KAUNO TECHNOLOGIJOS UNIVERSITETAS

KAMILĖ PETRAUSKIENĖ

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KAUNAS UNIVERSITY OF TECHNOLOGY

KAMILĖ PETRAUSKIENĖ

ASSESSMENT OF ELECTRIC, HYBRID AND CONVENTIONAL PASSENGER CARS USING A LIFE CYCLE APPROACH

Doctoral dissertation
Technological Sciences, Environmental Engineering (T 004)

2023, Kaunas

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TURINYS

LENTELIŲ SĄRAŠAS

PAVEIKSLŲ SĄRAŠAS

SANTRUMPŲ SĄRAŠAS

AEI – atsinaujinantys energijos ištekliai;
BCĮ – būvio ciklo įvertinimas;
CO_2 – anglies dioksidas;
Ekv. – ekvivalentas;
ENTP – eksploatuoti netinkama transporto priemonė;
ES – Europos Sąjunga;
IRT – informacinės ir ryšio technologijos;
IDIS – tarptautinė demontuotojų informacinė sistema (angl. *International Dismantling Information System*);
$KD_{2,5}$ – kietosios dalelės;
NMLOJ – ne metano lakieji organiniai junginiai;
NO_x – azoto oksidai;
PESTEL – politiniai, ekonominiai, socialiniai, technologiniai, aplinkosauginiai ir teisiniai veiksniai (angl. *Political, Economic, Social, Technological, Environmental, and Legal*);
SO_x – sieros oksidai;
SSGG – stiprybės, silpnybės, galimybės ir grėsmės;
STAN – medžiagų srautų analizės programinė įranga (angl. *subSTance flow ANalysis*);
ŠESD – šiltnamio efektą sukeliančios dujos.

1. ĮVADAS

Temos aktualumas

Transporto elektrifikavimas ir atsinaujinančių energijos išteklių (AEI) naudojimas miesto transporto sistemose tapo viena iš prioritetinių sričių Lietuvoje ir Europos Sąjungoje (ES), kovojant su klimato kaita, triukšmu bei oro tarša. Elektrinis transportas mažina oro taršą miestuose ir tokiu būdu saugo žmonių sveikatą nuo kvėpavimo takų ligų, o elektrinio transporto naudojama elektros energija, pagaminta iš vietinių AEI, prisidėtų prie mažesnės netiesioginės transporto oro taršos į aplinką ir padėtų įgyvendinti Nacionalinės energetikos nepriklausomybės tikslus [1]. Be to, ES 2050 metų ilgalaikė strategija siekia, kad ES šalių poveikis aplinkai iki 2050 metų taptų klimatui neutralus [2], o tai reiškia, kad būtina iš esmės keisti esamą transporto sistemą, kuri sukuria net ~23 % visų šiltnamio efektą sukeliančių dujų (ŠESD) emisijų ES [3]. Šiam tikslui pasiekti Europos Parlamentas 2022 m. birželio 8 d. pritarė Europos Komisijos pasiūlymui nuo 2035 m. ES šalyse prekiauti tik nulinės emisijos lengvaisiais keleiviniais ir komerciniais automobiliais [4]. Todėl miestuose vis mažiau liks automobilių su vidaus degimo varikliais, o transporto sistemos elektrifikavimas bei reikalingos infrastruktūros plėtra taps reikšmingu postūmiu darnių miestų kūrimui.

Integruojant elektrinį transportą, sprendimų priėmimo procese aktualus tampa aplinkosauginis ir ekonominis vertinimas. Todėl yra svarbu nustatyti transporto priemonių su skirtingų tipų varikliais poveikį aplinkai bei ekonomines sąnaudas, taikant būvio (gyvavimo) ciklo požiūrį. Taip pat reikšminga būtų įvertinti elektromobilio poveikį aplinkai naudojimo metu, kai baterijos įkrovimui naudojama elektra yra pagaminta esant įvairiems kuro ir AEI rūšių struktūros scenarijams, įgyvendinant Nacionalinės energetinės nepriklausomybės strategijos tikslus. O siekiant užtikrinti tvarų keleivinių automobilių, tapusių eksploatuoti netinkamomis transporto priemonėmis (ENTP), tvarkymą, svarbu įvertinti jų pakartotinio detalių panaudojimo ekonominę ir aplinkosauginę naudą žiedinės ekonomikos kontekste.

Tyrimo hipotezės

1) Elektros energijos gamybos pagal kuro ir AEI rūšis struktūra yra esminis veiksnys vertinant elektromobilio poveikį aplinkai naudojimo etape.

2) Elektromobilio ekonominės sąnaudos lyginant su kitų automobilių sąnaudomis yra mažiausios naudojimo stadijoje.

3) Keleiviniai automobiliai, tapę ENTP, turi reikšmingą detalių pakartotinio panaudojimo potencialą.

Disertacijos tikslas ir uždaviniai

Disertacijos tikslas – atlikti elektrinio, hibridinio ir įprastų keleivinių automobilių aplinkosauginį ir ekonominį vertinimą, taikant būvio ciklo požiūrį.

Šiam tikslui pasiekti buvo numatyti tokie uždaviniai:

1) išanalizuoti miesto transporto sistemos politikos priemones ir iniciatyvas Lietuvoje ir pasirinktuose Europos regionuose;

2) įvertinti ir palyginti elektrinio, hibridinio ir įprastų keleivinių automobilių poveikį aplinkai per visą būvio ciklą pagal prognozuojamus 2015–2050 metų skirtingus elektros gamybos scenarijus;

3) įvertinti ir palyginti elektrinio, hibridinio ir įprastų keleivinių automobilių ekonomines sąnaudas per visą būvio ciklą;

4) įvertinti ir palyginti elektrinio, hibridinio ir įprastų keleivinių automobilių, tapusių eksploatuoti netinkamomis transporto priemonėmis, pakartotinio detalių panaudojimo ekonominę ir aplinkosauginę naudą žiedinės ekonomikos kontekste.

Tyrimų objektas

Keleiviniai automobiliai su skirtingų tipų varikliais (elektrinis, hibridinis, benzininis ir dyzelinis).

Mokslinis naujumas

Jis pirmiausia yra susijęs su atliktu elektromobilio ir iškastinį kurą naudojančių keleivinių automobilių aplinkosauginiu būvio ciklo įvertinimu, rodančiu, kaip keisis poveikis aplinkai, kada elektrinio automobilio įkrovimui naudojama elektra yra pagaminta taikant įvairias AEI proporcijas pagal suprognozuotus elektros gamybos scenarijus nuo 2015 iki 2050 metų, įgyvendinant Nacionalinės energetinės nepriklausomybės strategijos tikslus. Tai leido įvertinti palankiausią aplinkai elektros energijos gamybos scenarijų ir identifikuoti nagrinėjamų automobilių „karštuosius taškus“ visame jų gyvavimo cikle. Antra, buvo atliktas elektromobilio ir iškastinį kurą naudojančių keleivinių automobilių ekonominis būvio ciklo įvertinimas, rodantis sąnaudas iš gamintojo ir vartotojo perspektyvų. Trečia, žiedinės ekonomikos kontekste buvo atlikta elektromobilio ir iškastinį kurą naudojančių keleivinių automobilių, tapusių eksploatuoti netinkamomis transporto priemonėmis (ENTP), pakartotinio detalių panaudojimo ekonominė nauda atliekų tvarkytojams ir vartotojams. Taip pat įvertinta ir aplinkosauginė nauda, rodanti, koks būtų CO_2 ekv. sutaupymo potencialas pakartotinai panaudojus detales po ENTP ardymo.

Darbo praktinė vertė

Vienas iš pagrindinių disertacijos tyrimų buvo orientuotas į būvio ciklo požiūriu paremtą automobilių su skirtingais varikliais poveikio aplinkai vertinimą gamybos, naudojimo ir atliekų tvarkymo etapuose. Atliktuose tyrimuose buvo akcentuojama elektromobilio aplinkosauginė analizė naudojimo etape, kai baterijos įkrovimui naudojama elektra yra pagaminta esant skirtingiems kuro ir energijos rūšių struktūros scenarijams, kurie buvo suprognozuoti 2015–2050 m. laikotarpiui, remiantis Nacionalinės energetinės nepriklausomybės strategijos tikslais. Atlikti tyrimai suteikia žinių įvairių šalių miesto transporto ir politikos planuotojams, ekspertams apie perėjimą nuo iškastinio kuro prie AEI naudojančių transporto priemonių. Tyrimo įžvalgos gali paskatinti toliau tobulinti elektrinių transporto priemonių integraciją, didinti visuomenės susidomėjimą mažiau taršiomis transporto priemonėmis, subsidijuoti elektrinių transporto priemonių įsigijimą ir plėsti įkrovimo infrastruktūrą šalyje. ES kontekste tai prisidėtų prie tarptautinių tikslų tapti klimatui neutralia šalimi iki 2050 metų.

Atlikti tyrimai, susiję su ENTP tvarkymu, patvirtino transporto priemonių, tapusių atliekomis, tvarkymo svarbą ir jų aplinkosauginio veiksmingumo bei ekonomikos augimo potencialą, tobulinant žiedinės ekonomikos principus. Tyrimo įžvalgos gali paskatinti politikos formuotojus ir kitas interesų grupes tobulinti politiką ir stiprinti paramą, susijusią su ENTP tvarkymu, o tai prisidėtų prie didesnės ekonominės, aplinkosauginės ir socialinės naudos. Be to, patobulinta politika prisidėtų prie nelegalaus ENTP tvarkymo stabdymo ir žalingo poveikio ES bei už jos ribų mažinimo, taip pat kasmet susidarančių atliekų kiekio mažinimo, medžiagų naudojimo efektyvumo didinimo ir pirminių žaliavų naudojimo mažinimo. Taip pat tikimasi, kad patobulinta politika labiausiai paveiks įmones, užsiimančias ENTP apdorojimu, perdirbimu ir jų dalių pardavimu, o tai gali paskatinti jų veiklos plėtrą. Veiklos plėtra nulems darbo vietų kūrimąsi šiame sektoriuje, kaip tik tai ir yra žiedinės ekonomikos pagrindas.

Tyrimų rezultatų aprobavimas

Disertacijos laikotarpiu moksliniai tyrimų rezultatai buvo paskelbti 7 publikacijose:

- 4 moksliniai straipsniai paskelbti tarptautiniuose žurnaluose: *Journal of Cleaner Production*, *Sustainability* ir *Waste Management*, turinčiuose cituojamumo rodiklį *Clarivate Analytics Web of Science* duomenų bazėje ir patenkančiuose į *Q1* arba *Q2* kvartilį.
- 1 publikacija – recenzuojamame tarptautinės konferencijos leidinyje;
- 2 publikacijos – nerecenzuojamuose tarptautinių konferencijų leidiniuose.

Mokslinių tyrimų rezultatai iš viso buvo pristatyti 5 tarptautinėse konferencijose, vykusiose kontaktiniu būdu Prancūzijoje (Nicoje bei Lilyje) ir nuotoliniu būdu Švedijoje, Vokietijoje bei Ispanijoje.

Disertacijos struktūra

Disertaciją sudaro: įvadas, 4 mokslinių straipsnių rinkinio apžvalga, išvados, santrauka anglų kalba, literatūros sąrašas, gyvenimo aprašymas, mokslinių straipsnių bei konferencijų sąrašas, mokslinių straipsnių kopijos ir padėka. Disertacijos apimtis 132 lapai, juose iš viso yra 9 paveikslai, 6 lentelės ir 81 literatūros šaltinis.

Literatūros apžvalga

ES susiduria su iššūkiais, siekdama įgyvendinti klimato ir energetikos politikos 2030 m. ir 2050 m. strategijas [5]. ES tikslas tapti klimatui neutralia šalimi yra apibrėžtas Europos žaliajame kurse, kuris siekia: „pertvarkyti ES į teisingą ir klestinčią visuomenę, pasižyminčią modernia, efektyviai išteklius naudojančia ir konkurencinga ekonomika, kurioje 2050 m. visai nebus grynojo išmetamo šiltnamio efektą sukeliančių dujų kiekio, o ekonomikos augimas bus atsietas nuo išteklių naudojimo“ [6]. Transporto sritis sukelia net ketvirtadalį visų ŠESD emisijų, iš kurių kelių transportas sudaro beveik tris ketvirtadalius emisijų [3]. Tad Europos žaliojo kurso strategijoje ši sritis apibrėžiama kaip viena reikšmingiausių ir reikalaujanti spartesnio perėjimo prie tvaraus mobilumo. Europos žaliajame kurse teigiama, kad norint neutralizuoti poveikį klimatui, transporto išmetamų emisijų kiekį iki 2050 m. reikia sumažinti net 90 % [6].

Transportas yra vienas didžiausių ŠESD šaltinių Lietuvoje. Remiantis nacionaline ŠESD kiekio apskaitos ataskaita už 2020 metus, transporto sektorius išskiria net 30,45 % viso susidariusio ŠESD kiekio (6145 kt CO_2 ekv.), iš kurio didžioji dalis (95 %) priklauso kelių transportui, o 52 % – keleiviniams automobiliams (3200 kt CO_2 ekv.). Lyginant su 2019 metais, 2020 m. dėl koronaviruso (COVID-19) pandemijos sukeltų apribojimų keleivinių automobilių ŠESD kiekis sumažėjo 5 %, tačiau vis tiek išliko reikšmingas. Taigi, lengvieji keleiviniai automobiliai išskiria net 16 % viso susidariusio ŠESD kiekio [7].

Transporto sektorius reikšmingai prisideda prie oro taršos Lietuvoje. Remiantis nacionalinės oro teršalų apskaitos duomenimis už 2020 metus, kelių transportas yra pagrindinis azoto oksidų (NO_x) teršalų šaltinis ir išskiria net 55,4 %, o lengvieji automobiliai – 17,1 %, skaičiuojant nuo viso šalyje išmesto NO_x kiekio. Taip pat keleiviniai lengvieji automobiliai prisideda ir prie kitų oro teršalų emisijų: 4,4 % – $KD_{2,5}$, 1,8 % – ne metano lakiųjų organinių junginių (NMLOJ), 0,2 % – sieros oksidų (SO_x), vertinant nuo bendro kiekio [8]. Yra įvertinta, kad su sveikata susijusios išorinės sąnaudos dėl oro taršos Lietuvoje viršija 1 mlrd. eurų per metus, į kuriuos įeina ne tik esminė sveiko gyvenimo vertė, bet ir tiesioginės išlaidos šalies ekonomikai. Šios tiesioginės ekonominės išlaidos yra susijusios su 488 000 darbo dienų, kurios kasmet prarandamos dėl ligų, sukeltų oro taršos; išlaidos darbdaviams siekia net 37 mln. eurų per metus, o sveikatos priežiūrai – daugiau nei 5 mln. eurų per metus [9].

Pasaulyje elektrinės transporto priemonės laikomos ateities transportu, prisidedančiu prie aplinkai draugiško miesto kūrimo. Jos sumažina vietinę oro taršą, ŠESD emisijas ir eismo triukšmą, o tai ypač aktualu didmiesčių gyventojams. Neturėdamos išmetimo vamzdžio, nesukelia ir tiesioginių teršalų emisijų į aplinkos orą, kaip kad įprastos transporto priemonės. Be to, elektrinis variklis veikia tyliai, ypač važiuojant mažesniu greičiu [10]. Kiti elektrinio transporto privalumai: 1) variklis yra daug efektyvesnis negu įprastų vidaus degimo variklių; 2) paprastesnė ir ekonomiškesnė priežiūra per visą eksploatavimo laiką; 3) elektra gali būti naudojama iš AEI; 4) baterijos, įjungtos į elektros tinklą, gali stabilizuoti tinklą ir subalansuoti elektros pasiūlą bei paklausą, taip palengvinant AEI integraciją [11].

Įvairūs moksliniai tyrimai teigia, jog elektrinių transporto priemonių pagrindinis privalumas – tai kur kas mažesnis poveikis aplinkai, jeigu baterijos įkrovimui būtų naudojama elektra, pagaminta iš AEI [12]–[16]. ES nustatė bendrą tikslą, kad iki 2020 m. AEI (įskaitant biometaną, skystąjį biokurą, „žaliąją elektrą“ ir vandenilį) turėtų sudaryti 10 % viso energijos kiekio, sunaudoto transporto srityje. Taigi, ES šį tikslą pasiekė su 10,2 % 2020 metais (padidėjo nuo 1,5 % 2004 m.) [17].

Lietuvoje iki 2020 m. AEI dalis galutiniame energijos suvartojime transporto sektoriuje turėjo siekti bent 10 %, bet, deja, šis tikslas nebuvo pasiektas su 5,5 % 2020 m. [18]. Be to, pagal Nacionalinę energetinės nepriklausomybės strategiją Lietuvos ateities tikslai yra dar ambicingesni: iki 2030 m. padidinti AEI dalį transporto sektoriuje iki 15 %, o iki 2050 m. – iki 50 % [1]. Pagal Lietuvos Respublikos Nacionalinį energetikos ir klimato srities veiksmų planą 2021–2030 m. viena iš planuojamų politikos priemonių transporto sektoriuje iki 2030 m. – elektromobilių naudojimo skatinimas ir jų įkrovimo infrastruktūros plėtra. Planuojamas rezultatas – 2025 m. 10 % M1 klasės metinių pirkimo sandorių (registruotų ir perregistruotų lengvųjų automobilių) sudarys elektromobiliai, 2030 m. – 50 % [19].

Elektrinis transportas turi tiek aplinkosauginių, tiek ekonominių privalumų ir prisideda prie darnaus miesto kūrimo. Išaugusios degalų kainos keičia gyventojų požiūrį į automobilius su vidaus degimo varikliais. Tą pademonstravo „Norstat“ ir „Moller Auto“ atlikta apklausa, kurios pagrindiniai rezultatai parodė, jog labiausiai Lietuvos gyventojus įsigyti elektromobilius skatina mokesčių lengvatos, mažesnės eksploatacijos sąnaudos ir mažesnis poveikis aplinkai. Taip pat miesto gyventojus motyvuoja parkavimo bei įvažiavimo rinkliavų lengvatos, taip pat privilegija važiuoti pirmąja eismo juosta ir galimybė aplenkti automobilių spūstis [20].

Remiantis 2022 m. pabaigos transporto priemonių registravimo duomenimis, didžiausią registruotų lengvųjų keleivinių automobilių dalį užima: dyzeliniai (67,6 %), toliau rikiuojasi benzininiai (23,1 %), suskystintosiomis naftos dujomis varomi (5,9 %), toliau hibridiniai (3 %) ir galiausiai elektromobiliai (0,4 %) [21]. Tokia elektromobilių skaičiaus dalis Lietuvoje – tai žymus teigiamas pokytis lyginant su praėjusiais metais. Lietuvoje 2022 m. pabaigoje buvo įregistruoti 7346 keleiviniai elektromobiliai (nauji ir naudoti), o 2020 m. pabaigoje buvo 2496, palyginimui 2018 m. – tik 969 elektromobiliai [21]. Toks reikšmingas elektromobilių kiekio padidėjimas – tai sėkmingo finansinio paskatinimo, pradėto įgyvendinti nuo 2020 metų pavasario, rezultatas. Fiziniams asmenims yra galimybė gauti 2500 eurų kompensaciją perkant naudotą (iki 4 metų) elektromobilį ir 5000 eurų kompensaciją perkant naują (iki 6 mėn.) elektromobilį [22]. Papildoma 1000 eurų kompensacija išmokama senų automobilių savininkams, kurie savo senus automobilius nemokamai atiduoda į ENTP surinkimo bei tvarkymo įmones, gauna sunaikinimo pažymėjimą ir tada perka elektrinį ar mažiau taršų (kurio bendras išmetamas CO_2 kiekis ne didesnis kaip 130 g/km) automobilį [23]. Taip pat yra įdiegta skatinimo programa elektromobiliams įsigyti juridiniams asmenims (ir fiziniams asmenims, kurie juos naudos ūkinei veiklai), kai perkant naują elektromobilį (iki 6 mėn.) yra skiriama

4000 eurų kompensacija [24]. Tokios finansinės paskatos yra puiki galimybė skatinti elektrinių transporto priemonių integraciją į miesto transporto sistemas.

Pagal Europos aplinkos agentūros paskelbtus duomenis, visoje Europoje pastebėtas reikšmingas grynųjų ir įkraunamųjų elektromobilių padidėjimas, t. y. 2020 m. buvo užregistruoti 1 061 497, o 2021 m. – 1 728 968 grynieji ir įkraunamieji elektromobiliai. Tai reiškia, kad vos per metus jų dalis bendrame naujų automobilių registracijų kiekyje padidėjo nuo 10,7 % iki 17,8 % (gryniesiems ir įkraunamiesiems elektromobiliams pasiskirsto atitinkamai 9 % ir 8,8 %). Lyderiaujančios šalys, kuriose užfiksuota didžiausia naujų grynųjų ir įkraunamųjų elektromobilių registracijų dalis bendrame naujų automobilių registracijų kiekyje 2021 metais, yra Norvegija (86 %), Islandija (64 %), Švedija (46 %), Danija (35 %), Suomija (32 %), Nyderlandai (30 %), Vokietija (27 %) ir t. t. O štai Lietuva (5 %) išlieka lyderė tik lyginant su Baltijos šalimis, t. y. Latvija (4 %) ir Estija (3 %) [25]. Lyderiaujančiose šalyse yra ypatingai skatinamas perėjimas nuo automobilių su vidaus degimo varikliais prie elektromobilių, todėl taikomos įvairios finansinės iniciatyvos, pavyzdžiui, subsidijos, skiriamos už įsigytą elektromobilį, pajamų, PVM mokesčių lengvatos, nemokamas krovimo taškų įrengimas namuose, registracijos mokesčių sumažinimas arba atleidimas nuo mokesčių ir kitos lengvatos [26]–[30].

Aplinkosauginis ir ekonominis naudingumas visada buvo ir bus varomoji jėga sprendimų priėmimo procese integruojant elektrines transporto priemones į miesto transporto sistemas, ypač kai vyrauja gyventojų maža perkamoji galia, o šalys susiduria su kitais iššūkiais ir kliūtimis [31], [32]. Todėl norint susidaryti bendrą įspūdį apie elektromobilių teikiamus privalumus, būtina atlikti tiek aplinkosauginį, tiek ekonominį vertinimą.

Šiame moksliniame darbe yra pateiktas išsamus būvio ciklo įvertinimas (BCĮ) iš aplinkosauginės (angl. *Life Cycle Assessment*) ir ekonominės (angl. *Life Cycle Costing*) perspektyvos. Anot Hauschild (2018), BCĮ naudojimas mobilumo srityje gali praversti: 1) lyginant skirtingų tipų transporto priemones gamybos etape; 2) analizuojant ir palyginant skirtingų transporto priemonių naudojamų degalų (elektros) poveikį aplinkai eksploatavimo metu; 3) lyginant skirtingų transporto priemonių, tapusių ENTP, tvarkymo būdus; 4) nustatant analizuojamų objektų „karštuosius taškus" ir pagrindinius jų privalumus bei trūkumus per tris gyvavimo ciklo etapus (gamybą, naudojimą bei atliekų tvarkymą) ir kt. [33]. BCĮ – tai universalus metodas, taikomas įvairiems tikslams ir įvairiuose gaminio ar sistemos gyvavimo etapuose, siekiant priimti atitinkamus sprendimus aplinkosauginiu ir ekonominiu požiūriu. Be to, BCĮ aplinkosauginis ir ekonominis vertinimas yra gyvavimo ciklo tvarumo vertinimo (angl. *Life Cycle Sustainability Assessment*) dedamosios dalys, kada susijungia trys darnaus vystymosi aspektai (aplinkosauginis, ekonominis ir socialinis), palaikantys būvio ciklo mąstymo idėją [34], [35].

Pasauliniu mastu buvo atlikta įvairių BCĮ tyrimų, nagrinėjančių elektrinių bei įprastų automobilių poveikį aplinkai ir ekonomines sąnaudas, tokiose šalyse kaip: Australija [36], Belgija [37], Brazilija [38], Čekija [39], Ispanija [40], Italija [41], Japonija [42], JAV [43]–[45], Kanada [46], Kinija [47]–[49], Lenkija [39], Nepalas [50], Prancūzija [51], Šveicarija [52], Vokietija [53]–[55].

Iki šiol Lietuvos mastu BCĮ tyrimų mobilumo kontekste dar nebuvo atlikta. Be to, Lietuva šiam moksliniam darbui buvo pasirinkta kaip reprezentacinė šalis, skatinanti ir integruojanti elektrines transporto priemones bei AEI į miesto transporto sistemas ir siekianti įgyvendinti tiek nacionalinius, tiek ES iškeltus tikslus. Šiame darbe buvo taikoma BCĮ metodika aplinkosauginiu ir ekonominiu požiūriu, skirta įvertinti keleivinių automobilių su skirtingų tipų varikliais (elektrinio, hibridinio, benzininio bei dyzelinio) poveikį aplinkai ir ekonomines sąnaudas per visą gyvavimo ciklą (gamybą, naudojimą ir atliekų tvarkymą). Be to, elektromobilio poveikis aplinkai naudojimo metu buvo įvertintas tuo atveju, kai baterijos įkrovimui naudojama elektra yra pagaminta esant įvairiems kuro ir energijos rūšių struktūros scenarijams, kurie buvo suprognozuoti taikant matematinį modeliavimą 2015–2050 m. laikotarpiui, remiantis Nacionalinės energetinės nepriklausomybės strategijos tikslais. Be to, tie patys keleiviniai automobiliai buvo įvertinti taikant būvio ciklo požiūrį žiedinės ekonomikos kontekste, nustatant ekonominę naudą ENTP tvarkytojams bei naudotų detalių pirkėjams. Taip pat, taikant CO_2 ekv. emisijų, susidarančių detalių medžiagų gamybos metu, ekvivalentus vienam kilogramui medžiagos, buvo įvertintas išmetamo CO_2 ekv. emisijų kiekio sumažinimo potencialas, jeigu analizuojamų automobilių detalės būtų pakartotinai panaudotos. Tai leido įvertinti ir palyginti detalių pakartotinio panaudojimo aplinkosauginę naudą.

Moksliniai straipsniai ir jų sąsajos

ES skatinamas kelių transporto elektrifikavimas, kuris tapo pagrindine tvaraus mobilumo tendencija, o dvi iš svarbiausių tendencijų, kurios vis labiau įsibėgėja Europos miestuose, yra elektrinių transporto priemonių ir AEI integravimas. Tokiu būdu šalys sumažintų vietinę taršą, triukšmą, prisidėtų prie klimato kaitos mažinimo ir plėtotų AEI naudojimą transporto sektoriuje. Siekiant nacionalinių ir tarptautinių tikslų įgyvendinimo, labai svarbu bendradarbiauti ir domėtis kitų šalių praktika elektrinio mobilumo srityje, taip pat pritaikyti gerąsias praktikas ir politines priemones savo šalyje. Tuo tikslu buvo išsikeltas uždavinys – išanalizuoti miesto transporto sistemų politikos priemones bei iniciatyvas Lietuvoje ir pasirinktuose Europos regionuose. Įgyvendinant šį uždavinį buvo atlikta analizė, kuri atskleidė politikos priemones ir iniciatyvas, susijusias su elektrinio mobilumo, AEI ir informacinių bei ryšio technologijų (IRT) integracija, tobulinant miesto transporto sistemas penkiuose Europos regionuose: Ispanijoje (Barselonoje), Italijoje (Lacijuje), Lietuvoje, Nyderlanduose (Amsterdame bei Flevolande) ir Švedijoje (Stokholme). Siekiant išsiaiškinti ir pabrėžti esamos mobilumo situacijos veiksnius, kliūtis, galimybes ir rizikas, buvo atlikta integruota stiprybių, silpnybių, galimybių ir grėsmių (SSGG) analizė kartu su politine, ekonomine, socialine, technologine, aplinkosaugine ir teisine (PESTEL) analize, kuri buvo paremta nagrinėjamų Europos šalių regionų esamomis politikos priemonėmis ir iniciatyvomis. Tyrimo rezultatai išsamiai pateikti ir publikuoti moksliniame straipsnyje ***Situation analysis of policies for electric mobility development: experience from five European regions*** [56].

Analizuojant transporto sukeliamą poveikį aplinkai yra labai svarbu išsamiai palyginti transporto priemones tarpusavyje, vertinant poveikį aplinkai nuo jų gamybos iki galutinio atliekų sutvarkymo, taikant būvio ciklo požiūrį. Tuo tikslu buvo atlikta analizė, paremta antruoju išsikeltu uždaviniu – įvertinti ir palyginti elektrinio, hibridinio ir įprastų keleivinių automobilių poveikį aplinkai per visą gyvavimo ciklą pagal prognozuojamus 2015–2050 metų skirtingus elektros gamybos scenarijus. Įgyvendinant šį uždavinį buvo atliktas elektrinio automobilio ir iškastinį kurą naudojančių keleivinių automobilių aplinkosauginis būvio ciklo įvertinimas. Pagal pasirinktas metodikas buvo nustatytas poveikis aplinkai nuo žaliavų išgavimo iki galutinio atliekų sutvarkymo. Elektromobilio naudojimo etape buvo įvertinta, kaip keisis poveikis aplinkai, kada baterijos įkrovimui naudojama elektra yra pagaminta taikant įvairias AEI proporcijas pagal suprognozuotus elektros gamybos scenarijus nuo 2015 iki 2050 metų, įgyvendinant Nacionalinės energetinės nepriklausomybės strategijos tikslus. Tyrimo rezultatai išsamiai pateikti ir publikuoti moksliniame straipsnyje ***Comparative environmental life cycle assessment of electric and conventional vehicles in Lithuania*** [57].

Vertinant miesto transporto sistemas, svarbus ne tik aplinkosauginis veiksmingumas, bet ir ekonominis naudingumas. Tuo tikslu buvo atlikta analizė, paremta trečiuoju išsikeltu uždaviniu – įvertinti ir palyginti įprastų, hibridinio ir elektrinio keleivinių automobilių ekonomines sąnaudas per visą būvio ciklą. Šiam uždaviniui įgyvendinti buvo atliktas būvio ciklo ekonominių sąnaudų vertinimas pasirinktiems skirtingų variklio tipų keleiviniams automobiliams (elektromobiliui, hibridiniam, benzininiam ir dyzeliniam automobiliams). Tyrimų rezultatai atskleidė nustatytas ekonomines sąnaudas per visą automobilių gyvavimo ciklą, t. y. nuo žaliavų išgavimo iki galutinio atliekų sutvarkymo, vertinant sąnaudas iš gamintojo ir vartotojo perspektyvos. Tyrimo rezultatai išsamiai pateikti ir publikuoti moksliniame straipsnyje ***Comparative environmental life cycle and cost assessment of electric, hybrid, and conventional vehicles in Lithuania*** [58].

Lietuva pasižymi senu transporto priemonių parku ir klestinčia naudotų automobilių prekyba bei nelegaliu ENTP ardymu. O automobilių, tapusių ENTP, detalės turi tiek ekonominę, tiek aplinkosauginę naudą. Taigi, ENTP gali prisidėti prie žiedinės ekonomikos plėtros. Tuo tikslu buvo atlikta analizė, paremta ketvirtuoju išsikeltu uždaviniu – įvertinti ir palyginti įprastų, hibridinio ir elektrinio keleivinių automobilių, tapusių ENTP, pakartotinio detalių panaudojimo ekonominę ir aplinkosauginę naudą žiedinės ekonomikos kontekste. Įgyvendinant šį uždavinį visų pirma atlikta medžiagų srautų analizė, kuri padėjo suprasti ENTP detalių medžiagų srautų judėjimą. Antra, atliktas keturių populiariausių naudotų Lietuvoje lengvųjų automobilių su skirtingų tipų varikliais ekonominis vertinimas, kuriuo įvertinta ekonominė nauda ENTP ardytojams ir naudotų detalių pirkėjams. Trečia, taikant CO_2 ekv. emisijų, susidarančių detalių medžiagų gamybos metu, ekvivalentus vienam kilogramui medžiagos, įvertintas išmetamo CO_2 ekv. emisijų kiekio sumažinimo potencialas, jeigu analizuojamų automobilių detalės būtų pakartotinai panaudotos. Pateiktas gamybos metu kiekvienos detalės išmetamas CO_2 ekv. emisijų kiekis, kuris padėjo įvertinti ir palyginti detalių pakartotinio panaudojimo aplinkosauginę naudą. Ketvirta, atlikta analizuojamų automobilių būvio ciklo analizė, orientuota į gamybos ir atliekų tvarkymo stadijas. Tyrimo rezultatai išsamiai pateikti ir publikuoti moksliniame straipsnyje ***Environmental and economic benefits of electric, hybrid and conventional vehicle treatment: a case study of Lithuania*** [59].

Disertantės ir bendraautorių mokslinis indėlis straipsniuose

Straipsnis nr. 1: ***Situation analysis of policies for electric mobility development: experience from five European regions*** [56].

Kamilė Petrauskienė – pirmoji autorė, taip pat ir autorė susisiekimui, prisidėjo prie straipsnio konceptualizavimo: idėjų generavimo, tyrimo eigos, tikslo ir uždavinių formulavimo; taip pat prisidėjo prie pradinio straipsnio juodraščio rašymo, parengtą straipsnį pateikė į žurnalą, administravo, po straipsnio recenzavimo etapo pateikė atsakymus recenzentams ir atitinkamai pakoregavo straipsnį pagal jų pastabas, galiausiai pateikė galutinę versiją į žurnalą. **Jolanta Dvarionienė** – antroji bendraautorė, prisidėjo prie komandos subūrimo, straipsnio idėjų generavimo, tyrimo eigos, tikslo ir uždavinių formulavimo. Taip pat prisidėjo prie projekto administravimo, pradinio ir galutinio straipsnio peržiūros. **Giedrius Kaveckis** – trečiasis bendraautoris, prisidėjo prie idėjų generavimo, tyrimo eigos, tikslo ir uždavinių formulavimo. Taip pat prisidėjo prie duomenų surinkimo, analizavimo ir pateikimo, pradinio straipsnio juodraščio rašymo. **Daina Kliaugaitė** – ketvirtoji bendraautorė, prisidėjo prie idėjų generavimo, tyrimo eigos, tikslo ir uždavinių formulavimo. Taip pat prisidėjo prie metodikos rengimo, vizualizacijos, pradinio straipsnio juodraščio rašymo. Kiti straipsnio bendraautoriai yra projekto EV ENERGY partneriai, kurie prisidėjo surinkdami ir pateikdami duomenis bei informaciją apie savo šalį. **Julie Chenadec** – penktoji bendraautorė, pateikė duomenis apie Nyderlandus, **Leonie Hehn** ir **Berta Pérez** – šeštoji ir septintoji bendraautorės, pateikė duomenis apie Ispaniją, **Claudio Bordi, Giorgio Scavino** ir **Andrea Vignoli** – aštuntasis, devintasis, dešimtasis bendraautoriai, pateikė duomenis apie Italiją ir **Michael Erman** – vienuoliktasis bendraautoris, pateikė duomenis apie Švediją. Taip pat visų bendraautorių indėlis yra pateiktas ir straipsnio pabaigoje.

Straipsnis nr. 2: ***Comparative environmental life cycle assessment of electric and conventional vehicles in Lithuania*** [57].

Kamilė Petrauskienė – pirmoji autorė, taip pat ir autorė susisiekimui, prisidėjo prie straipsnio konceptualizavimo: idėjų generavimo, tyrimo eigos, tikslo ir uždavinių formulavimo; prisidėjo prie straipsnio vizualizacijos, tyrimo metodikos kūrimo, duomenų surinkimo, tyrimo atlikimo, analizės; taip pat prisidėjo prie pradinio straipsnio juodraščio rašymo, parengtą straipsnį pateikė į žurnalą, administravo, po straipsnio recenzavimo etapo pateikė atsakymus recenzentams ir atitinkamai pakoregavo straipsnį pagal jų pastabas, galiausiai pateikė galutinę versiją į žurnalą. **Monika Skvarnavičiūtė** – antroji bendraautorė, prisidėjo prie tyrimui reikalingų duomenų surinkimo, metodikos kūrimo, tyrimo atlikimo, analizės, pradinio straipsnio juodraščio rašymo. **Jolanta Dvarionienė** – trečioji bendraautorė, prisidėjo prie idėjų generavimo, tyrimo eigos, tikslo ir uždavinių formulavimo, pradinio ir galutinio straipsnio peržiūros.

Straipsnis nr. 3: ***Comparative environmental life cycle and cost assessment of electric, hybrid, and conventional vehicles in Lithuania*** [58].

Kamilė Petrauskienė – pirmoji autorė, taip pat ir autorė susisiekimui, prisidėjo prie straipsnio konceptualizavimo: idėjų generavimo, tyrimo eigos, tikslo ir uždavinių formulavimo; prisidėjo prie straipsnio vizualizacijos, tyrimo metodikos kūrimo, tyrimo atlikimo, analizės; taip pat prisidėjo prie pradinio straipsnio juodraščio rašymo, parengtą straipsnį pateikė į žurnalą, administravo, po straipsnio recenzavimo etapo pateikė atsakymus recenzentams ir atitinkamai pakoregavo straipsnį pagal jų pastabas, galiausiai pateikė galutinę versiją į žurnalą. **Arvydas Galinis** – antrasis bendraautoris, prisidėjo prie duomenų pateikimo, tyrimo atlikimo, vizualizacijos, galutinės straipsnio versijos peržiūros. **Daina Kliaugaitė** – trečioji bendraautorė, prisidėjo prie metodikos rengimo, vizualizacijos, pradinės ir galutinės straipsnio versijos peržiūros. **Jolanta Dvarionienė** – ketvirtoji bendraautorė, prisidėjo prie straipsnio idėjų generavimo, tyrimo eigos, tikslo ir uždavinių formulavimo, pradinio ir galutinio straipsnio peržiūros.

Straipsnis nr. 4: ***Environmental and economic benefits of electric, hybrid and conventional vehicle treatment: a case study of Lithuania*** [59].

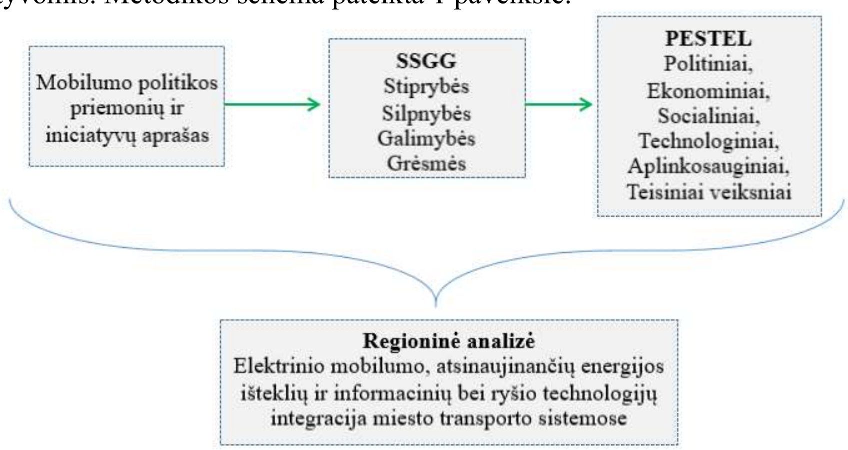
Kamilė Petrauskienė – pirmoji autorė, taip pat ir autorė susisiekimui, prisidėjo prie straipsnio konceptualizavimo: idėjų generavimo, tyrimo eigos, tikslo ir uždavinių formulavimo; prisidėjo prie straipsnio vizualizacijos, tyrimo metodikos kūrimo, duomenų surinkimo, tyrimo atlikimo, analizės; taip pat prisidėjo prie pradinio straipsnio juodraščio rašymo, parengtą straipsnį pateikė į žurnalą, administravo, po straipsnio recenzavimo etapo pateikė atsakymus recenzentams ir atitinkamai pakoregavo straipsnį pagal jų pastabas, galiausiai pateikė galutinę versiją į žurnalą. **Rasa Tverskytė** – antroji bendraautorė, prisidėjo prie tyrimui reikalingų duomenų surinkimo, metodikos pateikimo, vizualizacijos, tyrimo atlikimo, analizės, pradinio straipsnio juodraščio rašymo. **Jolanta Dvarionienė** – trečioji bendraautorė, prisidėjo prie straipsnio idėjų generavimo, tyrimo eigos, tikslo ir uždavinių formulavimo, pradinio ir galutinio straipsnio peržiūros.

2. POLITINIŲ PRIEMONIŲ IR INICIATYVŲ ELEKTRINIO MOBILUMO PLĖTROS KONTEKSTE ANALIZĖ EUROPOS REGIONUOSE

Šiame skyriuje pristatomos politikos priemonės ir iniciatyvos, susijusios su elektrinio mobilumo, AEI ir informacinių bei ryšio technologijų (IRT) integracija, plėtojant miesto transporto sistemas penkiuose Europos regionuose: Ispanijoje (Barselonoje), Italijoje (Lacijuje), Lietuvoje, Nyderlanduose (Amsterdame bei Flevolande) ir Švedijoje (Stokholme). Buvo atlikta integruota stiprybių, silpnybių, galimybių ir grėsmių (SSGG) analizė kartu su politine, ekonomine, socialine, technologine, aplinkosaugine ir teisine (PESTEL) analize, kuri buvo paremta nagrinėjamų Europos šalių regionų esamomis politikos priemonėmis ir iniciatyvomis. Šito tyrimo pagrindu buvo parengtas ir publikuotas mokslinis straipsnis ***Situation analysis of policies for electric mobility development: experience from five European regions*** [56]. Šiais publikuotais tyrimo rezultatais buvo įgyvendintas pirmasis disertacijoje išsikeltas uždavinys.

