Improvement of the energy planning process for the development of local and regional action plans

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SUMMARY

Climate change caused by human activities and their successful mitigation and adaptation to consequences is one of the crucial issues of humanity in the 21st century. One of the most common ways to tackle this issue is local and regional initiatives, which create energy plans for sustainable development. Sustainable energy planning at a local level is first time seen at some level, after the 1970s as a direct consequence of the energy crisis. A serious approach to sustainable local energy planning is noticed during the last 15 years, especially after European Commission started the Covenant of Mayor's initiative. The energy and climate goal of the European Union, till 2030 can be most easily achieved by planning sustainable development on a local level, due to a bottom-up approach, direct investments, and implementation. It is concluded that local governments have a crucial role in the mitigation of climate change. The most important steps in the development of local and regional energy plans are the analysis of the present situation considering energy consumption and GHG emissions, present and future energy and CO_2 balance and estimation of reduction potential; a strategy to reach targets, with targets' definition, measures, and implementation plan; and a regular plan for monitoring of the implementation and reaching the reduction goals. In this way, all phases in the process of local energy planning are included in the process.

The main objective of this doctoral thesis is to upgrade the methods for local and regional energy planning through an optimal selection of measures and alternative scenarios for the reduction of CO_2 emissions. The additional objective was to evaluate the possibility of mutual interaction and integration of measures through the development of predesigned sets of measures and to optimise the application of measures sets on local and regional levels considering economic, environmental, and social criteria. This thesis hypothesises is that with the use of optimisation models it is possible to find such sets of measures and alternative scenarios, which will with less financial means reach a minimal reduction of CO_2 emissions by 40% in local and regional energy systems. With aggregation of local and disaggregation of regional plans use of financial means and available financing mechanisms for the implementation of measures can be optimised.

The obtained results have shown that the optimisation of the measures can significantly influence the cost of mitigation measures needed for the fulfilment of the CO_2 emission targets. The optimisation of mitigation measures can result in financial savings of up to three times than baseline scenario. In this way, it could be possible to increase the overall implementation of

mitigation measures and avoid the problem of the lack of appropriate financial planning. Additionally, mutual interaction between measures, which influences the total result of energy consumption and CO_2 emissions reduction, can have either synergetic, negative, or neutral interaction between them. The analysis showed the negative interaction is prevailing and that the scenario approach resulted in lower CO_2 reduction potential than the individual assessment of each measure. It is recommended to use a scenario approach in the development of SECAP for the assessment of measures of CO_2 reduction potential. This will provide more efficient planning of measures for the reduction in CO_2 emissions on a local level and avoid overestimating the CO_2 reduction potential when developing SECAPs. Finally, the analysis of the application of multilevel governance demonstrated that the alignment of energy targets and coordinated actions from different levels of governance is leading to the effective implementation of mitigation measures.

KEY WORDS

Local energy planning, SECAP, measures for mitigation of CO_2 emissions, optimization, the interaction between measures, multi-level governance

SAŽETAK

Klimatske promjene uzrokovane ljudskim djelovanjem te njihovo uspješno ublažavanje i prilagodba jedno su od najvažnijih pitanja čovječanstva u 21. stoljeću. Jedan od najčešćih načina rješavanja ovog problema su lokalne i regionalne inicijative, koje stvaraju akcijske planove energetski održivog razvitka. Održivo energetsko planiranje na lokalnoj razini prvi put se pojavljuje u nekom obliku, nakon 1970-ih kao izravna posljedica energetske krize. Ozbiljan pristup održivom lokalnom energetskom planiranju primjetan je u posljednjih 15 godina, a posebice nakon što je Europska komisija pokrenula inicijativu Sporazum Gradonačelnika. Energetsko klimatske ciljeve Europske unije do 2030. godine najlakše je postići planiranjem održivog razvoja na lokalnoj razini, pristupom odozdo prema gore, izravnim ulaganjima i provedbom. Zaključeno je da lokalne samouprave imaju ključnu ulogu u ublažavanju klimatskih promjena. Najvažniji koraci u izradi lokalnih i regionalnih energetskih planova su analiza sadašnjeg stanja s obzirom na potrošnju energije i emisije stakleničkih plinova, sadašnja i buduća bilanca energije i CO_2 emisija te procjena potencijala njihovog smanjenja; strategiju za postizanje zadanih ciljeva, s definicijom ciljeva, mjerama i planom provedbe; te redoviti plan praćenja provedbe i postizanja smanjenja CO_2 emisija. Na ovaj način su u proces uključene sve faze u procesu lokalnog energetskog planiranja.

Glavni cilj ovog doktorskog rada je unaprijediti metode za lokalno i regionalno energetsko planiranje kroz optimalan odabir mjera i alternativnih scenarija za smanjenje emisija CO_2. Dodatni cilj bio je ispitati mogućnosti međusobne integracije i interakcije mjera kroz izradu predloženih skupova mjera te optimizirati primjenu skupova mjera na lokalnoj i regionalnoj razini s obzirom na ekonomske, društvene i okolišne kriterije. Hipoteza ovog rada je da se upotrebom optimizacijskih modela mogu pronaći takvi skupovi mjera i alternativnih scenarija koji će uz upotrebu manjih financijskih sredstava ostvariti minimalno smanjenje emisija CO_2 za 40% u lokalnim i regionalnom energetskim sustavima. Okrupnjavanjem lokalnih i rastavljanjem regionalnih planova optimizira se korištenje financijskih sredstava i raspoloživih financijskih mehanizama za provedbu mjera.

Dobiveni rezultati su pokazali da se optimizacijom mjera može značajno utjecati na troškove mjera ublažavanja potrebnih za ispunjenje ciljeva smanjenja emisija CO_2. Optimizacija mjera ublažavanja može rezultirati financijskim uštedama od tri puta u usporedbi s osnovnim scenarijem. Na taj način bi se mogla povećati ukupna provedba mjera ublažavanja klimatskih promjena i izbjeći problem nedostatka odgovarajućeg financijskih sredstava.

Dodatno, međusobna interakcija između mjera, koja utječe na ukupni rezultat potrošnje energije i smanjenja emisija CO_2, može imati bilo pozitivnu, negativnu ili neutralnu interakciju između njih. Analiza je pokazala da prevladava negativna interakcija i da je scenarijski pristup rezultirao manjim potencijalom smanjenja emisija CO_2 od procjene svake mjere pojedinačno. Preporuča se korištenje scenarijskog pristupa u izradi SECAP-a za procjenu potencijala mjera za smanjenje CO_2. Time će se omogućiti učinkovitije planiranje mjera za smanjenje emisija CO_2 na lokalnoj razini i izbjeći precjenjivanje potencijala smanjenja CO_2 prilikom izrade SECAP-ova. Konačno, analiza primjene višerazinskog upravljanja pokazala je da usklađivanje energetskih ciljeva i koordinirane akcije s različitih razina upravljanja dovode do učinkovite provedbe mjera ublažavanja.

KLJUČNE RIJEČI

Lokalno energetsko planiranje, SECAP, mjere za smanjenje emisija CO_2, optimizacija, interakcija između mjera, višerazinsko upravljanje

PROŠIRENI SAŽETAK

Održivo energetsko planiranje na lokalnoj razini pojavljuje se prvi put u nekom obliku 70-tih godina dvadesetog stoljeća kao izravna posljedica energetske krize te promjena izazvanih shvaćanjem konačnosti fosilnih goriva te antropološkog utjecaja na klimu i okoliš. Ozbiljniji pristup održivom lokalnom energetskom planiranju primjećuje se u posljednjih desetak godina, a naročito pokretanjem inicijative Sporazum gradonačelnika od strane Europske komisije. Ideja vodilja je bila da je cilj Europske unije 20-20-20 do 2020. godine najlakše ostvariv planiranjem održivog razvoja na lokalnoj razini, zbog pristupa odozdo prema gore, direktnih ulaganja i provedbe te je zaključeno da lokalne vlasti imaju ključnu ulogu u ublažavanju klimatskih promjena. Taj pristup je nastavljen s Europskim klimatsko energetskim ciljevima do 2030. godine te do postizanja klimatske neutralnosti što je cilj za 2050. godinu.

Održivi razvoj sastoji se od tri glavne dimenzije: ekonomije, društva i okoliša. Energetika je u interakciji sa sve tri dimenzije, o njoj ovisi ekonomija, a ima utjecaj na razvoj društva i okoliš. To se očituje kroz utjecaj na proizvodnu cijenu dobara, mobilnost, mogućnost povećanja ugodnosti stanovanja, ali i kvalitetu zraka, vode i tla. Unatoč sve većem broju lokalnih energetskih planova, ovo područje je još uvijek nedovoljno dokumentirano u znanstvenoj literaturi, iako je na lokalnoj razini moguće postići značajno smanjenje potrošnje energije i emisija stakleničkih plinova. Lokalne energetske politike koje su usmjerene na iskorištavanje potencijala obnovljivih izvora energije i energetske učinkovitosti mogu značajno pomoći i ojačati lokalne kapacitete proizvodnje energije. Iz tih razloga, potrebno je poticati lokalne i regionalne vlasti da održivom energetskom planiranju pristupaju uz podršku standardiziranih metoda koje su se pokazale efikasnima. Preporuke koje su dane uključuju razvoj standardizirane metode za praćenje emisija na lokalnoj razini, poput ISO 37120 standarda, razvoj indikatora za praćenje ostvarivanja ciljeva zadanih održivim energetskim planovima, potrebu za prikupljanjem mikroklimatskih podataka kao podršku lokalnom planiranju i uključivanje građana i ostalih dionika.

Osnovni koraci koji se provode u lokalnom i regionalnom energetskom planiranju su analiza trenutne situacije potrošnje energije i emisija stakleničkih plinova, izrada sadašnje i buduće energetske bilance te procjena mogućnosti smanjenja potrošnje energije i emisija CO_2, jasno definiranje budućih ciljeva s razvojem strategije za njihovo postizanje, mjere i izrada alternativnih scenarija za postizanje ciljeva i plan za praćenje provedbe zadanih mjera i ispunjavanje ciljeva. Na ovaj način obuhvaćene su sve faze u procesu lokalnog energetskog

planiranja. Procjena trenutne potrošnje energije i stanja emisija stakleničkih plinova može biti provedena pomoću globalnog protokola za emisije stakleničkih plinova, u kojem je razvijena metoda za praćenje emisija stakleničkih plinova u velikim gradovima, ili pomoću uputa Međuvladinog panela o klimatskih promjenama koje sadrže metodu za izračun emisija na razini država.

Kod izrade lokalnih i regionalnih energetskih planova uočen je problem nedostatka preciznih podataka o potrošnji energije na lokalnoj i regionalnoj razini te je zato potrebno razviti metode za procjenu potrošnje energije i emisija stakleničkih plinova. Od daljnji problema koji se javljaju kod lokalnog i regionalnog planiranja dodatno je istaknut problem uključivanja građana tj. NIMBY sindrom i zaseban razvoj prometnih planova koje je potrebno povezati s lokalnim energetskim planiranjem. Iz tog razloga, potrebno je razviti više inovativnih metoda i alata koji će podupirati lokalne i regionalne aktere u provedbi Akcijskih planova energetski održivog razvitka.

Glavni nedostatak koji je uočen kod izrade planova je nedovoljno planiranje odabira akcija i mjera kojima se želi postići zacrtane ciljeve smanjenja potrošnje energije i smanjenja emisija stakleničkih plinova. Odabir mjera također mora biti dio cjelokupne metodologije za lokalno energetsko planiranje. Pregledom dostupnih planova i metoda primijećeno je da ne postoji redoslijed provođenja mjera te da nisu analizirani međusobni utjecaji i međudjelovanje mjera po sektorima. Izrada alternativnih scenarija koji su preduvjet za ciljano smanjenje emisija CO_2 često je napravljena naprečac i nije vođena time da se uz najmanje troškove te najveći utjecaj na lokalnu ekonomiju ostvare zadani ciljevi. Analiziran je odabir mjera za smanjenje emisija CO_2 u općinama te mogućnost uključivanja obnovljivih izvora energije i jedan od osnovnih zaključaka je da je u malim općinama i gradovima, koji su uglavnom ruralni, moguća veća penetracija obnovljivih izvora energije u smanjenju emisija CO_2, dok se za velike gradove preporučuje korištenje mjera za povećanje energetske učinkovitosti.

Često se izradom alata i različitih scenarija pokušava aktivno uključiti lokalne dionike i donosioce odluka kako bi oni mogli sudjelovati u izboru alternativnih scenarija i tako odlučiti koji od njih je najbolji za njihovu lokalnu ili regionalnu jedinicu. To dovodi do izbora alternativnog scenarija i mjera za smanjenje CO_2 koje nisu uvijek optimalne sa strane ekonomskih, društvenih i ekoloških kriterija. Izbor mjera i akcija za smanjenje emisija CO_2 nije cjelovito obrađen jer ne postoji dovoljno podataka o njihovom međudjelovanju te postoji mogućnost da neke mjere imaju sinergijske učinke kada se provode zajedno, dok neke poništavaju dio dobrobiti drugih. To dovodi do prekomjernih trošenja financijskih sredstava te negativno utječe na ekonomiju jer se ne ostvaruju očekivani učinci. To je istraživano na primjeru uredskih zgrada u Kanadi, gdje se pokazalo da većina mjera, kada ih se provede zajedno, ima manji učinak na smanjenje potrošnje energije i emisija CO_2 od provođenja svake mjere pojedinačno.

Kako bi se mogla pratiti provedba energetskih planova, u razvoju metoda potrebno je posvetiti pažnju i razvoju indikatora kojima će se ocjenjivati uspješnost provođenja lokalnih i regionalnih održivih energetskih planova. Važnost indikatora se očituje u tome da oni omogućuju kvantificiranje napretka zajednice u provođenju svojih ciljeva, a s druge strane mora se osigurati primjenjivost indikatora na lokalnoj ili regionalnoj razini što podrazumijeva dostupnost određene količine podataka.

METODE I POSTUPCI

Istraživanje je započeto analizom akcijskih planova energetski održivog razvitka i klimatskih promjena koje su općine i gradovi razvili u sklopu inicijative Sporazum gradonačelnika. Posebna pažnja bila je posvećena metodama koje se koriste za izradu planova i to u području odabira mjera i scenarija za smanjenje potrošnje energije i emisija CO_2. Paralelno s time, detaljno je analizirana znanstvena i stručna literatura iz područja lokalnog i regionalnog energetskog planiranja. Dodatno su praćene aktivnosti koje provode ostala sveučilišta i znanstveni instituti te organizacije poput ICLEI-a (Lokalne vlasti za održivost), ELTIS-a (*engl. The urban mobility observatory*), JRC-a (Zajednički istraživački centar Europske komisije) i sl., koje su aktivne u ovom području. Praćenje je bilo radi pronalaženja dodatnih metoda za ocjenu međusobne interakcije između mjera za smanjenje potrošnje energije i emisija CO_2, budući da je do sada analiza međusobne interakcije mjera u akcijskim planovima izostala.

Istraživanje je bilo podijeljeno u tri dijela koja zajedno predstavljaju cjelinu. U prvoj fazi istraživanja provedena je analiza najfrekventnijih mjera i akcija za smanjenje potrošnje energije i smanjenje emisija stakleničkih plinova, posebno ugljičnog dioksida (CO_2), koje se koriste u akcijskim planovima energetski održivog razvitka i klimatskih promjena. Mjere za smanjenje potrošnje energije i emisija CO_2 grupiraju se najčešće prema sektorima potrošnje energije. Najčešći sektori potrošnje energije koji se navode u akcijskim planovima su zgradarstvo, promet, javna rasvjeta, industrija, vodovod i obrada otpadnih voda, i sl. Zgradarstvo je podijeljeno na pod sektore javnih zgrada, kućanstva tj. stambenih zgrada, i zgrada u komercijalnom i uslužnom sektoru. Sektor prometa se dijeli na vozila u vlasništvu lokalne i regionalne uprave, javni prijevoz i ostali cestovni promet. Tako su pronađene mjere koje se najčešće koriste po svakom sektoru te koji su njihovi očekivani učinci te troškovi povezani s njihovom implementacijom. Utvrđen je utjecaj relevantnih mjera na smanjenje potrošnje energije i emisija CO_2 te druge kriterije. Međusobna integracija između pojedinih mjera koje imaju utjecaj na ukupan rezultat smanjenja potrošnje energije i emisija CO_2 provedena je simulacijom gdje se na specifičnim slučajevima analizirala interakcija između istovremenog provođenja mjera i pojedinačnog provođenja mjera. Za simulaciju je korišten energetski računalni program LEAP (*engl. The Low Emissions Analysis Platform*). Na ovaj način se utvrdilo da li neke od mjera imaju sinergijski učinak, što bi značilo da zajedničkim provođenjem dolazi do povećanja smanjenja potrošnje energije i emisija CO_2, ili imaju međusobno negativan utjecaj jedna na drugu, što podrazumijeva smanjenje uštede energije i emisija CO_2 zajedničkim provođenjem. Treća opcija je da međudjelovanje između mjera ne postoji, tj. da one imaju neutralan utjecaj jedna na drugu.

U drugoj fazi istraživanja, s obzirom na rezultate međusobne interakcije mjera, izrađeni su skupovi mjera koji zadovoljavaju osnovne kriterije za smanjenje potrošnje energije i emisije CO_2. Skupovi mjera se sastoje od dvije ili više mjera za koje je utvrđeno analizom da ih je bolje provoditi zajedno. Osnovni kriteriji za smanjenje potrošnje energije i emisija CO_2 su minimalno smanjenje emisija za 40 % do 2030. godine u odnosu na stanje u referentnoj godini. Određeni su dodatni scenariji prema maksimalnom smanjenu emisija CO_2 te su izrađeni optimalni skupovi mjera za svaki pojedini scenarij. Rezultati su prikazani preko korištenja izmijenjene krivulje graničnih troškova za smanjenje emisija (*engl. Marginal Cost Abatement Curve*) koja je modificirana kako bi se mjere s negativnim troškovima pravilno rangirale.

U trećoj fazi istraživanja ispitano je na kojoj razini provedbe lokalni i regionalni planovi daju najbolje rezultate s obzirom na odabir optimalnih skupova mjera za pojedina raspoloživa financijska sredstva i mehanizme. Donesene su preporuke za lokalne i regionalne donosioce odluka na kojoj je razini bolje provoditi implementaciju skupova mjera. Zbog različite veličine jedinica lokalne i regionalne uprave, u nekim slučajevima je potrebno provedbu mjera spustiti na lokalnu razinu, a u ostalima se mjere moraju provoditi na regionalnoj razini kako bi se ostvarili željeni učinci s obzirom na raspoložive tehničke, ljudske i financijske kapacitete. Zbog toga je ispitana mogućnost provođenja energetskih planova kroz pristup vertikalnog višerazinskog upravljanja između različitih razina vlasti. Cilj ovog pristupa je postići ekonomiju razmjera i sinergijski učinak kod provođenja mjera za smanjenje potrošnje energije.

Zaključeno je da uspješnost provođenja mjere ovisi o potpori na svim razinama vlasti, lokalnoj, regionalnoj i nacionalnoj. Ako izostane potpora neke razine vlasti provođenje mjera je moguće, međutim je otežano.

CILJ I HIPOTEZA

Ciljevi ovoga istraživanja su:

- unaprijediti metode za lokalno i regionalno energetsko planiranje kroz optimalan odabir mjera i alternativnih scenarija za smanjenje emisija CO_2,
- ispitati mogućnosti međusobne integracije i interakcije mjera kroz izradu predloženih skupova mjera,
- optimizirati primjenu skupova mjera na lokalnoj i regionalnoj razini s obzirom na ekonomske, društvene i okolišne kriterije.

Hipoteza istraživanja je da se upotrebom optimizacijskih modela mogu pronaći takvi skupovi mjera i alternativnih scenarija koji će uz upotrebu manjih financijskih sredstava ostvariti minimalno smanjenje emisija CO_2 za 40 % u lokalnim i regionalnom energetskim sustavima. Okrupnjavanjem lokalnih i rastavljanjem regionalnih planova optimizira se korištenje financijskih sredstava i raspoloživih financijskih mehanizama za provedbu mjera.

ZNANSTVENI DOPRINOS

Znanstveni doprinos se očituje u:

- Unaprjeđenju metode optimalnog izbora mjera u energetskom planiranju na lokalnoj i regionalnoj razini pomoću modificirane krivulje graničnih troškova s obzirom na ekonomske kriterije.
- Povećanju točnosti postojećeg način prikaza odabira mjera za smanjenje emisija i alternativnih scenarija na lokalnoj i regionalnoj razini za dionike i donosioce odluka s obzirom na zadane kriterije ocjenjivanja.

KLJUČNE RIJEČI

Lokalno energetsko planiranje, SECAP, mjere za smanjenje emisija CO_2, optimizacija, interakcija između mjera, višerazinsko upravljanje

ABBREVIATIONS

CO_2	Carbon Dioxide
CoM	Covenant of Mayors
DH	District heating
DHS	District Heating System
DHW	Domestic Hot Water
e5	Programme for Energy-Efficient Towns and Municipalities
EEA	European Energy Award
EU	European Union
EV	Electric Vehicles
GAMS	General Algebraic Modeling System
GB	Gigabyte
GHG	Greenhouse Gas
GIS	Geographic Information System
ICLEI	Local Governments for Sustainability
IPCC	Intergovernmental Panel for Climate Change
IRR	Internal Rate of Return
ISO	International Organization for Standardization
JRC	Joint Research Centre
KEM	Climate and Energy Model
LEAP	The Low Emissions Analysis Platform
LED	Light-Emitting Diode
MLG	Multilevel Governance
NGO	Non-governmental Organisation
NLP	Non-Linear Problem
NZEB	Nearly Zero Energy Building
PV	Photovoltaic
R&D	Research and Development
RAM	Random Access Memory
RES	Renewable Energy Sources
SDEWES	Sustainable Development of Energy, Water and Environment Systems
SEAP	Sustainable Energy Action Plan
SECAP	Sustainable Energy and Climate Action Plan

SET-Plan	Strategic Energy Technology Plan
TJ	Terajoule

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1. INTRODUCTION

This section provides an introduction to the topic of the thesis by presenting the research background and giving more detail on the research motivation for the work. During this process, the details about local energy plans and multi-level governance are presented together with the focus of the research which is the selection of the mitigation measures. Furthermore, the objectives of the research are presented with the hypothesis which is followed by a short introduction of the methods used to reach research results.

1.1. Research background

A sustainable energy transition requires a transformation in both the energy sector and society. This requires actions to be transposed into energy and climate policies developed in the coordination of multiple levels of government. However, the realisation of the energy and climate goals cannot be achieved only through top-down activities from a national government. Still, it should be equally supported with a bottom-up approach [1] and include the active participation of all governments level [2]. Sustainable energy planning at a local level is an important part of the European Union's (EU) climate-neutral strategy for 2050 and the “Fit for 55” plan by 2030 [3]. A serious approach to sustainable local energy planning has been initiated during the last 15 years, especially after the European Commission started the Covenant of Mayors initiative. The energy and climate goal of the European Union, “Fit for 55” by 2030, can be most easily achieved by planning sustainable development on a local level, due to a bottom-up approach, direct investments, and implementation. It is concluded that local governments have a crucial role in the mitigation of climate change [4]. The importance of the local initiatives in the energy transition toward carbon-neutral societies can also be seen from a large number of signatories of the Covenant of Mayor’s initiative, which is more than 11,000 [5], and the fact that it includes more than half of the EU population [6].

Therefore, it is important to point out that the goals of the Covenant of Mayor's initiative are in line with the EU climate-neutral strategy for 2050 and that the signatories of the initiative commit to fulfilling several goals, among others to keep the global temperature rise below 1.5 °C. Furthermore, they commit to leading the transition to climate-neutral Europe and to do it in and fair, inclusive, and respectful way for their citizens. Their goal is to achieve decarbonised and resilient cities with affordable, sustainable, and secure energy by 2050 latest (Figure 1). Additionally, the signatories have four important steps to take. The first is to commit to achieving climate neutrality by 2050, the second is to engage local stakeholders, the third is to act to accelerate transition through the development of mitigation and adaptation plans and finally to network with other mayors and local leaders. These are detailly elaborated in the Sustainable Energy and Climate Action Plan (SECAP) which is a core document to achieve climate neutrality on the local level which will be explained in detail in the following sections.

Figure 1 The infographic with Covenant of Mayor's goals for local authorities [5]

Despite the growing number of SECAPs, this area has not been adequately documented in the scientific literature [7], even though local authorities can have a significant influence on the reduction of energy consumption and greenhouse gas (GHG) emissions [8]. A local energy policy that is focused on utilising the strong potential of renewable energy and energy efficiency can strengthen local capacities for energy production [9]. For those reasons, it is necessary to encourage local and regional governments to use efficient standardised methods when developing sustainable local energy plans [10]. Recommendations for further research in this area are given in [11] and they include the development of standardised methodologies for tracking emissions on a local level such as ISO 37120 standards, the introduction of different indicators for tracking the goals of sustainable energy plans, a collection of microclimate data as a support for local planning and involving citizens and stakeholders.

A lot of work regarding local energy planning is focused on how the cities and municipalities are responding to climate change and what are their main drivers. It is shown that national legislation in the EU has a strong impact as well as the Covenant of Mayors under which most of the local plans are developed [12]. Performance and implementation of local plans developed under the Covenant of Mayors are investigated, considering climate neutrality and positioning in line with the Paris Agreement. Salvia et al. [13] show that European cities with a reduction target of 47% are not on track to reach the Paris Agreement. Moreover, the developed plans, which have lower targets, also show problems with the execution due to the lack of the necessary financial and human resources assigned to the initiative [14]. Therefore, the Covenant of Mayors introduced new targets to increase the number of cities which are on track regarding the goals of the Paris Agreement [5].

On the other hand, more than 600 plans from the Covenant of Mayors are on track to reach their goals, and their characteristics are less ambitious targets, higher baseline emissions and more ambitious national targets [15]. Moreover, according to the monitoring reports from the Covenant of Mayors, the cities are on the right track to reducing emissions to nearly zero by 2050 [16]. This provides evidence that the initiative has medium success in implementation which could be further improved by integration between actions that cover multiple sectors as well as introducing the integrated urban vision for the start of the effective urban planning approach [17].

1.1.1. Sustainable energy and climate action plan (SECAP)

The current approach to the development of the local and regional energy plans consists of these main steps according to [18], which are the analysis of the present situation considering energy consumption and GHG emissions; present and future energy and CO_2 balance and estimation of reduction potential; a strategy to reach targets, with targets' definition, measures, and implementation plan; and a regular plan for monitoring the implementation and reaching the reduction goals. In this way, all phases in the process of local energy planning are included in the process. The general process of how the planning works is explained in [19], where steps are effectively shown as a circular activity with four main parts, namely strategic, tactical, operational, and reflective, while [20] provides an innovative tool for the development of SECAPs following the main guidelines of the Covenant of Mayors (CoM) which are presented in Figure 2. Those guidelines consist of three major steps which first is the signature of the adhesion form for joining the Covenant of Mayors for Climate and Energy initiative. This is followed by the so-called definition of the local territories' ambitions where the initial baseline emission inventory is developed together with the risk and vulnerability assessment regarding climate change. Furthermore, the final act of this step is the development of the Sustainable Energy and Climate Action Plan with mitigation and adaptation measures whose submission is the second step of the process.

The most important part of the process is the implementation of the developed action plan and measures which is important to create a monitoring process. This part is two to four years submitted to the CoM as a monitoring report which consists of the monitoring emission report and is the third step of the process. The process is then repeated with the readjusted priorities and measures to fulfil targets in a given time.

Figure 2 The general process of the development of SECAPs [21]

The methodologies for the analysis of the present situation when developing baseline emission inventory or monitoring inventory reports considering energy consumption and GHG emissions are constantly updated and one of the common approaches show how to calculate energy consumption and emissions is tested in Italy [22], while methodology for scaling data from the national level to the local one is given in [23]. The methodology considers the local area characteristics and carefully selects the appropriate energy usage indicators and explores the socio-economic profile of an area to appropriately adjust national-level energy data. The option to extend the accounted emissions and provide more potential for mitigation measures is provided and tested in Lombardy, showing that this approach can bring about an additional reduction of CO_2 emissions [24].

When it comes to the measures and their implementation, they are divided into sectors, of which the most common in energy plans are residential buildings, public lighting, local electricity production, transport, and tertiary buildings, including public ones [25]. The effects of different measures are also investigated by sectors in [26], showing that the greatest number of actions is related to municipal buildings, public lighting, and local electricity production which shows as well as in [23] that the transport sector is often neglected and too much focus is given to buildings. In addition, new approaches, other than just CO_2 emissions, can be used for tracking the implementation and reporting on climate change mitigation and sustainability, such as SDEWES Index which tracks 7 dimensions with 35 indicators [27]. Those dimensions include tracking of CO_2 emissions (fifth dimension) but also energy consumption and climate, CO_2 and energy saving measures, penetration and utilisation of RES, water and environment quality, industrial profile, urban planning and social welfare and lastly R&D, innovation and sustainability policies [28]. Since the index introduction in 2015 where it was used for example on 22 cities [28] in 2016 it was additionally tested on additional 12 cities [29], a then its use was tested on different examples all over the globe [27,30–33]. Finally, in 2019 it was tested on the example of 120 cities showing its usability and importance for benchmarking sustainability [34] [35]. However, since the calculation of the SDEWES index requires a large amount of data which is most difficult to acquire or even not possible, its usability in the case of the smaller or less developed cities is difficult or not convenient [27].

1.1.2. Multilevel governance approach

To successfully implement mitigation measures developed in SECAPs the cooperation and alignment between energy policies of different governmental levels need to be secured.

Therefore, multilevel governance (MLG) has, in recent years, arisen as a strategic element in reconstructing existing energy governance. It is argued that the success of climate and energy governance is indispensable to the mobilisation of all the governance levels, including the sub-national level [36]. There is an urgent need to systematically break down the national goals to the local level to meet GHG emission targets.

A general MLG structure representing vertical and horizontal interactions is given in Figure 3. The MLG concept describes a division of power in a non-hierarchical way between actors across the horizontal and vertical distribution of responsibilities. The MLG theory within the EU is manifested through different ways of communication and coordination for the decision-making process and implementation or evaluation of EU policies between governing authorities at all levels: the European, national, regional, and local layers. Interaction between layers is realised in two ways: through vertical and horizontal dimensions as shown in Figure 3. The vertical dimension refers to the interactions between different levels of government, while the horizontal relates to interactions with other relevant actors within the same level. In this way, EU decisions are placed as close as possible to the final consumers – citizens [37]. However, state management is not restricted only to the government actors but provides flexibility with the inclusion of non-state players such as various interest groups, organisations, and civil society [38]. The vital approach for the implementation of MLG reinforcement is the employment of the EU policies by the European Commission oriented to encourage actions at a local level. The MLG approach of the EU to climate and energy governance is via local-level initiatives contributing to strengthening dynamics in pioneering countries as well as to filling gaps in countries with weaknesses at the national level [36].

The CoM initiative is a widespread innovative model of MLG, thus an effective tool for fostering the activities on local and harmonisation of goals on various administrative levels [39]. In [40] Melica et al. discussed the horizontal cooperation between the municipalities in the framework of CoM. They have concluded that such collaboration is especially beneficial for the small and medium-sized municipalities which would otherwise most likely experience a lack of human and financial capacity, thus failing to adopt policies and develop their action plans. The CoM represents an explicit tool of MLG with the objectives set at the EU level and performed at the local level. In support of the initiative, recent studies showed that effective implementation of energy efficiency policies could hardly be carried out through traditional top-down approaches, but stronger cooperation between multiple levels of government is required [41].

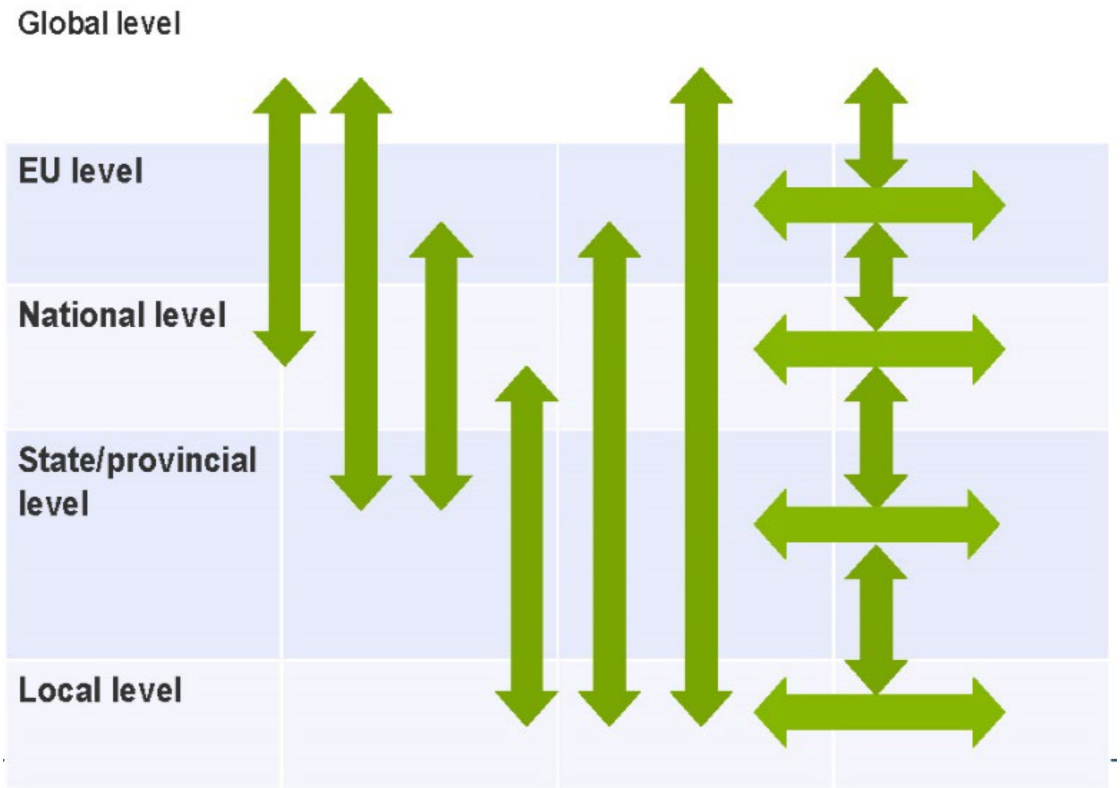

Figure 3 MLG approach structure: vertical and horizontal interactions (ARTICLE 3** [42])***

An assessment of 16 German municipalities and their local climate action plans showed their contribution to the national energy transition. Nevertheless, the advancement of MLG coordination is required to overcome existing shortcomings within the local administration, electricity grids or higher penetration of renewables in the heat and mobility sector. The development of local energy action plans is strongly supported by local initiatives such as the already mentioned CoM initiative. Local energy and climate initiatives have a critical role in supporting municipalities in the achievement of energy and climate change mitigation targets [43]. This is due to many reasons such as their responsibility for planning issues and use of resources, and policy development, especially in the domain of buildings and transport. Also, they are energy consumers and represent the closest administrative level to the citizens. Nonetheless, the evaluation of the contribution of local policies to climate change is not adequately controlled by local authorities as the local energy system is a part of a much larger national and international system. This requires in the first-place adequate evaluation of the policies but also coherent actions at all levels of governance.

The importance of the local level is evident from the pioneering countries Germany and Denmark being leaders in climate policy. Local-level actors have a significant and long-term impact on Danish renewable energy development, which is often described as a combination of bottom-up and top-down actions [44,45]. The review of 11 municipalities in Denmark, on the one hand, showed active local engagement in energy planning while on the other it stressed the need for strategic energy planning and defined institutional framework providing support to municipal planning from the national level [44].

The contribution of the local level climate policies to the long-term global response to climate change to protect people, livelihoods and ecosystems has been pointed out in the 2015 Paris Agreement [46]. Cities have Nevertheless, overall success depends on the harmonisation of local and national interests [47]. Assessment of the opportunities and barriers of multilevel decision-making and compatibility of EU and national climate policies with local policies for the case study of Helsinki proved that the lower levels of governance have the leading role in implementing the EU directives and national policy [48]. Moreover, cities as frontiers in implementing initiatives which show the feasibility of energy measures can serve as role models for their implementation at the national and the subnational level.

1.2. Research Motivation

During the process of the energy transition on the local level through Sustainable Energy and Climate Action Plans one of the deficiencies noticed during the literature analysis is insufficient planning of selection of measures and actions, which are set to reach goals in the reduction of energy usage and GHG emissions, since these need to be a part of the overall methodology for local energy planning. Currently, the process is mostly implemented by drafting a small group, consisting of a few of the most relevant municipal employees, which includes interested stakeholders, to reach a common decision on which measures should be implemented [49]. Furthermore, this small group can be further expanded by local citizens and the public who can participate through surveys.

Targeted reduction of CO_2 emissions is often conducted ad hoc and does not follow the rule to have the lowest costs and reach the maximal influence of the local economy while trying to reach the given reduction goals, which is particularly important when considering that most of the cities do not have sufficient budget for planned SECAP projects [50]. Furthermore, it is considered that future improvements in financial and technical support to cities could improve the implementation of several mitigation actions [51]. The selection of measures for the reduction of CO_2 emissions and implementation of renewables in municipalities is analysed in [52]. One of the basic conclusions reached is that in small cities and municipalities, which are mostly rural, there is a possibility to have a higher penetration of renewable energy sources in the reduction of CO_2 emissions [53], while in big cities, energy efficiency measures have priority. With the development of different tools and scenarios, local authorities are often trying to actively include local stakeholders and decision-makers so that they could be involved in the selection of alternative scenarios and select the most appropriate one for their own local or regional community [54]. Some authors argue that diverse stakeholders need to be involved to ensure that the process is participative, inclusive, holistic, simple, and transparent, to be successful [55].

This brings us to the choice of alternative measures and scenarios, which are not always optimal for common economic and environmental criteria, although some methods could help stakeholders find the optimal solution by giving them the possibility to evaluate different scenarios [56]. Therefore, different authors presented different options or criteria for selecting measures, but not in an optimal way considering common economic and environmental criteria. Authors in [57] developed a model which proposes measures are compared through several indicators that present the effectiveness of measures on environmental, financial, climate and socio-economic criteria while energy efficiency measures are compared through the internal rate of return (IRR) curve to provide different capital providers understandable information for the selection of suitable energy efficiency measures for investments [58]. In order to overcome these shortcomings, the method for the optimal choice of measures in energy planning on the local and regional level through a modified cost abatement curve considering economic criteria is developed through this research.

1.3. Objective and hypotheses of the research

The objective of this research is to:

- Upgrade the methods for local and regional energy planning through optimal selection of measures and alternative scenarios for the reduction of CO_2 emissions.
- To evaluate the possibility of mutual interaction and integration of measures through the development of predesigned sets of measures.
- Optimise the application of measures sets on local and regional levels considering economic, environmental, and social criteria.

This thesis hypothesises that with the use of optimisation models it is possible to find such sets of measures and alternative scenarios, which will with less financial means reach a minimal reduction of CO_2 emissions by 40% in local and regional energy systems. With aggregation of local and disaggregation of regional plans use of financial means and available financing mechanisms for the implementation of measures can be optimised.

1.4. Scientific contribution

The scientific contribution of this research is in the upgrading of a method for the optimal choice of measures in energy planning on the local and regional level through a modified cost abatement curve considering economic criteria. Furthermore, the contribution is in the increase of accuracy of the current way for the visualisation of choice of measures for emission reduction and alternative scenarios on the local and regional level for stakeholders and decision makers considering given evaluation criteria.

1.5. Applied methods

The overall research method followed the general method for the development of the SECAPs as recommended by the Joint Research Centre of EU (JRC) in the guidelines for the Covenant of Mayors [59]. The process was shortly explained in the introduction chapter and part of it focused on the development of the action plan can be seen in Figure 4. The process can be divided into the following steps:

- Collection of the energy consumption and emission data (explained in ARTICLES 1 and 2)
- Choice of energy planning software (explained in ARTICLES 2, 3, and 4)
- Development of future energy scenarios (explained in ARTICLES 2, 3, and 4)
- Selection of mitigation measures (explained in ARTICLE 4)

The data on energy consumption and greenhouse gas emissions should be compiled by sector and energy source. The critical areas for which the energy consumption should be calculated are residential and commercial, transportation and the public sector which might include public buildings, street lighting and public transport fleets. It is a good practice to collect data on energy consumption for at least 1 year and find energy consumption patterns for different sectors and distinct types of consumers. In the cases where energy consumption data are not available on the local level, a method presented in ARTICLE 1 [60] was developed for the estimation of the energy consumption. Shortly, the energy consumption of different sectors is estimated for all fuels by using many statistical parameters and adjusting the consumption from the higher administrative level. The current energy demand figures are used for modelling future energy demand, which is the first step toward understanding the critical parameters of future energy systems.

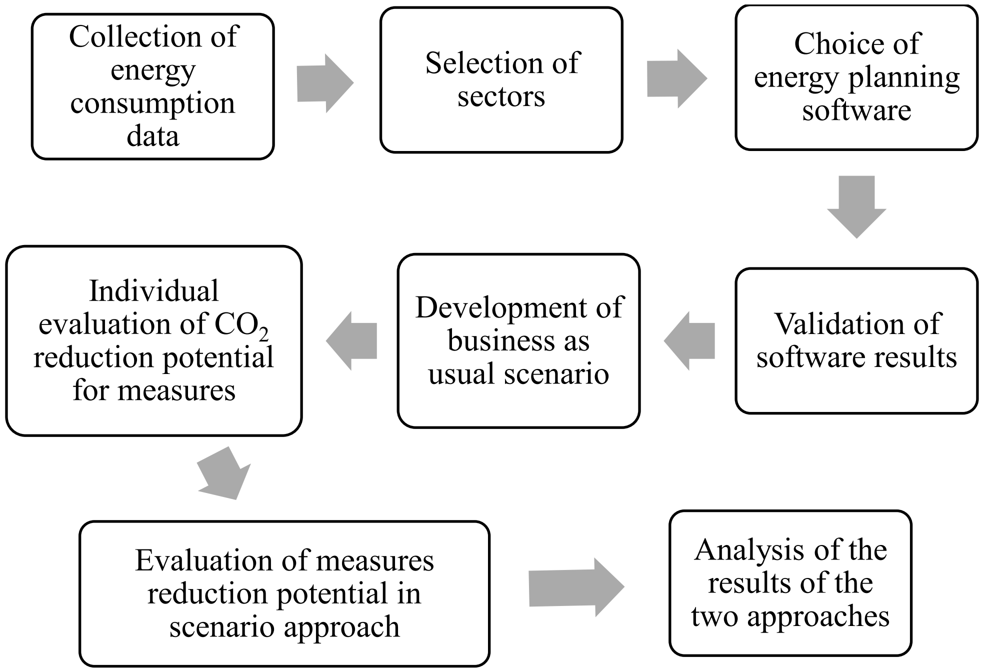

Figure 4 Flowchart of the methodology for comparison of measures used in ARTICLE 2 [61]

The current emissions of CO_2 are estimated in compliance with Intergovernmental panel for climate change (IPCC) instructions and recommended emission factors. A tool used for CO_2 emissions calculation was Local Governments for Sustainability (ICLEI) Europe's basic greenhouse gas inventory quantification tool.

The next step was the selection of the energy planning software where the Long-range Energy Alternatives (LEAP) was used. This is an energy planning software based on the accounting framework, which is a user-friendly, scenario-based and integrated energy-environment model-building tool [62]. The tool calculates energy demand and supply, the use of resources, environmental loads, and non-energy sector emissions, and makes the cost-benefit analysis. This tool can be used for medium to long-term energy planning, with annual time-step, and the simulation can be done for an unlimited number of years [63]. The data requirements for the tool are flexible, depending on their availability. In the beginning, the simulation can be done with a limited amount of new data. The model applies to almost every level of energy planning so that it can be used on the local, national or regional scale [63]. The tool can be used for strategic integrated energy-environment scenario studies, energy system forecasting, integrated resource planning, greenhouse gas mitigation analysis, energy balances and environmental inventories [64].

The energy demand is modelled via hierarchical accounting of energy, choice of methodologies and optional modelling of stock turnover.

