L.W.M. Beurskens, M. Hekkenberg, and P. Vethman. (2011) Energy Centre of the Netherlands: Renewable Energy Projections as Published in the National Renewable Energy Action Plans of the European Member States, update 28.11.11. [Online]. http://www.ecn.nl/docs/library/report/2010/e10069.pdf

[153] Tomislav Capuder, Hrvoje Pandžić, Igor Kuzle, and Davor Škrlec, "Specifics of integration of wind power plants into the Croatian transmission network," *Applied Energy*, 2012.

[154] Ronnie Belmans et al., "WindBalance - Balancing wind energy in the grid: an overall, techno-economic and coordinated approach," K.U.Leuven, Heverlee, Final report 2011.

[155] D. Connolly, S. MacLaughlin, and M. Leahy, "Development of a computer program to locate potential sites for pumped hydroelectric energy storage," *Energy*, vol. 32, pp. 375-381, 2010.

[156] Zvonimir Sever, Borislav Franković, Željko Pavlin, and Vladimir Stanković, *Hydroelectric power plants in Croatia*, Sever and Zvonimir, Eds. Zagreb, Croatia: Hrvataska elektroprivreda d.d., 2000.

[157] G. Krajačić et al., "Feed-in tariffs for promotion of energy storage technologies," *Energy Policy*, vol. 39, pp. 1410-1425, 2011.

ANNEX A - Renewislands methodology

As presented by Duić et. al. in “RenewIslands methodology for sustainable energy and resource planning for islands”, Renewable and Sustainable Energy Reviews 12 (2008) 1032–1062.

RenewIslands Methodology

The RenewIslands methodology is based on a four steps analysis approach that has to be applied to an island:

1. Mapping the island’s needs
2. Mapping the island’s resources
3. Devising scenaria with technologies that can use available resources to cover the needs
4. Modelling the scenaria

The described methodology is actually general and can be applied to systems other than islands. The islands’ specificities arise at more detailed level, when characterising the needs and resources and assessing the feasibility of the system, as classifying the different options will be based on islands conditionings.

The needs are commodities that the local community demands, not only energy (electricity, heat, cold, transport fuel, etc.), but also all other types of commodities (or utilities in the old command jargon), like water, waste treatment, wastewater treatment, etc., that might or might not depend on energy supply.

The resources are locally available ones, like wind, sun, geothermal energy, ocean energy, hydro potential, water resources, but also imported ones like grid electricity, piped or shipped natural gas, oil derivatives or oil, water shipped, the potential to dump waste and wastewater, etc.

The technologies can be commercial energy conversion technologies, like thermal, hydro and wind electricity generation or solar thermal water heating, commercial water, waste and wastewater treatment technologies including desalination, or emerging technologies, like geothermal energy usage, solar electricity conversion systems, or technologies in development, like fuel cells, wave energy, etc.

The scenaria should try to satisfy one or several needs, by using available resources, and satisfying preset criteria. Due to global warming and falling reserves, and sometimes security of supply problems, fossil fuels should generally be used as the option of last resort in setting scenaria, even though they will often provide the most economically viable solution with the current price levels, and advantage should be given to locally available renewable resources.

Step 1: mapping the needs

In order to map the needs, a questionnaire should be answered. The level of need for each commodity has to be defined locally, but generally, in order to have sustainable development, water and electricity will always be highly demanded, no matter what is the demand per person, or total actual demand, unless it is a community of only few households, that can then use individual solutions. Heat demand will be deemed high in cold climates, as cold will be deemed high in hot climates. Waste treatment and wastewater treatment will depend on the ability of local environment to absorb the dumped amounts.

Table 35. Mapping the island/remote area community needs.

Needs	Level	Geographic distribution	Code	Level	Distribution
Electricity	Low, Medium or High	Dispersed, Concentrated	**Elect**	+L/M/H/-	+D/C/-
Heat	Low, Medium or High	Dispersed, Concentrated	**Heat**	+L/M/H/-	+D/C/-
Cold	Low, Medium or High	Dispersed, Concentrated	**Cold**	+L/M/H/-	+D/C/-
Transport fuel	Low, Medium or High	Short, long distance	**Tran**	+L/M/H/-	+S/L/-
Water	Low, Medium or High	Dispersed, Concentrated	**Water**	+L/M/H/-	+D/C/-
Waste treatment	Low, Medium or High	Dispersed, Concentrated	**Waste**	+L/M/H/-	+D/C/-
Wastewater treatment	Low, Medium or High	Dispersed, Concentrated	**WWT**	+L/M/H/-	+D/C/-

Step 2: mapping the resources

Table 36. Mapping the island/remote area available resources.

Resource	Level	Code			
Local primary energy					
Wind	Low, Medium or High	**Wind**	WindL	WindM	WindH
Solar	Low, Medium or High	**Solar**	SolarL	SolarM	SolarH
Hydro (height)	Low, Medium or High	**Hydro**	HydroL	HydroM	HydroH
Biomass	Low, Medium or High	**Biom**	BiomL	BiomM	BiomH
Geothermal	Low, Medium or High	**Geoth**	GeothL	GeothM	GeothH
Energy import infrastructure					
Grid connection	None, Weak, Strong	**Grid**	GridN	GridW	GridS
Natural gas pipeline	No, Yes	**NGpl**	NGplN		NGplY
LNG terminal	No, Yes	**LNGt**	LNGtN		LNGtY
Oil terminal/refinery	No, Yes	**OilR**	OilRN		OilRY
Oil derivatives terminal	No, Yes	**OilD**	OilDN		OilDY
Water					
Precipitation	Low, Medium or High	**H2OP**	H2OPL	H2OPM	H2OPH
Ground water	Low, Medium or High	**H2OG**	H2OGL	H2OGM	H2OGH
Water pipeline	No, Yes	**Aqua**	AquaN		AquaY
Sea water	No, Yes	**H2OS**	H2OSN		H2OSY

Definition of level of the quality of a resource depends on the particular technology, and is not locally dependent. Those values are generally known. On the other hand, as conventional energy costs are higher in islands due to their isolation, endogenous resources that would not be competitive in other regions may became competitive if compared to the difficulties and costs of imported resources in islands. For example, in islands wind energy may become economically competitive for wind regimes characterized by lower wind speeds than in mainland regions.

It is possible to envisage potential energy carriers as a result of area needs and its resources. Generally, it will be electricity, one or two transport fuels, and district heating in very cold regions of the world.

Table 37. Potential energy carriers.

Potential energy carriers	Condition	Code
Electricity	IF ElectC	**ECEl**
District heating	IF HeatHC	**ECDH**
District cooling	IF ColdHC	**ECDC**
Hydrogen	IF (Tran OR ElectC)	**ECH2**
Natural gas	IF (NGplY OR LNGtY)	**ECNG**
Biogas	IF (BiomH OR WasteHC OR WWTHC)	**ECBG**
Petrol/Diesel	IF (OilRY OR OilDY)	**ECPD**
Bioethanol	IF (BiomH OR WasteHC)	**ECEt**
LPG	IF (OilRY OR OilDY)	**ECLPG**
Biodiesel	IF (BiomH OR WasteHC)	**ECBD**

Step 3: devising scenaria with technologies that can use available resources to cover needs

Generally, local energy sources will be given priority, due to security of supply reasons. Then, cheaper technologies will be given priority. Technologies will have to be assessed from both a local and global environmental point of view.

This step will have four sub steps:

1. Feasibility of technologies (energy conversion, water supply, waste treatment, wastewater technology treatment)
2. Feasibility of technologies for energy, water, waste and wastewater storage
3. Feasibility of integration of flows (cogeneration, trigeneration, polygeneration, etc.)
4. Devising potential scenaria

Substep 3.1 Feasibility of technologies. The technical feasibility of technologies generally depends on the existence of a particular demand, and availability of particular resource. Its economical viability depends on the status of technology, commercial, emerging, in development, on the quality of resources, but also on the matching of demand and resource. Also, environmental viability as well as social viability of technologies can be pondered. It might be beneficial to apply multicriterial analysis to various competing technologies, in order to choose ones that reach acceptable level of sustainability in given situation. The technologies that have to be taken into account are the ones in energy conversion, water supply, waste treatment and wastewater technology treatment.

WECS (wind energy conversion system) is for example feasible if there is high or medium need for electricity and if there are medium to high wind resources. Such an analysis should be made for each of the technologies, in order to get a list of relevant ones.

Table 38. Potential delivering technologies.

Technology	Condition	Code
Electricity conversion system		
WECS (Wind)	IF (ElectM OR ElectH) AND (WindM OR WindH)	**WECS**
SECS-PV (Solar PV)	IF (ElectL OR ElectM) AND (SolarM OR SolarH)	**PV**
SECS-Thermal (Solar thermal electricity)	IF (Elect) AND (SolarH)	**SECS**
HECS (Hydro)	IF (Elect) AND (HydroM OR HydroH)	**HECS**
GECS (Geothermal)	IF (ElectM OR ElectH) AND (GeothH)	**GECS**
BECS (Biomass)	IF (ElectM OR ElectH) AND (BiomH)	**BECS**
DEGS (Diesel engine)	IF (Elect) AND (NGplY OR LNGtY OR OilRY OR OilDY)	**DEGS**
CCGT (Combined cycle gas turbine)	IF (ElectH) AND (NGplY OR LNGtY OR OilRY OR OilDY)	**CCGT**
FC (Fuel cell)	IF (Elect) AND (H2Fuel)	**FC**
Heating system		
Solar collectors	IF (Heat) AND (SolarM OR SolarH)	**STCo**
Geothermal	IF (HeatH) AND (GeothM OR GeothH)	**GeTH**
Heat pumps	IF (HeatH AND ECEl)	**HPHe**
Biomass boilers	IF (HeatH) AND (BiomM OR BiomH)	**BMBo**
Gas boilers	IF (Heat) AND (NGplY OR LNGtY OR OilRY or OilDY or WasteG or WWG)	**GSBo**
Cooling		
Solar absorbers	IF (Cold) AND (SolarH)	**SAbs**
Heat pumps	IF (ColdH AND ECEl)	**HPCo**
Gas coolers	IF (ColdH) AND (NGplY OR LNGtY OR OilRY or OilDY or WasG or WWtG)	**GSCo**
Electricity coolers	IF (ColdH AND ECEl)	**ELCo**
Fuel		
Hydrogen	IF (Tran) AND (ECH2)	**H2Fuel**
Electricity	IF (Tran) AND (ECEl)	**ElFuel**
Bioethanol	IF (Tran) AND (ECEt)	**EthanolFuel**
Biodiesel	IF (Tran) AND (ECBD)	**BDFuel**
LPG	IF (Tran) AND (ECLPG)	**LPGFuel**
Natural Gas	IF (Tran) AND (ECNG)	**NGFuel**
Biogas	IF (Tran) AND (ECBG)	**BGFuel**
Petrol/Diesel	IF (Tran) AND (ECPD)	**PDFuel**
Water supply		
Water collection	IF (Water) AND (H2OPM OR H2OPH)	**WaterC**
Water wells	IF (Water) AND (H2OGM OR H2OGH)	**WaterW**
Desalination	IF (Water) AND (H2OSY)	**WaterD**
Waste		
Incineration	IF (WasteHC)	**WasteI**
Gasification	IF (WasteHC)	**WasteG**
Wastewater treatment		
Gasification	IF (WWTHC)	**WWG**