2.1. Tyrimų metodika

Tyrimo tikslas – identifikuoti politikos priemones ir iniciatyvas, susijusias su elektrinio mobilumo, atsinaujinančių energijos išteklių (AEI) ir informacinių bei ryšio technologijų (IRT) integracija, tobulinant miesto transporto sistemas penkiuose Europos regionuose: Ispanijoje (Barselonoje), Italijoje (Lacijuje), Lietuvoje, Nyderlanduose (Amsterdame bei Flevolande) ir Švedijoje (Stokholme). Tyrimai apima dvi dalis: 1) nagrinėjamų Europos šalių regionų mobilumo politikos priemonių ir iniciatyvų aprašą; 2) integruotą stiprybių, silpnybių, galimybių ir grėsmių (SSGG) analizę kartu su politine, ekonomine, socialine, technologine, aplinkosaugine ir teisine (PESTEL) analize, kuri buvo paremta minėtomis politikos priemonėmis ir iniciatyvomis. Metodikos schema pateikta 1 paveiksle.



1 pav. Metodikos schema

Regioninė analizė buvo paremta trimis dedamosiomis: elektrinio transporto, AEI ir IRT integracija. Elektrinio transporto aspektą apėmė įvairios subsidijos, paskatos elektrinio transporto įsigijimui, eismo reguliavimas, stovėjimo apmokestinimas, įkrovimo infrastruktūra ir kt. Lygiagrečiai buvo analizuojami AEI aspektas, apimantis paskatas ir priemones plėtojant vietinę AEI gamybą, finansinė parama statybai, leidimai, kainodara. Galiausiai IRT aspektas svarbus tuo, kad pažangesnė ir efektyvesnė elektrinio transporto ir AEI integracija būtų diegiama naudojant IRT priemones.

Visi projekto partneriai aktyviai dalyvavo mobilumo politikos priemonių ir iniciatyvų aprašo rengime, renkant duomenis pagal parengtus šablonus. Aprašas buvo parengtas analizuojant tokius šaltinius kaip: šalies įstatymai, reglamentai, atitinkamos interneto svetainės, viešai publikuotos ataskaitos, nacionaliniai bei tarptautiniai standartai ir kiti susiję šaltiniai.

Šis aprašas buvo tarsi pradinis taškas rinkti ir suprasti, kas valdo, reguliuoja ir užtikrina darnų mobilumą miestuose. Mobilumo politikos kryptys buvo sugrupuotos ir analizuojamos miesto / regioniniu, nacionaliniu ir tarptautiniu mastu. Be to, priemonės buvo suskirstytos į keturis skirtingus tipus, apimančius skirtingus mobilumo aspektus: elektrinį mobilumą, miestų ir erdvių planavimą, IRT priemones energetikos sistemoms, informuotumą ir įsisavinimą.

Antroji tyrimų metodikos dalis – tai integruota SSGG ir PESTEL analizė, kuri pagrįsta mobilumo politikos priemonių ir iniciatyvų pagrindu, siekiant išryškinti elektrinio mobilumo, AEI ir IRT integracijos stiprybes, silpnybes, galimybes ir grėsmes analizuojamuose Europos regionuose. Išsamesnei analizei atlikti papildomai yra integruojama PESTEL analizė, apimanti šešis veiksnius: politinius, ekonominius, socialinius, technologinius, aplinkosauginius ir teisinius.

Integruotos SSGG ir PESTEL analizės informacinis pagrindas buvo duomenys, surinkti taikant metodą „iš viršaus į apačią“ – tai esamų vietinių mobilumo priemonių, planavimo dokumentų peržiūra, statistinių bei mokslinių duomenų analizė; ir taikant metodą „iš apačios į viršų“ – tai įvairios ataskaitos bei rezultatai iš regioninių suinteresuotųjų šalių organizuojamų renginių. Kiekviename iš penkių dalyvavusių regionų vyko po keturis renginius, kuriuose valdžios, savivaldybių atstovai, ekspertai, verslo įmonių ir mokslo institucijų specialistai apžvelgė ir dalijosi mintimis apie konkretaus regiono potencialą ir iššūkius įvairiais aspektais.

2.2. Tyrimų rezultatai

Jie atskleidė penkių Europos regionų: Ispanijos (Barselonos), Italijos (Lacijaus), Lietuvos, Nyderlandų (Amsterdamo bei Flevolando) ir Švedijos (Stokholmo) integruotas SWOT ir PESTEL analizes, susijusias su elektrinio mobilumo, AEI ir IRT politikos priemonėmis bei iniciatyvomis. Šitame poskyryje plačiau aptarta Lietuvos situacija šioje srityje. Taigi, integruotos SSGG ir PESTEL analizės rezultatai Lietuvos atveju yra pateikti 1 lentelėje.

1 lentelė. Integruotos SSGG ir PESTEL analizės rezultatai Lietuvos atveju

Stiprybės	Silpnybės
• Autobusų ir taksi juostomis gali važiuoti elektrinis transportas (ET)	• Didelė ET ir baterijų kaina
• Nemokamas parkavimas	• Neišplėtota ET įkrovimo infrastruktūra
• Išplėtotas verslo atstovų bendradarbiavimas su pagrindinėmis ET plėtros kompanijomis	• Bendros EV politikos ir strategijos nebuvimas
• Stiprios verslo ir mokslo pozicijos informacinėse technologijose	• Kryžminio ministerijų koordinavimo ir bendradarbiavimo trūkumas
• Aktyvus bendruomenės susidomėjimas transporto keliamomis problemomis	• Nėra aiški ir nekokybiškai parengta ET reglamentuojanti dokumentacija
• Kompetentingos transporto priemonių restauravimo ir taisymo paslaugos	• Atsakingos už ET infrastruktūros plėtrą institucijos trūkumas
• Mažos ET priežiūros sąnaudos	• Ilgalaikių politinių ir teisės aktų trūkumas
• Paskirtas biudžetas elektriniam mobilumui plėtoti	• Ribotas darbuotojų pajėgumas ir žmogiškųjų išteklių trūkumas
• Didėjantis išmaniųjų telefonų naudojimas	• Nėra valstybinio registravimo mokesčio
• Kainos atžvilgiu konkurencingų elektromobilių dalinimosi schemos	• Mažas transporto priemonių apmokestinimas
Dideli automobilių įsigijimo rodikliai	• Žaliųjų pirkimų trūkumas
• Universitetai yra sukūrę ET prototipus	• Mažas visuomenės supratimas apie ET
• Universitetai dirba ET technologijų ir jų pritaikymo srityse	• Maža gyventojų perkamoji galia
• Suplanuotas ET įkrovimo tinklas	• Būdingas gyventojų dėmesys dideliems ir paprastiems automobiliams
• ET mažina miesto triukšmą ir oro taršą	• Mažas nuvažiuojamas atstumas su dauguma ET
• Visuomenės supratingumas dėl eismo keliamų aplinkosauginių problemų	• Senas transporto priemonių parkas
• Keleivių, naudojančių alternatyvų kurą, dalis yra 17 %	• Nėra patirties įprastos transporto priemonės transformavimui į ET

Galimybės	Grėsmės
• Suplanuotas ET viešųjų įkrovimo stočių tinklas	• Mažas ET augimas
• Vienodos ir universalios ET įkrovimo stočių taisyklės	• Nesutarimas tarp nacionalinių ir Europos Sąjungos teisės aktų
• Paramos mechanizmai ir subsidijos	• Politinės paramos nebuvimas
• Kolektyviniai savivaldos veiksmai	• ET įkrovimo operatorių taisyklių trūkumas
• Šalies transporto priemonių parko atnaujinimas	• ET įkrovimo stočių įrengimo reikalavimai nėra aiškūs
• Nepriklausomybė nuo iškastinio kuro naudojimo	• Nėra atskiros institucijos, kuri plėstų infrastruktūrą
• Verslo ir mokslo įsitraukimas į naujos rinkos plėtrą	• Atsiliekantys politiniai sprendimai
• Registravimo ir PVM mokesčio persvarstymas	• Nėra tiesioginių pajamų iš EV akcijų
• Automobilių dalijimosi paslaugos konkurencingumas	• Sumažintos degalų sąnaudos sumažina akcizo mokesčių pajamas
• ET rinka leistų prekiauti pertekliniais taršos leidimais	• Didelė panaudotų transporto priemonių prekyba
• Galimybė įgyti Darnaus miesto judumo plano plėtros finansavimą	• Ribotas ES viešojo transporto modernizavimo finansavimas
• Bendruomenių įtraukimas į Darnaus judumo mieste planą	• Ribotas nacionalinis finansavimas ET ir elektriniam mobilumui
• Visuomenės suvokimas apie darnaus transporto privalumus ir teikiamą naudą	• Lietuva yra viena iš 5 šalių, kuri negauna subsidijų ET
• Visuomenės suvokimas apie aplinkai draugišką važiavimą ir kultūrą	• Naudotų ET priemonių modifikavimo neapibrėžtumas
• Išmaniųjų miestų koncepcija motyvuoja visuomenę dalyvauti elektriniame mobilume ir išmaniajame tinkle	• Nemokama viešųjų įkrovimo stočių priežiūra finansuojama visų mokesčių mokėtojų
• Geresnės viešosios erdvės aplink gyvenamuosius kvartalus kontrolė ir valdymas	• Viešosios informacijos trūkumas
• Fiksuotas taršos lygis vidaus degimo varikliams	• Viešojo krovimo stotelės ilgainiui bus apmokestintos
• Elektrinių troleibusų parkas	

Ši integruota SSGG ir PESTEL analizė buvo atlikta, remiantis 2017–2018 m. Lietuvos situacija. Tuo metu Lietuvoje dar nebuvo tokio žymaus susidomėjimo elektriniais keleiviniais automobiliais, nes Lietuva apskritai pasižymi maža perkamąja galia ir dideliu senų automobilių parku (vidutinis automobilio amžius yra 16 m.).

Tačiau pastaraisiais metais vis daugiau ir daugiau jų atsiranda miestų gatvėse. Pagal VĮ „Regitra“ duomenis, 2022 m. pabaigoje buvo įregistruota net 7346 keleivinių elektromobilių, palyginimui 2021 m. pabaigoje – 4841, 2020 m. pabaigoje – 2496, 2019 m. – 1397, o 2018 m. pabaigoje – 969 [21]. Valdžios palaikymas kartu su reikšminga finansine iniciatyva atsirado 2020 m. pavasarį, kai buvo galima fiziniams asmenims įsigyti elektromobilį ir gauti 2000 eurų (vėlesniais metais – 2500 eurų) kompensaciją perkant dėvėtą elektromobilį arba 4000 eurų (vėlesniais metais – 5000 eurų) – perkant naują. Kitas elektromobilių privalumas – tai galimybė važiuoti specialiai pažymėtomis maršrutinio transporto eismo juostomis Vilniuje, naudotis parkavimo ir įvažiavimo rinkliavų lengvatomis Lietuvos miestuose: Vilniuje, Kaune, Klaipėdoje, Šiauliuose, Panevėžyje, Neringoje, Trakuose [60].

Pagal Lietuvos viešosios elektromobilių įkrovimo infrastruktūros plėtros planą iki 2030 m. (2022 m.), šiuo metu yra apie 600 viešųjų elektromobilių įkrovimo prieigų. Iki 2025 m. planuojama įrengti dar 1200 įkrovimo prieigų, o iki 2030 m. – turėti 6000 viešųjų įkrovimo prieigų. Bendrai iki 2030 m. Lietuvoje turi būti įrengta 60 tūkst. elektromobilių įkrovimo prieigų (viešų ir privačių) [61].

Pagal elektromobilių įkrovimo infrastruktūros plėtros planus: „Nuo 2023 m. sausio 1 d. visose statomose arba rekonstruojamose degalinėse turi būti įrengta bent viena viešoji didelės arba labai didelės galios elektromobilių įkrovimo prieiga; nuo 2023 m. sausio 1 d. visose statomose arba rekonstruojamose autobusų ir geležinkelio stotyse, oro uostuose ir jūrų uoste turi būti įrengta viešoji elektromobilių įkrovimo stotelė; viešųjų elektromobilių įkrovimo prieigų operatoriai turi sudaryti sąlygas elektromobilį įkrauti neturint tiesioginės sutarties su elektros energijos tiekėju ir (ar) elektromobilių įkrovimo prieigos operatoriumi, sudarant galimybę už elektromobilio įkrovimo paslaugą atsiskaityti vietoje, neturint išankstinių specialių identifikacinių kortelių ar kitų priemonių.“ [62]

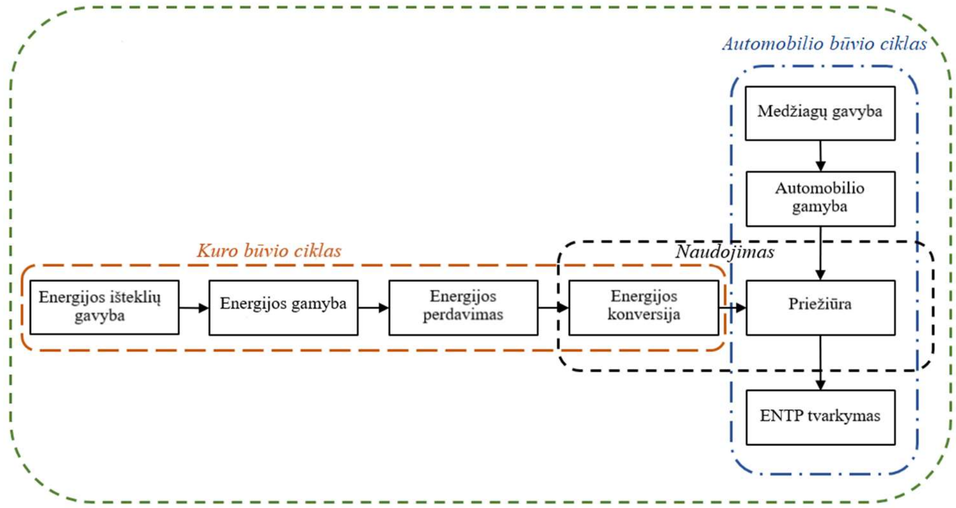
3. ELEKTROMOBILIO IR ĮPRASTŲ AUTOMOBILIŲ APLINKOSAUGINIS BŪVIO CIKLO ĮVERTINIMAS

Šiame skyriuje pristatomas elektromobilio ir iškastinį kurą naudojančių keleivinių automobilių aplinkosauginis būvio ciklo įvertinimo tyrimas. Pagal pasirinktas metodikas buvo nustatytas poveikis aplinkai nuo žaliavų išgavimo iki galutinio atliekų sutvarkymo. Tyrime buvo akcentuojama elektromobilio aplinkosauginė analizė naudojimo etape, kada baterijos įkrovimui naudojama elektra yra pagaminta esant skirtingiems kuro ir energijos rūšių struktūros scenarijams, kurie buvo suprognozuoti taikant matematinį modeliavimą 2015–2050 m. laikotarpiui, remiantis Nacionalinės energetinės nepriklausomybės strategijos tikslais. Šio tyrimo rezultatai buvo publikuoti moksliniame straipsnyje ***Comparative environmental life cycle assessment of electric and conventional vehicles in Lithuania*** [57]. Šiais publikuotais tyrimo rezultatais buvo įgyvendintas antrasis disertacijoje išsikeltas uždavinys.

3.1. Tyrimų metodika

Tyrimo tikslas – atlikti lyginamąją elektrinio, benzininio ir dyzelinio keleivinių automobilių būvio ciklo įvertinimą aplinkosauginiu požiūriu per visą gyvavimo ciklą, t. y. nuo žaliavų išgavimo iki galutinio atliekų sutvarkymo, remiantis Nacionalinės energetinės nepriklausomybės strategijos tikslais. Tyrimų objektas – populiariausios markės nauji registruoti Lietuvoje skirtingų tipų variklių lengvieji keleiviniai automobiliai: dyzelinis ir benzininis „Fiat Tipo 2018“ ir elektromobilis „Nissan Leaf 2018“. Tyrimui atlikti taikytas BCĮ metodas. BCĮ atliktas remiantis Tarptautinės standartizacijos organizacijos ISO 14040 ir ISO 14044 procedūromis ir rekomendacijomis. BCĮ tyrimų eiga apėmė: tikslo ir apimties apsibrėžimą, inventorinės analizės paruošimą, poveikio įvertinimą ir rezultatų interpretavimą [63], [64].

Nustatytas funkcinis vienetas – „1 km nuvažiuoto atstumo“ ir bendras poveikis aplinkai buvo įvertintas nuvažiavus 150 000 km atstumą. Poveikis aplinkai per visą būvio ciklą įvertintas atsižvelgiant į tai, kad elektromobilio baterijos keisti nereikėjo, t. y. šios analizės metu per visą elektromobilio nuvažiuotą atstumą buvo sunaudota viena baterija. Sistemos ribos apima kuro būvio ciklo analizę „nuo gręžinio iki ratų“ (angl. *Well-to-Wheel*) ir automobilio būvio ciklo analizę „nuo lopšio iki kapo“ (angl. *Cradle-to-Grave*). Kuro būvio ciklo analizė apima šiuos etapus: energijos išteklių gavyba, energijos gamyba bei perdavimas ir energijos konversija transporto priemonėje. O štai automobilio būvio ciklo analizė apima šiuos etapus: medžiagų gavyba, automobilio gamyba, priežiūra ir automobilio, tapusio ENTP, atliekų tvarkymas (2 pav.).



2 pav. Visos sistemos apimtis

Elektromobilis eksploatavimo metu tiesiogiai neišmeta emisijų į aplinką, tačiau šiuo atveju svarbiausias veiksnys yra elektros, reikalingos įkrauti elektromobilį, gamybos sukeliamas poveikis aplinkai. Dėl to šiame tyrime buvo atsižvelgta į Lietuvos energetikos instituto matematiniu modeliavimu suprognozuotus elektros energijos, pagamintos iš skirtingų pirminių energijos išteklių, struktūrų scenarijus 2015–2050 m. laikotarpiui. Atitinkamai BCĮ metodu buvo ištirtas elektromobilio poveikis aplinkai naudojimo etape, esant įvairiems elektros energijos gamybos pagal kuro ir energijos rūšis struktūros scenarijams 2015–2050 m. laikotarpiui Lietuvos sąlygomis.

Tyrime buvo taikomas ReCiPe metodas ir poveikis aplinkai buvo įvertintas poveikio kategorijose (angl. *Midpoint*) ir žalos kategorijose (angl. *Endpoint*). *Midpoint* lygyje poveikio kategorijos pasirinktos tokios, kuriose buvo nustatytos didžiausios vertės: klimato kaita (kg CO_2 ekv.), toksiškumas žmonėms (kg 1,4-DB ekv.), jonizuojančioji spinduliuotė (kBq U235 ekv.), metalų išeikvojimas (kg Fe ekv.), iškastinių išteklių išeikvojimas (kg naftos ekv.). *Endpoint* lygyje poveikio kategorijos susijungia į tris apibendrintas žalos kategorijas: žala žmonių sveikatai, žala ekosistemoms ir žala išteklių prieinamumui [65]. Būvio ciklo poveikio vertinimui ir interpretavimui buvo naudojama duomenų bazė *Ecoinvent 3* [66] ir *SimaPro 8.5* programinė įranga [67].

3.2. Tyrimų rezultatai

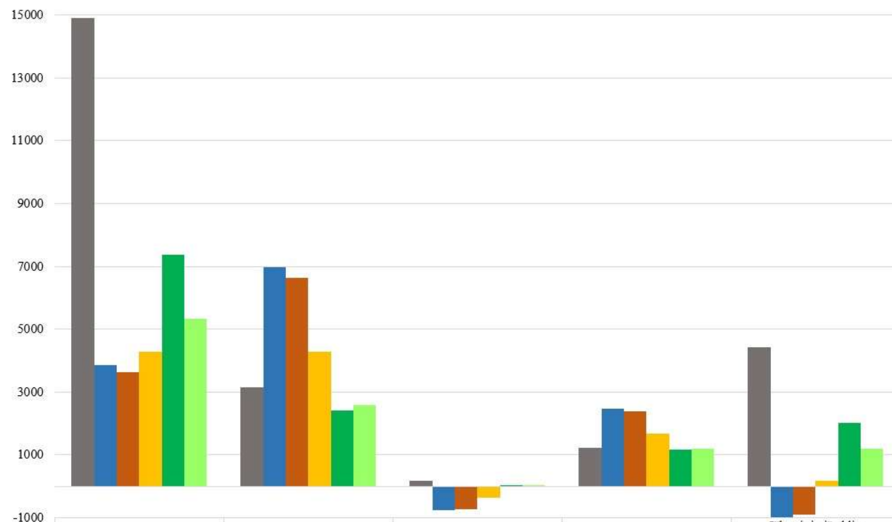
Elektromobilio kuro būvio ciklo analizė 2015–2050 m.

Remiantis Lietuvos energetikos instituto matematiniu modeliavimu suprognozuotais elektros energijos gamybos pagal kuro ir energijos rūšis struktūros scenarijais, buvo išnagrinėti elektros energijos gamybos duomenys 2015–2050 m. laikotarpiui Lietuvos sąlygomis, kurie pateikti 2 lentelėje. Pažymėtina, kad BCĮ analizė apima tik pirminės elektros energijos gamybos pagal kuro ir energijos rūšis struktūras, kurios gaminamos iš vietinių išteklių, nepaisant to, kad daugiau nei pusė elektros energijos Lietuvoje yra importuojama. Tokia prielaida buvo padaryta dėl to, kad nėra žinomi pirminiai energijos šaltiniai importuojamai elektros energijai gaminti.

2 lentelė. Prognostiniai elektros energijos gamybos pagal kuro ir energijos rūšis struktūros (%) scenarijai 2015–2050 m. laikotarpiui [68]

Kuro / energijos rūšies dalis, %	2015	2020	2025	2030	2035	2040	2045	2050
Atliekos	2,28	6,63	4,16	2,50	2,50	1,79	1,79	1,28
Biodujos	3,51	4,79	1,75	0,57	0,57	0,97	0,97	1,13
Biomasė	5,85	24,12	25,18	15,56	15,56	4,97	4,97	4,49
Gamtinės dujos	41,73	10,33	10,67	11,09	11,09	19,90	19,90	7,28
Vandens energija	20,55	6,97	5,28	4,44	4,44	6,34	6,34	5,72
Vėjo energija	14,56	36,76	38,58	52,40	52,40	34,86	34,86	33,61
Saulės energija	1,76	5,96	11,71	11,83	11,83	30,00	30,00	45,57
Geoterminė energija	5,19	4,45	2,68	1,60	1,60	1,17	1,17	0,93
Nafta	4,57	0,00	0,00	0,00	0,00	0,00	0,00	0,00

Nacionalinės energetinės nepriklausomybės strategijos strateginis tikslas – padidinti AEI dalį, lyginant su esamu bendru energijos suvartojimu. Vienas iš pagrindinių strateginių siekių – padidinti AEI dalį elektros suvartojimo balanse iki 30 % 2020 m., iki 45 % – 2030 m. ir iki 100 % – 2050 m. [1]. Pagal 2 lentelės duomenis prognozuojama, kad 2020 m. ir tolesniais metais iš naftos gaunama elektra sumažės nuo 4,57 % iki nulio. Taip pat sumažės ir gamtinių dujų dalis, t. y. net šešis kartus iki 2050 m. Biomasės dalis nuo 2015 m. iki 2025 m. padidės maždaug penkis kartus, o iki 2050 m. sumažės iki 4,49 %. Prognozuojama, kad iki 2050 m. elektros gamyba iš saulės ir vėjo energijos padidės atitinkamai nuo 1,76 % iki 45,57 % ir nuo 14,56 % iki 33,61 %, ir tai bus reikšmingiausi energijos šaltiniai Lietuvoje. Šie duomenys buvo panaudoti atliekant esamų ir ateities elektromobilių kuro būvio ciklo palyginamąją analizę. Rezultatai pateikti 3 paveiksle.



	Klimato kaita, kg CO2 ekv.	Toksiškumas žmogui, kg 1,4-DB ekv.	Jonizuojančioji spinduliuotė, kBq U235 ekv.	Metalų išeikvojimas, kg Fe ekv.	Iškastinių išteklių išeikvojimas, kg naftos ekv.
Elektromobilis – 2015	14907	3165	185	1224	4420
Elektromobilis – 2020	3850	6979	-770	2465	-1029
Elektromobilis – 2025	3624	6625	-723	2384	-893
Elektromobilis – 2030	4291	4292	-354	1683	183
Elektromobilis – 2040	7361	2418	33	1163	2004
Elektromobilis – 2050	5322	2585	4	1210	1195

3 pav. Elektromobilio kuro būvio ciklo analizės rezultatai

3 paveiksle vaizduojama, kaip keisis poveikis aplinkai, kada elektromobiliui įkrauti naudojama elektra, pagaminta taikant įvairius elektros energijos gamybos pagal kuro bei energijos rūšis struktūros scenarijus, ir kuris iš jų yra palankiausias aplinkai. Rezultatai rodo, kad 2015 m. dėl naftos ir didžiausios dalies gamtinių dujų sunaudojimo elektros gamyboje šis elektros energijos rūšių derinys yra taršiausias 3/5 poveikio kategorijose (klimato kaita, jonizuojančioji spinduliuotė ir iškastinių išteklių išeikvojimas). 2020 ir 2025 metų elektros energijos rūšių deriniai yra aplinkai palankūs, nes dėl biomasės, biodujų ir vėjo energijos naudojimo čia skaitinės vertės 3/5 poveikio kategorijų yra mažiausios. 2030 ir 2035 m. didžiausia dalis elektros gamybai atitenka vėjo energija, dėl to poveikis iškastinių išteklių išeikvojimo ir jonizuojančiosios spinduliuotės kategorijose vienas iš mažiausių. AEI labiausiai dominuoja 2050 m. elektros energijos rūšių derinyje, dėl to poveikis aplinkai visose kategorijose (ypač toksiškumas žmogui, jonizuojančioji spinduliuotė ir iškastinių išteklių išeikvojimas) yra vienas mažiausių. Apibendrinant galima teigti, kad nuo 2015 iki 2050 m. išryškėja žymus poveikio aplinkai sumažėjimas visose poveikio kategorijose. Be to, elektromobilis, įkrautas su 2050 metų elektros energijos rūšių deriniu, naudojimo metu sukurs atitinkamai 31 % ir 56 % mažiau ŠESD negu dyzelinis ir benzininis automobiliai. Taip yra dėl naftos eliminavimo ir AEI (daugiausiai vėjo ir saulės energijos) kiekio padidėjimo elektros energijos gamyboje.

Visų nagrinėjamų automobilių BCĮ lyginamoji analizė

3 lentelėje yra pateikti viso būvio ciklo (gamybos, naudojimo ir atliekų tvarkymo) suminiai rezultatai visų analizuojamų automobilių, įskaitant ir elektromobilių su skirtingais elektros energijos rūšių deriniais, rezultatai. Kaip ir ankstesniame grafike, taip ir šioje lentelėje yra pateiktos išanalizuotos tos poveikio kategorijos, kurios turi didžiausias skaitines vertes, t. y. sukuria reikšmingiausią poveikį aplinkai.

3 lentelė. Viso būvio ciklo rezultatai nagrinėjamų automobilių analizėje

Poveikio kategorija	Benz.	Dyzel.	Elektrom. 2015	Elektrom. 2020	Elektrom. 2025	Elektrom. 2030	Elektrom. 2040	Elektrom. 2050
Klimato kaita	15 787	11 394	21 304	10 247	10 021	10 688	13 758	11 719
Toksiškumas žmogui	1325	1095	11 555	15 369	15 015	12 682	10 808	10 975
Jonizuojančioji spinduliuotė	1973	1711	202	-752	-706	-337	51	21
Metalų išeikvojimas	-5424	-5760	3804	5045	4964	4264	3743	3866
Iškastinių išteklių išeikvojimas	13 669	10 498	6136	687	822	1898	3720	2910

čia: Benzininis automobilis – Benz.;
Dyzelinis automobilis – Dyzel.;
Elektromobilis – Elektrom.

3 lentelėje pateikti rezultatai rodo, kad ŠESD emisijos, susijusios su poveikiu klimato kaitai, elektromobilio su 2020, 2025, 2030 m. scenarijais bus mažesnės nei automobilių su vidaus degimo varikliais. 2050 m. šis poveikis būtų beveik lygus dyzelinio automobilio poveikiui. Benzininis automobilis yra taršiausias, lyginant su dyzeliniu automobiliu bei elektromobiliu, įkrautu su 2020–2050 m. elektros energijos rūšių deriniais. Be to, buvo nustatyta, kad elektromobilio toksiškumas žmogui yra didžiausias visais metais, nes šis rodiklis susijęs su elektromobilio ir ličio jonų baterijos gamyba. Maža to, tiek benzininis, tiek dyzelinis automobilis išsiskiria didžiule tarša jonizuojančiosios spinduliuotės ir iškastinių išteklių išeikvojimo kategorijose, nes tai yra susiję su benzino / dyzelino gamyba. Galiausiai, metalo išeikvojimo kategorijoje dominuoja elektromobiliai, kadangi šis rodiklis yra susijęs su ličio jonų baterijos gamyba. Apibendrinant galima teigti, kad elektromobilis, įkrautas su 2050 m. elektros energijos rūšių deriniu, turės mažiausias vertes beveik visose poveikio kategorijose lyginant su 2015 m. elektros energijos rūšių deriniu įkrautu elektromobiliu, nes indėlis į klimato kaitą sumažės 45 %, toksiškumas žmogui – 5 %, jonizuojančioji spinduliuotė – 89 %, iškastinių išteklių išeikvojimas – 53 %. Tai rodo, kad AEI integravimas į elektros energijos gamybą yra esminis veiksnys mažinant poveikį aplinkai.

4. ELEKTRINIO, HIBRIDINIO IR ĮPRASTŲ AUTOMOBILIŲ LYGINAMOJI ANALIZĖ APLINKOSAUGINIU IR EKONOMINIU BŪVIO CIKLO POŽIŪRIU

Šiame skyriuje pristatomas elektromobilio, hibridinio bei įprastų keleivinių automobilių poveikio aplinkai ir ekonominių sąnaudų tyrimas, taikant būvio ciklo požiūrį. Tiek aplinkosauginis, tiek ekonominis vertinimas apėmė stadijas nuo žaliavų išgavimo iki galutinio atliekų sutvarkymo. Šito tyrimo rezultatai publikuoti moksliniame straipsnyje ***Comparative environmental life cycle and cost assessment of electric, hybrid, and conventional vehicles in Lithuania*** [58]. Šiais publikuotais tyrimo rezultatais buvo įgyvendintas trečiasis disertacijoje išsikeltas uždavinys.

4.1. Tyrimų metodika

Tyrimo tikslas – atlikti lyginamąją elektrinio, hibridinio, benzininio ir dyzelinio keleivinių automobilių būvio ciklo įvertinimą aplinkosauginiu ir ekonominiu požiūriu per visą gyvavimo ciklą, t. y. nuo žaliavų išgavimo iki galutinio atliekų sutvarkymo. Čia atlikta aplinkosauginė analizė papildė jau 3 skyriuje pristatytą BCĮ tyrimą. O ekonominiu požiūriu buvo nustatytos ekonominės sąnaudos per visą gyvavimo ciklą, t. y. nuo žaliavų išgavimo iki galutinio atliekų sutvarkymo, vertinant sąnaudas iš gamintojo ir vartotojo perspektyvų.

Tyrimų objektas – populiariausios markės registruoti Lietuvoje skirtingų tipų variklių nauji keleiviniai automobiliai: dyzelinis ir benzininis „Volkswagen Golf 2019“, hibridinis „Toyota Prius 2018“ ir elektromobilis „Nissan Leaf 2018“. Visi modeliai priklauso vidutinio dydžio klasės automobiliams, yra panašūs pagal ilgį bei plotį, tad yra tinkami lyginamajai aplinkosauginei ir ekonominei analizei. Numatyta, kad pasirinktų transporto priemonių sąnaudos ir parametrai atitiks 2020 metų lygį, neprognozuojant jų pokyčių ir technologijų raidos ateityje.

Tyrimams atlikti taikytas BCĮ metodas ir būvio ciklo kaštų (angl. *Life Cycle Costing*) vertinimo metodas. Aplinkosauginis būvio ciklo ir ekonominių sąnaudų vertinimas atliktas remiantis Tarptautinės standartizacijos organizacijos ISO 14040 bei ISO 14044 procedūromis ir rekomendacijomis. Tyrimų eiga apėmė: tikslo ir apimties apsibrėžimą, inventorinės analizės paruošimą, poveikio įvertinimą ir rezultatų interpretavimą [63], [64].

Abiejuose tyrimuose buvo nustatytas funkcinis vienetas – „1 km nuvažiuoto atstumo“, o bendras poveikis aplinkai ir ekonominės sąnaudos buvo įvertintos nuvažiavus 150 000 km atstumą. Poveikis aplinkai per visą gyvavimo ciklą įvertintas atsižvelgiant į tai, kad elektromobilio baterijos keisti nereikėjo, t. y. šios analizės metu per visą elektromobilio nuvažiuotą atstumą buvo sunaudota viena baterija (ličio jonų akumuliatoriui suteikiama 8 metų arba 160 000 km ridos garantija [69]. Pažymėtina, kad vidutinis lengvųjų automobilių amžius Lietuvos automobilių parke yra 16 metų, tad pagal esamą situaciją 150 000 km rida gali lemti ne visų tipų transporto priemonių eksploatacijos pabaigą. Kadangi tai yra mokslinė analizė, 150 000 km rida buvo nustatyta atsižvelgiant ir į kitų tyrėjų atliktas BCĮ analizes [39], [70], [71]. Todėl tyrime buvo daroma prielaida, kad analizuojami automobiliai gali nuvažiuoti 150 000 km, tai pasirenkant kaip būvio ciklo ir ekonominės analizės atskaitos tašką.

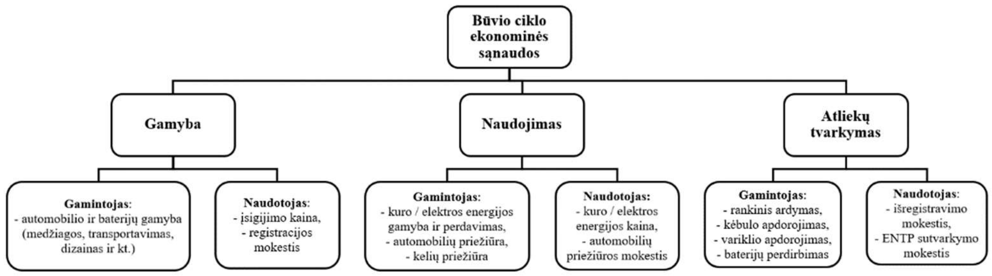
BCĮ ribos ir taikymas aplinkosauginiu požiūriu

Sistemos ribos apima kuro būvio ciklo analizę „nuo gręžinio iki ratų“ (angl. *Well-to-Wheel*) ir automobilio būvio ciklo analizę „nuo lopšio iki kapo“ (angl. *Cradle-to-Grave*). Kuro gyvavimo ciklo analizė apima šiuos etapus: energijos išteklių gavyba, energijos gamyba bei perdavimas ir energijos konversija transporto priemonėje. O štai automobilio gyvavimo ciklo analizė apima šiuos etapus: medžiagų gavyba, automobilio gamyba, priežiūra ir automobilio, tapusio ENTP, atliekų tvarkymas (2 pav.). Gamybos etapas apima transporto priemonės ir baterijų gamybą: ličio jonų baterijos (elektromobilio) ir nikelio metalo hidrido baterijos (hibridinio automobilio). Naudojimo etapas apima transporto ir kelių priežiūrą; taip pat išmetamųjų teršalų kiekį, susijusį su degalų deginimu (įprastiems bei hibridiniams automobiliams), ir teršalų kiekį, kurį sukelia kelių, padangų bei stabdžių nusidėvėjimas. Elektromobilio naudojimo etapas apima netiesioginio poveikio aplinkai įvertinimą, nustatant elektros energijos, reikalingos įkrauti elektromobilį, gamybos poveikį aplinkai. Dėl to šiame tyrime atsižvelgta į Lietuvos energetikos instituto matematiniu modeliavimu suprognozuotus elektros energijos, pagamintos iš skirtingų pirminių energijos išteklių, struktūrų scenarijus 2015–2050 m. laikotarpiui, įgyvendinant Nacionalinės energetinės nepriklausomybės strategijos tikslus. Atitinkamai BCĮ metodu buvo pateiktas elektromobilio poveikis aplinkai naudojimo etape, esant įvairiems elektros energijos gamybos pagal kuro ir energijos rūšis struktūros scenarijams 2015–2050 m. laikotarpiui Lietuvos sąlygomis. ENTP tvarkymo etapas apima šiuos tvarkymo procesus: transporto priemonės ardymą rankiniu būdu, variklio, kėbulo bei vidaus degimo variklio apdorojimą (smulkinimą), naudotų nikelio metalo hidrido bei ličio jonų baterijų apdorojimą (atitinkamai pirometalurginio bei hidrometalurginio proceso metu) ir švino rūgšties baterijoje esančio švino rūšiavimą bei perlydymą. Dėl duomenų bazės apribojimų nebuvo įmanoma pasirinkti atskirų automobilių dalių gamybos etape arba įvairesnių automobilių dalių apdorojimo jų tvarkymo etape.

Tyrime buvo taikomas *ReCiPe* metodas ir poveikis aplinkai buvo įvertintas poveikio kategorijose (angl. *Midpoint*) ir žalos kategorijose (angl. *Endpoint*). *Midpoint* lygyje poveikio kategorijos pasirinktos tokios, kuriose buvo nustatytos didžiausios vertės: klimato kaita (kg CO_2 ekv.), jonizuojančioji spinduliuotė (kBq U235 ekv.), kancerogeninis toksiškumas žmonėms (kg 1,4-DB ekv.), nekancerogeninis toksiškumas žmonėms (kg 1,4-DB ekv.), žemės naudojimas (m^2a žemės ekv.), iškastinių išteklių išeikvojimas (kg naftos ekv.). *Endpoint* lygyje poveikio kategorijos susijungia į tris apibendrintas žalos kategorijas: žala žmonių sveikatai, žala ekosistemoms ir žala išteklių prieinamumui [65]. Siekiant įvertinti ir interpretuoti būvio ciklo poveikį aplinkai buvo naudojama duomenų bazė *Ecoinvent 3.5* [66] ir *SimaPro 9.1* programinė įranga [67].

BCĮ ribos ir taikymas ekonominių sąnaudų požiūriu

BCĮ ekonominių sąnaudų požiūriu yra naudingas sprendimų priėmimo etape, kada įmanoma nustatyti galimus iššūkius iš įvairių perspektyvų, pavyzdžiui, produkto / paslaugos gamintojo ir naudotojo. Tad šiame tyrime ekonominės sąnaudos buvo įvertintos iš abiejų perspektyvų. Kaip ir aplinkosauginio, taip ir ekonominio vertinimo sistemos ribos apima analizę nuo gamybos iki atliekų tvarkymo. Sistemos ribos yra pavaizduotos 4 paveiksle.