Development of the future energy scenarios is based on the statistical data and the reference scenarios for the future energy demand developed on the higher administrative level. More details are available in the published articles. The MLG approach was analysed through desk research on the MLG governance structure to give a theoretical background from the EU perspective and the implementation of EU energy directives. Desk research is enhanced with a series of interviews for an energy policy analysis and a case study analysis for two representative sets of measures, which are top-down and bottom-up initiated. The interviews were provided by a national-level energy expert. The topics and questions of the interview were focused on the planned measures for the improvement of the local energy and climate policies. These interviews were also used to check and validate the results obtained by the desk research on the local initiatives and their success and role in the implementation of energy and climate policies.

Finally, the selection of measures was done based on the previous sustainable energy and climate action plans that are developed by cities and municipalities within the Covenant of Mayors' initiative. The focus of the analysis was to provide enough data on the cost-effectiveness of the measures to construct the basis for the optimisation analysis of potential measures. Based on the collected data on measures, the regression functions were created in Microsoft Excel tools. The regression functions can be updated through the changing of the coefficients when the new data are added from additional SECAPs. The functions were used for the generation of the equations which connect the cost of the measure with total CO_2 emission reduction potential. The functions were later used in the optimisation part of the research together with restrictions of the case study example to provide an optimal cost solution. The objective of the proposed optimisation problem is to minimise the objective function.

The modelled optimisation problem in article 4 represents a non-linear problem (NLP) as exponential functions and multiplication of variables occur in the modelled equations. The problem was solved in the GAMS tool with an NLP solver on a 16 GB RAM machine. In the final part of the method, visualisation of the results is achieved via the total cost abatement curve which, on the diagrams for the different total levels of CO_2 reduction, ranks measures based on their cost and abatement level from the most cost-effective to the least cost-effective.

2. SELECTED RESULTS AND DISCUSSION

This thesis presents the upgrade of methods for local and regional energy planning through the optimisation of choice of measures and alternative scenarios for the reduction of CO_2 emissions. It also questions the possibility of interaction and integration of measures through the development of scenarios containing measures and optimises their use on a local and regional level through a multi-level governance approach. During this process, economic, social, and environmental criteria as well as national and European energy policies are considered and evaluated. The development of the method and investigation is divided into four phases which are covered by published articles. Since the presented results are interconnected between published articles, they together form a unity, and their joint contribution surpasses their impact. The results and discussion section are organised according to these phases and is following the given structure:

1) Analysis of the most used mitigation measures and actions in SECAPs (covered in ARTICLE 1, 2 and 4)
2) Analysis of the interaction between mitigation measures (covered in ARTICLE 2)
3) Sets of measures and scenarios for reaching different levels of CO_2 emission reduction with measures optimisation and ranking on the total cost abatement curve for implementation (covered in ARTICLE 4)
4) Multilevel governance and implementation of mitigation measures on the local or regional level with the alignment to the national and European policy (covered in ARTICLE 1 and 3)

ARTICLE 1 also introduces a model for the development of the baseline emissions inventory if the local level data on energy consumption and CO_2 are not fully available. ARTICLE 1 also explains the difference between the individual and joint approaches to the CoM initiative, while ARTICLE 2 explained the structure of energy consumption analysis and division of measures per sector on the local level and validated the LEAP model as a tool for the development of SECAPs.

ARTICLE 3 additionally identified four main areas for improvement through the multilevel governance approach and proposed novel integrated MLG.

ARTICLE 4 also provides a model for the non-linear optimisation of the mitigation measures in SECAPs and provided results of the threshold for the CO_2 emission reduction without sector integration on the local level.

2.1. Most used mitigation measures and actions in SECAPs

In order to do the analysis and optimisation of the mitigation measures the analysis of the most used mitigation measures is performed. Before analysis of measures, the structure of the SECAPs regarding energy consumption and mitigation measures needs to be explained. The baseline emissions inventory and the mitigation measures are usually arranged per energy consumption sectors which are explained and shown in Figure 5 (ARTICLE 2).

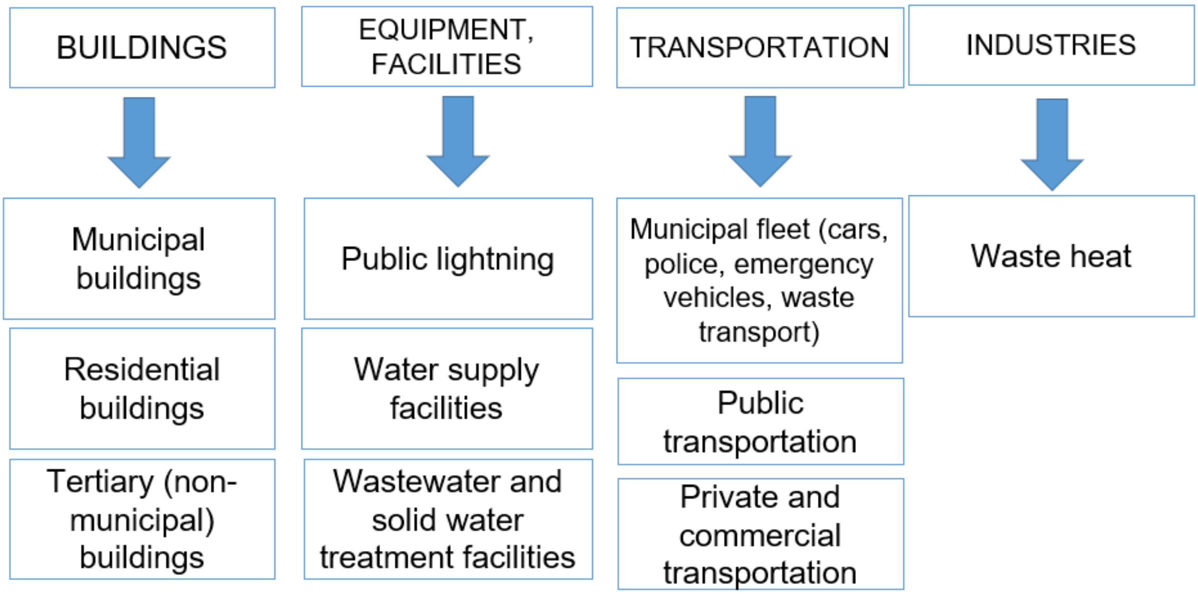

Figure 5 Different sectors for the implementation of measures for CO_2 reductions (ARTICLE 2 [61]*)*

Measures for the reduction in energy consumption and CO_2 emissions are most often grouped by sectors of energy consumption [21]. Areas of energy consumption listed in sustainable energy action plans are buildings, transport, public lighting, industry, water, and wastewater management. This study focused on the sectors which are included in most of the SECAPs which are buildings, transport, and public lighting. The buildings sector is subdivided into public buildings, households, and commercial buildings. The transport sector is divided into public transport, vehicles owned by the local and regional government, and private and commercial transportation.

The data on energy consumption and greenhouse gas emissions should be compiled by sector and energy source. The critical areas for which the energy consumption should be calculated are residential and commercial, industry, transportation and the public sector which might include public buildings, street lighting, public transport fleets, waste, and wastewater management systems. It is a good practice to collect data on energy consumption for at least 1 year and find energy consumption patterns for different sectors and distinct types of consumers. On the production side, it is recommended to collect data on the local electricity, heat and cold production, energy prices and energy import data with individual supply patterns [64].

Based on the energy consumption and CO_2 emission in different sectors in ARTICLE 1, whose case study is the Island of Korcula, 34 mitigation measures were selected for the reduction of CO_2, and they are listed in Table 1. In the public sector, there were selected 11 measures and their contribution to reductions of CO_2 from the baseline year was 31.36%. Modernization of public lighting will be contributing most to the reduction of CO_2 emissions because of the necessary reconstruction of lightning in the City of Korcula. In the household sector, nine measures were selected. They will reduce emissions by 25.37% in this sector compared to the baseline year. This reduction will be mostly contributed by the replacement of inefficient indoor lighting and replacement of household devices with more efficient ones. In the commercial sector, measures will bring a reduction in emissions by 1032 tCO_2. This reduction is mostly related to the reduction of electricity consumption and the local production of electricity from PV systems. Measures for the road transport sector will reduce emissions by around 22.92%. This is mostly achieved by the introduction of biofuels and eco-driving education.

Table 1 List of potential measures (ARTICLE 1 [60]***)***

For the public sector	**For the residential sector**
Replacement of existing lights with more efficient ones	Replacement of existing lights with more efficient ones
Introduction of solar collectors for hot water and heating	Replacement of appliances with more efficient ones
Replacement of fuel oil boilers with biomass/heat pumps	Co-financing of replacement of el. boilers with heat pumps
Insulation of the building's external envelope and roofs	Insulation of the building's external envelope and roofs
Replacement of external woodwork in public buildings	Replacement of external woodwork in households

Education of public employees	Co-financing of solar collectors for citizens
Introduction of small PV systems on roofs	Education of citizens and organization of energy days
Implementation of green public procurement	Introduction of small PV systems on the roofs
New vehicles according to green public procurement	Organization of energy cooperatives for citizens
Biofuel in public transport	
Modernization of public lightning	
For the commercial sector	**For the transport sector**
Replacement of existing lights with more efficient ones	Promotion of the car sharing model on the island
Organizing apartment renters into energy cooperative	Construction of bike paths and promotion of bicycles
Construction of large PV plants on the island	Promoting the purchase of electric vehicles
Insulation of the building's external envelope and roofs	Introduction of 10% biofuels in the transport
Replacement of external woodwork in buildings	Promotion of public transportation
Introduction of small PV systems on the roofs	Promotion of electric bicycles with solar chargers
Installation of reactive power compensators	Eco-driving education of drivers

Additional analysis of the most used measure was done in ARTICLE 2, which dealt with the case study of the City of Zagreb. The energy demand, in this case, was divided into three major sectors: buildings, transportation, and public lighting as shown in Figure 3. Buildings were further subdivided into public buildings which are owned by the local authorities, and residential and commercial buildings. Transport was divided into public transport, public vehicles owned by local authorities and private and commercial vehicles.

The selection of basic measures was done by modelling the future energy demand by all sectors and fuel consumption with penetration of new energy types and shift between existing ones based on the EU reference scenario for Croatia [38]. For the measures in public buildings, data from a national strategy for the renovation of public buildings [39] were used.

The other building's measures were modelled according to the presumptions used in the development of the Low Carbon Development Strategy of the Republic of Croatia [40] and the technical standard for buildings [41].

The additional measures were selected based on the several discussions which were held between the city of Zagreb representatives and other interested stakeholders. The basis for the measure's selection was SEAP of the City of Zagreb developed in 2010 [65]. Measures which were proven to be effective, in the period by 2015 [66], were selected and suggested to the stakeholder who then provided their suggestions and comments on the proposed outlook. Stakeholders included in the selection of measures were representatives of the energy supply companies, energy agencies, academia, and the NGO sector. Finally, the draft version of the document was put on public consultation.

The additional measures which were added to the different sectors are given below:

- Buildings:
    - NZEB - Energy renovation of existing building stock to nearly zero energy building (NZEB) level defined in [67] in all sectors by 4% yearly
    - 20% RES - Installation of 20% of renewable energy sources (RES) to cover energy consumption in NZEB renovated buildings
    - Quick measures - Small and low-cost energy efficiency and RES measures in buildings (Up to 2 kW PV, up to 4 m^2 of solar thermal for domestic hot water (DHW), thermoregulation valves, light-emitting diode (LED) lights, smart meters)
    - DHS efficiency - Increase in the district heating system (DHS) efficiency by replacement of old distribution pipes and the introduction of new efficient production units
    - DHS geothermal - Introduction of geothermal energy in the DHS
    - Heating modal shift – Introduction of zoning for DHS and natural gas network and change of 5% of consumers from natural gas to DHS by 2030
- Transport:
    - Transport modal shift - Integrated public transportation system with real-time information system and one unique ticket for all public transportation which will result in a modal change to the biking, walking and public transportation

- Tram efficiency - Increase energy efficiency in the electric tram public transport system
  - Electric vehicles (EVs) - Electrification of 10% of personal vehicles by 2030
  - Eco-driving – Eco-driving education in the public transportation sector and optimisation of city delivery routes for the trucks with the introduction of restrictive parking policy and penalisation of driving through the city centre
- Public lighting:
  - LED lighting – Replacement of all existing fixtures in the public lighting system with LED lights

Finally, in ARTICLE 4 [68] analysis of the measures in the existing SECAPs was performed. SECAPs for the cities and municipalities which were analysed are listed in Table 2. The analysed SECAPs range from small municipalities with a few thousand citizens, through Mediterranean islands and cities to large cities with 800,000 inhabitants, thus providing a good representation of different cases. The analysed SECAPs together with measures from ARTICLE 1 and ARTICLE 2 provided a baseline that was used for the selection of the most common measures for the reduction of CO_2 emissions which are grouped by sectors according to Figure 3 and divided into individual measures and set of measures.

Table 2 List of measures, coefficients and SECAPs which were used as the data source

Name of the Measure	**x Corresponding to the Measure**	**Coefficients for Calculation of the Measure**	**SECAPs Used as Data Sources** [5]
Integrated renovation of public buildings	x_1	k_{11} and k_{12}	City of Rijeka, City of Zadar, City of Osijek, City of Koprivnica, City of Varazdin, City of Cakovec
Energy renovation of public buildings	x_2	k_{21} and k_{22}	City of Novigrad, City of Porec, City of Pula, City of Rovinj, Municipality of Brtonigla, City of Buje, City of Labin, City of Pazin, Island of Brac
PV on public buildings	x_3	k_{31} and k_{32}	The city of Rijeka, City of Zadar, City of Osijek, City of Varazdin, City of

			Novigrad, City of Porec, City of Pula, City of Rovinj, Municipality of Brtonigla, City of Buje, City of Labin, City of Pazin, Island of Brac
Solar thermal on public buildings	x_4	k_{41} and k_{42}	City of Zadar, City of Osijek, City of Cakovec, City of Novigrad, City of Porec, City of Pula, City of Rovinj, Municipality of Brtonigla, City of Labin, City of Pazin
Electrification of public transport	x_5	k_{51} and k_{52}	City of Rijeka, City of Zadar, City of Osijek, City of Koprivnica, City of Varazdin
Integrated renovation of multi-apartment buildings	x_6	k_{61}, k_{62} and k_{63}	City of Rijeka, City of Zadar, City of Koprivnica, City of Varazdin
Integrated energy renovation of residential buildings	x_7	k_{71} and k_{72}	City of Rijeka, City of Zadar, City of Osijek, City of Koprivnica, City of Varazdin
Energy renovation of residential buildings	x_8	k_{81} and k_{82}	City of Osijek, City of Varazdin, City of Cakovec, City of Prelog
PV on residential buildings	x_9	k_{91} and k_{92}	The city of Rijeka, City of Zadar, City of Osijek, City of Varazdin, City of Cakovec, City of Novigrad, City of Porec, City of Pula, City of Rovinj, Municipality of Brtonigla, City of Buje, City of Labin, the City of Pazin, Island of Brac, City of Prelog
Energy renovation of commercial buildings	x_{10}	k_{101} and k_{102}	City of Rijeka, City of Zadar, City of Osijek, City of Koprivnica, City of Varazdin

PV on commercial buildings	x_{11}	k_{111} and k_{112}	The city of Rijeka, City of Zadar, City of Osijek, City of Varazdin, City of Cakovec, City of Novigrad, City of Porec, City of Pula, City of Rovinj, Municipality of Brtonigla, City of Buje, City of Labin, the City of Pazin, Island of Brac, City of Prelog
Modernisation of public lighting	x_{12}	k_{121} and k_{122}	The city of Rijeka, City of Zadar, City of Osijek, City of Koprivnica, City of Varazdin, City of Cakovec, City of Porec, City of Pula, City of Buje, City of Labin, City of Pazin, Island of Brac
Infrastructure for electric vehicles and bicycles	x_{13}	k_{131}, k_{132} and k_{133}	City of Zadar, City of Osijek, City of Koprivnica, City of Varazdin, City of Cakovec, City of Prelog
Purchasing of electric vehicles	x_{14}	k_{141} and k_{142}	City of Rijeka, City of Zadar, City of Osijek, City of Koprivnica, City of Varazdin
Additional SECAPs analysed used for measures development	Non-applicable	Non-applicable	The city of Buzet, Island of Korcula, City of Kastva, City of Krizevci, City of Ludbreg, Municipality of Matulji, City of Slatina, City of Velika Gorica, City of Virovitica, City of Zagreb

2.2. Interaction between mitigation measures

The interaction between different measures was the next step after the analysis of the most common measures used in the SECAPs. The analysis was performed in ARTICLE 2 using LEAP energy software on the example of the development of SECAP for the City of Zagreb. As discussed in the previous chapter, measures for the reduction of energy consumption and CO_2 emissions are subdivided into buildings, transport, and public lighting sectors, and therefore, their results are shown that way in the analysis. The results of the emission reduction in mentioned sectors are shown in Figure 6, reaching an overall 41.2% compared to baseline [69].

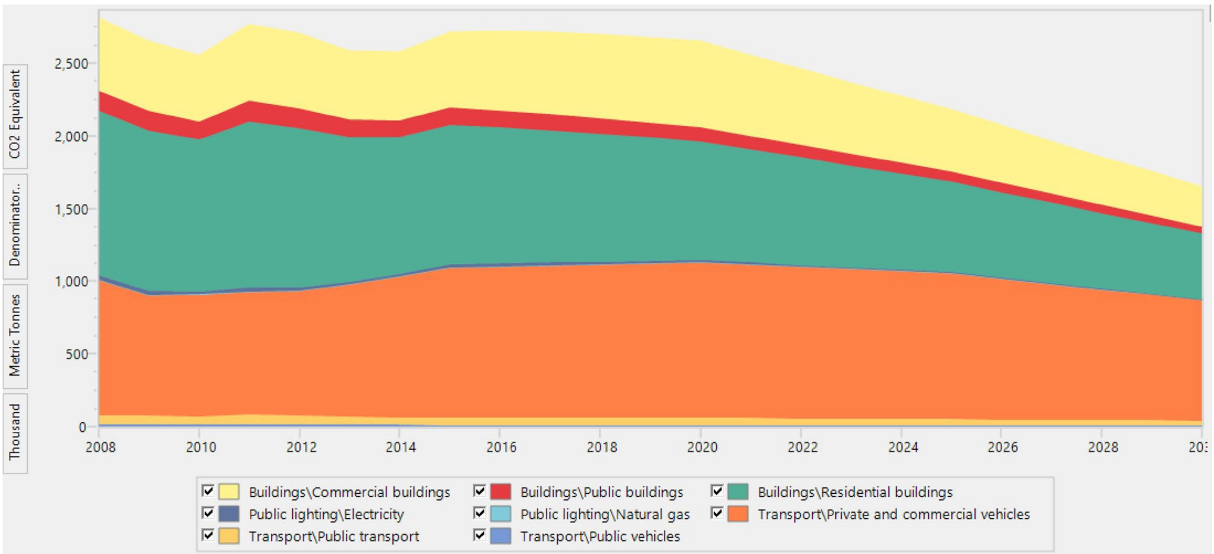

Figure 6 CO_2 equivalent emissions per sectors in a scenario with measures (ARTICLE 2 [69]***)***

Figure 6 shows that most of the reduction of CO_2 emissions will happen between 2020 and 2030 with the highest contribution of the building sector in the emissions reduction. The transport sector (private and commercial vehicles) will become 2030 the sector with the highest emissions of CO_2.

The comparison of measures of potential energy and emissions reduction in individual and in the scenario, analysis performed in ARTICLE 2 are shown in Table 3 and Table 4. The results show that in all sectors, estimated energy and CO_2 potential is higher than the results provided by the scenario analysis. This is best seen in the public lighting sector, where the estimated CO_2 reduction is 74% higher than the results of the scenario analysis. It is considered that this is mostly happening due to the decrease in the electricity CO_2 emission factor due to the penetration of renewables which is not correctly considered when calculating CO_2 emission reduction potential for the given measure.

Table 3 Comparison of energy reduction for measures based on estimated potential and scenario results (ARTICLE 2 [69]***)***

Sector	Measure	Energy consumption reduction potential [GWh]	Scenario achieved energy consumption reduction [GWh]	Difference between potential and scenario

Buildings	NZEB	2,588.20		
	20 % RES	-		
	Quick measures	32.32		
	DHS efficiency	-		
	DHS geothermal	-		
	Heating modal shift	-		
	Total	2,620.51	2,389.73	8.81 %
Transport	Transport modal shift	326.70		
	Tram efficiency	5.00		
	EVs	343.12		
	Eco-driving	245.40		
	Total	920.22	847.11	7.94 %
Public lighting	LED lighting	49.16	26.88	45.32 %
Total		3,589.89	3,263.73	9.09 %

The overall energy consumption reduction which is presented in Table 3 is different by 9.09% comparing the scenario approach and measures reduction potential, while CO_2 emissions are different by 16.23% (Table 4). When turned into absolute numbers, this shows that the reduction potential with given measures is overestimated by 170,031 tCO_2 (Table 4). The results of the analysis show that there is a potential to exceed the reduction potential of measures if the scenario analysis and calculation with chosen measures are not made.

Table 4 Comparison of CO_2 reduction for measures based on estimated potential and scenario results (ARTICLE 2 [69]***)***

Sector	Measure	CO_2 reduction potential [$ktCO_2e$]	Scenario CO_2 reduction potential [$ktCO_2e$]	Difference between potential and scenario
Buildings	NZEB	534.93		
	20 % RES	46.22		
	Quick measures	13.36		
	DHS efficiency	145.58		
	DHS geothermal	30.00		
	Heating modal shift	10.19		
	Total	780.28	648.30	16.91 %
Transport	Transport modal shift	83.51		
	Tram efficiency	0.55		
	EVs	108.11		
	Eco-driving	63.49		
	Total	255.66	226.05	11.58 %
Public lighting	LED lighting	11.41	2.96	74.07 %
Total		1,047.34	877.31	16.23 %

The results from ARTICLE 2 presented in Table 4 show that there is a significant difference in the predicted reduction of CO_2 emissions when evaluating measures potential individually and in the scenario approach by using the LEAP model. When compared to the emissions from the baseline year, the reduction of CO_2 emissions calculated in the scenario approach correspond to 6.06% of total emissions, which can be considered significant since the overall target for the reduction was 40%.

If the city planners develop SECAP by using individual measures assessment, instead of a scenario approach, they risk the possibility that their calculated reduction potential will not be achieved since mutual interaction between the measures is not considered. As it is seen in this example from ARTICLE 2 and the analysis of measures in buildings [70] the prevailing interaction between measures is negative, meaning that they have lower CO_2 reduction potential when implemented together than separately. This raises a question on how CO_2 reduction potential was calculated in the existing SECAPs and is the planned level of reduction of 26.19 % [53] possible and achievable with the given measures if their reduction potential was not analysed in a scenario approach.

The results of the measures interaction from ARTICLE 2 provided input for the final selection of the measures and scenarios used for the optimisation of measures for CO_2 reduction in SECAPs. The results were also used for modelling the limitations of the optimisation model which is developed in ARTICLE 4. In the next section, the final selection of mitigation measures used for optimisation is presented as well as the result of the optimisation model with the conclusions.

2.3. Sets of measures and scenarios for reaching different levels of CO_2 emission reduction

In ARTICLE 4 the final selected measures are presented and grouped per sector as shown in Figure 5. The measures are also divided into individual measures and sets of measures. The list of the individual measures and their factors used in the optimisation equation is the following:

- Energy renovation of public buildings (x_2);
- PV on public buildings (x_3);
- Solar thermal on public buildings (x_4);
- Electrification of public transport (x_5);
- Energy renovation of residential buildings (x_8);
- PV on residential buildings (x_9);
- Energy renovation of commercial buildings (x_{10});
- PV on commercial buildings (x_{11});
- Modernisation of public lighting (x_{12});

- Infrastructure for electric vehicles and bicycles (x_{13});
- Purchasing of electric vehicles (x_{14}).

Besides individual measures, there are also sets of measures which consist of a combination of at least two individual measures:

- Integrated renovation of public buildings (x_1);
- Integrated renovation of multi-apartment buildings (x_6);
- Integrated energy renovation of residential buildings (x_7);
- Electrification of transport ($x_{13} + x_{14}$).

The following figures from ARTICLE 4 show measures listed according to different sectors and show the relationship between the specific cost of CO_2 emission reduction and total CO_2 emission reduction. Figure 7 gives an overview of the measures and equations used in the calculation of cost for the reduction of CO_2 emissions in public buildings. The measures shown are integrated renovation of public buildings, energy renovation of public buildings, and PV and solar thermal on public buildings.

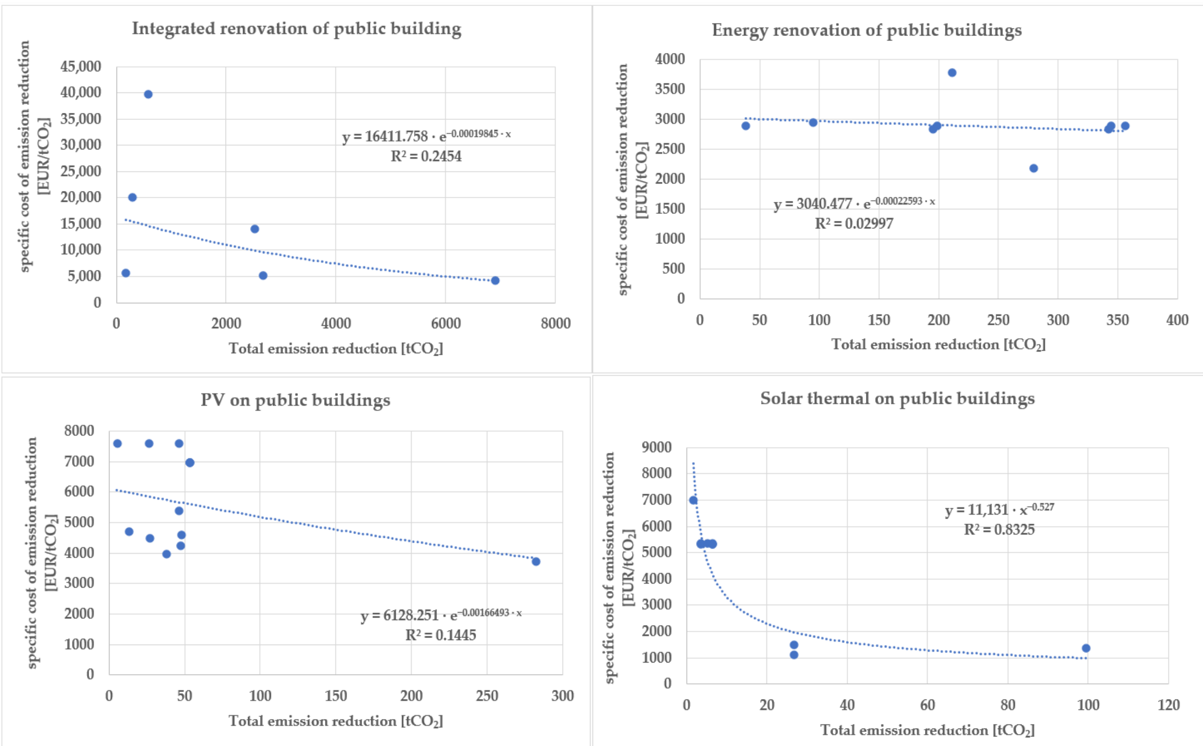

Figure 7 Functions used for the optimisation of public buildings measures (ARTICLE 4 [68]***)***

All the measures shown in Figure 7 have a reduction of specific costs with the increase of the total emission reduction. The specific cost ranges from min of 1000 EUR/tCO_2 for solar thermal on the public building to the max of 40,000 EUR/tCO_2 in the case of integrated renovation of public buildings. The average values of specific costs for measures range from 2000 to 8000 EUR/tCO_2. Figures 8–10 also show the relationship between the specific cost of CO_2 emission reduction and total CO_2 emission reduction just for the different sectors. Figure 8 shows the sector of commercial buildings while Figure 9 shows the transport and public lighting. Figure 10 gives an overview of measures in the residential sector.

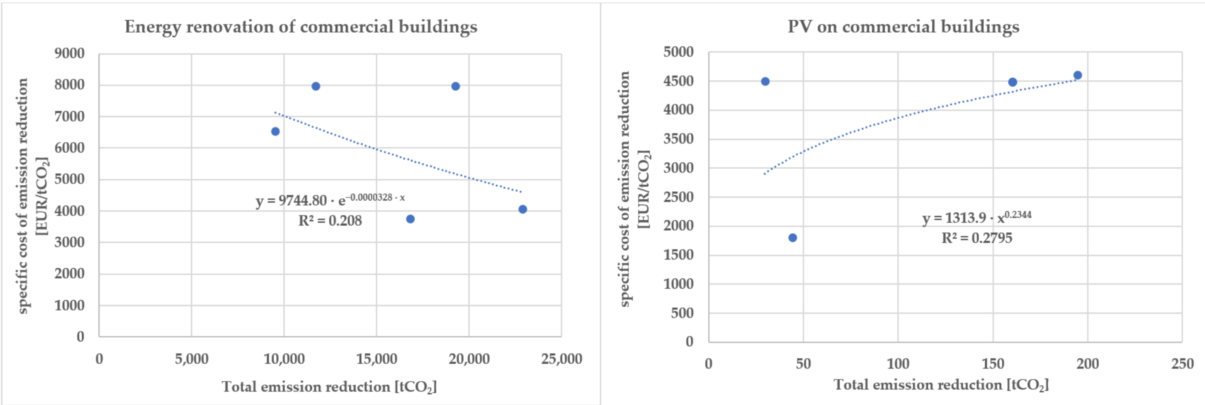

Figure 8 Functions used for the optimisation of measures in commercial buildings (ARTICLE 4 [68]

Figure 8 shows two measures in the commercial sector which are energy renovation of commercial buildings and PVs on commercial buildings. Specific costs for the energy renovation range from 4000 EUR/tCO_2 to 8000 EUR/tCO_2 while the cost of PVs on the commercial building is in the range of 1800 EUR/tCO_2 to 4600 EUR/tCO_2.

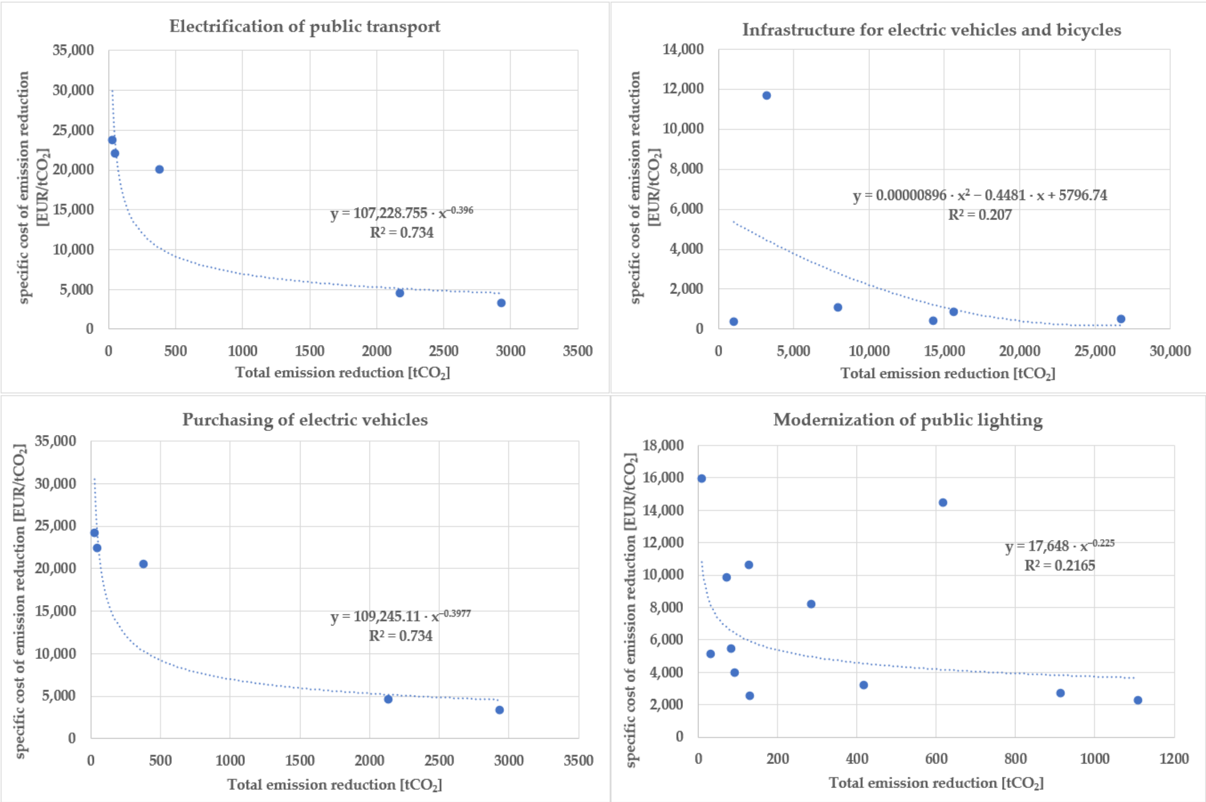

Figure 9 Functions used for the optimisation of measures in the transport and public lighting sector (ARTICLE 4 [68]

Figure 9 shows three measures in the transport sector and one for public lighting. The measure in the transport sector is the electrification of public transport, infrastructure for electric vehicles and bicycles and purchasing of electric vehicles. Modernisation of public lighting with LED light is the measure for the public lighting sector. Specific costs for the electrification of public transport range from 4000 EUR/tCO_2 to 25000 EUR/tCO_2 while the cost of infrastructure for electric vehicles and bicycles is in the range of 1000 EUR/tCO_2 to 12000 EUR/tCO_2. The specific cost for purchasing electric vehicles ranges from 4000 EUR/tCO_2 to 25000 EUR/tCO_2 and the cost of the modernisation of public lighting is from 2100 EUR/tCO_2 to 16000 EUR/tCO_2.

Furthermore, Figure 10 presents four measures for the residential buildings sector which are integrated renovation of multiapartment buildings, integrated renovation of residential buildings, energy renovation of residential buildings and PV on residential buildings. The specific cost of integrated renovation of multiapartment buildings ranges from 9500 EUR/tCO_2 to 21000 EUR/tCO_2 depending on the measures and the current status of the building's envelope and installations while the values for residential buildings are in the broader range from 5000 EUR/tCO_2 to 24000 EUR/tCO_2. Energy renovation of residential buildings which includes just the renovation of the envelope is ranged from 4200 EUR/tCO_2 to 10200 EUR/tCO_2 while the PV on residential buildings installation is ranged from 4500 EUR/tCO_2 to 7100 EUR/tCO_2.

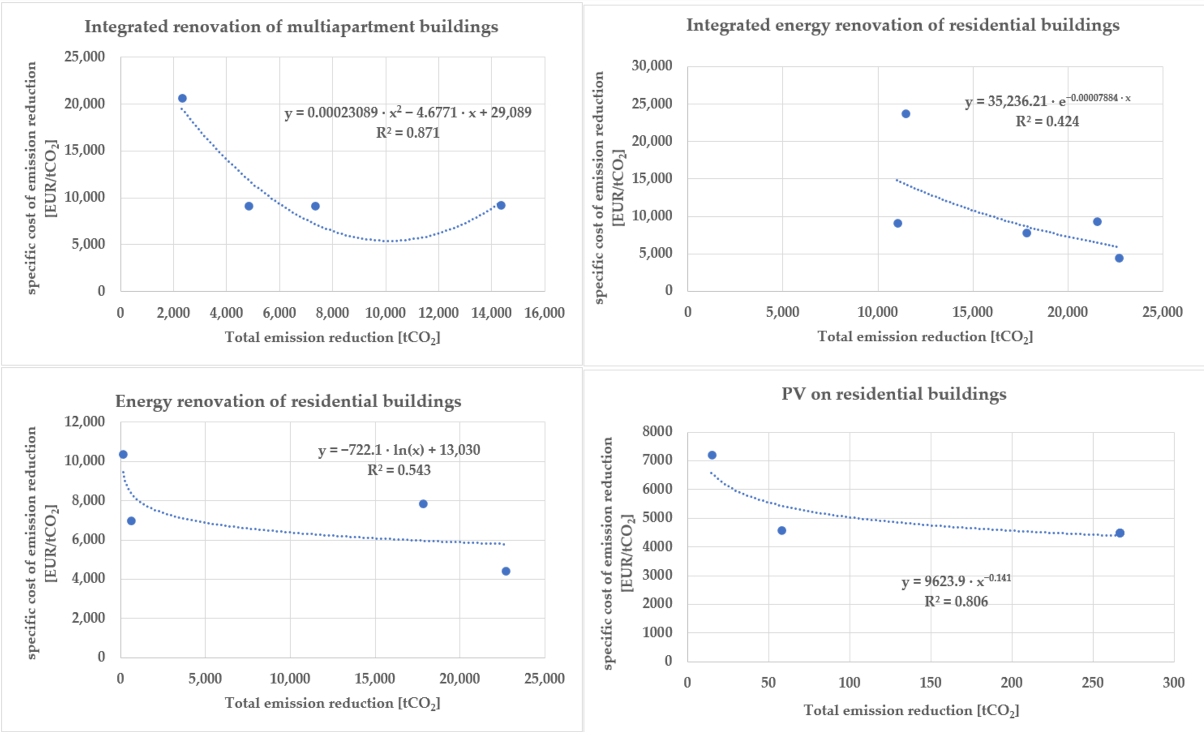

Figure 10 Functions used for the optimisation of measures in residential buildings (ARTICLE 4 [68]

Measures in all sectors experience the same trend in which the specific cost is reduced by the higher reduction of the total CO_2 emissions. The two measures are exceptions from this trend and those are PV on commercial buildings which shows a slight increase in the specific cost and energy renovation of the multi-apartment building which shows the first reduction and after some point increases in the specific cost. The reason why the specific cost has these trends should be further investigated since this was not the focus of the research and the specific cost data from SECAPs were used as an input for the optimisation model.

After the most common measures were analysed and written as the equation connecting the specific cost of emission reduction to the total emission reduction level, the equations were used to create a minimum cost equation. Together with the model limitations, a minimal cost equation was used for the optimisation of the implementation of the measures, whose results will be shown in the following figures. Details of the model limitations and minimal cost equation can be found in ARTICLE 4. To compare the current cost of the reduction of CO_2 emissions for the case study area with the optimisation of measures, implementing the calculation of the current plan cost was performed. The level of implementation of each measure and set of measures was taken from the existing SECAP for the wider Dubrovnik area [71]. The results of the implementation of the current plan with the order of implementation of measures and their specific cost and contribution to the total CO_2 emission reduction are shown in Figure 11. The contribution to the total CO_2 reduction can be seen on the horizontal axis while the specific cost is shown on the vertical one. The total cost of one measure in EUR is represented by the rectangular area showing each measure. Measures should be implemented in the order of how they are presented on the figure from those with the lowest to those with the highest specific costs.

The measures that most contribute to the CO_2 emission reduction are PVs on commercial buildings, energy renovation of commercial buildings, electrification of transport and integrated energy renovation of residential buildings. On the other hand, Figure 11 provides clear instructions on which measures should be implemented first and which should be implemented last to reach the reduction with the lowest cost possible. The current plan has an estimation of the total cost reaching a 40% reduction considering current CO_2 emissions of 401.5 MEUR.

To make it possible to reduce the current plan cost and reach the same level of CO_2 reduction for the case study area, the optimisation model was developed in ARTICLE 4. The results of the model optimisation of measures implementation are shown in Figure 12, while the total cost of the reduction reached 121.1 MEUR in this case. The optimisation model followed limitations given in Equations (3)– (9) from ARTICLE 4. The limitations are constraining the maximal CO_2 reduction level for public buildings, residential buildings, commercial buildings, and the transport sector. The optimisation model resulted in the need to implement only three measures to reach the 40% emission reduction for the given area. Those measures are, in the order of implementation, PV on commercial buildings, electrification of transport and PV on public buildings.

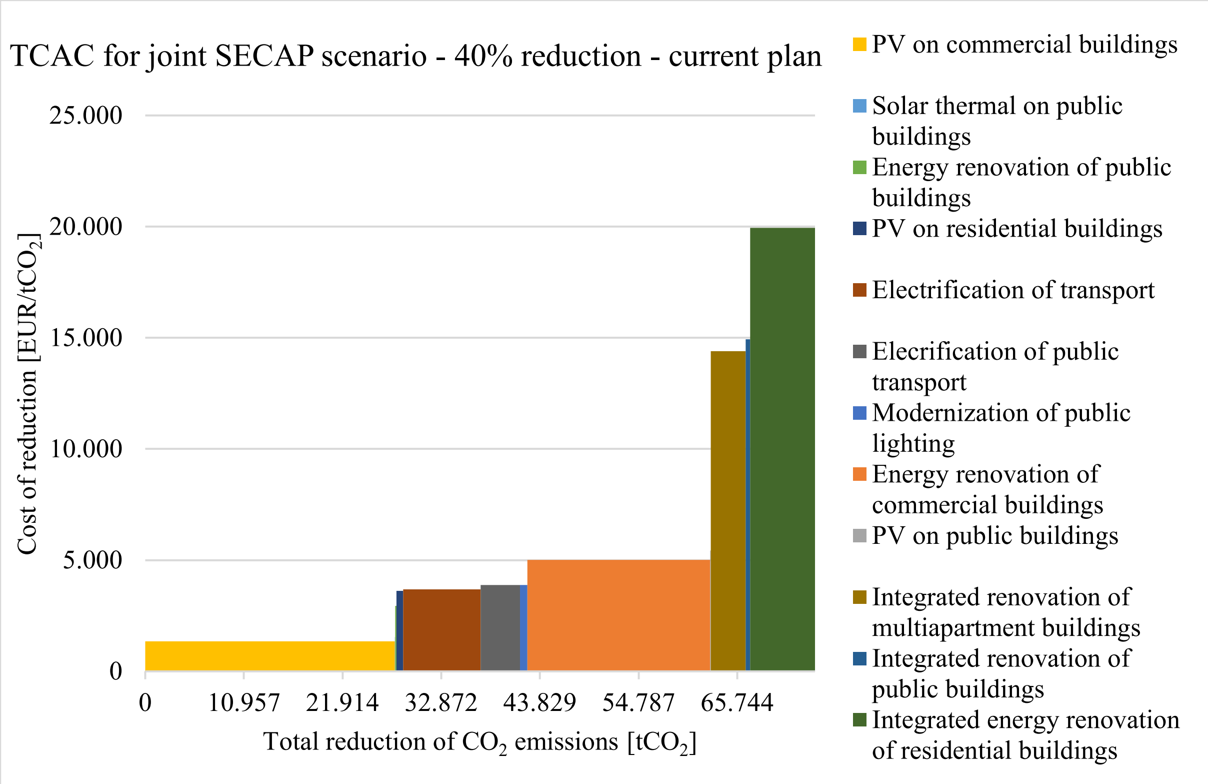

Figure 11 Total cost abatement curve for the 40% CO_2 reduction in the current plan (ARTICLE 4 [68]

Furthermore, to reach financial cost for a different level of CO_2 emission reduction and optimal sets of measures in that case the model was tested on the reduction of CO_2 emissions by more than 40% by increasing the wanted level of reduction by 5%, thus creating new goals of 45%, 50%, 55%, 60% and 65%, respectively. Those results are shown in Figure 13 and measures are organised in the order of how they should be implemented. The result for the reduction of the emissions by 65% was not possible to calculate since the limitations of the case study applied to the model allow reduction of emissions up to 63.52%.