Substep 3.2 Feasibility of storage. When there is no connection to the mainland, it is generally necessary to have storage. Water storage will generally be part of water supply system, even in case of water pipeline, in order to use gravity for keeping the pressure constant. Most islands will have oil derivatives storage, which will then be used to cover all other energy needs, like transport fuels, electricity generation, heat and cold supply. Those with hydro potential will sometimes have water reservoirs (Flores). In cold climates, heat can be stored (Ærø). Cold can be stored in ice banks. Waste is usually stored in waste fill where it will continue polluting during long time, while waste water will be stored in wastewater collectors before disposal into sea or some other water.

Table 39. Potential storage technologies.

Storage technology	**Condition**	**Code**
Electricity storage system		
Reversible hydro	IF (WECS AND HECS)	**RHECS**
Electrolyser + Hydrogen	IF (WECS OR SECS OR PV) AND NOT HECS	**ELYH2**
Reformer + Hydrogen	IF (ECNG OR ECBG OR ECPD OR ECEt OR ECLPG OR ECBD) AND NOT HECS	**REFH2**
Batteries	IF (SECS OR PV) AND NOT HECS AND NOT ECH2	**BAT**
Heat storage		
Heat storage	IF (HeatH)	**HeatS**
Cold bank	IF (ColdH)	**ColdS**
Fuel		
Hydrogen	IF H2Fuel	**H2stor**
Bioethanol	IF EthanolFuel	**Ethanolstor**
Biodiesel	IF BDFuel	**BDstor**
LPG	IF LPGFuel	**LPGstor**
NG	IF NGFuel	**NGstor**
BG	IF BGFuel	**BGstor**
Petrol/Diesel	IF PDFuel	**PDstor**
Water, Waste and Wastewater		
Water	IF Water	**WaterS**
Waste fill	IF Waste	**WasteF**
Wastewater tanks	IF WWT	**WWstor**

Electricity is difficult to store. The most economically efficient way to store excess of electricity is reversible hydro (as planned for El Hierro), by pumping water to the upper reservoir when there is excess of electricity and turbinating it when there is lack. That can be very efficient strategy for tackling higher penetrations of wind power, in case of hilly islands. There is a need for two reservoirs, which might be costly, a pump and a turbine, or if seawater is pumped, reversible hydro may work with only one, upper reservoir. Meanwhile, in case that there is no altitude difference for reversible hydro, the alternative is hydrogen storage. The excess of wind can be electrolysed into hydrogen and stored, and then the electricity lack can be produced from hydrogen by a fuel cell, internal combustion engine, or hydrogen can be used for powering transport. In case of small power systems, batteries can be used to store electricity.

Substep 3.3 Integration of flows. In order to increase the efficiency of the system, some resources and commodities flows may be integrated. For example, it is usual to integrate heat and power production, in so called cogeneration. But it only makes sense if heat and electricity demand are of similar time dependence, or at least made so by heat storage. If there is seasonal need for heat and cold, these two can be integrated with electricity, in technology called trigeneration.

Table 40. Integrating the flows.

Integration technology	Condition	Code
Combined heat and power	IF (Elect PROPORTIONAL Heat) AND (DEGS OR CCGT OR FC OR BECS OR SECS OR GECS)	**CHP**
Combined heat and cold	IF (Heat PROPORTIONAL Cold)	**CHC**
Trigeneration	IF (Elect PROPORTIONAL (Heat + Cold)) AND (DEGS OR CCGT OR FC OR BECS OR SECS OR GECS)	**3G-HPC**
Combined water and power	IF (HydroM OR HydroH) AND Water	**CWP**
Combined waste treatment and heat generation	IF (WasteI AND (HeatM OR HeatH))	**CWTH**
Combined waste treatment and power generation	IF (WasteI AND (ElectM OR ElectH))	**CWTP**
Combined waste treatment and heat and power generation	IF (WasteI AND (ElectM OR ElectH) AND Elect PROPORTIONAL Heat)	**3G-WTHP**
Combined waste treatment and heat, power and cold generation	IF (WasteI AND (ElectM OR ElectH) AND Elect PROPORTIONAL (Heat + Cold))	**4G-WTHPC**
Combined waste treatment and bioethanol production	IF (WasteG AND ECEt)	**CWTC2H5OH**
Combined waste treatment and gas production	IF (WasteG AND ECBG)	**CWTGas**
Combined wastewater treatment and gas production	IF (WWG AND ECBG)	**CWWTGas**
Combined power and hydrogen production	IF (WECS OR PV) AND ECH2	**CPH2**
Combined heat, power and hydrogen production	IF (SECS OR BECS OR GECS) AND ECH2	**3G-HPH2**
Combined heat, power, cold and hydrogen production	IF (SECS OR BECS OR GECS) AND ECH2	**4G-HPCH2**

A novel idea has been proposed for Corvo Island, to integrate water supply system with electricity generation, by using water as a mechanism for ironing demand. The main barrier to wider application of such integration lies in the traditional separateness of water and power utilities. Waste is commonly integrated with heat and/or power generation on the Continent, but rarely on islands, due to relatively small quantities of waste. The integration technologies are waste incineration to produce hear and/or electricity, biomass and/or waste (manure especially) gasification, ethanol production, etc. and using those fuels as energy carriers.

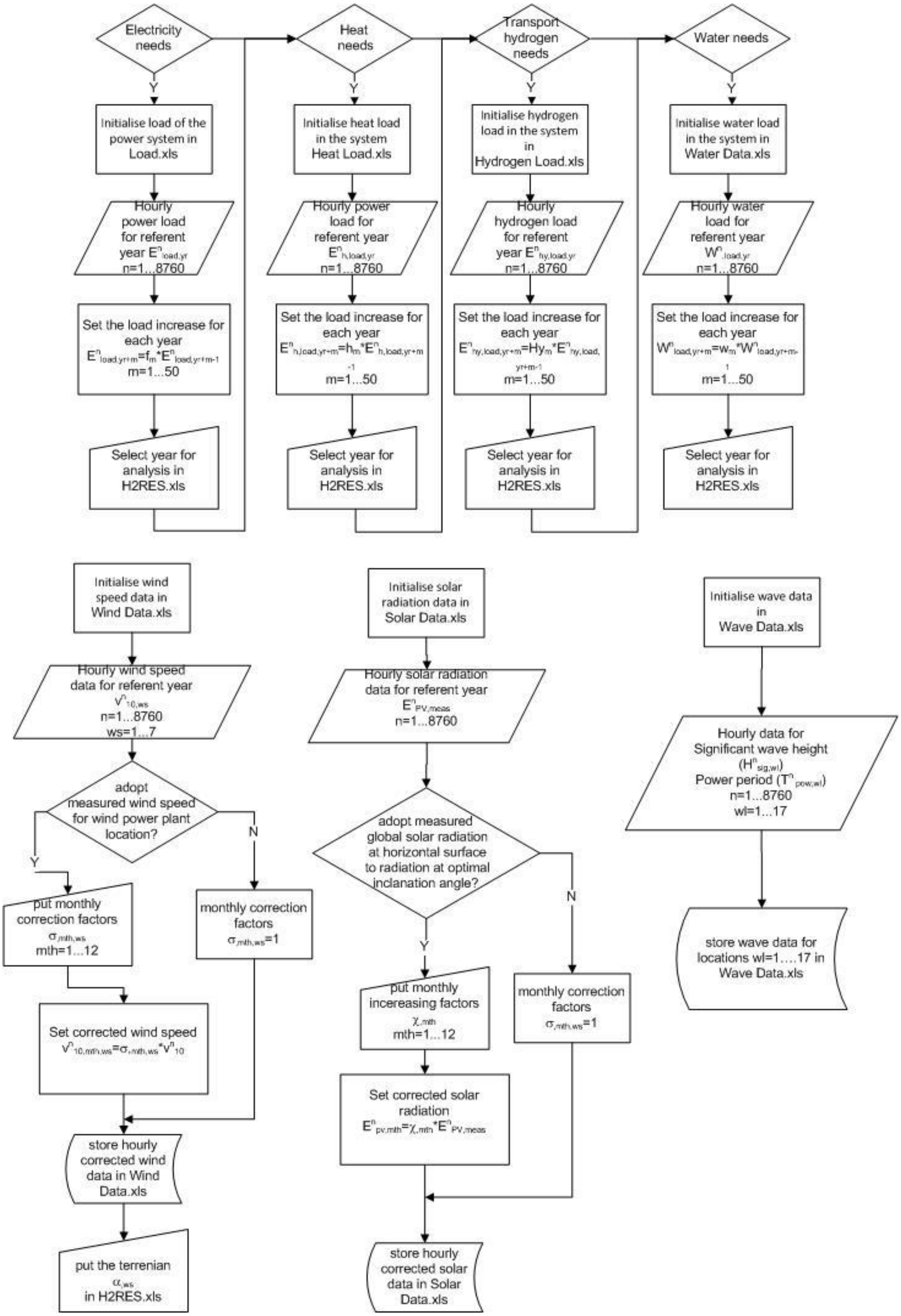
Wastewater treatment can also be integrated through gasification, and usage of gas as energy carrier. Waste and wastewater treatment are here considered supply technologies, since from the point of view of communities they supply clean environment.