4 pav. Būvio ciklo ekonominių sąnaudų vertinimo sistemos ribos

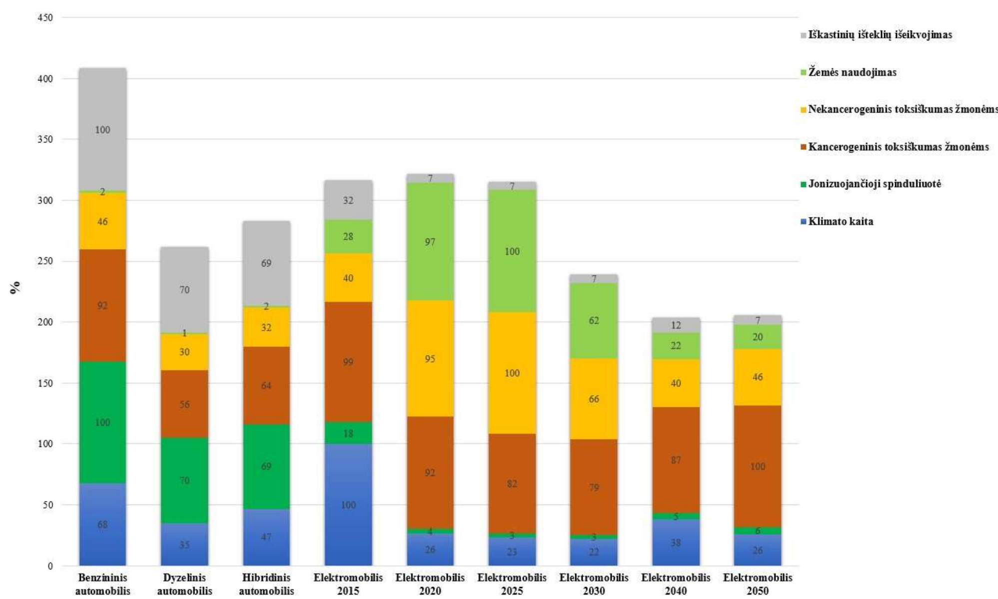
Ekonominių sąnaudų vertinimo rezultatai yra pateikti trimis etapais (gamyba, naudojimas ir atliekų tvarkymas) iš dviejų perspektyvų: gamintojo ir naudotojo. Procesai iš gamintojo pusės sutampa kaip ir atliekant aplinkosauginę analizę. Gamybos etape įtrauktos išlaidos, susijusios su transporto priemonių ir baterijų gamyba: ličio jonų ir nikelio metalo hidrido baterijomis. Naudojimo etape buvo įtrauktos kuro / elektros energijos gamybos bei paskirstymo ir automobilių bei kelių priežiūros išlaidos. Galiausiai atliekų tvarkymo etape buvo įtrauktos transporto priemonės tvarkymo išlaidos: rankinis ardymas, kėbulo ir vidaus degimo variklio apdorojimas, baterijų perdirbimas. Iš naudotojo perspektyvos gamybos etapas apėmė automobilio įsigijimo kainą ir registracijos mokestį. Naudojimo etape buvo įtraukta kuro / elektros energijos kaina ir automobilio priežiūros paslaugų mokesčiai. Galiausiai į atliekų tvarkymo etapą buvo įtrauktas tik išregistravimo mokestis ir ENTP sutvarkymo paslauga, kuri Lietuvoje yra nemokama. Pažymėtina, kad į analizę nebuvo įtrauktos visos automobilių naudojimo išlaidos, pavyzdžiui, draudimo, padangų ir remonto išlaidos, nes priimta prielaida, kad šios išlaidos nagrinėjamų automobilių atveju yra vienodos, todėl neturi įtakos lyginamajai analizei.

Ekonominių sąnaudų iš gamintojo perspektyvos vertinimui buvo naudojama *OpenLCA 1.10.2* programinė įranga [72] su *Ecoinvent 3.5* duomenų baze [66]. Ekonominių sąnaudų iš naudotojo perspektyvos analizė buvo atlikta renkant duomenis iš įvairių šaltinių.

4.2. Tyrimų rezultatai

BCĮ rezultatai kuro būvio ciklo analizėje

Rezultatai poveikio kategorijose parodė, kad pasirinktų analizei automobilių didžiausios vertės išsiskyrė šiose poveikio kategorijose: klimato kaita (kg CO_2 ekv.), jonizuojančioji spinduliuotė (kBq U235 ekv.), kancerogeninis toksiškumas žmonėms (kg 1,4-DB ekv.), nekancerogeninis toksiškumas žmonėms (kg 1,4-DB ekv.), žemės naudojimas (m^2a žemės ekv.) ir iškastinių išteklių išeikvojimas (kg naftos ekv.). Esminis veiksnys elektromobilio BCĮ yra jo poveikis aplinkai esant skirtingiems elektros energijos rūšių deriniams. Dėl to minėtos poveikio kategorijos yra pateiktos kuro būvio ciklo (angl. *Well-to-Wheel*) analizėje (5 pav.), kuri parodo kuro gyvavimo ciklo, t. y. nuo energijos išteklių gavybos iki automobilio eksploatacijos etapo, poveikį aplinkai, taikant įvairius elektros energijos gamybos scenarijus, suprognozuotus 2015–2050 metams Lietuvos sąlygomis. Gautos skaitinės vertės poveikio kategorijose buvo normalizuotos pagal reikšmingiausią atitinkamos poveikio kategorijos veiksnį. Pavyzdžiui, benzininis automobilis turi didžiausias vertes iškastinių išteklių išeikvojimo ir jonizuojančiosios spinduliuotės kategorijose, todėl šios reikšmės buvo prilyginamos 100 %, ir pagal tai apskaičiuojamos kitų analizuojamų automobilių poveikio vertės. Tokiu pačiu būdu nustatyti visi reikšmingiausi poveikio kategorijų veiksniai ir atitinkamai įvertintas visų automobilių poveikis aplinkai pasirinktose kategorijose.

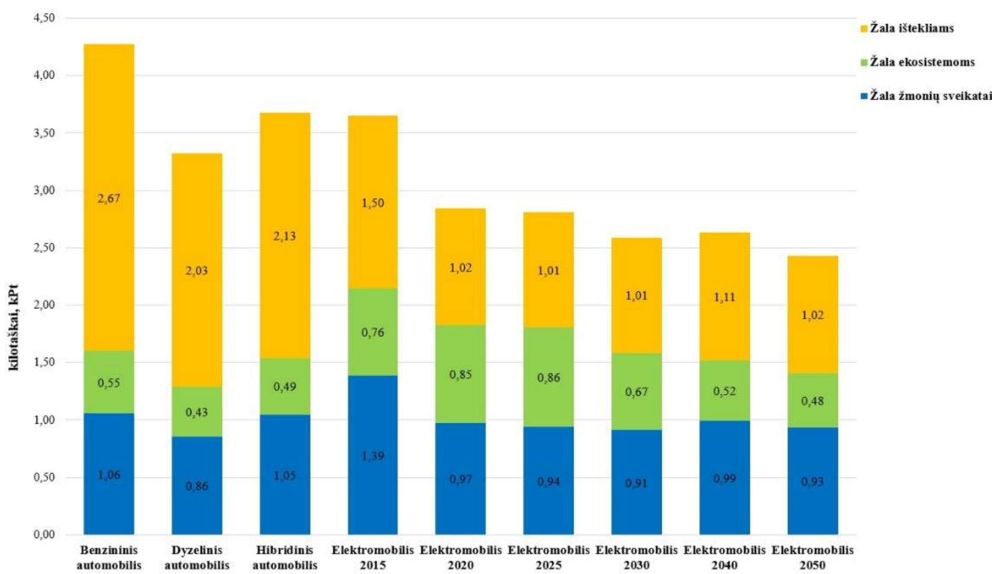


5 pav. BCĮ rezultatai kuro būvio ciklo analizėje

Rezultatai rodo, kad elektromobilis, įkrautas su 2015 metų elektros energijos rūšių deriniu, dėl gamtinių dujų (kaip didžiausios dalies) ir naftos naudojimo buvo taršiausias pagal klimato kaitos poveikio kategoriją. Taip pat pagal šią poveikio kategoriją elektromobilis, įkrautas su 2020–2050 m. elektros energijos rūšių deriniais, yra ~62–78 % mažiau taršus negu elektromobilis, įkrautas su 2015 m. elektros energijos rūšių deriniu, ir 30–46 % mažiau taršus negu benzininis automobilis. Be to, vertinant iškastinių išteklių išeikvojimo kategoriją, visi elektromobiliai, įkrauti su 2020–2050 m. elektros energijos rūšių deriniais, yra maždaug 10 ir 14 kartų palankesni aplinkai nei atitinkamai dyzelinis ir benzininis automobiliai. Rezultatai rodo, kad elektromobiliai, įkrauti su 2040 ir 2050 m. elektros energijos rūšių deriniais, yra palankiausi aplinkai, nes beveik visų poveikio kategorijų vertės yra vienos mažiausių (išskyrus kancerogeninį toksiškumą žmogui). Taip yra todėl, kad šiuose scenarijuose taikoma saulės ir vėjo energetika yra pagrindiniai elektros energijos šaltiniai.

BCĮ rezultatai žalos kategorijose

Šie rezultatai apibendrina suminį poveikį aplinkai kaip žalą ištekliams, žalą ekosistemoms ir žalą žmonių sveikatai. Rezultatai yra išreiškiami matavimo vienetais, vadinamaisiais taškais (Pt) ir kilotaškais (kPt) šiuo atveju (6 pav.).



6 pav. Analizuotų automobilių BCĮ rezultatai žalos kategorijose

Rezultatai rodo, kad benzininis automobilis sukuria didžiausią žalą aplinkai, lyginant su visais analizuotais lengvaisiais automobiliais. Hibridinis automobilis ir elektromobilis, įkrautas su 2015 m. elektros energijos rūšių deriniu, sukuria beveik tokią pačią žalą aplinkai, o tai yra 14 % mažesnė žala nei benzininio automobilio. Be to, dyzelinis automobilis sukuria 10 % mažesnį poveikį aplinkai nei hibridinis. Galiausiai, elektromobilis, įkrautas su 2020–2050 m. elektros energijos rūšių deriniais, kuriuose daugiausia AEI, sukuria mažiausią žalą aplinkai. Šie rezultatai rodo, kad perėjimas nuo iškastinio kuro prie AEI naudojimo yra neabejotinai naudingas skatinant darnų miesto transportą.

BCĮ rezultatai ekonominiu požiūriu

Būvio ciklo ekonominių sąnaudų analizė buvo atlikta tiek iš gamintojo, tiek iš naudotojo perspektyvos. 4 lentelėje pateikiamos sąnaudos, susijusios su analizuojamų keleivinių automobilių gamyba, naudojimu ir atliekų tvarkymu iš vartotojo pusės Lietuvos sąlygomis. Gamybos etapas apima: įsigijimo sąnaudas ir registracijos mokesčius. Naudojimo etapas apima: automobilio priežiūros ir kuro (elektros) išlaidas. Atliekų tvarkymo etapas apima tik išregistravimo mokesčius, kadangi automobilių savininkai gali nemokamai atiduoti ENTP į atliekų tvarkymo įmones tinkamam sutvarkymui ir apdorojimui.

Rezultatai rodo, kad hibridinis automobilis ir elektromobilis yra brangiausi vertinant įsigijimo sąnaudas. Tačiau, lyginant naudojimo etapą, elektromobilio išlaikymas yra ~37 % pigesnis negu dyzelinio ir net ~60 % pigesnis negu benzininio automobilio. Tyrime buvo priimta prielaida, kad elektromobilis įkraunamas namuose esant vidutinei metinei 0,13 Eur/kWh kainai namų ūkio vartotojams (2019 m.) [73]. Skatinant elektrinių transporto priemonių įsigijimą, nuo 2020 metų pavasario buvo teikiamos kompensacijos elektromobilių pirkėjams. Gyventojai galėjo gauti 2000 eurų kompensaciją pirkdami naudotą elektromobilį ir 4000 eurų kompensaciją pirkdami naują elektromobilį [22]. 4 lentelėje yra įtraukta 4000 eurų kompensacija. Pastebėtina, kad ši kompensacija 2022 m. buvo padidinta iki 2500 eurų perkant naudotą (iki 4 metų) ir iki 5000 eurų perkant naują (iki 6 mėn.) elektromobilį.

4 lentelė. Ekonominės sąnaudos iš vartotojo perspektyvos

Ekonominės sąnaudos iš vartotojo perspektyvos								
Keleivinis automobilis	Gamyba		Naudojimas		Atliekų tvarkymas	Pajamos	Suminės sąnaudos, eurais/ 150 000 km	Suminės sąnaudos, eurais/km
	Įsigijimo kaina, eurais	Registracijos mokesčiai, eurais	Kuro kaina, eurais/ 150 000 km	Priežiūra, eurais/ 150 000 km	Išregistravimo mokesčiai, eurais	Kompensacija		
Benzininis automobilis	22 328	21,68	10 954	1186	2,9	0	34 492	**0,23**
Dyzelinis automobilis	23 831	21,68	6581	1072	2,9	0	31 508	**0,21**
Hibridinis automobilis	28 190	21,68	7590	2034	2,9	0	37 839	**0,25**
Elektromobilis	31 880	21,68	4017	817	2,9	-4000	32 739	**0,22**

Lyginant visų analizuotų automobilių sumines sąnaudas, rezultatai rodo, kad konkurencingiausi yra elektromobiliai ir dyzeliniai automobiliai, kurių gyvavimo ciklo sąnaudos yra apytiksliai 5–15 % mažesnės nei kitų.

Vertinant gyvavimo ciklo sąnaudas iš gamintojo pusės, taip pat įvertinti gamybos, naudojimo ir atliekų tvarkymo etapai. Gamybos etapas apima automobilio ir baterijos gamybą, naudojimo etapas – kuro (elektros) gamybą bei tiekimą ir automobilių bei kelių priežiūrą; galiausiai, atliekų tvarkymo etapas apima ENTP rankinį išardymą, kėbulo, variklio, baterijų apdorojimą, sutvarkymą. Kaip kad buvo minėta metodikos skyriuje, skaitinės vertės gautos naudojant *OpenLCA 1.10.2* programinę įrangą su *Ecoinvent 3.5* duomenų baze, kurioje duomenys buvo 2005 m. Dėl šių apribojimų duomenys galimai skirtųsi nuo dabartinių laikų, tačiau idėja buvo išryškinti pagrindinius rezultatus, jog elektromobilio sąnaudos, lyginant su kitais automobiliais, didžiausios yra gamybos etape, o mažiausios – naudojimo etape.

5. EKSPLOATUOTI NETINKAMŲ TRANSPORTO PRIEMONIŲ EKONOMINĖ IR APLINKOSAUGINĖ ANALIZĖ ŽIEDINĖS EKONOMIKOS KONTEKSTE

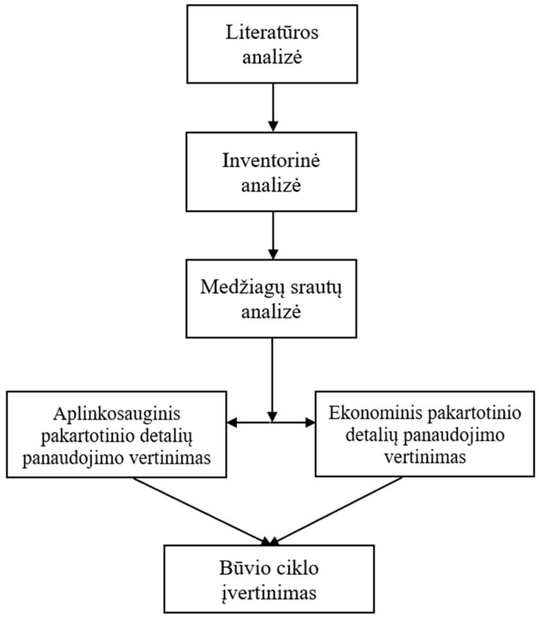
Šiame skyriuje pristatomas ENTP aplinkosauginio ir ekonominio vertinimo tyrimas, taikant būvio ciklo požiūrį žiedinės ekonomikos kontekste. Pirmiausia pagal pasirinktas metodikas buvo atlikta medžiagų srautų analizė, kuri padėjo suprasti ENTP detalių medžiagų srautų judėjimą. Antra, buvo atliktas ekonominis pakartotinio detalių panaudojimo vertinimas, kurio metu įvertinta ekonominė nauda ENTP tvarkytojams ir naudotų detalių pirkėjams. Trečia, buvo atliktas aplinkosauginis pakartotinio detalių panaudojimo vertinimas, nustatant CO_2 ekv. emisijų sumažinimo potencialą, jeigu analizuojamų automobilių detalės būtų pakartotinai panaudotos. Ketvirta, buvo atlikta automobilių būvio ciklo analizė, orientuota į gamybos ir atliekų tvarkymo stadijas. Šito tyrimo rezultatai publikuoti moksliniame straipsnyje ***Environmental and economic benefits of electric, hybrid and conventional vehicle treatment: a case study of Lithuania*** [59]. Šiais publikuotais tyrimo rezultatais buvo įgyvendintas ketvirtasis disertacijoje išsikeltas uždavinys.

5.1. Tyrimų metodika

Tyrimo tikslas – atlikti ENTP aplinkosauginį ir ekonominį vertinimą taikant būvio ciklo požiūrį žiedinės ekonomikos kontekste.

Tyrimų objektas – populiariausios markės registruoti Lietuvoje skirtingų tipų variklių naudoti lengvieji automobiliai: dyzelinis ir benzininis „Volkswagen Golf Plus 2005–2008“, hibridinis „Toyota Prius 2003–2009“ ir elektromobilis „Nissan Leaf 2011–2013“.

Tyrimai apima keturias dalis: 1) pirmoje dalyje atlikta medžiagų srautų analizė, kuri padėjo suprasti ENTP detalių medžiagų srautų judėjimą; 2) antroje dalyje atliktas keturių populiariausių Lietuvoje naudotų lengvųjų automobilių su skirtingais varikliais ekonominis vertinimas, kuriuo buvo įvertinta ekonominė nauda ENTP tvarkytojams ir naudotų detalių pirkėjams; 3) trečioje dalyje, taikant CO_2 ekv. emisijų, susidarančių detalių medžiagų gamybos metu, ekvivalentus vienam kilogramui medžiagos, buvo įvertintas išmetamo CO_2 ekv. emisijų kiekio sumažinimo potencialas, jeigu analizuojamų automobilių detalės būtų pakartotinai panaudotos. Pateiktas kiekvienos detalės gamybos metu išmetamas CO_2 ekv. emisijų kiekis, kuris padėjo įvertinti ir palyginti detalių pakartotinio panaudojimo aplinkosauginę naudą; 4) ketvirtoje dalyje atlikta pasirinktų automobilių būvio ciklo analizė, orientuota į gamybos ir atliekų tvarkymo stadijas. Tyrimų eiga pateikta 7 paveiksle.



7 pav. Tyrimų eiga

1) Medžiagų srautų analizė (MSA) – tai sistemingas medžiagų srautų ir sankaupų sistemoje įvertinimas, kai sistema apibrėžiama erdvėje bei laike ir jungia medžiagas nuo šaltinio iki galutinio produkto bei atliekų susidarymo [74]. MSA metodas yra praktinė priemonė efektyvesniam išteklių ir atliekų valdymui. Rezultatai pateikiami naudojant STAN (angl. *subSTance flow ANalysis*) programinę įrangą, kuri leidžia grafiškai pavaizduoti medžiagų srautus, sistemos ribas ir procesus. Modelio grafikas pavaizduotas *Sankey* diagramos, kurioje srauto plotis yra proporcingas jo vertei, pavidalu [75].

MSA atlikti naudota informacija iš VĮ „Regitra" duomenų bazės ir IDIS (angl. *International Dismantling Information System*) sistemos. IDIS yra pažangi ir išsami informacinė sistema, suteikianti prieigą prie didelės duomenų bazės su praktine informacija apie ENTP išmontavimą, apdorojimą ir kt. Čia galima rasti informaciją apie daugumos automobilių detalių masę, sudėtines medžiagas, pavojingas medžiagas, taip pat ši informacija yra pateikiama vizualiai [76].

IDIS buvo sukurta dėl to, kad remiantis Europos Parlamento ir Tarybos direktyvos 2000 m. rugsėjo 18 d. dėl eksploatuoti netinkamų transporto priemonių (2000/53/EC) reikalavimais, transporto priemonių gamintojai privalo suteikti informaciją apie transporto priemonių išmontavimą. Todėl sistema palengvina informacijos prieinamumą ENTP ardytojams ir gamintojai išvengia jų užklausų [77]. IDIS šiame tyrime padėjo surinkti informaciją, reikalingą MSA atlikti bei nustatyti, kiek ir kokių medžiagų bei detalių yra automobilio sudėtyje.

MSA ribos yra nuo ENTP patekimo į atliekų tvarkymo įmonę iki medžiagų / atliekų patekimo į perdirbimą, deginimą, šalinimo sąvartyną ir pakartotinį panaudojimą.

Automobilių tvarkymo įmonėse ENTP ardymas vyksta tokia tvarka: automobilio priėmimas, vizuali apžiūra, ENTP ardymas, detalių rūšiavimas į pavojingas / nepavojingas atliekas bei pakartotiniam naudojimui tinkamas detales. Pavojingos / nepavojingos atliekos yra atskirai perduodamos tokių atliekų tvarkytojams, o pakartotiniam naudojimui tinkamos detalės yra parduodamos pirkėjams.

2) Atliekant ekonominį vertinimą detalių kainai sužinoti buvo naršomi įvairūs internetiniai detalių pardavimo tinklalapiai, tokie kaip: https://autoplius.lt, https://skelbiu.lt, https://autodoc.lt, https://autoaibe.lt, https://srotas24.lt. Juose rašomos detalių kainos, taip pat galima pasirinkti detales pagal automobilio modelį. Be to, siekiant patikrinti kai kurių retesnių naujų dalių kainas, apklausti automobilių dalių platintojai Lietuvoje, taip pat, norint išsiaiškinti detalių paklausą Lietuvos rinkoje, apklaustos penkios vietinės ENTP ardymo įmonės. Tada kainos palygintos su kainomis įvairiose elektroninėse parduotuvėse ir įvertintas kainų vidurkis, kuris taikytas atliekant analizę. Ekonominė nauda ENTP tvarkytojams įvertinta skaičiuojant naudotų detalių kainas, atliekų tvarkymo sąnaudas, antrinių medžiagų ekonominę vertę. Žmonių darbas, įrangos ir patalpų priežiūra nebuvo vertinama kaip ekonominės analizės dalis.

3) Tyrimo metu buvo įvertinta ir palyginta ENTP detalių pakartotinio naudojimo aplinkosauginė nauda. Taikant CO_2 ekv. emisijų, susidarančių detalių medžiagų gamybos metu, ekvivalentus vienam kilogramui medžiagos, buvo įvertintas išmetamo CO_2 ekv. emisijų kiekio sumažinimo potencialas, jeigu analizuojamų automobilių detalės būtų pakartotinai panaudotos. Pateiktas kiekvienos detalės gamybos metu išmetamas CO_2 ekv. emisijų kiekis, kuris padėjo įvertinti ir palyginti detalių pakartotinio naudojimo aplinkosauginę naudą. Ši metodika pasirinkta remiantis mokslininkų Rovinaru (2019) bei Sato (2018) atliktais tyrimais [78], [79]. Įvertintos tik pakartotinai panaudojamos detalės. Detalės, kurių pakartotinio naudojimo tikimybė yra didelė, buvo vertinamos 100 % išskiriamo CO_2 ekv. emisijų sumažinimu, detalės, kurių tikimybė pakartotinai panaudoti yra vidutinė, buvo vertinamos 50 % išskiriamo CO_2 ekv. emisijų sumažinimu, o detalės, kurių tikimybė pakartotinai panaudoti yra maža, nebuvo vertinamos. Tam tikrų medžiagų ekologinis pėdsakas apskaičiuotas pagal formules, pateiktas Sato (2018) tyrime [79].

4) Aplinkosauginis ENTP vertinimas atliktas taikant BCĮ metodiką. Atliktas elektrinio, hibridinio, benzininio ir dyzelinio automobilių BCĮ, vadovaujantis Europos standartų serijose ISO 14040 ir ISO 14044 nurodyta tvarka ir rekomendacijomis [63], [64]. Šito BCĮ tikslas – įvertinti analizuojamų automobilių poveikį aplinkai gamybos ir šių automobilių, tapusių ENTP, tvarkymo etapuose. Gamybos etapas apima transporto priemonės ir baterijų gamybą. Tvarkymo etapas apima šiuos procesus: transporto priemonės ardymą rankiniu būdu, variklio, kėbulo bei vidaus degimo variklio apdorojimą (smulkinimą), naudotų nikelio metalo hidrido bei ličio jonų baterijų apdorojimą (atitinkamai pirometalurginiu bei hidrometalurginiu procesu) ir švino rūgšties baterijoje esančio švino rūšiavimą bei perlydymą. Dėl duomenų bazės apribojimų nebuvo įmanoma pasirinkti atskirų automobilių dalių gamybos etape arba įvairesnių automobilių dalių apdorojimo jų tvarkymo etape.

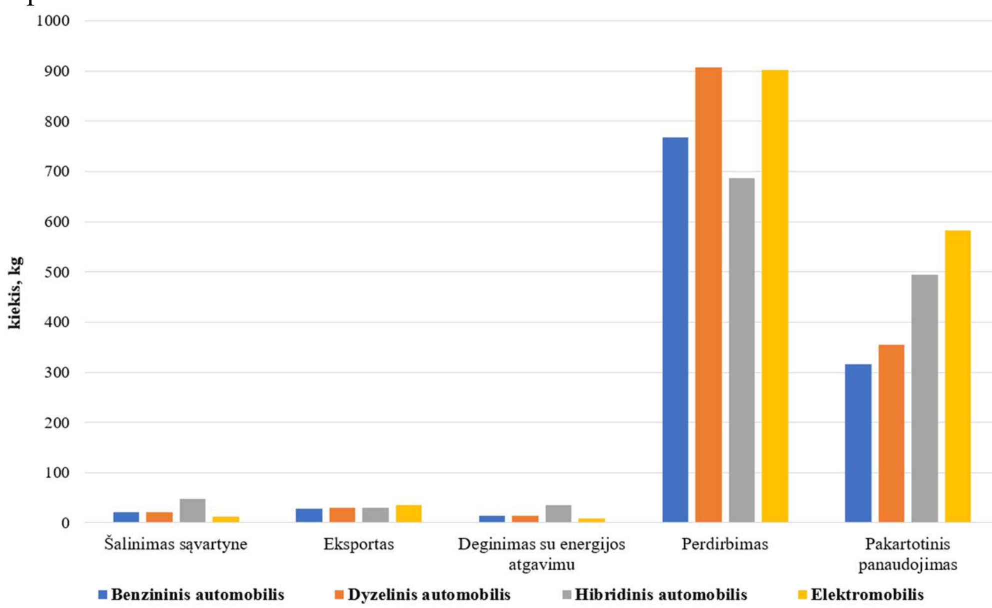
BCĮ analizei buvo pasirinktas funkcinis vienetas – „1 km važiavimo atstumas" ir bendras poveikis aplinkai buvo įvertintas nuvažiavus 150 000 km atstumą. Poveikis aplinkai per visą būvio ciklą įvertintas atsižvelgiant į tai, kad elektromobilio baterijos keisti nereikėjo, t. y. šios analizės metu per visą elektromobilio nuvažiuotą atstumą buvo sunaudota viena baterija. Pažymėtina, kad vidutinis lengvųjų automobilių amžius Lietuvos automobilių parke yra 16 metų, tad pagal esamą situaciją 150 000 km rida gali lemti ne visų tipų transporto priemonių eksploatacijos pabaigą. Todėl tyrimo metu buvo daroma prielaida, kad analizuojami automobiliai gali nuvažiuoti 150 000 km (ir tai pasirinkta kaip BCĮ analizės atskaitos taškas).

Tyrime buvo taikomas ReCiPe metodas ir poveikis aplinkai buvo įvertintas poveikio kategorijose (angl. *Midpoint*), kuriose buvo nustatytos didžiausios vertės: visuotinis atšilimas (kg CO_2 ekv.), iškastinių išteklių trūkumas (kg naftos ekv.), nekancerogeninis toksiškumas žmonėms (kg 1,4-DCB ekv.) ir kancerogeninis toksiškumas žmonėms (kg 1,4-DCB ekv.) [65]. Būsenos ciklo poveikio vertinimui ir interpretavimui buvo naudojama duomenų bazė *Ecoinvent 3.5* [66] ir *SimaPro 9.1* programinė įranga [67].

5.2. Tyrimų rezultatai

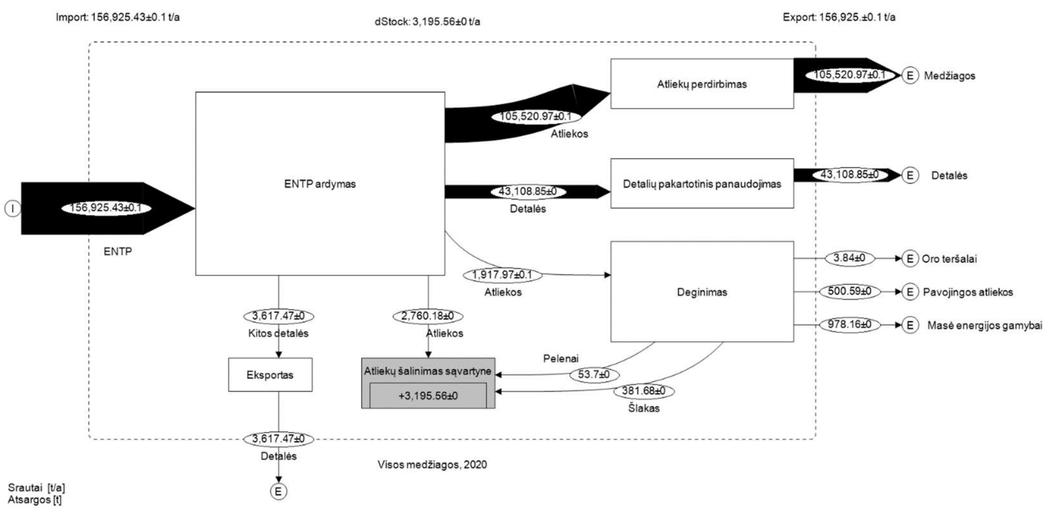
Medžiagų srautų analizės rezultatai

Pagal Aplinkos apsaugos agentūros duomenis ir ENTP tvarkymo įmonių pateiktą informaciją, įvertintas kiekvieno automobilio tipo masės srautų pasiskirstymas pagal skirtingus atliekų tvarkymo būdus. Rezultatai pateikti 8 paveiksle.



8 pav. ENTP atliekų pasiskirstymas pagal tvarkymo būdus Lietuvoje

Iš diagramos akivaizdu, kad vyrauja medžiagų / atliekų perdirbimas (53–68 %) ir pakartotinis panaudojimas (27–38 %), mažiausia atliekų dalis yra perduodama deginimui su energijos atgavimu (0,6–2,71 %). Daugiausiai atliekų yra perdirbama iš elektrinio ir dyzelinio automobilių, taip pat daugiausia detalių yra pakartotinai panaudojama iš elektromobilio. Medžiagų / atliekų eksportas yra pakankamai nežymus ir tolygus, kuris siekia apie 2 % kiekvieno automobilio masės. Šalinimas sąvartyne taip pat gana nereikšmingas, tačiau didžiausia medžiagų dalis, patenkanti į sąvartyną, kuri siekia 3,6 %, susidaro iš hibridinio automobilio, o kitų automobilių šalinama medžiagų dalis svyruoja tarp 0,8–1,8 %. Taip yra todėl, kad hibridiniame automobilyje daugiausia pavojingų atliekų, kurios nėra perdirbamos ar pakartotinai naudojamos. Didžiausia deginamų medžiagų dalis, kuri siekia 2,7 %, patenka iš hibridinio automobilio, o taip yra dėl mišraus plastiko, kuris negali būti perdirbamas, buvimo automobilio sudėtyje.



9 pav. Medžiagų / atliekų srautų diagrama po ENTP ardymo

Remiantis 8 paveikslo informacija apie ENTP tvarkymą ir duomenimis apie išregistruotų automobilių pagal degalų (kuro) rūšį skaičių [21], buvo pavaizduota nagrinėjamų automobilių, tapusių ENTP, medžiagų srautų analizė, kuri pateikta *Sankey* diagramoje (9 pav.). Čia išregistruotų automobilių skaičius padaugintas iš jų masės srautų ir gauti bendri masės srautai, susidarę po ENTP ardymo 2020 m. Medžiagų srautai, susidarę po deginimo su energijos atgavimu, buvo paremti proporcingais skaičiavimais iš poveikio aplinkai vertinimo dokumentų [80], [81].

ENTP detalių pakartotinio naudojimo ekonominis vertinimas

Ekonominio vertinimo metu apskaičiuota, kokia automobilio masės dalis gali būti pakartotinai panaudojama. Ji apskaičiuota pagal tai, kokia detalių paklausa yra rinkoje. Paklausios detalės rinkoje buvo įvertintos kaip 100 % panaudojamos pakartotinai, vidutiniškai paklausios detalės buvo įvertintos kaip 50 % panaudojamos pakartotinai nuo visos detalės masės, o nepaklausios detalės nebuvo vertinamos.

Ekonominė nauda automobilių naudotojams bei atliekų tvarkymo įmonėms / demontuotojams ir pakartotinai panaudojama automobilių masės dalis (%) pateikta 5 lentelėje.

5 lentelė. Pasirinktų transporto priemonių ekonominė nauda (eurais) automobilių naudotojams bei atliekų tvarkymo įmonėms / demontuotojams ir pakartotinai panaudojama automobilių masės dalis (%)

Keleivinis automobilis	Automobilio masės dalis, galinti būti pakartotinai naudojama, %	Naudotų detalių kaina, eurais	Kaina, perkant naujas detales, eurais	Ekonominė nauda pirkėjui, eurais	Ekonominė nauda tvarkytojams, eurais
Benzininis automobilis	28	2640	13 460	10 815	1753
Dyzelinis automobilis	27	2845	17 480	14 635	1997
Hibridinis automobilis	38	4001	21 429	17 428	3471
Elektromobilis	38	8334	16 737	8403	5518

Rezultatai rodo, kad elektromobilis ir hibridinis automobilis turi didžiausią automobilių detalių pakartotinio panaudojimo dalį (38 %). O štai mažiausia detalių pakartotinio naudojimo dalis tenka dyzeliniam (27 %) ir benzininiam (28 %) automobiliams.

ENTP tvarkymo įmonėms ekonominė nauda svyruoja nuo 1753 (benzininio automobilio) iki 5518 eurų (elektromobilio). Daugiausiai sutaupo tie pirkėjai, kurie perka naudotas hibridinio automobilio detales (17 428 eurus), o mažiausias skirtumas tarp naudotų ir naujų detalių yra elektrinių automobilių naudotojams (8 403 eurai). Hibridinio automobilio savininkai yra žymiai labiau suinteresuoti pirkti naudotas detales savo automobiliui, panašiai kaip ir dyzelinio automobilio savininkai, kai ekonominė nauda siekia 14 635 eurus.

Įvertinus 2020 metais išregistruotų keleivinių automobilių skaičių pagal degalų (kuro) tipą ir darant prielaidą, kad jie buvo ardyti Lietuvoje, bendra ekonominė nauda pirkėjams ir tvarkytojams / demontuotojams siektų atitinkamai 1,64 mlrd. ir 0,24 mlrd. eurų.

ENTP detalių pakartotinio naudojimo aplinkosauginis vertinimas

Šis aplinkosauginis tyrimas yra grindžiamas CO_2 ekv. emisijų kiekio sumažinimo potencialo įvertinimu, kada automobilių savininkai pirktų naudotas detales vietoj naujų, ir tokiu būdu neišsiskirtų CO_2 ekv. emisijų kiekis naujų detalių gamybos metu. Tyrimo rezultatai pateikti 6 lentelėje.

6 lentelė. CO_2 ekv. emisijų kiekio sumažinimo potencialas iš pakartotinai panaudojamų automobilių detalių

Keleivinis automobilis	CO_2 ekv. emisijų kiekio sumažinimo potencialas iš pakartotinai panaudojamų automobilių detalių (vienam vienetui), kg	CO_2 ekv. emisijų kiekio sumažinimo potencialas iš pakartotinai panaudojamų automobilių detalių (visam išregistruotų ENTP metiniam kiekiui), kg
Benzininis automobilis	1828	101 122 756
Dyzelinis automobilis	1880	124 629 939
Hibridinis automobilis	2403	9 983 001
Elektromobilis	6420	776 871
Iš viso:	**12 531**	**236 512 567**

Rezultatai parodė, kad didžiausias CO_2 ekv. emisijų kiekio sutaupymo potencialas yra iš elektromobilio detalių pakartotinio naudojimo (6420 kg). Taip yra todėl, kad elektromobilis turi ličio jonų bateriją, kurios gamybos metu išskiriama ~8 tonų CO_2 ekv. emisijų kiekio. Kadangi šių naudotų baterijų pardavimo tikimybė yra vidutinė, tad vertinama 50 % išskiriamo CO_2 ekv. emisijų kiekio. Benzininiame ir dyzeliniame automobiliuose CO_2 ekv. kiekio sumažinimo potencialas skiriasi nedaug, t. y. atitinkamai 1828 kg ir 1880 kg. O didžiausias CO_2 ekv. emisijų kiekio sutaupymo potencialas šiuose automobiliuose yra iš švino rūgšties baterijų, kurios yra dažnai naudojamos pakartotinai. Šiek tiek daugiau CO_2 ekv. sutaupoma iš hibridinio automobilio detalių pakartotinio panaudojimo, t. y. 2403 kg, bet gerokai mažiau negu iš elektromobilio, nes hibridiniame automobilyje esančios nikelio metalo hidrido baterijos gamybai CO_2 ekv. yra išskiriama žymiai mažiau (9 kg). Atsižvelgus į bendrą išregistruotą ENTP kiekį Lietuvoje, bendra aplinkosauginė pakartotinio detalių panaudojimo nauda Lietuvoje yra ~236 513 t CO_2 ekv.

6. IŠVADOS

1. Atlikus miesto transporto sistemos politikos priemonių bei iniciatyvų Lietuvoje ir pasirinktuose Europos regionuose analizę, buvo nustatyti pagrindiniai veiksniai, kliūtys bei iššūkiai, susiję su elektrinio mobilumo, AEI ir IRT integracija miesto transporto sistemose. Įvairios politinės priemonės, iniciatyvos, gerosios praktikos buvo apžvelgtos ne tik nacionaliniu, vietiniu, bet ir tarptautiniu lygmeniu. Politinių priemonių ir iniciatyvų analizė Europos regionuose leido įvertinti šalių perėjimą nuo iškastinį kurą naudojančių prie AEI varomų transporto priemonių. Be to, ši analizė sudarė pagrindą išnagrinėti ir palyginti keleivinius automobilius iš ekonominės ir aplinkosauginės perspektyvos, taikant būvio ciklo požiūrį ir atsižvelgiant į Nacionalinės energetinės nepriklausomybės strategijos tikslus. Tokie tyrimai padėtų miesto planuotojams, ekspertams ir politikos formuotojams priimti sprendimus, kuriant darnią miesto transporto sistemą.

2. Atlikus elektromobilio, hibridinio ir įprastų keleivinių automobilių poveikį aplinkai per visą būvio ciklą pagal prognozuojamus 2015–2050 metų skirtingus elektros gamybos scenarijus nustatyta, kad elektromobilio, įkrauto su 2050 m. elektros energijos rūšių deriniu (kuriame vyrauja saulės ir vėjo energijos), indėlis į klimato kaitą yra mažesnis 45 %, toksiškumas žmogui – 5 %, jonizuojančioji spinduliuotė – 89 %, iškastinių išteklių išeikvojimas – 53 %, lyginant su elektromobiliu, įkrautu su 2015 m. elektros energijos rūšių deriniu (kuriame naudojama didžiausia dalis gamtinių dujų ir naftos). Taip pat nustatyta, kad benzininis automobilis sukuria didžiausią žalą aplinkai, lyginant su visais analizuotais keleiviniais automobiliais. Hibridinis automobilis ir elektromobilis, įkrautas su 2015 m. elektros energijos rūšių deriniu, sukuria beveik tokią pačią žalą aplinkai, o tai yra 14 % mažesnė žala nei benzininio automobilio. Be to, dyzelinis automobilis sukuria 10 % mažesnį poveikį aplinkai nei hibridinis. Galiausiai, elektromobilis, įkrautas su 2020–2050 m. elektros energijos rūšių deriniais, kuriuose daugiausia AEI, sukuria mažiausią žalą aplinkai. Pavyzdžiui, elektromobilis, įkrautas su 2050 m. elektros energija, sukuria 43 %, 33 % ir 27 % mažesnį poveikį aplinkai visame gyvavimo cikle negu benzininis, hibridinis, dyzelinis automobiliai, atitinkamai. Gauti rezultatai įrodo, kad AEI integravimas į elektros energijos gamybą yra esminis veiksnys mažinant poveikį aplinkai.

3. Atlikus elektrinio, hibridinio ir įprastų keleivinių automobilių ekonominių sąnaudų per visą būvio ciklą analizę nustatyta, kad konkurencingiausi automobiliai yra elektromobiliai ir dyzeliniai automobiliai, kurių sąnaudos vartotojui buvo 5–15 % mažesnės negu kitų automobilių. Be to, analizė parodė, kad tiek iš gamintojo, tiek iš vartotojo perspektyvos elektromobilis yra ekonomiškiausia transporto priemonė naudojimo etape (su maždaug perpus mažesnėmis išlaidomis).

4. Atlikus ENTP medžiagų srautų analizę nustatyta, kad automobilio didžiausia masės dalis, kuri gali būti pakartotinai panaudojama, priklauso elektromobiliui (38 %) ir hibridiniam automobiliui (38 %), toliau eina benzininis (28 %) ir dyzelinis automobilis (27 %). ENTP ekonominio tyrimo rezultatai parodė, kad automobilių savininkai, pirkdami naudotas detales, sutaupytų 51 281 eurą, o tvarkytojai gautų

finansinę naudą 12 739 eurų (iš keturių skirtingų tipų ENTP). Be to, vertinant bendrą Lietuvoje išregistruojamų ENTP (dyzelinių, benzininių, hibridinių ir elektrinių keleivinių automobilių) kiekį per metus, metinė automobilių dalių pakartotinio naudojimo ekonominė nauda tvarkytojams ir naudotojams būtų 0,24 mlrd. eurų ir 1,64 mlrd. eurų atitinkamai. Aplinkosauginis ENTP vertinimas, taikant CO_2 ekv. emisijų, susidarančių detalių medžiagų gamybos metu, ekvivalentus vienam kilogramui medžiagos, parodė, kad elektromobilis turi didžiausią CO_2 ekv. emisijų kiekio sumažinimo potencialą, kuris yra lygus 6420 kg CO_2 ekv. Hibridiniai, dyzeliniai ir benzininiai automobiliai atitinkamai sutaupytų 2403 kg CO_2 ekv., 1880 kg CO_2 ekv. ir 1828 kg CO_2 ekv. Be to, vertinant bendrą Lietuvoje išregistruojamų ENTP (dyzelinių, benzininių, hibridinių ir elektrinių keleivinių automobilių) kiekį per metus, metinė pakartotinio detalių panaudojimo nauda siektų ~236 513 t CO_2 ekv.