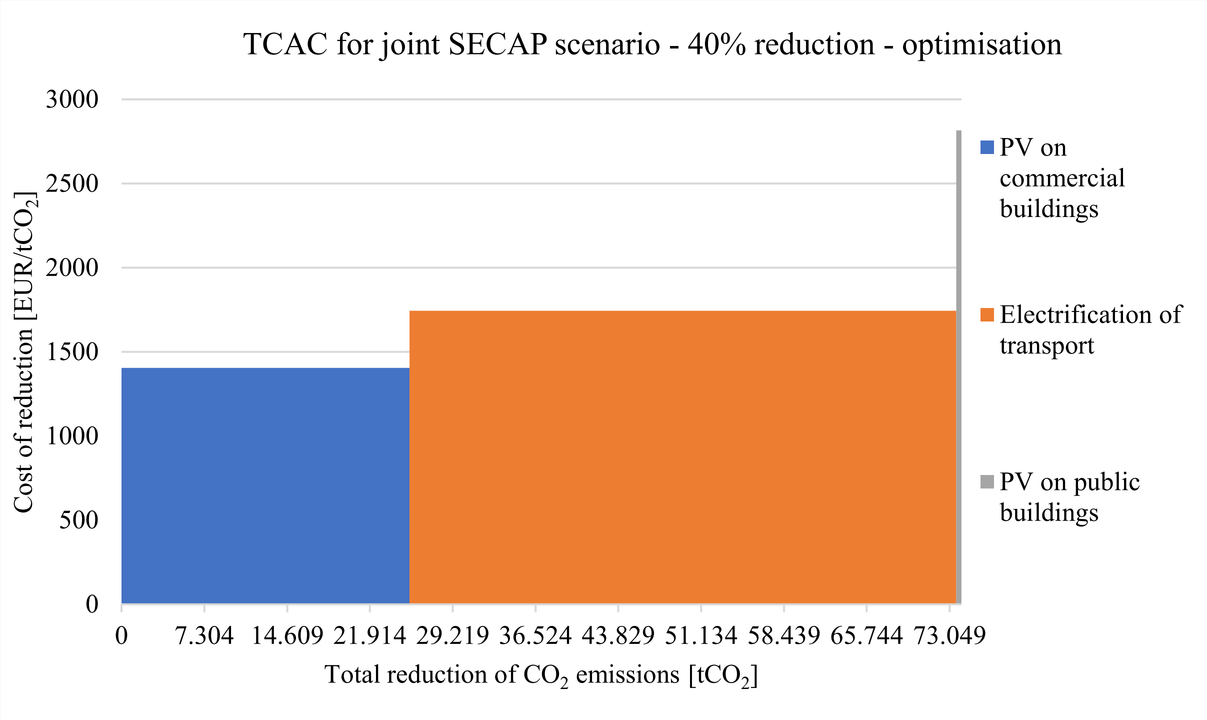

Figure 12 Total cost abatement curve in the case of optimisation of measures for the 40% CO_2 reduction (ARTICLE 4 [68]

The results for the reduction of emission for 45% have the same measures as the 40% ones except they add a measure of implementation of PVs in residential buildings. When looking at the 55% reduction, two additional measures are added: renovation of public buildings and electrification of public transport. The last emission reduction level of 63.5% which is shown in Figure 13 adds three new measures, which are the modernisation of public lighting, renovation of multi-apartment buildings and energy renovation of commercial buildings.

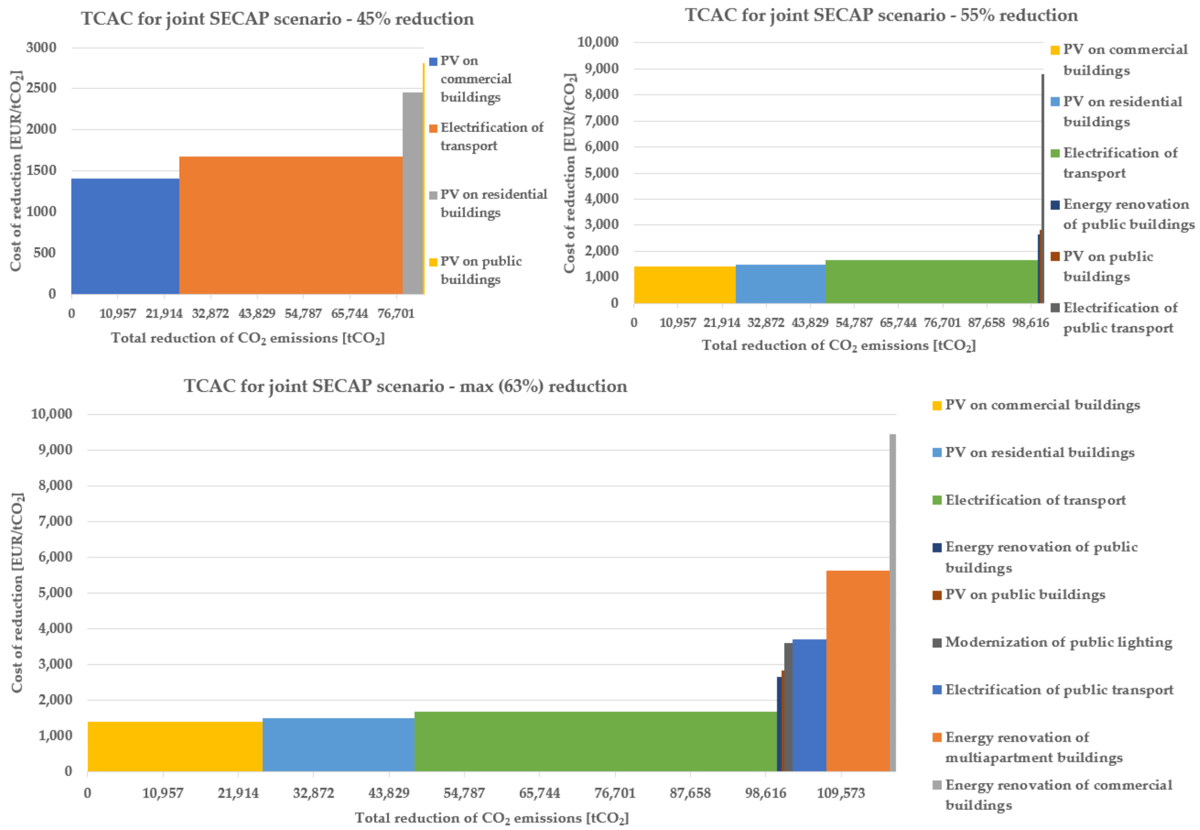

Figure 13 Total cost abatement curve in the case of optimisation of measures for the 45%, 55% and maximal (63%) CO_2 reduction (ARTICLE 4 [68]

The results shown in Figure 12 and Figure 13 show that the most promising measures for the reduction are those which promote the installation of PVs and electrification of transport. This is expected since the highest reduction potential is in the transportation sector while electricity is the highest energy source consumed in the case study area. The other reason is that those measures have the lowest specific cost when implemented on a large scale which can be shown from the results of the analysis of developed SECAPs in Figures 7–10.

The comparison of the total cost of the CO_2 emission reduction for different levels comparing the original scenario and optimisation ones from 40% to 63.5% is provided in Figure 12. The total costs of the optimisation scenarios are much lower than the original, which shows that it is possible to reach the same or higher levels of CO_2 emission reduction with lower use of financial resources.

The results presented in the previous figures provide a good overview of the actions for the reduction of energy consumption and CO_2 emissions for the SECAPs in Croatia. When the given list of measures is correlated with the specifics of the case study, the most suitable measures are highlighted as the ones which should be first implemented. The case study area has a Mediterranean climate and high penetration of electricity with a low CO_2 emission factor in the consumption of buildings, thereby promoting transport as the highest emitting sector. This has a large impact on the selection of the measures for reducing CO_2 emissions where the electrification of transport is the measure with the highest reduction potential. The other actions which are presented in all optimisation scenarios are related to the installation of PVs on buildings which will provide further reduction of CO_2 emissions from electricity and open the path for further penetration of electrification in all buildings and transport sectors. The production of energy on the site of consumption will increase the level of self-sufficiency from the energy point of view and in the wider logic of self-efficient social communities [72]. The proposed measures are in line with other analyses performed on the most common actions in which local electricity production is highlighted as one of the best measures for energy and emission reductions [26].

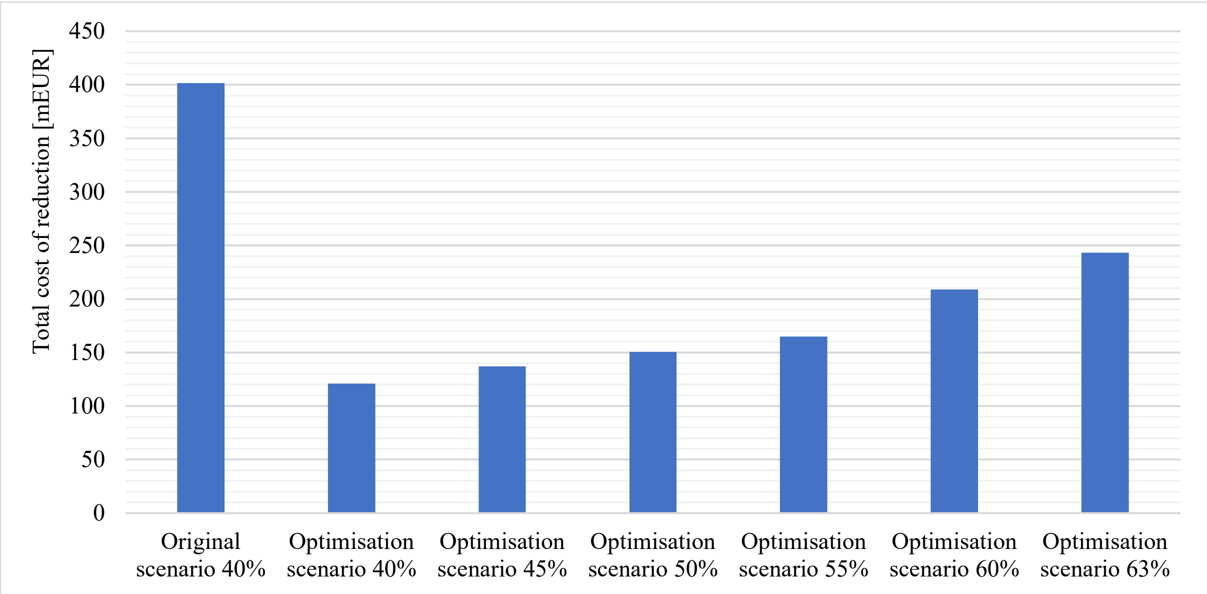

Figure 14 The total cost of mitigation measures in analysed scenarios in million EUR (ARTICLE 4 [68]

The result of the measures optimisation is the key enabling factor for high reduction of the CO_2 emissions and mitigation actions on the analysed territory since the model supports the alignment with the baseline emission inventory by focusing the implementation in the sectors with the highest emission, i.e., transport. The alignment of the measures with the highest emitting sectors is the most important since it allows local authorities to achieve ambitious reduction goals [73].

The specific cost for the reduction of CO_2 emissions is in a wide range from 1000 EUR/tCO_2 to 40,000 EUR/tCO_2 with the average values being between 2000 and 8000

EUR/tCO_2. This can be considered rather high compared to the previous analysis [26] but it has to be taken into account that in this work we only took into account so-called hard measures. The resulting cost of the measures is based on the minimisation of the cost function with the coefficients calculated based on the mitigation measures from the previously developed SECAPs. This approach has limited power since the changing of the form of the function can lead to different conclusions as well as changes in the coefficients.

The results of measures cost from the analysis considering the measures per sector are in line with the previous research showing that the highest cost is related to the measures in residential buildings and the lowest with the measures for local electricity production [26]. On the other hand, the electrification of transport is one of the cheapest measures in our analysis, but in the previous research [26] it was one of the most expensive. This could be due to the specifics of the case study with very low emissions from the electricity and buildings and very high emissions from transport. A similar conclusion can be taken from other studies where cases were cities which had high emissions from the transport sector and where the main measures which should have been prioritised are the ones in the transport sector [74]. Additionally, the measures in the transport sector could be more easily implemented than the measures in the buildings sector since it has fewer key decision makers [75]. Another benefit of focusing on the reduction of CO_2 emissions from the transport sector is also the reduction of air pollutant emissions, which is not always clear for the residential sector, where CO_2 emissions can be reduced but air pollutant emissions are increased, for example, in the case of introducing biomass heating [76]. The reduction of local air pollutant emissions is also increased by the installation of PVs on buildings, which is another measure that is prioritised in our case. This can be beneficial for reducing local air pollutants from local electricity production as well as for heating if the PVs are combined with heat pumps. Another measure that is beneficial both for local air quality and the reduction of CO_2 emissions is energy renovation of buildings [76], which is the next measure in terms of prioritisation in our case study (Figure 13). Since the benefits of air pollution reduction are not validated in the model, this should be part of future research as well as the validation of other external costs reduced by implementation of measures such as additional green jobs, health, and social benefits for the community.

The results of the optimisation of measures are also important to organise measures in order of implementation by prioritising lower-cost measures. In this way, it could be possible to increase the overall implementation of SECAP measures which is currently considered to be low, with only 19% of measures fully implemented [77]. Moreover, in this way, the lack of appropriate financial planning which is marked as the constant and most common element in existing SECAPs [72] is being reduced since lower financial means are required. The lack of financial and cost-benefit analysis in current SECAPs, as well as business plans and risk analysis, is a very negative element in implementation that needs to be properly addressed in the future [72].

The other important benefit of measures prioritisation and optimisation is the financial savings, but also the saving of other resources such as human and organisational [78]. This could provide a significant saving in our case, from 70% to 3 times reduction of costs for achieving the same or higher reduction of CO_2 emissions. The results of the prioritisation can be helpful to the policymakers in the cities and municipalities to forge their mitigation strategies and to give an answer on which sectors and measures they should focus their activities on. Even though the prioritisation provides the most cost-beneficial measures to be implemented first, the policymakers should also work on the integrated and mixed mitigation strategies, considering the influence and interaction between the measures from different sectors as shown in ARTICLE 2 [61] since the potential synergies and trade-offs between different policies could provide acceleration in the reaching of the mitigation goals [79]. The prioritisation could also provide a faster reduction of the emissions in the beginning and thus could encourage good practice, inspire both green investments and energy savings and go beyond the target set without increasing public debt [80]. Moreover, the prioritising of measures provides a strong tool for the local government which has opted for smart planning, sustainable development, environmental protection and increasing security of supply as pointed out in [81]. Additionally, the increased implementation can have social benefits such as increased employment and reduced cost of the import of fossil fuels [82].

Finally, another specific factor of the case study is that it consists of small municipalities and one city with less than 50,000 inhabitants which without a joint approach could not reach the economy of scale for the cost-effective optimisation of the measures as shown in Figures 7–10. With the joint implementation of measures, the small municipalities need coordination from the upper regional level which can provide tailor-made solutions for sustainable energy planning as well as concrete financing opportunities for mitigation measures in their territories [40]. Another benefit of the joint development of the action plan is the support received from the upper level in the calculation of baseline and monitoring emission inventory and development of the action plan [40]. More details on the importance of multi-level governance and its role in the sustainable energy plan will be provided in the next section where the main results of ARTICLE 3 are presented.

2.4. Multilevel governance and implementation of mitigation measures

To explain the importance of multilevel governance in reaching the energy and climate targets on the local level the case study for the Styria region in Austria in ARTICLE 3 was analysed. Firstly, there will be explained initiatives for sustainable development which are used on the local level and then are going to be given the main results for the improvement of the MLG concept to speed up the energy transition.

2.4.1. Initiatives for sustainable energy development at the local level

At the local level, sustainable energy and climate action plans aim to support national and regional initiatives for sustainable energy development. In the analysed case study from Austria, they are designed as a part of the following programmes:

- e5 – Programme for energy-efficient towns and municipalities (municipal level) [83]
- Climate and Energy Model Regions (KEM) (District level – a group of municipalities) [84]
- Covenant of Mayors (municipal level) [5]

In the targeted federal province of Styria in 2018, there were 3 CoM signatories, 11 e5-municipalities and 25 KEMs including 114 municipalities. The analysis in ARTICLE 3 provides the main characteristics of each initiative and is supported by the interviews with energy experts from Energy Agency Styria.

All the initiatives have a voluntary basis meaning that the goals of the initiative can be or can't be fulfilled without any consequences. Only the Covenant of Mayors has a quantifiable target for CO_2 emission reduction while others have only qualitative targets. Despite this all initiatives have the same goal of sustainable energy development, increasing energy efficiency and security of supply which is currently of the most importance. On the other hand, CoM doesn't have a predefined set of measures, but similar measures are used in all plans while KEM has a list of 90 measures which are available for implementation, and which provide a comparison between different cases.

Despite the difference between the initiatives, they all have common steps when it comes to the implementation of the action plans. Common steps to all initiatives are:

1) Initiation process
2) Application and accession to the initiative
3) Baseline energy and GHG emissions review
4) Design or revision of measures through an action plan
5) Implementation of measures
6) Evaluation of measures implementation and reporting on the success

In the case of the KEM, unlike the e5 and the CoM, the commitment is made on the regional level where regions apply for the call of the Climate and Energy Fund, which opens once a year to become part of the initiative and receive financial support. All initiatives contain an evaluation of the measures as an indicator of success which serves as a motivator when the municipality/region was on track or a “modifier” when it failed to keep track. Therefore, the evaluation can be considered the most important part of the ongoing process. Assessment and reporting are continuous processes in CoM and e5 initiatives while for KEM, this is often the final stage because most of the regions quit after the first phase is finished. Quality control is performed by external bodies, which contribute to the credibility and reliability of the initiatives. At least every three years, the KEM municipalities undergo an evaluation by an independent commission depending on the progress, they are accordingly awarded the “e” level representing the percentage of the measure implementation. Esurance that the submitted action plans of the CoM initiative are carried out is done by the European Commission’s Joint Research Centre.

The CoM and KEM analyse various sectors while e5 include only the municipal sector. Energy analysis of the municipal sector gives high chances for accuracy of the analysed data; however, omitting the other sectors significantly reduces areas with great potential for improvement. The key CoM sectors include buildings, equipment/facilities and industries, public lighting, and transport. On the other hand, KEM also analyses all the sectors, but measures could be designed in a way that none of the sectors is directly influenced, but they aim at awareness-raising, educational and social activities. Additionally, CoM provides both soft and hard measures in its plans, therefore, taking the best from both other initiatives.

Analysis of the current energy situation of the municipality/region as well as the proposed measures are done in the form of a report. Similar templates are provided for the municipalities/regions of CoM and KEM initiatives. Their detailed reporting in a transparent way is useful not only for the municipality/region itself but also for the other municipalities/regions willing to take part in the initiative and develop their action plans. Even though e5 has a detailed uniform template for evaluation, the lack of transparency is observed as the full evaluation is available only to the e5 quality management team, and a limited version for the municipality and brief certificate is published online.

Variations between initiatives appear for financial and human capacity. The highest level of municipal commitment to secure its funding is in the case of CoM. This is because the initiative arises from the EU level, but direct funding is not provided. The action plan lists possible business plans and sources of funding while online CoM support provides an interactive funding guide with links for the most relevant financing publications and initiatives. On the other hand, participation in e5 has a small license fee whose costs are along with the costs of professional support during the implementation phase and of creating human resources in the state or the region covered by each respective national funding body. In the case of KEM, projects are funded to a certain extent. Financial support is a great motivator to take part in the initiative, which can be seen from the number of participating municipalities (Figure 16). However, the requirements of the application process discourage participants to continue.

2.4.2. The improvement of multilevel governance in local sustainable initiatives

The indication of the MLG approach exists in all the initiatives. Communities participating in the e5 program are also participating in the European Energy Award (EEA) program at the European level [85]. At the European level, the initiative is interlocked with other programmes and activities, such as CoM. At the national level, it is in line with national climate and energy goals. At the regional or local level, it is compatible with the creation and implementation of climate and energy policies. The EEA also has a multilevel organisational structure on the international, national, and local levels with the addition of external audits of municipalities and EEA advisors. Within the KEM initial concept strategies and roadmaps for the regions are analysed, and projects are designed to be in line with local, regional, and national energy action plans and strategies. The commitments for CoM signatories are linked to the EU's Climate and energy policy framework while action plans identify and analyse the existing municipal, regional and national policies, plans, procedures, and regulations that affect energy and climate issues within the local authority which enables better policy integration.

Moreover, measures for the specific sector are highly advised to follow EU policies and directives. Even though the link between strategies on the local level and the strategies on regional, national, and European exists, its applicability and viability in practice are questionable. This is due to the lack of precise top-down directions and a continuous feedback loop from a lower to a higher level of governance and vice-versa. Strategies on the national and provincial levels set general goals not considering the particularities of different municipalities regarding their RES potential and/or energy needs. On the other hand, the involvement of the lower levels is observed, such as in the Austrian energy strategy [86], though cooperation is not transposed into the definition of specific goals for each province.

In the end, the analysis and interviews with energy experts in ARTICLE 3 gave four areas where improvements in multilevel governance are needed, namely territorial fragmentation, data availability, spatial planning, and flexible governance. Thus, this case study results in present improvements in the four areas to develop a background for the new flexible energy planning methods and policies.

2.4.2.1. Territorial fragmentation

The province of Styria covering 16,401 km^2 in 2017 had 1,237,298 inhabitants [87]. The state is divided into 287 municipalities which are the lowest hierarchical level of administrative division. Municipalities had undergone a structural reform in 2015 when their number was almost halved. Reform intended to reduce the cost and human capacity for the operation of the municipalities. The municipalities are still generally small with a low number of inhabitants. In 2017 only 14 municipalities had more than 10,000 people with a 37% share of the total population of the state but accounting for only 5.8% area (Figure 15).

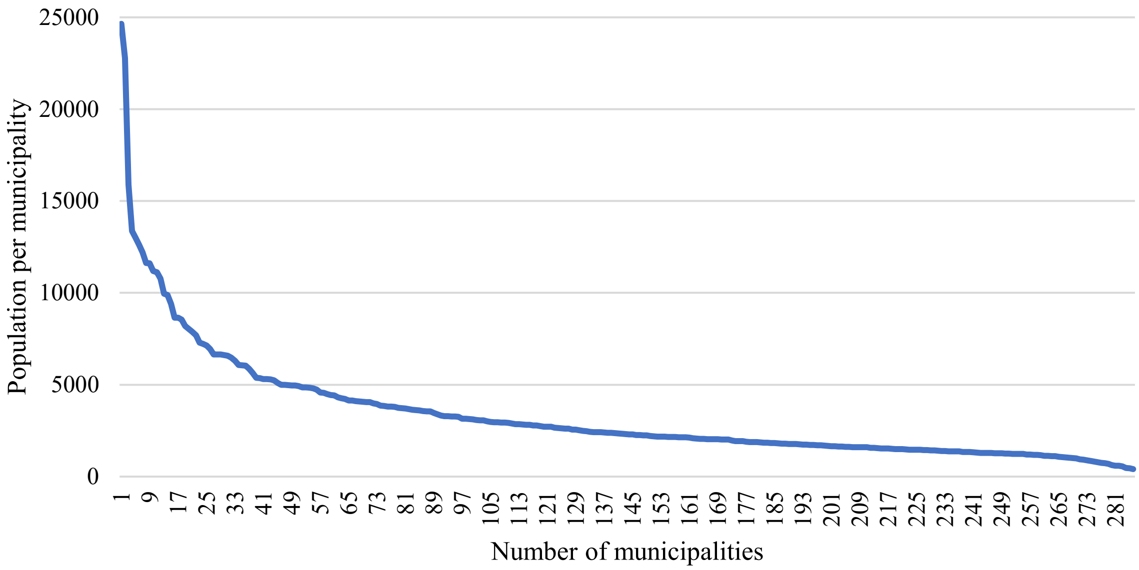

Figure 15 Municipalities in Styria per number of inhabitants (ARTICLE 3 [42]***)***

Most small municipalities have a restricted financial and human capacity for developing their local energy action plans and taking energy measures. Therefore, the option of joint participation with the support of the local authorities from each municipality is seen as a solution. Such an option exists in the CoM initiative. The initiative is not very widespread in Austria as the other two initiatives e5 and KEM, have long existence and a high level of acceptance. To overcome this barrier, the option of joint participation with the support of the local authorities should be introduced in e5 and KEM initiatives. Support from local authorities is of high importance for the acceptance and implementation of energy projects in all sectors. The analysis of municipalities participating in one of the local initiatives in Styria is presented in Figure 16, where some of the municipalities are part of more than one initiative. Nevertheless, most of the municipalities are part of the KEM initiative, which does not guarantee long-term commitment. Thus, the risk that municipalities will not continue their participation is rather high.

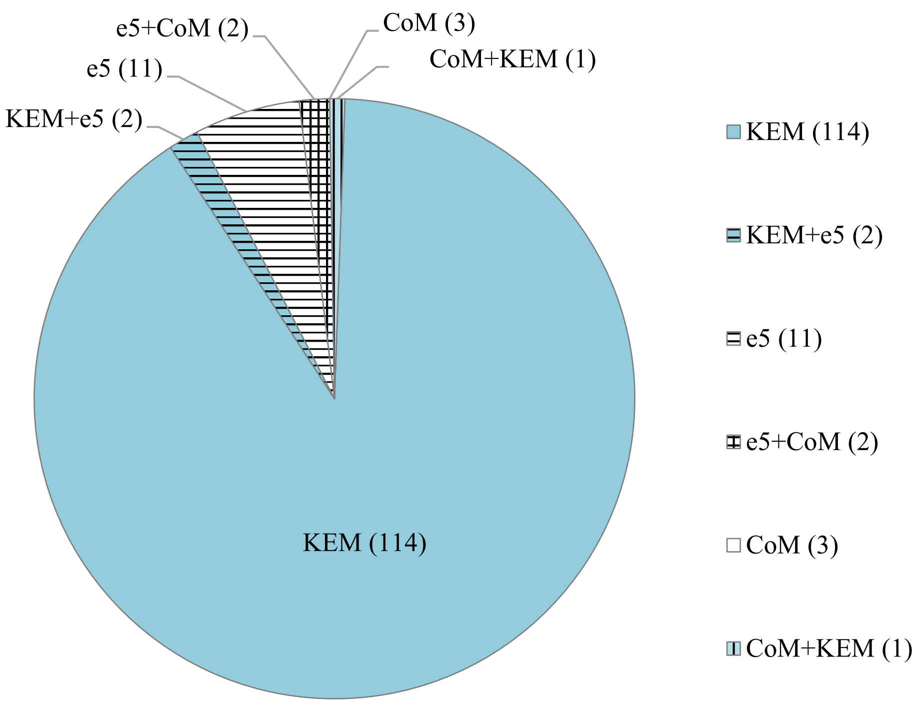

Figure 16 The share of municipalities per type of the energy and climate local initiative (ARTICLE 3 [42]***)***

2.4.2.2. Data availability

Data availability in Austria, and other EU countries, has been highlighted as a critical point in the development of flexible MLG energy planning and policy. Data availability varies between federal states. In the focus state of Styria, the weak points could be found within all three categories, namely economic, privacy and information quality. A comprehensive automatically updated database in directly usable form requires additional expenses for the data collection and processing, while on the other hand, this would significantly reduce time, financial and human resources but also rise the accuracy of local energy plans. Data quality is another big issue of the currently available data, which reduces the accuracy of energy strategy development. Even though quality management teams of local initiatives such as e5 are putting much effort to keep the high quality of the energy documents, clear framework and guidelines on the data availability, collection and processing are inevitable to facilitate the procedure of opening data. The difficulty to obtain data, as well as the need for open energy data, has also been discussed within the CoM initiative. As the CoM is a bottom-up initiative, it especially requires detailed and possibly granulated data at the local level. Required data can be obtained from energy suppliers. However, as at one location, several suppliers may be active, it is more convenient to obtain data from grid operators. Both energy suppliers and grid operators are often reluctant to provide such data as it is generally considered commercially sensitive due to confidentiality, commercial secrecy, and administrative burden. Therefore, in most cases, it is possible to get only aggregated data [21]. Nevertheless, energy market operators within all the member states must "provide on request, but not more than once a year, aggregated statistical information on their final customers" to an agency assigned by the Government [88]. Aggregated data are generally available from the statistics at a regional or national level [87], but this is mostly not appropriate for use in the case of local initiatives, as mentioned before.

2.4.2.3. Spatial energy planning

National level government has the power of defining spatial planning regulations by an appropriate spatial planning act. Local authorities are responsible for land allocation, where area usage is defined in the zoning plan. Moreover, urban planning and urban law fall within the competencies of national government while the execution of the laws belongs to the responsibility of the local authorities, namely the jurisdiction of the mayors [89]. Even though the regulation of spatial planning is well defined and established, and the Styrian Spatial Planning Act defines that energy transition and climate protection should be considered, energy aspects are seldom considered. The province of Styria opened the call for proposals on 03/08/2018 to support municipalities in defining energy measures taking into consideration spatial dimensions [90]. Until February 2019 only two municipalities have developed their Concepts for the Energy Sector.

Local communities have, a high but unutilised opportunity to include energy planning in their spatial plans. Spatial energy planning has become a significant topic within the European cities that are gradually developing approaches to introduce energy policy instruments [91–93]. Until now, in Austria, concrete actions on spatial energy planning have not at all or rarely been taken into consideration within local energy action plans. Spatial energy planning has been mentioned as an important instrument to reach the energy and climate protection goals within the Austrian Energy and Climate Protection Strategy. The present situation of low exploitation rate of spatial energy planning measures can be best seen from the analysis of the most common measures in KEM (Figure 17).

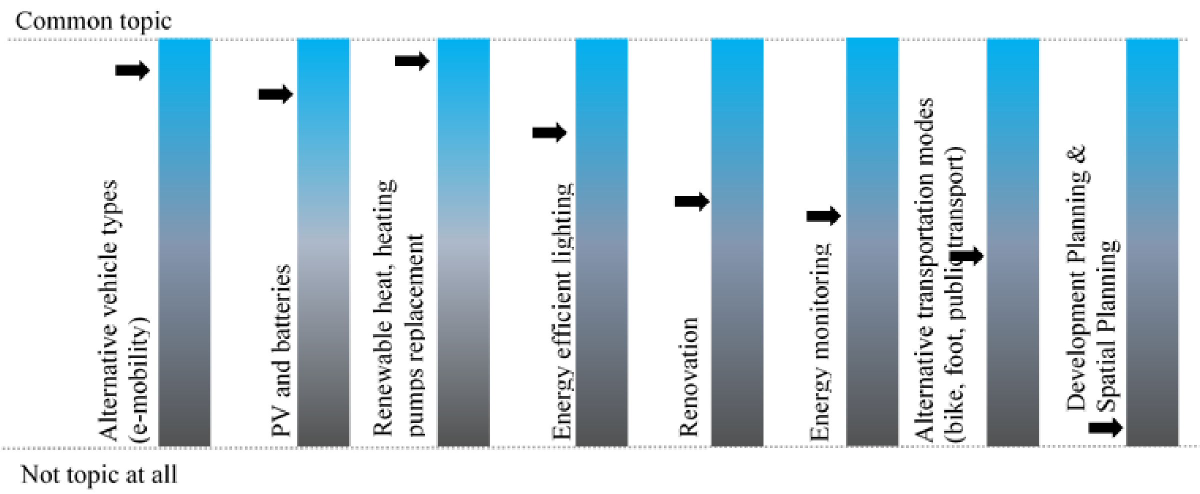

Figure 17 Analysis of the focus areas in KEM implementation concepts (January 2018) [94] ***(ARTICLE 3*** [42]***)***

Concrete public regulation and administrative processes for spatial energy planning have the potential to define energy zones for specific energy technologies and uses thus exploiting energy and services such as public transportation or DH network most efficiently and economically. Thus, the availability and quality of energy data with an emphasis on georeferenced data is of critical importance. Energy zoning has the potential of achieving technically, economically and ecologically suitable energy transition within the municipalities as the area allocation, i.e. the way land is utilised is inseparably linked [95]. Defining the best suitable technology according to the availability of the RES and customer demand in the specific zone would not just contribute to the optimised allocation of technologies and bring benefits to the efficiency of the energy system but also contribute to market innovations. Such an example is the technological and market uptake in Denmark, which is a result of the appropriate land allocation [96,97].

2.4.2.4. *New integrated multilevel governance*

Challenges of sustainable development are not limited to the respective administrative border. They intertwine horizontally between the areas of the same administrative level as well as vertically in both directions from the highest administrative level to the lowest and vice-versa [98]. Often actions are not taken within the artificially bordered administrative levels but rather within functional geographical areas such as neighbourhoods, metropolitan areas, cross borders, and macro-regions where the integration of different policies exists. Due to the constant changes of the geographical area, i.e., growth of the city metropolitan boundaries, the levels of functional geographies, namely neighbourhoods and metropolitan areas should rather be kept as flexible levels, where important activities are carried out in less formal ways. The idea of flexible MLG arises from Jacquier C. [99]. However, the interpretation of flexible MLG in this paper follows the idea presented in I. Tosics [98] where both hierarchies exist at the same time. This type of new governance is introduced in Figure 18 as a new integrated action space.

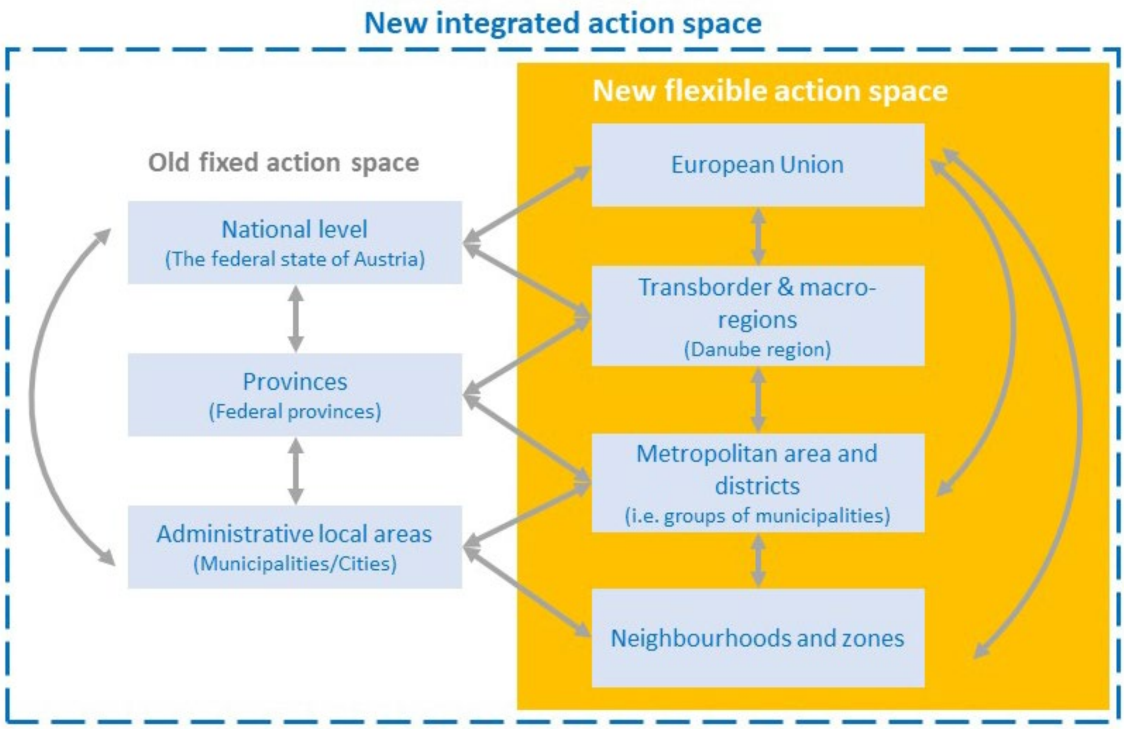

Figure 18 New integrated action space (Modification based on [98]***) (ARTICLE 3*** [42]***)***

The energy objectives at different levels of governance must coincide with each other, and they are in line with the European objectives. The objectives are to take into account the top-down definition by taking into consideration the bottom-up approach throughout the consultation with the provincial representatives and relevant chambers of the provincial governments. Even though cooperation of the different levels of governance is seen, it should be strengthened with a stronger influence of the bottom-up approach and horizontal cooperation. Therefore, in a proposed future MLG structure with a new integrated action space, it is important to keep fixed action for defining the framework and giving the guidelines while giving the space for more flexibility to non-administrative areas. In a fixed action space, all levels of governance would strengthen their role through a more specific definition of activities for the energy transition. The national state should provide a more precise framework for energy transition with a concrete focus on the potential and the needs of administrative areas of the lower level. Moreover, it would create preconditions for implementing local initiatives through solving the issues of data availability and stimulating spatial energy planning. On the other hand, municipalities and cities would provide constant feedback on the strategy implementation progress by taking a bigger role in drafting the national and regional energy policy and implementing more actively proposed measures. The flexible action space would enable it to cover land characteristics arising from the development of the defined administrative area but also to consider renewable energy potential, which is rarely defined with administratively imposed borders. The smallest level of flexible action space, i.e., districts or neighbourhoods, would have a key role in spatial energy planning acting as the energy zones. In this way, reorganisation of the current division of power could ensure more effective implementation of local initiatives.

2.4.2.5. Implementation of measures through MLG

The results of the implementation of the measures in the case study example from the ARTICLE 3 which is the city of Judenburg is showing that coordinated actions from different levels of governance lead to effective implementation. The remaining non-conventional biomass potential is enough to increase the share of DH in Judenburg for residential buildings from 16.3% to 30.8%. The building refurbishment, which contributes to the reduction of heating demand, is increasing the DH share to 32%. Total heat demand for space heating and hot water preparation after the implementation of both measures was 317.54 TJ. Fuel types used to cover heat demand after the implementation of both measures are presented in Figure 19.

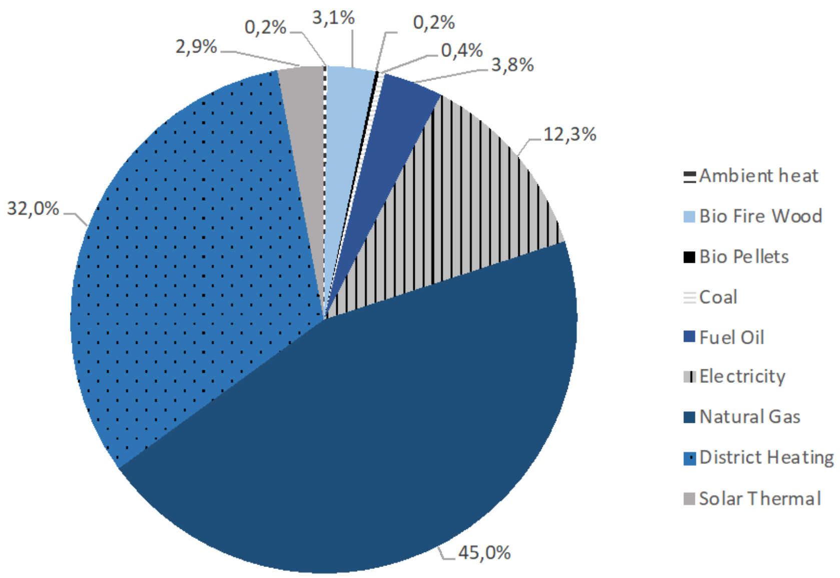

Figure 19 Fuel shares for heat demand (ARTICLE 3 [42]***)***

Both measures were applied only to zones with an existing DH network, namely zones 3, 4, 5 and 6 (Figure 20) due to the potential for new DH connections and renovation of buildings. Therefore, the implementation of the measures in these zones led to increasing in DH share from an initial 19.5% to 52.3%. This enabled to phase of coal and residual fuel oil completely and reduced natural gas for space heating and domestic hot water preparation by 82.5%. The approach represents the introduction to spatial energy planning through MLG. Defining zones that should be supplied by DH or natural gas respectively enable the establishment of an efficient and low-emission energy system, and also prevents investments in infrastructure [97]. Future research should include mapping the renewable energy potential and energy demand to develop the method for designing energy zones on the local and regional levels. Due to the exploited biomass potential future work should examine the potential of production of additional non-conventional biomass such as fast rotation plantation or algae. Moreover, further analysis should include other sectors and economic analysis of the implemented measures.

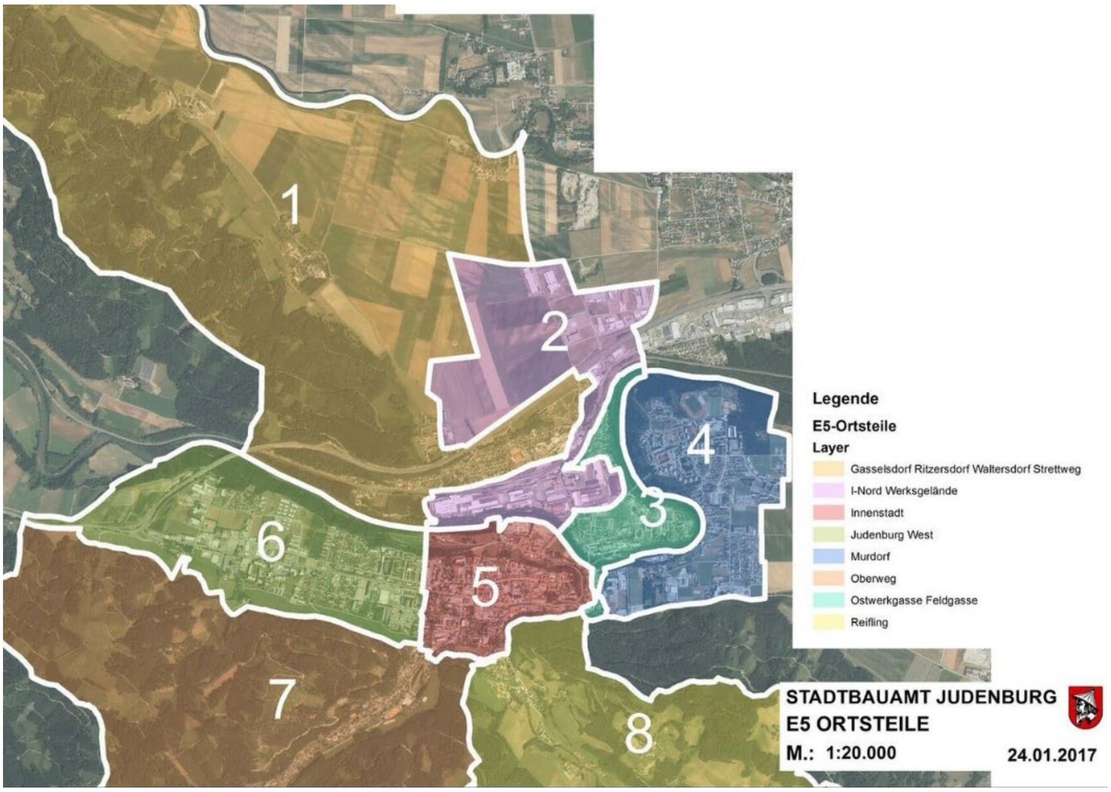

Figure 20 Map of Judenburg city with city zones (ARTICLE 3** [42]**)

2.4.3. Comparison of cost for individual and joint measures implementation

Since in the previous section was shown that the MLG approach has a positive influence on the implementation of one measure, in ARTICLE 1 a simple comparison between the implementation of measures was done on the level of one municipality and in a joint approach with several municipalities. The comparison is showing the potential importance of MLG in achieving economies of scale which can significantly reduce costs related to the implementation of mitigation measures. In the given case, from ARTICLE 1, the following measures from the household sector which are listed in Table 5 are compared: 1 - Co-financing of replacement of electric boilers with heat pumps, 2 - Insulation of buildings external envelope and roofs, 3 - Replacement of external woodwork in households and 4 - Introduction of small PV systems on the roofs. The biggest investment of individual measures does not cross 65 000 € which is a small amount for potential investors. With joint planning, the smallest amount is around 150 000 €. Even though this is still a relatively small amount it is 3 times bigger than the largest individual and therefore 3 times more interesting to potential investors. This shows that more municipalities in the area should join to make the measures more economical. Integration of four SECAPs and adding one more municipality into the initiative with this method shows good potential. Therefore, it is suggested to small municipalities, with a similar background integrate their current SECAPs with neighbouring local authorities to achieve the benefits that this approach provides. The second step that is suggested is the integration of SECAP with the Sustainable Urban Mobility Plan since this would additionally improve local energy planning on islands where transport is the biggest emitter of CO_2.