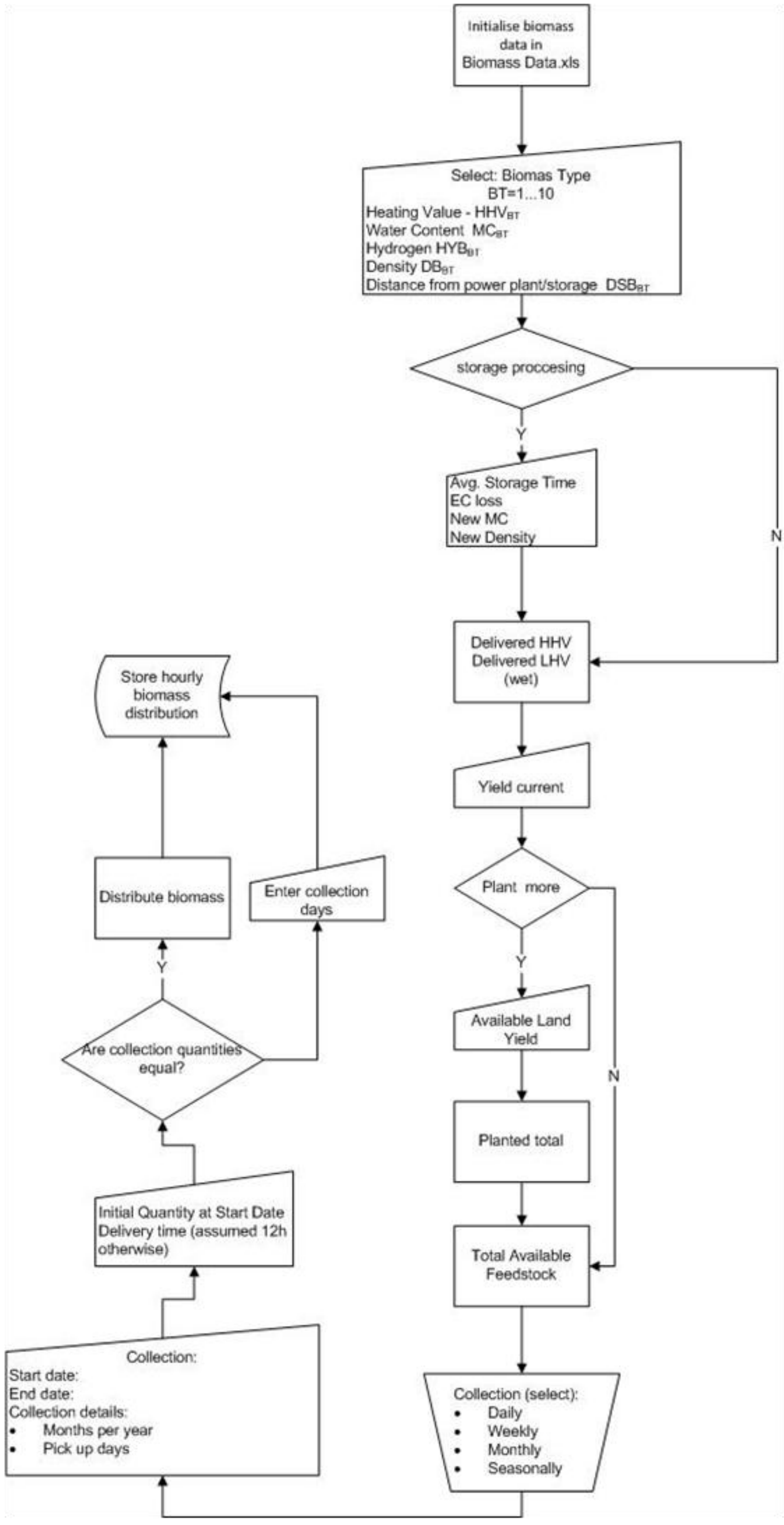
Substep 3.4 Devising the scenaria. The number of potential scenaria is vast, with many branches and loops. It is essential to weed out improbable scenaria, by following previous steps and removing all the combinations depending on low demand of certain commodity, or low resource. When devising scenaria, one should also consider policy issues. Energy policy should give different weighting factors and minimum thresholds to security of energy supply, economic viability, environmental viability, social acceptance. Applying energy policy issues at this stage will weed out some unacceptable scenaria, but others will show to be unacceptable only after detailed modelling.

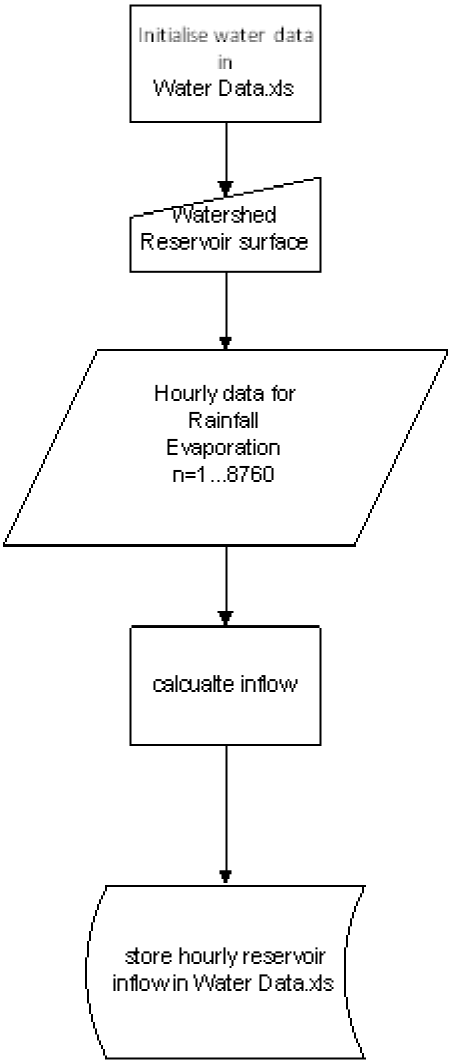
Step 4: modelling

Since complicated strongly coupled flows depend on timing of resources, demands, etc, the only practical way to check the viability of the scenaria is to model them in detail. After the technical viability of scenaria is thus checked, and many of the potential ones are dropped due to not being acceptable or viable, the economic viability should be checked, even when it is clearly demonstration activity.

ANNEX B - Mapping the needs and resources H_2RES model.




Initialise biomass data in Biomass Data.xls
Select: Biomas Type
BT=1...10
Heating Value - HHV_BT
Water Content MC_BT
Hydrogen HYB_BT
Density DB_BT
Distance from power plant/storage DSB_BT
storage proccesing
Y
N
Avg. Storage Time
EC loss
New MC
New Density
Delivered HHV
Delivered LHV
(wet)
Yield current
Plant more
Y
N
Available Land
Yield
Planted total
Total Available Feedstock
Collection (select):
Daily
Weekly
Monthly
Seasonally
Collection:
Start date:
End date:
Collection details:
Months per year
Pick up days
Initial Quantity at Start Date
Delivery time (assumed 12h otherwise)
Are collection quantities equal?
Y
Distribute biomass
Enter collection days
Store hourly biomass distribution


Initialise water data in Water Data.xls
Watershed Reservoir surface
Hourly data for Rainfall Evaporation n=1...8760
calcualte inflow
store hourly reservoir inflow in Water Data.xls

ANNEX C - EnergyPLAN energy system analysis procedure

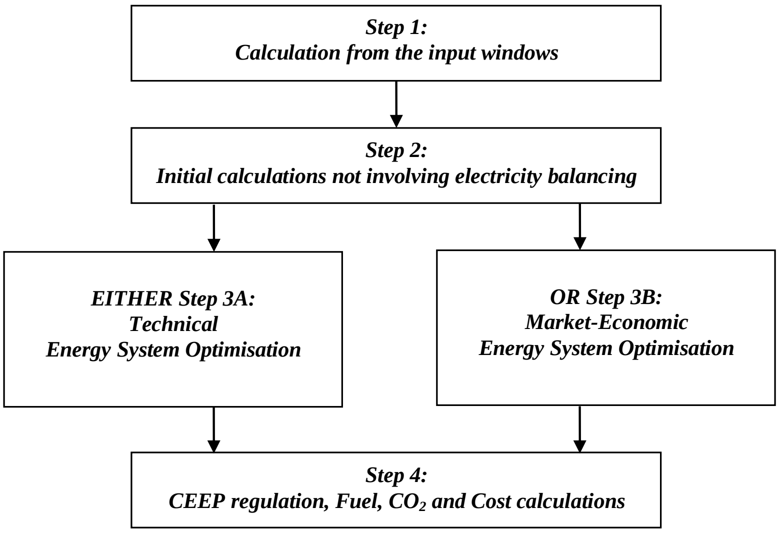


Figure 47. Overall structure of the energy system analysis procedure [45].

Step 1: Calculation from the input windows:

1. Electricity demand is calculated as in input window
2. Solar thermal
3. RES1, … RES4
4. Hydro Power input
5. Nuclear Power or Geothermal
6. Individual solar thermal, boilers, CHPs and heat pumps are calculated (If electrolysers for hydrogen productions are not specified, then the model will identify a minimum capacity and define an electrolyser)
7. Biofuels for transportation and CHP/Boilers produced on waste
8. Market prices of external market

Step 2: Initial calculations not involving electricity balancing

1. Fixed import/export of electricity specified in the Electricity demand window
2. District heating demands incl. heating demands from absorption cooling
3. Industrial and Waste district heating and electricity productions
4. Fixed Boiler production subtracted from the district heating demand
5. Boiler production in district heating group 1

EITHER Step 3A: Technical Energy System Analysis

1. CHP, Heat Pumps and boilers in groups 2 and 3 (regulation 1 or 4)

2. Flexible electricity demand (including dump charge BEV)

3. CHP, Heat Pumps and boilers in groups 2 and 3 (regulation 2 or 3) If chosen (overrules production of regulation 1 or 4)

4. Hydro power

5. Individual CHP and Heat Pump systems

6. Electrolyser for micro CHP, Transportation, DH group 3 and DH group 2

7. Heat storage in groups 3 and 2

8. Transportation (Smart charge and V2G)

9. Electricity storage

The calculation of condensing power and import/export including CEEP and EEEP (Critical and Exportable Excess Electricity production) are calculated continuously more or less after each of the sequences in the technical energy system analysis procedure .