7. SUMMARY

7.1. Introduction

Motivation and relevance of the problem

The electrification of transport and the use of renewable energy sources (RES) in city transport systems have become one of the priority areas in Lithuania and the European Union (EU) in the fight against climate change, noise, and air pollution. Electric transport reduces air pollution in cities and thus protects people's health from respiratory diseases. Moreover, electricity produced from local RES would contribute to lower indirect air pollution to the environment and help to achieve the goals of National Energy Independence Strategy [1]. In addition, the EU 2050 long-term strategy aims for the EU countries to become climate neutral by 2050 [2], which means that it is necessary to fundamentally change the existing transport system, which generates as much as ~23% of all greenhouse gas (GHG) emissions in the EU [3]. To achieve this goal, the European Parliament on June 8, 2022 supported the European Commission's proposal to market only zero-emission light passenger and commercial cars in EU countries from 2035 [4]. As a result, there will be fewer internal combustion engine cars in cities. Consequently, electrification of the transport system and the development of the necessary infrastructure will be a significant boost to sustainable cities.

Environmental and economic assessments are becoming important in the decision-making process when integrating electric transport. It is therefore necessary to evaluate the environmental impacts and economic costs of vehicles with different types of engines using a life cycle approach. It is particularly important to analyse the environmental impact of an electric vehicle during the use stage, when the electricity used to charge the battery is produced under different fuel and energy mix scenarios, in line with the objectives of the National Energy Independence Strategy. Finally, in order to ensure the sustainable management of End-of-Life Vehicles (ELVs), it is significant to assess the economic and environmental benefits of reusing their parts in the context of circular economy.

Research hypotheses

1) The structure of electricity generation in terms of fuels and RES is a key factor in assessing the impact on the environment of an electric vehicle during the use phase.

2) The economic costs of an electric car are the lowest compared to other vehicles in the use phase.

3) Passenger cars that have become ELVs have a significant potential for reuse of parts.

Aim and objectives of the doctoral thesis

The aim of the doctoral thesis is to evaluate electric, hybrid, and conventional passenger cars using a life cycle approach from environmental and economic perspectives.

To achieve this aim, the following objectives are planned:

1. To analyse city transport system policies and initiatives in Lithuania and selected European regions.
2. To assess and compare life cycle environmental impacts of electric, hybrid and, conventional passenger cars under different electricity generation scenarios projected for 2015–2050.
3. To evaluate and compare the life cycle economic costs of electric, hybrid, and conventional passenger cars.
4. To assess and compare the economic and environmental benefits of reusing parts from electric, hybrid, and conventional passenger cars that have become ELVs in the context of circular economy.

Research object

Passenger cars with different types of engines (electric, hybrid, petrol, and diesel).

Scientific novelty

Firstly, the scientific novelty relates to the environmental life cycle assessment of an electric passenger car, showing how the environmental impact will change when the electricity used to charge an electric car is produced using different proportions of RES under projected electricity generation scenarios 2015–2050, implementing the objectives of the National Energy Independence Strategy. Such analysis allowed to assess the most environmentally friendly electricity generation scenario and identify the hotspots throughout the life cycle of the analysed cars. Secondly, a life cycle costing of electric, hybrid, and conventional passenger cars was carried out, showing the costs from the producer and consumer perspectives. Thirdly, the economic benefits for waste managers and consumers of the reuse of car parts from ELVs have been analysed in the context of the circular economy. Additionally, the environmental benefits were also assessed, showing the potential for CO_2 eq savings from the reuse of parts after ELVs dismantling.

Practical value of work

One of the main studies of the thesis focused on the life cycle-based assessment of the environmental impacts of cars with different engines in the production, use, and waste management phases. The research concentrated on the environmental analysis of an electric vehicle in the use phase, where the electricity used to charge the battery is produced under different fuel and energy mix scenarios, which have been projected for the period 2015–2050, based on the objectives of the National Energy

Independence Strategy. The research provides insights for city transport and policy planners and experts in different countries on the transition from fossil fuels to RES-based vehicles. The insights from the research can lead to further development of the integration of electric vehicles, to increase public interest in less polluting vehicles, to subsidise the purchase of electric vehicles and to develop charging infrastructure in the country. In the EU context, this would contribute to the international goals of becoming a climate neutral by 2050.

The studies have confirmed the importance of ELVs management and their potential for environmental performance and economic growth through the development of circular economy principles. The insights from the study can encourage policy makers and other stakeholders to improve policies and strengthen support for the management of ELVs, which would contribute to increased economic, environmental, and social benefits. In addition, improved policies would contribute to stopping illegal management of ELVs and reducing their negative impacts in the EU and beyond, as well as to reducing the amount of waste generated each year, increasing material efficiency and reducing the use of raw materials. The improved policy is also expected to have a major impact on companies involved in the treatment, recycling, and sale of ELVs and their parts, which may lead to the expansion of their activities. This will lead to job creation in this sector, which is the basis of circular economy.

Approbation

The scientific results were published in seven publications during the period of the dissertation research:

✓ Four scientific articles were published in the international journals: Journal of Cleaner Production, Sustainability and Waste Management, which are referred in ISI Web of Science database, and have the Q1 or Q2 quartiles.

✓ One publication in a peer-reviewed publication of an international conference;

✓ Two publications in non-reviewed publications of international conferences.

Research results were presented at five international conferences, held in France (Nice and Lille) and remotely in Sweden, Germany, and Spain.

Structure of the thesis

The dissertation consists of: an introduction, a chapter based on the review of the four articles, conclusions, a summary in English, a list of references, a curriculum vitae, a list of research articles and conferences, copies of research articles, and acknowledgments. The volume of the dissertation is 132 pages, including 9 pictures, 6 tables, and 81 bibliographic references.

Literature review

The EU faces challenges in achieving the 2030 and 2050 climate and energy strategies [5]. The EU's goal of becoming a climate-neutral country is defined in the

European Green Deal, which aims to: "transform the EU into a fair and prosperous society with a modern, resource-efficient and competitive economy, with zero net greenhouse gas emissions by 2050 and economic growth decoupled from the use of resources" [6]. The field of transport causes as much as a quarter of all GHG emissions, of which road transport accounts for almost three quarters of GHG emissions [3]. Therefore, in the strategy of the European Green Deal, this area is defined as one of the most significant and requires a faster transition to sustainable mobility. The European Green Deal states that in order to neutralize the impact on the climate, transport emissions need to be reduced by as much as 90% by 2050 [6].

Transport is one of the greatest sources of GHG emissions in Lithuania. According to the national GHG accounting report for 2020, the transport sector accounts for as much as 30.45% of the total GHG emissions (6,145 kt CO_2 eq), of which the majority (95%) belongs to road transport, and 52% to passenger cars (3,200 kt CO_2 eq.). Compared to 2019, GHG emissions from passenger cars decreased by 5% in 2020 due to restrictions caused by the coronavirus (COVID-19) pandemic, but remained significant. Thus, passenger cars account for as much as 16% of the total amount of GHG emissions [7].

Furthermore, the transport sector significantly contributes to air pollution in Lithuania. According to the national air pollutant accounting data for 2020, road transport is the main source of nitrogen oxides (NO_x) emissions, accounting for as much as 55.4%, while passenger cars – 17.1% of the total amount of NO_x emitted in the country. Also, passenger cars contribute to other air pollutant emissions: 4.4% – $KD_{2,5}$, 1.8% – non-methane volatile organic compounds (NMVOCs), 0.2% – sulphur oxides (SO_x), in terms of the total quantity [8].

It has been estimated that health-related external costs due to air pollution in Lithuania exceed 1 billion euros/year, which includes not only the essential value of a healthy life, but also the direct costs for the country's economy. These direct economic costs are related to 488,000 working days lost each year due to illnesses caused by air pollution, costs for employers reach as much as 37 million euros/year, and more than 5 million euros/year for healthcare [9].

Worldwide, electric vehicles are considered as future transport, contributing to the creation of an environmentally friendly city. They reduce local air pollution, GHG emissions, and traffic noise, which is especially relevant for residents of big cities. Electric vehicles do not have an exhaust pipe, so they do not cause direct emissions of pollutants into the ambient air, like conventional ones. In addition, the electric motor runs quietly, especially at lower speeds [10]. Other advantages of electric transport include: 1) electric powertrains are significantly more energy efficient than conventional internal combustion engines; 2) simpler and more economical maintenance during the exploitation; 3) electricity can make direct use of energy from RES; 4) when connected to the power grid, batteries of electric vehicles could stabilize the grid and balance supply and demand facilitating the integration of RES [11].

Moreover, electric vehicles would be more advantageous if the electricity for charging the battery is produced by RES [12]–[16]. The EU agreed to set a common target for the share of RES (including biomethane, liquid biofuels, "green electricity," and hydrogen) of 10% of the total used in transport by 2020. Thus, the EU reached this goal with 10.2% in 2020 (increased from 1.5% in 2004) [17].

In Lithuania, the part of RES of the final energy consumption in the transportation should have been to at least 10% by 2020 in all means of transport, yet unfortunately, the aim has not been achieved, with only 5.5% attained in 2020 [18]. Furthermore, according to the National Energy Independence Strategy, future goals are even more ambitious, increasing the part of RES used in the transport sector to 15% by 2030 and 50% by 2050 [1].

Electric transport has both environmental and economic advantages and contributes to sustainable urban development. Rising fuel prices are changing people's attitudes towards cars with internal combustion engines. This was shown by a survey conducted by Norstar and Moller Auto. The main results of the survey showed that Lithuanian residents are mostly encouraged to buy electric cars by tax benefits, lower operating costs, and lesser impact on the environment. City residents are also motivated by discounts on parking and entrance fees, and the opportunity of driving in the first lane, thus, overtake traffic jams [20]. According to the National Energy and Climate Action Plan of the Republic of Lithuania 2021–2030, one of the planned policy measures in the transport sector is the promotion of the use of electric cars and the development of their charging infrastructure by 2030. The planned result is 10% of annual M1 class car purchase transactions (registered and re-registered passenger cars) will be electric cars by 2025, and 50% – by 2030 [19].

According to the end of 2022 vehicle registration data of Lithuania, the largest share of registered passenger cars is: diesel (67.6%), followed by gasoline (23.1%), liquefied petroleum gas (5.9%), followed by hybrids (3%) and finally electric cars (0.4%) [21]. Such a share of the number of electric cars in Lithuania is a significant positive change compared to last year. At the end of 2022, 7,346 electric cars (new and used) were registered in Lithuania, while at the end of 2020 there were 2,496, and in 2018 – only 969 electric cars [21]. Such a meaningful increase in the number of electric cars is the result of a successful financial incentive that began to be implemented in the spring of 2020. Individuals can receive compensation of 2,500 euros when buying a used (up to 4 years old) electric car, and 5,000 euros when buying a new (up to 6 months old) electric car [22]. Additional compensation of 1,000 euros is paid to old car owners who return their old cars free of charge to ELVs treatment companies, obtain a certificate of destruction, and then buy an electric or less polluting (with a total CO_2 emission of no more than 130 g/km) car [23]. Also, there is an incentive program for the purchase of electric cars for legal entities (and individuals who will use the electric car for economic activities), when a compensation of 4,000 euros is given when buying a new electric car (up to 6 months) [24]. Such financial incentives create a great opportunity to promote the integration of electric vehicles into city transport systems.

According to data published by the European Environment Agency, a significant increase in pure and plug-in electric cars has been observed across Europe, i.e., 1,061,497 electric cars were registered in 2020, and 1,728,968 in 2021. This means that in just one year, the share of electric cars in the total number of new car registrations increased from 10.7% to 17.8% (9% and 8.8% are distributed between pure and plug-in electric cars, respectively). The leading countries with the largest share of new pure and plug-in electric car registrations in total new car registrations in 2021 are Norway (86%), Iceland (64%), Sweden (46%), Denmark (35%), Finland (32%), the Netherlands (30%), Germany (27%), etc. Meanwhile, Lithuania (5%) remains the leader only in comparison with the Baltic countries, i.e., Latvia (4%) and Estonia (3%) [25]. In the leading countries, the transition from internal combustion engine cars to electric cars is particularly encouraged through various financial initiatives, such as subsidies for the purchase of an electric car, income, VAT tax breaks, free installation of charging points at home, reduced or exempted registration fees and other benefits [26]–[30].

Environmental and economic benefits have always been a driving force in the decision-making process when integrating electric vehicles into city transport systems, especially when people have low purchasing power and countries face other challenges and obstacles [31], [32]. Therefore, in order to get an overall impression of the advantages provided by electric cars, it is necessary to conduct both an environmental and an economic assessment.

Thus, this research provides a comprehensive life cycle environmental and economic assessment, which are also called life cycle assessment (LCA) and life cycle costing (LCC). The LCA and LCC in the field of mobility can be used to: (1) analyse and compare different fuel types and the impact of the vehicle operation; (2) compare various end-of-life scenarios and treatment options; (3) identify hotspots of the analysis and main advantages and disadvantages of different vehicles across three major life cycle phases (production, use, and end-of-life) [33]. LCA and LCC are versatile techniques applicable to a range of purposes and at various stages of the product or system in order to support decision-making from the environmental and economic perspectives, respectively. Moreover, LCA and LCC are parts of a life cycle sustainability assessment (LCSA). The development of the LCSA originates from the need to combine the three aspects of sustainable development (environmental, economic, and social) in a single formulation, supporting life cycle thinking [34], [35].

Globally, various LCA studies examining the environmental impacts and economic costs of electric and conventional cars have been conducted in countries such as: Australia [36], Belgium [37], Brazil [38], the Czech Republic [39], Spain [40], Italy [41], Japan [42], USA [43]–[45], Canada [46], China [47]–[49], Poland [39], Nepal [50], France [51], Switzerland [52], and Germany [53]–[55].

Despite these studies, no research has yet been performed on the LCA and LCC of passenger electric, hybrid, and conventional passenger cars in Lithuania. Moreover, Lithuania was chosen as a representative country, as it initiates the integration of electric vehicles and RES into city transport systems, which pursues both national and EU goals. This research used the LCA methodology from an environmental and economic point of view to assess the environmental impact and economic costs of passenger cars with different engines (electric, hybrid, petrol, and diesel) during the entire life cycle. In addition, the LCA of the electric car was additionally evaluated under various electricity mix scenarios and electricity production technologies for the years 2015–2050 in Lithuania. The same passenger cars were assessed using a life cycle approach in the context of a circular economy, determining the economic benefits for ELVs dismantlers and consumers of used parts. In addition, to assess and compare the environmental benefits of reusing car parts, CO_2 eq emissions savings per vehicle were estimated, using CO_2 equivalents per kilogram of a substance emitted during its production.

7.2. Policies and initiatives for electric mobility in European regions

This chapter presents policies and initiatives related to the integration of electric mobility, RES and information and communication technologies (ICT) in the development of urban transport systems in five European regions: Spain (Barcelona), Italy (Lazio), Lithuania, the Netherlands (Amsterdam and Flevoland) and Sweden (Stockholm). An integrated Strengths, Weaknesses, Opportunities and Threats (SWOT) analysis was conducted, together with a Political, Economic, Social, Technological, Environmental and Legal (PESTEL) analysis, based on the existing policies and initiatives in the European regions. Based on this study, a scientific paper was prepared and published – **Situation analysis of policies for electric mobility development: experience from five European regions** [56]. These published research results fulfilled the first objective of the thesis.

Research methodology

In order to develop a framework of innovative policymaking, a comprehensive situation analysis of mobility policies and initiatives (MPI) needs to be conducted. The research area of the current study consists of five European regions: Italy (Lazio), Lithuania, Spain (Barcelona), Sweden (Stockholm) and the Netherlands (Amsterdam and Flevoland). The consortium of regions was formed by dedicated cities at the forefront of the integration between renewable energy and electric mobility and committed to evaluating and disseminating the results of their insights. Situation analyses of policies and initiatives were performed in each EV ENERGY project partner regions by using an integrated SWOT and PESTEL qualitative methodology.

The situation analyses were based on the three aspects: 1) Policies and initiatives related to electric vehicles; 2) Policies and initiatives related to RES; 3) Policies and initiatives related to information and communication technology (ICT) tools for energy and mobility. An overall methodological approach was developed in order to identify and compare features of policies for the integration of electric vehicles/RES/ICT in different regions of Europe. The implemented methodology consists of the following two steps (Figure 1):

1) Inventory of Mobility Policies and Initiatives (IMPI);
2) Conduction of SWOT and PESTEL analysis (based on IMPI);

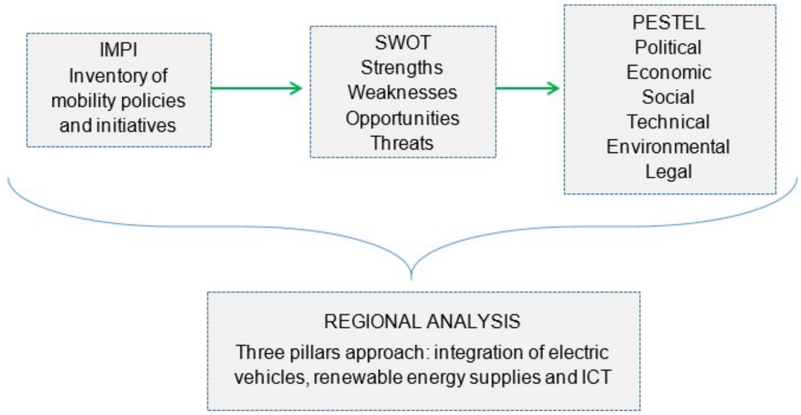


Fig. 1. Illustrated methodology adopted for the research process

Results and discussion

The research results provided the integrated SWOT and PESTEL analyses of electric mobility, RES and ICT-related policies and initiatives in five European regions. Various policies were overviewed and collected not only at the national and local levels of the analyzed countries, but also at EU and international levels. In this subsection, the situation in Lithuania is discussed in more detail. Thus, the results of the integrated SWOT and PESTEL analysis in the case of Lithuania are presented in Figure 2.

Strengths	Weaknesses
• Bus and taxi lanes for EVs	• Systematic approach to power demonstration
• Ministry support	• The old age of the vehicle fleet
• Good business connections with major EV development companies	• The absence of common EV policy and strategy
• Strong positions of businesses and science in IT	• Lack of cross-ministry coordination and cooperation
• Community activity in transport issues	• Low quality and unclear documentation regulating EVs
• Competent vehicle restoration and repair businesses	• Lack of body responsible for infrastructure development
• Allocated budget for e-mobility	• Lack of permanent legislation and politics
• Low maintenance costs of EVs	• High purchase prices of EVs and batteries
• Growing smartphone use	• Unknown approaches of traditional vehicle conversion to EV
• Cost-competitive EVs in car share schemes	• Strong secondary market of old gas/diesel-powered vehicles
• High car ownership	• Minimum taxation of vehicles
• Developed EVs' prototypes by universities	• Lack of sustainable/green procurement
• Universities working on e-mobility technologies and applications	• Low public awareness of EVs
• Planned EV-charging network	• Low resident purchasing power
• High awareness of traffic-related environmental impact	• Prevailing attitude on large, sophisticated, diesel vehicles
• The share of passengers' cars powered by alternative fuels is 17%	• Undeveloped EV-charging infrastructure
• Supporting EV websites	• Limited cooperation between municipalities and universities
Opportunities	**Threats**
• Unified and universal rules for EV-charging stations	• Lack of political support
• Support mechanisms and subsidies	• Disagreement between national and EU legislation
• Collective municipal actions	• Fragmented EV growth
• Rejuvenation of national car pool	• Maintenance of free public EV-charging financed by all taxpayers
• Independence from fast depleting petroleum	• Lack of EV-charging operator rules
• Businesses and science engagement in the development of new markets	• EV-charging station installation requirements unclear
• Registration tax for gas/diesel/petrol-powered vehicles	• The disadvantage of EU subsidiary rule
• Car share competitiveness	• No single body for infrastructure development
• Trade in surplus allowances of EVs	• Lagging political decisions
• Sale of surplus pollution permits	• No direct income from EV promotions
• Opportunities to obtain SUMP development funding	• Reduced fuel consumption reduces excise tax income
• Understanding of sustainable transport benefits	• The strong second-hand vehicle market
• Available support mechanisms and subsidies	• Limited EU funding for public transport modernization
• Low emission zones and their accessibility	• Limited national funding for EVs and e-mobility
• The planned network of public EV-charging stations	• Lithuania, one of five countries without subsidies for EVs
• Better control and management of communal space around residential blocks	• The uncertainty of retrofitting of used EVs

Fig. 2. Integrated SWOT and PESTEL analysis in Lithuania

This integrated SWOT and PESTEL analysis was conducted based on the 2017–2018 situation in Lithuania. At that time, there was no such significant interest in electric passenger cars in Lithuania, because Lithuania in general is characterized by a low purchasing power and a large old car fleet (the average age of a car is 16 years). Notwithstanding, in recent years, more and more of them have appeared on the streets of cities. According to the data of State Enterprise "Regitra", as many as 7,346 passenger electric cars were registered at the end of 2022, while at the end of 2021 – 4,841, at the end of 2020 – 2,496, in 2019 – 1,397, and in 2018 – 969 [21]. The support of the government along with a significant financial initiative appeared in the spring of 2020, when it was possible for individuals to purchase an electric car and receive compensation of €2,500 when buying a used electric car or €5,000 when buying a new one. Another advantage of electric cars is the possibility to drive on specially marked route traffic lanes in Vilnius, next, to use discounts on parking and entrance fees in Lithuanian cities: Vilnius, Kaunas, Klaipėda, Šiauliai, Panevėžys, Neringa, Trakai [60]. According to the Lithuanian public electric vehicle charging infrastructure development plan until 2030, there are currently about 600 public electric vehicle charging points. It is planned to install another 1,200 charging points by 2025, and to have 6,000 public charging points by 2030. In total, 60,000 electric car charging points (public and private) have to be installed in Lithuania by 2030 [61].

7.3. The LCA of electric and conventional cars

This section presents an environmental life cycle assessment study of a battery electric vehicle (BEV) and internal combustion engine vehicles powered with diesel (ICEV-diesel) and petrol (ICEV-petrol). The methodologies chosen were used to determine the environmental impacts from raw material extraction to final waste management. The study focused on the environmental analysis of the electric vehicle in the use phase, where the electricity used to charge the battery is produced under different fuel and energy mix scenarios, which were projected using mathematical modelling for the period 2015–2050, based on the objectives of the National Energy Independence Strategy. The results of this study were published in a scientific paper – **Comparative environmental life cycle assessment of electric and conventional vehicles in Lithuania** [57]. These published research results fulfilled the second objective of the thesis.

Research methodology

This research uses LCA methodology to assess the environmental impacts related to the production, use, and end-of-life phases of electric and internal combustion passenger cars powered with diesel and petrol. The LCA of electric, and conventional passenger cars were performed according to the procedures specified in the European standards series ISO 14040/14044 [63], [64].

The research object – the most popular models of new cars registered in Lithuania with different engine types: the diesel and petrol cars Fiat TIPO 2018 and the electric car Nissan Leaf ACENTA 2018. They are similar in weight and length and belong to the medium-size class; therefore, they are applicable for comparative life cycle analysis.

The environmental emissions of selected vehicles were based on a functional unit of "1 km driving distance", and the impact were assessed for 150,000 km driving distance. The environmental impacts were calculated for the life cycle assuming that for electric cars, no battery replacement is required (the lithium-ion battery has an 8-year or 160,000 km mileage warranty [69]). Therefore, in this analysis, one battery for the electric car is used during the total mileage. It is important to mention that 150,000 km mileage of all types of selected vehicles will not lead to the end-of-life stage in the current practice, as the average age of passenger cars in the Lithuanian vehicle fleet is 16 years [21]. However, this is a scientific analysis, and a 150,000 km mileage was determined according to the analyses conducted also by other researchers [39], [70], [71]. Therefore, the study assumed that the ICEVs, and BEV could drive 150,000 km as the baseline for the comparative LCA analysis.

The scope of this study shows a "complete LCA", which includes the vehicle life cycle as Cradle-to-Grave analysis, and the fuel cycle as Well-to-Wheel analysis. The system boundaries of a "complete LCA" are presented in Figure 3.

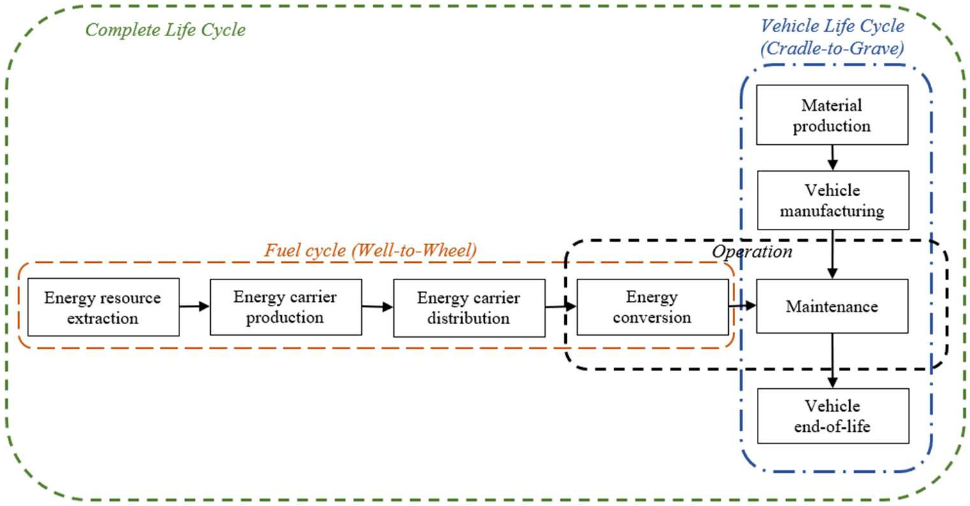


Fig. 3. System scope including vehicle and fuel life cycle

The results of the LCA are described in three stages: production, use, and end-of-life. An electric car does not exhaust direct emissions during operation, but it is highly important how the electricity for charging the battery is produced. Therefore, the indirect impact on the environments is generated. For this reason, the boundary of the electric car flow covers the individual electricity mix in Lithuania 2015–2050 that is simulated and prognosticated by Lithuanian Energy Institute (2017) [68]. As a result, this research uses the LCA method to calculate and compare the environmental impact of electric car in 2015, 2020, 2025, 2030, 2035, 2040, 2045, and 2050, including different electricity mixes and electricity production technologies under Lithuanian conditions.

In this study, the ReCiPe method at the midpoint and endpoint levels is used to perform the impact assessment based on ReCiPe 2016 by the National Institute for Public Health and the Environment (2017) [65]. LCA database Ecoinvent 3 was used as a source of background Life Cycle Inventory data [66]. To determine and compare the impact of electric and conventional vehicles on the environment throughout their cycle, analysis was performed using the SimaPro 8.5 software [67], which calculates the environmental load and shows which stages of the vehicles' life cycle contribute most.

Results and discussion

The full LCA results (including production, use and disposal phases) of electric cars in 2015–2050 and comparison with passenger cars powered with petrol and diesel are shown in the Table 1. Impact categories are displayed according to the highest values that have a major impact on the environment.

Table 1. Results of the full LCA of petrol, diesel, and electric passenger cars under prognosticated energy mix scenarios 2015–2050

Impact category	Unit	ICEV – petrol	ICEV – diesel	BEV 2015	BEV 2020	BEV 2025	BEV 2030	BEV 2040	BEV 2050
Climate change	kg CO_2 eq	15,787	11,394	21,304	10,247	10,021	10,688	13,758	11,719
Human toxicity	kg 1,4-DB eq	1,325	1,095	11,555	15,369	15,015	12,682	10,808	10,975
Ionising radiation	kBq U235 eq	1,973	1,711	202	-752	-706	-337	51	21
Metal depletion	kg Fe eq	-5,424	-5,760	3,804	5,045	4,964	4,264	3,743	3,866
Fossil depletion	kg oil eq	13,669	10,498	6,136	687	822	1,898	3,720	2,910

First, it was assessed that GHG emissions related to the impact on climate change of electric car would be lower in 2020, 2025, 2030, and 2035 scenarios than those for petrol and diesel cars. Second, petrol car is the most polluting, comparing to diesel and electric car in 2020 and later scenarios in this impact category. Next, it was determined that human toxicity of an electric car is expected to be the highest in all energy mix scenarios, which indicator is related to the production of electric car and Li-ion battery, accounting for 36% and 31%, respectively. Then, ionising radiation and fossil depletion indicators are significantly higher for both petrol and diesel cars. The main factor of such a result is production of petrol/diesel. Lastly, the metal depletion indicator is considerably dominant for electric car in the current and future energy mix scenarios. This indicator is related to the production of the battery and accounts for 75% of this impact. The results show that electric car in the 2050 scenario has one of the lowest values in almost all impact categories comparing to the 2015 scenario, as the contribution to the climate change will decrease by 45%, human toxicity – 5%, ionising radiation – 89%, fossil depletion – 53%. This demonstrates that RES integration into electricity production has a positive effect on reducing the impact on the environment.

7.4. LCA and LCC of electric, hybrid, and conventional cars

This section presents a study on the environmental impact and economic costs of an electric, hybrid, and conventional passenger cars using a life cycle approach. Both the environmental and economic assessment covered the stages from the extraction of raw materials to the final disposal of waste. The results of this study were published in a scientific paper – **Comparative environmental life cycle and cost assessment of electric, hybrid and conventional vehicles in Lithuania** [58]. These published research results fulfilled the third objective of the thesis.

Research methodology

This research uses LCA and LCC methodologies to evaluate the environmental impact and economic costs related to the production, use, and end-of-life stages of electric, hybrid, and conventional passenger cars powered with diesel and petrol. The LCA and LCC were performed according to the procedures specified in the European standards series ISO 14040/14044 [63], [64]. The methods are both aligned with these ISO standards on LCA in terms of system scope, functional units, and methodological steps and regard all phases in the life cycle.

The research object – the most popular models of new cars registered in Lithuania with different engine types: the diesel and petrol cars Volkswagen Golf 2019, the hybrid car Toyota Prius 2018, and the electric car Nissan Leaf ACENTA 2018. They are similar in weight and length and belong to the medium-size class; therefore, they are applicable for comparative life cycle and cost analyses. The costs and parameters of the selected vehicles were assumed to be on the level of 2020 year without prognosing their changes and technology evolution in the future.

The functional unit, scope, and system boundaries are the same as in the previous research. Similarly, this research uses the LCA method to assess and compare the environmental impact of electric car in 2015, 2020, 2025, 2030, 2040, and 2050, including various electricity mixes and electricity generation technologies that are forecasted by the Lithuanian Energy Institute under Lithuanian conditions. In this research, the ReCiPe method at the midpoint and endpoint levels was used to fulfil the impact assessment [65]. The LCA database Ecoinvent 3.5 was applied as the background source for life cycle impact analysis [66]. The life cycle environmental weights and potential impacts were calculated using the LCA software SimaPro 9.1 [67].

Economic costs were analysed by performing the LCC, which was carried out from manufacturer and user perspectives. This type of LCC is aligned with the LCA, where the boundaries cover the vehicle cycle and the fuel cycle, bringing the scope to a "Complete LCC". The system boundaries of the LCC are presented in Figure 4.

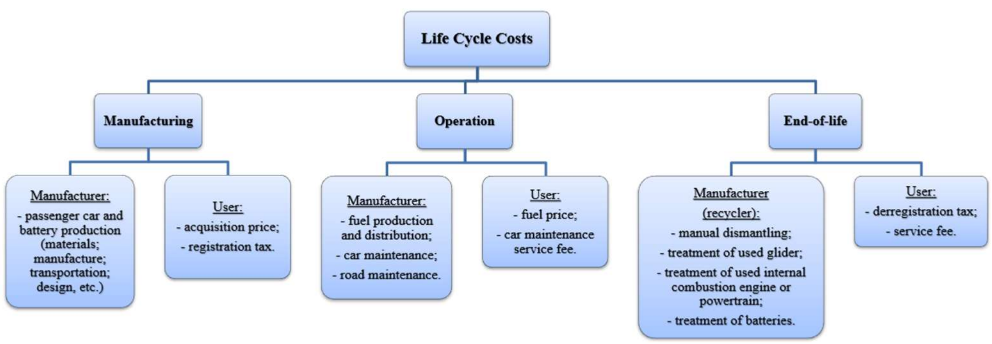


Figure 4. System boundaries of the life cycle costing

The results of the LCC are presented in three combined phases (manufacturing, operation, and end-of-life) from two different perspectives: manufacturer and user.

The manufacturing phase included costs linked to the production of vehicles and batteries. Next, the operation phase included the costs of fuel production and distribution and car and road maintenance. Finally, the end-of-life stage included the costs of vehicle treatment processes: manual dismantling, treatment of the glider, powertrain or internal combustion engine and batteries. From the user perspective, the manufacturing phase included the acquisition price and car registration tax. Next, the operation phase included the fuel/electricity price and car maintenance service fees. Lastly, the end-of-life phase included only the deregistration tax and service fee for the passenger car disposal, which is free of charge in Lithuania. For the LCC analysis, OpenLCA 1.10 software [72] with the Ecoinvent 3.5 database was used as the measure of financial impact from the manufacturer perspective [66]. The analysis from the user point of view was performed by collecting the necessary data from various sources.

Results and discussion

The impact on the environment for the electric car depends on the electricity production mix. Therefore, Figure 5 presents the Well-to-Wheel analysis, showing the impact of the fuel cycle from the energy resource extraction until operation, using various electricity production scenarios that are forecasted for the years 2015–2050 under Lithuanian conditions. All impacts were normalised according to the major contributor in the corresponding impact category. For instance, petrol car has the highest values in fossil resource scarcity and ionising radiation; therefore, these values are equated to 100%, and the impact values of the other analysed vehicles are calculated accordingly. Similarly, the most significant contributors to the other impact categories were identified, and the impact of the other vehicles was assessed accordingly.

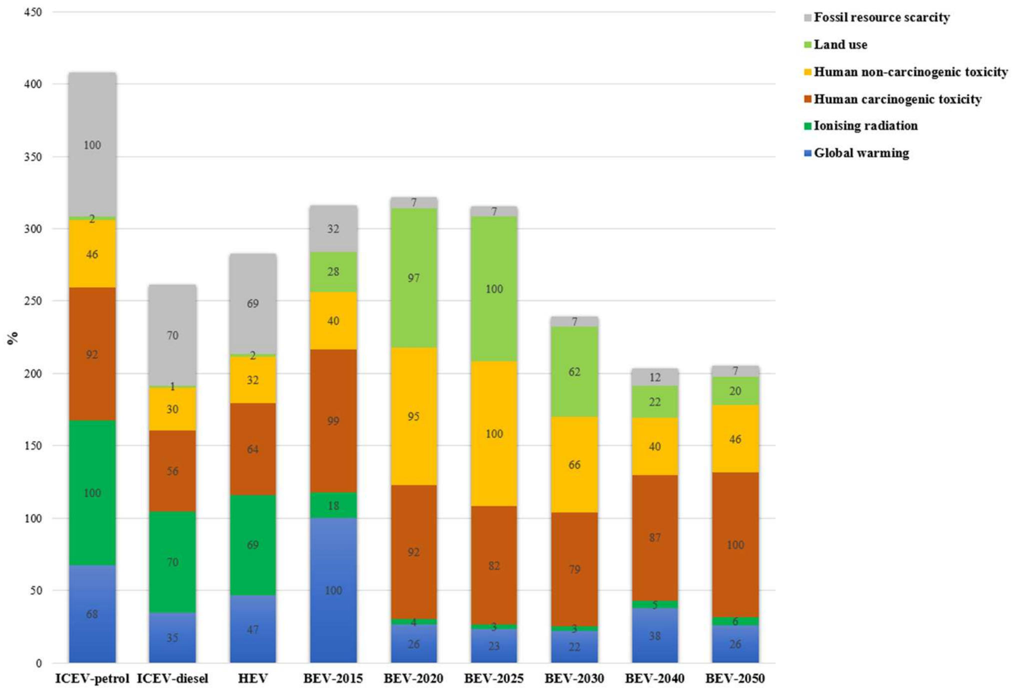


Figure 5. Results (%) of the fuel cycle analysis of petrol, diesel, hybrid, and electric (current and future) cars in Lithuania

The results show that in 2015, due to the use of natural gas (as the largest share) and oil, this electricity mix was the most polluting in terms of global warming potential. In terms of fossil resource scarcity, the electric car with electricity mix from 2020 to 2050 are approximately 10 and 14 times more advantageous than the diesel and petrol car, respectively. The results reveal that the BEVs with electricity scenarios of 2040 and 2050 are the most desirable, with the values in almost all the impact categories among the lowest (except human carcinogenic toxicity). This is because solar and wind energy are actively used as the predominant sources in these scenarios.

The results of the environmental LCA all over the entire life cycle (production, use and end-of-life) are shown in Figure 6, which summarise the total environmental load as damage to resources, ecosystems, and human health.

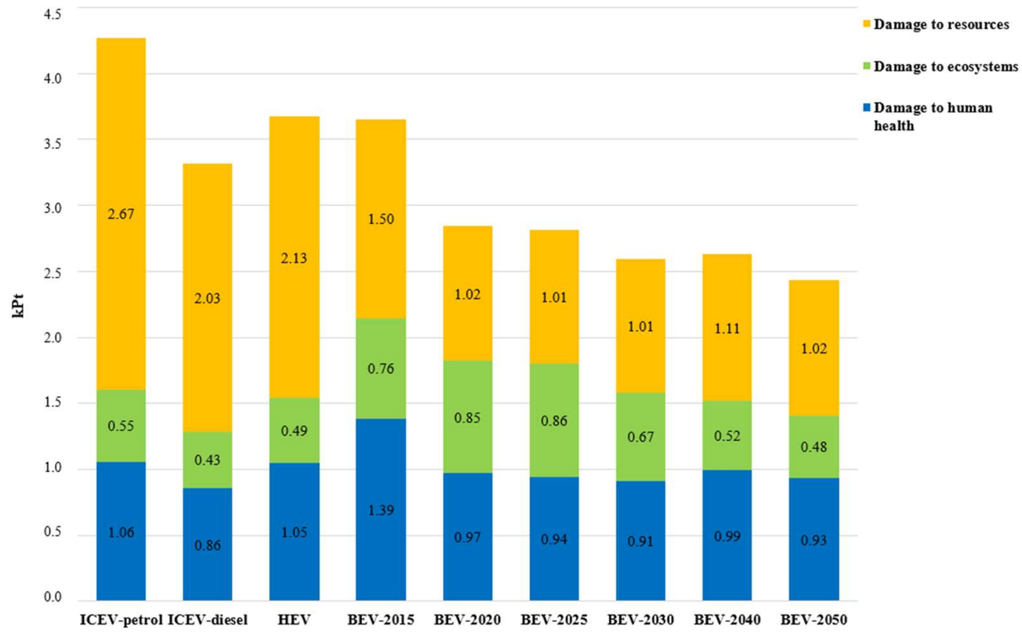


Figure 6. Results of selected passenger cars at the endpoint level

The results reveal that the petrol car has the greatest environmental damage compared with all the analysed passenger cars. Furthermore, the electric car with electricity mix scenarios from 2020 to 2050, which are composed mostly of RES, provide the least environmental damage. These results reveal that switching from the use of fossil fuels to renewables and expansion the RES share in electricity generation has a meaningful benefit in fostering sustainable city transportation.

The results of the LCC from consumer perspective show that hybrid and battery electric cars have the highest costs because of the high purchase prices, while diesel and petrol cars have the lowest prices. However, comparing the operation stage, the electric cars are approximately 37% less costly than diesel cars and 60% less than petrol cars. It is assumed that an electric car is charged at home at the average cost of electricity of 0.13 €/kWh in 2019 for household consumers [73]. This charging scenario was used because charging at the public charging stations is more unpredictable due to price difference and more rare and stochastic usage. In 2020, spring financial incentives have been implemented to promote the purchase of electric passenger cars. Consumers can potentially receive a compensation of €2,000 to purchase a used electric car and €4,000 for the purchase of a new electric car. Therefore, the compensation of €4,000 was included in the analysis. Comparing the total costs, the results indicate that electric and diesel cars are the most competitive, where the total consumer life cycle costs are approximately 5–15% less than others.