Table 5 Comparison of action costs in individual and joint SEAP (ARTICLE 1** [60]**)

	City of Korcula [47]	Municipality of Lumbarda	Municipality of Smokvica [48]	Municipality of Blato [49]	Municipality of Vela Luka [50]	The Island of Korcula
1	59 600 €	-	11 900 €	35 800 €	47 700 €	155 000 €
2	63 600 €	-	15 900 €	47 700 €	47 700 €	175 000 €
3	63 600 €	-	15 900 €	47 700 €	47 700 €	175 000 €
4	40 000 €	-	26 500 €	40 000 €	40 000 €	146 500 €

3. CONCLUSION AND FUTURE WORK

Tackling climate change on the local level requires additional effort from the local, but also regional and national governments. Through the development of sustainable energy action plans like SECAPs, this effort is quantified and described so that the local governments have guidebooks on how to successfully transform local energy consumption from fossil fuels to low carbon. Since this process is highly investment and financial intensive, local governments need effective tools to optimise their scarce resources to provide the biggest impact on the reduction of CO_2 emissions. This thesis presents a method for the optimal choice of measures in energy planning on the local and regional level through a modified cost abatement curve considering economic criteria. Additionally, it increases the accuracy of the visualisation of the choice of measures for emission reduction on the local and regional level for stakeholders and decision makers considering given evaluation criteria.

The objective of the thesis was achieved through several articles published in scientific journals depending on the different stages of the research. In the first phase, the analysis of the most used mitigation measures in sustainable energy action plans was done. The most used measures were preselected in ARTICLES 1 and 2 and then the final selection of measures which were divided into individual sets of measures was done in ARTICLE 4. The most used measures in ARTICLE 2 were used to analyse the relationship between potential measures for the reduction of energy consumption and CO_2 emissions in an individual assessment and the results of the scenario analysis, which takes into consideration the interaction between measures.

The results between individual potential analysis and scenario approach showed that the individual approach significantly overestimated measures potential in the analysed case. This provided the conclusion that most of the measures have a negative interaction with each other and that there could be needed additional efforts in SECAPs to reach given targets which would demand additional financial and human resources. With the use of the individual analysis of measures, a significant overestimation of the measure's reduction potential can be made. This can generate a significant error in the future calculation of CO_2 emissions if scenario analysis of measures interaction is not done.

Furthermore, the last scenario approach potentially means that current SECAP targets are overestimated and that measures planned in existing SECAPs will not reach expected CO_2 emissions reduction, which provides important insight both to academic research and practical implementation of SECAPs. If the development of the SECAP is done by using individual measures assessment, instead of a scenario approach, the city risks the possibility that their calculated reduction potential will not be achieved since mutual interaction between the measures is not considered.

Additionally, the interaction and integration of different measures were evaluated also in ARTICLE 4 and it was shown that transport sector measures for electrification need to be jointly implemented and that integrated renovation of the building does not reduce the cost of implementation and reaches a high reduction level due to the limited levels of CO_2 emissions from buildings in the analysed case study. Another integration of measures that should be further investigated is the joint implementation of adaptation and mitigation measures which will result in higher costs but could provide additional benefits in CO_2 and local pollution reduction. An option for this integration could be the use of the SET-Plan on the regional and local levels through MLG thus creating synergies between different stakeholders [100].

To further investigate the role of MLG governance in measures implementation this approach was tested in ARTICLE 3. The Austrian energy policy system showed that energy transition goals and pathways are in line with the global and European energy targets at all levels of authority from national, and provincial to local, namely cities and municipalities. Moreover, solid cooperation of different levels of governance from a top-down and bottom-up perspective has been observed. The general willingness of Austrian municipalities to take part in local energy actions is analysed through local initiatives. The review of the three ongoing local initiatives in the federal province of Styria enabled us to highlight the most important four areas for their implementation at various levels of governance.

These areas are namely territorial fragmentation, data availability, spatial energy planning and new integrated MLG governance. To overcome the lack of financial and human capacity of individual local authorities due to territorial fragmentation, the paper elaborates on the idea of restructuring the existing local energy initiatives. This means that local initiatives would allow the grouping of smaller local authorities while having the political support of the local authorities. This option is already available for the CoM signatories; however, the CoM initiative has a low rate of acceptance in Austria due to the other well-established initiatives.

Additionally, the lack of open energy data inevitable to design high energy plans makes it difficult to create quality strategies as well as sound monitoring of the implemented measures. The regulations on data availability must be set with clear guidelines at the top level of governance. Moreover, almost none of the local initiatives cover the area of spatial energy planning which is suggested as an important part of a holistic strategy for the energy transition. The utilisation of space and energy demand are directly interlinked and inseparable. Moreover, since the local authorities have a strong influence on the matter of spatial planning, it is argued that there is both the potential and the need to enhance spatial energy planning activities.

The proposed new integrated MLG action space serves as a background to accomplish suggested measures. It entails a combination of fixed old action space and new flexible action space. This means that a firm government structure would still define a clear framework while at the same time having enough flexibility to include all the territorial particularities of areas outside the strict administrative borders. The fixed action space should be enhanced through a constant feedback system to ensure that national and regional strategies are developed, taking into consideration all the aspects of the specific energy potential and demand of the local area.

The case study of Judenburg city showed how coordinated activities from higher and lower administrative levels could lead to accomplishing national, regional, and local energy goals. The need for spatial energy planning was especially outlined by considering the remaining potential of non-conventional biomass resources. Zoning the areas would not just enhance the most efficient use of the technology and measures but would enable the exploitation of the potential of RES in the most effective way.

Furthermore, in ARTICLE 1 the investments for measures in the household sector in joint and individual approaches were compared and it was concluded that achieving economy of scale with an integrated approach would accelerate their implementation. The integrated approach enables small neighbouring municipalities to develop one strategy and act together towards achieving goals taken by submitting to the Covenant of Mayors.

Finally, in ARTICLE 3 it is concluded that the results of the optimisation of measures are important to organise measures in order of implementation by prioritising lower-cost measures. This is achieved through the visualisation of the results via the total cost abatement curve which ranks measures from the most cost-effective to the least cost-effective. In this way, it could be possible to increase the overall implementation of SECAP measures.

Moreover, in this way, the lack of appropriate financial planning which is marked as the constant and most common element in existing SECAPs [72] is being reduced since lower financial means are required. total costs of the optimisation scenarios are much lower than the original, which shows that it is possible to reach the same or higher levels of CO_2 emission reduction with lower use of financial resources. This gives a positive answer to the hypothesis and concludes that with the use of optimisation models, it is possible to find such sets of measures and alternative scenarios, which will, with less financial means, reach a minimal reduction of CO_2 emissions by 40% in local and regional energy systems and result in significant financial savings. In this way, it could be possible to increase the overall implementation of SECAP measures and mitigate the problem of the lack of appropriate financial planning.

For further research, a similar process of comparing the potential between individual analysis of measures for CO_2 reduction and scenario analysis is recommended. For the better planning of the future SECAPs, there should be investigated a relationship between adaptation and mitigation measures which will result in higher costs but could provide additional benefits in CO_2 and local pollution reduction. Furthermore, the interaction of measures and optimisation should be integrated with the spatial planning and GIS systems so that the best measures are selected for each specific zone given by the spatial planners. Finally, updating and tracking the implementation of the measures in an automated way could be investigated since tracking progress for smaller municipalities and cities could demand significant human and financial resources.

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5. CURRICULUM VITAE

Nikola Matak was born on the 10th of August 1990 in Zagreb, Croatia, where he finished V. High school in 2009. In the same year, he started the undergraduate program in Mechanical Engineering at the Faculty of Mechanical Engineering and Naval Architecture, University of Zagreb. He finished the undergraduate program and began with the graduate study program in 2013., which he finished in 2015. The same year he started his PhD studies in the field of Process and Energy Engineering at the Faculty of Mechanical Engineering and Naval Architecture, University of Zagreb. He is currently employed at The International Centre for Sustainable Development of Energy, Water and Environment Systems – SDEWES Centre working as project manager on the project YENESIS – Youth Employment Network for Energy Sustainability in Islands. He also worked as a project manager for the projects COASTENERGY – Blue Energy in ports and coastal urban areas, JointSECAP – Joint strategies for Climate Change Adaptation in coastal areas and KeepWarm – Improving the performance of district heating systems in Central and Eastern Europe. Between 2017 and 2019 he worked as a research assistant at the Department of Energy and Power Engineering, Faculty of Mechanical Engineering and Naval Architecture, the University of Zagreb on the RESFLEX project funded by the Croatian Science Foundation. His research interests include energy planning and sustainable development on local, regional, and national levels as well as the development of innovative business models for the implementation of renewable energy projects. He participates in the organisation of the SDEWES conference series as a part of the local organising committee and is a co-author of 5 scientific papers and his h-index is 4.

List of published scientific journal papers:

Nikola Matak, Marko Mimica, Goran Krajačić: Optimising the Cost of Reducing the CO_2 Emissions in Sustainable Energy and Climate Action Plans, Sustainability 2022, 14(6), 3462, DOI: https://doi.org/10.3390/su14063462

Viktorija Dobravec, **Nikola Matak**, Christian Sakulin, Goran Krajačić: Multilevel governance energy planning and policy: a view on local energy initiatives, *Energy, Sustainability and Society* 11, 2 (2021). https://doi.org/10.1186/s13705-020-00277-y

Nikola Matak, Goran Krajačić: Assessment of mitigation measures contribution to CO_2 reduction in sustainable energy action plan, *Clean Technologies and Environmental Policy volume 22, pages 2039–2052 (2020)* https://doi.org/10.1007/s10098-019-01793-y

Nikola Matak, Goran Krajačić, Ana Marija Pilato: Integrating sustainable energy action plans for island municipalities: Case study of Korcula, *THERMAL SCIENCE:* Year 2016, Vol. 20, No. 4, pp. DOI: 1037-1048. 10.2298/TSCI151127109M

Nikola Matak, Tihomir Tomić, Daniel Rolph Schneider, Goran Krajačić: Integration of WtE and district cooling in existing Gas-CHP based district heating system – Central European city perspective, Smart Energy, Volume 4, November 2021, 100043, https://doi.org/10.1016/j.segy.2021.100043

6. SUMMARY OF ARTICLES

ARTICLE 1

Nikola Matak, Goran Krajačić, Ana Marija Pilato: Integrating sustainable energy action plans for island municipalities: Case study of Korcula, *THERMAL SCIENCE:* Year 2016, Vol. 20, No. 4, pp. DOI: 1037-1048. 10.2298/TSCI151127109M

The goal of the European Union is to reduce CO_2 emissions by 20% till 2020. This objective is transferred to municipalities through the Covenant of Mayors initiative which was established by the European Commission in 2008. In line with this, this paper presents an integration of Sustainable Energy Action Plans on the Croatian island of Korcula. This was developed through a methodology that uses factors, derived from the statistic, that have an influence on the energy consumption. Energy consumption and the Baseline CO_2 emissions inventory for municipalities on Korcula in the public sector, households, tertiary sector and road transport are calculated. Total CO_2 emissions for listed sectors in baseline 2012 are 42,923 tCO_2, and with recommended actions and measures this can be reduced by approx. 22% till 2020. There are planned joint actions, so all municipalities on the island can cooperate together to maximise their limited financial and human capacities. There has been suggested the establishment of action group for actions implementation which will include representatives from municipalities and other stakeholders. Investments for measures in household sector in joint and individual approach was compared and it was concluded that achieving economy of scale with an integrated approach would accelerate their implementation. The integrated approach enables small neighbouring municipalities to develop one strategy and act together towards achieving goals taken by submitting to the Covenant of Mayors.

In ARTICLE 1 Nikola Matak contributed with the conceptualization, methodology, analysis, investigation, visualization, software, resources, writing of the original draft, and editing of the revised manuscript. Assistant Professor Goran Krajačić was responsible for conceptualization, methodology, reviewing and editing of the revised manuscript, supervision, project administration and funding acquisition. Ana Marija Pilato contributed to the conceptualization, resources and editing of the revised manuscript. The paper was written by Nikola Matak and reviewed by Goran Krajačić and Ana Marija Pilato.

ARTICLE 2

Nikola Matak, Goran Krajačić: Assessment of mitigation measures contribution to CO_2 reduction in sustainable energy action plan, *Clean Technologies and Environmental Policy volume 22, pages 2039–2052 (2020)* https://doi.org/10.1007/s10098-019-01793-y

The paper shows the process of the development of the sustainable energy action plan (SEAP) for the city of Zagreb and analysis of the interaction between measures, which are used for the reduction in energy consumption and CO_2 emissions. The energy savings and CO_2 reduction potential of measures are compared in a scenario and individual approach. Sectors of energy consumption listed in SEAP are buildings, transport and public lighting. The buildings sector is divided into public buildings, residential and commercial buildings. The transport sector is subdivided on public transport, public vehicles and private and commercial transport. Measures for CO_2 emission reduction are selected by a discussion with relevant stakeholders and most effective measures from the previous SEAP. Mutual interaction between measures, which influences the total result of energy consumption and CO_2 emissions reduction, is done through simulation in LEAP. In this way, it can be shown that measures have either synergetic, negative or neutral interaction between them. The analysis showed the negative interaction is prevailing and scenario approach resulted in 16.23% lower CO_2 reduction potential than the individual assessment of each measure. It is recommended to use a scenario approach in the development of SEAP for the assessment of measures CO_2 reduction potential. This will provide more efficient planning of measures for the reduction in CO_2 emissions on a local level and avoid overestimating of the CO_2 reduction potential when developing SEAPs.

In ARTICLE 2 Nikola Matak contributed with the conceptualization, methodology, analysis, investigation, visualization, software, resources, writing of the original draft, and editing of the revised manuscript. Assistant Professor Goran Krajačić was responsible for conceptualization, methodology, reviewing and editing of the revised manuscript, supervision, project administration and funding acquisition. The paper was written by Nikola Matak and reviewed by Goran Krajačić.

ARTICLE 3

Viktorija Dobravec, **Nikola Matak**, Christian Sakulin, Goran Krajačić: Multilevel governance energy planning and policy: a view on local energy initiatives, *Energy, Sustainability and Society* 11, 2 (2021). https://doi.org/10.1186/s13705-020-00277-y

Background: A sustainable energy system based on renewables, energy-efficiency, decentralisation of energy generation and synergies between different sectors requires new energy planning methods and policies. Energy transition and climate change mitigation achievement can no longer be seen only through top-down activities from a national government. Local and regional governments have a crucial role in delivering public policies relevant to such endeavour. Therefore, the implementation of multilevel governance (MLG) has become a priority for fostering local and regional development more inclusively. Paper analyses the existing energy planning governance in Austria throughout the MLG structure by focusing on the alignment between the local energy and climate initiatives and the national and EU goals. Also, the paper examined the effectiveness of the current MLG structures and outlined the fields where improvements are needed. The successfulness of the MLG approach is shown on Judenburg city case study. Desk research is enhanced by a series of interviews with energy policy experts and implementation of case study measures in TIMES model.

Results: The MLG analysis showed the solid alignment of different governance levels. In contrast, the comparison of the energy and climate initiatives on the local level outlined recommendations for the design of more effective energy planning approach. Four areas of action are identified for further improvement: territorial fragmentation, data availability, spatial energy planning and new integrated MLG. The remaining non-conventional biomass potential of the Murtal region is enough to increase the share of district heating for the residential buildings of the Judenburg city from 16.3 to 30.8% while the building refurbishment increases district heating share to 32%.

Conclusion: Application of MLG analysis demonstrated the alignment of energy targets in Austrian policy on different governance levels. The general willingness of Austrian municipalities to take part in local energy actions was shown through the local initiatives' analysis. It is argued that strengthening the listed areas of work is necessary to raise the effectiveness of the local initiatives. The case study for the city of Judenburg developed in the TIMES model confirmed that coordinated actions from different levels of governance lead to effective implementation of measures.

In ARTICLE 3 Nikola Matak contributed to the analysis, conceptualization, methodology, visualization and editing of the revised manuscript. Viktorija Dobravec contributed with the conceptualization, methodology, analysis, investigation, visualization, software, resources and writing of the original draft. Assistant Professor Goran Krajačić was responsible for conceptualization, methodology, reviewing and editing of the revised manuscript, supervision, project administration and funding acquisition. Christian Sakulin contributed to the conceptualization, resources and editing of the revised manuscript. The paper was written by Viktorija Dobravec and Nikola Matak and reviewed by Nikola Matak, Goran Krajačić and Criastian Sakulin.

ARTICLE 4

Nikola Matak, Marko Mimica, Goran Krajačić: Optimising the Cost of Reducing the CO_2 Emissions in Sustainable Energy and Climate Action Plans, Sustainability 2022, 14(6), 3462, DOI: https://doi.org/10.3390/su14063462

Tackling climate change can be achieved through local and regional initiatives, such as the Covenant of Mayors, which create energy and climate plans with mitigation measures. Upon the development of energy plans, the mitigation of greenhouse gas emissions (GHG) can be achieved through an individual or joint approach. The research aims to upgrade methods for local and regional energy planning through the choice of mitigation actions and alternative scenarios for the reduction of GHG emissions. This is achieved through optimisation of the selection of mitigation measures in the case of the wider Dubrovnik area in Croatia by choosing the most suitable option for implementation when comparing individual and joint approaches for the planning of the measures. Moreover, the implementation of single and sets of mitigation measures is compared through the total cost abatement curve. The modelled problem represents a non-linear problem as exponential functions and multiplication of variables occurs in the modelled equations. Visualisation of the results is achieved via the total cost abatement curve which ranks measures from the most cost-effective to the least cost-effective. It is shown that with the use of optimisation models, it is possible to find such sets of measures and alternative scenarios, which will, with less financial means, reach a minimal reduction of CO_2 emissions by 40% in local and regional energy systems and result in financial savings of three times in the analysed case. In this way, it could be possible to increase the overall implementation of SECAP measures and mitigate the problem of the lack of appropriate financial planning.

In ARTICLE 4 Nikola Matak contributed with the conceptualization, methodology, analysis, investigation, visualization, software, resources, writing of the original draft, and editing of the revised manuscript. Marko Mimica contributed to the conceptualization, methodology and software. Assistant Professor Goran Krajačić was responsible for conceptualization, methodology, reviewing and editing of the revised manuscript, supervision, project administration and funding acquisition. The paper was written by Nikola Matak and reviewed by Goran Krajačić and Marko Mimica.

ARTICLES

ARTICLE 1

Preprint of the published journal article.

INTEGRATING SUSTAINABLE ENERGY ACTION PLANS FOR ISLAND MUNICIPALITIES: CASE STUDY OF KORCULA

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The goal of the European Union is to reduce CO_2 emissions by 20% till 2020. This objective is transferred to municipalities through the Covenant of Mayors initiative which was established by the European Commission in 2008. In line with this, this paper presents an integration of Sustainable Energy Action Plans on the Croatian island of Korcula. This was developed through a methodology that uses factors, derived from the statistic, that have an influence on the energy consumption. Energy consumption and the Baseline CO_2 emissions inventory for municipalities on Korcula in the public sector, households, tertiary sector and road transport are calculated. Total CO_2 emissions for listed sectors in baseline 2012 are 42 923 tCO_2, and with recommended actions and measures this can be reduced by approx. 22% till 2020. There are planned joint actions, so all municipalities on the island can cooperate together to maximise their limited financial and human capacities. There has been suggested the establishment of action group for actions implementation which will include representatives from municipalities and other stakeholders. Investments for measures in household sector in joint and individual approach was compared and it was concluded that achieving economy of scale with an integrated approach would accelerate their implementation. The integrated approach enables small neighbouring municipalities to develop one strategy and act together towards achieving goals taken by submitting to the Covenant of Mayors.

Key words: *Covenant of Mayors, CO_2 emissions inventory, island of Korcula, individual approach, integrated approach, comparison*

1. Introduction

The Covenant of Mayors initiative was established by the European Commission in 2008, after the adoption of the 2020 EU Climate and Energy Package, to help municipalities in the implementation of sustainable energy policy [1]. The goal of the initiative is to reduce CO_2 emissions by 20% till 2020 which is in accordance with the EU 20-20-20 goal. This is the biggest initiative in the Europe of this type which gathered 6 620 municipalities and more than 211 million citizens in November 2015 [1]. In the process are also included covenant supporters, coordinators and others, which help municipalities to bring and implement Sustainable Energy Action Plans (SEAPs). Their number was more than 370 [1]. Most of the municipalities have less than 50 000 residents and they make out more that 88% of the initiative. In Croatia, the initiative gathers 60 municipalities, which included 8 of the 10 largest cities, and more than 2.5 million citizens [2].

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Local energy planning, that the Covenant of Mayors is supporting, has not been thoroughly analysed in the literature [3], even though local authorities can have a significant influence on the reduction of energy consumption and GHG emissions [4]. An energy policy that is focused on utilizing the strong potential of renewable energy and energy efficiency can strengthen local capacities for energy production [5]. Recommendations for further research in this area are given in [6] and they include the development of standardised methodologies for tracking emissions on a local level, the introduction of different indicators, a collection of microclimate data and support for involving citizens and stakeholders. Lack of communication and information available to the citizens has been pointed out as the main issue, but once citizens were properly informed they strongly supported activities carried out by the Covenant initiative. Regarding the development and implementation of SEAP in rural communities, main issues, needs and priorities are given and explained in several cases in [7].

The most important steps in developing SEAP according to [8] are the analysis of the present situation, present and future energy and CO_2 balance and estimation of reduction potential; a strategy to reach targets, with targets' definition, measures and implementation plan; and a regular plan's monitoring. Estimation of current energy consumption and emissions status can be done with a developed method for tracking GHG emissions in cities [9], or using a system which is developed for countries [10]. Each of these methods requires large amounts of input data and neither is adjusted to smaller municipalities that are mostly joining the Covenant [2], as it is the case in this paper. A methodology that characterises energy systems at the regional level and that takes into account policy background, energy uses, infrastructures, market behaviour and community attitude for sustainable development is developed in [11]. A lack of good input data is analysed in [12] where it is identified to being a big problem. Methodology and a tool for the calculation of energy consumption and GHG emissions for the development of sustainable local energy and climate plans are tested and presented in [13]. Methods for assessing energy consumption and emissions for residential sector are developed in [14]. For estimation of GHG emissions from statistical data available in Finland, Monni and Syri [15] developed a methodology that could be altered and used in other cases. Estimation of emissions from public buildings could be done based on methodology presented in [16] and for road traffic, a methodology is developed in [17]. Municipal policy support for the bioenergy projects in the area of direct support of innovation, infrastructure, regulation (protection and standards) and public engagement in the case of Norway is show by Rygg in [18]. On the other hand, problems with lack of municipal support and the role of public administration which has to set example to private sector in reducing GHG emissions is analysed in [19], and problems with lack of citizens support and development of sustainable urban mobility plans in transport sector that are not connected with Covenant is pointed in [20]. More tools and methods for small municipalities that are developing SEAP needs to be developed, according to Amorim in [8], since they play an important role in the local energy planning [21]. One of the tools that can be helpful for local governance officers in local RES planning is developed in [22].

When looking at emissions reduction, implementation of energy efficiency and renewable energy sources, it is shown in [23] that large cities and more urban areas have a higher potential for reduction of emissions and energy efficiency, but small municipalities can implement more renewables. Choice of actions and measures for reduction of CO_2 and implementation of renewables was analysed in [24] and new methodology for selection of actions is proposed in [25]. Penetration of more renewables could be increased with the implementation of smart grid technology similar to one described in [26]. One of the key measures that are implemented in all municipalities is the replacement of public lightning and it is recommended to follow the methodology developed in [27] when dealing with this measure. The selection of most cost effective measures and ones that should be implemented later is given in [28]. Finally, tracking the emission reduction can be done with different types of indicators that are introduced in [29] and [30] where are given indexes for tracking the current sustainability status of the local communities. Another index that could be used is the SDEWES index [31] and [32] which tracks seven different types of sustainability in cities.

Municipalities can join the Covenant individually or jointly with neighbouring municipalities – denoted Option 1 and Option 2 respectively. Joint SEAP is targeting neighbouring municipalities with less than 10 000 inhabitants and urban agglomerations with suburbs and gravitating satellite administrative areas [33]. There are currently 71 groups of municipalities that have made a joint approach, of which 65 have joined according to the option 2 [33]. Municipalities, which jointly approached, didn't try to integrate individual approach to get joint SEAP, as it is done in this paper. Generally, all documents and tasks in joint option 2 are done shared for all municipalities that are in the group, except submission of SEAP City Council Approval. This is different from the individual and joint approach option 1 where almost everything is done individually, as shown in Table 1. This paper will compare individual and joint measures developed in SEAP since it has been noticed that there could be achieved benefits for small municipalities if they decide to join the initiative together.

Table 1. Differences in the ways of joining the initiative [33]

	Individual SEAP	Joint SEAP option 1	Joint SEAP option 2
CO_2 Emissions reduction target	Individual	Individual	Shared
Emission Inventory	Individual	Individual	Shared
SEAP Actions	Individual	Shared	Shared
SEAP City Council Approval	Individual	Individual	Individual
SEAP Template Submission	Individual	Individual	Shared
SEAP Document Submission	Individual	Shared	Shared
Signatory profile in the Website	Individual	Individual	Shared

This paper presents indicators that are used for the calculation of Baseline emissions inventory and compares the two different types of the joining the Covenant of Mayors initiative, individual and joint approach. Firstly, it will be described the process of joint approach to the Covenant of Mayors, with outlining the four characteristic phases: initiation phase, planning phase, implementation phase and monitoring and reporting phase. Then factors used for the calculation of energy consumption and emissions for the area chosen are presented. Main results in the form of the emissions calculated with the presented factors are given and possible reductions in CO_2 emissions are presented by sectors. Comparison between the two different types of the approaches in the initiative for the presented case is given together with a discussion on the best way for small municipalities to join the initiative. Finally, in the conclusion, main results of the joint approach are presented, differences between joint and individual approach are outlined with the possibilities for future work in the area.

2. Methods

Here are described the factors that are used for the creation of Baseline Emissions Inventory and the method that is used for the development of the joint SEAP. There are four phases in the joint SEAP process and they will be shortly described. Everything starts with municipalities signing the Covenant Adhesion Form, but this time as a part of the group of municipalities instead of an individual. According to the joint approach by option 2, group of municipalities is making one BEI and one SEAP which has to contain joint measures. In the initiation phase, it is important to secure political commitment with the signing of the Covenant. Administrative municipal structures should be adapted to address all necessary challenges and organized in action group which will include representatives from all municipalities, regional authority, local action group, regional and local development agencies, different associations, citizens and other stakeholders from the municipalities that have decided to join together in the group. There should be selected coordinator of the group and external support from the educational, scientific and the developing institutions should be secured. The coordinator of the group should be chosen from the regional authority/agency that is responsible for all municipalities included in the joint approach, rather than from the one of the municipalities. It is very important that the SEAP is compliant with other strategic documents and initiatives of the local government and administrative departments.

2.1. Calculation BEI and SEAP

Planning phase comes second with the development of BEI and SEAP. There needs to be chosen baseline year for SEAP and data on the energy consumption collected or calculated. Data are estimated according to the methodology described below. Sectors of energy consumption are divided into public buildings, public lighting, households, commercial, public transport, government vehicles and other road transport. Energy consumption of commercial and household sector is estimated for all fuels except electricity for which data was provided. Consumption of other fuels was calculated from county level by using many statistical parameters. Consumption of biomass was estimated with factor f_1 shown in the eq. (1), where USP_{opc} is a total living area in the municipality, USP_{zup} in the county, PNS_{opc} is an area of abandoned apartments in the municipality and PNS_{zup} in the county. Factor f_1 represents the ratio of the heating area that is used in county and municipality.

$$f_1 = \frac{USP_{opc} - PNS_{opc}}{USP_{zup} - PNS_{zup}} \tag{1}$$

The second factor used for estimation of biomass is f_2 shown in the eq. (2), where S_{opc} is a number of citizens in the municipality and S_{zup} in the county. This factor gives the ratio between a number of the citizens that live in the municipality and the county.

$$f_2 = S_{opc}/S_{zup} \tag{2}$$

Consumption of biomass is estimated with the eq. (3), where B_{zup} is consumption of biomass in the county.

$$B_{opc} = \frac{f_1 + f_2}{2} \cdot B_{zup} \tag{3}$$

Factors used for estimation of fuel oil and liquefied petroleum gas (LPG) in households are shown in eq. (4), eq. (5) and eq. (6). Factor f_3 is calculated with the eq. (4), where N is a number of tourists overnight stays in municipality and county. This factor represents the ratio between tourist overnight stays in the municipality and in the county.

$$f_3 = N_{opc}/N_{zup} \tag{4}$$

Factor f_4 is calculated according to eq. (5), in which NS is a number of settled apartments, PNS is a number of temporarily settled apartments, SOR is a number of apartments for recreation and rest, SIT is a number of apartments for renting to tourists, and SOD is a number of apartments for other activities. Factor f_4 represents the ratio between a number of apartments in the municipality and the county that are used at least for a couple of months during the year.

$$f_4 = \frac{NS_{opc}+PNS_{opc}+SOR_{opc}+SIT_{opc}+SOD_{opc}}{NS_{zup}+PNS_{zup}+SOR_{zup}+SIT_{zup}+SOD_{zup}} \tag{5}$$

Factor f_5 is calculated in a way shown in eq. (6), where OS is a number of well-equipped apartments, those that have kitchen and bathroom and toilet. It represents the ratio of well-equipped apartments in the municipality and in the county.

$$f_5 = OS_{opc}/OS_{zup} \tag{6}$$

Consumption of LPG in households in the municipality is calculated by eq. (7).

$$UNP_{opc} = \frac{f_1+f_2+f_3+f_4+f_5}{5} \cdot UNP_{zup} \tag{7}$$

Consumption of fuel oil in households is calculated by eq. (8).

$$LO_{opc} = \frac{f_1+f_2+f_3+f_4+f_5}{5} \cdot LO_{zup} \tag{8}$$

Consumption of LPG and fuel oil in the commercial sector is estimated by eq. (9).

$$USL_{opc} = \frac{f_2+f_3}{2} \cdot USL_{zup} \tag{9}$$

Consumption in other road transport is estimated by eq. (10), in which BV is a number of vehicles of a specific type in the municipality, SPG is a specific consumption of that type of vehicle in the municipality, and PBK is the average number of yearly passed kilometres of that type of vehicle. Consumptions are separately calculated for diesel and petrol fuel, and there were 4 types of vehicles: mopeds and motorcycles, cars, light trucks (<3.5 tonnes) and heavy trucks.

$$P_G = \sum_{tip=1}^{4} \frac{BV_{tip} \cdot SPG_{tip} \cdot PBK_{tip}}{100} \tag{10}$$

Calculation of CO_2 emissions is compliant with Intergovernmental Panel for Climate Change (IPCC) and used emission factors are shown in Table 2. A tool used for emissions calculation is ICLEI Europe's Basic Greenhouse Gas Inventory Quantification Tool. For electricity emission factor, it is used national factor for 2012 [34] since that year is chosen for baseline year. Measures proposed for reduction of CO_2 emissions are chosen according to the measures and actions from [35] and [36], other measures are selected from standard measures from the Croatian Environmental Protection and Energy Efficiency Fund (EPEEF) [37]. National Action Plan for Renewable Energy Sources [38], Energy Strategy of the

Republic of Croatia [39], Programme of Energy Renovation of Family Houses [40], SEAPs [1] of other Adriatic municipalities and Guidebook [41] were used for selection of additional measures. Production of electricity from photovoltaics was estimated by using PVGIS calculator [42].

Table 2. CO_2 emission factors used for calculation [41]

Fuel type	CO_2 emission coefficient, [g/kWh]
Electricity	310
LPG	227
Fuel oil	279
Petrol	249
Diesel	267
Biomass	0.468

2.2. Approval, implementation and monitoring of plan

Approval of the plan by the municipal council is a most important step for SEAP implementation. With joint approach according to the option 2 municipalities on the island are making a commitment that they will together act towards the achieving goals taken by joining the initiative. For the monitoring of the Action plan every two years, there should be submitted a monitoring report to the Covenant of Mayors Office. At least every four years, action group must submit Monitoring Emissions Inventory (MEI) and action group with representatives of the municipalities is responsible for SEAP implementation.

3. Results

The results of the described methodology are tested in the case of the island of Korcula and main outcomes are presented. Energy consumption for the baseline year with emissions of CO_2 is calculated. Local energy production and the potential for implementation of RES are analysed. There are presented measures for the reduction of the emissions for at least 20% till 2020. This was done so that results could be compared with the results of the individual approach to the initiative that the municipalities located on the island have done. In the last paragraph, the cost of measures and potential for investment is compared between joint approach for all public authorities on the island and individual joining. This was done for the selected measures from the household sector because they are most common for the reduction of CO_2 emissions.

3.1. Case of the Korcula island

The island of Korcula is located in the south of Croatia in Dubrovnik-Neretva County and is the sixth island by size in Croatia with an area of 279 km^2 [43]. Administratively it is divided into one city and four municipalities which together have 15 521 inhabitants. Municipalities that are located on the island are Vela Luka, Blato, Smokvica and Lumbarda, and the City of Korcula which is the largest local administration on the island. Municipalities of Vela Luka, Blato and Smokvica, and the City of Korcula have developed SEAP with help from UNIZAG FSB and this paper is used to compare two different ways to join the initiative, and integration of individual SEAPs.

3.2. Local energy consumption and production

Final energy consumption of the island of Korcula in 2012 was estimated at 176 GWh and by sector and fuel type is shown in Table 3. If we look at this consumption by sectors, highest consumption has the sector of the other road transport, 78 788 MWh and his share is 44.68%. It is followed by the households with a share of 37.53% and the commercial sector with 15.16%. Public sectors have shares lower than 1%, and together they have a share of 2.63%. By fuel type, highest consumption is of electricity with a share of 32.92%. It is followed by diesel, 27.99% and petrol with 17.66%. On the island of Korcula, there are not located big power plants or similar facilities. According to the available data, the only energy produced on the island was from solar collectors for heating of the hot water and in 2012, it was estimated at 78 MWh. In the City of Korcula is installed PV plant Gojko Arneri with 50 kW of installed capacity, but it was not operational in 2012. The average yearly value of insolation at the horizontal surface is from 1.5 to 1.55 MWh/m^2, and for optimal slope, from 34° to 36°, this is from 1.69 to 1.93 MWh/m^2, which represents big solar potential. Wind potential also exists, but the law is very restrictive regarding construction of wind farms on islands. Biomass from wood is mostly used because 30% of the households is heating on it. Since agriculture is very important on the island there should be tested the potential of producing energy from leftovers after production of wine and olive oil. Geothermal energy has a low gradient but it could be used for ground source heat pumps [44].

Table 3. Energy consumption by sector and fuel type

Sector/Fuel type [MWh]	Electricity	LPG	Fuel oil	Biomass	Petrol	Diesel	Total
Public buildings	595	309	336	-	-	-	1 240
Public lightning	1 680	-	-	-	-	-	1 680
Households	34 384	4 423	4 924	22 440	-	-	66 171
Commercial	21 630	997	4 343	-	-	-	26 733
Government vehicles	-	-	-	-	59	444	502
Public transport	-	-	-	-	-	1 220	1 220
Other road transport	-	-	-	-	31 088	47 701	78 788
Total	58 052	5 729	9 603	22 440	31 146	49 365	176 335

3.3. Baseline Emissions Inventory

Total emissions in the analysed sectors on the island of Korcula for 2012 were 42 923 tCO_2, from which 1 328 tCO_2 was from public sector giving it a share of 3.1%. For each sector, share of the emissions is given in Figure 1. Emissions, consumption of energy, energy intensity, the share of the emissions and average emissions per resident are shown over fuel type in Table 4. Most of the emissions, 17 996 tCO_2, comes from the electricity consumption and they have a share of 41.8%. It is followed by diesel and petrol fuel with shares of 30.7% and 18.1%. Average energy consumption per resident on the island of Korcula is 11 361 kWh, which is lower than national average without industry, air, railroad and sea transport, that is 12 814 kWh [45], [34]. Average emissions per resident on the island are 2.774 tCO_2 which is also lower than the national average from the energy sector, 3.956 tCO_2 [46]. This had to be taken with reservation because some sectors like industry, other transport, agriculture and construction are not taken into account in the SEAP.

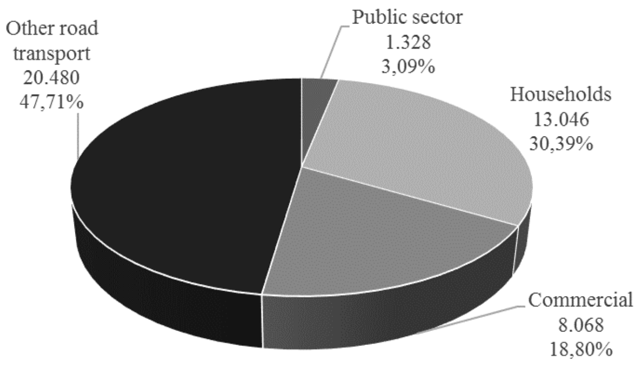

Figure 1. CO_2 emissions by sectors

Table 4. Emissions, energy consumption, emissions share, average emissions and energy consumption by fuel type

Fuel type	Emissions [tCO_2]	Consumption [MWh]	Emissions share [%]	Average emissions [tCO_2/resident]	Average consumption [MWh/resident]
Electricity	17 996	58 052	41.80%	1.159	3.740
Fuel oil	2 676	9 603	6.21%	0.172	0.619
Diesel	13 169	49 365	30.68%	0.848	3.181
Petrol	7 770	31 146	18.10%	0.501	2.007
LPG	1 301	5 729	3.02%	0.084	0.369
Biomass	11	22 440	0.02%	0.001	1.446
Total	42 923	176 335	100.00%	2.765	11.361

3.4. Actions and measures for the reduction of CO_2

34 measures were selected for the reduction of CO_2 on the island and they are going to be listed in Table 5. In the public sector, there were selected 11 measures and their contribution to reductions of CO_2 by 2020 is 416 tCO_2 which will result in a reduction from baseline year for 31.36%. Modernization of the public lighting will be contributing mostly to the reduction of CO_2 emissions because of necessary reconstruction of lightning in the City of Korcula. In the household sector, nine measures were selected. They will reduce emissions by 25.37% in this sector by 2020, compared to the baseline year. This reduction will be mostly contributed by replacement of inefficient indoor lighting and replacement of household devices with more efficient ones, for which EPEEF gives subsidies [37]. In the commercial sector, measures will bring a reduction of emissions by 1 032 tCO_2 till 2020. This reduction is mostly related to the reduction of electricity consumption and the local production of electricity from PV systems. Measures for the road transport sector will reduce emissions by around 22.92%. This is mostly achieved by introduction of the biofuels and the eco-driving education.

Table 5. Measures

Name of the measure	Energy saved /produced [MWh]	Emissions reduced [tCO_2]
For the public sector		
Replacement of existing lights with more efficient ones	54.8	16.99
Introduction of solar collectors for hot water and heating	41.1	12.74
Replacement of fuel oil boilers with biomass/heat pumps	101	26.79
Insulation of buildings external envelope and roofs	49.59	15.37
Replacement of external woodwork in public buildings	12.39	3.84
Education of public employees	61.99	19.22
Introduction of small PV systems on roofs	67.4	20.9
Implementation of green public procurement	9.92	3.07
New vehicles according to green public procurement	71.8	23.93
Biofuel in public transport	fuel replacement	65.11
Modernization of public lightning	672.04	208.33
Total	1 142	416.3
For the residential sector		
Replacement of existing lights with more efficient ones	4 433	1 374
Co-financing of solar collectors for citizens	393.75	122.06
Co-financing of replacement of el. boilers with heat pumps	175.95	54.54
Insulation of buildings external envelope and roofs	316.68	98.17
Replacement of external woodwork in households	105.55	32.72
Replacement of appliances with more efficient ones	3 438	1 066
Education of citizens and organization of energy days	1 323	261
Introduction of small PV systems on the roofs	594	184.14
Organization of energy cooperatives for citizens	379.08	117.51
Total	11 159	3 310
For the commercial sector		
Replacement of existing lights with more efficient ones	598.82	185.6
Organizing apartment renters into energy cooperative	147.03	44.38
Construction of large PV plants on island	1 460	452.6

Insulation of buildings external envelope and roofs	667.26	201.39
Replacement of external woodwork in buildings	166.81	50.35
Introduction of small PV systems on the roofs	102.3	31.71
Installation if reactive power compensators	213.94	66.32
Total	3 356	1 032
For the transport sector		
Promotion of the car sharing model on the island	588.15	152.88
Promoting the purchase of electric vehicles	1 333	346.54
Construction of bike paths and promotion of bicycles	49.74	12.93
Introduction of 10% biofuels in the transport	fuel replacement	1 888
Promotion of public transportation	2 353	611.53
Promotion of electric bicycles with solar chargers	2 531	657.82
Eco driving education of drivers	3 939	1 024
Total	10 794	4 694

3.5. Comparison of expenses for individual and joint measures

Several measures were compared from the household sector in Table 6: 1 - Co-financing of replacement of el. boilers with heat pumps, 2 - Insulation of buildings external envelope and roofs, 3 - Replacement of external woodwork in households and 4 - Introduction of small PV systems on the roofs. The biggest investment of individual measures does not cross 65 000 € which is a small amount for potential investors. With joint planning, smallest amount is around 150 000 €. Even though this is still relatively small amount it is 3 times bigger than largest individual and therefore 3 times more interesting to the potential investors. This shows that more municipalities in the area should join to make the measures more economical. Integration of four SEAP and adding one more municipality into the initiative with this method shows a good potential. Therefore, it is suggested to the small municipalities, with a similar background to integrate their current SEAPs with neighbouring local authorities to achieve benefits that this approach provides. The second step that is suggested is the integration of SEAP with Sustainable Urban Mobility Plan since this would additionally improve local energy planning on islands where transport is the biggest emitter of CO_2.

Table 6. Comparison of action costs in individual and joint SEAP

	City of Korcula [47]	Municipality of Lumbarda	Municipality of Smokvica [48]	Municipality of Blato [49]	Municipality of Vela Luka [50]	The Island of Korcula
1	59 600 €	-	11 900 €	35 800 €	47 700 €	155 000 €
2	63 600 €	-	15 900 €	47 700 €	47 700 €	175 000 €
3	63 600 €	-	15 900 €	47 700 €	47 700 €	175 000 €
4	40 000 €	-	26 500 €	40 000 €	40 000 €	146 500 €

4. Conclusion

Integrated SEAP gives small municipalities possibility to make one strategic document with common goals, which enables them to have less utilization of their limited human and financial resources. For the implementation of more complex measures, this removes administrative boundaries and supports mutual communication and cooperation between neighbouring municipalities. There can also be achieved knowledge transfer between more advanced municipalities in the area to ones less advanced.

There was analysed consumption in four municipalities and one city on the island of Korcula. Final energy consumption in baseline 2012 was estimated to be 176 GWh and this comes from seven analysed sectors. Electricity is most common used fuel with a share in consumption of 32.92%, but most energy is consumed in road transport sector. Total emissions from analysed sectors are 42 923 tCO_2, which means that each citizen emits 2.765 tCO_2 yearly. Total reduction of emissions which can be achieved by proposed measures is 9 453 tCO_2, which is a reduction of 22.02% till 2020 which is shown on Figure 2.