OR Step 3B: Market-Economic Energy System Analysis

1. Market economic optimisation

2. CHP3 minimum production

3. Hydrogen and electricity demands for transportation and micro CHP

Step 4: CEEP regulation, Fuel, CO2 and Cost calculations

1. Fixed boiler production is added to the boilers in groups 2 and 3

2. Critical Excess Regulation

3. Grid stabilisation

4. Heat balances in district heating systems

5. Fuel consumptions

6. CO_2 emissions

7. Cost

ANNEX D - Methodology for calculation of hourly energy production of wind power plants in Croatia

The methodology consists of 5 simple steps or procedures that are applied to solve the problem of how to determine and predict, with acceptable uncertainty or error, the hourly power production of wind power plants from field measurements in southern Croatia.

1. Overview of available measured data, factors, levels, and range of measurements
2. Description of selected measurements
3. Data analysis and validation
4. Statistical analysis
5. Calculation of wind power production

Overview of available data factors, levels, and range of measurements

A wide range of publicly available meteorological data exists and can be found on the internet. Personal Weather Stations have been installed in many places and provide a lot of historical weather data. The problem with these data is that there is no quality control behind the measurements, so their use brings another level of uncertainty into the calculations. There are also certain data available from the Croatian Meteorological and Hydrological Institute and paid professional programs [**80**] that use official meteorological data, but these could be expensive and provide measurements from meteorological stations located in towns, which are not representative of sites where wind turbines will be installed. The best available data that were publicly available were from the EU financed project -Assessment of Wind and Solar Energy Resources in Croatian Pilot Region – AWSERCRO [**66**].

Important factors, levels, and ranges for determination of wind power production in the selected region are given below (parameters available from AWSERCRO project are given in bold text):

- **wind location**
- **wind speed**
- **wind direction (at least two levels 10, 44 m)**
- **height of instrument (10, 30, 44, 46 m)**
- terrain roughness
- turbulence intensity
- wind shear (vertical and horizontal)
- terrain slope and configuration
- **distance from the measurement / between locations**
- direction between locations

- **barometric pressure**
- **temperature (three levels 0.05 m, 2m, 40m)**
- **height above sea level**
- **air density**
- humidity
- **solar radiation**
- cloudiness
- precipitation
- **yearly, seasonal, monthly, diurnal (daily), hourly variations, 10 minute**

Description of the selected measurements

AWSERCRO-Assessment of Wind and Solar Energy Resources in Croatian Pilot Region was a project financed by the European Commission as part of its technical assistance under the CARDS program. A major component of this project was a measurement campaign and acquisition of the wind and solar. On-site wind measurements were taken from June 2007 until March 2009 by the Energy Institute Hrvoje Pozar. The measurement locations are on well exposed and remote sites located in the region of Southern Dalmatia to achieve a high spatial density of measured data [**66**]. The same authors provided descriptions of the measurement equipment and measurement sites used. The names of the measuring sites are as follows:

1. Pusto polje CRO W01
2. Debelo brdo CRO W02
3. Kasumi CRO W03
4. Zelovo CRO W04
5. Borajica CRO W05
6. Promina CRO W06
7. Voštane CRO W07
8. Orah CRO W08
9. Smokovljani CRO W09
10. Brač CRO W10

A map and geographical distribution of measurement sites is presented in Figure 48 and the distances between measurement sites are listed in the Table 41, while geographical coordinates and the locations' heights above sea level are given in Table 42.

Figure 48. Locations of the AWSERCRO measurement stations.

Table 41. Distance between locations of the measurement stations [km].

		Pusto polje	Debelo brdo	Kasumi	Zelovo	Borajica	Promina	Voštane	Orah	Smokovljani	Brač
		W01	W02	W03	W04	W05	W06	W07	W08	W09	W10
Pusto polje	W01	**0,0**	39,4	31,8	75,6	78,7	45,1	101,9	162,9	216,7	124,9
Debelo brdo	W02	39,4	**0,0**	44,3	85,9	70,9	52,4	116,4	173,7	225,3	124,8
Kasumi	W03	31,8	44,3	**0,0**	45,6	48,1	13,4	74,5	134,3	187,5	93,2
Zelovo	W04	75,6	85,9	45,6	**0,0**	36,5	34,0	30,8	88,7	141,9	52,3
Borajica	W05	78,7	70,9	48,1	36,5	**0,0**	36,0	62,3	108,9	157,4	54,6
Promina	W06	45,1	52,4	13,4	34,0	36,0	**0,0**	64,0	122,6	175,4	80,0
Voštane	W07	101,9	116,4	74,5	30,8	62,3	64,0	**0,0**	61,2	115,3	46,7
Orah	W08	162,9	173,7	134,3	88,7	108,9	122,6	61,2	**0,0**	54,2	59,7
Smokovljani	W09	216,7	225,3	187,5	141,9	157,4	175,4	115,3	54,2	**0,0**	103,6
Brač	W10	124,9	124,8	93,2	52,3	54,6	80,0	46,7	59,7	103,6	**0,0**

Table 42. Geographical coordinates and height above sea level of measurement stations.

			Latitude	Longitude	Google Earth h.a.s.l [m]	h.a.s.l [m]
Pusto polje	W01	Dec Degrees	44,304083	15,97333	958	956
Debelo brdo	W02	Dec Degrees	44,102583	15,56739	335	336
Kasumi	W03	Dec Degrees	44,036695	16,11377	315	318
Zelovo	W04	Dec Degrees	43,751361	16,52322	921	919
Borajica	W05	Dec Degrees	43,603748	16,11768	577	548
Promina	W06	Dec Degrees	43,924694	16,17422	1067	1025
Voštane	W07	Dec Degrees	43,666389	16,88744	1071	1065
Orah	W08	Dec Degrees	43,242778	17,37108	593	561
Smokovljani	W09	Dec Degrees	42,845083	17,75736	318	280
Brač	W10	Dec Degrees	43,287963	16,63585	721	709

Wind data analysis

Data Validation- the measured data obtained from AWSERCRO website cover the period from 01/06/2007 until 30/03/2009. As there were some difficulties in measurements and in order to use a unique time period for all the sites that can be used for planning purposes, the data finally used cover the period from 01/01/2008 until 31/12/2008. For this period, it was possible to record in total 52,704 values representing 10 min measurements. The rate of data recovery per site and type of measurement is shown in Table 43.

To validate the data a special procedure was followed by a simple range test and visual inspection. In this way, it was possible to determine errors in data records and a similar way the missing data were inspected. The results showed that location W06 is not representative for calculation of the power production, as for some measurements 50% of the data were missing. After inspection of all the data, valid data files were created for use in further analysis.

Statistical analysis

Wind speed distribution - The most widely used distribution that explains wind speed is the Weibull distribution. Its probability density function is given by the formula:

$$\mathbf{f(v) = \frac{k}{c}\left(\frac{v}{c}\right)^{k-1} e^{-\left(\frac{v}{c}\right)^{k}}} \tag{40}$$

where k is the Weibull shape factor and c is the scale factor. The cumulative distribution function of the velocity v gives us the fraction of time (or probability) that the wind velocity is equal to or lower than *v*. Thus the cumulative distribution *f(v)* is the integral of the probability density function:

$$F(v) = \int_{0}^{\infty} f(v)dv = 1 - e^{-\left(\frac{v}{c}\right)^{k}} \tag{41}$$

Average wind velocity of a regime, following the Weibull distribution is given by:

$$\mathbf{v_m = \int_{0}^{\infty} vf(v)dv} \tag{42}$$

The energy produced by a wind turbine could be calculated using Eq. 40

$$\mathbf{E} = \mathbf{t}\int_{0}^{\infty} \mathbf{P_v f(v) dv} \tag{43}$$

where E is energy produced in time *t*, *v* is the wind speed, P_v power of wind turbine for the wind speed *v*.

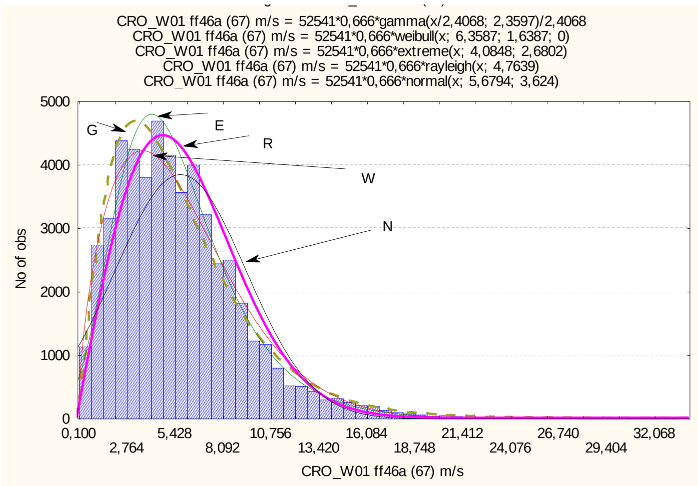


Figure 49. Histograms of measured wind speed distribution at 46m for location W01 compared to different distribution curves.

Basic statistics for 10 min average wind speeds measured at all locations and all heights for year 2008 are given in Figure 8. The minimum mean speed ranges from 2.7 m/s at 10m height at W08 to maximum mean speed of 7.45 m/s at 46m at location W05. It is significant that standard error for all sites falls in the range of permissible limits of error for first-class cup anemometers.

Table 43. Basic statistics for measured 10min average wind speeds at all locations for year 2008.