7.5. Economic and environmental assessment of ELVs in the context of the circular economy

This section presents a study on the environmental and economic assessment of ELVs using a life cycle approach in the context of the circular economy. Firstly, a material flow analysis has been conducted according to the selected methodologies to understand the material flows of the ELVs components. Secondly, an economic evaluation of the reuse of parts was performed to assess the economic benefits for ELVs managers and buyers of used parts. Thirdly, an environmental assessment was conducted to determine the potential for CO_2 eq emission reductions if the parts of the analysed cars were reused. Fourthly, a life cycle analysis of the cars focused on the production and waste management phases. The results of this study have been published in a scientific paper – **Environmental and economic benefits of electric, hybrid and conventional vehicle treatment: a case study of Lithuania** [59]. These published research results fulfilled the fourth objective of the thesis.

Research methodology

This study uses various methodologies to assess the environmental and economic benefits of electric, hybrid, and conventional passenger cars treatment. The research object – the most popular models of used cars registered in Lithuania with different engine types: the diesel and petrol cars Volkswagen Golf Plus 2005–2008, the hybrid car Toyota Prius 2003–2009, and the electric car Nissan Leaf 2011–2013.

The research can be divided into four parts as follows: 1) a Material Flow Analysis (MFA) was performed to understand the movement of ELVs parts/materials; 2) an economic evaluation was carried out to assess the economic benefits for ELVs dismantlers and consumers of used parts; 3) environmental benefits of reusing car parts were evaluated to assess CO_2 eq emissions savings per vehicle, using CO_2 equivalents per kilogram of a substance emitted during its production; 4) an LCA methodology was applied to assess the environmental impact throughout the production and end-of-life stages of the selected vehicles. The methodology is presented in Figure 7.

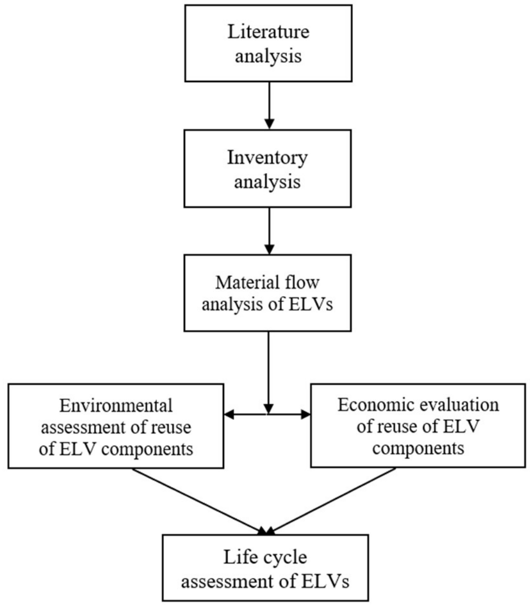


Figure 7. Methodology scheme

Results and discussion

The results of an economic assessment of the reuse of ELVs components revealed that the electric and hybrid cars accounted for the largest share of car parts reuse (38%). Simultaneously, the lowest share of parts reuse was attributed to the diesel (27%) and petrol (28%) cars. The economic benefits for the car dismantling companies range from €1,753 to €5,518, from the petrol to electric cars, respectively. In terms of the economic benefits to users of the car parts, the hybrid car provided users benefits of up to €17,428, and the electric car provided the least benefits, at €8,403. As a result, hybrid cars owners may feel much more motivated to look for alternatives instead of buying new parts. Similarly, buying used car parts of the diesel and petrol cars provided an economic benefit of €14,635 and €10,815, respectively, to users. Referring to the numbers of passenger cars deregistered in 2020 by the type of fuel, and assuming they were dismantled in Lithuania, the total economic benefit to consumers and dismantlers in Lithuania would amount to €1.64 billion and €0.24 billion, respectively.

The results of environmental assessment of the reuse of ELVs components show how many kg of CO_2 eq emissions would be saved if car owners choose to purchase used car parts. The results revealed the highest CO_2 eq saving potential is 6,420 kg CO_2 eq from the electric ELV. The CO_2 eq saving potential for petrol and diesel cars slightly differ (1,828 kg CO_2 eq and 1,880 kg CO_2 eq, respectively) with considerably more CO_2 eq being saved by reusing the hybrid ELV parts (2,403 kg CO_2 eq). Referring to the numbers of passenger cars deregistered in 2020 by the type of fuel, and assuming they were dismantled in Lithuania, the total environmental benefit of parts reuse in Lithuania is a saving potential of approximately 236,513 t CO_2 eq emissions.

7.6. Conclusions

1. An analysis of city transport system policies and initiatives in Lithuania and selected European regions has identified the main factors, barriers, and challenges related to the integration of electric mobility, RES, and ICT in city transport systems. Various policies, initiatives and good practices were reviewed not only at national, local but also at international level. The analysis of policies and initiatives in European regions allowed to assess the transition of countries from fossil fuel to RES powered vehicles. It also provided a basis for examining and comparing passenger cars from an economic and environmental perspective, using a life-cycle approach, and considering the objectives of the National Energy Independence Strategy. Such studies would help urban planners, experts, and policy makers to take decisions in developing a sustainable city transport system.

2. The environmental impacts of electric, hybrid and conventional passenger cars over the entire life cycle according to the different electricity generation scenarios projected for 2015–2050 show that: an electric car charged with electricity mix of 2050 (where solar and wind energy dominates) have a 45% reduction in contribution to climate change; 5% – to human toxicity; 89% – to ionising radiation; and 53% – to depletion of fossil resources, compared to an electric car charged with electricity mix of 2015 (which consists of the largest part of natural gas and oil). Next, it was assessed that the petrol car is the most polluting of all the passenger cars analysed. In addition, a hybrid car and an electric car charged with electricity mix of 2015 create almost the same amount of environmental damage, which is 14% less than the petrol car. Furthermore, a diesel car generates 10% less environmental impact than a hybrid one. Finally, an electric car charged with electricity mix of 2020–2050, which mostly consists of RES, generates the lowest environmental damage. For example, an electric car charged with electricity mix of 2050 creates 43%, 33%, and 27% lower life cycle environmental impacts than petrol, hybrid diesel cars, respectively. The results show that the integration of RES into electricity generation is a key factor in reducing environmental impacts.

3. The analysis of the life cycle economic costs of electric, hybrid, and conventional passenger cars showed that the most competitive cars were electric and diesel cars, which had 5–15% lower costs to the consumer than other cars. Furthermore, the analysis showed that from both the manufacturer's and the consumer's perspective, the electric car is the most cost-effective vehicle at the use stage (with costs roughly halved).

4. The analysis of the ELVs material flows shows that the largest share of the mass of a car that can be reused is for the electric car (38%) and the hybrid car (38%), followed by the petrol car (28%) and the diesel car (27%). The results of the economic study on ELVs showed that car owners would save €51,281 by buying used parts and

managers would benefit financially by €12,739 (from four different types of ELVs). Moreover, considering the total number of ELVs (diesel, petrol, hybrid, and electric passenger cars) that are registered in Lithuania per year, the annual economic benefits of reusing car parts would be €0.24 billion and €1.64 billion for waste managers and users, respectively. The environmental assessment of the ELVs showed that the electric car has the highest CO_2 eq emission reduction potential, equivalent to 6,420 kg CO_2 eq. Hybrid, diesel, and petrol cars would save 2,403 kg CO_2 eq, 1,880 kg CO_2 eq and 1,828 kg CO_2 eq, respectively. In addition, considering the total number of ELVs (diesel, petrol, hybrid, and electric passenger cars) that are registered in Lithuania per year, the annual environmental benefit of reusing parts would be ~236,513 t CO_2 eq.

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9. GYVENIMO APRAŠYMAS

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Vasaros mokykla	• Dalyvauta vasaros mokykloje Berlyne, Vokietijoje. Data: 2019-08-28–2019-09-01. *The 8th International Summer School on Life Cycle Approaches to Sustainable Regional Development*. Organizatorius*: Forum for Sustainability through Life Cycle Innovation*.

10. STRAIPSNIŲ IR MOKSLINIŲ KONFERENCIJŲ SĄRAŠAS

Straipsniai recenzuojamuose mokslo leidiniuose

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2. **Petrauskienė, Kamilė**; Galinis, Arvydas; Kliaugaitė, Daina; Dvarionienė, Jolanta. Comparative environmental life cycle and cost assessment of electric, hybrid, and conventional vehicles in Lithuania // Sustainability. Basel : MDPI. ISSN 2071-1050. 2021, vol. 13, iss. 2, art. no. 957, p. 1-17. DOI: 10.3390/su13020957. [Science Citation Index Expanded (Web of Science); Scopus; DOAJ] [IF: 3,251; AIF: 5,860; IF/AIF: 0,554; Q2 (2020, InCites JCR SCIE)] [M.kr.: T 004, S 004] [Indėlis: 0,250]
3. **Petrauskiene, Kamile**; Dvarioniene, Jolanta; Kaveckis, Giedrius; Kliaugaite, Daina; Chenadec, Julie; Hehn, Leonie; Pérez, Berta; Bordi, Claudio; Scavino, Giorgio; Vignoli, Andrea; Erman, Michael. Situation analysis of policies for electric mobility development: experience from five European regions // Sustainability. Basel : MDPI. ISSN 2071-1050. 2020, vol. 12, iss. 7, art. no. 2935, p. 1-21. DOI: 10.3390/su12072935. [Science Citation Index Expanded (Web of Science); Scopus; DOAJ] [IF: 3,251; AIF: 5,860; IF/AIF: 0,554; Q2 (2020, InCites JCR SCIE)] [M.kr.: T 004] [Indėlis: 0,200]
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Kituose recenzuojamuose mokslo leidiniuose
Užsienio šalių leidyklose

Petrauskienė, Kamilė; Dvarionienė, Jolanta; Kliaugaitė, Daina; Kaveckis, Giedrius; Chenadec, Julie; Hehn, Leonie. Situation analysis of electric vehicles, renewable energy and smart grids for sustainable urban mobility in five European regions // Energy 2018: Eighth international conference on smart grids, green communications and IT energy-aware technologies, May 20 - 24, 2018, Nice, France. [S.l.] : IARIA, 2018. ISBN 9781612086354. ISSN 2308-412X. p. 23-25. [M.kr.: T 004] [Indėlis: 0,170]

Kitos konferencijų tezės ir straipsniai nerecenzuojamoje konferencijų pranešimų medžiagoje

1. Tverskytė, Rasa; **Petrauskienė, Kamilė**; Dvarionienė, Jolanta. Economic and environmental benefits of electric, hybrid and conventional vehicle treatment in Lithuania // GREEN 2020: the fifth international conference on green communications, computing and technologies, November 21-25, 2020 / B. Gersbeck-Schierholz. Wilmington, DE : IARIA, 2020. ISBN 9781612088266. ISSN 2519-8483. p. 1-3. [M.kr.: T 004]

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11. PADĖKA

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12. PUBLIKACIJŲ KOPIJOS

Pateikiamos 4 mokslinių publikacijų, kurių pagrindu parengta disertacijos mokslinių straipsnių ir jų sąsajų apžvalga, kopijos.

sustainability

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Article

Situation Analysis of Policies for Electric Mobility Development: Experience from Five European Regions

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Abstract: The decarbonization of the mobility and energy sector is one of the major necessary trends for achieving targets set for the European Union (EU) in the 2020 and 2030 climate and energy frameworks. Two key technologies which offer great potential for climate change mitigation are electric vehicles (EVs) and renewable energies (REs). Thus, there is the need for innovative and stable policies in order to favor these technologies. The purpose of the study is to identify and compare features of policies for the integration of EVs, REs, and information and communication technology (ICT). This study uses an integrated Strengths, Weaknesses, Opportunities and Threats (SWOT), and Political, Economic, Social, Technological, Environmental and Legal (PESTEL) qualitative methodology in order to show different policies and initiatives, related to e-mobility, RE and ICT, collected from five European regions. This research provides discernments to the EVs and RE challenges, such as the lack of capacity to deal with high energy demands or limited EV-charging infrastructure. On the contrary, a high percentage of REs share, raising climate change awareness, and decreasing EV prices which are great opportunities for the whole EU. Such insights encourage policymakers and other groups of interest to improve their RE and mobility policies, which could lead to effective sustainable mobility systems in urban areas.

Keywords: electric vehicle; renewable energy; transport policy; sustainable mobility

1. Introduction

Europe faces challenges in achieving targets set for the 2020 and 2030 climate and energy frameworks, as well as, the 2050 long-term strategy [1]. The transportation sector in the EU has a significant impact on the environment, and is responsible for 33.1% of total energy consumption. Road transport is one of the most energy expending modes of transport, where consumption rose by 23.3% since 1990 [2]. In addition, the transportation sector has the largest oil demand in the EU, where 77% of total consumption of oil-derived fuels in 2016 accounts for road transport [3].

Electrification of road transport has become a principal tendency for sustainable mobility, and two of the most significant trends which are gaining momentum in European cities are EVs electric vehicles (EVs) and renewable energies (REs). Therefore, it is important to co-develop a framework of experiences and policies where energy and mobility will work together and not act as different entities. For this reason, the INTERREG EUROPE EV ENERGY (Electric Vehicles for City Renewable Energy Supply) project consortium was created. The partners from five European regions (Italy, Lithuania, Spain, Sweden and the Netherlands) have identified a need for a common framework and repository of interrelated and analyzed policies and initiatives to lay the basis for systematic interregional dissemination. The majority of the partners have gained experience in analyzing opportunities and developing actions and policies. This research provides insight into the EV and RE challenges and opportunities within the European Region project partners.

Registrations of new electric cars in 2017 reached over 1 million sales worldwide; as a result, the global stock exceeded 3 million electric cars in 2017 [4]. That notwithstanding, EVs will be even more advantageous if electricity is generated by RE sources [5,6]. The implementation growth of support schemes for RE technology and decreasing costs of RE systems made a positive impact in the consumption of RE [7]. The share of RE in gross final energy consumption reached 18.9% in 2018 (from 8.5% in 2004). Moreover, the transport sector increased the share of RE to 8.3% in 2018, compared to 3.1% in 2007 [8]. Smart charging applications could also boost the share of RE used to charge the EVs; in particular, wind and solar energy is becoming an important research topic. Ultimately, the vehicle-to-grid (V2G) strategies have shown a promising solution to the energy market [9].

Chen et al. (2020) revealed that the V2G capability and EV-charging time attribute was the most significant factor of e-mobility in determining prospective EV integration. In addition, financial savings, the fuel economy, and environmental value were also one of the strongest predictors [10]. Furthermore, Noel et al. (2018) revealed an extensive range of benefits for both EVs and V2G, such as emissions, economic savings, and RE integration, as well as noise reduction and better performance. Moreover, authors revealed that V2G benefits covered topics like vehicle-to-home and solar integration, as well as, vehicle-to-telescope and emergency power backup [11].

Both the growth of the EV fleets and the increase of RE production can contribute significantly to climate change mitigation, but their intelligent integration is of a high priority. Different, fragmented policies are observed, favoring EVs through incentives at local, regional and national level. In order to boost e-mobility technologies and sustainable transportation, innovative and stable policies are required.

There are research studies that have been performed on EV legislation, policies, good practices, drivers and barriers, challenges and opportunities. Bekiaris et al. (2017) conducted research on legislation, in order to underline the importance of e-mobility [12]. Biresselioglu et al. (2018) undertook a detailed review of literature analysis covering motivators and barriers for integration of EVs in the EU, covering environmental, economic, technical and other aspects [13]. Rietmann and Lieven (2019) explored the influence of policy measures supporting EVs in 20 countries worldwide, showing various policy incentives, which promote the implementation of EVs. In addition, the study highlighted the need for collaboration between the public and private sectors in order to promote EVs [14]. Global EV adoption and the impact of policy measures have also been analyzed by Haddadian et al. (2015), who concluded: "In order for EVs to achieve a large-scale market presence, the corresponding regulatory framework should be designed to incorporate both push and pull factors within its incentive schemes." The authors also emphasized that countries should learn from each other's experiences and set up forceful policies based on their national priorities and technical resources in order to promote sustainable transportation [15]. Another international viewpoint was stated by Wang et al. (2019), who analyzed the adoption of EVs across 30 countries for the year 2015. The authors summarized that fuel price, chargers' density and road priority are significantly effective factors correlated with a country's EVs market share [16]. Furthermore, another study was carried out by Cansino et al. (2018), where authors focused on measures to promote e-mobility within the EU28. The authors summed up that the most important policy instruments to promote EVs are tax and infrastructure measures together with financial incentives for purchasing and supporting R&D projects [17].

There are research studies that have been carried out regarding potential trends, policies, good practices, drivers and barriers in the e-mobility sector in various individual countries: Austria [18], Brazil [19,20], China [21], Denmark [22], Ireland [23], Germany [24], Latvia [25], Lithuania [26], Norway [27,28], Portugal [29], Spain [30–32], Sweden [33], the USA [34], Nordic countries [35], etc. For instance, case studies in Norway revealed a positive EV integration when various incentives were implemented: permanent exemption for vehicle registration tax, exemption for yearly fee and road toll, exemption for value-added tax, reduced tax for company cars, free parking on municipal parking spots, permanent access bus lanes, exemption congestion charge, and fast charging infrastructure availability [27,28]. Besides, users of BEV drivers also described their EVs as more comfortable than their (previous) cars with internal combustion engine, both by means of driving experiences and technical equipment [28]. Next, a Spanish case introduced its national legal framework and policy measures to promote the use of EVs in Spain: financial support and incentives for residents and public authorities for the purchase of EVs, and financing for R&D projects. In addition, there are also two relevant taxes for vehicles: tax on vehicle's ownership and a tax regarding CO_2 emissions (g/km). Consequently, EVs have exemptions for these taxes [30]. Moreover, another Spanish case showed a good example of moving towards a sustainable sharing economy business model. Ampudia-Renuncio et al. (2018) performed a research showing a holistic evaluation of the impacts generated by electric free-floating car-sharing (FFCS) on user behavior of university students in Madrid. Authors also revealed the positive effects of FFCS to the environment and a possibility to complement public transportation [31]. Furthermore, Luna et al. (2020), analyzed the incentive policy of the first e-car-sharing scheme in Brazil, which showed a significant reduction (29%) in carbon emissions and increase (36%) of awareness and adoption of EVs [19]. According to the U.S. Department of Transportation, Federal Highway Administration (2016), a number of social, environmental and economic benefits have been identified from the use of shared mobility modes. Several studies have documented reduced vehicle use, ownership, and vehicle distance travelled. Additionally, cost savings and convenience are often cited as popular reasons for shifting to a car-sharing mode [36].

However, no study has yet been performed related to features of policies and incentives for the integration of e-mobility, RE, and information and communication technology (ICT) in different regions of Europe. Therefore, the main objective of the study was to identify and compare features of policies for the integration of EVs, RE, and ICT in five European regions: Italy (Lazio), Lithuania, Spain (Barcelona), Sweden (Stockholm) and the Netherlands (Amsterdam and Flevoland). In order to highlight drivers and barriers, possibilities and risks of the mobility conditions in these countries, the integrated Strengths, Weaknesses, Opportunities and Threats (SWOT), and Political, Economic, Social, Technological, Environmental and Legal (PESTEL) analysis based on local mobility policies and initiatives was carried out.

Such comprehensive situation analysis would inform urban transport planners, experts and policymakers about the transition from internal combustion to renewable energy-fueled vehicles, as well as show mobility policies, good practices, and circumstances that are the most appropriate for the integration of sustainable urban mobility. Moreover, it is important for countries to learn from each other's good practices in order to determine significant local policies and apply initiatives that could promote a healthy, environmentally friendly city transport system.

2. Methodology

In order to develop a framework of innovative policymaking, a comprehensive situation analysis of mobility policies and initiatives (MPI) needs to be performed. The study area of the current research consists of five European regions: Italy (Lazio), Lithuania, Spain (Barcelona), Sweden (Stockholm) and the Netherlands (Amsterdam and Flevoland). The consortium of regions was formed by dedicated cities at the forefront of the integration between RE and e-mobility, and committed to evaluating and disseminating the results of their insights. Situation analyses of policies and initiatives were carried out in each EV ENERGY project partner regions by using an integrated SWOT and PESTEL qualitative methodology [37–40]. The situation analyses were based on the three pillars approach:

(1) Policies and initiatives related to EVs

Every region worked on the identification of specific local MPI related to EVs. This included incentives and measures stimulating EVs, such as purchasing, their traffic participation, parking and charging circumstances.

(2) Policies and initiatives related to Renewable Energy Supplies (RES)

In parallel, policies and initiatives of RE were identified and analyzed. This included incentives and measures stimulating local RE, namely financial support constructions, permitting procedures, energy pricing, and net metering arrangements, etc.

(3) Policies and initiatives related to ICT Tools for Energy and Mobility

This analysis took into particular account the appropriate rollout of policies of the three combined disciplines, optimization of RE and increased deployment of EVs and their intelligent integration using ICT.

In the context of the current research, an overall methodological approach was developed in order to identify and compare features of policies for the integration of EVs/RES/ICT in different regions of Europe. The implemented methodological approach consists of the following two steps (Figure 1):

(1) Inventory of Mobility Policies and Initiatives (IMPI);
(2) Conduction of SWOT and PESTEL analysis (based on IMPI);

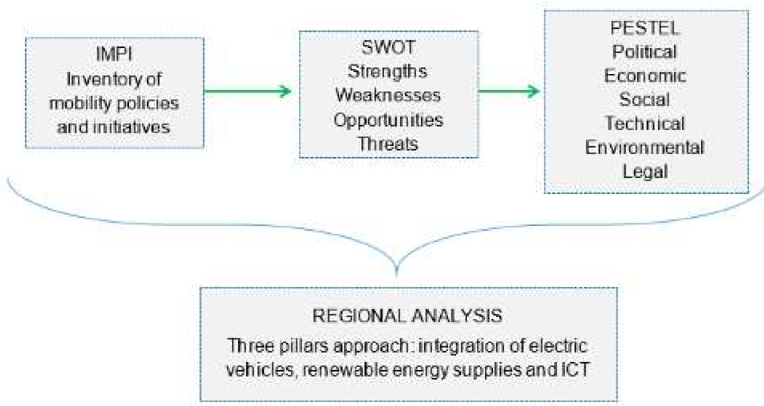

Figure 1. Illustrated methodology approach adopted for the current research process.

All partners were actively involved in the data collection process for IMPI. To ensure the harmonization of information and data collection, templates for the IMPI (Table 1) were prepared and spread among partners. IMPI was obtained by analyzing secondary resources: bibliography, laws/regulations, relevant sites, public reports, national and international standards, and other related initiatives.

2.1. Inventory of Mobility Policies and Initiatives

The IMPI was the starting point for collecting and understanding what governs, regulates, and perhaps, controls the growth of clean and energy efficient mobility. The most relevant policy aspects for EVs/RES/ICT in five analyzed regions were investigated.

Mobility policies were grouped and analyzed on city/regional, national and EU (international) scale. Additionally, IMPI were grouped into four different types, covering different aspects of mobility:

e-mobility, urban and spatial planning, ICT tools for energy systems, awareness and adoption (Table 1). E-mobility is more extensive than others.

Table 1. Template for the IMPI

Region Name:			
Inventory of Mobility Policies and Initiatives	**City/Regional**	**National**	**EU**
Policy Type			
E-mobility – may include issues such as: taxation/value-added tax; energy pricing/regulations; incentives such as parking, access, and other; charging			
Urban planning – may include: land-use regulations, parking, energy efficiency levels, employee transport plans			
ICT-energy system (incl. REs and production and consumption) – may include issues such as: feed-in tariffs; net metering; funding by purchase; grid energy exchange measures			
Awareness and adoption (jobs, growth and investment) – include investment in REs/Sustainable environment; transport and ICT; new jobs in low carbon economy etc.			

The initiatives are interpreted as stories of successful projects implemented in the five countries of EV ENERGY project partners. Each project partner had to present several successful initiatives, which they are proud of and which would have the potential to be transferred to other countries.

In this study, the presentation of initiatives was not too detailed and was mentioned in line with the policies. Therefore, all selected initiatives (in EV ENERGY project called Good Practices) will be reported and submitted to the INTERREG Europe Program website.

2.2. *Conduction of Integrated SWOT and PESTEL Analysis*

The second step of the implemented methodological approach consists of the conduction of integrated SWOT and PESTEL analysis based on local MPI in order to highlight strengths, weaknesses, opportunities and threats of mobility conditions in analyzed European regions. The SWOT analysis was presented individually for three main pillars of the project: EVs/REs/ICT. Therefore, SWOT analysis was performed in line with PESTEL, with the assessment of the six factors: political, economic, social, technological, environmental and legal.

The methodology could be successfully used in different fields: for the development of industry [41], for studying government challenges [42], and for integrated Strategy Framework development [43]. The result of the PESTEL analysis is often used to identify threats and weaknesses as input for a SWOT analysis. These tools are often used together as they complement each other [40].

Information basis for the SWOT and PESTEL analysis was data, collected using top-down approach—study of existing local MPI, planning documents, analysis of statistical and scientific data and using bottom-up approach—participatory approach, reports and outputs from regional stakeholder events. Four events were held in each of the five regions, where representatives from government, municipalities, experts, and professionals from business companies and research institutions shared and overviewed preconditions, potentials and challenges of the particular region in form of many different thoughts and aspects related to EVs and related smart solutions.

3. Data Analysis Results and Discussions

One of the project's objectives was to collect MPIs, which are the starting point for understanding what regulates, governs and controls the growth of EVs, REs and ICT in regions of the project partners.

3.1. Mobility Policies and Initiatives

The MPIs, as well as other policies, can be grouped into city/regional, national and international scale. Additionally, MPIs were grouped into different types covering different aspects of mobility: e-mobility, urban and spatial planning, ICT energy systems, awareness and adoption.

On the international scale, the Kyoto Protocol is a well-known treaty. This treaty extends the 1992 United Nations Framework Convention on Climate Change. This framework requires states to reduce greenhouse gas emissions, while in the EU alone, about 12% CO_2 is emitted by passenger cars [44].

Other well-known international policies are focused on EU level. For instance, the Clean Vehicles Directive (2009/33/EC) encourages clean and energy-efficient road transport vehicles, the Alternate Fuels for Sustainable Mobility in Europe Directive (2014/94/EC) focuses on the deployment of an alternative fuel's infrastructure. Additionally, a number of various European regulations cover various aspects of e-mobility: setting emission performance standards for new passenger cars as a part of the community's integrated approach to reduce CO_2 emissions from light-duty vehicles (443/2009); approval of motor vehicles with respect to emissions from light passenger and commercial vehicles (Euro 5 and Euro 6) and on access to vehicle repair and maintenance information (715/2007); sound level of motor vehicles and of replacement silencing systems (540/5014); and setting emission performance standards for new light commercial vehicles as part of the Union's integrated approach to reduce CO_2 emissions from light-duty vehicles (510/2011). In 2011, the European Commission adopted a roadmap (Roadmap to a Single European Transport Area—Towards a competitive and resource efficient transport system) of 40 concrete initiatives to build a competitive transport system, which would increase mobility, reduce Europe's dependence on imported oil and reduce carbon emissions in transport by 60% by 2050 [45].

Despite EU regulations and directives, a list of communications between the European Commission, the European Parliament, the European Council and various EU committees' documents concerning e-mobility have been released: Towards Europe-wide Safer, Cleaner and Efficient Mobility: The First Intelligent Car Report (COM/2007/0541); Greening Transport (COM/2008/433); Action Plan on Urban Mobility (COM/2009/0490); A European strategy on clean and energy efficient vehicles (COM/2010/0186); Clean Power for Transport: A European alternative fuels strategy (COM/2013/17). The urban and spatial planning addressing mobility policies in Europe are highlighted in the previously mentioned white paper—the Roadmap to a Single European Transport Area (COM/2011/0144) for the EU, which aims to increase cooperation between the EU Member States, Cities, and the European Commission by utilizing sustainable growth of European cities. The ICT domain is addressed by the Renewable Energy Directive (2009/28/EC), which enacts a general policy for production and promotion of energy from renewable sources.

Additionally, ICT is covered by EU communication documents identifying A Stronger European Industry for Growth and Economic Recovery (COM/2012/582); A Strategy for Smart, Sustainable and Inclusive Growth (COM/2010/2020) and A Roadmap for Moving to a Competitive Low Carbon Economy in 2050 (COM/2011/112). The awareness and adoption are addressed by the Horizon 2020 program, which is an EU research and innovation initiative covering energy, ICT, transport, environmental and climate actions, and by an EU funding instrument, called Connecting Europe Facility (CEF), which promotes the growth of jobs and competitiveness through infrastructure investment within the sectors of energy, transport and telecommunications. All these international level policies present a good basis for national policies, which intend to tackle EV, ICT, and energy-related issues on a national level. However, in order to transfer policies from one region to another, the results (Table 2) of inventoried city/regional and national policies were segregated by the countries of project partners.

Table 2. National and local/regional policies and initiatives addressing EVs, RE, ICT spatial planning and social awareness in EV ENERGY project countries.

	Italy	Lithuania	Spain	Sweden	The Netherlands
National policies and initiatives	National Energy Efficiency Fund	National Energy Independence Strategy	Mobility Impulse Plan	Pump Act ensuring access to renewable fuels at fuel stations	National Charging Infrastructure Knowledge Platform
	Retrofit	National Transport Development Program	Vehicle impulse strategy with alternative energy (2014–2020)—Industry, Energy and Tourism Ministry	Climate Step giving grants, e.g., for charging infrastructure	ElaadNL knowledge center
	National Strategic Framework	Lithuanian Long-Term Strategy for Development of the Transport System	Spanish strategy for sustainable mobility—Ministry of Development	Electric bus purchase subsidy	Formule E-Team
	Incentives for the purchase of new cars with reduced CO_2 emissions.	Feasibility study on Electric Transport Development	White Paper on Sustainability in Spanish Urban Planning—Ministry of Development	Public transport and cycling support by national climate goal to reduce greenhouse emissions from the transport sector by 70% compared to 2010	Administrative Agreement on Zero-Emission Buses
	Deduction in 10 years of 50% of the expenses incurred for the purchase and installation of a private charging station	Detailed EV Development Strategy report	Infrastructure, Transport and Housing Plan—2012–2024—Ministry of Development	State grant for purchasing environmentally friendly cars	Green Deal
	Ecotax for polluting vehicles with emissions over 160 CO_2 g/km	National Strategy for the Development of Renewable Energy Sources	Aid program for modal shift actions and more efficient use of modes of transport—Industry, Energy and Tourism Ministry	Solar panel investment support for private households	Association of Netherlands Municipalities
		Energy Efficiency Action Plan	National Energy Efficiency Fund—Industry, Energy and Tourism Ministry	Regulation on Feed-in-tariff for private producers of solar energy/electricity	Energieakkoord (Energy Agreement)
		Forecast of the Use of Renewable Energy Sources		City environmental agreement supporting local transition projects	SDE+ (Stimulating Renewable Energy)
		Lithuanian Innovation Strategy for 2010–2020		Grants for purchasing electric bikes (25% of prize)	Energy Top Sector—Urban Energy TKI
		Operational Program for Promotion of Cohesion for 2014–2020		Political climate framework for Sweden—goal of net zero emissions 2045	Energy Investment Allowance
		Guidelines for e-cars charging infrastructure		Power agreement for Sweden—fossil-free electricity production latest 2040	Regeling Groenprojecten (Settlement Green Projects)

Table 2. *Cont.*

	Italy	Lithuania	Spain	Sweden	The Netherlands
Local/Regional policies and initiatives	Lazio Region Taxation Law	EV-charging schemes	PIRVEC Plan 2016–2019—Strategic Plan for the Deployment of Charging Infrastructure for Electric Vehicles	Grants for increasing EV-charging infrastructure in the Stockholm region (based on State grants)	Clean Air policy in Amsterdam
	Retrofit	Public transport modernization	Strategy for the impulse of electric vehicles in Catalonia	Regional development plan for the Stockholm region	Metropole Region Amsterdam
	SUMP policies regarding e-mobility	Park and Ride, Bike and Ride	Urban Mobility Plan—2013–2018. City of Barcelona	List of policy instruments for cities and municipalities	Mobility vision 2030
	Implementation of local fiscal policies	Master Plans for majority of cities	Urban Mobility Metropolitan Plan—Barcelona Metropolitan Area	Solar maps for entire region and City of Stockholm	Solar Energy Amsterdam
	The Strategy for the Energy Plan of the Lazio Region		Mobility Masterplan—2013–2018		Program mobility and space
	National Strategic Framework for e-infrastructures		National Agreement on Energy Transition in Catalonia—2016–2050		Lelystadt sustainability framework
			Plan to improve air quality in Barcelona 2015–2018		Mobility plan of Almeire
			Program of Anti-air Pollution Measures		

In Italy the main EV and its infrastructure outlying policy is the National Strategic Framework for e-infrastructures aiming to install a network of EV-charging points, with the ambition to spread adequate e-infrastructures in the Italian territory for over 130,000 electric vehicles, adding to the current 9,000 EV-charging points, up to 19,000 charging points including up to 6,000 "high power" charging points. This policy constitutes the electricity section of the national strategic framework for the development of the alternative fuels market in the transport sector and the construction of the related infrastructure. Among the most important financial instruments to support the implementation of interventions aimed at ensuring the achievement of the National Strategic Framework for e-infrastructures and the Italian energy efficiency targets, in line with the provisions of the Kyoto Protocol, the measure of the "National Fund for Energy Efficiency" aimed at supporting the implementation of energy efficiency interventions carried out by Companies, ESCO and Public Administration on buildings, plants and production processes and integrates incentive tools dedicated to achieving national energy efficiency objectives. This fund introduces infrastructure for charging EVs and provides grants to implement charging infrastructure in order to replace and/or transform public transport and waste collection with EVs. Another regulation is called Retrofit, which addresses installation procedures of energy regeneration systems for EVs. On a regional level, the region of Lazio EV users is exempt from motor vehicle taxes for five years after first registration. The urban planning as well as ICT and energy system in Lazio is not centralized, but rather regulated by individual municipalities, which develop their own policies, mobility and parking management facilities and infrastructure development.

In the context of Lithuania, the taxation policies are not as generous for EV users as they are in Sweden or the Netherlands, as Lithuania does not have any tax benefits. The future of the Lithuanian energy sector until the year 2050 is drawn by the National Energy Independence Strategy, which defines the vision of the Lithuanian energy sector and its implementation principles, strategic directions, goals and objectives. Furthermore, it emphasizes the results to be achieved regarding REs in transport sector by 2050. The other initiative, the National Transport Development Program, is defined for a shorter period, until 2020. This program is intended to support policies by developing a sustainable transportation system, effectively managing resources and EU funding, increasing the sector's competitiveness. The other policy, known as the Lithuanian Long-Term Strategy for Development of the Transport System is valid until 2025. It covers land-use regulations, governmental policies, sharing mobility and possible measures required to improve mobility. Concerning EVs and REs, the Ministry of Transport and Communication have developed guidelines for EV-charging infrastructure and allocated funds for installing charging points along main highways. Furthermore, the Ministries of Transport, Economy and Energy shared a commissioned feasibility study on Electric Transport Development. The urban planning, ICT, and REs are addressed by the Law on Renewable Energy Resources, National Strategy for the Development of Renewable Energy Sources, Energy Efficiency Action Plan, Forecast of the Use of Renewable Energy Sources and Lithuanian Innovation Strategy for 2010–2020. On the city level, EV-charging schemes and public transport modernization (alternative fuel or electric busses) exist for 25 cities. The cities of Vilnius, Kaunas, Klaipeda and Druskininkai installed "Park and Ride" and "Bike and Ride" stations used for combined mobility. Moreover, each city in Lithuania has its own Master Plan, which is the core policy document defining land-use regulations, infrastructure plans and feasibility studies.

On a national level, the Ministry of Economy, Industry and Competitiveness in Spain issued the Mobility Impulse Plan. It promotes EVs and the implementation of charging infrastructure. While on a regional level, the Catalan Government initiated PIRVEC Plan 2016–2019, which is a strategic plan for the deployment of charging infrastructure in the region. The other plans, such as Urban Mobility Plan (2013–2018) and Urban Mobility Metropolitan (Barcelona) Plan and Mobility Master Plan regulate urban planning and mobility policies. The ICT and RE sectors are affected by the National Agreement on Energy Transition in Catalonia 2016–2050, by the Barcelona City Plan to improve air quality in 2015–2018, and by the Program of Anti-Air Pollution Measures, applied in 40 municipalities around Catalonia.

In Sweden, the tax policy ensures that EV users do not have to pay annual circulation tax, companies' EVs can be used for commercial and private purposes, there are more parking spaces for EVs, and generous purchase subsidies. Moreover, the Pump Act (2005:1248) obligates operators to provide renewable fuels at filling stations. Meanwhile, the National Swedish Energy Agency issued a policy called Climate Step, which supports investment for carbon reduction measures, for instance, charging infrastructure. Concerning the public transport in Sweden, the Ministry of Environment and Energy subsidizes regional and public transport, and promotes bicycles. The RE is a high priority in Sweden as well—county administrative boards provide investment support for households willing to install solar and wind power plants and energy storages. Furthermore, such households obtain tax reductions by producing and selling RE to the state. On a higher level, counties and municipalities are supported by a state-issued policy called the City Environmental Agreement, which supports developing a sustainable urban environment. On a city level, Stockholm promotes EVs and e-mobility by changing its own fleet to EVs and by installing 1,000 public charging points by 2020 (this goal was achieved already in 2019 with 1,500 public charging points) and 15,000–25,000 until 2030. Stockholm, as well as other Swedish cities, has comprehensive policies defining regional goals, initiatives and planning on a local level, detailed development plans representing functions, forms and use of public spaces, transportation plans, and regulations and local ordinances for parking, public streets and spaces. Concerning RE, many municipalities have solar maps showing the potential for installing solar panels.

The Province of Flevoland and Green IT Amsterdam created an inventory of the policies related to e-mobility, urban/spatial planning, ICT tools for energy systems, awareness and adoption. The high inclusion of citizens in the development of the policies are materialized through a demand-driven positioning of charging points where private and semi-public charging points are growing faster than public charging points. In the Netherlands, the Green Deal initiative achieved very positive results, which emerged as a governmental, municipal and private contribution to initiate a joint deployment of publicly accessible EVs. Namely, the goal is to improve and expand the charging infrastructure for EVs and to employ the EVs' storage capacity, which could be used by RE and for the stability of the grid.

Moreover, the country is pushing forward the City Deals, concrete cooperation agreements laid down between cities, the central government, local and regional authorities, and companies and social organizations. This involvement and cooperation are a great example of bottom-up approach strategies. On a local level, the city of Amsterdam has a clear strategy for the roll-out of EVs such as implementing EV-charging points directly available in the public space or subsidizing the purchase of electric commercial vehicles. The municipalities in the Amsterdam Metropolitan Area co-operate to stimulate e-mobility and enhance the realization of a good network of charging stations in the whole area. Cross-over policies foster the development of the region itself while lowering the barriers between the various sectors involved such as mobility, RE, new transport mode, stimulating ICT measures, etc.

3.2. *Integrated SWOT and PESTEL Analysis*

This part of the paper presents features of EV, RE and ICT sectors from political, economic, social, technological, environmental and legal (PESTEL) perspectives in five countries of the EV ENERGY project partners. Features are presented as strengths, weaknesses, opportunities and threats, which were identified through integrated SWOT and PESTEL analyses. Features are grouped according to the regions, the same way as MPI, in order to identify drivers and barriers, risks and possibilities in each region.

3.2.1. Italy

Italy has a high number of initiatives supporting the introduction of EVs. These initiatives support not only in form of legislation, regulations, and standards, but also in promotions and project demonstrations. On a municipality level, a number of municipalities in Italy have committed to implementing a Sustainable Energy and Climate Action Plan. From an economic perspective, Italy has a

National Energy Efficiency Fund, which grants about 310 million euros to support sustainable mobility. Additionally, Italy implemented a taxation policy, which liberates EV users from motor vehicle tax for five years, and new buildings' regulations require that new buildings should have an EV-charging infrastructure. Moreover, the Ministry of Infrastructure and Transport provides substantial funding for local and regional initiatives. Additionally, Italy increases its RE production—in 2016, 44% of all produced energy came from renewable sources and that contributed to lower emissions. As a result, from 2015, Lazio is ranked 12th with 6.4 tCO_2 below the national average.

Despite these advantages, the public sector in Italy has low awareness of EVs and e-mobility. Mainly, this is due to duplication and overlap of competences. The public sector, enterprises, research, and public bodies have weak relationships, especially in managing innovative projects. The Italian government lacks a clear legislative basis and national/regional financial instruments, which would subsidize EV purchase. Available funding is limited not only by the government, but also by private initiatives. For instance, small and medium companies spending in R&D only make up for 0.53% of Gross Domestic Product (2011 data), which limits the companies' competitiveness. Another issue is the limited EV popularity combined with a high motorization rate in Rome—9 vehicles per 10 inhabitants. This causes high pollution, noise and congestion.

Most of the opportunities of e-mobility have been identified on a political level. For instance, one of the targets is the Paris Climate Agreement, which could contribute to implementing e-mobility related projects and reduce greenhouse emissions. On a municipal level, according to the new building regulations, new housing must have EV-charging infrastructure. In addition, the government initiated the National Strategic Framework for e-infrastructures to develop a recharging system in Italy, and a Single National Platform to collect information on charging infrastructure accessible to citizens and operators. The other opportunities are growing EV popularity and increasing EV numbers in Europe and Italy.