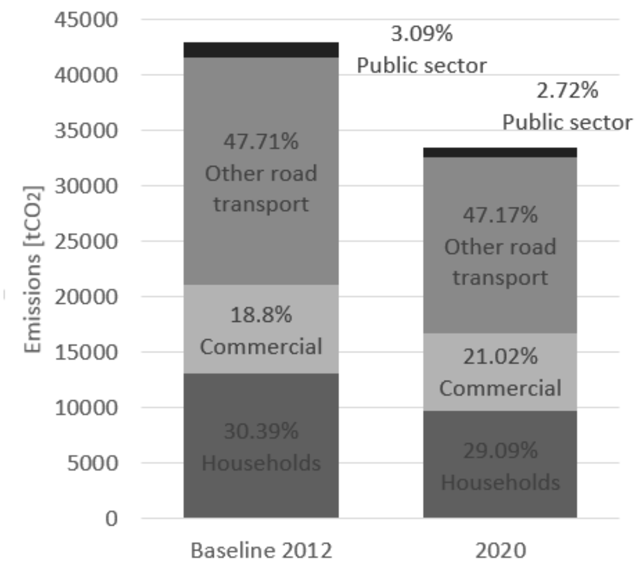

Figure 2. CO_2 emissions by sectors in 2012 and 2020

The integrated approach in the Croatian case for rural municipalities can be easily done with Local Action Groups (LAGs) [51]. There is currently 61 LAG and they are covering almost all territory in Croatia, except large cities. Their task is to encourage local sustainable development so that development of SEAP could be an additional tool which will bring them closer to achieving their goals. One of the biggest advantages of an integrated approach is a joint planning of measures that are increasing and thus achieving possibility to aces EU funds and simplifies planning process. With joint procurement, there can be achieved economy of scale which will reduce expenses. Educational activities are easier to plan on the island scale and there is achieved the easier transfer of knowledge between municipalities. This also simplifies procedures for construction of larger RES plants that are crossing the border of one municipality. With a joint approach to the Covenant of Mayors, small municipalities which do not have enough human or financial capacity are joining their capacities and can more efficiently act on the reduction of CO_2 emissions, an increase of energy efficiency and penetration of RES.

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ARTICLE 2

Preprint of the published journal article.

Assessment of mitigation measures contribution to CO_2 reduction in Sustainable energy action plan

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ABSTRACT

The paper shows the process of the development of the Sustainable Energy Action Plan (SEAP) for the city of Zagreb and analysis of the interaction between measures, which are used for the reduction of energy consumption and CO_2 emissions. The energy savings and CO_2 reduction potential of measures are compared in a scenario and individual approach. Sectors of energy consumption listed in SEAP are buildings, transport and public lighting. The buildings sector is divided into public buildings, residential and commercial buildings. The transport sector is subdivided on public transport, public vehicles and private and commercial transport. Measures for CO_2 emission reduction are selected by a discussion with relevant stakeholders and most effective measures from the previous SEAP. Mutual interaction between measures, which influences the total result of energy consumption and CO_2 emissions reduction, is done through simulation in LEAP. In this way, it can be shown that measures have either synergetic, negative or neutral interaction between them. The analysis showed the negative interaction is prevailing and scenario approach resulted in 16.23 % lower CO_2 reduction potential than the individual assessment of each measure. It is recommended to use a scenario approach in the development of SEAP for the assessment of measures CO_2 reduction potential. This will provide more efficient planning of measures for the reduction of CO_2 emissions on a local level and avoid overestimating of the CO_2 reduction potential when developing SEAPs.

KEYWORDS

CO_2 mitigation, Sustainable Energy Action Plans, local energy planning, the interaction of measures, scenario approach

INTRODUCTION

Sustainable energy planning at a local level is first time seen, at some level, after the 1970s as a direct consequence of the energy crisis and change caused by an understanding of the limited amount of fossil fuels and human influence on the environment and climate (Lerch et al. 2017). A serious approach to the sustainable local energy planning is noticed during the last 10 years, and especially after the European Commission started the Covenant of Mayors initiative. The energy and climate goal of the European Union (European Commission 2014), 20 % reduction of CO_2 emissions, 20 % improvement in energy efficiency, and 20 % share of renewables, till 2020 can be most easily achieved by planning the sustainable development on a local level, due to a bottom-up approach, direct investments and implementation. It is concluded that local governments have a crucial role in the mitigation of climate change (Global Covenant of Mayors 2018). This goal is further transferred to the new European goal for 2030 (European Comission 2018) which are currently set at 40 % CO_2 emissions reduction, 32 % share of renewables and 32.5 % improvement in the energy efficiency. Sustainable development, which should be achieved by the implementation of local plans consists of three main pillars: economy, society and environment. Energy is interacting with all three of them. The economy depends on it, and it influences the development of society and the environment. This is seen through influence on the production cost of manufacturing, mobility, increasing of living standards, air, water and soil quality. The connection between the positive influence of renewable energy consumption in the EU countries on the long term is shown by Saad and Taleb (2018). This shows that renewables have an essential role in stimulating economic growth.

Despite the growing number of local energy plans, this area has not been adequately documented in the scientific literature (Neves et al. 2015). Even though local authorities can have a considerable influence on the reduction of energy consumption and greenhouse gas emissions (GHG) emissions, as shown by Azevedo and Leal (2017). A local energy policy that is focused on utilising the strong potential for renewable energy and energy efficiency can strengthen local capacities for energy production (Hasovic et al. 2015). For those reasons, it is necessary to encourage local and regional governments to use efficient, standardised methods when developing sustainable local energy plans. Recommendations for further research in this area are given in Pasimeni et al. (2014). Recommendations include the development of standardised methodologies for tracking emissions on a local level, like ISO 37120 standards (Kona et al. 2015), the introduction of different indicators for monitoring the goals of sustainable energy plans (Cipriano et al. 2017), SDEWES index which can be used for monitoring and setting baseline (Kilkis 2015), a collection of microclimate data as a support for local planning and involving citizens and stakeholders.

This paper shows the process of the development of SEAP and the calculation of future energy consumption and CO_2 emissions, both in business as usual and in the scenario with measures. The main objective of the study is to compare the energy and CO_2 emissions reduction potential of selected measures when potential is calculated for each measure individually and in a scenario approach. The goal of this comparison is to investigate do the measures have a negative, neutral or positive effect during the joint implementation on CO_2 reduction potential. The comparison is made by using the Long-range Energy Alternatives Planning System (LEAP) for scenario approach and standard SEAP development process described in (Bertoldi et al. 2018) on the case of the City of Zagreb. The results showed that the measures have a mostly negative effect since the scenario approach resulted in the 16 % lower CO_2 reduction potential. The smaller reduction potential and negative interaction between measures provide significant contribution both too academic research and practical implementation of SEAPs. These negative effect needs to be considered in further SEAP development since they could require additional efforts in existing and planned SEAPs to reach given targets. Additional efforts could lead to further financial and human resources needed from cities and municipalities to enable them to fulfil their energy and climate goals.

The study is organised in six main sections. After the Introduction, Literature review presents previous studies related to the SEAP development and focuses on the measure's selection, development and evaluation. Methodology section shows the process of SEAP development, explains software used and the development of business as usual and scenario with measures. The validation of LEAP model results with scenarios results and the analysis of the measures reduction potential is given in the Results section. The Discussion section describes the importance of the study shown in the paper for the research and the practical application when developing SEAPs. The paper ends with a conclusion in the last section.

LITERATURE REVIEW

The essential steps in the development of local and regional energy plans, according to Amorim (2014) are the analysis of the present situation, considering energy consumption and GHG emissions. Present and future energy and CO_2 balance and estimation of reduction potential are deemed necessary. A strategy to reach targets, with targets' definition, measures and implementation plan and a regular procedure for monitoring of the implementation and reaching the reduction goals is essential as well (Jekabsone et al. 2019). In this way, all phases in the process of local energy planning are included in the process. For the development of each of the steps mentioned above, specific knowledge, methodology and software's are needed. Estimation of current energy consumption and emissions status can be done with Global Protocol for Greenhouse Gas Emissions (ICLEI 2014), which is a developed method for tracking GHG emissions in cities. Intergovernmental Panel on Climate Change (IPCC et al. 2019) provides instructions for estimating energy consumption and emissions level, which are designed for countries. A methodology that assesses the current state at the regional level, and that considers policy background, energy uses, and infrastructures are developed in Cosmi et al. (2015). One approach used on the local level is also presented by Margaritis et al. (2016). An integrated strategy for the surveying, controlling and managing of the SEAPs is given on the example of the city of Genoa. The tool showed that cost-benefit analysis, bankability, peer review and participatory level were the most critical elements for the SEAP monitoring (Delponte et al. 2017).

Insufficient planning off a selection of measures to reach goals in the reduction of energy usage and GHG emissions is deficiency noticed during the literature analysis. Strategy on how to reach energy and emissions targets needs to be a part of the overall methodology for local energy planning. This deficiency can be covered by the inclusion of the citizen, local stakeholders and policymakers in the development of models and local environmental policies shown by Bernardo and D'Alessandro (2019). They can have a crucial role in the selection of appropriate measures due to their knowledge of local content, even though they may lack knowledge of spatial and energy planning (Bernardo and Alessandro 2019). Definition of the measures and actions which will be included in the plan is addressed by Nuss-Girona et al. (2016). They are suggesting organisation of team of professionals on the EU level which will be dealing with the selection and the development of the optimal actions for plan. They are also suggesting that these experts should resolve data issues, provide methods and tools for stakeholders engagement, verify execution of projects and find financing sources.

During the analysis of available plans and methods, it is noticed that there is no developed merit order for the implementation of measures and that interrelations and mutual influences between measures are not analysed. The measures should be ranked according to their relevance by various criteria, and the process of their prioritisation should involve stakeholders (Schenone et al. 2015). Alternative scenarios that are the basis for the targeted reduction of CO_2 emissions are often done ad hoc and are not following the rule to have lowest costs and reach the maximal influence on local economy while trying to reach given reduction goals. The selection of measures can be made based on the best practice examples from previously developed plans and their influence on the future energy consumption estimated by energy forecasting equations (Salvia et al. 2015). Selection of measures for the reduction of CO_2 emissions and the implementation of renewables in municipalities is analysed in Fiaschi et al. (2012). One of the primary conclusions which are imposed is that in small cities and municipalities, which are mostly rural, there is a possibility to have a higher penetration of renewable energy sources in the reduction of CO_2 emissions (Pablo-Romero et al. 2015), while in big cities energy efficiency measures have a priority. The actions and policy recommendations for urban policymakers when developing a mitigation strategy are shown in Croci et al. (2017) and Coelho et al. (2018). With the development of different tools and scenarios, they are often trying to actively include local stakeholders and decision-makers (Marinakis et al. 2017) so that they could be involved in the selection of alternative scenarios and select the most appropriate one for their own local or regional community (Dall'O' et al. 2013). This brings to the choice of alternative measures and scenarios, which are not always optimal for standard economic, environmental and social criteria (Bernardo and Alessandro 2019). Selection of measures and actions for the reduction of CO_2 emissions is not thoroughly processed since there is not enough data on their interaction, and there is a possibility that some measures have synergy effect when implemented together, while others reduce the impact of one implemented jointly with them. This brings to the overspending of financial resources, which has a negative influence on a local economy since expected effects concerning energy and CO_2 emissions reduction are not achieved (Delponte et al. 2017). This was investigated in the example of office buildings in Canada (Chidiac et al. 2011). It was shown that most of the measures, when implemented together, have a smaller influence on the energy and CO_2 emissions reduction than when applied separately. Further investigation of this matter was not done on the case of the development of the SEAP.

In this paper, the process of the SEAP development was shown, and the influence of the measures on their CO_2 reduction potential was investigated. This was done for a separate evaluation of measures and in the scenario approach where interaction between them is modelled. Firstly, this study validated and developed the LEAP model. Then the business as usual scenario was developed. Measures reduction potential is then calculated individually and finally jointly in the scenario analysis. In this way, it can be seen, do the measures have negative, neutral or positive effect on CO_2 reduction when developing SEAP.

METHODOLOGY

The methodology section explains the data used in the modelling, energy consumption sectors, energy planning software, case study selected, development of the scenarios and the selection of measures. The flowchart which shows the research process is given in Figure 1.

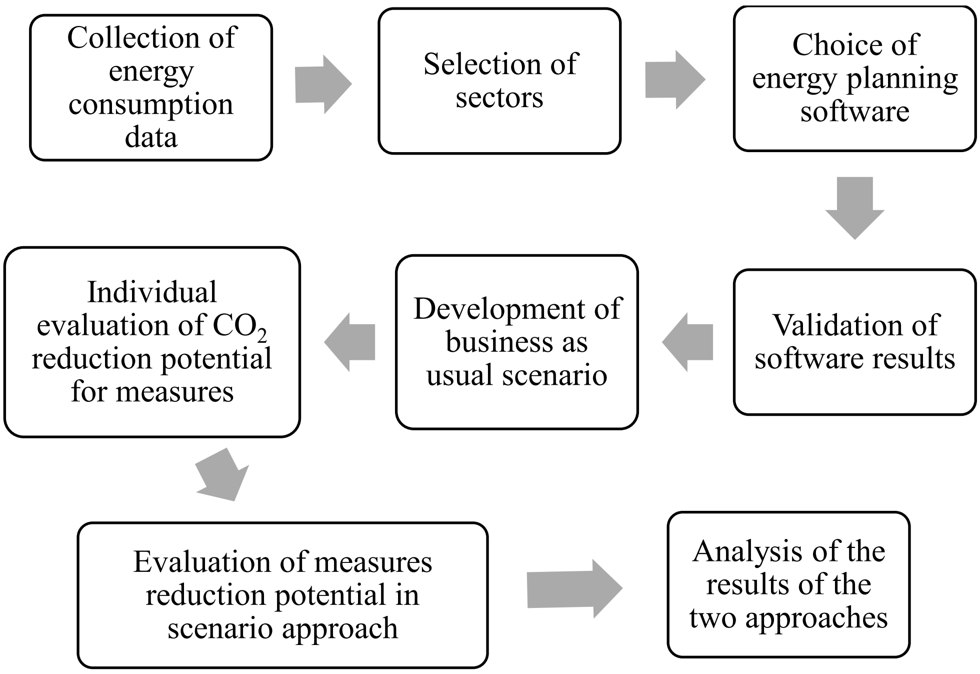

Fig 1 Flowchart of the overall research process

Regardless of the model used, for most cities the first step in the energy planning process should be a determination of the current level of energy consumption, available infrastructure and energy supply, i.e. establishing the energy balance. Energy balance is an accounting framework for the compilation and reconciliation of data on all energy products entering, exiting and used within the territory of a given local authority during a reference period. Such a balance must necessarily express all forms of energy in a typical accounting unit and show the relationship between inputs and outputs of the energy transformation processes. The energy balance should be as complete as possible so that all energy flows are, in principle, accounted. The energy balance should be based firmly on the first law of thermodynamics stating that the amount of energy within any closed system is fixed and can be neither increased nor diminished unless energy is brought into or sent out from that system (United Nations Statistics Division 2017).

Measures for the reduction of energy consumption and CO_2 emissions are most often grouped by sectors of energy consumption (Bertoldi et al. 2018). Areas of energy consumption listed in sustainable energy action plans are buildings, transport, public lighting, industry, water and wastewater management. This study focused on the sectors which are included in the SEAP of the City of Zagreb; buildings, transport and public lighting. The buildings sector is subdivided into public buildings, households and commercial buildings. The transport sector is divided on public transport, vehicles owned by the local and regional government, private and commercial transportation. This division is shown in Figure 2.

The data on energy consumption and greenhouse gas emissions should be compiled by sector and energy source. The critical areas for which the energy consumption should be calculated are residential and commercial, industry, transportation and the public sector which might include public buildings, street lighting, public transport fleets, waste and wastewater management systems. It is a good practice to collect data on energy consumption for at least one year and find energy consumption patterns for different sectors and distinct types of consumers. On the production side, it is recommended to collect data on the local electricity, heat and cold production, energy prices and energy import data with individual supply patterns (Kazakevicius et al. 2018). The current energy demand figures are used for modelling future energy demand, which is the first step towards the understanding of critical parameters of the future energy systems. For the modelling of the future energy demand, it is chosen LEAP energy planning software (Heaps 2016).

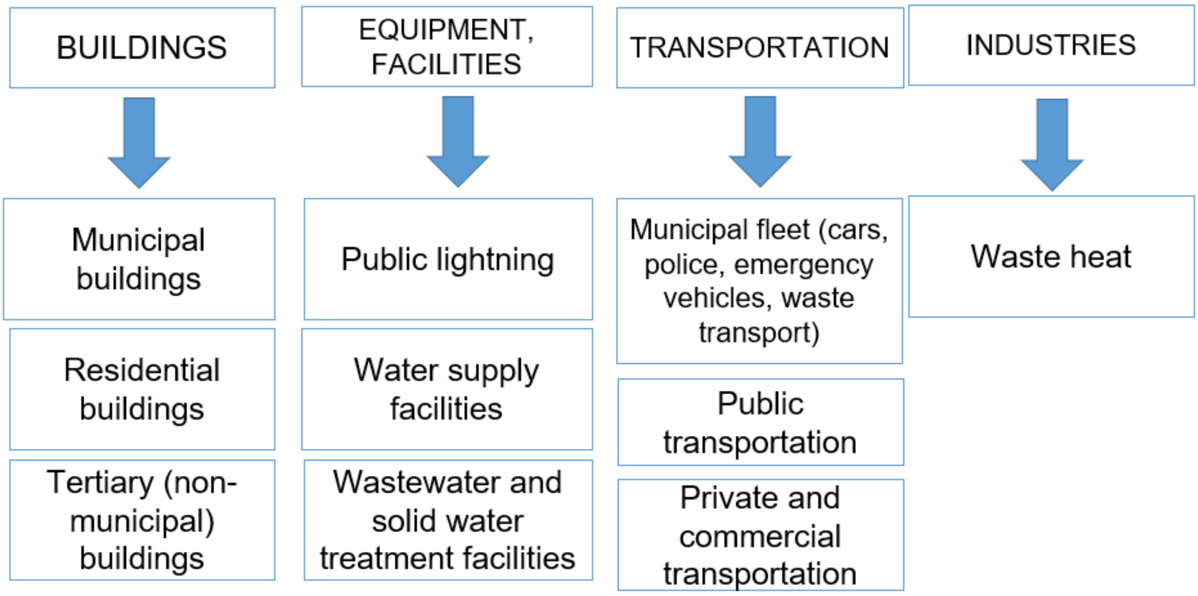

Fig 2 Different sectors for the implementation of measures for CO_2 reductions

LEAP energy planning software

The Long-range Energy Alternatives (LEAP) is an energy planning software based on the accounting framework, which is user-friendly, scenario-based and integrated energy-environment model-building tool (Connolly et al. 2010). The tool calculates energy demand and supply, the use of resources, environmental loads, non-energy sector emissions, and makes the cost-benefit analysis. This tool can be used for medium to long-term energy planning, with annual time-step, and the simulation can be done for an unlimited number of years (Hall and Buckley 2016). The device represents a flexible approach to energy modelling, in which fundamental relationships are all based on non-controversial physical accounting (Heaps 2016). The data requirements for the tool are also flexible, depending on their availability. In the beginning, the simulation can be done with a limited amount of new data. The model includes the Technology and Environmental Database (TED) with technical characteristics, costs and emission factors of around 1000 energy technologies (Heaps 2016). The model applies to almost every level of energy planning so that it can be used on the local, national or regional scale (Hall and Buckley 2016). The model is free for students, governments, non-governmental and academic organisations from developing countries (all except high-income countries on the World Bank's list) (Heaps 2016). The tool can be used for strategic integrated energy-environment scenario studies, energy system forecasting, integrated resource planning, greenhouse gas mitigation analysis, energy balances and environmental inventories (Kazakevicius et al. 2018). The energy demand is modelled via hierarchical accounting of energy, choice of methodologies and optional modelling of stock turnover. The energy resources are shaped by tracking production, sufficiency, imports and exports (García-Gusano et al. 2019). The model performs optional land-area based accounting for biomass and renewable resources. The model can simulate any energy conversion sector. The electric system dispatch is based on electrical load-duration curves (Rivera-González et al. 2019). All system costs like capital, operation and maintenance, fuel, saved energy, environmental externalities and others are included in the model. All sources and sinks of emissions of the energy system and non-energy sector are also included in the model (Kazakevicius et al. 2018).

Using simulations and modelling of future demand in LEAP software, it will be determined which measures are used in each sector and what are their expected effects considering energy consumption and CO_2 emissions reduction. Mutual interaction between measures, which influence the total result of energy consumption reduction, will be done through simulation on the specific case in which interaction between the simultaneous implementation of measures will be analysed. On this way, it is possible to determine if measures have a synergetic effect, which means that with the joint application they bring higher energy and CO_2 emissions reduction, or they have a negative influence on each other, which means that the reduction of CO_2 emissions and energy saving will be lower with joint implementation. The third option is that joint application does not have any influence on the results of the CO_2 emissions reduction.

The case of the city of Zagreb

The city of Zagreb is the largest city in the Republic of Croatia and the capital. It covers an area of 641.35 km^2 and has a population of 790,017 according to the census from 2011. The city is a cultural scientific, economic, political and administrative centre of Croatia. The first written document dates the city origins to the 11^{th} century. The city is located on the south slopes of the Medvednica mountain, and river Sava divides the town into two parts.

When it comes to energy infrastructure, the city has developed electricity, heat and gas networks. The buildings are mostly in poor shape without energy insulation and with average heating energy consumption per square meter of 170 kWh. The road and railroad network is well developed in and around the city. Public transportation consists of buses, trams and railroad. The public lighting is well developed with more than 120,000 lamps in the city. One part of the public lighting, because of historical reasons, is still using natural gas. The most used fuel for heating is natural gas and for transportation diesel. Most of the heat is produced from two natural gas-powered cogenerations which are located on opposite sides of the city.

Modelling of the Business as usual scenario

During the modelling of the Business as usual (BAU) scenario, several assumptions were used which need to be explained before presenting results. Since modelling of the energy system was done on a local level, the most attention was given to the future energy demand while energy production to satisfy this demand was looked to be imported from the national level. The CO_2 emissions factors for electricity for each known year were taken from the Energy in Croatia publication (Energy Institute Hrvoje Pozar 2017), while future emissions factor was calculated following the current trends in the emissions factor from 2008 to 2016. The emission from the heat production was calculated based on the data provided by HEP Toplinarstvo, national district heating company, which operates the district heating system (DHS) in the analysed city. Other emission factors were taken from the integrated TED database.

The modelling of the future energy demand was done till 2030 since the new goals of the Covenant of Mayors initiative, which gathers cities and municipalities tackling energy and climate issues, are set for that year (Neves et al. 2016). The baseline year used for modelling was 2008 (Segon et al. 2010), and 2015 (Mehadzic et al. 2017) was used as a monitoring year. The energy demand was divided into three major sectors: buildings, transportation and public lighting. Buildings were further subdivided into public buildings which are owned by the local authorities, residential and commercial buildings. Transport was divided on public transport, public vehicles owned by local authorities and private and commercial vehicles. The modelling of the future energy demand by all sectors and fuel consumption with penetration of new energy types and shift between existing ones was done based on the EU reference scenario for Croatia (European Comission 2014). For the modelling of the demand for public buildings, data from a national strategy for the renovation of public buildings (Ministry of Construction and Physical Planning 2017) were used. The increase of used surface in buildings was modelled according to the presumptions used in the development of the Low Carbon Development Strategy of the Republic of Croatia (Jelavic et al. 2017) and the energy consumption of new buildings was modelled according to the technical standard for buildings (Ministry of Construction and Physical Planning 2015).

Modelling of the scenario with measures

The scenario with measures was modelled in LEAP, based on the business as usual scenario, with adding additional measures to reach the goal of CO_2 emissions reduction of at least 40 %

in 2030, compared to the base 2008 year. The additional measures were selected based on the several discussions which were held between the city of Zagreb representatives and other interested stakeholders. The basis for the measures selection was SEAP of the City of Zagreb developed in 2010 (Segon et al. 2010). Measures which were proven to be effective, in the period by 2015 (Mehadzic et al. 2017), were selected and suggested to stakeholder who then provided their suggestions and comments on the proposed outlook. Stakeholders included in the selection of measures were representatives of the energy supply companies, energy agency, academia and NGO sector. Finally, the draft version of the document was put on public consultation.

The additional measures which were added to the different sector are given below:

- Buildings:
    - NZEB - Energy renovation of existing building stock to nearly zero energy building (NZEB) level defined in (Ministry of Construction and Physical Planning 2015) in all sectors by 4 % yearly
    - 20 % RES - Installation of 20 % of renewable energy sources (RES) to cover energy consumption in NZEB renovated buildings
    - Quick measures - Small and low-cost energy efficiency and RES measures in buildings (Up to 2 kW PV, up to 4 m^2 of solar thermal for domestic hot water (DHW), thermoregulation valves, light-emitting diode (LED) lights, smart meters)
    - DHS efficiency - Increase in the DHS efficiency by replacement of old distribution pipes and the introduction of new efficient production units
    - DHS geothermal - Introduction of geothermal energy in the DHS
    - Heating modal shift – Introduction of zoning for DHS and natural gas network and change of 5 % of consumers from natural gas to DHS by 2030

- Transport:
    - Transport modal shift - Integrated public transportation system with real-time information system and one unique ticket for all public transportation which will result in a modal change to the biking, walking and public transportation
    - Tram efficiency - Increase of energy efficiency in the electric tram public transport system
    - Electric vehicles (EVs) - Electrification of 10 % of personal vehicles by 2030
    - Eco-driving – Eco-driving education in the public transportation sector and optimisation of city delivery routes for the trucks with the introduction of restrictive parking policy and penalisation of driving through the city centre
- Public lighting:
    - LED lighting – Replacement of all existing fixtures in the public lighting system with LED lights

RESULT AND ANALYSIS

In this section, the results of the model will be presented. The modelling of the energy demand, the effect and interaction between measures is done in the case of the City of Zagreb. The modelling of the baseline and validation of LEAP results will be shown in the first subsection. The main results of the modelling of the Business as usual (BAU) scenario will be given in the second subsection while the results of the scenario with measures will be presented in the third subsection together with the analysis on the achieved goals and comparison with the BAU scenario. In the fourth subsection, the results of measures interaction and analysis of their interaction were given.

Baseline and validation of LEAP results

The share of different fuels in energy consumption and CO_2 emissions modelled by the LEAP for the base year 2008 and 2015 are shown in Figure 3 while the total consumption and emissions by different fuels are given in Table 3 and Table 4.

As can be seen in Figure 3, the most significant share in the energy consumption in 2008 and 2015 is taken by natural gas, although its share has slightly reduced by 2015. Regarding CO_2 emissions in 2008, natural gas is dominant, but in 2015, diesel has the most significant share. Large shares in energy consumption and CO_2 emissions are also taken by electricity, diesel, heat and gasoline. The total energy consumption rose from 2008 to 2015 from 11,442 GWh to 12,057 GWh while emissions have dropped from 2,807.98 ktCO_2e to 2,712.48 ktCO_2e mainly due to the reduction of the national CO_2 coefficient for electricity and the local CO_2 coefficient for heat. The decrease was also pushed by the increased use of renewables and biomass, while the increase in the consumption of oil products (mainly diesel) compensated for that.

Before the development of the business as usual scenario and the scenario with measures in the LEAP model, the results of the LEAP model were validated with the results presented in SEAP (Segon et al. 2010) and SEAP monitoring report (Mehadzic et al. 2017). The comparison was made for years 2008 and 2015 and by energy sources and different sectors. The results for 2008 are shown in Table 1, where energy consumption in TJ is demonstrated both by sectors and by different fuels. The most significant relative difference in the energy consumption by sector are seen for natural gas in public lighting and geothermal energy for heating, but both are less than 5 %, and they represent less than 0.05 % of total energy consumption.

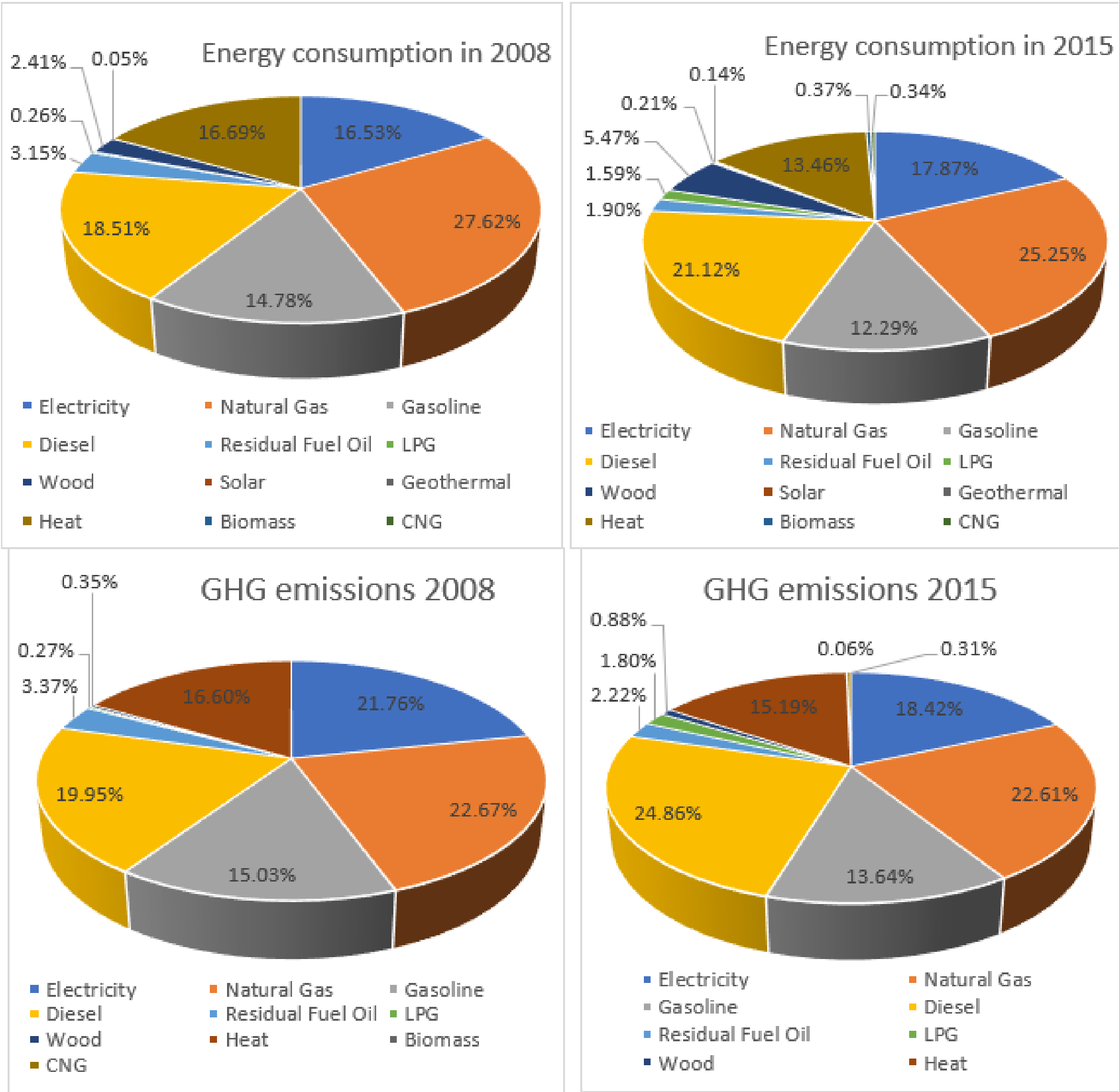

Fig 3 Energy consumption and emissions for the base year and 2015

The model was also validated for 2015 since data for that year also existed, and this is shown in Table 2. The results showed that the most significant relative difference was found for the LPG in the transport sector and this was 2.17 %. The consumption of LPG in transport is only 0.26 % of total energy consumption in 2015.

Table 1 Validation of LEAP model results for the base year (2008)

Energy consumption TJ	**SEAP 2008**				**LEAP 2008**				**Difference between SEAP and LEAP**			
Fuels	**Public lighting**	**Transport**	**Buildings**	**Total**	**Public lighting**	**Transport**	**Buildings**	**Total**	**Public lighting**	**Transport**	**Buildings**	**Total**
Electricity	324.4	250.5	6,231.8	6,806.6	325.1	250.2	6,233.6	6,808.9	0.22 %	0.12 %	0.03 %	**0.03 %**
Natural Gas	1.3	-	11,376.5	11,379.4	1.3	1.6	11,373.9	11,376.8	3.18 %	NA	0.02 %	**0.02 %**
Gasoline	-	6,090.6	-	6,090.6	-	6,088.7	-	6,088.7	NA	0.03 %	NA	**0.03 %**
Diesel	-	7,623.3	-	7,623.3	-	7,624.0	-	7,624.0	NA	0.01 %	NA	**0.01 %**
Residual Fuel Oil	-	-	1,296.6	1,296.6	-	-	1,297.3	1,297.3	NA	NA	0.06 %	**0.06 %**
Liquefied petroleum gas (LPG)	-	108.8	0.9	108.1	-	107.6	0.9	108.5	NA	1.14 %	0.01 %	**0.35 %**
Wood	-	-	991.0	991.0	-	-	990.9	990.9	NA	NA	0.01 %	**0.01 %**
Solar	-	-	-	-	-	-	-	-	NA	NA	NA	**NA**
Geothermal	-	-	22.3	22.3	-	-	21.7	21.7	NA	NA	2.42 %	**2.42 %**
Heat	-	-	6,877.3	6,877.3	-	-	6,875.6	6,875.6	NA	NA	0.03 %	**0.03 %**
Biomass	-	-	-	-	-	-	-	-	NA	NA	NA	**NA**
Compressed natural gas (CNG)	-	-	-	-	-	-	-	-	NA	NA	NA	**NA**
Total	**325.6**	**14,073.2**	**26,796.4**	**41,195.3**	**326.4**	**14,072.1**	**26,794.0**	**41,192.4**	**0.23 %**	**0.01 %**	**0.01 %**	**0.01 %**

Table 2 Validation of LEAP model results for monitoring year (2015)

Energy consumption TJ	SEAP 2015				LEAP 2015				Difference between SEAP and LEAP			
Fuels	**Public lighting**	**Transport**	**Buildings**	**Total**	**Public lighting**	**Transport**	**Buildings**	**Total**	**Public lighting**	**Transport**	**Buildings**	**Total**
Electricity	292.7	255.6	7,205.8	7,754.1	292.6	257.1	7,205.5	7,755.2	0.00 %	0.61 %	0.00 %	**0.02 %**
Natural Gas	10.4	-	10,949.5	10,960.0	10.5	-	10,947.9	10,958.4	0.62 %	NA	0.01 %	**0.01 %**
Gasoline	-	5,312.6	-	5,312.6	-	5,336.5	-	5,336.5	NA	0.45 %	NA	**0.45 %**
Diesel	-	9,079.4	-	9,079.4	-	9,165.9	-	9,165.9	NA	0.95 %	NA	**0.95 %**
Residual Fuel Oil	-	-	824.4	824.4	-	-	824.4	824.4	NA	NA	0.00 %	**0.00 %**
LPG	-	407.4	291.4	698.8	-	398.8	292.4	691.2	NA	2.17 %	0.35 %	**1.11 %**
Wood	-	-	2,354.8	2,354.8	-	-	2,374.6	2,374.6	NA	NA	0.84 %	**0.84 %**
Solar	-	-	90.0	90.0	-	-	90.1	90.1	NA	NA	0.12 %	**0.12 %**
Geothermal	-	-	60.4	60.4	-	-	60.4	60.4	NA	NA	0.12 %	**0.12 %**
Heat	-	-	5,842.4	5,842.4	-	-	5,841.1	5,841.1	NA	NA	0.02 %	**0.02 %**
Biomass	-	-	162.7	162.7	-	-	161.8	161.8	NA	NA	0.58 %	**0.58 %**
CNG	-	147.2	-	147.18	-	147.0	-	147.0	NA	0.14 %	NA	**0.14 %**
Total	**303.1**	**15,202.1**	**27,781.4**	**43,286.5**	**303.1**	**15,305.2**	**27,798.3**	**43,406.6**	**0.02 %**	**0.68 %**	**0.06 %**	**0.28 %**

Business as usual scenario

Business as usual scenario, as described before, was modelled considering EU reference scenario for Croatia and national documents which covered different sectors. From the results shown in Table 3 and Table 4, it can be seen that both energy consumption and emissions will be rising by 2020 and then will start to fall. This is primarily driven by the increase of new heating area in residential and commercial buildings and commercial goods transportation. The drop in energy consumption and emissions after 2020 is driven by NZEB energy standard for new buildings and a slight increase in transportation efficiency, which is expected because of the rejuvenation of the transportation fleet. Currently, the average age of road vehicles is 14 years. The emission reduction is also driven by the increase of penetration of renewables in the electricity and heat production, which will reduce emission factors for those two fuel types.

Table 3 Energy consumption for selected years in BAU scenario

Fuels [GWh]	2008	2015	2020	2025	2030
Natural Gas	3,160.24	3,084.83	3,477.30	3,323.71	3,122.81
Renewables	6.04	41.82	54.22	52.07	50.76
Biomass	275.24	704.55	601.96	595.20	528.60
Electricity	1,891.35	2,154.23	2,499.26	2,356.29	2,238.03
Oil Products	4,199.59	4,449.43	4,576.26	4,436.39	4,368.09
Heat	1,909.89	1,622.53	2,016.83	2,106.79	2,232.99
Total	**11,442.34**	**12,057.40**	**13,225.83**	**12,870.45**	**12,541.29**

Table 4 CO_2 equivalent emissions for selected years in BAU scenario

Emissions [$ktCO_2e$]	2008	2015	2020	2025	2030
Natural Gas	636.62	621.59	700.66	669.76	629.30
Biomass	9.97	25.52	21.80	21.56	19.14
Electricity	610.91	499.77	487.35	359.33	246.18

Oil Products	1,084.47	1,153.48	1,187.19	1,151.16	1,133.66
Heat	466.01	412.12	492.11	492.99	500.19
Total	**2,807.98**	**2,712.48**	**2,889.09**	**2,694.80**	**2,528.46**

Scenario with measures

For the scenario with measures, results are shown in Table 5, Table 6, Figure 4 and Figure 5. The tables show total energy consumption and emissions by different fuels for selected years until 2030, while Figure 4 shows emissions reduction potential for various sectors. Figure 5 shows CO_2 equivalent emissions per sectors in a scenario with measures. The energy and emissions reduction were primarily driven by the increase of the integrated building renovation according to the NZEB standard and introduction of renewables on the site of the building. The decrease in the field of electricity consumption was also driven by the decline in the use of lighting and other electric appliances. Mostly due to the introduction of LED light both for in-house and public lighting.

Table 5 Energy consumption for selected years in a scenario with measures

Fuels [GWh]	**2008**	**2015**	**2020**	**2025**	**2030**
Natural Gas	3,160.24	3,084.83	3,110.76	2,538.89	1,897.23
Renewables	6.04	41.82	124.46	220.95	319.71
Biomass	275.24	704.55	540.37	463.69	351.85
Electricity	1,891.35	2,154.23	2,297.81	2,026.33	1,809.30
Oil Products	4,199.59	4,449.10	4,551.83	4,067.32	3,272.65
Heat	1,909.89	1,622.53	1,784.43	1,709.69	1,626.83
Total	**11,442.34**	**12,057.06**	**12,409.66**	**11,026.88**	**9,277.57**

The measures for the building sector have shown a reduction of more than 56 % of CO_2 emissions for the buildings sector by 2030. This was achieved by the annual renovation of 4 % of existing building stock for the commercial, residential and public buildings to NZEB level with the introduction of 20 % of RES in renovated buildings. The large share of reduction was also achieved by fuel switch from natural gas to DHS and renovation of DHS. Higher penetration of solar thermal and modern biomass also significantly contributed to the achieved reduction. In the buildings sector, the reduction in energy consumption was only 22 %.

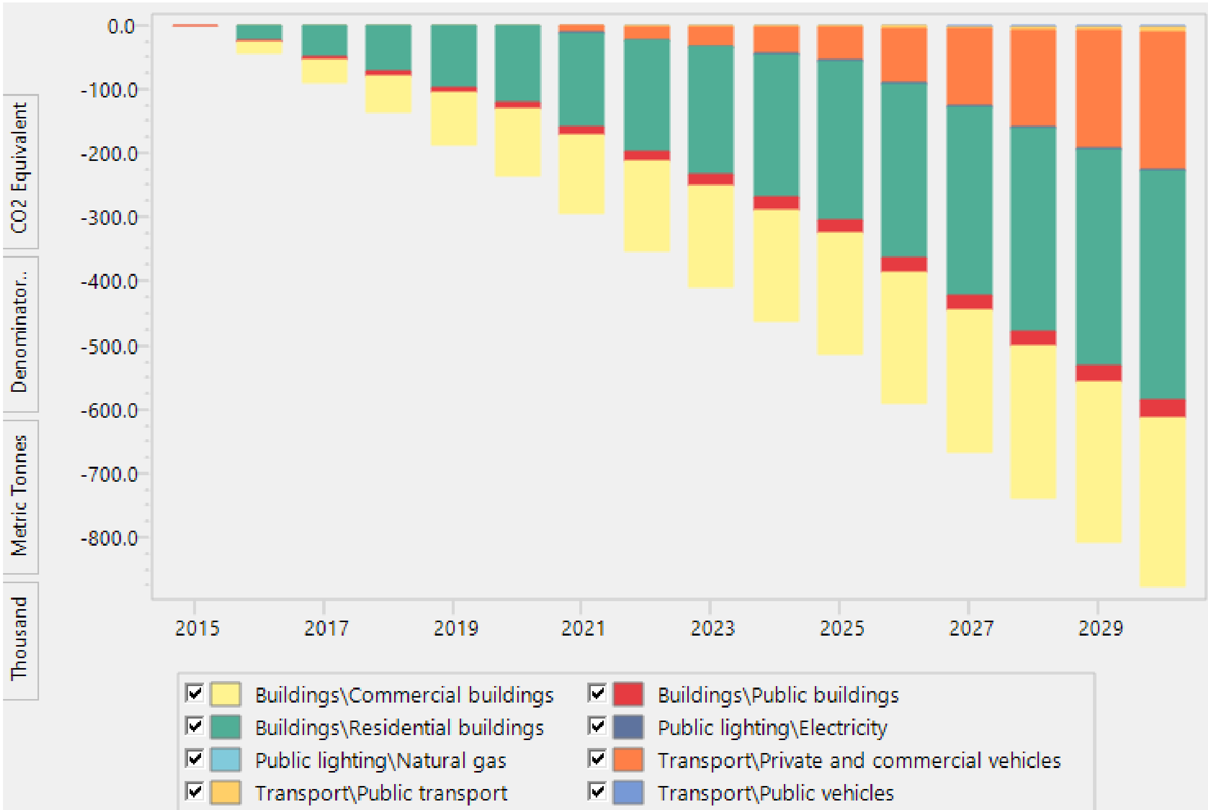

Fig 4 The emissions reduction potential by different sectors

The transportation sector achieved a small level of CO_2 emissions reduction and its emissions in 2030 should be lower by 13.7 % compared to the base year. This is mostly attributed to the penetration of electric vehicles in the sector, modal shift to public transportation and the increase in biking and walking. The diesel consumption in transport remained approximately at the same level as in base year due to the increased efficiency but also due to the increased number of passenger and tonne-kilometres.

The public lighting reached the highest CO_2 emissions reduction due to the expected modernisation and replacement of all lights with LED ones. The expected decline in CO_2

emissions is calculated to be 86 % compared to the baseline, even though the energy consumption reduced only for 61 %. This is expected due to the reduction of national electricity emissions factor, which is expected to be around 110 gCO_2/kWh.

Table 6 CO_2 equivalent emissions for selected years in a scenario with measures

Emissions [$ktCO_2e$]	2008	2015	2020	2025	2030
Natural Gas	636.62	621.59	626.82	511.65	382.37
Biomass	9.97	25.52	19.57	16.79	12.74
Electricity	610.91	499.77	442.14	296.53	184.29
Oil Products	1,084.47	1,153.40	1,180.77	1,055.27	849.89
Heat	466.01	412.12	383.28	300.20	221.87
Total	**2,807.98**	**2,712.39**	**2,652.58**	**2,180.44**	**1,651.15**

The overall reduction of CO_2 emissions in 2030 is 41.2 % compared to the base year. The energy consumption is reduced by 18.92 %. When it comes to sectors, the energy consumption of private and commercial vehicles will reach a consumption of residential buildings by 2030. When it comes to emissions, the transportation sector will pass not only residential buildings but all buildings and thus become the most significant sector when it comes to emissions.