Variable	Descriptive Statistics (a_all_time_Final) Include condition: v26=2008														
	Valid N	% Valid obs.	Mean	Confidence -95,000%	Confidence 95,000	Median	Mode	Freq. of Mode	Sum	Min.	Max.	Variance	Std.Dev.	Coef.Var.	Standard Error
W01 ff10a	52694	99,981	5,1247	5,0959286	5,1534773	4,6	3,10	950	270041,	0	30,6	11,3573	3,37006	65,7611	0,01468
W01 ff30a	52694	99,981	5,4756	5,4454923	5,5057126	4,9	4,90	922	288531,	0	33,1	12,4362	3,52651	64,4041	0,01536
W01 ff44a	52694	99,981	5,6330	5,6023266	5,6638175	5,1	4,70	905	296829,	0	33,3	12,9666	3,60091	63,9246	0,01568
W01 ff46a	52694	99,981	5,6628	5,6318645	5,6938803	5,1	2,90	904	298399,	0	33,4	13,1889	3,63165	64,1310	0,01582
W02 ff10a	51761	98,2108	4,9458	4,9218447	4,9699038	4,5	2,90	1127	256003,	0,1	23,3	7,7803	2,78932	56,3970	0,01226
W02 ff30a	51756	98,2013	6,0545	6,0244797	6,084616	5,5	3,50	884	313359,	0,1	28,9	12,1811	3,49015	57,6451	0,01534
W02 ff44a	51752	98,1937	6,4084	6,3758953	6,4409696	5,8	3,70	809	331649,	0,1	31,4	14,2623	3,77654	58,9309	0,01660
W02 ff46a	51752	98,1937	6,4540	6,4212614	6,4868967	5,9	4,10	826	334011,	0,1	31,5	14,5092	3,80910	59,0185	0,01674
W03 ff10a	52552	99,7116	3,9830	3,9637778	4,0022710	3,4	2,90	1799	209315,	0,1	19,4	5,06759	2,25113	56,5181	0,00982
W03 ff30a	45662	86,6386	4,7347	4,7073699	4,7621495	4,3	,100	2469	216198,	0,1	24,3	8,91738	2,98619	63,0697	0,01397
W03 ff44a	52551	99,7097	5,4538	5,4274178	5,4803175	4,9	3,90	1026	286606,	0,1	26,2	9,57042	3,0936	56,7232	0,01349
W03 ff46a	52551	99,7097	5,5059	5,4791473	5,5328257	5	4,10	1017	289345,	0,1	26,7	9,8542	3,1391	57,0133	0,01369
W04 ff10a	52702	99,9962	4,3686	4,344124	4,3932140	3,9	2,70	1178	230237,	0,1	23,9	8,26521	2,87492	65,8078	0,01252
W04 ff30a	52702	99,9962	5,0099	4,9820724	5,0377218	4,5	3,10	1009	264031,	0,1	28,5	10,6216	3,25908	65,0529	0,01419
W04 ff44a	52702	99,9962	5,2071	5,1782135	5,2360060	4,7	,100	1030	274425,	0,1	29,9	11,4555	3,3846	64,9995	0,01474
W04 ff46a	52702	99,9962	5,2385	5,209665	5,2673831	4,7	3,30	988	276080,	0,1	30,1	11,4259	3,38022	64,5263	0,01472
W05 ff10a	52497	99,6072	5,8488	5,8180446	5,8797308	5,07	3,90	799	307049,	0	22,7	13,0003	3,6056	61,6459	0,01573
W05 ff30a	52497	99,6072	7,0705	7,0338102	7,1072545	6,2	4,50	638	371181,	0	26,5	18,4287	4,29286	60,7149	0,01873
W05 ff44a	52497	99,6072	7,3517	7,313649	7,3898269	6,5	5,50	596	385944,	0	27,3	19,8258	4,45262	60,5656	0,01943
W05 ff46a	52497	99,6072	7,4594	7,4211651	7,4977981	6,6	5,90	585	391600,	0	27,8	20,0636	4,47924	60,0477	0,01955
W06 ff10a	50748	96,2887	6,5294	6,4895981	6,5692691	5,4	2,90	891	331355,	0,1	34,7	20,9634	4,57858	70,1222	0,02032
W06 ff30a	40121	76,1252	7,3288	7,2732887	7,3844814	5,9	,100	3671	294042,	0,1	36,1	32,2825	5,68177	77,5257	0,02836
W06 ff44a	26827	50,9013	6,6194	6,5452432	6,6937398	4,5	,500	967	177581,	0,1	35,5	38,4989	6,2047	93,7345	0,03788
W06 ff46a	27524	52,2237	7,2013	7,1388073	7,2638303	5,6	2,90	469	198209,	0,1	30,3	27,9985	5,29136	73,4777	0,03189
W07 ff10a	52695	99,9829	4,9835	4,9508412	5,0162068	3,7	2,70	1453	262606,	0	27,2	14,6525	3,8278	76,8103	0,01667
W07 ff30a	52693	99,9791	4,4478	4,4065585	4,4891960	3,3	,100	9263	234372	0	31,8	23,4180	4,83922	108,798	0,02108
W07 ff44a	52693	99,9791	6,1622	6,1214541	6,2030367	4,8	4,30	911	324707,	0	33,5	22,8239	4,77744	77,5276	0,02081
W07 ff46a	52693	99,9791	6,2134	6,1718968	6,2550061	4,9	3,90	894	327405,	0	34	23,6862	4,86684	78,3276	0,02120
W08 ff10a	52653	99,9032	2,7367	2,7183090	2,7552138	2,1	1,10	2326	144098,	0,1	19,7	4,66694	2,16031	78,9367	0,00941
W08 ff30a	52298	99,2297	3,3991	3,3758206	3,422519	2,6	1,50	1775	177769,	0,1	23,4	7,42236	2,72440	80,1490	0,01191
W08 ff44a	52653	99,9032	3,6468	3,6219626	3,6716601	2,8	1,60	856	192015,	0,07	26,1	8,46322	2,90916	79,7727	0,01267
W08 ff46a	52653	99,9032	3,6569	3,6319957	3,681950	2,8	1,70	1582	192550,	0,1	26,3	8,55101	2,92421	79,9626	0,01274
W09 ff10a	47751	90,6022	5,3813	5,3531587	5,4094682	4,7	3,90	1035	256963,	0,1	20,9	9,85348	3,13902	58,3319	0,01436
W09 ff30a	47751	90,6022	6,0835	6,0515240	6,1155761	5,3	5,10	929	290495,	0,1	23,2	12,7495	3,57064	58,6934	0,0163
W09 ff44a	47751	90,6022	6,2525	6,2187558	6,2863183	5,4	3,90	892	298564,	0,1	23,3	14,1852	3,76633	60,2368	0,01723
W09 ff46a	47749	90,5984	5,7210	5,6850646	5,7569634	5	,100	3072	273172,	0,1	22,6	16,0639	4,00798	70,0572	0,01834
W10 ff10a	52703	99,9981	3,8949	3,8755285	3,9143126	3,4	2,90	1715	20527	0,1	16,5	5,15926	2,27140	58,3170	0,00989
W10 ff30a	52703	99,9981	5,2842	5,2570235	5,3113842	4,7	2,90	1071	278493,	0,1	22,1	10,1355	3,18364	60,2483	0,01386
W10 ff44a	52703	99,9981	5,7458	5,7155197	5,7760765	5,1	3,10	1006	302820,	0,1	23,9	12,5778	3,54652	61,7238	0,01544
W10 ff46a	52703	99,9981	5,8514	5,8207518	5,8822366	5,2	3,10	998	308391,	0,1	24,3	12,9662	3,60086	61,5375	0,01568

Wind speed variation with height

The wind speed near the ground changes with height, which requires an equation that predicts the wind speed at one height in terms of the measured speed at another height. The most common expression for the variation of wind speed with hub height is the power law having the following form:

$$\frac{\mathbf{v_2}}{\mathbf{v_1}} = \left(\frac{\mathbf{h_2}}{\mathbf{h_1}}\right)^{\boldsymbol{\alpha}} \qquad (44)$$

where v_2 and v_1 are the mean wind speeds at heights h_2 and h_1, respectively. The exponent α depends on such factors as surface roughness and atmospheric stability. Numerically, it lies in the range 0.05–0.5 with the most frequently adopted value being 0.14 (widely applicable to low surface and well exposed sites).

Figure 16, shown in the chapter on resource mapping illustrates seasonal changes of monthly wind speed for locations W02, W05 and W10. As explained by many other authors, typical behaviour of monthly variations cannot be defined by a single year's data, so the data in Figure 16, just represent monthly variations for the specific year. Seasonal changes of monthly wind speed for one location at all measured heights are given in Figure 50. Similarly, Figure 51 shows the standard deviation of the wind speed measured at location W05 at 46 m height. Available power varies even more, as it is calculated by the third exponent of wind speed.

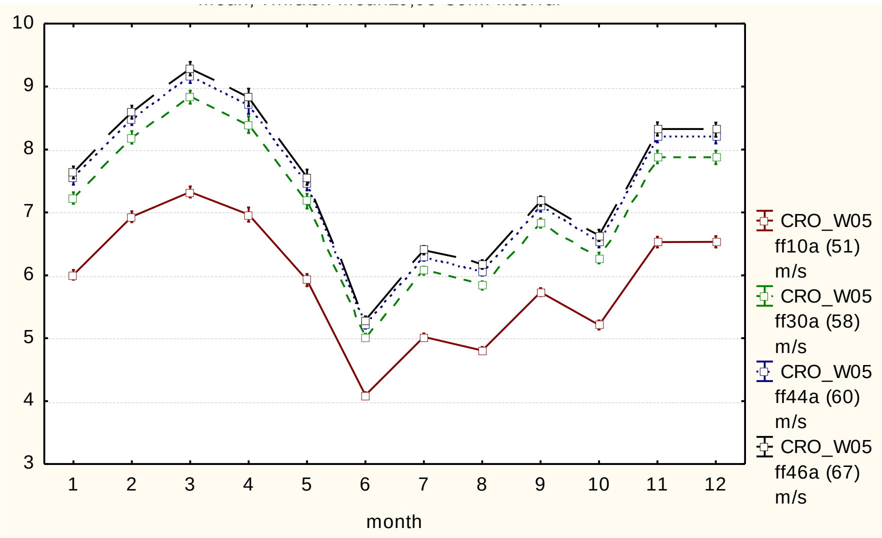


Figure 50. Seasonal changes of monthly wind speed for location W05 at all measured heights.