While there were more opportunities for policies, more economic and technology-related threats have been identified. First of all, the high purchase price of EVs and their batteries are the main economic risk, which could limit EVs. Other economic issues are the low degree of company internalization rate and a strong dependence on traditional energy sources. A structured integrated SWOT and PESTEL analysis of Italy is presented in Table 3.

Table 3. Integrated SWOT and PESTEL analysis for EV, RE and ICT sectors in Italy.

Strengths	Weaknesses
• National Energy Efficiency Fund supports sustainable mobility • Taxation policy • Increasing production of RE • New buildings with EV-charging infrastructure • Local and regional initiatives funded by the Ministry of Infrastructure and Transport • Expansion of electric car-sharing • Innovation is driven by great innovative companies	• The weak relationship between enterprises, research, and public • Low awareness in the public sector • Lack of a clear National Legislative address strongly geared towards e-mobility • Lack of National and Regional financial instruments for new policies • Limited competitiveness • High car ownership and congestion • Lack of needed funds to implement new infrastructures and technologies • Lack of true electrical corridors and recharge station infrastructure
Opportunities	**Threats**
• Contribution to the Paris Climate Change Agreement • Support of EU Directives • New building regulations help to develop EV-charging networks • National Strategic Framework for e-infrastructures • Three Year Plan for National Electricity Research • An increasing number of EV models on the market • Growing EV popularity	• High costs of EVs as a barrier of broad market penetration • Limited EV-charging infrastructure • Still very low degree of internationalization of enterprises • Strong dependence on traditional energy sources (oil products)

3.2.2. Lithuania

EVs and e-mobility is a relatively new topic in Lithuania; therefore, the political strength is that the government and municipalities are aware of these topics and provide their support. The businesses and IT-related sciences are willing to take part in the whole process. Businesses have good connections with major EV developers. Additionally, Lithuanian authorities promote the use of EVs by allowing them to use the bus and taxi lanes as well as providing free parking within any of the cities' paid parking zones. From an economic perspective, although EVs are not so favorable in Lithuania, active business actors exist. On a national level, the Ministry of Transport and Communications allocated a specific budget for EVs and their infrastructure. On a household level, the ownership of cars is high and people are aware of the maintenance costs—EVs have lower maintenance costs compared to gas/diesel-powered vehicles (gas price, oil change, engine repair, etc.). Another motivation is the growing use of smartphones. Successful integration of ICT, EVs and smartphones, growing car-sharing schemes and similar initiatives motivate people to use sustainable transport. Furthermore, an EV-supporting website, for example, https://elv.lt, has recently been developed in order to increase a public awareness of EVs, maintenance services, charging stations, etc.

Unfortunately, Lithuania experiences a series of weaknesses in all domains. The most important political issues are the absence of a common EV policy and strategy at a national level, which limits initiatives at local and regional levels, and creates a lack of political will and knowledge at a local level. Limited coordination and cooperation between ministries, a lack of responsibility for EV-charging infrastructure, and the absence of permanent legislation and politics are further problems. In general, the high purchase price of EVs and their batteries are probably the most significant problem in Lithuania, limiting EV popularity. A lack of vehicle taxation mechanisms motivates people to use second-hand vehicles, which have a strong demand in Lithuania.

Additionally, there are very few sustainability-promoting procurement options, which would help reduce high costs of EV-charging infrastructure and limit companies and staff capable of providing full EV services. Considering the social weaknesses, most Lithuanians have a limited income and prefer large, sophisticated, diesel vehicles. Probably the most important technology-related issue in Lithuania is limited EV-charging infrastructure, especially for intercity travel. The growth of EVs is a great opportunity for Lithuania and a registration tax for high pollution-emitting vehicles powered with diesel/petrol/gas has already been initiated. According to the law on motor vehicle registration tax (published in December 2019), the vehicle registration fee will come into force in July 2020. The fee will range from 13.50 to 540 euros, depending on the type of vehicle and CO_2 emissions, if they exceed 130 g CO_2 per kilometer.

An increase of EVs in Lithuania would also dramatically rejuvenate the national car pool, and would help reduce dependence on oil products. Additionally, EVs give new opportunities for business and science in the development of new markets, and increase car-sharing competitiveness, additional subsidies, and support mechanisms. From an economic/environmental perspective, the EV market would enable the trade of surplus in allowances, pollution permits, and use emission trading schemes, while Sustainable Urban Mobility Plans (SUMP) guidelines and development funds give new opportunities for smaller municipalities to obtain additional funding. An increase of EVs would require EV-charging stations, which could be installed around communal blocks and flats— this would improve space management concerning apartment structures. By 2022, the Lithuanian Road Administration and local municipalities will install a network of public access EV chargers. A great opportunity for Lithuania is that the development of EV-charging networks would not only connect major traffic arteries in the biggest cities, but would also imply a renovation of the power grid.

From an environmental perspective, e-mobility would help reduce air pollution and noise in the cities caused by internal combustion engine vehicles powered by petrol or diesel. EVs could be promoted by establishing low emission zones around city centers and limit the access for high pollution and freight vehicles.

The market of EVs, REs, and ICT in Lithuania has a list of foreseen threats. First of all, EVs and their infrastructure in Lithuania do not have much political support; such political decisions are lagging behind other EU states. The national legislation distorts EU recommendations and formulates a negative opinion about the EU. At the same time, EU subsidiary rule prevents a common standard among all EU Member States. There is no single body responsible for EV-charging infrastructure development; therefore, missing coordination leads to fragmented and delayed growth. The legislation and documentation should also be improved, as there are no EV-charging operator rules, and installation requirements are unclear. The number of potential economic threats in Lithuania increases the risk of successful e-mobility integration. Lithuania alone has very limited possibilities to fund EV and e-mobility development. Most of the initiatives are funded by the EU; consequently, funding could be provided due to the fact that Lithuania is among the five EU countries which do not have subsidies for EVs. Regarding the average household, people prefer to have a cheap second-hand vehicle than an expensive EV. Moreover, although the second-hand vehicle market is strong in Lithuania, there is a risk that second-hand EVs will be more expensive than fuel-powered cars. A structured integrated SWOT and PESTEL analysis of Lithuania is presented in Table 4.

Table 4. Integrated SWOT and PESTEL analysis for EV, RE and ICT sectors in Lithuania.

Strengths	Weaknesses
• Bus and taxi lanes for EVs	• Systematic approach to power demonstration
• Ministry support	• The old age of the vehicle fleet
• Good business connections with major EV development companies	• The absence of common EV policy and strategy
• Strong positions of businesses and science in IT	• Lack of cross-ministry coordination and cooperation
• Community activity in transport issues	• Low quality and unclear documentation regulating EVs
• Competent vehicle restoration and repair businesses	• Lack of body responsible for infrastructure development
• Allocated budget for e-mobility	• Lack of permanent legislation and politics
• Low maintenance costs of EVs	• High purchase prices of EVs and batteries
• Growing smartphone use	• Unknown approaches of traditional vehicle conversion to EV
• Cost-competitive EVs in car share schemes	• Strong secondary market of old gas/diesel-powered vehicles
• High car ownership	• Minimum taxation of vehicles
• Developed EVs' prototypes by universities	• Lack of sustainable/green procurement
• Universities working on e-mobility technologies and applications	• Low public awareness of EVs
• Planned EV-charging network	• Low resident purchasing power
• High awareness of traffic-related environmental impact	• Prevailing attitude on large, sophisticated, diesel vehicles
• The share of passengers' cars powered by alternative fuels is 17%	• Undeveloped EV-charging infrastructure
• Supporting EV websites	• Limited cooperation between municipalities and universities
Opportunities	**Threats**
• Unified and universal rules for EV-charging stations	• Lack of political support
• Support mechanisms and subsidies	• Disagreement between national and EU legislation
• Collective municipal actions	• Fragmented EV growth
• Rejuvenation of national car pool	• Maintenance of free public EV-charging financed by all taxpayers
• Independence from fast depleting petroleum	• Lack of EV-charging operator rules
• Businesses and science engagement in the development of new markets	• EV-charging station installation requirements unclear
• Registration tax for gas/diesel/petrol-powered vehicles	• The disadvantage of EU subsidiary rule
• Car share competitiveness	• No single body for infrastructure development
• Trade in surplus allowances of EVs	• Lagging political decisions
• Sale of surplus pollution permits	• No direct income from EV promotions
• Opportunities to obtain SUMP development funding	• Reduced fuel consumption reduces excise tax income
• Understanding of sustainable transport benefits	• The strong second-hand vehicle market
• Available support mechanisms and subsidies	• Limited EU funding for public transport modernization
• Low emission zones and their accessibility	• Limited national funding for EVs and e-mobility
• The planned network of public EV-charging stations	• Lithuania, one of five countries without subsidies for EVs
• Better control and management of communal space around residential blocks	• The uncertainty of retrofitting of used EVs

3.2.3. Spain

Spain is an advanced country regarding RE, and Barcelona is a leading city in e-mobility. It has a high number of plans, incentives, and projects, which helped to gain valuable experience in the sectors of EVs, RE and ICT. Another strong aspect in Spain is a comprehensive political and financial support for the development of EV-charging infrastructure. Regarding the average household, Spain has a list of financial initiatives, which lower EV purchase and maintenance costs, where most of the EV customers are concentrated around Barcelona. It can be seen as a positive aspect because developed infrastructure gives better access to recharge EVs. From another point of view, the concentration around Barcelona shows great territorial imbalances and limitations of EV use, ICT and RE developments. Moreover, Spain experiences a high solar radiation, compared with the rest of Europe, this represents a great potential for solar photovoltaic (PV) electricity generation. Despite a number of strengths, EV, RE and ICT sectors experience many weaknesses. In political terms, the general problem is that decisions are quite fragmented. Another problem is that only one actor in Spain is qualified to charge for reselling energy. This can limit fair competitiveness in all energy-related sectors. Furthermore, in Spain, the R&D of the RE in private companies is the lowest among European countries. Although the EV-charging and RE infrastructure are well developed, limited finances slow down the development of new infrastructure and technologies. For the average household, most people purchase gas/diesel-powered vehicles. EVs and hybrids only have 0.4% of the market share. Additionally, people miss public information about the advantages of EVs and e-mobility.

Besides the identified strengths and weaknesses, the sectors of EVs, RE and ICT offer many opportunities. At international and city levels, the use of such advanced technologies is a very positive advertisement for the city and country itself. Barcelona, for instance, is a city which hosts a high number of congresses and expositions, e.g., Expoelectric, the most important event in southern Europe bringing together enthusiasts and companies from the entire world. Among the economic opportunities are the growing investments and positive market developments, such as price decrease of solar energy (by 80% in the last six years) and an increase of EV owners. From a social point of view, technologies improve the quality of life—decreasing air pollution in Barcelona reduces deaths and illnesses caused by bad air quality, and positively changing mobility patterns increases people's health.

Among the main political threats are the missing facilitating regulations, standards, training and framework for implementation as well as various barriers for public access to EV-charging stations. The technical side would have even more threats. Firstly, although much of EV-charging infrastructure is newly developed, it could be obsolete soon because of the rapid technological advancement. Secondly, the local power distribution is weak (already mentioned in the list of weaknesses). Thirdly, the energy sector does not have many control mechanisms to store surplus energy, and to generate additional energy during high demand. A structured integrated SWOT and PESTEL analysis of Spain is presented in Table 5.

Table 5. Integrated SWOT and PESTEL analysis for EV, RE and ICT sectors in Spain.

Strengths	Weaknesses
• Strong political and financial support for EV-charging infrastructure's development • Number of initiatives for EVs' purchase and cost- saving • The high potential of solar PV integration in electricity production compared with the rest of Europe	• Irregular investment cycles • Private company spending of R&D of RE is lowest in Europe • Low share of purchases and ownership of EVs and hybrids compared to gas/diesel-powered vehicles • Mobility and congestion in Barcelona Metropolitan area has increased • Missing public information on the advantages of e-mobility • Limited experience with smart grid projects • Limited infrastructure and EV service capacities • High dependence on natural gas due to high accessibility in the cities
Opportunities	**Threats**
• Keep the positioning of Barcelona related to e-mobility and smart grids • Contribution to the reduction of greenhouse gasses in Europe • Growing investments • Positive market developments • Improved life quality • A higher share of locally-generated energy in Barcelona • PRIVEC initiative to develop EV-charging infrastructure • Acceleration and motivation of R&D in the energy sector • Easier introduction of new RE producers due to power grid regulations	• Political issues regarding public accessibility and facilitation • Smart grid integrity is not territorially-balanced • Price of electricity highly dependent on the price of natural gas • Resistance from car owners to use the car battery for temporary energy storage • Misinformation among citizens regarding EVs • The negative impact of Catalonia's investments in hydrogen fuel cell vehicles • Current EV-charging infrastructure can be outdated due to technological advancement • RE dependency on changing the weather and seasonal patterns • Higher purchase costs of ICT tools • Weak local power distribution • Limited control of peaks and shifts in power demand • Emissions of EVs depends on electric mix

3.2.4. Sweden

The strengths of political aspects in Sweden are solid agreements between political parties on the importance of energy and climate transition towards fossil-independent systems. There is a high number of ambitious goals, programs and plans. For instance, the city of Stockholm supports EV-charging station installations by giving public street space to companies building them. From an economic perspective, Sweden has implemented a number of subsidy and tax reduction mechanisms for EVs; meanwhile, the EV fleets and power procurement options are already in place. Although the higher concentration of EV customers around Stockholm has a positive effect (concentrated services and infrastructure give better accessibility), another part of the Stockholm region might have weaker preconditions for a massive introduction of EVs due to lower household incomes and less charging infrastructure. A high advantage that Sweden has regarding e-mobility is that the power grid used for the EV-charging network is powered mostly by RE, which helps the city of Stockholm to move towards a zero-emission society.

The main political weakness in Sweden is due to different goals and ambitions between state, local municipalities and businesses. For instance, mitigation goals of the transport sector disagree with political budgets on all levels—from state to regional and municipal level. Another problem is a lack of political steering on a national level to promote rural areas more actively. Therefore, although an EV-charging infrastructure network is developed, most of the infrastructure is concentrated on city centers, leaving rural areas offside. Addressing economic-related issues, the highest economic concern in Sweden is that with the higher EV popularity, a need of investments increases as well. Another challenge is that companies expect a high return of investments, while at the same time, the second-hand value of EVs still is rather uncertain. This increases the risk of a lack of profitability, not only when it comes to EVs, but also in ICT and the RE sector, where technological advancement is fast. In addition, people miss information about advantages of e-mobility and payment possibilities. Additionally, they are concerned about privacy, which might be violated through open data used in e-mobility and ICT.

A political opportunity in Sweden related to EVs is that the costs can be shared between stakeholders, which could lead to a faster EV introduction. While a number of potential incentives and smart city or grid initiatives give great possibilities for a successful EV, RE and ICT integration. People in Sweden are eager to produce their own energy and use it on their own mobility. This also encourages the creation of small local power production facilities, which in turn create jobs and increase the sustainability of local communities. If such communities have car-sharing or carpool systems, it is even better. Technical-related opportunities in Sweden address new ways of street and city design, electricity-supplied rapid transport systems, quick technology development and easier access to the RE market for new players.

Although Sweden has a high number of initiatives, there is still the need for public incentives and more user-friendly rules, e.g., parking facilities and local energy production taxation. Another possible threat is that affordable EVs might increase mobility and traffic congestion and reduce the use of public or other types of transport (e.g., walking, cycling). Therefore, a modal shift is essential in order to encourage more sustainable modes of travel. Furthermore, another problem is that the local power supply in parts of the Stockholm region is too weak for a massive introduction of EVs. Parts of the local power supply might experience a lack of enough power effect and thereby a certain instability of the system. A structured integrated SWOT and PESTEL analysis of Sweden is presented in Table 6.

Table 6. Integrated SWOT and PESTEL analysis for EV, RE and ICT sectors in Sweden.

Strengths	Weaknesses
• Clear targets of the agreements between government and agencies • EV stimulation has been politically accepted by regions and municipalities in the form of plans, targets, and incentives • Good financial support for the development of EV-charging network • Stockholm's initiative to install e-chargers and allocate parking places for no costs • National organizations and agencies promote ICT and EVs • Subsidies and tax reduction for EVs • EV fleets and power procurement options are already operational • E-mobility contributes to silent and healthy cities • Positive attitude and lifestyle change • Higher environmental awareness and consciousness • Higher customer concentration around Stockholm • People's willingness to support the environment • Electric and autonomous vehicles can increase public transport service coverage • The power grid required by EV-charging network is already developed • Most of the power in Sweden is renewable	• Many ambitious political decisions experience difficulties • Transport policy does not match with the economic and political decisions • High technology advancements increase risks of profitability • High investments, purchase price and operational costs limit use of EVs • EVs have a high exception on the return of investments but the low expected second-hand value
Opportunities	**Threats**
• Costs of the EVs can be shared between partners • Synergies between political levels can reduce risks and costs • Tourism – a possibility to show EV advantages • Development of national supercharger network • Cheaper public and freight transport due to sharing economy • The good economic potential with light EVs • Possibility to produce "own" fuel (electricity) • Local electricity production creates jobs • Easy entry of new RE producers due to good power grid regulations	• Conflicts between business economy and environmental needs • Procurement model for municipalities is an obstacle for EVs • Budget limitations for high EV costs • Subventions for fossil-based economy • Affordable private mobility solutions are a threat to public transport, walking and cycling • Habits and attitudes are difficult to change • Weak power distribution locally • Lower power supply security when uses from local sources only • Rapid technology advancement has a risk to be outdated

3.2.5. The Netherlands

In a recent report of International Energy Agency, the Netherlands is the second EV market—after Norway—with up to 6.4% EV market share [46]. This was the result of a favorable environment policy in recent years, ranging from incentives, tax reduction, CO_2-based taxation, and citizen involvement.

The Metropolitan Region of Amsterdam is considered to be one of the most dynamic regions in relation to the development of new cross-sector policies and the subsequent implementation of initiatives that aim to transfer knowledge and experiences between European cities.

When looking at the development of integrated policies for sustainable energy and e-mobility, the Province of Flevoland has a lot of opportunities to influence existing policies and develop new ones. From a political aspect, various existing policies are supporting Flevoland's ambition in increasing the share of RE.

From an economic point of view, an ongoing trend enables the price of solar PV technology, EVs, and EV-charging equipment to drop, compared to the previous year. This opportunity will benefit the roll-out of such strategies and hence, meeting the objective more rapidly.

When it comes to the social aspect of sustainability performance, the province of Flevoland is involved in various projects with different purposes. However, the integration of energy in Flevoland is limited. Hence, EV ENERGY integrates scopes that define Flevoland's energy and mobility ambition. Another level of social cooperation is the stakeholders. They represent the key towards the successful implementation of an initiative or projects. For the Province of Flevoland, it is materialized through multi-stakeholder cooperation, where every expertise will improve the overall end goal. For example, with the initiative of PowerParking, business, knowledge partners and public administration are gathered to exchange and cooperate for a common result.

The region is expressing more and more awareness for the need of an integrated energy system, with further opportunities to balance the grid. Technological innovation lies in the renovation of a more modern energy network, which is of crucial importance for the implementation of energy and ICT innovations. There is a growing interest for (temporary) energy storage from energy companies, as well as a new business model for second-life batteries. For instance, Amsterdam ArenA has partnered up with Nissan for a 10-year deal to provide back-up power from used Nissan LEAF batteries. Amsterdam ArenA stated that using Nissan LEAF batteries, the system designed for the Amsterdam ArenA project, will be the largest energy storage system powered by second-life batteries used by a commercial business in Europe and will have four megawatts of power and four megawatts of storage capacity. This incredible public and private partnership is providing financial, energy and new business model opportunities for a lot of stakeholders throughout Europe and the world. From an environmental perspective, a Dutch carpark is responsible for 12% of the total CO_2 emissions in the Netherlands, while one goal is to reduce this emission by 17% in 2030 and by 60% in 2050 compared to 1990. A structured integrated SWOT and PESTEL analysis of the Netherlands is presented in Table 7.

Table 7. Integrated SWOT and PESTEL analysis for EV, RE and ICT sectors in the Netherlands.

Strengths	Weaknesses
• Strong sustainability goals of Flevoland (in 2030—energy neutral, transport included) • Active policy framework for solar PV promotion goals (goal is to create space for 1000 ha PV) • Part of the MRA Elektrisch programs to develop the charging infrastructure in the provinces Noord-Holland, Utrecht, and Flevoland • Running projects of PowerParking and energy storage • Culture of close public-private cooperation • Regional inventory on the possibilities to combine wind parks and road infrastructure with PV	• The complexity of integrated energy projects shows to be slow process • Limited stakeholder cooperation • Limited experience with integrated energy projects
Opportunities	**Threats**
• Spacious cities: large surfaces in the cities available for PV and for solar carparks • Decrease of PV, EV and charging equipment prices • Interest for (temporary) energy storage is raised by energy companies • The market for second-life batteries is developing • Funding opportunities • Presence of a large number of lease companies in the province (Athlon, LeasePlan) • Relatively modern energy network	• Unstable/short-term national policies regarding EV support (no favorable conditions for hybrid cars anymore) • A large part of PV installation in rural areas → Connection with EV not so obvious • Concerning EV promotion: lack of awareness among citizens, charging infrastructure is still limited

4. Conclusions and Discussions

This paper has presented SWOT and PESTEL analyses of EV, RE and ICT-related policies and initiatives in five European regions. Various policies were overviewed and collected not only at the national and local levels of the analyzed countries, but also at EU and international levels. Meanwhile, only selected policies were inventoried and investigated in this paper. Based on policies and initiatives, the integrated SWOT and PESTEL analyses have been done.

Besides EU directives, regulations and documents, EVs, e-mobility, RE, spatial planning and social awareness in the analyzed countries are affected by national and local policies. Most of these national policies in the Netherlands and Sweden are related to a high number of privately-supported initiatives and incentives; meanwhile, there are only a few such initiatives in Lithuania, Spain and Italy. Lithuania has very limited private support, therefore, the sector mostly relies on national strategies and programs. On a local level, cities in all analyzed countries have relevant innovative plans and motivation.

Good initiatives such as successfully-applied projects from different regions are intended to be shared with other EU countries. For instance, the Netherlands and Italy emphasize EV stimulation projects; meanwhile, Lithuania and Spain have experience in increasing cooperation between the public and private sector or society. Self-efficiency is highly appreciated in the Netherlands and Spain. Other good examples are the funding programs (Sweden and Italy), public transport (Lithuania and the Netherlands), and the development of charging infrastructure (Spain and Italy). Additionally, countries have successful projects in EVs and solar PV integration and flexible energy systems (the Netherlands), websites for EV users (Sweden, Lithuania), changes of vehicle fleets to EVs and family/location-oriented smart projects (Sweden), increasing company efficiency and competitiveness, improvement of public policies (Spain), and developing EV-promoting legislation (Italy).

Considering the main drivers and barriers, possibilities and risks related to e-mobility policies and initiatives, each country has different features, which have been identified in this paper. Sweden, for instance, has many plans and incentives, good financial support for EV-charging infrastructure and tax reduction measures for EV users. The EV-charging infrastructure and RE sector are already well-developed, and many people use EVs daily. The main barriers in Sweden are typical for other countries—expensive EVs for households, limited possibilities to deal with high energy demands and risks towards profitability. Lithuania has to brace up in order to compete with other countries. Due to the low purchasing power, limited EV-charging infrastructure and a strong second-hand vehicle market, EVs are not so popular. Private initiatives are very limited, as well as national funding and EV-friendly legislations. Although the RE sector is well-developed, compared to other regions, EV-charging infrastructure in Lithuania is limited. Therefore, to most of its strengths, Lithuania responds with measures on a planning level—high governmental awareness and activity by municipalities, interest from business and science, good business connections with developers, and planned infrastructure. EVs are new in the market of Lithuania, so it might open new opportunities, such as implementation of registration tax for gas/diesel/petrol-powered vehicles, rejuvenation of car fleets and municipalities as test pilot areas for electric and autonomous vehicles. Spain and Italy have similar features. Both countries have a high number of initiatives, favorable legislation, good financial support, experienced stakeholders, a well-developed RE sector and appropriate taxation measures. The main problems both countries identified are fragmented political decisions, weak relations between the public and private sector, and limited private investment into R&D. Comparing all five European regions, the Netherlands has the greatest experience in EV-related projects and highest technology advancement. It is followed by Sweden, where government and households are more and more interested in the adoption of EVs. Spain and Italy have a number of initiatives, but they experience some difficulties which might slow down their ambitious plans. Finally, Lithuania, with the lowest purchasing power and a high market of used vehicles has a lot to learn from others, but might have a great potential if national-level incentives will continue. However, local authorities of EU countries still seem to be unprepared to optimize strategies for effectively interconnecting RE resources with the electric grid. This does not bode well for the EU that drives car production in the world. Despite the aforementioned limitations, the five analyzed EU countries are going towards positive changes in EVs, RE, ICT policy and practices in order to promote environmentally benign mobility in a city's transport system.

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Comparative environmental life cycle assessment of electric and conventional vehicles in Lithuania

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ABSTRACT

Electrification of city transport and the use of renewable energy sources (RES) in transport systems have become leading trends for sustainable transportation. Many researchers state potential environmental benefits of electric vehicle (EV) when integrating RES into production of electricity, which is needed to recharge the EV's battery. However, it is still unclear under what electricity mix scenarios environmental advantage will be the most significant and what technologies/fuel type have a major impact on the environment. For this reason, the article presents a comparative environmental life cycle assessment (LCA) of a battery electric vehicle (BEV) and internal combustion engine vehicles (ICEVs) fuelled with petrol and diesel. Besides, LCA of BEV under different electricity mix scenarios, that are prognosticated for the years 2015 2050 in Lithuania, is assessed. The paper shows a complete life cycle, composed of "Well-to-Wheel" and "Cradle-to-Grave" analysis for conventional and electric vehicles. This study uses ReCiPe methodology including both midpoint and endpoint indicators in order to express the impact on the environment. The results at the midpoint level reveal that in terms of climate change BEVs of 2015 electricity mix generate 26 and 47% more greenhouse gas emissions than those of ICEVs fuelled with petrol and diesel, respectively. Although in 2020 2050 electricity mix scenarios oil is expected to be eliminated and the use of RES will be highly increased, ICEV-petrol is expected to be the most polluting, comparing to ICEV-diesel and BEV in 2020 and later scenarios. Similar results are revealed at the endpoint level, as ICEV-petrol has the highest environmental damage in all categories: human health, ecosystems and resources. Next comes ICEV-diesel with 28% less total environmental damage, followed by BEV of 2015 electricity mix with 42% less impact than ICEV-diesel. Finally, BEV with electricity mix of 2050 has 54% smaller impact than BEV with electricity mix of 2015.

1. Introduction

Worldwide electric vehicles (EVs) are promoted as future transport that have potential environmental benefits in order to promote sustainable urban transportation. In particular, light-weight battery electric vehicles (BEVs) are the most popular models catching global attention and have huge integration possibilities in city transport systems. In 2017, registration of electric cars reached over 1 million sales worldwide. Therefore, the world stock overtook 3 million electric cars in 2017 and increased by 54% compared with 2016 (International Energy Agency, 2018).

Lithuania, as a country of the European Union (EU), is encouraging the electrification of road transport as well. In 2015, Lithuania adopted guidelines for the development of EV public charging infrastructure. One of the goals mentioned in the guidelines is to achieve that 10% of all the new purchased cars would be electric by 2025. Another important goal is to install at least 100 public electric vehicle charging stations in cities and suburbs of Lithuania with more than 25,000 inhabitants by the end of 2020 (Order of the Minister of Transport and Communications of the Republic of Lithuania, 2015). The growth of BEVs and hybrid electric vehicles (HEV) in Lithuania is presented in Fig. 1.

Fig. 1 shows the increasing numbers of both BEV and HEV according to vehicle registration statistics. HEV and BEV account for 1.05% and 0.07%, respectively, of all the registered passengers' cars in Lithuania, while diesel (68.11%) and petrol (23.39%) cars occupy the largest market share (State enterprise "Regitra", 2019). Low EV growth is due to some weaknesses that Lithuania is experiencing: low purchasing power of residents; high global prices of EVs; prevailing secondary market of old vehicles; the lack of initiatives

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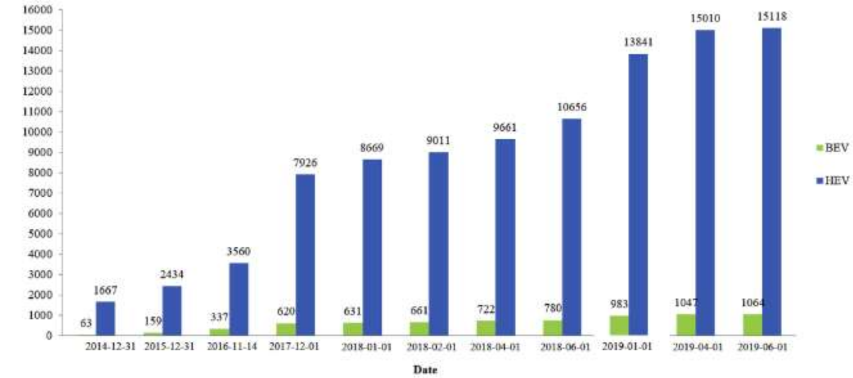


Fig. 1. Total number of registered passenger electric and hybrid electric vehicles in Lithuania (State enterprise "Regitra", 2019).

and competences in a substantial part of common municipalities, etc. (Raslavičius et al., 2015). Nevertheless, Lithuania has also implemented some tools in order to encourage the usage of EVs, such as the possibility to drive on specially marked public transport traffic lanes in the capital city Vilnius or exemption from parking and entry fees in many Lithuanian cities (Ministry of Transport and Communications, 2019). In addition, there is an EV supporting website created: https://www.elv.lt, which helps EV drivers to find information about charging stations, electric car sharing or renting services, car repair services, etc. (Public institution "Aplinkos apsaugos institutas", 2019).

From the environmental perspective, e-mobility would help to reduce environmental pollution and noise. The extensive need of BEVs integration into the city transport system is caused by the EU road transportation sector, which has not reduced greenhouse gas (GHG) emissions by 2016 compared to the 1990 level (European Environmental Agency, 2016). Moreover, European Environmental Agency also stated that road transport GHG emissions are 16% above the 1990 level. In addition, in 2016, road transport had a 72% share of transport GHG emissions (European Environmental Agency, 2016). Another big concern about road transport is the air pollution that it causes. Road transport air pollutants include: gaseous pollutants (e.g. SO_2, NO_x, CO, ozone, VOC), persistent organic pollutants (e.g. dioxins), heavy metals (e.g. lead, mercury), particulate matter. Air pollution has both acute and chronic effects on human health, affecting a number of different systems and organs (Kampa and Castanas, 2008). Furthermore, noise is another health problem caused by road transport that should be of serious concern. As reported by the NOISE Observation & Information Service, road traffic is the main source of environmental noise in Europe. Noise levels from roads that exceed 55 dB L_{den} (day, evening and night periods) affect an estimated one in four people in Europe (European Environmental Agency, 2019). One of the key goals in the EU White Paper (2011) is to forbid all conventionally-fuelled cars in cities by 2050. This would help contribute to cutting transport GHG emissions by 60%, compared to the 1990 level, by 2050 (European Commission, 2011). BEVs do not have an internal combustion engine; therefore, they do not emit direct air pollutants to the environment.

Moreover, EVs would be even more advantaged if electricity was produced by renewable energy sources (RES) (Bellocchi et al., 2018). In the EU, the share of RES in gross final energy consumption reached 17.5% in 2017 (from 8.5% in 2004). In the EU transportation sector, RES amounted to 7.6% in 2017 and increased by 6.2%, compared to 2004 (EUROSTAT. Statistics explained, 2019). Besides, the growth in electricity generated from RES (2007 2017) largely shows an expansion in wind, solar power and solid biofuels (including renewable wastes) (EUROSTAT. Statistics explained, 2019).

In terms of RES integration in Lithuania, according to the directive 2009/28/EC of the European Parliament and of the Council on the promotion of the use of energy from RES, Lithuania is committed to reach 23% of RES share in total final energy consumption of the country by 2020 and this target is met with 25.83% in 2017. Besides, the share of RES compared to final energy consumption in the transport sector should be increased to at least 10% in all modes of transport, yet unfortunately, the goal has not been reached, with 3.69% in 2017 (Ministry of Energy of the Republic of Lithuania, 2019). Moreover, in 2018, Seimas of the Republic of Lithuania approved an updated version of the National Energy Independence Strategy, where the desired results in Lithuanian energy sector in 2020, 2030 and 2050 are stated. One of them is to increase the share of electricity consumed from RES compared to final electricity consumption to 30% by 2020, 45% by 2030, and 100% by 2050 (Seimas of the Republic of Lithuania, 2018). This is an ambitious goal, considering that the share of renewables in the electricity mix of final consumption reached 18.25% in 2017 (Ministry of Energy of the Republic of Lithuania, 2019).

In addition, other research studies revealed that when EVs are charged with electricity generated by RES, it can lower the global warming potential by 20 24%, compared with ICEVs fuelled with petrol and by 10 14%, compared with ICEVs fuelled with diesel (Hawkins et al., 2013). Besides, Faria et al. (2013) did a LCA of an EV in three different countries (Poland, France and Portugal) and found that the biggest air pollution by an EV will be caused in Poland, where most of the electricity is produced from coal, while France had the best results where electricity is mainly generated in nuclear plants. Athanasopoulou et al. (2018) revealed similar results that BEVs are advanced than ICEVs in countries with high ratio of nuclear or RES in their electricity production mix, while electricity generation from fossil fuels, especially oil and coal is the main factor that directly increases the GHG emissions of BEV's operation stage. Souza et al. (2018) evaluated and compared the environmental impacts of vehicles in the Brazilian context, which showed that BEV had minor environmental impacts in general. It was also stated that Brazilian government should increase its investment and develop the use of EVs, since the country's electric mix is from RES.

According to the National Energy Independence Strategy of Lithuania, one of the goals is to achieve that all electricity consumed in Lithuania would be produced from local renewable sources by 2050. This would mean that Lithuania's plan to promote e-mobility would be progressive, taking into account that RES is the most environmentally friendly choice to charge EVs.

According to Hauschild et al. (2018), successful implementation of EVs in the automotive market depends on three key factors: costs, customer satisfaction and engineering performance. In this regard, the environmental impact of an EV plays an important role towards its market acceptance and is one of the main reasons for their development in the first place. For this reason, LCA in the field of (electric) mobility can be used to answer such challenges: 1) comparisons between different types of EVs and ICEVs; 2) the effect of the energy mix used to power vehicles; 3) the evaluation of weight reduction strategies; 4) the analysis of the contribution of the traction battery to the overall environmental impact of an EV; 5) the analysis of disposal scenarios, mainly regarding the treatment of the main components, especially batteries, electric motors and car body (Hauschild et al., 2018).

There are research studies that have been carried out regarding LCA of BEV and ICEV in individual countries: Belgium (Van Mierlo et al., 2017), Brazil (Souza et al., 2018; Choma, 2017), Canada (Bicer and Dincer, 2018), China (Qiao et al., 2019; Shi et al., 2019; Wu et al., 2018; Ke et al., 2017), Czech Republic (Burchart-Korol et al., 2018), Greece (Athanasopoulou et al., 2018), Italy (Del Pero et al., 2018), Japan (Kosai et al., 2018), Poland (Burchart-Korol et al., 2018), Sweden (Nordelof et al., 2014), Switzerland (Bauer et al., 2015; Yazdanie et al., 2014) U.S. (Onat et al., 2015, 2018), etc.

However, no study has yet been performed related to LCA of passenger's electric and conventional cars in the Lithuanian context. Therefore, the goal of this study is to evaluate and compare the environmental impacts of electric and internal combustion vehicles in Lithuania. Furthermore, to analyse the BEV's operation stage under different electricity generation scenarios that are forecasted for the years 2015 2050 and to assess the most preferable electricity mix scenario and generation technologies under which the environmental load would be the least.

This study uses the LCA method to calculate and compare the impact on the environment throughout the life cycle from BEVs and ICEVs fuelled with petrol and diesel. Additionally, the LCA of BEV was performed under different scenarios, including different electricity mixes and electricity generation technologies prognosticated for the years 2015 2050 in Lithuania. Moreover, environmental emissions from generating 1 kWh electricity are presented in order to show which source of electricity production is the most polluting and which one is considered the most environmentally friendly.

This research is novel firstly because it provides a comprehensive, comparative analysis that considers the performance of both commercially new vehicles with multiple electricity generation pathways and forecasts of changes in the energy systems for the period 2015 2050. Secondly, it applies directly to the Lithuanian situation; and thirdly, the analysis offers a unique comparison of LCA results for BEVs and ICEVs, which have been obtained by other authors.

2. Methodology

Life cycle assessment (LCA) is a methodology to quantify the potential environmental impacts associated with the product, process, or activity throughout the product's life cycle. The LCA study of electric and conventional vehicles was carried out following the procedure and recommendations indicated in the European standards series ISO 14040 and ISO 14044 (ISO 14040, 2006; ISO 14044, 2006). In accordance with the standards, the LCA analyses were performed in the following main steps:

1) Definition of the goal and scope of the study; identification of functional unit and system boundaries.
2) Life-cycle inventory analysis.
3) Life-cycle impact assessment and interpretation.

2.1. Goal, scope of analysis and life cycle impact assessment method

The goal of the LCA was to evaluate and compare the environmental impacts associated with the production, use and disposal of electric and conventional vehicles. For comparing the environmental emissions of different vehicles, a functional unit of "1 km driving distance" is determined. Electric vehicles are assumed to have an average lifetime of 14.1 years with the total mileage of about 150,000 km. Therefore, this research assumes that both ICEV and BEV can drive 150,000 km as the baseline and the environmental impacts are calculated for such a life cycle ensuring that no battery replacement is required.

The scope of this analysis represents a "complete LCA", which includes the fuel cycle as "Well-To-Wheel" (WTW) analysis and the vehicle life cycle that follows a "Cradle-to-Grave" approach. The WTW stages cover energy resource extraction, energy carrier production and distribution as well as energy conversion in the vehicle. The equipment life cycle or "Cradle-to-Grave" analysis covers materials production, equipment manufacturing, maintenance, end-of-life of vehicle and road infrastructure. The final stage the end-of-life involves dismantling and recovery of vehicle's parts, also shredding, recycling and disposal of residues. The system boundaries of a complete life cycle are presented in Fig. 2.

The results of the LCA are presented in three combined phases: production, use and disposal. These phases with BEV and ICEV flows are elaborated in Fig. 3.

The phases include vehicle and battery production, operation, maintenance, disposal and the road infrastructure. The operation of the vehicles included all the direct emissions caused by fuel combustion (for ICEVs fuelled with petrol or diesel) and non-exhaust emissions, which are emissions resulting from brakes, tires and road wear.

BEVs do not exhaust direct emissions during operation, but it is very important how the electricity for charging the battery is produced. Therefore, the indirect impact on the environments is generated. For this reason, the boundary of the BEV flow covers the individual electricity mix in Lithuania from 2015 to 2050 that is simulated and prognosticated by Lithuanian Energy Institute (2017). As a result, this study uses the LCA method to calculate and compare the environmental impact of BEV in 2015, 2020, 2025, 2030, 2035, 2040, 2045 and 2050, including different electricity mixes and electricity production technologies in Lithuania.

In this study, the ReCiPe method at the midpoint and endpoint levels is used to perform the impact assessment based on ReCiPe 2008 by Goedkoop et al. (2013) and an updated version ReCiPe 2016 by the National Institute for Public Health and the Environment (2017). In terms of the environmental impact categories at the midpoint, climate change, human toxicity, ionising

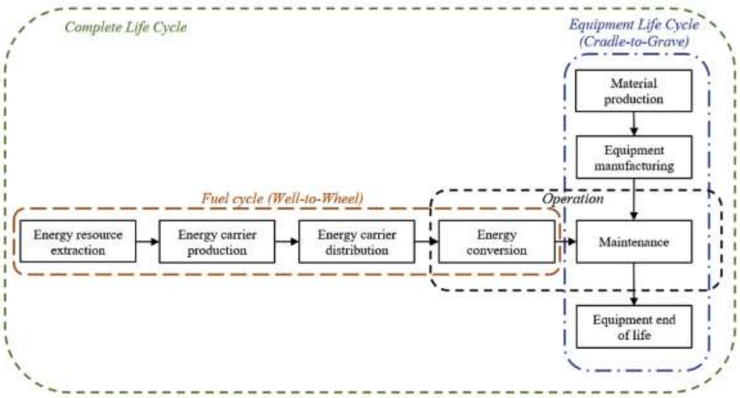


Fig. 2. System boundaries including fuel and equipment life cycle (adapted from Nordelof et al., 2014).