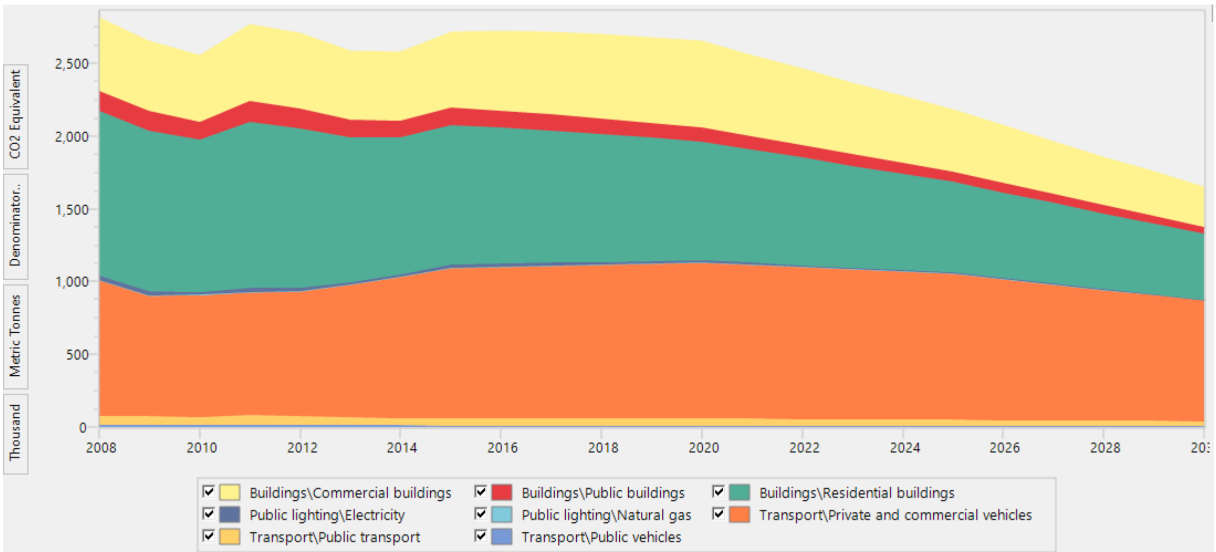

Fig 5 CO_2 equivalent emissions per sectors in a scenario with measures

Analysis of measures interaction

As discussed before, measures for the reduction of the energy consumption and CO_2 emissions are subdivided in buildings, transport and public lighting sectors, and therefore, their results are shown that way in the analysis. The measures potential energy and emissions reduction in the scenario analysis are shown in Table 7 and Table 8. The results show that in all sector, estimated energy and CO_2 potential is higher than the results provided by the scenario analysis. This is best seen in the public lighting sector, where the estimated CO_2 reduction is 74 % higher than the results of the scenario analysis. It is considered that this is mostly happening due to the decrease in the electricity CO_2 emission factor due to the penetration of renewables which is not correctly considered when calculating CO_2 emission reduction potential for the given measure.

Table 7 Comparison of energy reduction for measures based on estimated potential and scenario results

Sector	Measure	Energy consumption reduction potential [GWh]	Scenario achieved energy consumption reduction [GWh]	Difference between potential and scenario
Buildings	NZEB	2,588.20		
	20 % RES	-		
	Quick measures	32.32		
	DHS efficiency	-		
	DHS geothermal	-		
	Heating modal shift	-		
	Total	2,620.51	2,389.73	8.81 %
Transport	Transport modal shift	326.70		
	Tram efficiency	5.00		
	EVs	343.12		
	Eco-driving	245.40		

	Total	920.22	847.11	7.94 %
Public lighting	LED lighting	49.16	26.88	45.32 %
	Total	**3,589.89**	**3,263.73**	**9.09 %**

The overall energy consumption reduction is different by 9.09 % comparing the scenario approach and measures reduction potential, while CO_2 emissions are different for 16.23 %. When turned into absolute numbers, this shows that the reduction potential with given measures is overestimated by 170,031 tCO_2. The results of the analysis show that there is a potential to exceed the reduction potential of measures if the scenario analysis and calculation with chosen measures are not made.

Table 8 Comparison of CO_2 reduction for measures based on estimated potential and scenario results

Sector	Measure	CO_2 reduction potential [$ktCO_2e$]	Scenario CO_2 reduction potential [$ktCO_2e$]	Difference between potential and scenario
Buildings	**NZEB**	534.93		
	20 % RES	46.22		
	Quick measures	13.36		
	DHS efficiency	145.58		
	DHS geothermal	30.00		
	Heating modal shift	10.19		
	Total	780.28	648.30	16.91 %
Transport	Transport modal shift	83.51		
	Tram efficiency	0.55		
	EVs	108.11		
	Eco-driving	63.49		
	Total	255.66	226.05	11.58 %
Public lighting	LED lighting	11.41	2.96	74.07 %

Total	**1,047.34**	**877.31**	**16.23 %**

DISCUSSION

This section will show the implications of the results of SEAP development and discuss the significance of the findings. The results from Table 8 show that there is a significant difference in the predicted reduction of CO_2 emissions when evaluating measures potential individually and in the scenario approach by using the LEAP model. When compared to the emissions from the baseline year, the reduction of CO_2 emissions calculated in the scenario approach correspond to 6.06 % off total emissions, which can be considered significant since the overall target for the reduction was 40 %.

If the city planners develop SEAP by using individual measures assessment, instead of scenario approach, they risk the possibility that their calculated reduction potential will not be achieved since mutual interaction between the measures is not considered. As it is seen in this paper and from the analysis of measures in buildings (Chidiac et al. 2011) the prevailing interaction between measures is negative, meaning that they have lower CO_2 reduction potential when implementing together than separately. This raises a question on how CO_2 reduction potential was calculated in the existing SEAPs and is the planned level of reduction of 26.19 % (Pablo-Romero et al. 2015) possible and achievable with the given measures if their reduction potential was not analysed in a scenario approach. On the limited number of 62 SEAPs submitted to the Covenant of Mayors from Croatia, the CO_2 reduction potential of measures was calculated using individual assessment of each measure potential. The average CO_2 emissions reduction potential of 22.24 % compared to the base year could be overestimated resulting in unfulfilling the Covenant of Mayors goal for 2020 of 20 % of CO_2 emissions reduction. Since the study was limited to the case study of one city, no general conclusion on the total amount of the overestimation of reduction potential can be made.

For the analysis of the measures, the scenario approach is proposed in order to avoid the possibility of overestimating the CO_2 reduction potential. A long list of tools which can be used for the scenario approach is provided by (Mirakyan and De Guio 2013) where cities can select the best available tool for them, based on their preferences. With the list of modelling tools, authors also present a four-step methodology for energy planning of cities over 50,000 inhabitants. The methodology can be easily applied to even smaller cities, but the complexity of the approach and use of different software's can be overwhelming for the limited human resources in the smaller cities. Nevertheless, the scenario approach should be used in the assessment of the SEAP CO_2 reduction potential in order to avoid overestimation of CO_2 reduction in proposed plans.

CONCLUSION

This paper showed the process used for the development of the new SEAP of the City of Zagreb for 2030 during which relationship between potential measures for the reduction of energy consumption and CO_2 emissions in individual and scenario approach was investigated. The results of the modelling of the business as usual scenario showed that the energy consumption would slightly increase compared to the baseline 2008 year. This will be mostly distributed through oil products, natural gas, electricity and heat. The shares of biomass and other renewables will be low. The emissions will be reduced by 9.95 %, which is mostly attributed to the expected electrification in all sectors while the electricity emissions factor will be reduced due to the penetration of renewables.

With the implementation of measures in the building, transport and public lighting sectors, the emissions are reduced by more than 41 % compared to the base 2008 year. Most of the decline is achieved in the buildings sector where integral building renovation, fuel switch, penetration of renewables and refurbishment of the DHS are suggested for implementation. The transport sector becomes the highest emission sector by 2030 due to the increased number of vehicles and both passenger and goods transport activity. Although the proposed modal shift, eco-driving policies and EVs significantly reduce the emissions, there is still considerable progress needed in this sector to reduce emissions further.

The objective of the study was to analyse the relationship between potential measures for the reduction of energy consumption and CO_2 emissions in an individual assessment and the results of the scenario analysis, which takes into consideration the interaction between measures. The total difference between individual potential analysis and scenario approach showed that individual approach overestimated measures potential for 16.23 %. This provided the conclusion that most of the measures have negative interaction between each other and that there could be needed additional efforts in SEAPs to reach given targets which would demand additional financial and human resources. Since the overestimation of the measures reduction potential in this example is more than 6 % of the baseline emissions, a significant error can be made in future calculation emissions if scenario analysis of measures interaction is not done. This also potentially means that current SEAP targets are overestimated and that measures planned in existing SEAPs will not reach expected CO_2 emissions reduction, which provides important insight both to academic research and practical implementation of SEAPs. If the development of the SEAP is done by using individual measures assessment, instead of scenario approach, the city risks the possibility that their calculated reduction potential will not be achieved since mutual interaction between the measures is not considered.

For further research, similar process of comparing the potential between individual analysis of measures for CO_2 reduction and scenario analysis is recommended. For the better planning of the future SEAPs, there should be investigated the relationship between each measure in the scenario approach so that the combination of ones with negative interaction could be avoided as much as possible. The future research should be focused on the optimisation of measures selection so that the measures proposed in the SEAP have lower negative interaction between each other. Since for the provided case, it is shown that CO_2 reduction in scenario analysis is lower than in individual assessments, future research should consider how this effect is related with the costs for the measure's implementation and their economic saving potential.

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(IRES)

ARTICLE 3

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Multilevel Governance Energy Planning and Policy: A view on Local Energy Initiatives

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ABSTRACT

Background:

A sustainable energy system based on renewables, energy-efficiency, decentralisation of energy generation and synergies between different sectors requires new energy planning methods and policies. Energy transition and climate change mitigation achievement can no longer be seen only through top-down activities from a national government. Local and regional governments have a crucial role in delivering public policies relevant to such endeavour. Therefore, the implementation of multilevel governance (MLG) has become a priority for fostering local and regional development more inclusively. Paper analyses the existing energy planning governance in Austria throughout the MLG structure by focusing on the alignment between the local energy and climate initiatives and the national and EU goals. Also, the paper examined the effectiveness of the current MLG structures and outlined the fields where improvements are needed. The successfulness of the MLG approach is shown on Judenburg city case study. Desk research is enhanced by a series of interviews with energy policy experts and implementation of case study measures in TIMES model.

Results:

The MLG analysis showed the solid alignment of different governance levels. In contrast, the comparison of the energy and climate initiatives on the local level outlined recommendations for the design of more effective energy planning approach. Four areas of action are identified for further improvement: territorial fragmentation, data availability, spatial energy planning and new integrated MLG. The remaining non-conventional biomass potential of the Murtal region is enough to increase the share of district heating for the residential buildings of the Judenburg city from 16.3% to 30.8% while the building refurbishment increases district heating share to 32%.

Conclusion:

Application of MLG analysis demonstrated the alignment of energy targets in Austrian policy on different governance levels. The general willingness of Austrian municipalities to take part in local energy actions was shown through the local initiatives' analysis. It is argued that strengthening the listed areas of work is necessary to raise the effectiveness of the local initiatives. The case study for the city of Judenburg developed in the TIMES model confirmed that coordinated actions from different levels of governance lead to effective implementation of measures.

KEYWORDS

energy planning, local energy initiatives, multilevel governance, non-conventional biomass

BACKGROUND

A sustainable energy transition requires a transformation in both the energy sector and society. This requires actions to be transposed into energy and climate policies developed in the coordination of multiple levels of government. However, the realisation of the energy and climate goals cannot be achieved only through top-down activities from a national government. Still, it should be equally supported with a bottom-up approach [1] and include the active participation of all governments level [2]. Therefore, multilevel governance (MLG) has, in recent years, arose as a strategic element in reconstructing existing energy governance. It is argued that the success of the climate and energy governance is indispensable from the mobilisation of all the governance levels, including the sub-national level [3]. There is an urgent need to systematically break down the national goals to the local level to meet greenhouse gas (GHG) emission targets.

Moreover, local climate policies and initiatives need to be massively expanded and upscaled throughout multilevel energy governance [4]. Successful energy transition to low carbon and 100% renewable energy systems from the resource potentials, technical and economical perspective has been analysed within several studies [5–7]. Despite the identified feasible technical solutions, their implementation can only be realised throughout an effective governance mechanism. The importance of the governance transition and complexity of policy change has been highlighted in P. Söderholm et al. [8] through an assessment of several energy scenario studies.

Since the introduction of the idea in European level policy studies in the early 1990s [9], it has gained substantial popularity over the past ten years and has been used in energy and climate policy [10]. MLG development has been inspired by the evolution of the EU. It has been used to describe a new model of global sustainability governance with a focus on the local level and multi-sectoral economic development since the 'Agenda 21' of the UN Earth Summit in Rio de Janeiro in 1992 [3]. The EU is characterised by strong integration through the number and scope of policy areas, and the way policy is developed. Thus, it is often interpreted as an example of MLG [35]. The MLG theory within the EU is manifested throughout different ways of communication and coordination for the decision-making process and implementation or evaluation of EU policies between governing authorities at all levels: the European, national, regional and local layers. Interaction between layers is realised in two ways: through vertical and horizontal dimension. Vertical dimension refers to the interactions between different levels of government, while horizontal relates to interactions with other relevant actors within the same level. In this way, EU decisions are placed as close as possible to the final consumers – citizens [36]. In the last years, the analysis of the governance structure and the role of different actors in the energy transition have been observed through MLG approach. It describes a division of power in a non-hierarchical way between actors across the horizontal and vertical distribution of responsibilities. However, state management is not restricted only to the government actors but provides flexibility with the inclusion of non-state players such as various interest groups, organisation and civil society [35]. The vital approach for the implementation of MLG reinforcement is the employment of the EU policies by the European Commission oriented to encourage actions at a local level. The MLG approach of the EU to climate and energy governance is via local-level initiatives contributing to strengthen dynamics in pioneering countries as well as to fill gaps in countries with weaknesses at the national level [3].

To support the implementation of the EU legislation at the local and regional level, the EU has established the European Committee of the Regions (CoR). The CoR actively implements MLG approaches which have significant importance for the EU [11],[12],[13]. Moreover, in 2014 the CoR adopted a Charter for Multilevel Governance in Europe [11], [14] calling public authorities of all levels of governance (local, national and European) to use and promote MLG in their future undertakings. The EU Cohesion Policy for 2014-2020 with almost a third of the total EU budget is pointing out the need for the new ways to increase ownership on vertical and horizontal levels of governance by emphasising the significance of MLG and partnership strengthening for the EU policy-making [15].

The MLG has been successfully applied to analyse the complexity of renewable energy governance in developing countries, pointing out struggles on implementation of renewable energy act due to powerful local authorities, unclear responsibilities, conflicting regulations, a lack of awareness for national intentions and missing consultation [16]. The impact of MLG structure in the energy field in Romania has shown significant shortcomings in the implementation of the European governance structure. The main incoherence has found a lack of communication paths and autonomy of different administrative levels. Although the structure was copied from the EU level, through MLG was not established since clear responsibilities, cooperation and decision-making process were not clearly defined [17].

The MLG approach has proved to be particularly advantageous in highlighting the functions of different governance levels. Assessment of the existing climate and energy regime of Thailand through MLG framework showed that the national government has a significant role in the energy transition. However, a lack of independent planning agencies is observed as the major governance issue along with the need for active engagement of actors on different level [18]. Y. Peng et al. [19] examined the way of emerging and evolving energy policies within the overall policy framework. The observed strong vertical structure between national and local governance demonstrates the importance of combining national government with the potentials and goals of the city. For some countries, the clear top-down support from the state is inevitable in directing sustainable energy transition on local level [20] while in others sub-national levels of governance are crucial in the implementation of climate and energy policy [3].

The importance of the local level is evident from the pioneering countries Germany and Denmark being leaders in energy transition policy. Local-level actors have a significant and long-term impact on Danish renewable energy development, which is often described as a combination of bottom-up and top-down actions [21],[22].

Followed by the increased interest in MLG approach, the significance of local authorities in the realisation of sustainable energy policies has gained importance in the mid-1990s, [23–25]. S. Fudge et al. [26] discussed the changing position of local authorities due to their potential to involve a wider community in implementing effective policies concerning energy and environmental issues. The enhanced role of the local authorities requires reinforcement and transformation of the state role, thus calling for the comprehensive investigation of the integrated policy and governance transformation [21]. This question has already been raised in the early 2000s by Hooghe and Marks [27] describing the need for coordinated activities of subnational and national government within the scope of the MLG system. The national climate mitigation policies are often too general and tend to oversee specific needs and variations between the municipalities. Westskog et al. [28] argue that adaptive co-management between national, regional and local levels can serve as a tool to complement the existing gap. However, the solution is not straightforward due to the several limitations, such as the demand for more resources for addressing current and future climate change adaptation. The review of 11 municipalities in Denmark, on the one hand, showed active local engagement in energy planning. At the same time, on the other, it stressed the need for strategic energy planning and defined institutional framework providing support to municipal planning from national level [21].

The contribution of the local level mitigation policies for the long-term global response to climate change to protect people, livelihoods and ecosystems have been pointed out in the 2015 Paris Agreement [29]. In [30], Bulkeley and Betsill discussed the crucial role of the local governments in climate policy implementation. They reviewed urban politics of climate change considering MLG and emphasised the increasing role of the non-state actors in defining the urban climate governance as well as the growth of municipal voluntarism and strategic urbanism. Due to the economic development with a more than half of the world's population living in cities and the tendency of their continuous growth, they are often concerned as the source of energy issues but also the key contributors to the energy transition process [31–33] since they have the power to act as drivers of change.

Nevertheless, overall success depends on the harmonisation of local and national interests [34]. Assessment of the opportunities and barriers of multilevel decision making and compatibility of European Union (EU) and national climate policies with local policies for the case study of Helsinki proved that the lower levels of governance have the leading role in implementing the EU directives and national policy [35]. Moreover, cities as frontiers in implementing initiatives which show the feasibility of energy measures can serve as role models for their implementation at the national and the subnational level.

As has been emphasised in the previous paragraphs, cities can play a crucial role in climate change mitigation since they are an important factor in vertical implementation. There is also a need for horizontal cooperation since these increases cities capabilities. Therefore, the International Council for Local Environment Initiatives established Green Climate Cities (GCC) programme [36]. The GCC methodology is built upon nine steps divided into three big groups: Analyse, Act, and Accelerate. The seventh step is mainly focused on MLG through vertical and horizontal collaboration and development of the connections with the similar cities around the world [37]. Another global initiative, i.e. network of large cities committed to contributing to the Paris Agreement target at the local level, represents active international cooperation at the horizontal level of governance [38].

Countries in the EU have recognised the importance of MLG in sustainable energy planning and development of policies, plans and strategies [39]. In support of the EU Climate and Energy Package, the Directorate-General for Energy launched the Covent of Mayors (CoM) initiative. The CoM represents an explicit tool of MLG with the objectives set at the EU level and performed at the local level. In support of the initiative, recent studies showed that effective implementation of energy efficiency policies could hardly be carried out through traditional top-down approaches, but stronger cooperation between multiple levels of government is required [40]. In [41] G. Melica et al. discussed the horizontal cooperation between the municipalities in the framework of CoM. They have concluded that such collaboration is especially beneficial for the small and medium-size municipalities which would otherwise most likely experience the lack of human and financial capacity, thus failing to adopt policies and develop their action plans. The CoM initiative is a widespread innovative model of MLG, thus effective tool for fostering the activities on local and harmonisation of goals on various administrative levels [42]. An assessment of 16 German municipalities and their local energy action plans showed their contribution to the national energy transition. Nevertheless, the advancement of MLG coordination is required to overcome existing shortcomings within the local administration, electricity grids or higher penetration of renewables in heat and mobility sector.

Local energy and climate initiatives have a critical role in supporting municipalities in the achievement of energy and climate change mitigation targets [43]. This is due to their responsibility on planning issues and the use of resources, policy development, especially in the domain of buildings and transport. Also, they are energy consumers and represent the closest administrative level to the citizens. Nonetheless, the evaluation of the contribution of local policies to climate change is not adequately controlled by local authorities as the local energy system is a part of a much larger national and international system. This requires in the first-place adequate evaluation of the policies but also coherent actions at all levels of governance.

This paper provides an analysis of the division of power and elements of existing governance structure and mechanisms within the energy sector in Austria. For an EU member state with a federal structure, the authors were able to identify the presence of different initiatives coming from five levels of governance, from global to local level and vice versa, which made an excellent base for a study. Moreover, Austria applies the MLG approach to the vertical distribution of the institutional actors' responsibilities to assess the effectiveness of energy and climate policies and implementation processes with a focus given to the initiatives for sustainable development on the local level. The initiatives provide support and framework for the implementation of the EU and national energy and climate policies on the local level. The main hypothesis of the paper is that the continuous feedback from the lower level of governance and firm management from the political top is needed to establish an environment that would foster the implementation of successful energy policy. In this endeavour, the reinforcement of specific observed area of action is inevitable to increase the effectiveness of local initiatives. Based on the assessment of three types of local initiatives, Austrian municipal level, District level – group of municipalities and EU municipal level 4 areas for recommendations were suggested. Recommendations on the improvements in governance structure in these areas were provided. Moreover, the hypothesis of the paper was examined through the case study, which encompassed two measures, one arising from top-down and another from a bottom-up perspective on the city where remaining non-conventional biomass potential of the region was utilised.

The paper is organised into four sections. The Background section gives the state-of-the-art of the MLG approach concerning the energy and climate field emphasising the growing importance of local authorities in the energy transition. The Methods section presents interviews held, software used and describes a case study with scenario development. The analyses of the division of power in Austria with detailed analysis of the local initiative's recommendations based on the evaluation of the effectiveness of local initiatives and MLG structure and results of the scenario for two given measures are provided in the Results and Discussion sections. All findings are summarised in the Conclusion section.

METHODS

The study is built upon desk research on the MLG governance structure to give a theoretical background from the EU perspective and the implementation of EU energy directives within the Republic of Austria. A general MLG structure representing vertical and horizontal interactions is given in Figure 1.

Desk research is enhanced with a series of interviews for an energy policy analysis of the Austrian energy policy system and a case study analysis for two representative sets of measures, which are top-down and bottom-up initiated. The case study area is the city of Judenburg while the analysis of the higher level of governance was done following the location of the city with a bottom-up perspective. The city of Judenburg is part of Styria, one of nine federal provinces in Austria. Judenburg has been chosen for a case study city as it is actively working on sustainable development and is involved in two local initiatives, CoM and e5, and several finished and ongoing European projects. Therefore, it could serve as a best practice example for the other Austrian cities.

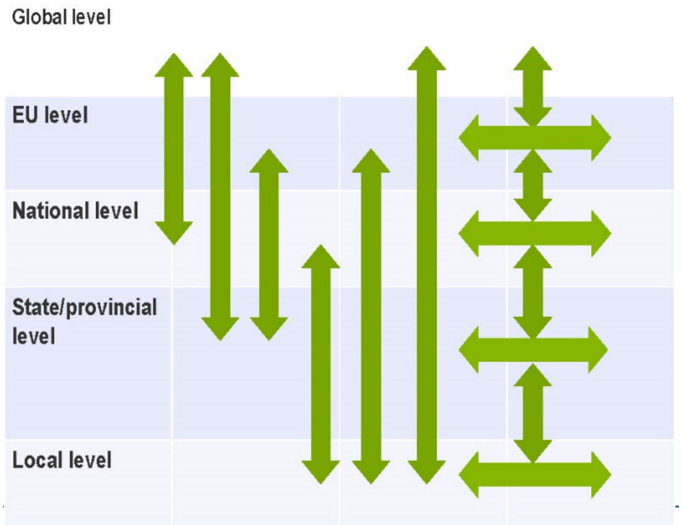

Figure 1. MLG governance structure: vertical and horizontal interactions [44]

The methods for the development of the results were twofold. Firstly, the interviews were provided by the national level of energy expert. The topics and questions of the interview were focused on the planned measures for the improvement of the local energy and climate policies in the case study city. Those topics were covering the usage of biomass in the district heating systems covering top-down political and financial decisions, ministries roles and decisions making regarding national, regional and local energy policies, change of national ministries organisation and its effects on the implementation of energy policies. With the quality control manager for the local energy initiatives in Austria, the second set of interviews was done. In this way, more detail information on the functioning of these initiatives was obtained. These interviews were also used to check and validate the results obtained by the desk research on the local initiatives and their success and role in the implementation of energy and climate policies.

The goal of these interviews was to provide insights on the MLG approach used for the implementation of the energy and climate policies in Austria both from the local and regional/national levels. The comments and the inputs from the interviewed experts are integrated with the results of the desk research and shown in the results section. They are divided into two subsections Framework of the energy governance structure in Austria: top-down division of power and Initiatives for sustainable energy development at the local level. The conclusions which were drawn from the interviews were summaries in the four areas of interest for which improvements were provided in the case study results subsection of the results and discussion.

In the TIMES model scenario development and the modelling of the case study was done. The Integrated Markal-EFOM System TIMES is a model generator developed within the Energy Technology System Analysis Programme (ETSAP), a Technology Collaboration Programme of the International Energy Agency [45]. TIMES model is a long-term accounting model that can be used for the penetration of modern technologies and the phase-out of old ones. The tool can be used on the global, multi-regional, national, state/province, or community level. Model is complex but provides many possibilities for simulation. It can provide detailed modelling and simulation of energy systems, costs, the effect of different policies and constraints [46].

The modelling of the case study city was done by the TIMES City model, which was integrated into the SureCity platform [47]. The platform consists of a TIMES City Model, a Scenario Generator and a software interface. The TIMES-City model represents a city's energy system, covering both the supply technologies and their infrastructure and the demand technologies used in buildings, transportation and industry. TIMES-City model aims to provide support for efficient integrated long-term energy and resource planning at the city level. More specific, to support local governments in identifying and understanding the critical steps needed to perform an energy transition of the urban energy system. This is important both to define consistent long-term targets and policies, and when communicating system-level implications of proposed policies and investments to other stakeholders. The model is set to capture the municipality's activities and operations (travels, building stock, public lighting, etc.) separately from the remaining urban energy system, thus, can be used for either a city's organisation (own building stock, own vehicles, etc.) or the entire city territory [48].

The modelling of the case study was done on the example of the residential sector through the implementation of the top-down and bottom-up energy measures, namely, expansion of DH and building refurbishment. This sector was used to show the results which can be obtained if the MLG approach is applied to the implementation of the energy and climate policy.

Case study and scenarios development

In the baseline year 2015, approximately 20% of all buildings were connected to DH, and 15% of total energy consumption in the residential sector was coming from DH [47]. According to the Urban developmental and traffic concepts city is divided into eight zones which served to capture its spatial characteristics, as shown in Figure 2. The DH network is passing along the city from west to east through zones 3, 4, 5 and 6. The utility Judenburg is planning to expand the network primarily in two central zones 5 and 6, mainly used for residential purposes.

Moreover, the city aims to achieve 100% renewable energy supply for heating purposes, thus increasing the use of traditional local energy sources such as waste and biomass. The scenario with implemented measures was developed to follow the defined goals of the city and to calculate the potential of the unused non-conventional biomass [47]. New DH is modelled to reduce the share of fossil fuels in zone 3, 4, 5 and 6. Primarily residual fuel oil, coal and natural gas to a certain extent. Natural gas is reduced according to the total potential of non-conventional biomass within the Murtal district. Murtal district including Judenburg encompasses 20 municipalities with a land area of 1,676 km² and 72, 842 inhabitants while the city of Judenburg covers an area of 63.76 km² and in 2015 had 10,072 inhabitants [49]. The heat for the Judenburg DH is not produced within the city borders as but imported. Therefore, the expansion of the DH system is not in the city authority and represents a measure initiated from a top-down level. Building regulations which define standards for energy performance of the buildings are within the provincial authority and execution at the local level while local authority has a strong influence on the building refurbishment. Therefore, this measure is initiated from a bottom-up level. The renovation of the building is also applied to the zones 3,4, 5 and 6 to examine how much increase in the energy efficiency of buildings can contribute to increasing the share of DH in zones and overall in the city. The average specific heat consumption in the targeted zones is 81,4 kWh/m^2. Within the second measure renovation rate of 3% until the year 2030 has been applied based on the obligation for the central government buildings defined in the Energy Efficiency Directive (2012/27/EU) [50]. The renovation level taken for this case is based on the analysis provided by E. Stocker et al. [51]. They showed on the case of Austria that the cost-optimal performance lies at an annual heating energy demand of about 30 kWh/m^2 excluding domestic hot water and technical equipment.

The existing DH system of the Judenburg city has been constructed based on the strong MLG efforts, thus supporting the paper hypothesis for the need of the MLG structure. The project initiated from the provincial level aimed to construct DH system for several municipalities based on non-conventional biomass and excess heat from the pulp and paper industry thus replacing two small gas DH systems and individual mainly gas boilers. The project depended on the active cooperation between different level of governance and various stakeholders. EU subsidies for projects favourable for environment and climate are transposed to the Umweltförderung im Inland (environment subsidies within Austria) and managed by the ministry responsible for the energy (currently BMNT). Subventions are among others available for the biomass DH systems. Province of Styria provides additional grants for the biomass DH systems, thus creating favourable condition for biomass DH. Coordination of all three-level, EU, national and provincial throughout subsidy system and efforts on the provincial and local level of municipalities, companies and industry resulted in a high success of the project development.

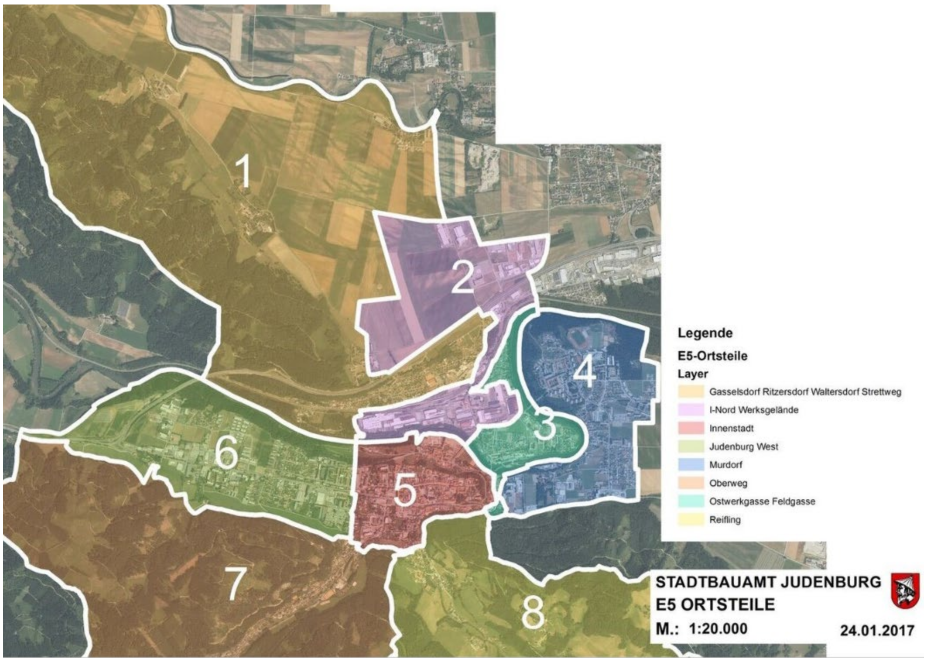

Figure 2. Map of Judenburg city with city zones [52]

<u>*Biomass potential*</u>

Biomass is traditionally highly accepted renewable energy source (RES) in Austria, thus utilised to a great extent. In Styria, more than 80% of available biomass potential is already exploited for various purposes such as for production of humus, biofuel, in combined heat and power plants, etc. The potential includes woody biomass, industrial waste, agricultural residues, manure, miscanthus and other. The remaining potential is also envisaged to be utilised [53]. The potential used for this study refers only to existing non-conventional biomass resources within the district of Murtal calculated based on the aggregated potential for the federal state of Styria and specific value of potential per inhabitant.

RESULTS AND DISCUSSION

The results and discussion section are subdivided into three parts. In the first part, "The framework of the energy governance structure in Austria: top-down division of power", results of the desk research, and interviews with the national-level energy expert is given. The second part, "Initiatives for sustainable energy development at the local level" provides information on the local level initiatives present in the case study area and ends with the main recommendations for critical areas of action: territorial fragmentation, data availability, spatial energy planning and new integrated MLG. In the end, the result of the implementation of two previously described measures in MLG approach on the fulfilling of the energy and climate local goals is given.

The framework of the energy governance structure in Austria: top-down division of power

The administrative structure of the Federal State of Austria consists of three levels of subdivision, each with corresponding administrative organisations [54]:

- At the central government level, the federal government
- At the federal level, the administration of the federal provinces of 9 federal provinces
- At the local self-administration, the municipal administration of 2,098 municipalities

In Austria, there are also 94 administrative districts representing organisational authorities integrated into the administration of federal provinces or within a greater city. Districts are not independent territorial authorities (Figure 3). The highest share of power belongs to the national level, i.e. federal government including legislative and executive power in matters such as mining, forestry, regulation and standardisation of electrical plants and establishments as well as safety measures in this field; provisions about electric power transmission in so far as the transmission extends over two or more provinces; matters of steam and other power-driven engines. The federal provinces have certain legislative competences, but their primary function is administrative and executive. In the issues such as electricity (in so far as it does not fall under the above mentioned) or environmental impact assessment for projects relating to these matters where material effects on the environment are to be anticipated; in so far as a need for the issue of uniform regulations is considered to exist, the approval of such projects legislation is the business of the Federation, while execution is the matter of the provinces [55]. Municipalities have no legislative power, and they stand solely as an administrative body. They represent self-governing bodies, meaning that they act independently from the federal state and federal provinces in some fields. Districts are groups of municipalities and in charge of the administration of all matters of administrative law of federal state and federal provinces. A statutory town performs municipal and district administrative duties.

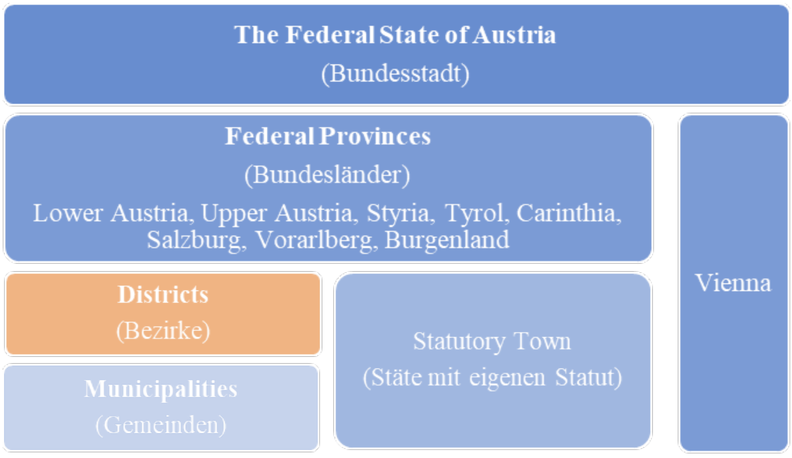

Figure 3. The vertical state organisation of the Republic of Austria [55], [56]

Duties and designations of the Federal Ministries are established based on the Amended Ministerial Law [57] (Figure 4). Ministry primarily responsible for energy is the Federal Ministry of Sustainability and Tourism (Bundesministerium für Nachhaltigkeit und Tourismus – BMNT). Ministry performs several tasks within the field of energy and activities directly affecting energy business, such as spatial planning. The ministry responsible for the research, technology and innovation in the field of energy is the BMVIT. To define the pathway for energy research and innovation policy, BMVIT and the Climate and Energy Funds developed Energy research and innovation strategy [58]. The strategy is in line with the EU 20-20-20 goals and the Strategic Energy Technology Plan for Europe [59].

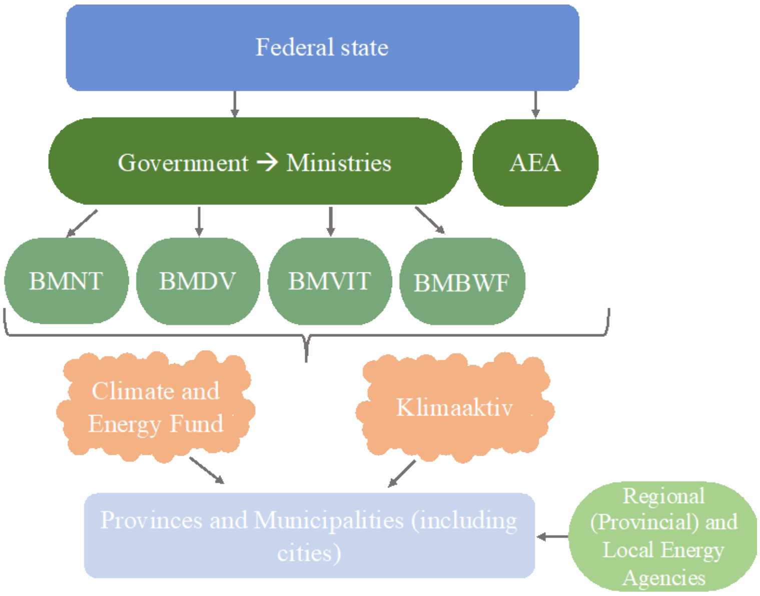

Figure 4. Structure of the main actors in the vertical energy governance in the Republic of Austria

The klimaaktiv climate protection initiative and network was founded in 2004 as a governance tool for the energy transition. It is maintained by BMNT and is supporting municipalities, households and companies in their climate protection activities. The initiative is linked with the Austrian Energy Agency (AEA) which is responsible for implementing programs and projects. Together with the BMNT and AEA, klimaaktiv is operating e5 program for energy-efficient towns and municipalities in Austria (e5 –Programm für energieeffiziente Gemeinden) [58]. The e5 program is a part of the European Energy Award, the European program for local authorities [59].

The Climate and Energy Fund supports the implementation of a sustainable and climate-friendly energy supply system, reduction of greenhouse gas emissions and implementation of the short-, medium- and long-term climate strategy in Austria [60]. The Climate and Energy Fund is maintained by the BMNT and BMVIT. The Fund aims to foster energy transition at the local level throughout the Climate and Energy Model Regions (Klima- und Energie- Modelle Regionen - KEM) [61] and Climate Change Adaptation Model Regions (Klimawandel-Anpassungsmodellregionen - KLAR) [62] programmes and Smart Cities initiative [63].

As an EU member state, Austria is having an active role in implementing EU energy policies. EU climate and energy targets for 2020 and Climate and Energy Package 2009 [64] were translated into Energy Strategy Austria and communicated to the European Commission in June 2010 [65]. Austrian energy strategy is based on three main pillars: security of supply, energy efficiency and renewable energy with an emphasis given to energy efficiency. The Strategy is developed in cooperation with the provinces to harmonise the provincial strategies (Figure 5). The implementation of the energy strategy is the responsibility of the Austrian Federal Government.

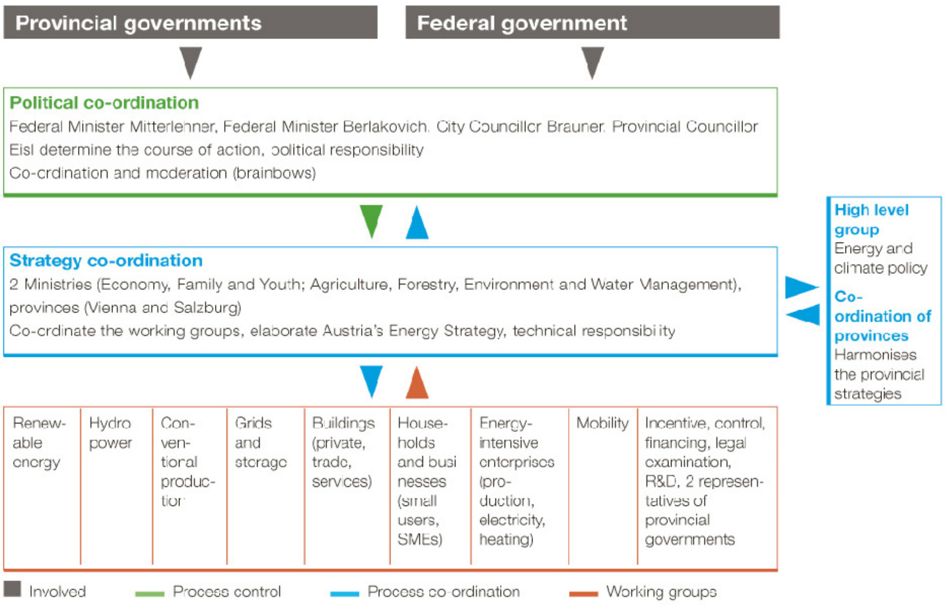

Figure 5. Austrian energy strategy design scheme [65]

Austria has signed and ratified a globally binding Paris climate agreement. To bring the agreement to life, it developed integrated long-term Austrian energy and climate strategy [66], [67]. The Strategy is following and emphasising the importance of multi-stakeholders' approach in implementing energy policy. EU and international targets in particular and the Strategy in general are the basis for developing the Integrated National Energy and Climate Plan for Austria [68].

Member states of the EU are obliged to develop and submit to the European Commission Individual National Renewable Energy Action Plan (NREAPs) [69]. NREAPs describes national pathways for meeting 2020 goals, increase of renewable energy, improvement in energy efficiency and GHG emission reduction. NREAP for Austria has been developed in line with the EU Directive 2009/28/EC and based on the Austrian Energy Strategy (2010) [70]. NREAP is monitored throughout the biannual progress reports, and so far, Austria has developed four progress reports [71–74]. Under the EU Energy Efficiency Directive 2012/27/EC, each member state is obliged to draw up every three years of National Energy Efficiency Action Plans (NEEAPs) [50]. So far, Austria has developed NEEAP for 2014 [75] and 2017 [76]. The implementation of the directive contributed to the introduction Energy Efficiency Act in 2014. The NEEAP of Austria was drawn up in cooperation with the Federal Government and provinces [76].

The decision in the field of energy and energy strategy development in Austria is following the general framework of the MLG governance. These processes are designed in the cooperation of the national governance of the federal state and the representatives for the energy of the provinces. Depending on the importance of the matter, the representatives of the provinces are discussing the issue at the provincial level with the responsible chambers. Following vertical structure from the top-down perspective, energy strategy at the provincial level has also been analysed. As explained in the methods section, the focus was placed on the federal province of Styria.

Province of Styria decided to combine strategies on energy and climate change into a Climate and Energy Strategy 2030. The strategy is in line with the goals set on the national level which cover four areas of action: GHG emission reduction, energy efficiency increase, the share of RES and affordable energy and security of supply.

Initiatives for sustainable energy development at the local level

At the local level, energy efficiency action plans aim to support national and provincial initiative for sustainable energy development. In Austria they are designed as a part of the following programmes:

- e5 – Programme for energy-efficient towns and municipalities (e5 Österreich – Programm für energieeffiziente Gemeinden (e5)) (municipal level) [58]
- Energy-saving municipality programme (Energiespar Gemeinde) equal to the e5 programme but only in Upper Austria (municipal level) [77]
- Climate and Energy Model Regions (Klima- und Energiemodelle Regionen (KEM) (District level – a group of municipalities) [61]
- Covenant of Mayors (municipal level) [78]

In the targeted federal province, i.e. Styria in 2018 there were 3 CoM signatories, 11 e5-municipalities and 25 KEMs including 114 municipalities. The analysis of the effectiveness of the local initiatives has underlined the main characteristic of each initiative, and it was supplemented by the interviews with the quality management team members of e5 and KEM initiative from the Energy Agency Styria.

All the initiatives are based on voluntary commitment; therefore, its execution is highly flexible and without legal or financial consequences in the cases of the failure. Legally binding measures with penalties for non-execution could, however, support a more serious approach in the implementation of the action plans. Such changes should arise from the top-level, namely national political governance and should be equally followed and harmonised with the policy rules on the provincial and local level.

Among all the initiatives, only the CoM defines the quantifiable target of CO_2 emission reduction. Quantified targets can quickly be evaluated, and they represent a clear indicator of the success of each initiative and the way how they contribute to national and European goals. Unlike CoM, e5 and KEM set qualitative targets. Nevertheless, the general objectives of all initiatives can be compiled to a uniform goal of achieving sustainable energy development, increasing the energy efficiency and enhancing the security of supply. The choice of the measures in CoM is arbitrary if the total sum gives the required emission reduction. Although in most of the cases a similar set of measures is used, the predefined set of measures from which each signatory could choose does not exist. On the other hand, in the case of KEM, the list contains 90 measures, thus providing international benchmarking and comparison.