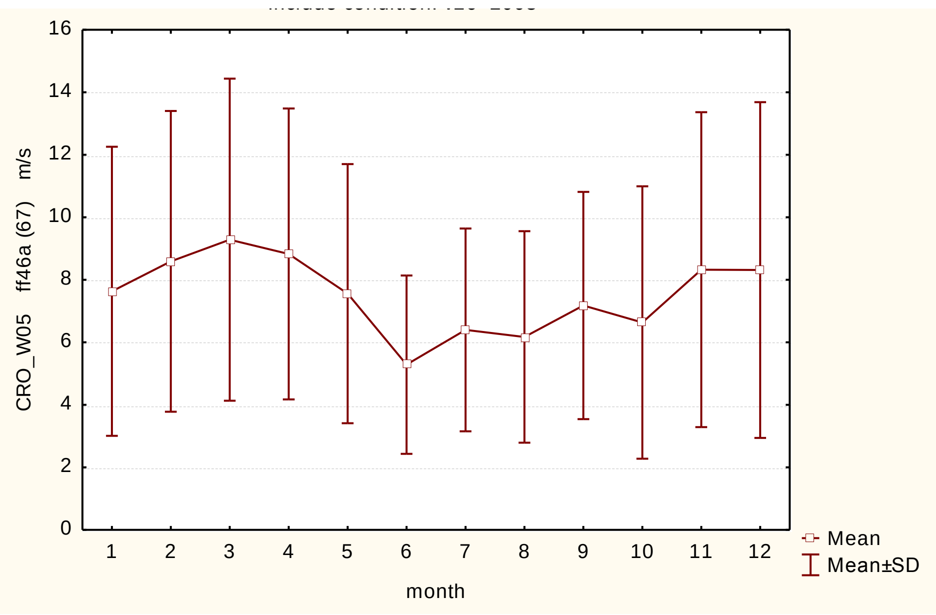


Figure 51. Standard deviation of monthly mean wind speed at location W05 at 46 m height.

On a yearly basis it is possible to calculate a vertical wind profile at all sites from the mean wind speeds. The vertical wind profile for locations with the most available data is presented in Figure 52, while vertical profiles from measured data with a significant number of missing data for certain heights are presented, but they did not have a neutral, normal logarithmic shape.

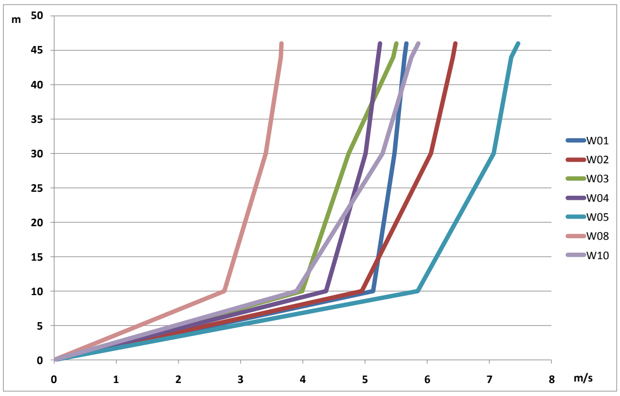


Figure 52. Vertical wind profile at measurement locations (mean wind speeds calculated from measured data at all heights).

Similar to wind speed statistics, it is possible to analyse wind directions. A wind rose is the standard tool for description of wind directions and it has been tested for all sites. As was expected, characteristic directions for the Adriatic region are Northeast and Southeast winds. Only one site had maximal winds from the southwest.

Estimation of wind speed at higher heights by use of multiple regression

Current commercial onshore wind turbines with installed capacity from 1.5 to 3 MW have hub heights from 80-120 meters, so to calculate power production from these turbines it is also necessary to have wind speeds at their hub heights. Usually, wind speeds at different heights are calculated by a power formula (44) or by logarithmic formulas that include terrain roughness. As there were data available for determination of the power coefficient at most of the measured 10 minute periods, it was decided to try to find a formula that would give the minimal deviation from the measured wind speed at 46 m height and calculate wind speeds at the same height but with the use of wind speeds below 46 m. By use of multiple regression, several formulas have been tested and formula (45) gave the smallest deviation measured by R^2.

$$v_{46} = \frac{v_{10} \cdot \left[\left(\frac{z_{46}}{z_{10}}\right)^{\left(\frac{ln\frac{v_{30}}{v_{10}}}{ln\frac{z_{30}}{z_{10}}}\right)} + \left(\frac{z_{46}}{z_{10}}\right)^{\left(\frac{ln\frac{v_{44}}{v_{10}}}{ln\frac{z_{44}}{z_{10}}}\right)} \right] + v_{30} \cdot \left(\frac{z_{46}}{z_{30}}\right)^{\left(\frac{ln\frac{v_{44}}{v_{30}}}{ln\frac{z_{44}}{z_{30}}}\right)} + v_{44} \left(\frac{z_{46}}{z_{44}}\right)^{\frac{\left(\frac{ln\frac{v_{44}}{v_{30}}}{ln\frac{z_{44}}{z_{30}}} + \frac{ln\frac{v_{44}}{v_{10}}}{ln\frac{z_{44}}{z_{10}}} + \frac{ln\frac{v_{30}}{v_{10}}}{ln\frac{z_{30}}{z_{10}}}\right)}{3}}}{4} \quad (45)$$

Multiple regression results for predicted wind speed at 46 m with improved formula (44) and measured wind speed as observed variable at location W01 resulted in R^2: 0.99865729, standard error of estimate is 0.131765215 and std. error: 0.0010697 with the value t(52487) = 26.923 and significance level $p < 0.0000$. Plot of predicted vs. observed wind speeds at location W01 is given in Figure 53 and shows a good match.

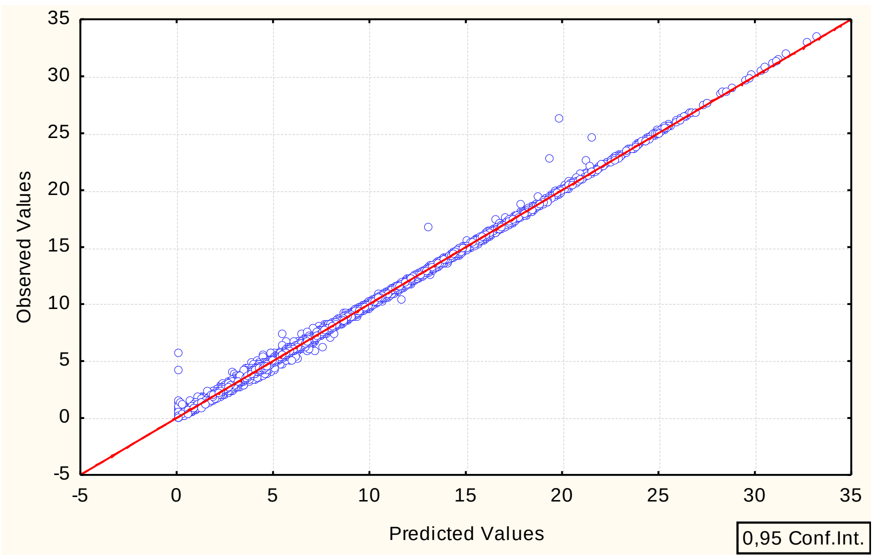


Figure 53. Plot of predicted vs. observed wind speeds [m/s] at 46 m height at location W01.

Residual analysis of the predicted data showed that there were certain errors in some cases, so after the exclusion of 50 problematic values, the following results of multiple regression were obtained $R^2 = 0.99907539$, standard error of estimate at 0.109131515, std.error: 0.0008874 with value t(52437) = 34.967 and p < 0.0000.

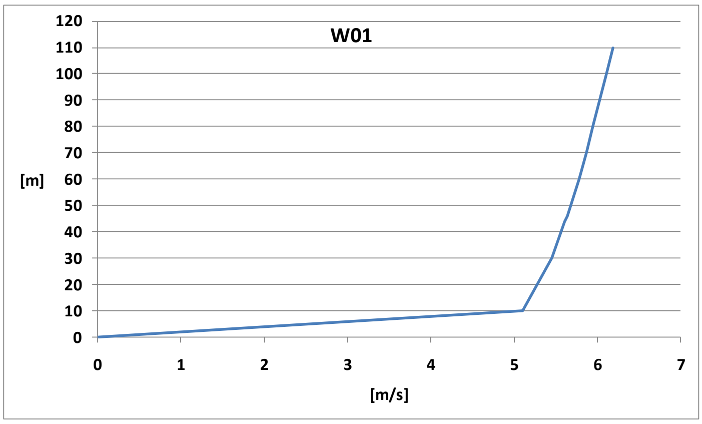


Figure 54. Vertical wind profile at measurement location W01 (mean wind speeds calculated from measured data at heights 10-46m and extrapolated data 60-110m).

By application of the same formula to predict wind speeds at heights above 46 m and by using all the measured data, it was possible to get the vertical wind profile for all sites and for all desired heights. Figure 54 presents the calculated vertical wind profile at measurement location W01, with wind speeds calculated from measured data at heights 10-46 m and extrapolated data 60-110 m. The shape fits the profile of the neutral atmospheric stability. Figure 55 compares Weibull distributions for predicted 10 min mean wind speed at 60 m height and measured wind speed at 46 m. There were no significant deviations from basic Weibull shapes, but there were still some problematic values. Monthly plots of predicted mean wind speeds for 10 minute periods at all heights at location W01 with excluded problematic values are presented in Figure 56.

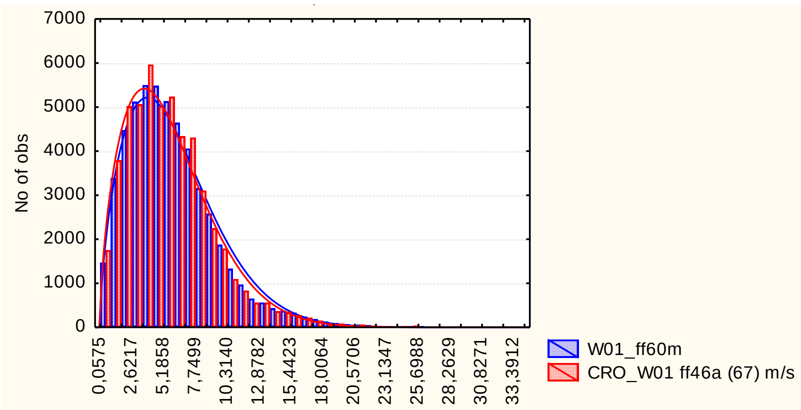


Figure 55. Weibull distribution for predicted 10 min mean wind speed at 60 m height and measured at 46m.