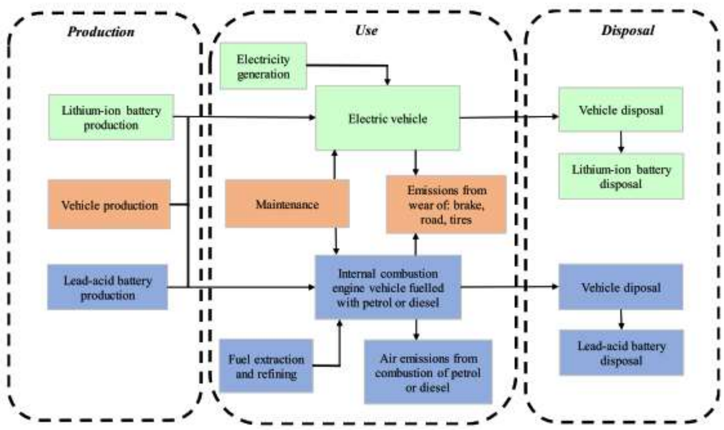


Fig. 3. Detailed production, use and disposal phases of BEV and ICEV (green background for BEV, blue for ICEV and brown for both) (adapted from Burchart-Korol et al., 2018). (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

radiation, metal depletion and fossil depletion are determined according to the categories where the burden was the greatest in the analysis. At the endpoint level, three higher aggregation levels are assessed: effect on human health, ecosystem quality and resource scarcity. The unit for human health damage (DALYs (disability adjusted life years)) represents the years that are lost or that a person is disabled due to a disease or an accident. The unit for the ecosystem quality (species · year) is a local relative species loss in terrestrial, freshwater and marine ecosystems, respectively, integrated over space and time. The unit for resource scarcity ($) represents the extra costs involved for future mineral and fossil resource extraction (National Institute for Public Health and the Environment, 2017). The result at the endpoint level can be expressed as one unit single score (Pt), in which characterization, damage assessment, normalization and weighting are combined (PRé Consultants, 2019).

LCA database Ecoinvent 3 was used as a source of background Life Cycle Inventory (LCI) data (Swiss Centre for Life Cycle Inventories, 2017). In order to determine and compare the impact of electric and conventional vehicles on the environment throughout their cycle, analysis was carried out using the SimaPro 8.5 software, which calculates the environmental load and shows which stages of the vehicles' life cycle contribute most.

2.2. Inventory analysis

Vehicle model specification is the basic assumption for analysis and significantly influences the results. This research aims to reveal the real situation in Lithuania, so the vehicle model must match the market in Lithuania. According to the State enterprise "Regitra" (2019), the most popular new BEV registered in Lithuania is Nissan Leaf and the vehicle with internal combustion engine is Fiat. Since this study is forward-looking and will measure the impact on the environment according 2015 2050 prognosticated electricity mixes using renewable energy resources, the latest Nissan Leaf 2018, model ACENTA was chosen. Besides, Fiat 2018, model TIPO fuelled with petrol and diesel was determined. Nissan Leaf ACENTA and Fiat TIPO fuelled with petrol and diesel belong to the medium-size class, are similar in weight and length, therefore they are suitable for a comparative life cycle analysis. Technical specifications of these vehicles published by manufacturers are presented in Table 1 and Table 2.

With the total mass of the electric vehicle of 1,545 kg, the rated consumption for the vehicle is 0.206 kWh for 1 km driving. This value was rated by Worldwide Harmonised Light Vehicle Test Procedure (WLTP) laboratory, which uses the test to measure fuel consumption and CO_2 emissions from passenger cars. Therefore, 0.206 kWh include charging losses. This value leads to a range of around 270 km, with the lithium-ion battery mass of 296 kg.

3. Results and discussion

3.1. Results of the LCA at the midpoint level

3.1.1. LCA results of BEV in 2015 and ICEVs

Results from the comparative LCA regarding environmental impact categories of BEVs and ICEVs in Lithuania are presented in Fig. 4. It illustrates the results of the greatest impacts of BEVs with electricity mix of 2015 and ICEVs fuelled with petrol and diesel in such categories: climate change, human toxicity, ionizing radiation, metal depletion and fossil depletion.

Table 1
Electric vehicle technical specification (Electric Vehicle Database, 2019).

Parameter	Default value
Car body	Hatchback
Length	4490 mm
Width	1788 mm
Height	1530 mm
Vehicle weight without battery	1249 kg
Battery weight	296 kg
Battery capacity	40 kWh
Range (WLTP)	270 km
Vehicle energy consumption (WLTP)	0.206 kWh/km

Table 2
Vehicles with internal combustion engine technical specifications (JSC "Autobrava Motors", 2019).

Parameter	Default value	Default value
Fuel	Petrol	Diesel
Engine	1.3 T4	1.3 MultiJet
Car body	Hatchback	Hatchback
Length	4265 mm	4265 mm
Width	1796 mm	1796 mm
Height	1495 mm	1495 mm
Kerb weight	1395 kg	1395 kg
Fuel consumption (urban)	7.4 l/100 km	5.2 l/100 km
Fuel consumption (extra urban)	5.4 5.9 l/100 km	3.5 4 l/100 km
Fuel consumption (combined)	6.1 6.5 l/100 km	4.2 4.6 l/100 km
Emission standard	EURO 6	EURO 6

Graph a) shows that the greatest value of CO_2 eq throughout the whole life cycle is 21,304 CO_2 eq for BEV, where the highest impact on the environment occurs in the use stage (14,903 CO_2 eq). ICEV fuelled with petrol takes the second place after BEV with total 15,787 CO_2 eq and 12,077 CO_2 eq in the use stage. ICEV fuelled with diesel has the least impact on the environment with total 11,394 CO_2 eq and 7,669 CO_2 eq in the use phase, which is almost double time less than BEV. In every diagram the disposal phase impact on the environment is the least of all phases, even showing that the score is negative, which indicates that the credits are larger than the burdens. Thus, in the further analysis the disposal will be not considered.

Graph b) displays the impact on human health, which is the highest in BEV production (7,803 kg 1,4-DB eq) accounting for 68% of the total impact. This is so due to the lithium-ion battery production, which creates about 46% of this burden.

Graph c) shows one of the advantages of BEV with the least impact in ionizing radiation category, where it is ~10 times less than ICEV-petrol. The total impact in ICEV-petrol has the greatest value of 1,974 kBq U235 eq, followed by ICEV-diesel with 1,712 kBq U235 eq, where the use phase in both vehicles has the greatest burden (90%) of the total impact.

Graph d) shows the impact on metal depletion, which has the greatest value in BEV production (7,406 kg Fe eq), where 75% of the impact is due lithium-ion battery production and the rest 25% vehicle production. The negative value in ICEVs shows that their total LCA does not strongly contribute to the total environmental burdens.

Finally, Graph e) presents the impact on fossil depletion, which is the greatest in ICEV-petrol (total 13,669 kg oil eq), followed by ICEV-diesel (total 10,498 kg oil eq). In both vehicles, the use phase has the greatest impact (90%) of the total burden, therefore, it proves that this phase is related to the use of fossil fuels. Although BEV in this field is advantaged, having almost double time less environmental burden in this category.

The results of BEV of 2015 electricity mix and ICEV-diesel and ICEV-petrol show that BEV is superior to the ICEVs in such significant impact categories as ionizing radiation and fossil depletion; and ICEVs are advantaged in the rest impact categories: climate change, human toxicity and metal depletion.

3.1.2. LCA results of current and future BEVs

According to the inventory of gross electricity generation by fuel type and technology in Lithuania for the years 2015 2050, data for current and future electricity production were analysed. Shares (in percent) of electricity production in Lithuania's energy systems were apportioned and presented in Table 3.

According to the National energy dependency strategy, the strategic objective of RES will be to increase the share of RES compared to the country's total final energy consumption. One of the main strategic goals of renewable energy directions is to increase the share of electricity consumed from RES to 30% of final electricity consumption in 2020, 45% in 2030 and 100% in 2050.

Natural gas and hydro energy currently are the dominant sources of electricity, but this is expected to change in the near future. Electricity obtained from oil will be decreased from 4.57 to zero in 2020, and this source is not expected to be used in Lithuania later on. The share of natural gas will decline six times by 2050, while biomass will increase about five times in 2020 2025, but decrease in further years and reach 4.49 in 2050. Currently, waste,

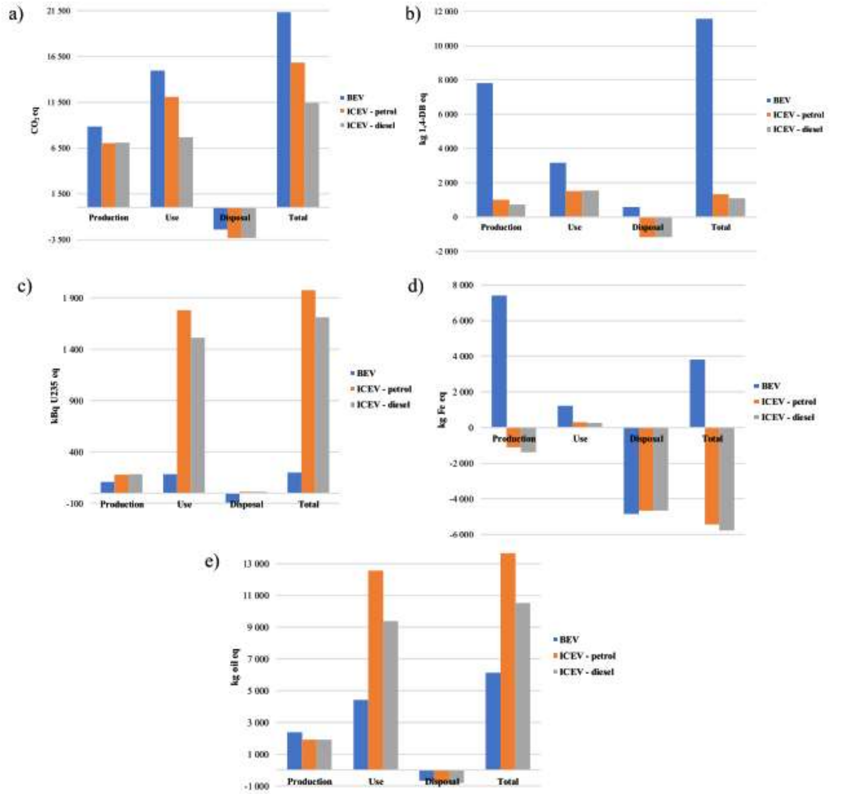


Fig. 4. BEV (electricity mix of 2015) and ICEVs assessment of these environmental indicators: a) climate change; b) human toxicity; c) ionizing radiation; d) metal depletion; e) fossil depletion.

Table 3
Proportions of electricity production in the energy system by source in Lithuania (2015 2050) (Lithuanian Energy Institute, 2017).

Unit, %	2015	2020	2025	2030	2035	2040	2045	2050
Waste	2.28	6.63	4.16	2.50	2.50	1.79	1.79	1.28
Biogas	3.51	4.79	1.75	0.57	0.57	0.97	0.97	1.13
Biomass	5.85	24.12	25.18	15.56	15.56	4.97	4.97	4.49
Natural gas	41.73	10.33	10.67	11.09	11.09	19.90	19.90	7.28
Hydro	20.55	6.97	5.28	4.44	4.44	6.34	6.34	5.72
Wind	14.56	36.76	38.58	52.40	52.40	34.86	34.86	33.61
Solar	1.76	5.96	11.71	11.83	11.83	30.00	30.00	45.57
Geothermal	5.19	4.45	2.68	1.60	1.60	1.17	1.17	0.93
Oil	4.57	0.00	0.00	0.00	0.00	0.00	0.00	0.00

biogas and geothermal have insignificant shares in the energy system and are forecasted to reduce as well. It is prognosticated that the shares of solar and wind energy will increase markedly through the year 2050, from 1.76 to 45.57 and from 14.56 to 33.61, respectively, and will be the most important energy sources in Lithuania. The shares of the sources of electricity production in 2015 2050 have been used to perform the LCA analyses of current and future BEVs in Lithuania.

In addition, according to the ReCiPe midpoint method, environmental impact of 1 kWh electricity production by different technologies and fuel type was assessed and presented in Table 4. The impact categories (climate change, human toxicity, ionizing radiation, metal depletion and fossil depletion) that have the major impact on the environment have been chosen. The results of all the

Table 4
Environmental impact of 1 kWh electricity production by different technologies and fuel types.

Impact category	Electricity from oil	Electricity from municipal waste incineration	Electricity from natural gas	Electricity from biogas	Electricity from solar photovoltaic technology	Electricity from hydropower	Electricity from geothermal technology	Electricity from wind turbine
Climate change	2.896	0.823	0.636	−0.281	0.114	0.112	0.083	0.015
Human toxicity	0.185	0.024	0.006	0.705	0.055	0.062	0.007	0.004
Ionising radiation	0.164	0.034	0.011	−0.116	0.002	−0.008	0.004	0.000
Metal depletion	0.022	0.010	0.009	0.228	0.039	0.045	0.021	0.014
Fossil depletion	1.001	0.187	0.244	−0.339	0.030	−0.017	0.018	0.004

eighteen impact categories with units are displayed in Appendix A.

Table 4 reveals the environmental impact of the most significant categories of electricity production by different technologies and fuel types, that are displayed from the most polluting oil - to the most environmentally friendly wind energy. Oil has the highest impact in three from five (3/5) categories (climate change, ionising radiation and fossil depletion) and biogas 2/5 (human toxicity and metal depletion), whereas wind energy has the minor impact in 3/5 categories (climate change, human toxicity and ionising radiation), municipal waste incineration 1/5 (metal depletion) and biogas also 1/5 (fossil depletion).

According to the sources of electricity production in the energy systems of Lithuania in 2015 2050, the LCA of current and future electric vehicle is assessed. Different electricity mixes cause changes in BEV's operation stage, therefore the use phase is presented in Fig. 5.

Fig. 5 shows the same impact categories that have the major impact on the environment. In the year 2015, due to the use of oil and the biggest share of natural gas, this electricity mix was the most polluting in 3/5 impact categories (climate change, ionising radiation and fossil depletion). Year 2020 and 2025 are expected to be the most environmentally friendly as values in 3/5 impact categories are the least due to the use of biomass, biogas and wind energy, nevertheless, the human toxicity will be increased. In 2030 and 2035, the major share of wind energy will be used for electricity generation, therefore one of the minor values are expected to be in fossil depletion, ionising radiation. In 2040 and 2045, the share of natural gas will be increased, consequently, the impact in climate change and fossil depletion will be risen. Renewable energy resources will be actively used in the scenario of 2050, which is one of the desirable, as values in all impact categories are among the lowest, especially in human toxicity, ionising radiation and fossil depletion.

To sum up, the results show that from 2015 to 2050 there is a reduction in values of environmental indicators for each impact category. Besides, the use phase of BEV (2050 electricity mix) will emit 31% and 56% less GHG emissions than ICEV-diesel and ICEV-petrol, respectively. This is due to the elimination of oil and increase of renewable energy (mainly wind and solar) in the sources of energy used for electricity generation.

3.1.3. LCA results of BEV in 2015 2050 and comparison with ICEVs

Table 5 below shows a comparative analysis of the full LCA (including production, use and disposal phases) of ICEVs fuelled with petrol and diesel, and BEVs under different energy mix scenarios 2015 2050. Impact categories are displayed according to the highest values that have a major impact on the environment. Results of all the eighteen impact categories are presented in Appendix B.

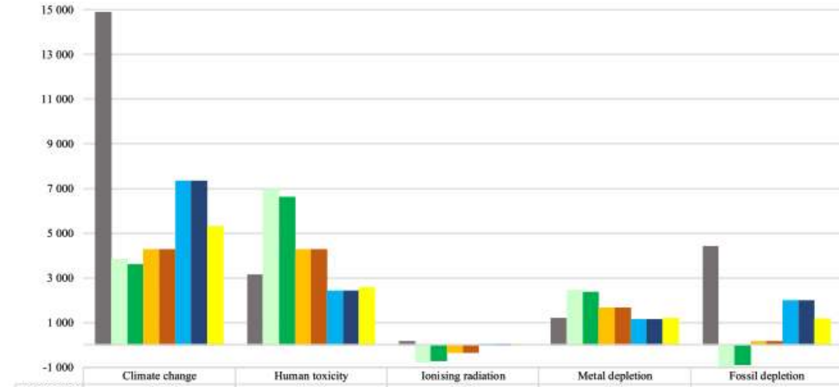
First of all, it was assessed that GHG emissions related to the impact on climate change of BEV would be lower in 2020, 2025, 2030 and 2035 scenarios than those for ICEVs. In 2050, this impact would be almost equal to ICEV-diesel. ICEV-petrol are the most polluting, comparing to ICEV-diesel and BEV in 2020 and later scenarios in this impact category. Next, it was determined that human toxicity of BEV is expected to be the highest in all energy mix scenarios. This indicator is related to the production of electric car and Li-ion battery, accounting for 36 and 31%, respectively. Then, ionising radiation and fossil depletion indicators are significantly higher for both ICEVs. The main factor of such a result is production of petrol/diesel. Lastly, the metal depletion indicator is considerably dominant for BEV in the current and future energy mix scenarios. This indicator is related to the production of the battery and accounts for 75% of this impact.

The results show that BEV in 2050 scenario has one of the lowest values in almost all categories comparing to the 2015 scenario, as the contribution to the climate change will decrease by 45%, human toxicity 5%, ionising radiation 89%, fossil depletion 53%. This demonstrates that RES integration into electricity production has a positive effect on reducing the impact on the environment.

3.2. LCA results of BEV (2015 and 2050) and comparison with ICEVs at the endpoint level

The environmental life cycle assessment of BEV and ICEVs fuelled with petrol and diesel was also performed according to ReCiPe method at the endpoint level. The results in Fig. 6 are expressed as single score, measuring the total environmental load. The units are called points (Pt), kilo points (kPt) in our case.

The diagram shows that ICEV fuelled with petrol has the greatest impact in damage assessment, where the impact on human health and resources contributes the most. Next, ICEV fuelled with diesel follow with 28% less total "environmental damage", where both impacts on human health and resources have equally 0.9 kPt, and the least impact refers to ecosystems with 0.4 kPt. Moreover, the results showed that the total impact of BEV (electricity mix of 2015) is 42% lower than ICEV-diesel and 57% less than ICEV-petrol. The BEV has a smaller impact in damage assessment with only 1.2 kPt, with almost zero damage for ecosystems, 0.8 kPt resources and 0.4 kPt human health. Furthermore, it is identified that the "environmental damage" of BEV with electricity mix of 2050 is 54% smaller than that of BEV with electricity mix of 2015, where the impact on ecosystems is zero and the impact on human health and resources is 0.1 and 0.5 kPt, respectively. This explains that turning from the usage of fossil fuels to RES and increasing their share in electricity production has a significant advantage in order to promote a healthy and environmentally benign urban transportation.



	Climate change	Human toxicity	Ionising radiation	Metal depletion	Fossil depletion
BEV, 2015	14 907	3 165	185	1 224	4 420
BEV, 2020	3 850	6 979	-770	2 465	-1 029
BEV, 2025	3 624	6 625	-723	2 384	-893
BEV, 2030	4 291	4 292	-354	1 683	183
BEV, 2035	4 291	4 292	-354	1 683	183
BEV, 2040	7 361	2 418	33	1 163	2 004
BEV, 2045	7 361	2 418	33	1 163	2 004
BEV, 2050	5 322	2 585	4	1 210	1 195

Fig. 5. Results of the use phase of currents and future battery electric vehicle in Lithuania.

Table 5
Results of full LCA of ICEVs and BEV under prognosticated energy mix scenarios 2015 2050.

Impact category	Unit	ICEV - petrol	ICEV - diesel	BEV 2015	BEV 2020	BEV 2025	BEV 2030	BEV 2035	BEV 2040	BEV 2045	BEV 2050
Climate change	kg CO_2 eq	15 787	11 394	21 304	10 247	10 021	10 688	10 688	13 758	13 758	11 719
Human toxicity	kg 1,4-DB eq	1 325	1 095	11 555	15 369	15 015	12 682	12 682	10 808	10 808	10 975
Ionising radiation	kBq U235 eq	1 973	1 711	202	−752	−706	−337	−337	51	51	21
Metal depletion	kg Fe eq	−5 424	−5 760	3 804	5 045	4 964	4 264	4 264	3 743	3 743	3 866
Fossil depletion	kg oil eq	13 669	10 498	6 136	687	822	1 898	1 898	3 720	3 720	2 910

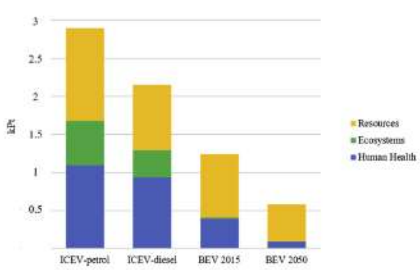


Fig. 6. Endpoint results of ICEVs and BEV (electricity mix of 2015 and 2050).

3.3. Comparison of results with results obtained by other authors

LCA results of BEV and ICEVs with the results obtained by other authors for a functional unit of "1 km driven" are presented in Table 6. The most significant and widely analysed impact categories (climate change and human toxicity) are chosen.

Comparison of the LCA results carried out by various researchers reveals that the results of LCA will always differ in value, because there were no articles with the same or similar results, as presented in Table 6. This can be explained by the fact that each researcher makes a different data inventory, uses different software or databases. When performing a comparison of ICEV's and BEV's LCA, technical vehicles' characteristics, especially the kerb weight, the battery of BEV weight are among important factors when analysing the environmental impact in the manufacturing phase. Next, when analysing the use phase for ICEVs, the fuel type and the average fuel consumption are the main factors. Besides, the year of the car manufacture also plays an important role, since the newer the car model, the lower the fuel consumption will be. Furthermore, for

Table 6
Comparison with LCA results obtained by other authors.

Study	Region	Results	
		Climate change, kg CO_2 eq/km	Human toxicity, kg 1,4-DB eq/km
This paper	Lithuania	BEV 2015: 0.142 BEV 2050: 0.078 ICEV-petrol: 0.105 ICEV-diesel: 0.076	BEV 2015: 0.077 BEV 2050: 0.073 ICEV-petrol: 0.009 ICEV-diesel: 0.0073
Qiao et al. (2019)	China	BEV 2015: 0.273 BEV 2020: 0.227 ICEV: 0.333	
Burchart-Korol et al. (2018)	Poland	BEV 2015: 0.276 BEV 2050: 0.172 ICEV-petrol: 0.284	BEV 2015: 0.331 BEV 2050: 0.234 ICEV-petrol: 0.085
Burchart-Korol et al. (2018)	Czech Republic	BEV 2015: 0.214 BEV 2050: 0.145 ICEV-petrol: 0.284	BEV 2015: 0.306 BEV 2050: 0.234 ICEV-petrol: 0.085
Bicer and Dincer (2018)	Canada	BEV: 0.160 ICEV-petrol: 0.270 ICEV-diesel: 0.23	BEV: 0.26 ICEV-petrol: 0.03 ICEV-diesel: 0.04
Wu et al., 2018	China	BEV 2010: 0.283 BEV 2014: 0.209 BEV 2020: 0.171 0.183 ICEV 2010: 0.265 ICEV 2014: 0.233 ICEV 2020: 0.198	
Del Pero et al., 2018	Italy	BEV: 0.129 ICEV: 0.203	BEV: 0.027 ICEV: 0.00057
Tagliaferri et al., 2016	Italy	BEV: 0.120 ICEV-diesel: 0.160	
Bauer et al. (2015)	Switzerland	BEV 2012: 0.220 BEV 2030: 0.090 ICEV-petrol 2012: 0.30 ICEV-petrol 2030: 0.24 ICEV-diesel 2012: 0.26 ICEV-diesel 2030: 0.21	BEV 2012: 1.0 BEV 2030: 0.3 ICEV-petrol 2012: 0.26 ICEV-petrol 2030: 0.24 ICEV-diesel 2012: 0.27 ICEV-diesel 2030: 0.25
Onat et al. (2015)	United States	BEV: 0.180 ICEV: 0.260	
Girardi et al. (2015)	Italy	BEV: 0.155 ICEV-petrol: 0.300	BEV: 0.136 ICEV-petrol: 0.095
Nordelof et al. (2014)	Sweden		BEV: 0.460 ICEV-petrol: 0.27 ICEV-diesel: 0.25
Hawkins et al. (2013)	Norway	BEV: 0.61 1 ICEV-petrol: 0.81 ICEV-diesel: 0.7	BEV: 0.7 1 ICEV-petrol: 0.25 ICEV-diesel: 0.24

BEVs operation assessment it is important what electricity generation fuel source or technology are determined, as electricity mix influences the impact on the environment when the battery of an electric car is charged. Many scientists use the region's average electricity mix in their LCA if they want to show the overall pollution of an electric car in that region. Moreover, the sources of electricity generation are changing year by year, as countries are encouraged to switch to cleaner energy production and increase the share of renewable energy resources in electricity generation.

4. Conclusions

Comparative LCA of BEV and ICEVs fuelled with petrol and diesel was performed based on ReCiPe method's midpoint and endpoint indicators. In addition, LCA of BEV was carried out under different electricity mix scenarios, that are prognosticated for 2015 2050 in Lithuania.

At the midpoint level, it was assessed that throughout the whole life cycle BEV of 2015 electricity mix is advantaged in ionizing radiation and fossil depletion, while both ICEVs had lower impact in climate change, human toxicity and metal depletion. The BEV impact on climate change is 26 and 47% bigger than that of ICEVs fuelled with petrol and diesel, respectively. This is because the BEV's operation phase amounts to 70% of the total burden, where electricity (used to recharge the battery) of 2015 was produced with natural gases (41.7%) and oil (5%), which will be eliminated for the later scenarios. Furthermore, human toxicity of BEV is the highest in all energy mix scenarios, and this indicator is associated with the production of an electric car and Li-ion battery, accounting for 36 and 31% of the total impact, respectively. Besides, it was identified that GHG emissions of BEV would be lower than those for ICEVs in the 2020, 2025, 2030 and 2035 scenarios. This is because wind energy and biomass are the main sources in electricity production and the use of natural gases is decreased approximately 4 times for these years. Next, BEV in the 2050 scenario has one of the lowest values in almost all the categories comparing to the 2015 scenario. In addition, the use phase is expected to reduce by 64 and 73% in terms of the climate change and fossil depletion, respectively. Besides, the use phase of BEV (2050 electricity mix) will emit 31 and 56% less GHG emissions than ICEV-diesel and ICEV-petrol, respectively. This is because the electricity mix of 2050 consists of the main sources solar (45.6%) and wind energy (33.6%). Lastly, the metal depletion indicator is considerably significant for BEV in the current and future energy mix scenarios as this indicator is related to the production of the battery and accounts for 75% of this impact.

At the endpoint level, the results showed that ICEV fuelled with petrol has a major impact in damage assessment, where the impact on human health (38%) and resources (42%) contribute the most. Next, ICEV fuelled with diesel follow with 28% less total environmental damage, where both impacts on human health and resources contribute equally and the least impact belongs to ecosystems. Moreover, the results showed that BEV of 2015 electricity mix has almost zero damage for ecosystems and the total impact is 42 and 57% less than ICEV-diesel and ICEV-petrol, respectively. Furthermore, it is assessed that the "environmental damage" of BEV with electricity mix of 2050 is 54% smaller than that of BEV with electricity mix of 2015, and 73 and 80% less than ICEVs fuelled with diesel and petrol, respectively.

The results prove that integration of RES into electricity production has potential environmental benefits of BEV performance in the transport system. Besides, the results explain how different proportions of RES integrated into the electricity mix provide different impacts on the environment when analysing and comparing the BEV's operation stage. More research should be carried out not only from the environmental, but also social and economic point of view, i.e. social life cycle assessment and life cycle costing would be advanced to perform in order to reach a better understanding of all the benefits that e-mobility can provide.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Appendix A. Environmental impact of 1 kWh electricity production by different technologies and fuel types in all impact categories

Impact category	Unit	Electricity from oil	Electricity from municipal waste incineration	Electricity from natural gas	Electricity from biomass	Electricity from solar photovoltaic technology	Electricity from hydropower	Electricity from geothermal technology	Electricity from wind turbine
Climate change	kg CO_2 eq	2.896	0.823	0.636	−0.281	0.114	0.112	0.083	0.015
Ozone depletion	kg CFC-11 eq	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Terrestrial acidification	kg SO_2 eq	0.022	0.004	0.001	−0.001	0.000	0.000	0.000	0.000
Freshwater eutrophication	kg P eq	0.000	0.000	0.000	0,000	0.000	0.000	0.000	0.000
Marine eutrophication	kg N eq	0.001	0.000	0.000	0.001	0.000	0.000	0.000	0.000
Human toxicity	kg 1,4-DB eq	0.185	0.024	0.006	0.705	0.055	0.062	0.007	0.004
Photochemical oxidant formation	kg NMVOC	0.012	0.002	0.001	0.008	0.000	0.001	0.000	0.000
Particulate matter formation	kg PM10 eq	0.006	0.003	0.000	−0.004	0.000	0.000	0.000	0.000
Terrestrial ecotoxicity	kg 1,4-DB eq	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Freshwater ecotoxicity	kg 1,4-DB eq	0.001	0.000	0.000	0.003	0.000	0.000	0.000	0.000
Marine ecotoxicity	kg 1,4-DB eq	0.004	0.000	0.000	0.003	0.002	0.000	0.000	0.000
Ionising radiation	kBq U235 eq	0.164	0.034	0.011	−0.116	0.002	−0.008	0.004	0.000
Agricultural land occupation	m^2a	0.374	0.005	0.000	−4.576	0.008	−0.355	0.005	0.002
Urban land occupation	m^2a	0.008	0.005	0.001	0.000	0.001	0.002	0.001	0.001
Natural land transformation	m^2	0.001	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Water depletion	m^3	0.017	0.005	0.001	−0.102	0.003	−0.007	0.001	0.000
Metal depletion	kg Fe eq	0.022	0.010	0.009	0.228	0.039	0.045	0.021	0.014
Fossil depletion	kg oil eq	1.001	0.187	0.244	−0.339	0.030	−0.017	0.018	0.004

Appendix B. Results of full LCA of ICEVs and BEV under prognosticated energy mix scenarios 2015 2050 in all impact categories

Impact category	Unit	ICEV-petrol	ICEV-diesel	BEV, 2015	BEV, 2020	BEV, 2025	BEV, 2030	BEV, 2035	BEV, 2040	BEV, 2045	BEV, 2050
Climate change	kg CO_2 eq	15 787	11 394	21 304	10 247	10 021	10 688	10 688	13 758	13 758	11 719
Ozone depletion	kg CFC-11 eq	0	0	0	0	0	0	0	0	0	0
Terrestrial acidification	kg SO_2 eq	536	523	−416	−456	−458	−457	−457	−454	−454	−459
Freshwater eutrophication	kg P eq	3	3	5	3	3	4	4	6	6	6
Marine eutrophication	kg N eq	1	1	5	10	9	6	6	3	3	3
Human toxicity	kg 1,4-DB eq	1 325	1 095	11 555	15 369	15 015	12 682	12 682	10 808	10 808	10 975
Photochemical oxidant formation	kg NMVOC	96	83	40	63	57	30	30	9	9	6
Particulate matter formation	kg PM10 eq	124	117	−70	−100	−100	−88	−88	−75	−75	−75
Terrestrial ecotoxicity	kg 1,4-DB eq	5	4	6	6	6	6	6	7	7	7
Freshwater ecotoxicity	kg 1,4-DB eq	71	66	87	103	101	90	90	81	81	81
Marine ecotoxicity	kg 1,4-DB eq	6	−2	76	86	87	79	79	82	82	90
Ionising radiation	kBq U235 eq	1 973	1 711	202	−752	−706	−337	−337	51	51	21
Agricultural land occupation	m^2a	8 969	3 797	−13 986	−40 675	−37 866	−22 678	−22 678	−8 521	−8 521	−8 046
Urban land occupation	m^2a	254	195	1	−5	−7	−6	−6	−3	−3	0
Natural land transformation	m^2	13	10	4	−1	−1	0	0	1	1	1
Water depletion	m^3	376	225	−219	−834	−769	−431	−431	−95	−95	−75
Metal depletion	kg Fe eq	−5 424	−5 760	3 804	5 045	4 964	4 264	4 264	3 743	3 743	3 866
Fossil depletion	kg oil eq	13 669	10 498	6 136	687	822	1 898	1 898	3 720	3 720	2 910

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Comparative Environmental Life Cycle and Cost Assessment of Electric, Hybrid, and Conventional Vehicles in Lithuania

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Abstract: Electric mobility is promoted as a future transport option that has environmental and economic benefits and encourages sustainable urban transportation. The aim of this study is to reveal the changes in environmental and economic performance if we switched from internal combustion engine vehicles (ICEVs) to battery electric (BEV) or hybrid electric (HEV) vehicles. Therefore, this research presents a comparative environmental life cycle assessment (LCA) from the Cradle-to-Grave perspective of the vehicles and a Well-to-Wheel analysis of their fuel supply. Moreover, an LCA of a BEV was performed under diverse electricity mix scenarios, which are forecasted for 2015–2050 in Lithuania. From an economic point of view, a life cycle costing was conducted for the same vehicles to estimate the economic impacts over the vehicle life cycles under Lithuanian conditions. The results show that ICEV-petrol contributes the major environmental damage in all damage categories. BEVs with the electricity mix of 2020–2050 scenarios, which are composed mainly of renewable energy sources, provide the least environmental impact. The economic results reveal that BEV and ICEV-diesel are the most cost-efficient vehicles, with the total consumer life cycle costs of approximately 5% and 15% less than ICEV-petrol and HEV, respectively.

Keywords: renewable energy; life cycle assessment; environmental impact; electric vehicle; life cycle cost assessment; conventional car; sustainable mobility

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1. Introduction

The European Union (EU) faces the challenge of achieving goals set for the 2020 and 2030 climate and energy frameworks and the 2050 long-term strategy [1]. The EU's ambition to become climate-neutral by 2050 is described in the European Green Deal, which claims a new growth strategy and aims to accelerate the shift to smart and sustainable mobility [2]. The EU According to the European Environmental Protection Agency, the transport sector, accounts for a quarter of the EU's total greenhouse gas (GHG) emissions. In addition, as of 2018, GHG emissions from transport have increased by 32% compared with 1990. Moreover, road transport is the most significant factor with nearly three-quarters of the transport-related GHG emissions [3]. To achieve climate neutrality, a 90% reduction in all modes of transport emissions is necessary by 2050 [2].

Road transport is the most substantial emissions source in the transportation area in Lithuania. In 2018, GHG emissions from road transport increased by 6.4% compared with the previous year, and this increase is primarily caused by a 7% increase in diesel oil fuel and 9% in gasoline consumption by road transportation. According to Lithuania's GHG Inventory report of 2018, transport is responsible for 30.2% of the total GHG emissions (6111.4 kt CO_2 eq), of which 95.7% comes from road transport and passenger cars account for 56% (3421 kt CO_2 eq). As a result, passenger cars contribute 17% of the total GHG emissions [4].

In terms of air pollution, passenger cars are one of the most predominant contributors of air pollutants of all vehicle types and are responsible for 7.2% of NOx, 3.5% of NMVOC, 9.3% of PM2.5, 4.8% of PM10, and 10.2% Pb of the total emissions from all sectors [4]. It has been assessed that the health-related external costs from air pollution in Lithuania are over 1 billion Eur/year (income adjusted, 2010), which includes not only the essential value of living a complete healthy life but also direct costs to the economy. These direct economic costs relate to 488,000 workdays lost every year due to illness related to air pollution, with related costs for employers of 37 million Eur/year and of more than 5 million Eur/year for healthcare (income adjusted, 2010) [5].

Air pollution is caused by passenger cars, which are the most fuel-consuming vehicle type, followed by heavy-duty and light-duty vehicles, and two-wheelers, in decreasing order [4]. Higher fuel consumption also depends on the vehicle age. According to the statistics of State Enterprise "Regitra", the average age of passenger cars is approximately 16 years old, with European emission standards of EURO 3 and EURO 4 [6].

Electric vehicles (EVs) are considered to be environmentally friendly modes of transport and offer significant opportunities to reduce local air pollution, GHG emissions, and traffic noise. EVs do not release tailpipe emissions of air pollutants such as nitrogen oxides and particulate matter. In addition, EVs are quiet during operation, especially at lower speeds, and they are less noisy than conventional vehicles [7]. Furthermore, electric mobility is supposed to play a significant role in achieving these goals for three reasons: (1) electric powertrains are considerably more energy efficient than conventional engines; (2) electricity can directly use renewable energy sources (RES) for transport, and (3) when connected to the power grid, EV batteries can stabilise the grid and balance the supply and demand, facilitating the integration of RES [8].

Moreover, EVs would be even more favourable if the electricity for charging the battery is produced by RES [9–12]. The EU agreed to set a common target for the share of RES (including biomethane, liquid biofuels, "green electricity", and hydrogen) of 10% of the total used in transport by 2020. In the EU transport area, RES equalled to 8.3% in 2018 (boosted from 1.5% in 2004) [13].

In Lithuania, the part of RES of the final energy consumption in the transportation should be raised to at least 10% by 2020 in all means of transport, yet unfortunately, the aim has not been achieved, with only 3.69% achieved in 2017 [14]. Furthermore, according to the National Energy Independence Strategy, future goals are even more ambitious, increasing the part of RES used in the transport sector to 15% by 2030 and 50% by 2050 [15].

One of the planned policy tools in the transport area from the National Energy and Climate Action Plan of the Republic of Lithuania 2021–2030 is promoting the use of EVs and expanding the recharging infrastructure. As a result, EVs are required to account for 10% of annual class M1 purchase transactions in 2025 and 50% in 2030 [16].

According to recent vehicle registration statistics, the largest market share is occupied by internal combustion engine vehicles (ICEVs) powered with diesel (68.3%), followed by ICEVs powered with petrol (23.4%), then ICEVs powered with liquefied petroleum gas (6.4%) while hybrid electric vehicles (HEVs) accounts for only 1.7% and battery electric vehicles (BEVs)—0.15%. Notwithstanding, such BEV statistics show a huge improvement in recent years in Lithuania.

According to the recent data of European Automobile Manufacturers Association, not only in Lithuania, but also in other Baltic states—Latvia and Estonia, in 2020, a significant increase was occurred in new BEVs registration in the car fleet. As a result, in 1–3 quarters of 2020, there were around three times more new BEVs registrations than in 1–3 quarters of 2019. The number of new BEVs registered in Lithuania was the highest, with 52% and 43% higher number than in Estonia and Latvia, respectively, in quarters 1–3 of 2020 [17].

In Lithuania, at the beginning of December 2020, 2390 battery electric passenger cars (new and used) were registered, while at the end of 2019, a total of 1397 were registered, and at the end of 2018, there were only 969 [6]. Such an increase in the BEV reveals a successful financial incentive that was implemented in the spring of 2020. For individuals, there is a possibility of receiving a compensation of 2000 Eur to purchase a second-hand electric vehicle up to 5 years of age and 4000 Eur for the purchase of a new electric car [18].

An additional compensation of 1000 Eur is paid to the old cars' owners, who deposited their vehicles at an authorised treatment facility for the proper treatment and recovery and have already obtained a certificate of destruction for the old car [19]. Furthermore, additional business support for the purchase of new electric cars and buses has been recently implemented, offering a 4000 Eur compensation for a new electric passenger car or 10,000 Eur compensation for the purchase of a new electric bus [20]. Such financial incentives are great opportunities for the promotion of EV integration into city transport systems.

Economic feasibility will always be a driving force in the decision-making process when integrating EVs in city life, especially when people have low purchasing power and countries face other challenges and barriers [21]. Therefore, an economic assessment is necessary to present an overall impression of the benefits that EVs may provide.

This research provides a comprehensive life cycle environmental and economic assessment, which are also called life cycle assessment (LCA) and life cycle costing (LCC). According to Hauschild et al. (2018), LCA and LCC in the field of mobility can be used to: (1) compare different engines; (2) analyse and compare different fuel types and the impact of the vehicle operation; (3) compare various end-of-life scenarios and treatment options; (4) identify hotspots of the analysis and main benefits and drawbacks of different vehicles across three major life cycle phases (production, use, and end-of-life) [22]. LCA and LCC are versatile techniques applicable to a range of purposes and at various stages of the product or system in order to support decision-making from the environmental and economic perspectives, respectively. In addition, LCC has been found to positively drive life cycle management by spreading the life cycle idea [23]. Moreover, LCA and LCC are parts of a life cycle sustainability assessment (LCSA). The development of the LCSA originates from the need to combine the three aspects of sustainable development (environmental, economic, and social) in a single formulation, supporting life cycle thinking [24,25].

Some studies have been explored regarding the LCCs of BEVs and ICEVs in various countries: Australia [26], France [27], Germany [28–30], Italy [31], Switzerland [32], and the USA [33–36]. However, no studies have been performed on the LCCs of passenger electric, conventional, or hybrid cars in Lithuania. Moreover, Lithuania was chosen as a representative country, as it initiates the integration of electric vehicles and renewable energy resources into city transport systems, which pursues both national and EU goals to become climate-neutral by 2050. Therefore, the goal of this research is to (1) analyse and compare the environmental impacts and costs of electric, hybrid, and internal combustion engine vehicles under Lithuanian conditions; (2) assess the BEV's operation stage under different electricity generation scenarios prognosticated for the years 2015–2050; and (3) assess the electricity mix scenario with the minimum environmental impact. Our research goals examine the hypothesis that electricity mix is a crucial factor for the environmental performance of the BEV.