Analysis of the development process has resulted in finding the steps common to all initiatives: 1) Initiation, 2) Application and accession 3) Baseline energy review 4) Design or revision of measures 5) Implementation 6) Evaluation and reporting. In the case of the KEM, unlike the e5 and the CoM, the commitment is not required from the municipal level, but it exists independently from the municipal government which affects the scope of the area where measures can be applied. Moreover, KEM regions apply for the call of the Climate and Energy Fund, which opens once a year to become part of the initiative and receive financial support. Application to the call requires from the regions to set the measures in advance. However, the measures can be revised and changed to a certain extent afterwards.

All initiatives contain an evaluation of the measures as an indicator of the success which serves as a motivator when the municipality/region was on track or “modifier” when it failed to keep the track. Therefore, the evaluation can be considered as the most important part of the ongoing process. Assessment and reporting are continuous processes in CoM and e5 initiatives while for KEM, this is often the final stage because most of the regions quit after the first phase is finished. The quality control is performed by the external bodies, which contribute to the credibility and reliability of the initiatives. At least every three years, the KEM municipalities undergo an evaluation by an independent commission depended on the progress, they are accordingly awarded “e” level representing the percentage of the measure implementation. Esurance that the submitted action plans of CoM initiative are carried out is done by the European Commission’s Joint Research Centre.

Whereas e5 and CoM are made for the municipalities or cities being the first level of territorial political division, KEM covers regions including at least two municipalities. CoM, however, has an option to group small municipalities which is beneficial from the perspective of financial and human capacity. The CoM and KEM analyse various sectors while e5 include only the municipal sector. Energy analysis of the municipal sector gives high chances for accuracy of the analysed data; however, omitting the other sectors significantly reduces areas with great potential for improvement. The key CoM sectors include buildings, equipment/facilities and industries, public lighting and transport. On the other hand, KEM also analyses all the sectors but measures could be designed in the way that none of the sectors is directly influenced, but they aim at awareness-raising, educational and social activities.

Analysis of the current situation of the municipality/region as well as the proposed measures are done in the form of a report. Availability of the report is one of the steps in the opening data process. The unique form of reporting facilitates traceability and comparability between municipalities/regions. Similar templates are provided for the municipalities/regions of CoM and KEM initiatives. Their detailed reporting in a transparent way is useful not only for the municipality/region itself but also for the other municipalities/regions willing to take part in the initiative and develop their action plans. Even though e5 has detailed uniform template for evaluation, the lack of transparency is observed as the full evaluation is available only to the e5 quality management team, limited version for the municipality and brief certificate is published online.

Variations between initiatives appear for financial and human capacity. The highest level of municipal commitment to secure its funding is in the case of CoM. This is because the initiative arises from the EU level, but direct funding is not provided. The action plan lists possible business plans and sources of funding while online CoM support provides interactive funding guide with links for the most relevant financing publications and initiatives. On the other hand, participation in e5 has small license fee whose costs are along with the costs of professional support during the implementation phase and of creating human resources in the state or the region covered by each respective national funding body. In the case of KEM, projects are funded to a certain extent. Financial support is a great motivator to take part in the initiative, which can be seen from the numbers of participating municipalities (Figure 7). However, the requirements of the application process discourage participants to continue.

The indication of the MLG approach exists in all the initiatives. Communities participating in the e5 program are also participating in the European Energy Award (EEA) program at European level [59]. At the European level, the initiative is interlocked with other programmes and activities, such as CoM. At the national level, it is in line with national climate and energy goals. At the regional or local level, it is compatible with the creation and implementation of climate and energy policies. The EEA also has a multilevel organisational structure on the international, national and local level with the addition of external audits of municipalities and EEA advisors. Within the KEM initial concept strategies and roadmaps for the regions are analysed, and projects are designed to be in line with local, regional and national energy action plans and strategies. The commitments for CoM signatories are linked to the EU's Climate and energy policy framework while action plans identify and analyses the existing municipal, regional and national policies, plans, procedures and regulations that affect energy and climate issues within the local authority which enables better policy integration.

Moreover, measures for the specific sector are highly advised to follow EU policies and directives. Even though the link between strategies on the local level with the strategies on regional, national and European exists, its applicability and viability in practice are questionable. This is due to the lack of precise top-down directions and continuous feedback loop from lower to a higher level of governance and vice-versa. Strategies on the national and provincial level set general goals not considering particularities of different municipalities regarding their RES potential and/or energy needs. On the other hand, the involvement of the lower levels is observed, such as in the Austrian energy strategy [65], though cooperation is not transposed into the definition of specific goals to each province.

Analysis and interviews gave four areas where improvements are needed, namely territorial fragmentation, data availability, spatial planning, flexible governance. Thus, this paper presents improvements in the four areas to develop a background for the new flexible energy planning methods and policies. Moreover, the hypothesis of the paper was examined through the implementation of two types of measure arising from a different level of governance.

Case study results

Territorial fragmentation

The province of Styria covering 16,401 km^2 in 2017 had 1,237,298 inhabitants [49]. The state is divided into 287 municipalities which are the lowest hierarchical level of administrative division. Municipalities had undergone a structural reform in 2015 when their number was almost halved. Reform intended to reduce the cost and human capacity for the operation of the municipalities. The municipalities are still generally small with a low number of inhabitants. In 2017 only 14 municipalities had more than 10,000 people with a 37% share in the total population of the state but accounting for only 5.8% area (Figure 6).

Most of the small municipalities have a restricted financial and human capacity for developing their local energy action plans and taking the energy measures. Therefore, the option of joint participation with the support of the local authorities from each of the municipality is seen as a solution. Such an option exists in the CoM initiative. The initiative is not very widespread over Austria as the other two initiatives e5 and KEM, which have long existence and high level of acceptance. To overcome this barrier, the option of joint participation with the support of the local authorities should be introduced in e5 and KEM initiatives. Support from local authorities is of high importance for the acceptance and implementation of energy projects in all sectors. The analysis of municipalities participating in one of the local initiatives in Styria is presented in Figure 7, where it can be seen that some of the municipalities are part of more than one initiative. Nevertheless, most of the municipalities are part of the KEM initiative, which does not guarantee long-term commitment. Thus, the risk that municipalities will not continue their participation is rather high.

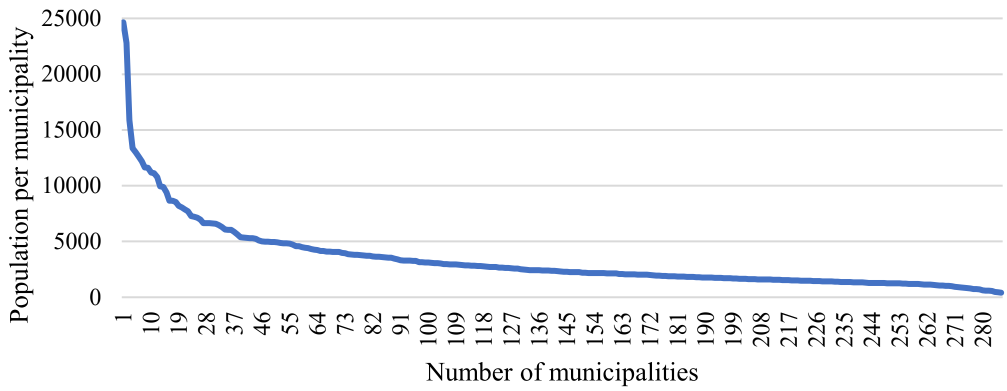

Figure 6. Municipalities in Styria per number of inhabitants

Data availability

Data availability in Austria has been highlighted as a critical point in the development of flexible MLG energy planning and policy. Data availability varies between federal state. In the focus state of Styria, the weak points could be found within all three categories, namely economic, privacy and information quality. Comprehensive automatically updated database in directly usable form requires additional expenses for the data collection and processing, while on the other hand, this would significantly reduce time, financial and human resources but also rise the accuracy of local energy plans. Data quality is another big issue of the currently available data, which reduces the accuracy of energy strategy development. Even though quality management teams of local initiatives such as e5 are putting much effort to keep the high quality of the energy documents, clear framework and guidelines on the data availability, collection and processing are inevitable to facilitate the procedure of opening data. The difficulty to obtain data, as well as the need for the open energy data, has also been discussed within the CoM initiative. As the CoM is a bottom-up initiative, it especially requires detailed and possibly granulated data at the local level. Required data can be obtained from energy suppliers. However, as at the one location, several suppliers may be active, it is more convenient to obtain data from grid operators. Both energy suppliers and grid operators are often reluctant to provide such data as it is generally considered as commercially sensitive and due to the confidentiality, commercial secrecy, and administrative burden. Therefore, in most of the cases, it is possible to get only aggregated data [79]. Nevertheless, energy market operators within all the member states must "*provide on request, but not more than once a year, aggregated statistical information on their final customers*" to an agency assigned by the Government [50]. Aggregated data are generally available from the statistics at a regional or national level [49], but this is mostly not appropriate for use in the case of the local initiatives, as mentioned before.

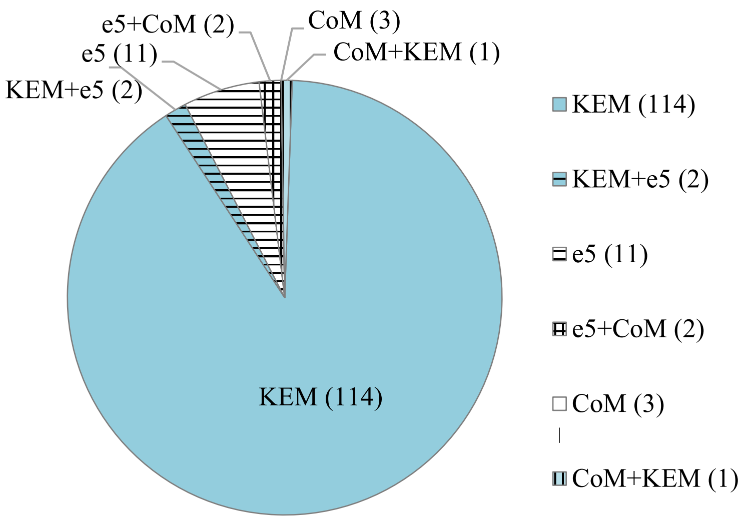

Figure 7. The share of municipalities per type of the energy and climate local initiative

<u>*Spatial energy planning*</u>

Federal states are in the power of defining spatial planning regulations by an appropriate spatial planning act. Local authorities are responsible for land allocation, where area usage is defined in the zoning plan. Moreover, the urban planning and urban law fall within the competences of federal states while the execution of the laws belongs to responsibility of the local authorities, namely the jurisdiction of the mayor [70]. Even though the regulation of spatial planning is well defined and established, and the Styrian Spatial Planning Act defines that the energy transition and climate protection should be considered, energy aspects are seldom considered. The province of Styria opened the call for proposals on 03/08/2018 to support municipalities in defining energy measures taking into consideration spatial dimension [80]. Until February 2019 only two municipalities have developed their Concepts for the Energy Sector (Sachbereichskonzept Energie), namely municipality of Semriach and Kapfmeberg.

Local communities have, high but unutilised opportunity to include energy planning into their spatial plans. Spatial energy planning has become a significant topic within the European cities that are gradually developing approaches to introduce energy policy instruments [81–83]. Until now, in Austria, concrete actions on spatial energy planning have not at all or rarely been taken into consideration within local energy action plans. Spatial energy planning has been mentioned as an important instrument to reach the energy and climate protection goals within the Austrian Energy and Climate Protection Strategy. The present situation of low exploitation rate of spatial energy planning measures can be best seen from the analysis of the most common measures in KEM (Figure 8).

Concrete public regulation and administrative processes for spatial energy planning have the potential to define energy zones for specific energy technologies and uses thus exploiting energy and services such as public transportation or DH network most efficiently and economically. Thus, the availability and quality of energy data with an emphasis on georeferenced data is of critical importance. Energy zoning has the potential of achieving technically, economically and ecologically suitable energy transition within the municipalities as the area allocation, i.e. the way land is utilised is inseparably linked [84]. Defining best suitable technology according to the availability of the RES and customers demand the specific zone would not just contribute to optimised allocation of technologies and bring benefits to the efficiency of the energy system but also contribute to the market innovations. Such an example is the technological and market uptake in Denmark, which is a result of the appropriate land allocation [85], [86].

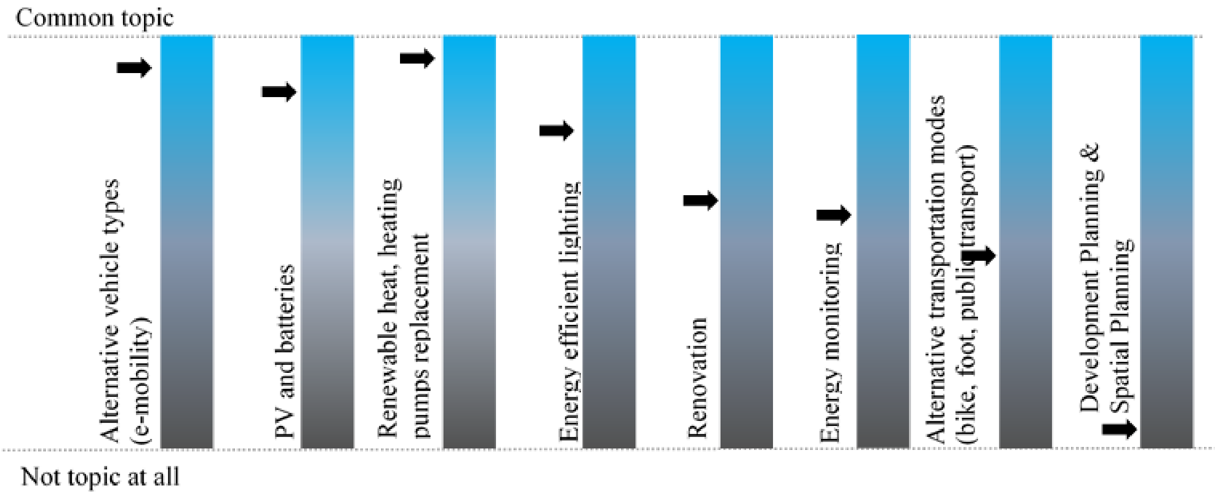

Figure 8. Analysis of the focus areas in KEM implementation concepts (January 2018) [87]

New integrated multilevel governance

Challenges of sustainable development are not limited to the respective administrative border. They intertwine horizontally between the areas of the same administrative level as well as vertically in both directions from the highest administrative level to the lowest and vice-versa [88]. Often actions are not taken within the artificially bordered administrative levels but rather within functional geographical areas such as neighbourhoods, metropolitan areas, cross border and macro-regions where the integration of different policies exists. Due to the constant changes of the geographical area, i.e. growth of the city metropolitan boundaries the levels of functional geographies, namely neighbourhoods and metropolitan areas should rather be kept as flexible levels, where important activities are carried out in less formal ways. The idea of flexible MLG arises from Jacquier C. [89]. However, the interpretation of flexible MLG in this paper follows the idea presented in I. Tosics [88] where both hierarchies exist at the same time. This type of new governance is introduced in Figure 9 as a new integrated action space.

It can be seen throughout the section *Framework of the energy governance structure in Austria: top-down division of power* that energy objectives at different levels of governance coincide with each other and they are in line with the European objectives. The objectives are taking account top-down definition by taking into consideration the bottom-up approach throughout the consultation with the provincial representatives and relevant chambers of the provincial governments. Even though cooperation of the different level of governance is seen, it should be strengthened with a stronger influence of the bottom-up approach and horizontal cooperation. Therefore, in a proposed future MLG structure with a new integrated action space, it is important to keep fixed action for defining framework and giving the guidelines while giving the space for more flexibility to non-administrative areas. In a fixed action space, all levels of governance would strengthen their role throughout a more specific definition of activities for the energy transition. The national state should provide a more precise framework for energy transition with a concrete focus on the potentials and the needs of administrative areas of the lower level. Moreover, it would create preconditions for implementing local initiatives through solving the issues of data availability and stimulating spatial energy planning. On the other hand, municipalities and cities would provide constant feedback on the strategy implementation progress by taking a bigger role in drafting the national and provincial energy policy an implementing more actively proposed measure. The flexible action space would enable to cover land characteristics arising from the development of the defined administrative area but also to consider renewable energy potential, which is rarely defined with administratively imposed borders. The smallest level of flexible action space, i.e. districts or neighbourhoods, would have the key role in spatial energy planning acting as the energy zones. In this way, reorganisation of the current division of power could ensure more effective implementation of local initiatives.

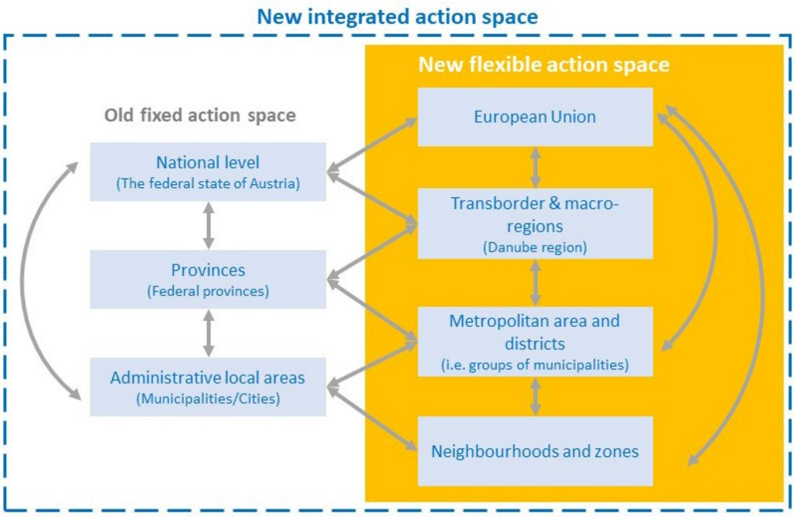

Figure 9. New integrated action space (Modification based on [89])

Implementation of measures

The results of the implementation of the measures in the city of Judenburg showed that coordinated actions from different levels of governance lead to effective implementation. The remaining non-conventional biomass potential is enough to increase the share of DH in Judenburg for the residential buildings from 16.3% to 30.8%. The building refurbishment, which contributes to the reduction of heating demand, is increasing the DH share to 32%. Total heat demand for space heating and hot water preparation after the implementation of both measures was 317.54 TJ. Fuel types used to cover heat demand after the implementation of both measures are presented in Figure 10.

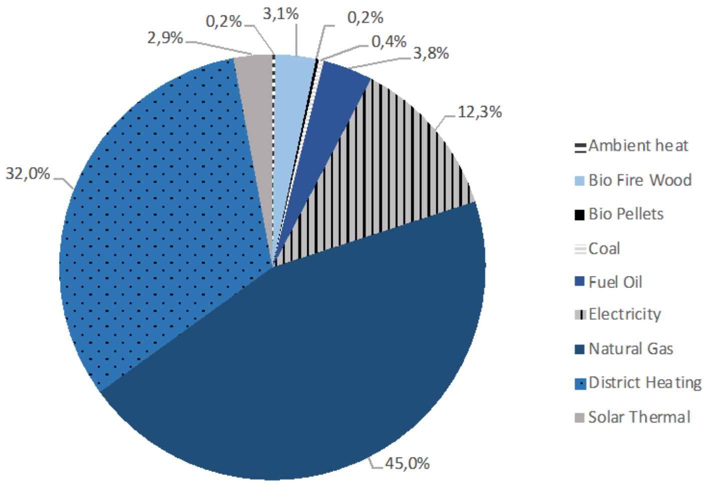

Figure 10. Fuel shares for heat demand

Both measures were applied only to zones with an existing DH network, namely zones 3, 4, 5 and 6 due to the potential for new DH connections and renovation of buildings. Therefore, the implementation of the measures in these zones led to increasing of DH share from initial 19.5% to 52.3%. This enabled to phase out coal and residual fuel oil completely and to reduce natural gas for space heating and domestic hot water preparation for 82.5%. The approach represents the introduction to spatial energy planning through MLG. Defining zones that should be supplied by DH or natural gas, respectively enable to establish efficient and low-emission energy system and also prevents over investments in infrastructure [86]. Future research should include mapping the renewable energy potential and energy demand to develop the method for designing energy zones on the local and regional level. Due to the exploited biomass potential future work should examine the potential of production of additional non-conventional biomass such as fast rotation plantation or algae. Moreover, further analysis should include other sectors and economic analysis of the implemented measures.

CONCLUSIONS

The application of MLG governance approach to the Austrian energy policy system showed that energy transition goals and pathways are in line with the global and European energy targets at all level of authorities from national, provincial to local, namely cities and municipalities. Moreover, solid cooperation of different levels of governance from top-down and bottom-up perspective has been observed. The general willingness of Austrian municipalities to take part in local energy actions is analysed through the local initiatives. The review of the three ongoing local initiatives in the federal province of Styria enabled to highlight the most important four areas for their implementation to various level of governance.

It is argued that strengthening the listed area of action is necessary to raise the effectiveness and the general quality of the local initiatives. The main observed areas of actions are divided into four groups, namely territorial fragmentation, data availability, spatial energy planning and new integrated MLG governance. To overcome the lack of financial and human capacity of individual local authority due to the territorial fragmentation, the paper elaborates the idea of restructuring the existing local energy initiatives. This means that local initiatives would allow grouping smaller local authorities while having the political support of the local authorities. This option is already available for the CoM signatories; however, the CoM initiative has a low rate of acceptance in Austria due to the other well-established initiatives.

Additionally, the lack of open energy data inevitable to design high energy plans makes it difficult to create quality strategies as well as sound monitoring of the implemented measures. The regulations on data availability must be set with clear guidelines at the top level of governance. Moreover, almost none of the local initiatives cover the area of spatial energy planning which is suggested as an important part of a holistic strategy for the energy transition. The utilisation of space and energy demand are directly interlinked and inseparable. Moreover, since the local authorities have a strong influence within the matter of spatial planning, it is argued that there is both the potential and the need to enhance spatial energy planning activities. Proposed new integrated MLG action space serves a background to accomplish listed activities. It entails a combination of fixed old action space and new flexible action space. This means that firm government structure would still define clear framework while at the same time having enough flexibility to include all the territorial particularities of areas outside the strict administrative borders. The fixed action space should be enhanced through a constant feedback system to ensure that national and regional strategies are developed, taking into consideration all the aspects of the specific energy potential and demand of the local area.

The case study of Judenburg city showed how coordinated activities from higher and lower administrative levels could lead to accomplishing national, regional and local goals. The need for spatial energy planning was especially outlined by considering the remaining potential of non-conventional biomass resources. Zoning the areas would not just enhance the most efficient use of the technology and measures but would enable to exploit the potential of RES in the most effective way.

DECLARATIONS

Ethics approval and consent to participate

Not applicable

Consent for publication

Not applicable

Availability of data and materials

The data that support the findings of this study are obtained from several sources where some are publicly available while the others obtained from the city of Judenburg and the Austrian Institute of Technology are subject to the third-party restrictions.

Publicly available data used for the case study include:

- Energieaktionsplan Judenburg 2020 [available at: www.eumayors.eu]
- D. Preiß, T. Baumhackl, B. Fischer, and M. Umgeher, "Klima- und Energiestrategie Steiermark," November 2017. [available at: www.technik.steiermark.at]
- D. Suna, A. G. Marijuán, E. Volkar, C. Sakulin, N. Pardo-Garcia Deliverable 2.1.2 Status-quo for the city of Judenburg including presentation of the possible future scenarios [available at http://surecityproject.eu/]
- Statistical data from the www.statistik.at

Competing interests

The authors declare that they have no competing interests

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Author Contributions

Viktorija Dobravec performed literature analysis, data collection and multilevel governance analysis for the case of Austria with a focus on the local level energy and climate initiatives and programmes. She also performed the analysis of the district heating expansion and building refurbishment for the case study of the city of Judenburg. Nikola Matak updated results and restructured the paper. Christian Sakulin and Goran Krajačić supported and supervised these activities. All the authors contributed, read, and checked the paper.

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Article

Optimising the Cost of Reducing the CO_2 Emissions in Sustainable Energy and Climate Action Plans

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Abstract: Tackling climate change can be achieved through local and regional initiatives, such as the Covenant of Mayors, which create energy and climate plans with mitigation measures. Upon the development of energy plans, the mitigation of greenhouse gas emissions (GHG) can be achieved through an individual or joint approach. The research aims to upgrade methods for local and regional energy planning through the choice of mitigation actions and alternative scenarios for the reduction of GHG emissions. This is achieved through optimisation of the selection of mitigation measures in the case of the wider Dubrovnik area in Croatia by choosing the most suitable option for implementation when comparing individual and joint approaches for the planning of the measures. Moreover, the implementation of single and sets of mitigation measures is compared through the total cost abatement curve. The modelled problem represents a non-linear problem as exponential functions and multiplication of variables occurs in the modelled equations. Visualisation of the results is achieved via the total cost abatement curve which ranks measures from the most cost-effective to the least cost-effective. It is shown that with the use of optimisation models, it is possible to find such sets of measures and alternative scenarios, which will, with less financial means, reach a minimal reduction of CO_2 emissions by 40% in local and regional energy systems and result in financial savings of three times in the analysed case. In this way, it could be possible to increase the overall implementation of SECAP measures and mitigate the problem of the lack of appropriate financial planning.

Keywords: mitigation actions; Covenant of Mayors; local energy plans; SECAP; optimisation

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1. Introduction

Sustainable energy planning at a local level is an important part of the European Union (EU) climate neutral strategy for 2050 and Fit for 55 plan by 2030 [1]. A serious approach to sustainable local energy planning has been initiated during the last 15 years, and especially after the European Commission started the Covenant of Mayor's initiative. The energy and climate goal of the European Union, Fit for 55 by 2030, can be most easily achieved by planning the sustainable development on a local level, due to a bottom-up approach, direct investments, and implementation. It is concluded that local governments have a crucial role in the mitigation of climate change [2]. The importance of the local initiatives in the energy transition towards carbon neutral societies can also be seen from the large number of signatories of the Covenant of Mayor's initiative, which is more than 10,000, and the fact that it includes more than half of the EU population [3].

Despite the growing number of sustainable energy and climate action plans, this area has not been adequately documented in the scientific literature [4], even though local authorities can have a significant influence on the reduction of energy consumption and greenhouse gas (GHG) emissions [5]. A local energy policy that is focused on utilising the strong potential of renewable energy and energy efficiency can strengthen local capacities for energy production [6]. For those reasons, it is necessary to encourage local and regional governments to use efficient standardised methods when developing sustainable local energy plans [7]. Recommendations for further research in this area are given in [8] and they include the development of standardised methodologies for tracking emissions on a local level such as ISO 37120 standards, the introduction of different indicators for tracking the goals of sustainable energy plans, a collection of microclimate data as a support for local planning and involving citizens and stakeholders.

Much work regarding local energy planning is focused on how the cities and municipalities are responding to climate change and what are their main drivers. It is shown that national legislation in the EU has a strong impact as well as the Covenant of Mayors under which most of the local plans are developed [9]. Performance and implementation of local plans developed under the Covenant of Mayors are investigated, considering climate neutrality and positioning in line with the Paris Agreement. Slavia et al. [10] show that European cities with a reduction target of 47% are not on track to reach the Paris Agreement. Moreover, the developed plans, which have lower targets, also show problems with the execution due to the lack of the necessary financial and human resources assigned to the initiative [11]. On the other hand, more than 600 plans from the Covenant of Mayors are on track to reach their goals, and their characteristics are less ambitious targets, higher baseline emissions and more ambitious national targets [12]. Moreover, according to the monitoring reports from the Covenant of Mayors, the cities are on the right track to reduce emissions to nearly zero by 2050 [13]. This provides evidence that the initiative has medium success in implementation which could be further improved by integration between actions that cover multiple sectors [14].

The most important steps in the development of local and regional energy plans according to [15] are the analysis of the present situation considering energy consumption and GHG emissions; present and future energy and CO_2 balance and estimation of reduction potential; a strategy to reach targets, with targets' definition, measures and implementation plan; and a regular plan for monitoring the implementation and reaching the reduction goals. In this way, all phases in the process of local energy planning are included in the process. The general process of how the planning works is explained in [16], where steps are effectively shown as a circular activity with four main parts, namely strategic, tactical, operational and reflective, while [17] provides an innovative tool for the development of SECAPs following the main guidelines of the Covenant of Mayors. The methodologies for the analysis of the present situation considering energy consumption and GHG emissions are constantly updated and one of the common approaches which shows how to calculate energy consumption and emissions is tested in Italy [18], while methodology for scaling data from the national level is given in [19]. The option to extend the accounted emissions and provide more potential for mitigation measures is provided and tested in Lombardy, showing that this approach can bring about an additional reduction of CO_2 emissions [20]. When it comes to the measures and their implementation, they are divided into sectors, of which the most common in energy plans are residential buildings, public lighting, local electricity production, transport and tertiary buildings, including public ones [21]. The effects of different measures are also investigated by sectors in [22], showing that the greatest number of actions is related to municipal buildings, public lighting and local electricity production. In addition, new approaches, other than just CO_2 emissions, can be used for tracking the implementation and reporting on climate change mitigation and sustainability, such as SDEWES Index which tracks 7 dimensions with 35 indicators [23].

One of the deficiencies noticed during the literature analysis is insufficient planning of selection of measures and actions, which are set in order to reach goals in the reduction of energy usage and GHG emissions, since these need to be a part of the overall methodology for local energy planning. Currently, the process is mostly implemented by drafting a small group, consisting of a few of the most relevant municipal employees, which includes interested stakeholders, to reach a common decision on which measures should be implemented [24]. Targeted reduction of CO_2 emissions is often conducted ad hoc and does not follow the rule to have the lowest costs and reach the maximal influence of the local economy while trying to reach the given reduction goals, which is particularly important when considering that most of the cities do not have sufficient budget for planned SECAP projects [25]. The selection of measures for the reduction of CO_2 emissions and implementation of renewables in municipalities is analysed in [26]. One of the basic conclusions reached is that in small cities and municipalities, which are mostly rural, there is a possibility to have a higher penetration of renewable energy sources in the reduction of CO_2 emissions [27], while in big cities, energy efficiency measures have priority. With the development of different tools and scenarios, local authorities are often trying to actively include local stakeholders and decision makers so that they could be involved in the selection of alternative scenarios and select the most appropriate one for their own local or regional community [28]. Some authors argue that diverse stakeholders need to be involved to ensure that the process is participative, inclusive, holistic, simple and transparent, in order to be successful [29]. This brings us to the choice of alternative measures and scenarios, which are not always optimal for common economic and environmental criteria, although some methods could help stakeholders find the optimal solution by giving them the possibility to evaluate different scenarios [30].

The objective of this research is to upgrade the methods for local and regional energy planning through optimal selection of measures and alternative scenarios for the reduction of CO_2 emissions. We aim to optimise the application of measures on local and regional levels considering economic and environmental criteria. The hypothesis is that with the use of optimisation models it is possible to find such sets of measures and alternative scenarios that will allow those with less financial means to reach a minimal reduction of CO_2 emissions of 40% in local and regional energy systems. With aggregation of local plans and disaggregation of regional plans, use of financial means and available financing mechanisms for the implementation of measures can be optimised. This will result in the upgrade of a method for the optimal choice of measures in the energy planning on the local and regional level through a modified total cost abatement curve considering economic criteria. This will increase the accuracy of the current method for the visualisation of choice of measures for emission reduction and alternative scenarios on the local and regional level and provide stakeholders and decision makers with a new tool for the selection of mitigation measures.

The paper is structured as follows. After Section 1 in which the introduction to the topic and literature review is given, in the Section 2, method used for the optimisation of measures and presentation of the results is given. Then, Section 3 provides the data on the case study location as well as the results of the mitigation measures analysis and the results of the optimisation. In the final section, results are discussed in comparison with the already published work from this research topic.

2. Materials and Methods

To reach the objective of the research, the methodology was developed. The methodology consists of several parts. In the first part, the analysis of sustainable energy and climate action plans that are developed by cities and municipalities within the Covenant of Mayors' initiative is performed. Due to the availability of many sustainable energy and climate action plans, it is considered that in this way enough methods and approaches, which were used for their development, will be covered. The focus was on the SECAPs developed in Croatia due to the accessibility of the data on the cost and mitigation measures. During the analysis, special attention was focused on the measures and the development of alternative scenarios for the reduction of energy consumption and CO_2 emissions. The focus of the analysis was to provide enough data on the cost-effectiveness of the measures to construct the basis for the optimisation analysis of potential measures. The data which were used from the existing plans are CO_2 reduction potential, reduction of energy consumption, production of renewable energy and total cost of the measure implementation.

Measures for the reduction of energy consumption and CO_2 emissions are most often grouped by sectors of energy consumption. Analysed measures can be found in sectors of energy consumption listed in sustainable energy action plans such as buildings, transport, public lighting, industry, water and wastewater management, etc. The sector of buildings is further subdivided into public buildings, households and commercial buildings. The transport sector is subdivided into public transport, vehicles owned by the local and regional government and other road transport. In this way, it is determined which measures are mostly used in each sector and what are their expected effects and how large are the costs connected to their implementation. The potential influence of each measure on the reduction of energy consumption and CO_2 emissions is determined.

In the second part of the research, based on the collected data on measures, the regression functions were created in Microsoft Excel tools. The regression functions can be updated through the changing of the coefficients when the new data are added from additional SECAPs. The SECAPs used for the development of the functions and coefficients are listed in Appendix A, Table A1. The functions were used for the generation of the equations which connect the cost of the measure with total CO_2 emission reduction potential. The functions were later used in the optimisation part of the research together with restrictions of the case study example to provide an optimal cost solution. The objective of the proposed optimisation problem is to minimise the objective function f given in Equation (1). The objective function includes all previously defined regression functions and represents the overall cost of implemented measures. Thus, the objective of the problem is to minimise the overall cost of the implementation of the mitigation measures.

$$\begin{aligned} min\, f \triangleq min\{ & x_1 \cdot k_{11} \cdot e^{-k_{12} \cdot x_1} + x_2 \cdot k_{21} \cdot e^{-k_{22} \cdot x_2} + x_3 \cdot k_{31} \cdot e^{-k_{32} \cdot x_3} + x_4 \cdot k_{41} \cdot {x_4}^{-k_{42}} + x_5 \cdot k_{51} \cdot {x_5}^{-k_{52}} + x_6 \\ & \cdot (k_{61} \cdot {x_6}^2 - k_{62} \cdot x_6 + k_{63}) + x_7 \cdot k_{71} \cdot e^{-k_{72} \cdot x_7} - x_8 \cdot (k_{81} \cdot \ln x_8 - k_{82}) - x_9 \cdot (k_{91} \cdot \ln x_9 - k_{92}) + x_{10} \cdot k_{101} \\ & \cdot e^{-k_{102} \cdot x_{10}} - x_{11} \cdot (k_{111} \cdot \ln x_{11} - k_{112}) + x_{12} \cdot (k_{121} \cdot {x_{12}}^{k_{122}}) + x_{13} \cdot (k_{131} \cdot {x_{13}}^2 - k_{132} \cdot x_{13} + k_{133}) + x_{14} \\ & \cdot k_{141} \cdot {x_{14}}^{k_{142}}\} \end{aligned} \tag{1}$$

where:

- x_1 is the level of reduction of CO_2 emissions by the implementation of integrated renovation of public buildings;
- k_{11} and k_{12}—coefficients for the calculation of specific cost gained from regression analysis of integrated renovation of public buildings from other SECAPs, k_{11} = 16,411.76, k_{12} = 0.00019845;
- x_2 is the level of reduction of CO_2 emissions by the implementation of energy renovation of public buildings;
- k_{21} and k_{22}—coefficients for the calculation of specific cost gained from regression analysis of energy renovation of public buildings from other SECAPs, k_{21} = 3040.48, k_{22} = 0.00022593;
- x_3 is the level of reduction of CO_2 emissions by the implementation of PVs on public buildings;
- k_{31} and k_{32}—coefficients for the calculation of specific cost gained from regression analysis of PVs on public buildings from other SECAPs, k_{31} = 6128.25, k_{32} = 0.0016649;
- x_4 is the level of reduction of CO_2 emissions by the implementation of solar thermal on public buildings;
- k_{41} and k_{42}—coefficients for the calculation of specific cost gained from regression analysis of solar thermal on public buildings from other SECAPs, k_{41} = 11,131, k_{42} = 0.527;
- x_5 is the level of reduction of CO_2 emissions by the implementation of electrification of public transport;
- k_{51} and k_{52}—coefficients for the calculation of specific cost gained from regression analysis of electrification of public transport from other SECAPs, k_{51} = 107,229, k_{52} = 0.396;

- x_6 is the level of reduction of CO_2 emissions by the implementation of integrated renovation of multi-apartment buildings;
- k_{61}, k_{62} and k_{63}—coefficients for the calculation of specific cost gained from regression analysis of integrated renovation of multi-apartment buildings from other SECAPs, k_{61} = 0.00023089, k_{62} = 4.67701, k_{63} = 29,089.21;
- x_7 is the level of reduction of CO_2 emissions by the implementation of integrated energy renovation of residential buildings;
- k_{71} and k_{72}—coefficients for the calculation of specific cost gained from regression analysis of integrated energy renovation of residential buildings from other SECAPs, k_{71} = 35,236.21, k_{72} = 0.00007884;
- x_8 is the level of reduction of CO_2 emissions by the implementation of energy renovation of residential buildings;
- k_{81} and k_{82}—coefficients for the calculation of specific cost gained from regression analysis of energy renovation of residential buildings from other SECAPs, k_{81} = 722.1, k_{82} = 13,030;
- x_9 is the level of reduction of CO_2 emissions by the implementation of PVs on residential buildings;
- k_{91} and k_{92}—coefficients for the calculation of specific cost gained from regression analysis of PVs on residential buildings from other SECAPs, k_{91} = 627.8, k_{92} = 7772.2;
- x_{10} is the level of reduction of CO_2 emissions by the implementation of energy renovation of commercial buildings;
- k_{101} and k_{102}—coefficients for the calculation of specific cost gained from regression analysis of energy renovation of commercial buildings from other SECAPs, k_{101} = 9744.8, k_{102} = 0.0000328;
- x_{11} is the level of reduction of CO_2 emissions by the implementation of PVs on commercial buildings;
- k_{111} and k_{112}—coefficients for the calculation of specific cost gained from regression analysis of PVs on commercial buildings from other SECAPs, k_{111} = 627.8, k_{112} = 7772.2;
- x_{12} is the level of reduction of CO_2 emissions by the implementation of modernisation of public lighting;
- k_{121} and k_{122}—coefficients for the calculation of specific cost gained from regression analysis of modernisation of public lighting from other SECAPs, k_{121} = 17,648, k_{122} = 0.225;
- x_{13} is the level of reduction of CO_2 emissions by the implementation of infrastructure for electric vehicles and bicycles;
- k_{131}, k_{132} and k_{133}—coefficients for the calculation of specific cost gained from regression analysis of infrastructure for electric vehicles and bicycles from other SECAPs, k_{131} = 0.00000896, k_{132} = 0.4481, k_{133} = 5796.741;
- x_{14} is the level of reduction of CO_2 emissions by the implementation of purchasing of electric vehicles;
- k_{141} and k_{142}—coefficients for the calculation of specific cost gained from regression analysis of purchasing of electric vehicles from other SECAPs, k_{141} = 109,245.1, k_{142} = 0.3977;

Other equations provide restrictions based on the physical limitations for the reduction of CO_2 in the case study used for the demonstration of the optimisation model. Equation (2) gives the required reduction of CO_2 emissions level for the model. Equation (3) provides the limit for the maximal reduction of CO_2 emissions in the public building by limiting the effect of measures 1, 2, 3 and 4 which contribute to the reduction of CO_2 in public buildings. Furthermore, Equation (4) provides a limitation for the reduction of CO_2 emissions with measures in residential buildings, while Equation (5) provides limitations for commercial buildings. Additionally, Equation (6) gives a limit for the maximal CO_2 reduction in the transport sector and Equations (7) and (8) provide correlation between two transport sector measures optimised in the paper. The last Equation (9) provides a limit that one measure can contribute only to the maximal level of reduction, which is possible to achieve by that measure.

$$\sum_{i=1}^{n} x_i \geq requested\ level\ of\ CO_2\ reduction \tag{2}$$

$$x_1 + x_2 + x_3 + x_4 \leq \text{max } CO_2 \text{ reduction in public buildings} \tag{3}$$

$$x_6 + x_7 + x_8 + x_9 \leq \text{max } CO_2 \text{ reduction in residential buildings} \tag{4}$$

$$x_{10} + x_{11} \leq \text{max } CO_2 \text{ reduction in commercial buildings} \tag{5}$$

$$x_{13} + x_{14} \leq \text{max } CO_2 \text{ reduction in the transport sector} \tag{6}$$

$$\frac{x_3}{x_{3max}} \approx \frac{x_4}{x_{4max}} \tag{7}$$

$$\frac{x_3}{x_{3max}} + \frac{x_4}{x_{4max}} \leq 1 \tag{8}$$

$$x_i^n \leq {x_{max}}_i^n \tag{9}$$

The next step in the methodology is the optimisation of the measures based on the given equations and parameters of the case study. The modelled problem represents a non-linear (NLP) problem as exponential functions and multiplication of variables occurs in the modelled equations. This means that the solution of the problem will not guarantee a global optimum and that the problem must be solved by implementing iterative techniques. However, since the described problem does not have a significant number of variables (15 variables and 9 constraints), the solution of such a problem will have a neglectable deviation from the global optimum. Thus, the problem was solved in the GAMS tool with an NLP solver on a 16 GB RAM machine, similar to [31].

In the final part of the method, visualisation of the results is achieved via the total cost abatement curve which, on the diagrams for the different total levels of CO_2 reduction, rank measures based on their cost and abatement level from the most cost-effective to the least cost-effective.

3. Results

The results section is divided into three subsections. In the first subsection, the basic data of the case study location are presented with a summary of the area and the data on the energy consumption in different sectors and by different fuels as well as emissions of CO_2 emitted from those sectors. The second subsection gives details on the analysed measures and SECAPs which were investigated to provide data for the analysis. It also provides figures which show the inputs for the equations of the optimisation model, and which were used to calculate the costs of the reference scenario which was developed in the stakeholders' participatory approach as a part of the Joint_SECAP Interreg Italy Croatia project. The last subsection of the results chapter provides results of the optimisation model as a total cost abatement curve for different levels of CO_2 reduction, respectively, 40%, 45%, 55% and 63%, which is maximal considering given constraints.

3.1. Data on the Case Study

The case study location, referred to as the wider Dubrovnik area, represents the southernmost part of the Republic of Croatia which consists of five administrative units which gravitate towards the city of Dubrovnik, namely: Municipality of Konavle, Municipality of Zupa Dubrovacka, Municipality of Dubrovacko primorje and Municipality of Ston. The area is surrounded by the Bosnian border on the north and east, the Montenegro border on the south and the sea on the west. The main economic activity in the area is tourism and agriculture, mainly aquaculture, and therefore sustainability is a priority for the local authorities. The energy consumption of the area in 2015, which is used as a baseline year for the development of the SECAP, is given in Table 1, while Table 2 gives the yearly CO_2 emissions. The CO_2 emissions per different fuel and sector shown in Table 2 are calculated based on the standard emission factors provided in Table 3.

Table 1. The energy consumption of the analysed area.

MWh/year	Residential Buildings	Commercial Buildings	Transportation	Public Vehicles	Public Buildings	Public Lighting	Public Transportation	Total
Electricity	149,276	171,617	0	0	3153	10,072	0	**334,118**
Fuel oil	26,589	19,497	0	0	2310	0	0	**48,396**
LPG	17,690	6626	6427	0	1198	0	0	**31,941**
Biomass	71,707	0	0	0	0	0	0	**71,707**
Diesel	0	0	264,904	4249	0	0	23,214	**292,367**
Petrol	0	0	132,862	259	0	0	0	**133,121**
Total	**265,261**	**197,740**	**404,194**	**4508**	**6661**	**10,072**	**23,214**	**911,649**

Electricity is the most consumed energy source in the area, followed by diesel and petrol fuels. The sector consuming most of the energy is transportation, followed by residential and commercial buildings. On the other hand, diesel fuel emits the highest emissions while electricity takes second place due to the low CO_2 national emission factor. The sector with the highest emissions is transportation, which emits almost 58% of total emissions, making it the first candidate for the CO_2 reduction measures. Since in buildings, most of the energy is covered by electricity and biomass which have low CO_2 emission factors, buildings are not the main emitter of CO_2.