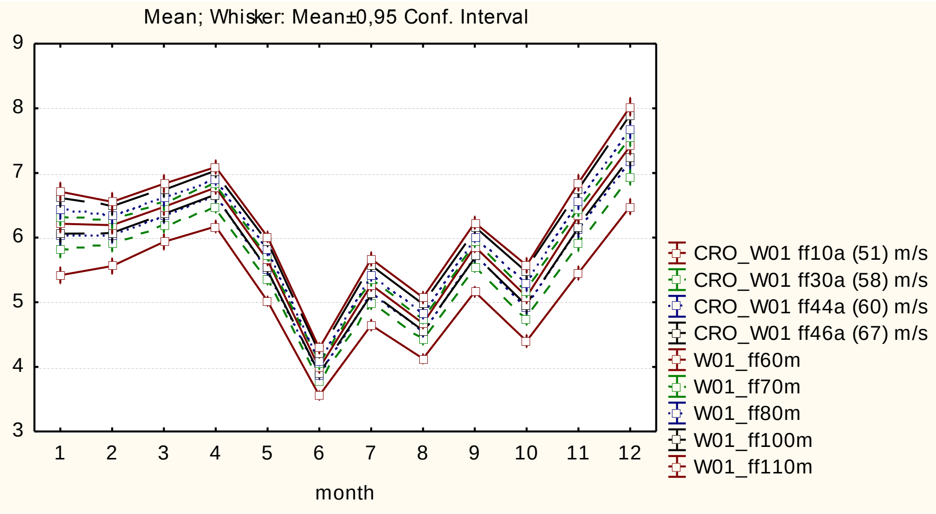


Figure 56. Monthly plot of predicted mean 10min wind speeds at all heights at location W01 with excluded problematic values.

The calculated vertical wind profile at measurement locations W02, W03, W04, W05, W08 and W10 from measured wind speeds is presented in Figure 57. The shapes have characteristics ranging unstable to neutral and stable atmospheric conditions.

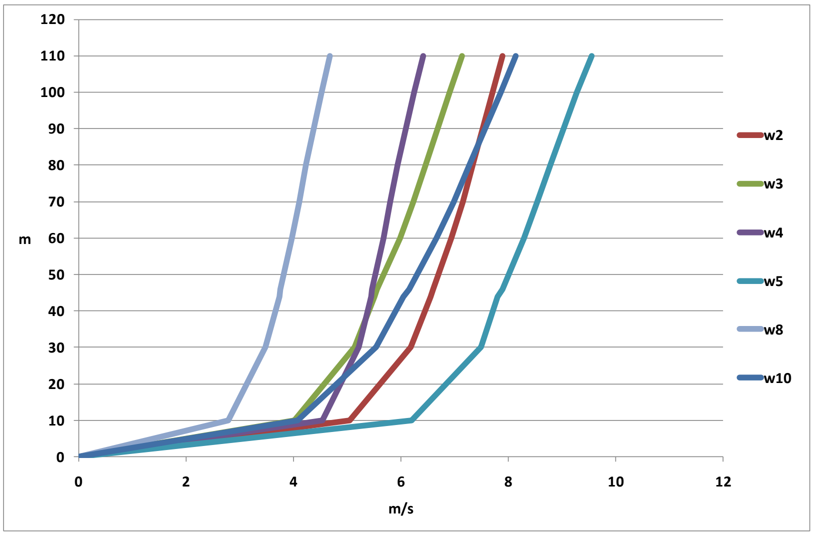


Figure 57. Vertical wind profile at measurement locations W02, W03, W04, W05, W08, W10 (mean wind speeds calculated from measured data at heights 10-46m and extrapolated data for 60-110m).

Correlation of wind speeds and energy production between sites

Final calculations were related to correlation between wind speeds (Table 44 and

Table 45) and predicted wind production at chosen sites.

Table 44. Correlation of wind speed at 46 m above ground level (means and standard deviations are expressed in m/s).

Variable	Means	Std.Dev.	CRO_W01 ff46a (67) m/s	CRO_W02 ff46a (67) m/s	CRO_W03 ff46a (67) m/s	CRO_W04 ff46a (67) m/s	CRO_W05 ff46a (67) m/s	CRO_W07 ff46a (67) m/s	CRO_W08 ff46a (67) m/s	CRO_W10 ff46a (67) m/s
CRO_W01 ff46a (67) m/s	5,65536	3,59506	1,00000	0,66158	0,54663	0,65575	0,60539	0,58643	0,50039	0,54352
CRO_W02 ff46a (67) m/s	6,45667	3,81773	0,66158	1,00000	0,66763	0,65823	0,64498	0,64026	0,39907	0,65779
CRO_W03 ff46a (67) m/s	5,51450	3,10249	0,54663	0,66763	1,00000	0,57905	0,44702	0,55925	0,37933	0,47110
CRO_W04 ff46a (67) m/s	5,26517	3,37480	0,65575	0,65823	0,57905	1,00000	0,58324	0,78280	0,58979	0,64037
CRO_W05 ff46a (67) m/s	7,47965	4,47404	0,60539	0,64498	0,44702	0,58324	1,00000	0,52510	0,48116	0,72249
CRO_W07 ff46a (67) m/s	6,22870	4,83989	0,58643	0,64026	0,55925	0,78280	0,52510	1,00000	0,52749	0,66783
CRO_W08 ff46a (67) m/s	3,67449	2,91177	0,50039	0,39907	0,37933	0,58979	0,48116	0,52749	1,00000	0,49251
CRO_W10 ff46a (67) m/s	5,85541	3,57462	0,54352	0,65779	0,47110	0,64037	0,72249	0,66783	0,49251	1,00000

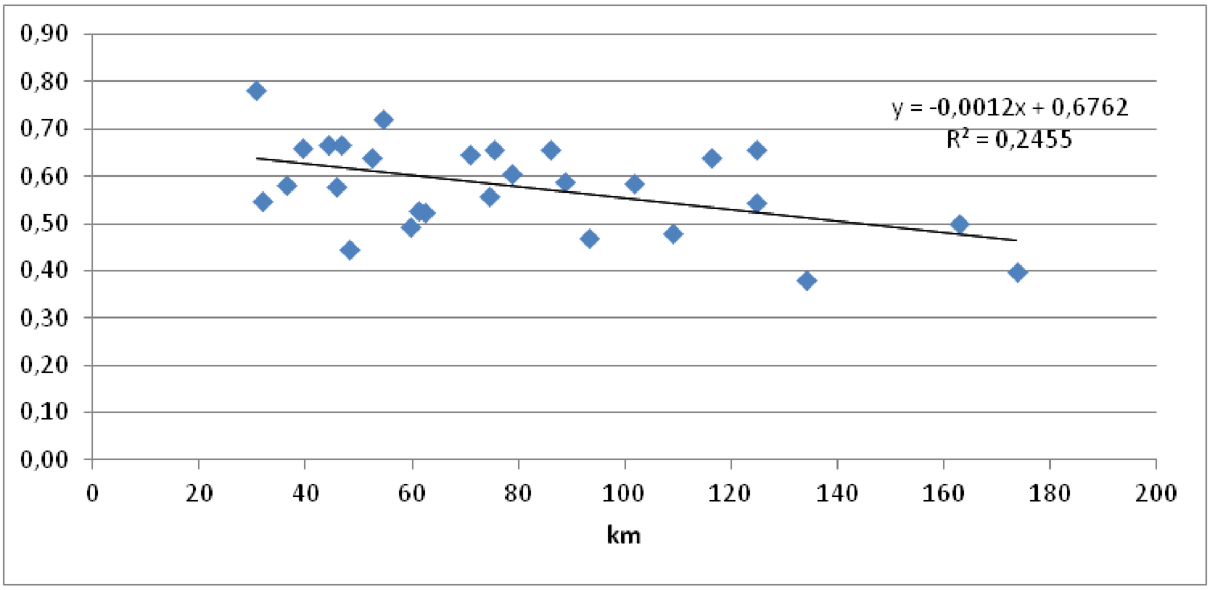


Figure 58. Correlation of wind speed at 46 m above ground level sorted by distances between locations.

Table 45. Correlation of 10 min mean power production at selected sites (mean and standard deviation are in kWh/h).

Variable	Means	Std.Dev.	W01_ECOTEC_100	W02_ECOTEC_100	W03_ECOTEC_100	W04_ECOTEC_100	W05_ECOTEC_100	W07_ECOTEC_100	W08_ECOTEC_100	W09_ECOTEC_100	W10_ECOTEC_100
W01_ECOTEC_10	694,25	887,27	1,00000	0,59506	0,43853	0,57739	0,49991	0,42649	0,39958	0,42499	0,48845
W02_ECOTEC_10	1092,18	1125,47	0,59506	1,00000	0,44922	0,53294	0,55369	0,41791	0,27118	0,43204	0,56233
W03_ECOTEC_10	639,72	864,56	0,43853	0,44922	1,00000	0,44557	0,30596	0,37498	0,29937	0,23986	0,36684
W04_ECOTEC_10	670,97	891,87	0,57739	0,53294	0,44557	1,00000	0,46250	0,49984	0,49856	0,38205	0,57973
W05_ECOTEC_10	1303,36	1185,55	0,49991	0,55369	0,30596	0,46250	1,00000	0,37608	0,31950	0,46061	0,62248
W07_ECOTEC_10	722,52	1050,72	0,42649	0,41791	0,37498	0,49984	0,37608	1,00000	0,32350	0,31994	0,49017
W08_ECOTEC_10	410,14	763,52	0,39958	0,27118	0,29937	0,49856	0,31950	0,32350	1,00000	0,29720	0,39549
W09_ECOTEC_10	767,79	1012,25	0,42499	0,43204	0,23986	0,38205	0,46061	0,31994	0,29720	1,00000	0,45754
W10_ECOTEC_10	1038,16	1100,06	0,48845	0,56233	0,36684	0,57973	0,62248	0,49017	0,39549	0,45754	1,00000

ANNEX E - Calculated FIT for Croatian case studies

Table 46. Cost estimation for PHS Vinodol in EUR.

Equipment – Cost symbol	Case a) new pumps, penstocks and reservoir	Case b) new pumps and reservoir	Case c) new turbines, pumps, penstocks and reservoir	Case d) new PHS with two reservoirs
Hydro-turbine (C_T)	-	-	17,255,570	17,255,570
Pumps (C_P)	8,159,013	8,159,013	8,159,013	8,159,013
Penstock ($C_{Penstock}$)	6,205,795	600,561	12,411,591	12,411,591
Reservoir (C_R)	21,928,976	21,928,976	21,928,976	43,857,952
Grid connection (C_{GC})	1,451,751	1,227,542	2,390,206	3,267,365
Control system (C_{CS})	580,701	491,017	956,082	1,306,946
Transportation of equipment (C_T)	871,051	736,525	1,434,124	1,960,419
Personal (C_P)	10,888,135	9,206,565	17,926,545	24,505,238
Others (C_O)	2,540,565	2,148,198	4,182,860	5,717,889
TOTAL INVESTMENT	**52,625,987**	**44,498,397**	**86,644,967**	**118,441,982**
Yearly Operation and Maintenance (OMC_{PHS})	1,052,520	889,968	1,732,899	2,368,840

Table 47. Cost of the electricity production from PHS in €/MWh, based on 870 full load hours of turbines or energy equivalent.

Interest rate	*Case a)* 6	8	10	*Case b)* 6	8	10	*Case c)* 6	8	10	*Case d)* 6	8	10
	Payback period [years]											
	Cost of the electricity production without the cost of the wind electricity for pumping.											
6%	143	116	100	121	98	84	185	150	129	253	205	177
8%	151	124	108	128	105	91	196	161	140	268	220	192
10%	160	133	117	135	112	99	207	172	152	283	235	207
	Cost of the electricity production with the cost of 97.5 €/MWh for the wind electricity for pumping.											
6%	267	240	224	245	222	209	310	275	254	378	330	301
8%	276	249	233	252	229	216	321	286	265	393	345	316
10%	284	257	241	260	237	223	332	297	276	408	360	332

Table 48. Cost of the electricity production from PHS in €/MWh, based on 1750 full load hours of turbines or energy equivalent.

Interest rate	*Case a)* 6	8	10	*Case b)* 6	8	10	*Case c)* 6	8	10	*Case d)* 6	8	10
	Payback period [years]											
	Cost of the electricity production without the cost of the wind electricity for pumping.											
6%	71	58	50	60	49	42	92	75	64	126	102	88
8%	75	62	54	64	52	45	98	80	70	133	109	95
10%	79	66	58	67	56	49	103	86	75	141	117	103
	Cost of the electricity production with the cost of 97.5 €/MWh for the wind electricity for pumping.											
6%	196	182	174	185	173	166	218	200	190	250	227	212
8%	200	186	178	188	177	170	223	206	195	258	234	220
10%	204	191	183	192	180	174	229	211	201	265	241	228

Table 49. Cost of the electricity production from PHS in €/MWh, based on 2630 full load hours of turbines or energy equivalent.

		Case a)			*Case b)*			*Case c)*			*Case d)*		
		Payback period [years]											
		6	8	10	6	8	10	6	8	10	6	8	10
		Cost of the electricity production without the cost of the wind electricity for pumping.											
Interest rate	6%	47	38	33	40	32	28	61	50	43	84	68	58
	8%	50	41	36	42	35	30	65	53	46	89	73	63
	10%	53	44	39	45	37	33	69	57	50	94	78	69
		Cost of the electricity production with the cost of 97.5 €/MWh for the wind electricity for pumping.											
	6%	172	163	157	164	157	152	186	174	167	208	192	183
	8%	175	166	160	167	159	155	189	178	171	213	197	188
	10%	177	168	163	169	162	157	193	181	175	218	202	193

Table 50. Cost estimation for PHS on the Island of Krk.

Equipment – Cost symbol	Cost Estimation (€)
Hydro-turbine (C_T)	2,860,157
Pumps (C_P)	1,106,961
Penstock ($C_{Penstock}$)	4,112,296
Reservoir (C_R)	6,656,551
Grid connection (C_{GC})	589,439
Control system (C_{CS})	235,775
Transportation of equipment (C_T)	353,663
Personal (C_P)	4,420,790
Others (C_O)	1,031,518
TOTAL	**21,367,150**
Operation and Maintenance (OMC_{PHS})	427,343

Table 51. FIT for kWh of electricity from PHS on the Island of Krk [€/kWh].

		Payback [years]		
		6	8	10
Interest rate	6%	462	410	380
	8%	478	426	396
	10%	494	443	413

Table 52. Cost of electricity production from PHS without price of energy from the grid (PV electricity) in the case of the Island of Krk, [€/kWh].

		Payback[years]		
		6	8	10
Interest rate	6%	273	221	190
	8%	289	237	206
	10%	305	253	223

Table 53. FIT according to capacity factor in the case the case of the Island of Krk.

Working hours at full load (or energy equivalent),	**FIT**
<1750 h	selected $FIT_{PHS_{WGO}}$ from Table 51
1750-2750	199.8 €/MWh
>2750	190.3 €/MWh

BIOGRAPHY

Goran Krajacic, dipl. Ing., was born in Karlovac in 1979. He finished elementary and Technical school in Karlovac and he graduated at FSB-UZ in 2004. Since then he has been working as a researcher at the Department of Energy, Power Engineering and Environment at the Faculty of Mechanical Engineering and Naval Architecture, University of Zagreb. From 2004 to 2007 he worked on the FP-6 project **ADEG** - “Advanced Decentralised Energy Generation Systems in Western Balkans”. Most of his work on the ADEG project was connected with the development of the H_2RES computer program for energy planning. From 2007 to 2010 he worked on the Intelligent Energy Europe (IEE) project **STORIES – “**Addressing barriers to storage technologies for increasing the penetration of intermittent energy sources”. He also helped with the preparation and implementation of the FP-6 project WEB-MOB, five IEE projects (GERONIMO, STORIES, SMART, BIOSIRE, FLICK THE SWITCH), two FP-7 projects JoRIEW and DISKNET and 4DH project coordinated by AAU. In 2011 he helped the team of Prof. Joško Deur in the successful preparation of the HRZZ project ICT-aided integration of Electric Vehicles into the Energy Systems with a high share of Renewable Energy Sources.

Since 2007 he has been working on the national scientific project: Smart Energy Storage for Sustainable Development of Energy Systems, financed by Ministry of Science, Education and Sport of the Republic of Croatia. In 2007 he spent 6 months as a guest researcher in the Research Group on Energy and Sustainable Development, Instituto Superior Técnico, Lisbon, Portugal, where he investigated the application of small decentralised power generation and energy storages technologies. Results of his work have been published in 11 papers in the CC/SCI database and have been cited more than 60 times. He reviews papers for Energy Policy and Applied Energy. He participates in teaching the Introduction to Energy Management and Energy Planning cources.

In 2002 as a good student he received the "Hrvoje Pozar" scholarship from the Croatian Energy Council. Since 2001 he has been involved in organization of the SDEWES conference and since 2009 he has been the Secretary of the International Centre for Sustainable Development of Energy, Water and Environment Systems.

List of published works:

1. Krajačić, Goran; Duić, Neven; Zmijarević, Zlatko; Mathiesen, Brian Vad; Anić Vučinić, Aleksandra; Carvalho, Maria da Graça; Planning for a 100% Independent Energy System

based on Smart Energy Storage for Integration of Renewables and CO2 Emissions Reduction.// Applied Thermal Engineering. 31, (2011) 2073-2083

2. Ćosić, Boris; Markovska, Natasa; Krajačić, Goran; Taseska, Verica; Duić, Neven. Environmental and economic aspects of higher RES penetration into Macedonian power system. // Applied thermal engineering. (2011) – article in press
3. Krajačić, Goran; Duić, Neven; Carvalho, Maria da Graça. How to achieve a 100% RES electricity supply for Portugal?. // Applied energy. 88 (2011) , 2; 508-517
4. Krajačić, Goran; Duić, Neven; Tsikalakis, Antonis; Zoulias, Manos; Caralis, George; Panteri, Eirini; Carvalho, Maria Graça. Feed-in tariffs for promotion of energy storage technologies. // Energy policy. 39 (2011) , 3; 1410-1425
5. Segurado, Raquel; Krajačić, Goran; Duić, Neven; Alves, Luis Manuel. Increasing the penetration of renewable energy resources in S. Vicente, Cape Verde. // Applied energy. 88 (2011) , 2; 466-472
6. Fowler, Patrick (Pat); Krajačić, Goran; Lončar, Dražen; Duić, Neven. Modeling The Energy Potential of Biomass - H2RES. // International journal of hydrogen energy. 34 (2009) ; 7027-1-7040-13
7. Krajačić, Goran; Duić, Neven; Carvalho, Maria Graça. H2RES, Energy planning tool for island energy systems – The case of the Island of Mljet. // International journal of hydrogen energy. 34 (2009) ; 7015-1-7026-11
8. Busuttil, Antoine; Krajačić, Goran; Duić, Neven. Energy scenarios for Malta. // International Journal of Hydrogen Energy. 33 (2008) , 16; 4235-4246
9. Duić, Neven; Krajačić, Goran; Carvalho, Maria Graça. RenewIslands methodology for sustainable energy and resource planning for islands. // Renewable and Sustainable Energy Reviews. 12 (2008) , 4; 1032-1062
10. Krajačić, Goran; Martins, Rui; Busuttil, Antoine; Duić, Neven; Carvalho, Maria Graça. Hydrogen as an energy vector in the islands' energy supply. // International Journal of Hydrogen Energy. 33 (2008) , 4; 1091-1103
11. Lund, Henrik; Duić, Neven; Krajačić, Goran; Carvalho, Maria Graça. Two energy system analysis models: A comparison of methodologies and results. // Energy. 32 (2007) , 6SI; 948-954
12. Krajačić, Goran; Duić, Neven; Vad Mathiesen, Brian; Carvalho, Maria Graça. Increasing RES Penetration and Security of Energy Supply by use of Energy Storages and Heat Pumps in Croatian Energy System // Energy Options Impact on Regional Security / Barbir, Frano ; Ulgiati, Sergio (ur.). Dordrecht : Springer, 2010. Str. 159-171.