Table 2. The yearly CO_2 emissions of the analysed area.

tCO_2/year	Residential Buildings	Commercial Buildings	Transportation	Public Vehicles	Public Buildings	Public Lighting	Public Transportation	Total
Electricity	22,093	25,399	0	0	467	1491	0	**49,449**
Fuel oil	7965	5841	0	0	692	0	0	**14,498**
LPG	4615	1728	1677	0	313	0	0	**8333**
Biomass	34	0	0	0	0	0	0	**34**
Diesel	0	0	70,729	1134	0	0	6198	**78,062**
Petrol	0	0	33,083	64	0	0	0	**33,147**
Total	**34,707**	**32,969**	**105,489**	**1199**	**1471**	**1491**	**6198**	**183,523**

Table 3. CO_2 emission factors for different energy carriers used in the analysed area [32].

	gCO_2/kWh
Electricity	0.1480
Fuel oil	0.2996
LPG	0.2609
Biomass	0.0005
Diesel	0.2670
Petrol	0.2490
PV electricity	0.0000

3.2. Measures for the Reduction of CO_2 Emissions

To provide measures for the CO_2 emission reduction in the given area, analysis of the measures in the existing SECAPs was performed. SECAPs for the cities and municipalities which were analysed are listed in Appendix A, Table A1. The analysed SECAPs range from small municipalities with a few thousand citizens, through Mediterranean islands and cities to a large city with 800,000 inhabitants, thus providing a good representation of different cases. The analysed SECAPs provided a baseline that was used for the selection of the most common measures for the reduction of CO_2 emissions which are grouped by sectors and divided on individual measures and set of measures. The list of the individual measures and their factors used in the optimisation equation is the following:

- Energy renovation of public buildings (x_2);

- PV on public buildings (x_3);
- Solar thermal on public buildings (x_4);
- Electrification of public transport (x_5);
- Energy renovation of residential buildings (x_8);
- PV on residential buildings (x_9);
- Energy renovation of commercial buildings (x_{10});
- PV on commercial buildings (x_{11});
- Modernisation of public lighting (x_{12});
- Infrastructure for electric vehicles and bicycles (x_{13});
- Purchasing of electric vehicles (x_{14}).

Besides individual measures, there are also sets of measures which consist of a combination of at least two individual measures:

- Integrated renovation of public buildings (x_1);
- Integrated renovation of multi-apartment buildings (x_6);
- Integrated energy renovation of residential buildings (x_7);
- Electrification of transport ($x_{13} + x_{14}$).

The measures are also listed according to sectors and those are shown in the following figures, which also show the relationship between the specific cost of CO_2 emission reduction and total CO_2 emission reduction. These inputs were used to model the minimum cost optimisation function. Figure 1 gives the overview of the measures and equations used in the calculation of cost for the reduction of CO_2 emissions in public buildings.

All the measures shown in Figure 1 have a reduction of specific costs with the increase of the total emission reduction. The specific cost ranges from min of 1000 EUR/tCO_2 for solar thermal on the public building to the max of 40,000 EUR/tCO_2 in the case of integrated renovation of public buildings. The average values of specific costs for measures range from 2000 to 8000 EUR/tCO_2. Figures 2–4 also show the relationship between the specific cost of CO_2 emission reduction and total CO_2 emission reduction just for the different sectors. Figure 2 shows the sector of commercial buildings while Figure 3 shows the transport and public lighting. Figure 4 gives an overview of measures in the residential sector.

Measures in all sectors experience the same trend as the ones in the public building sector in which the specific cost is reduced by the higher reduction of the total CO_2 emissions. The two measures are exceptions from this trend and those are PV on commercial buildings which shows a slight increase of the specific cost and energy renovation of the multi-apartment building which shows the first reduction and after some point increases in the specific cost. The reason why the specific cost has these trends should be further investigated since this was not the focus of the research and the specific cost data from SECAPs were used as an input for the optimisation model.

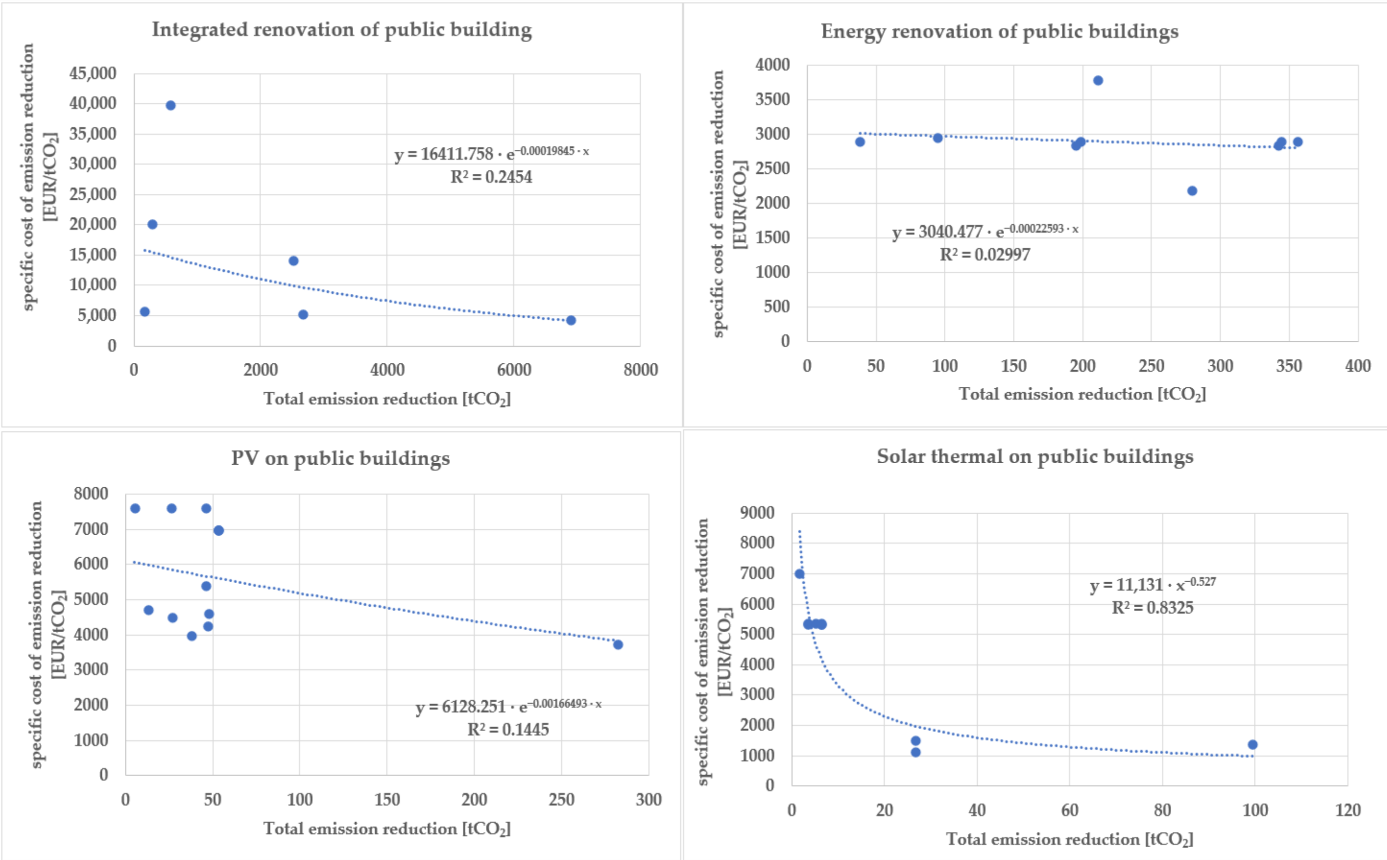

Figure 1. Functions used for the optimisation of public buildings measures.

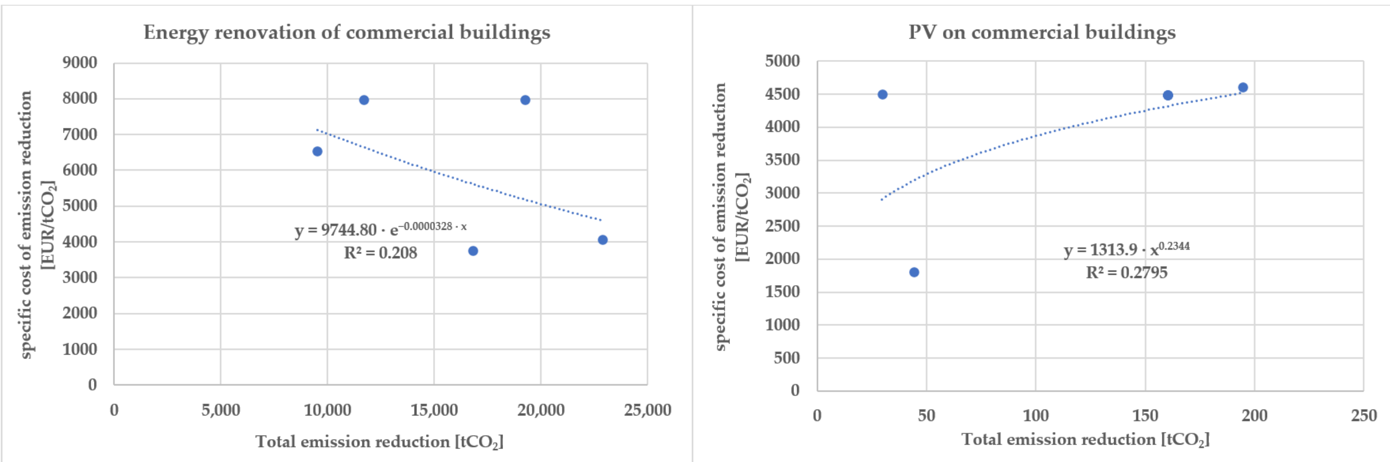

Figure 2. Functions used for the optimisation of measures in commercial buildings.

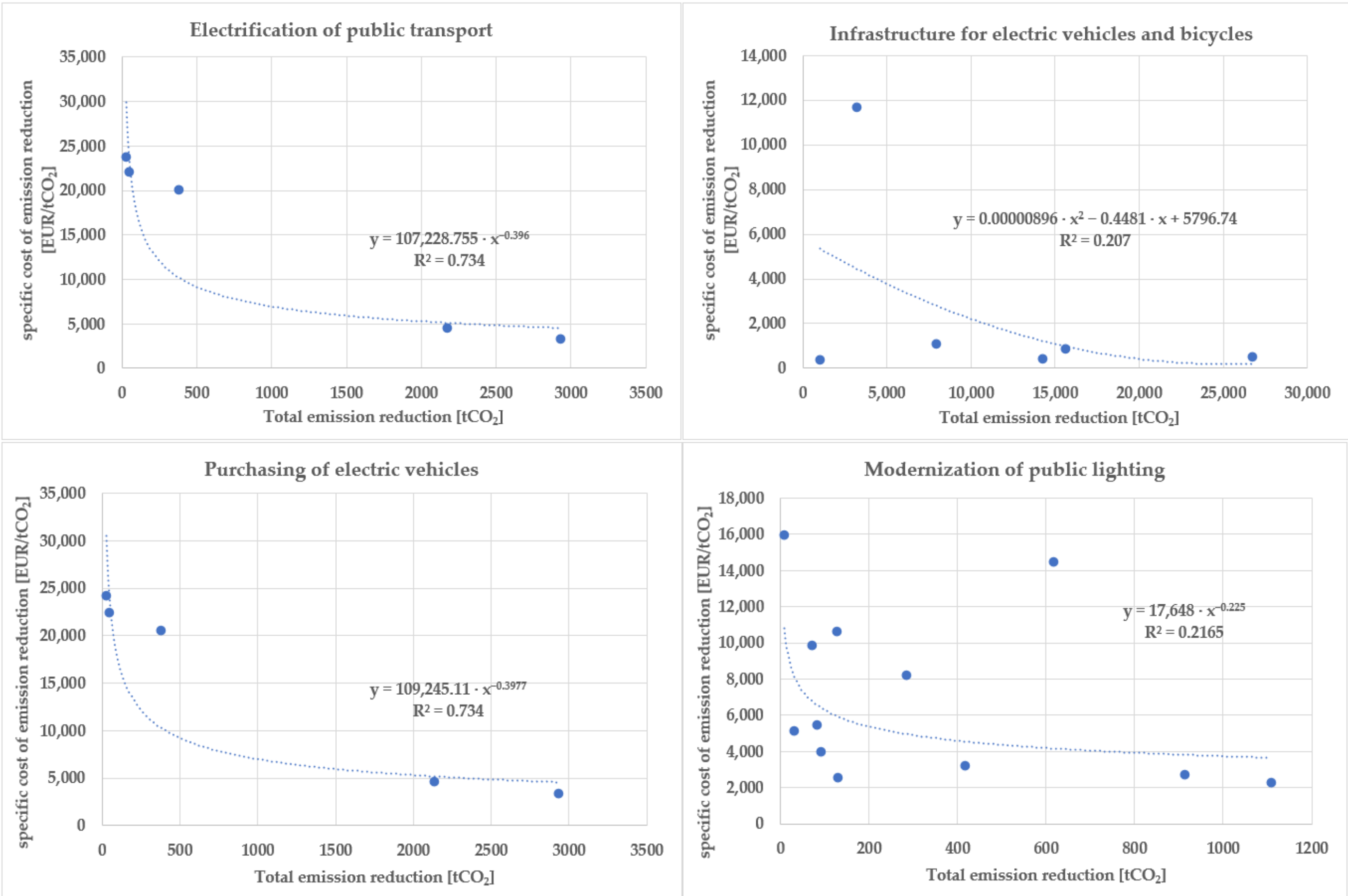

Figure 3. Functions used for the optimisation of measures in the transport and public lighting sector.

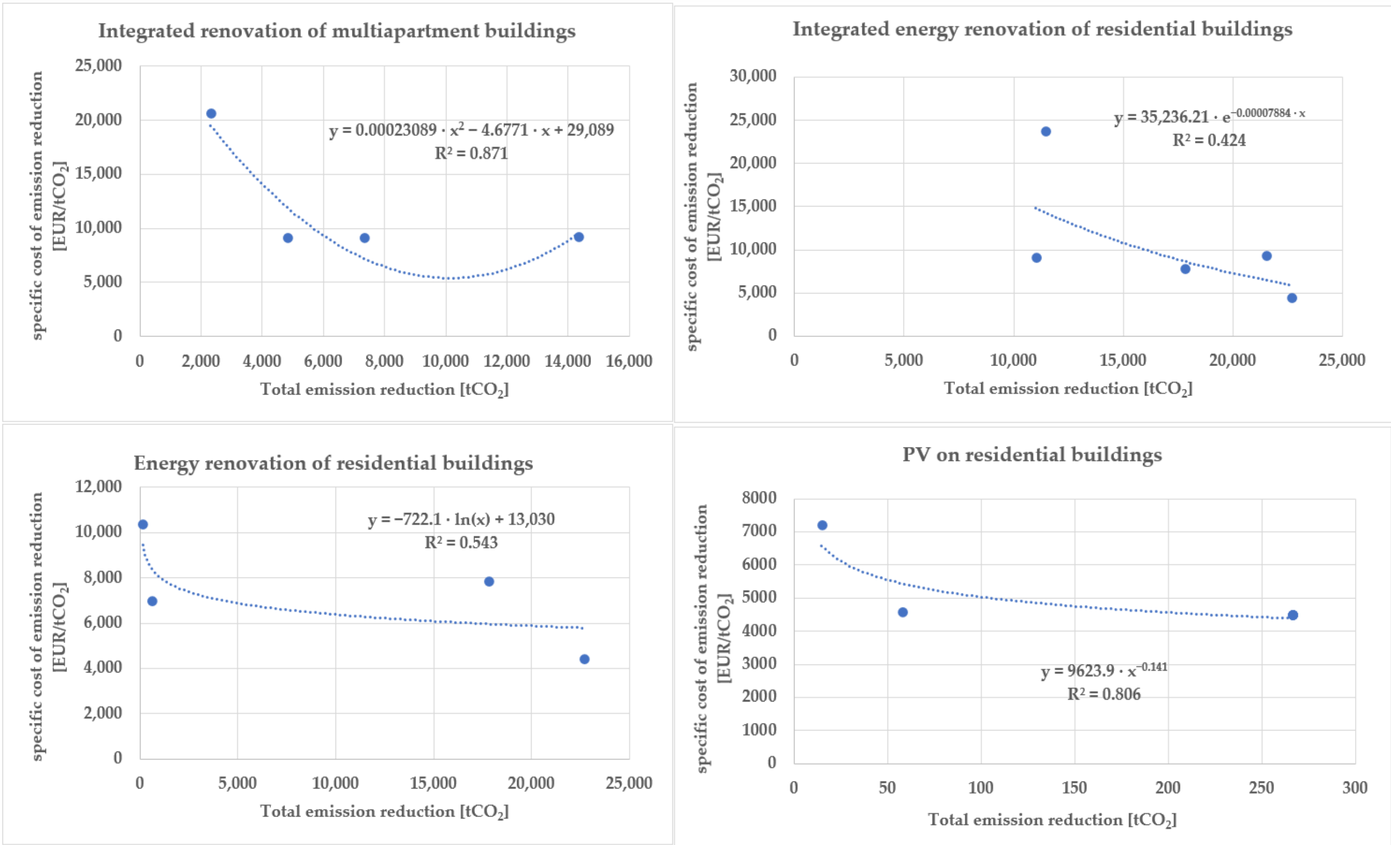

Figure 4. Functions used for the optimisation of measures in residential buildings**.**

3.3. Optimisation of Measures Implementation

After the most common measures were analysed and written as the equation connecting the specific cost of emission reduction to the total emission reduction level, the equations were used to create a minimum cost equation. Together with the model limitations, a minimal cost equation was used for the optimisation of the implementation of the measures, whose results will be shown in the following figures. To compare the current cost of the reduction of CO_2 emissions for the case study area with the optimisation of measures, implementing the calculation of the current plan cost was performed. The level of implementation of each measure and set of measures was taken from the existing SECAP for the wider Dubrovnik area [33]. The results of the implementation of the current plan with the order of implementation of measures and their specific cost and contribution to the total CO_2 emission reduction are shown in Figure 5. The contribution to the total CO_2 reduction can be seen on the horizontal axis while the specific cost is shown on the vertical one. The total cost of one measure in EUR is represented by the rectangular area showing each measure. Measures should be implemented in the order of how they are presented on the figure from those with the lowest to those with the highest specific costs.

The measures that most contribute to the CO_2 emission reduction are PVs on commercial buildings, energy renovation of commercial buildings, electrification of transport and integrated energy renovation of residential buildings. On the other hand, Figure 5 provides clear instructions on which measures should be implemented first and which should be implemented last to reach the reduction with the lowest cost possible. The current plan has an estimation of the total cost reaching a 40% reduction considering current CO_2 emissions of 401.5 MEUR. To make it possible to reduce the current plan cost and reach the same level of CO_2 reduction for the case study area, the before mentioned optimisation model was developed. The results of the model optimisation of measures implementation are shown in Figure 6, while the total cost of the reduction reached 121.1 MEUR in this case. The optimisation model followed limitations given in Equations (3)–(8) and resulted in the need to implement only three measures to reach the 40% emission reduction for the given area. Those measures are, in the order of implementation, PV on commercial buildings, electrification of transport and PV on public buildings. Furthermore, the model was tested on the reduction of CO_2 emissions by more than 40% by increasing the wanted level of reduction by 5%, thus creating new goals of 45%, 50%, 55%, 60% and 65%, respectively. Those results are shown in Figure 7 and measures are organised in the order of how they should be implemented. The result for the reduction of the emissions by 65% was not possible to calculate since the limitations of the case study applied to the model allow reduction of emission up to 63.52%.

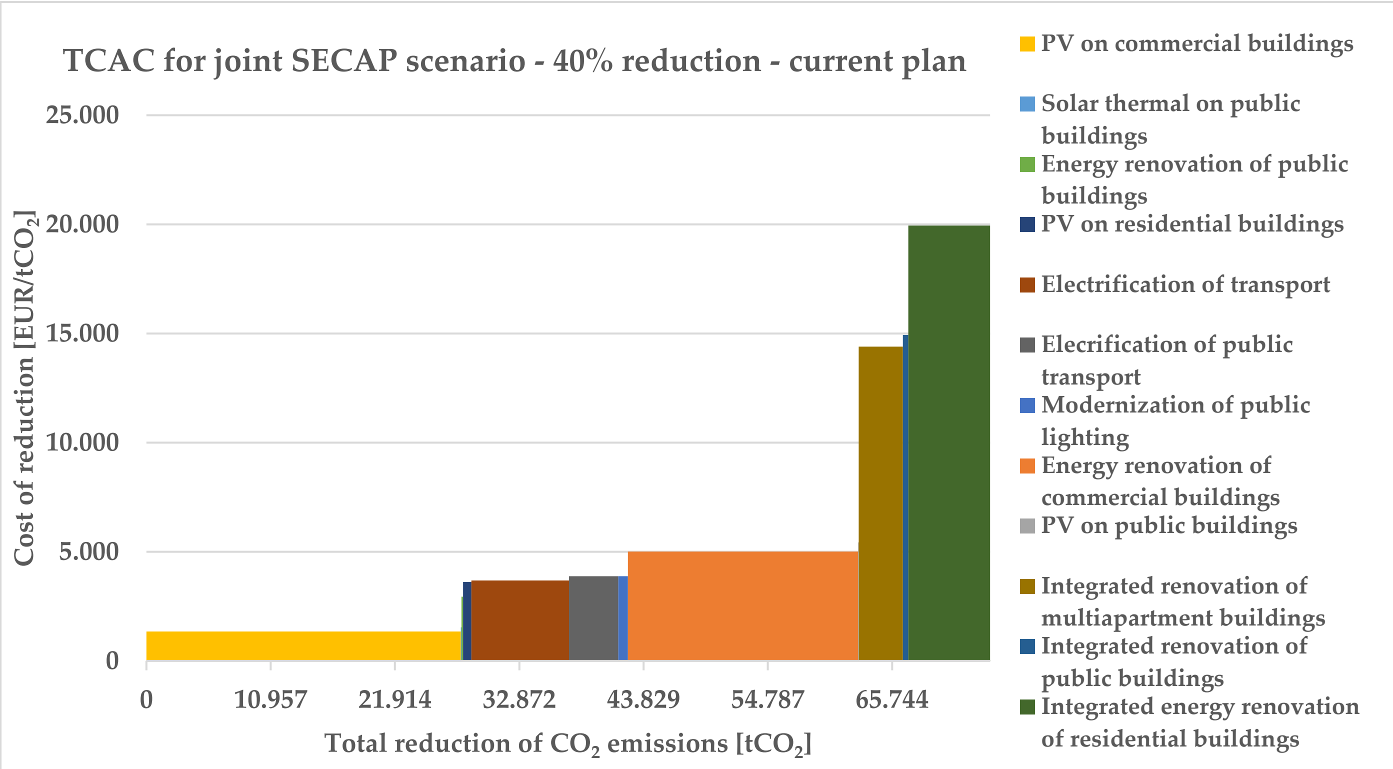

Figure 5. Total cost abatement curve for the 40% CO_2 reduction in the current plan.

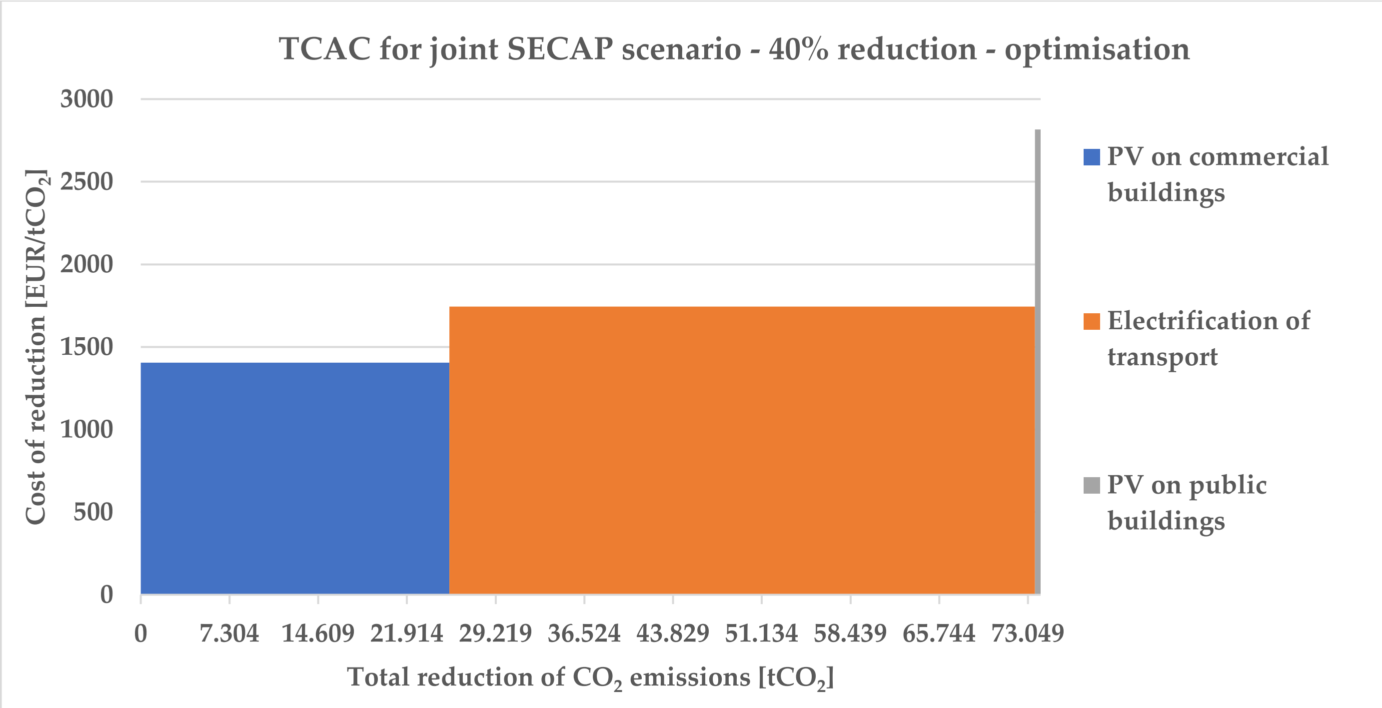

Figure 6. Total cost abatement curve in the case of optimisation of measures for the 40% CO_2 reduction**.**

The results for the reduction of emission for 45% have the same measures as the 40% ones except they add a measure of implementation of PVs in residential buildings. When looking at the 55% reduction, the two additional measures are added: renovation of public buildings and electrification of public transport. The last emission reduction level of 63.5% which is shown in Figure 7 adds three new measures, which are the modernisation of public lighting, renovation of multi-apartment buildings and energy renovation of commercial buildings.

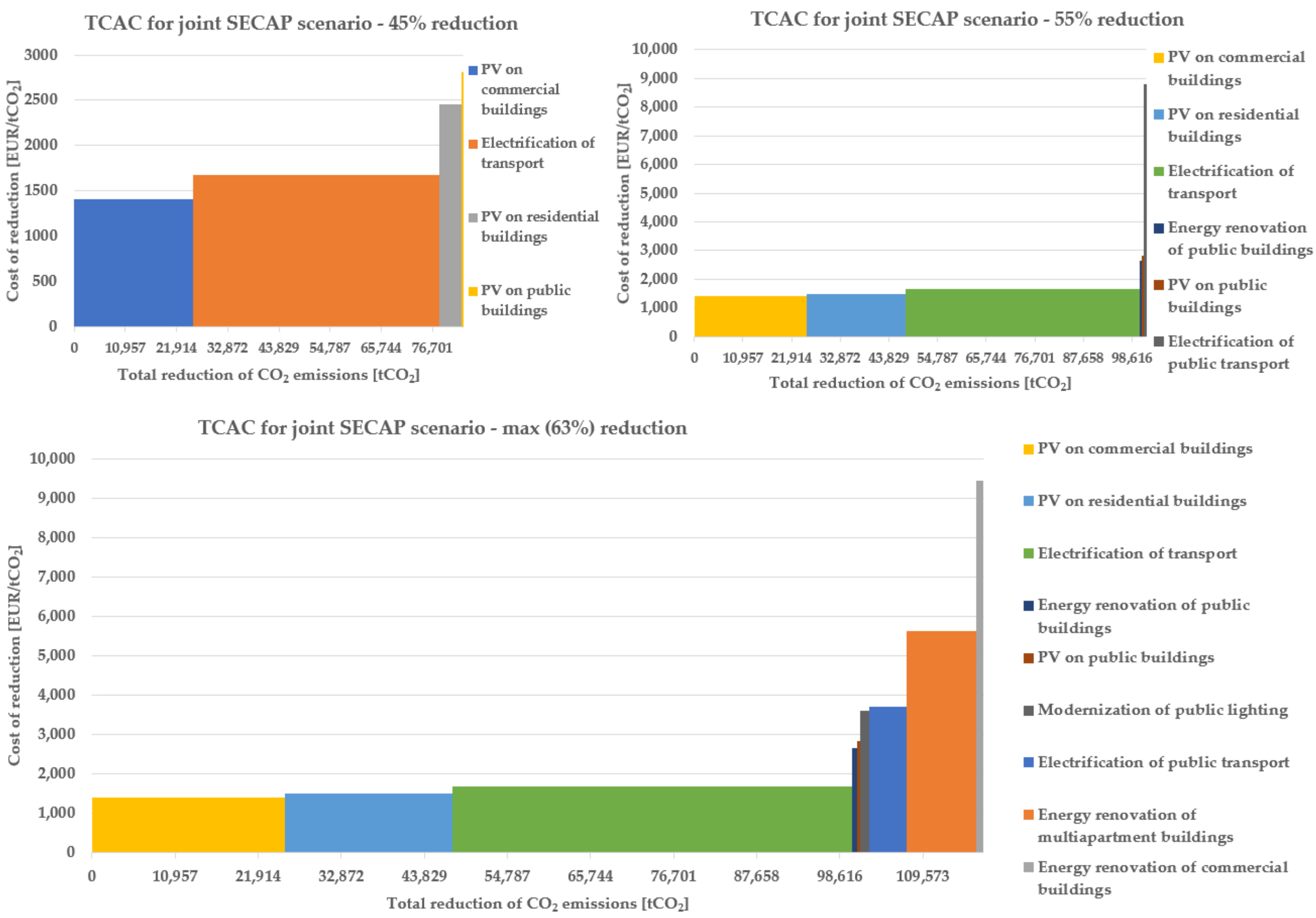

Figure 7. Total cost abatement curve in the case of optimisation of measures for the 45%, 55% and maximal (63%) CO_2 reduction.

The results shown in the previous two figures show that the most promising measures for the reduction are those which promote the installation of PVs and electrification of transport. This is expected since the highest reduction potential is in the transportation sector while electricity is the highest energy source consumed in the case study area. The other reason is that those measures have the lowest specific cost when implemented on a large scale which can be shown from the results of the analysis from developed SECAPs in Figures 1–4. The comparison of the total cost of the CO_2 emission reduction for different levels comparing the original scenario and optimisation ones from 40% to 63.5% is provided in Figure 8. The total costs of the optimisation scenarios are much lower than the original, which shows that it is possible to reach the same or higher levels of CO_2 emission reduction with lower use of financial resources.

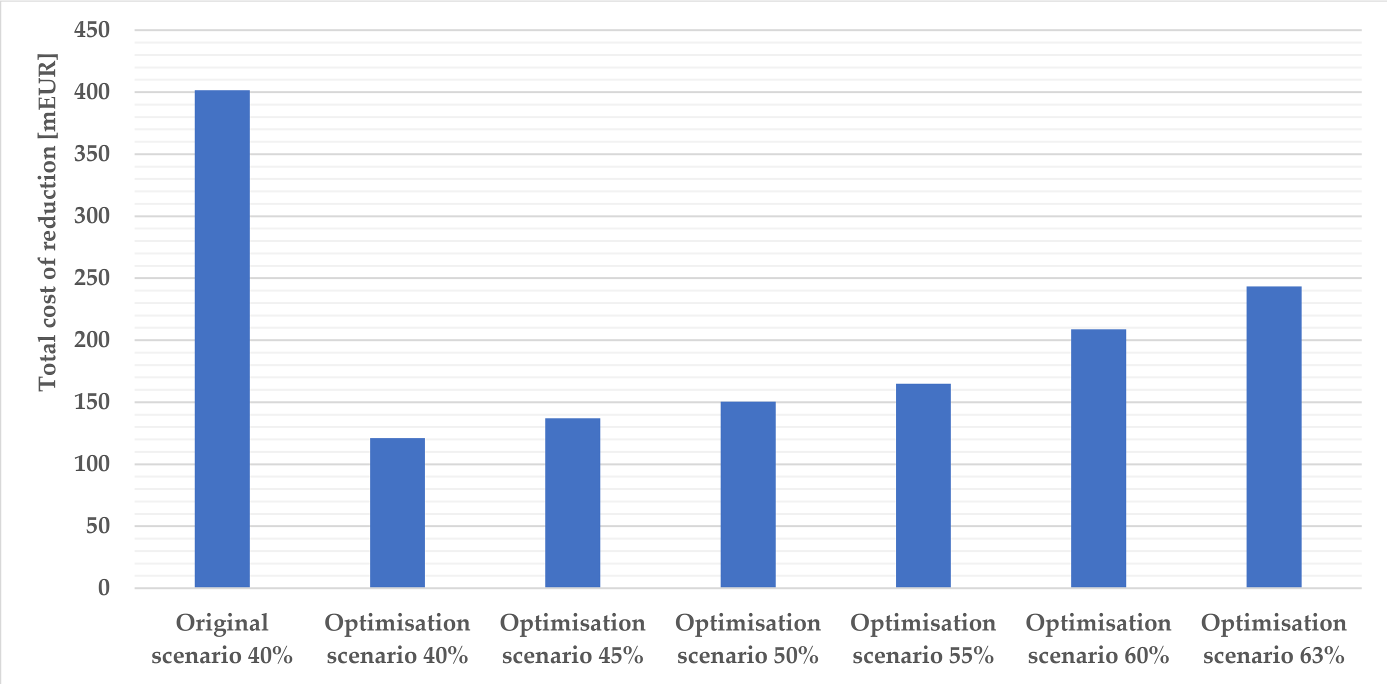

Figure 8. The total cost of mitigation measures in analysed scenarios in million EUR.

4. Discussion and Conclusions

The results presented in the previous chapter provide a good overview of the actions for the reduction of energy consumption and CO_2 emissions for the SECAPs in Croatia. When the given list of measures is correlated with the specifics of the case study, the most suitable measures are highlighted as the ones which should be first implemented. The case study area has a Mediterranean climate and high penetration of electricity with low CO_2 emission factor in the consumption of buildings, thereby promoting transport as the highest emitting sector. This has a large impact on the selection of the measures for reducing CO_2 emissions where the electrification of transport is the measure with the highest reduction potential. The other actions which are presented in all optimisation scenarios are related to the installation of PVs on buildings which will provide further reduction of CO_2 emissions from electricity and open the path for further penetration of electrification in all buildings and transport sectors. The production of energy on the site of consumption will increase the level of self-sufficiency from the energy point of view and in the wider logic of self-efficient social communities [34]. The proposed measures are in line with other analyses performed on the most common actions in which the local electricity production is highlighted as one of the best measures for energy and emission reductions [22].

The result of the measures optimisation is the key enabling factor for high reduction of the CO_2 emissions and mitigation actions on the analysed territory since the model supports the alignment with the baseline emission inventory by focusing the implementation in the sectors with the highest emission, i.e., transport. The alignment of the measures with the highest emitting sectors is the most important since it allows local authorities to achieve ambitious reduction goals [35].

Another specific factor of the case study is that it consists of small municipalities and one city with less than 50,000 inhabitants which without a joint approach could not reach the economy of scale for the cost-effective optimisation of the measures as shown in Figures 1–4. With the joint implementation of measures, the small municipalities need coordination from the upper regional level which can provide tailor-made solutions for sustainable energy planning as well as concrete financing opportunities for mitigation measures on their territories [36]. Another benefit of the joint development of the action plan is the support received from the upper level in the calculation of baseline and monitoring emission inventory and development of the action plan [36].

The specific cost for the reduction of CO_2 emissions is in a wide range from 1000 EUR/tCO_2 to 40,000 EUR/tCO_2 with the average values being between 2000 and 8000 EUR/tCO_2. This can be considered rather high compared to the previous analysis [22] but it has to be taken into account that in this work we only took into account so-called hard measures. The resulting cost of the measures is based on the minimisation of the cost function with the coefficients calculated based on the mitigation measures from the previously developed SECAPs. This approach has limited power since the changing of the form of the function can lead to different conclusions as well as changes in the coefficients.

The results of measures cost from the analysis considering the measures per sector are in line with the previous research showing that the highest cost is related to the measures in residential buildings and the lowest with the measures for local electricity production [22]. On the other hand, the electrification of transport is one of the cheapest measures in our analysis, but in the previous research [22] it was one of the most expensive. This could be due to the specifics of the case study with very low emissions from the electricity and buildings and very high emissions from transport. A similar conclusion can be taken from other studies where cases were cities which had high emissions from the transport sector and where the main measures which should have been prioritised are the ones in the transport sector [37]. Additionally, the measures in the transport sector could be more easily implemented than the measures in the buildings sector since it has fewer key decision makers [38]. Another benefit of focusing on the reduction of CO_2 emissions from the transport sector is also the reduction of air pollutant emissions, which is not always clear for the residential sector, where CO_2 emissions can be reduced but air pollutant emissions are increased, for example, in the case of introducing biomass heating [39]. The reduction of local air pollutant emissions is also increased by the installation of the PVs on buildings, which is another measure that is prioritised in our case. This can be beneficial for reducing local air pollutants from local electricity production as well as for heating if the PVs are combined with heat pumps. Another measure that is beneficial both for local air quality and the reduction of CO_2 emissions is energy renovation of buildings [39], which is the next measure in terms of prioritisation in our case study (Figure 7). Since the benefits of the air pollution reduction are not validated in the model, this should be part of the future research as well as the validation of other external costs reduced by implementation of measures such as additional green jobs, health and social benefits for the community.

The results of the optimisation of measures are also important to organise measures in order of implementation by prioritising lower cost measures. In this way, it could be possible to increase the overall implementation of SECAP measures which is currently considered to be low, with only 19% of measures fully implemented [40]. Moreover, in this way, the lack of appropriate financial planning which is marked as the constant and most common element in existing SECAPs [34] is being reduced since lower financial means are required. The lack of the financial and cost-benefit analysis in current SECAPs, as well as business plans and risk analysis, is a very negative element in implementation that needs to be properly addressed in the future [34].

The other important benefit of measures prioritisation and optimisation is the financial savings, but also the saving of other resources such as human and organisational [41]. This could provide a significant saving in our case, from 70% to 3 times reduction of costs for achieving the same or higher reduction of CO_2 emissions. The results of the prioritisation can be helpful to the policymakers in the cities and municipalities to forge their mitigation strategies and to give an answer on which sectors and measures they should focus their activities. Even though the prioritisation provides the most cost-beneficial measures to be implemented first, the policymakers should also work on the integrated and mixed mitigation strategies, considering the influence and interaction [42] between the measures from different sectors since the potential synergies and trade-offs between different policies could provide acceleration in the reaching of the mitigation goals [43]. The prioritisation could also provide a faster reduction of the emissions in the beginning and thus could encourage good practice, inspire both green investments and energy savings and go beyond the target set without increasing public debt [44]. Moreover, the prioritising of measures provides a strong tool for the local government which has opted for smart planning, sustainable development, environmental protection and increasing security of supply as pointed out in [45]. Additionally, the increased implementation can have social benefits such as increased employment and reduced cost for the import of fossil fuels [46].

In future work, the interaction and integration of different measures need to be further investigated since they could have different effects on each other as shown in [42]. This was evaluated to some level and it was shown that transport sector measures for electrification need to be jointly implemented and that integrated renovation of the building does not reduce the cost of implementation and reach a high reduction level due to the limited levels of CO_2 emissions from buildings in our case. Another integration of measures that should be further investigated is the joint implementation of adaptation and mitigation measures which will result in higher costs but could provide additional benefits in CO_2 and local pollution reduction. An option for this integration could be the use of the SET-Plan on the regional and local levels by implementing synergies between different stakeholders [47].

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Appendix A

Table A1. List of measures, coefficients and SECAPs which were used as the data source

Name of the Measure	x Corresponding to the Measure	Coefficients for Calculation of the Measure	SECAPs Used as Data Sources [48]
Integrated renovation of public buildings	x_1	k_{11} and k_{12}	City of Rijeka, City of Zadar, City of Osijek, City of Koprivnica, City of Varazdin, City of Cakovec
Energy renovation of public buildings	x_2	k_{21} and k_{22}	City of Novigrad, City of Porec, City of Pula, City of Rovinj, Municipality of Brtonigla, City of Buje, City of Labin, City of Pazin, Island of Brac
PV on public buildings	x_3	k_{31} and k_{32}	The city of Rijeka, City of Zadar, City of Osijek, City of Varazdin, City of Novigrad, City of Porec, City of Pula, City of Rovinj, Municipality of Brtonigla, City of Buje, City of Labin, City of Pazin, Island of Brac
Solar thermal on public buildings	x_4	k_{41} and k_{42}	City of Zadar, City of Osijek, City of Cakovec, City of Novigrad, City of Porec, City of Pula, City of Rovinj, Municipality of Brtonigla, City of Labin, City of Pazin

Electrification of public transport	x_5	k_{51} and k_{52}	City of Rijeka, City of Zadar, City of Osijek, City of Koprivnica, City of Varazdin
Integrated renovation of multi-apartment buildings	x_6	k_{61}, k_{62} and k_{63}	City of Rijeka, City of Zadar, City of Koprivnica, City of Varazdin
Integrated energy renovation of residential buildings	x_7	k_{71} and k_{72}	City of Rijeka, City of Zadar, City of Osijek, City of Koprivnica, City of Varazdin
Energy renovation of residential buildings	x_8	k_{81} and k_{82}	City of Osijek, City of Varazdin, City of Cakovec, City of Prelog
PV on residential buildings	x_9	k_{91} and k_{92}	The city of Rijeka, City of Zadar, City of Osijek, City of Varazdin, City of Cakovec, City of Novigrad, City of Porec, City of Pula, City of Rovinj, Municipality of Brtonigla, City of Buje, City of Labin, the City of Pazin, Island of Brac, City of Prelog
Energy renovation of commercial buildings	x_{10}	k_{101} and k_{102}	City of Rijeka, City of Zadar, City of Osijek, City of Koprivnica, City of Varazdin
PV on commercial buildings	x_{11}	k_{111} and k_{112}	The city of Rijeka, City of Zadar, City of Osijek, City of Varazdin, City of Cakovec, City of Novigrad, City of Porec, City of Pula, City of Rovinj, Municipality of Brtonigla, City of Buje, City of Labin, the City of Pazin, Island of Brac, City of Prelog
Modernisation of public lighting	x_{12}	k_{121} and k_{122}	City of Rijeka, City of Zadar, City of Osijek, City of Koprivnica, City of Varazdin, City of Cakovec, City of Porec, City of Pula, City of Buje, City of Labin, City of Pazin, Island of Brac
Infrastructure for electric vehicles and bicycles	x_{13}	k_{131}, k_{132} and k_{133}	City of Zadar, City of Osijek, City of Koprivnica, City of Varazdin, City of Cakovec, City of Prelog
Purchasing of electric vehicles	x_{14}	k_{141} and k_{142}	City of Rijeka, City of Zadar, City of Osijek, City of Koprivnica, City of Varazdin
Additional SECAPs analysed used for measures development	Non-applicable	Non-applicable	The city of Buzet, Island of Korcula, City of Kastva, City of Krizevci, City of Ludbreg, Municipality of Matulji, City of Slatina, City of Velika Gorica, City of Virovitica, City of Zagreb

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