This research used LCA and LCC methodologies to evaluate the impact on the environment and costs all over the life cycle of BEVs, HEVs, and ICEVs powered with petrol and diesel. In addition, the LCA of BEVs was carried out under various electricity mix scenarios and electricity production technologies for the years 2015–2050 in Lithuania. The novelty of this research is a combined LCA and LCC analysis of different engine-type passenger cars under Lithuanian conditions, where the LCCs are performed from the consumer and manufacturer points of view. Moreover, the forecasted electricity production costs for the electricity mix scenarios of 2020 and 2040 under Lithuanian conditions were compared.

2. Methodology

In this research, LCA and LCC methodologies were used to evaluate the environmental impacts and costs related to the process, product, or activity all over the product's life cycle. The LCAs and LCCs of electric, hybrid, and conventional vehicles were performed according to the procedures specified in the European standards series ISO 14040/14044 [37,38].

The methods are both aligned with these ISO standards on LCA in terms of system scope, functional units, and methodological steps and regard all phases in the life cycle.

The aim of the LCA and LCC was to assess and compare the environmental impacts and costs related with the production, use, and end-of-life stages of electric, hybrid, and conventional vehicles powered with diesel and petrol. The environmental emissions of selected vehicles were based on a functional unit of "1 km driving distance", and the impact/costs were assessed for 150,000 km driving distance. The environmental impacts and costs were calculated for the life cycle assuming that for electric cars, no battery replacement is required (the lithium-ion battery has an 8-year or 160,000 km mileage warranty [39]). Therefore, in this analysis, one battery for the BEV is used during the total mileage. It is important to mention that 150,000 km mileage of all types of selected vehicles will not lead to the end-of-life stage in the current practise, as the average age of passenger cars in the Lithuanian vehicle fleet is 16 years [6]. However, this is a scientific analysis, and a 150,000 km mileage was determined according to the analyses conducted also by other researchers [40–42]. Therefore, the study assumed that the ICEVs, HEV, and BEV could drive 150,000 km as the baseline for the comparative LCA and LCC analyses.

2.1. Scope of Analysis and Life Cycle Impact Assessment Method for the LCA

The scope of this study shows a "complete LCA", which includes the vehicle life cycle as Cradle-to-Grave analysis, and the fuel cycle that follows a Well-To-Wheel (WTW) approach. The WTW parts combine energy resource extraction, energy production and distribution, and energy conversion in the vehicle. The vehicle life cycle or Cradle-to-Grave investigation involves the materials production, vehicle manufacture, maintenance, and end-of-life. The system boundaries of a "complete LCA" are presented in Figure 1.

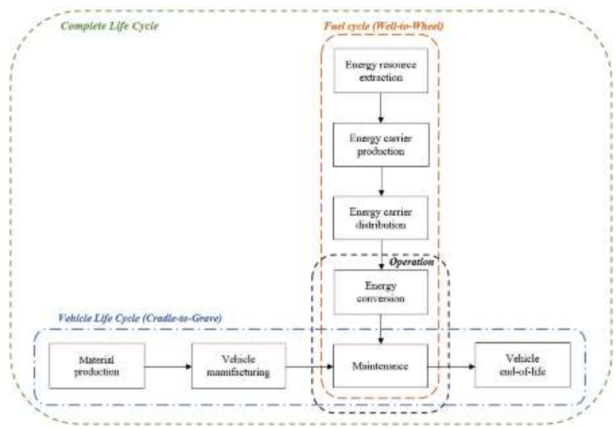

Figure 1. System scope including vehicle and fuel life cycle.

The results of the LCA are described in three stages: production, use, and end-of-life. The production stage includes the production of the vehicle and the batteries: an Li-ion battery for the BEV and an Ni-metal hydride battery for the HEV. Next, the use phase includes car and road maintenance as well as exhaust emissions caused by fuel combustion (for HEV-petrol, ICEV-petrol, and ICEV-diesel) and non-exhaust emissions caused from road wear, tires, and brakes. BEVs do not release direct emissions during the use phase, but indirect emissions are caused by electricity production. Therefore, it is crucial to determine how the electricity for charging the battery is produced. Therefore, the scope of the BEV case involves the electricity mix scenarios 2015–2050, which were forecasted by the Lithuanian Energy Institute (2017) under Lithuanian conditions. Consequently, this research used the LCA method to assess and parallel the environmental impact of BEVs in 2015, 2020, 2025, 2030, 2040, and 2050, including diverse electricity mixes and electricity generation technologies. The end-of-life phase, which includes manual dismantling of a vehicle, treatment (shredding) of the used glider, internal combustion engine, and powertrain, treatment of the used Li-ion battery by a hydrometallurgical process, treatment of the used Ni-metal hydride battery by a pyrometallurgical process, and sorting and remelting of the lead contained in the lead acid battery. In the end-of-life stage, all types of vehicle were treated by the same processes, which are chosen from the LCA database.

In this research, the ReCiPe method at the midpoint and endpoint levels was used to fulfil the impact assessment [43]. At the midpoint level, the environmental impact categories were determined as those with the highest values identified in the study. At the endpoint level, three higher combination levels were evaluated: damage to human health, ecosystems, and resource availability.

The LCA database Ecoinvent v3.5 was applied as the background source for life cycle impact analysis [44]. The life cycle environmental weights and potential impacts were calculated using the LCA software SimaPro 9.1 [45].

2.2. Scope and Costs Assessment Method for the LCC

The LCC can form an economic aspect in a life cycle sustainability assessment complementing environmental and social concepts. It is useful for making good decisions and identify challenges from various perspectives, such as a product or service developer or consumer. Therefore, the LCC was performed from both perspectives. The boundaries were determined using the Cradle-to-Grave approach and covered all three life cycle phases: manufacturing, operation, and end-of-life. Furthermore, the fuel cycle was evaluating, bringing the scope to a "Complete LCC". This type of LCC, which is aligned with the LCA, is also called an environmental LCC, which may also include external costs (also termed externalities), but only if they are expressed in monetary units. In this study, due to a lack of data, the externalities were eliminated from the analysis. The system boundaries of the LCC are presented in Figure 2.

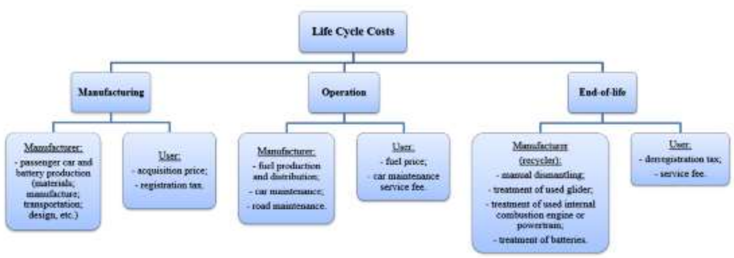

Figure 2. System boundaries of the life cycle costing (LCC).

The results of the LCC are presented as a comparison of the analysed passenger cars in three combined phases (manufacturing, operation, and end-of-life) from two different perspectives: manufacturer and user/consumer. From the manufacturer side, the costs of the processes were aligned with the LCA. The manufacturing phase included costs linked to the production of vehicles and batteries: Li-ion and Ni-metal hydride batteries. Next, the operation phase included the costs of fuel production and distribution and car and road maintenance. Finally, the end-of-life stage included the costs of vehicle treatment processes: manual dismantling, treatment of the glider, internal combustion engine or powertrain, and batteries. From the consumer perspective, the manufacturing phase included the acquisition price and car registration tax. Next, the operation phase included the fuel/electricity price and car maintenance service fees. Finally, the end-of-life phase included only the deregistration tax and service fee for the passenger car (turned to the end-of-life vehicle) disposal, which is free of charge in Lithuania. It should be noted that the analysis did not include all passenger car usage costs. For instance, insurance, tires, and repair costs were excluded because they were assumed to be equal; therefore, they would not influence the comparative analysis.

For the LCC analysis, OpenLCA 1.10 software with the Ecoinvent 3.5 database was used as the measure of financial impact from the manufacturer point of view [46]. The analysis from the consumer side was performed by collecting the necessary data from various sources. The costs were quantified in euros.

2.3. Inventory Analysis

This study aimed to show the current situation in Lithuania according to the existing information, technologies, and available databases. As reported by the State enterprise "Regitra" (2020), the most popular BEV registered in Lithuania is the Nissan Leaf, the most popular HEV is the Toyota Prius, and the most popular ICEV is the Volkswagen Golf. As this research will measure the impact on the environment according to 2015–2050 forecasted electricity mixes using RES, the 2018 Nissan Leaf Acenta was chosen. In addition, the 2019 Volkswagen Golf powered with petrol and diesel was selected. The Nissan Leaf Acenta, Toyota Prius, and Volkswagen Golf powered with petrol and diesel are similar in weight and length and belong to the medium-size class; therefore, they are applicable for comparative life cycle and cost analyses. The costs and parameters of the selected vehicles were assumed to be on the level of 2020 year without prognosing their changes and technology evolution in the future.

The technical specifications of these passenger cars, published by representatives, are shown in Tables 1 and 2.

Table 1. Technical specification of selected battery electric vehicle (BEV) [47].

Parameter	Value
Fuel	Electricity
Car body	Hatchback
Height	1530 mm
Length	4490 mm
Width	1788 mm
Battery capacity	40 kWh
Battery weight	296 kg
Vehicle weight without battery	1249 kg
Vehicle energy consumption (WLTP)	20.6 kWh/100 km

Table 2. Technical specifications of selected internal combustion engine vehicles (ICEVs) and hybrid electric vehicle (HEV) and [48,49].

Parameter	Value	Value	Value
Fuel	Petrol	Diesel	Petrol/electricity
Engine	1.5 TSI ACT (150 Hp), 1498 cm^3	2.0 TDI (115 Hp), 1968 cm^3	1.8 (99 Hp) 1798 cm^3
Car body	Hatchback	Hatchback	Hatchback
Length	4284 mm	4284 mm	4540 mm
Width	1789 mm	1789 mm	1760 mm
Height	1456 mm	1456 mm	1490 mm
Kerb weight	1265 kg	1305 kg	1375 kg
Fuel consumption (combined) (WLTP)	6.2–6.5 L/100 km	4.1 L/100 km	4.2–4.6 L/100 km
Emission standard	EURO 6	EURO 6	EURO 6

The combined fuel consumption was determined according to the HEV's and ICEVs' specifications. This value was evaluated by the Worldwide Harmonized Light Vehicle Test Procedure (WLTP) laboratory, which utilises the test to calculate fuel consumption and carbon dioxide emissions from cars. Furthermore, according to the BEV specifications, the electricity consumption (20.6 kWh/100 km, including charging losses) was also rated by WLTP. The fuel/electricity consumption was the most important factor when calculating the use phase in the LCA, while the kerb weight and battery weight were taken into account when assessing the production stage. Furthermore, when assessing the environmental impact, the weight of a Li-ion battery (296 kg) for the BEV and the weight of a NiMH battery (39.3 kg) for the HEV were taken into account.

Inventory Analysis Regarding Electricity Mix Production

Utilising the inventory of electricity production by fuel type in Lithuania for the years 2015–2050, the data for present and future electricity production were investigated. Shares of electricity generation in Lithuania's energy systems were apportioned and are presented in Table 3. Notably, the LCA analysis includes only the annual electricity generation mixes that are expected to be provided by local resources, although more than half of the electricity is imported in Lithuania, which is projected to decline to zero by 2050. This assumption was because the primary energy sources for the production of imported electricity are not known.

Table 3. Amount (%) of electricity generation in the energy system by source (2015–2050) [50].

Unit, %	2015	2020	2025	2030	2040	2050
Waste	2.28	6.63	4.16	2.50	1.79	1.28
Biogas	3.51	4.79	1.75	0.57	0.97	1.13
Biomass	5.85	24.12	25.18	15.56	4.97	4.49
Natural gas	41.73	10.33	10.67	11.09	19.90	7.28
Hydro	20.55	6.97	5.28	4.44	6.34	5.72
Wind	14.56	36.76	38.58	52.40	34.86	33.61
Solar	1.76	5.96	11.71	11.83	30.00	45.57
Geothermal	5.19	4.45	2.68	1.60	1.17	0.93
Oil	4.57	0.00	0.00	0.00	0.00	0.00

A strategic objective of the National Energy Independency Strategy is to boost the share of RESs in comparison with the present total energy consumption. One of the primary strategic ambitions is to enhance the share of electricity consumed from RESs to 30% of the total electricity consumption in 2020, 45% in 2030, and 100% in 2050 [16]. Electricity obtained from oil is projected to decrease from 4.57 to zero in the 2020 and later scenarios. The share of natural gas is projected to lower six times by 2050, while biomass will raise by approximately five times from 2020 to 2025 and decline further to 4.49 by 2050. At present, geothermal, biogas, and waste have inconsequential shares in the energy system and are prognosticated to be reduced as well. The shares of wind and solar energy are projected to boost considerably over the year 2050, from 1.76 to 45.57 and from 14.56 to 33.61, respectively, and they will be the most substantial energy sources in Lithuania. The amount (%) of electricity generation in the energy system by source were utilised to perform the LCA analyses of present and future BEVs and to carry out a comparative fuel cycle analysis of BEVs, HEV, and ICEVs powered with diesel and petrol.

3. Results and Discussion

3.1. Midpoint Results of the LCA

The midpoint results of the LCA regarding the analysed environmental impact categories of BEV, HEV, and ICEVs powered with diesel and petrol are presented in Figure 3. The results reveal the major impacts of the BEV with the electricity mix of 2015, HEV, and ICEVs in the impact categories of global warming, ionising radiation, human carcinogenic toxicity, human non-carcinogenic toxicity, land use, and fossil resource scarcity as those with the highest values identified in the study.

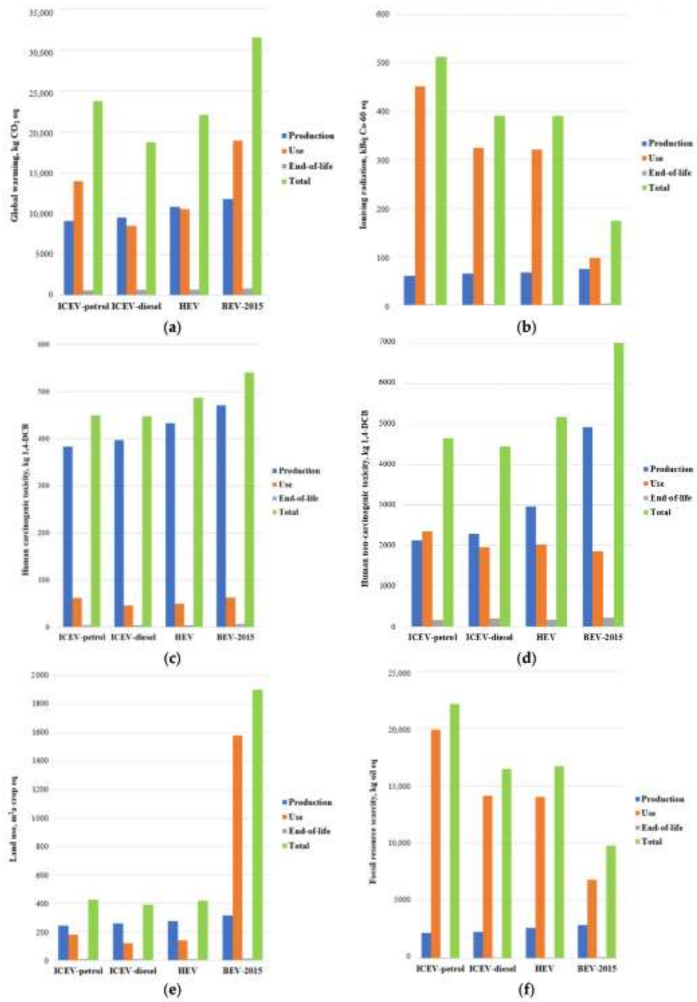

Figure 3. ICEVs, HEV, and BEV (electricity mix of 2015) life cycle assessment (LCA) of the impact categories: (**a**) global warming; (**b**) ionising radiation; (**c**) human carcinogenic toxicity; (**d**) human non-carcinogenic toxicity; (**e**) land use; (**f**) fossil resource scarcity.

The diagram (a) reveals that the value of CO_2 eq all over the entire life cycle is 31,543 CO_2 eq for the BEV, where the greatest impact (60%) on the environment is during the use phase. While ICEVs powered with diesel have the lowest total value of 18,721 CO_2 eq. The impact of the end-of-life phase is similar among all the analysed passenger cars and accounts for 2.7–3.8%, but the greatest values of CO_2 eq, as well as in all other impact categories, are for the BEV (electricity mix of 2015) because of the battery treatment. The graph (b) presents the impact of ionising radiation, which is the highest in the ICEVs and HEV because of the fuel production and distribution. The diagrams (c) and (d) display the human carcinogenic and non-carcinogenic toxicity, where the BEV creates the most substantial burden. Notwithstanding, the production stage exhibits considerable impacts for all car types because of the passenger car manufacturer. The diagram (e) provides the impact on land use, which has the greatest total values for the BEV (1906 m^2a crop eq), where 83% of the total impact is due to electricity production in the 2015 mix energy scenario. Finally, the diagram (f) presents the impact on fossil resource scarcity, which clearly shows that fuel production from fossil fuels creates the highest values for the ICEV-petrol. The ICEV-diesel and HEV, which have almost the same value, provide 25% less impact than the ICEV-petrol, while the BEV contributes almost half the impact of the HEV and ICEV-diesel.

The midpoint results show that the BEV with the 2015 electricity mix is advantageous in terms of fossil resource scarcity and ionising radiation, while the ICEVs and HEV lead in the categories of global warming, human carcinogenic and non-carcinogenic toxicity, and land use.

3.2. Comparative Well-to-Wheel Results of BEV (Electricity Mix Scenarios 2015–2050), HEV, and ICEVs at the Midpoint Level

The impact on the environment for the BEV depends on the electricity production mix. Therefore, Figure 4 presents the Well-to-Wheel analysis, showing the impact of the fuel cycle from the energy resource extraction until operation using various electricity production scenarios that are forecasted for the years 2015–2050 under Lithuanian conditions. All impacts were normalised according to the major contributor in the corresponding impact category. For instance, ICEV-petrol has the highest values in fossil resource scarcity and ionising radiation; therefore, these values are equated to 100%, and the impact values of the other analysed vehicles are calculated accordingly. Similarly, the most significant contributors to the other impact categories were identified, and the impact of the other vehicles was assessed accordingly.

The results show that in 2015, due to the use of natural gas (as the largest share) and oil, this electricity mix was the most polluting in terms of global warming potential. The BEV with an electricity mix of 2020–2050 is about 60–78% less than the BEV with the electricity mix of 2015 and ICEV-petrol, 45% less than the HEV, and 25% less than the ICEV-diesel. Furthermore, in terms of fossil resource scarcity, all the BEVs with electricity mixes from 2020 to 2050 are approximately 10 and 14 times more advantageous than the diesel and petrol car, respectively. The results reveal that the BEVs with electricity scenarios of 2040 and 2050 are the most desirable, with the values in almost all the impact categories among the lowest (except human carcinogenic toxicity). This is because solar and wind energy are actively used as the predominant sources in these scenarios.

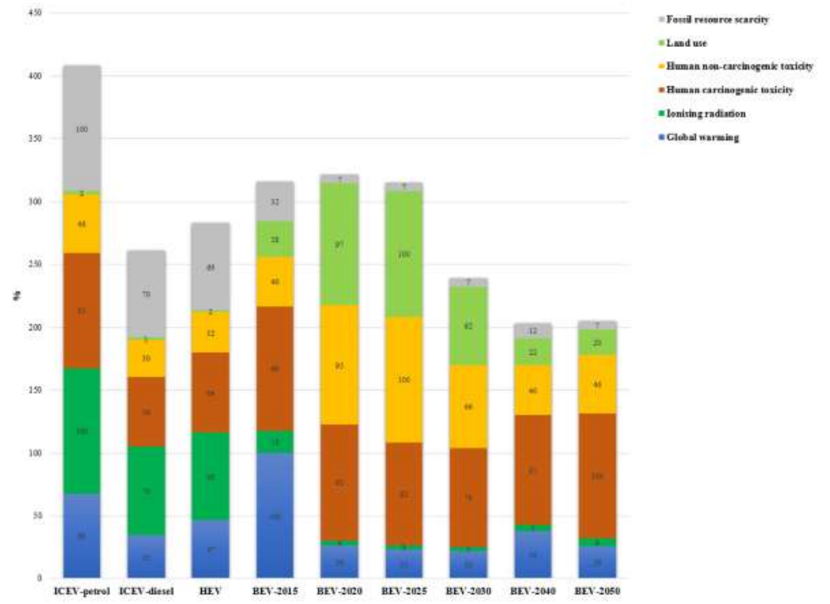

Figure 4. Results (%) of the fuel cycle analysis of ICEVs, HEV, and current and future BEVs in Lithuania.

3.3. Endpoint Results of the LCA

The environmental LCA all over the entire life cycle (production, use, and end-of-life) was also investigated at the endpoint level. The results are shown in Figure 5 and summarise the total environmental load as damage to resources, ecosystems, and human health. The results are expressed as a single score, in which the characterisation, damage assessment, normalisation, and weighting are combined. The units are called points (Pt) and kilo points (kPt) in this case.

The results reveal that the ICEV-petrol has the greatest environmental damage compared with all the analysed passenger cars. The HEV and BEV with the electricity mix of 2015 have almost the same environmental damage, which is 14% less than that of the ICEV-petrol. Next, the ICEV-diesel contributes 10% less impact than the HEV and BEV. Furthermore, the BEVs with electricity mix scenarios from 2020 to 2050, which are composed primarily of RESs, provide the least environmental damage. These results reveal that switching from the usage of fossil fuels to renewables and expansion the RES share in electricity generation has a meaningful benefit in fostering sustainable city transportation.

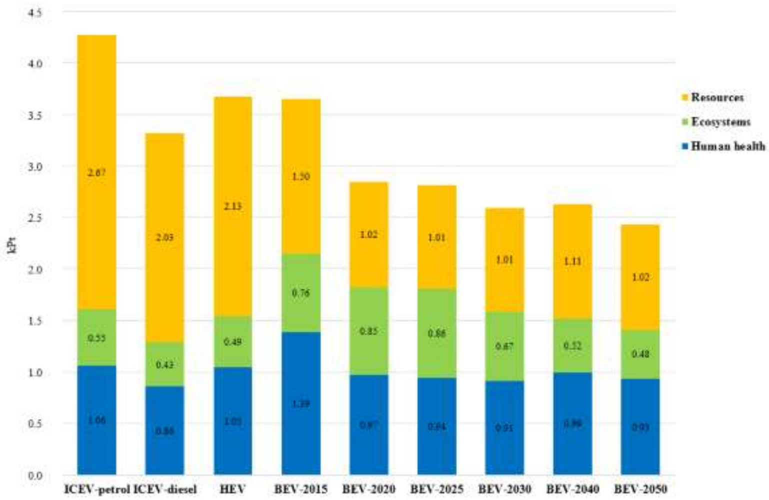

Figure 5. Results of selected passenger cars at the endpoint level.

3.4. Results of the Life Cycle Costing

3.4.1. Results of the LCC from Consumer Side

The results of the LCC from the consumer side are presented in Figure 6.

The graph presents the results of the comparative LCC analysis of the same passenger cars from the consumer side under Lithuanian conditions. The manufacturing phase includes acquisition and registration tax; the operation phase includes maintenance and fuel price; the end-of-life phase includes only deregistration tax. When owners of a specified vehicle intend to discard their vehicles as waste, they have to deposit that vehicle at an authorised treatment facility for proper treatment and recovery, which is free of charge; therefore, it was omitted. All the costs include a value-added tax of 21%.

The results show that hybrid and battery electric cars have the highest costs because of the high purchase prices, while internal combustion vehicles have the lowest prices. However, comparing the operation stage, the electric cars are approximately 37% less costly than diesel cars and 60% less than petrol cars. It is assumed that an electric car is charged at home at the average cost of electricity of 0.13 Eur/kWh in 2019 for household consumers [51]. This charging scenario was used because charging at the public charging stations is more unpredictable due to the prices' differences and more rare and stochastic usage. Moreover, the operation costs for electric car owners can be even less because most public charging stations are free of charge.

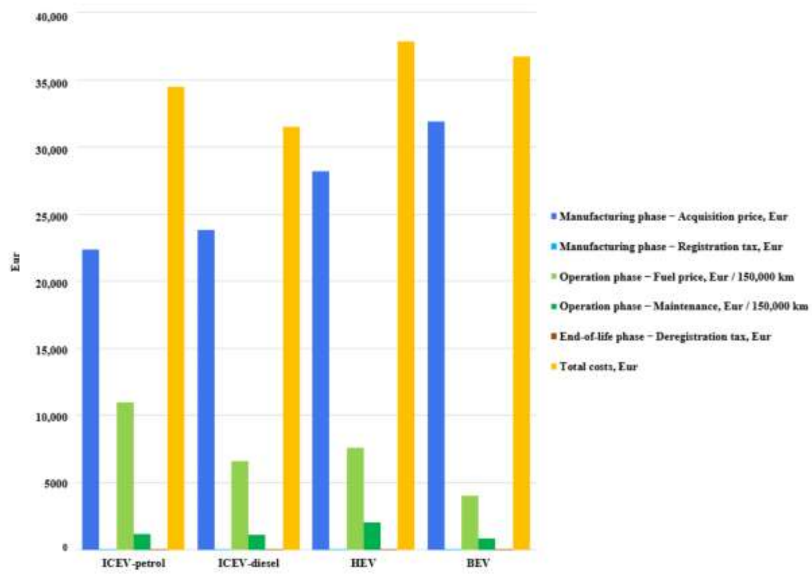

Figure 6. The results of the life cycle costing (LCC) from consumer perspective.

In 2020, spring financial incentives have been implemented to promote the purchase of electric passenger cars. Consumers can potentially receive a compensation of 2000 Eur to purchase a used electric car and 4000 Eur for the purchase of a new electric car. Therefore, Table 4 shows the same comparative results of the LCC from a consumer point of view, but with the compensation included.

Table 4. Total consumer life cycle costs.

Total Consumer Life Cycle Costs								
Passenger Vehicle	Manufacturing Phase		Operation Phase		End-of-Life Phase	Revenues	Total Costs, Eur/150,000 km	Total Cost, Eur/km
	Acquisition Price, Eur	Registration Tax, Eur	Fuel Price, Eur/150,000 km	Maintenance, Eur/150,000 km	Deregistration Tax, Eur	Compensation		
ICEV-petrol	22,328	21.68	10,954	1186	2.9	0	34,492	0.23
ICEV-diesel	23,831	21.68	6581	1072	2.9	0	31,508	0.21
HEV	28,190	21.68	7590	2034	2.9	0	37,839	0.25
BEV	31,880	21.68	4017	817	2.9	−4000	32,739	0.22

Comparing the total costs, the results indicate that electric and diesel cars are the most competitive, where the total consumer life cycle costs are approximately 5–15% less than others.

3.4.2. Results of the LCC from Manufacturer Side

A complete life cycle cost analysis should be performed not only on the consumer side, but also for the manufacturer. Therefore, Figure 7 presents the results from the manufacturer side, combining the manufacturing phase, which includes the passenger car and battery production, the operation phase, with fuel production and distribution and road and car maintenance, and the end-of-life phase, with manual dismantling, treatment of glider, powertrain or internal combustion engine, and batteries.

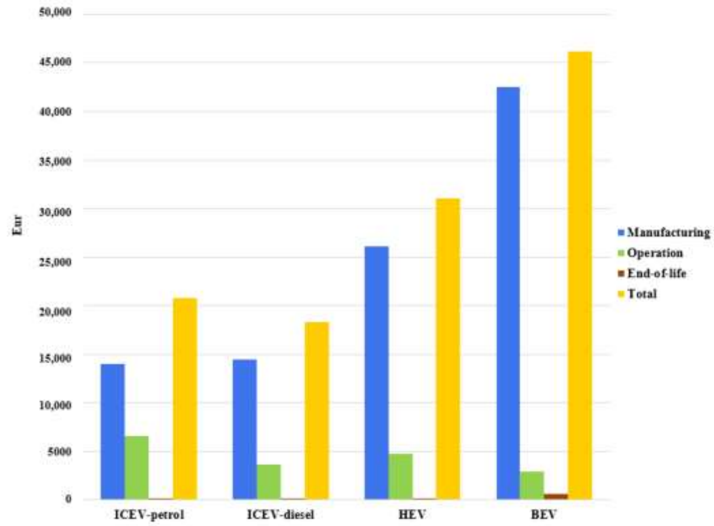

Figure 7. The results of the LCC from manufacturer perspective.

As mentioned in the methodology, the values were obtained using OpenLCA software with the Ecoinvent v3.5 database. It is necessary to mention that the data from the database were provided for 2005. Accordingly, due to data limitations, the results may differ from the present times. Nevertheless, the analysis intended to highlight that these results are similar to the previous graph in that the BEV has the highest costs in the production stage and the lowest costs during the operation stage.

3.4.3. Electricity Production Costs for 2020 and 2040 Scenarios

Electricity production plays a critical role in measuring the most advantageous electricity mix and the most cost-effective time to charge the BEV. Figure 8 shows a comparison of electricity production costs (euro cent/kWh) for 2020 and 2040, which are projected under Lithuanian conditions.

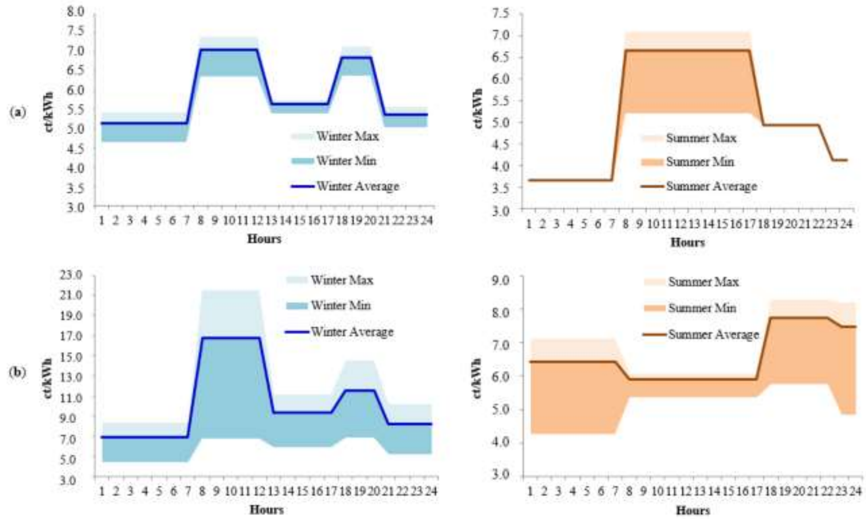

Figure 8. The results of electricity production costs for (**a**) 2020 and (**b**) 2040.

The present results show that in the winter and summer seasons of 2020 as well as in the winter of 2040, the most cost-effective price to charge the BEV is from the late evening until 7 a.m. The short time interval in the middle of the day in terms of the price of electricity is also favourable for charging electric cars. In the summer season of 2040, the cheapest electricity is from 8 a.m. to 5 p.m. This is because solar energy is the dominant source (30%) in the 2040 scenario and generates excess energy during the summer. On the contrary, in 2020, solar energy accounts for only 6% of the electricity mix and the dominant source is wind (37%); therefore, solar energy does not generate excess energy during the summer, which leads to a higher price from 8 a.m to 5 p.m., while the cost-effective price is from the late evening until 7 a.m. In addition, it should be mentioned that the volatility of wind and solar power generation increases electricity price fluctuations. This is clearly seen when comparing the possible price deviations from the average price in 2020 and 2040. The use of smart BEV charging options would partially rationally use these electricity price fluctuations to increase transportation efficiency as well as contribute to balancing electricity generation and consumption at individual points in time.

4. Conclusions

This research aims to reveal the current situation in Lithuania according to the existing information, technologies, and available databases. The main focus in LCA was assessment of BEV's performance with different electricity mix scenarios prognosticated using scientific modelling for the years 2015–2050, according to the goals stated in National Energy Independency Strategy of Lithuania. The idea was to show how the impact on the environment would change if the electricity mix used to recharge the battery was generated from various proportions of renewable energy sources.

In accordance with the assumptions and limitations declared in the methodology, the following conclusions of LCA and LCC were drawn. The results at the midpoint level showed that all over the entire life cycle, the BEV with the 2015 electricity mix is advantageous in terms of fossil resource scarcity and ionising radiation, while the HEV and ICEVs caused a lower impact on global warming, land use, and human cancerogenic and non-carcinogenic toxicity. However, in the 2020–2050 electricity mix scenarios, renewable energy sources will be increased significantly. As a result, in terms of global warming, the contribution of the BEVs (electricity mix of 2050) will decrease by approximately 40%. Endpoint results showed that the petrol car has the most environmental damage (especially in resources). The HEV and BEV with the electricity mix of 2015 cause the same environmental damage, which is 14% less than that of the ICEV-petrol. Next, the ICEV-diesel contributes 10% less impact than the HEV. Furthermore, the BEVs with the 2020–2050 electricity mix scenarios, which are composed primarily of RESs, have the least environmental damage. As a result, the BEV with an electricity mix of 2050 contributes 43%, 33%, and 27% smaller environmental impacts than the ICEV-petrol, BEV (electricity mix of 2015), and ICEV-diesel, respectively.

A life cycle cost analysis was carried out from an economic perspective for the same passenger cars to estimate and compare costs over the life cycle under Lithuanian conditions. The life cycle cost analysis indicated that electric and diesel cars are the most competitive, where the total consumer life cycle costs are approximately 5–15% less than the others. In addition, the analyses from both the manufacturer and consumer sides determined that the BEV is the most cost-efficient vehicle during the operation stage (with approximately half less expenses), which can be even more beneficial if the BEV is charged from the late evening until 7 a.m.

More research is necessary not only from an environmental and economic perspectives but also from a social aspect. A social life cycle analysis would be valuable to better understand all the advantages that electric mobility can ensure as well as to fulfil the analysis of the life cycle sustainability assessment.

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Environmental and economic benefits of electric, hybrid and conventional vehicle treatment: A case study of Lithuania

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ABSTRACT

Reuse, recovery, and recycling of end-of-life vehicles (ELVs) are encouraged owing to various economic and environmental benefits. Automotive remanufacturing serves as a specific circular marketing system for the reuse of recovered parts that can bring economic benefits for both dismantling companies and consumers. This study aimed to reveal the economic and environmental benefits of the end-of-life treatment of electric, hybrid, and conventional passenger cars. This research presents an economic assessment of the reuse of ELV parts based on a material flow analysis (MFA) and a practical analysis of the prices of these parts in the Lithuanian market. The environmental assessment of the reuse of ELV parts was performed using an MFA, the CO_2 equivalents for the production of different materials, and a life cycle assessment methodology. The results showed that 38% of all electric and hybrid ELV parts, and 27% and 28% of diesel- and petrol-powered ELV parts, respectively, can be sold (reused). The economic benefit across all four types of ELVs could amount to savings of up to 12,739 Eur and 51,281 Eur for the dismantlers and passenger car consumers, respectively. The greatest CO_2 savings result from reusing the parts of electric ELVs, whilst the lowest savings come from petrol ELVs.

1. Introduction

According to the principles of a circular economy, reuse, remanufacturing, and refurbishing strengthens the global economy (Korhonen et al., 2018). Automotive recycling plays a significant role in improving both the environmental and economic sectors, especially with an increasing number of end-of-life vehicles (ELVs) being generated worldwide (Eurostat. Statistics explained, 2021). Therefore, the European Commission seeks to revise Directive 2000/53/EC on ELVs by the end of 2022, proposing the improved collection, treatment, and recycling of ELVs in order to ensure consistency with the objectives set out in the Circular Economy Action Plan and the European Green Deal (European Commission, 2020a). According to the Circular Economy Action Plan, the Commission will also propose to revise the rules on end-of-life vehicles with a view to promote more circular business models by linking design issues to end-of-life treatment, considering rules on mandatory recycled content for certain materials of components, and improving recycling efficiency (European Commission, 2020b). Furthermore, the European Green Deal identifies vehicles as a product where "the Commission will consider legal requirements to boost the market of secondary raw materials with mandatory recycled content." (European Commission, 2019). Therefore, the use of secondary resources, promotion of ELV recycling technologies, and the increasing use of recovered and recycled materials provide a promising outlook to gain economic and environmental benefits.

As ELVs are considered hazardous waste, proper management of them is essential to improving a country's environmental performance. As waste avoidance is among the top priorities of waste management, and the reuse of vehicle parts is a key aspect in this endeavour, it is important to clarify the significance of this process from an environmental and economic perspective.

In 2020, there were 1,558,977 registered passenger cars in the Lithuanian market (State enterprise "Regitra", 2021), meaning that more than 50% of Lithuanian residents own cars. Economic growth and an increasing pace of life have led to an increase in the number of registered passenger cars, and in turn, an increase in the number of ELVs. In 2020, there were 138,289 ELVs generated in Lithuania (State enterprise "Regitra", 2021). Directive 2000/53/EC on ELVs states: "No later than 1 January 2015, for all ELVs, the reuse and recovery shall be increased to a minimum of 95% by an average weight per vehicle and year. Within the same time limit, the reuse and recycling shall be increased to a minimum of 85% by an average weight per vehicle and

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year" (European Parliament and the Council, 2000). According to the data of the Environmental Protection Agency of Lithuania, in 2018, the ELV reuse and recovery rate reached 95.4%, and the reuse and recycling rate was 92.4%. European Union (EU) member states are required to meet these targets, while car manufacturers and importers must meet the requirements suggested under the extended producer responsibility. Under the producer responsibility principle, vehicle manufacturers and importers are responsible for the environmental impact of vehicles they place on the market throughout their life cycle. This covers all stages from production to safe treatment of ELVs, and includes the organisation and financing of collection, transport, recycling, recovery, and disposal systems; the performance of ELV management tasks; the provision of information regarding vehicles and their waste management to users and waste managers, and; the acceptance, management, and financial responsibility for such activities (Seimas of the Republic of Lithuania, 1998).

However, the large number of unreported, `missing vehicles`, remains an important issue that needs to be addressed. According to research performed by the Environmental Protection Institute in 2017, approximately 82% of ELVs in Lithuania were dismantled illegally. This illegal dismantling of ELVs means that the country may not collect taxes from 33 million euros per year receivables for the waste delivered (Environmental Protection Institute, 2018). Shadow ELV treatment persists in the EU, and according to a study carried out by the Oeko-Institut e.V. (2016), in 2013, between 3.6 and 4.6 million ELVs were not registered in the EU. Companies engaged in illegal ELV dismantling activities often do not dismantle cars to the standards required by the EU. Knowing the economic and environmental benefits of reusing ELV parts will make it easier for decision makers to find arguments for, and promote, legal ELV management activities and increase consumer awareness. While consumers can choose either to buy a used car part or a new one, the prices have a significant impact on their decision making.

The management of ELVs is of considerable importance for circular economy, sustainable development, and environmental conservation, and various studies performed by researchers worldwide focus on ELV management, and the environmental and/or economic benefits of ELV treatment. For example, Karagoz et al. (2020) reviewed 232 studies published between 2000 and 2019 regarding ELV management worldwide. Tian and Chen (2016) performed an environmental and economic analysis of five different ELV dismantling scenarios in China. Additionally, Lin et al. (2018) investigated the material flows and analysed the economics of ELV treatment in small islands using Kinmen, Taiwan as a case study. Petronijević et al. (2020) performed a case study of the Republic of Serbia, where they analysed the potential of the ELV recycling process as an energy generator and presented possibilities for its energy recovery. Their results showed that higher ELV generation rates may lead to higher energy recovery as well as environmental and socio-economic sustainability. Chen et al. (2019) used a life cycle assessment (LCA) model to calculate and analyse the environmental burden caused by dismantling, reverse logistics, and recycling, while simultaneously assessing the environmental advantages of remanufactured engines, recycled materials, and recovered energy. Li et al. (2016) performed a case study of China, using the LCA method to analyse the environmental impact of the three different ELV recycling scenarios (Li et al., 2016). Similarly, Zhang et al. (2020) used the LCA method to establish a cost-profit model and investigate the potential environmental impact and economic benefits of the dismantling process, including equipment and plant factors. Qiao et al. (2019) performed a scientific evaluation on the economic and environmental benefits of electric vehicle recycling in China. Their results indicated that the gross income per electric vehicle recycled is approximately 473.9 USD, and the reductions of energy consumption and greenhouse gas (GHG) emissions are approximately 25.6 GJ and 4.1 t CO_2 eq, respectively. Another study by Qiao et al. (2020) presented both cost and GHG emission benefits for the entire life cycles of EVs in China including battery recycling and material recovery. Belboom et al. (2016) used the LCA method to analyse and calculate the environmental impacts of the three ELV recycling routes in Belgium. Farel et al. (2013) proposed a model to investigate the potential costs and benefits of recycling ELV glazing for value chain stakeholders, and for the network as a whole. The simulation revealed a boost in income and significant cost savings as a result of the recycling network in some future scenarios. Sato et al. (2019) presented a case study of Japan using a material flow analysis (MFA), where the benefits of ELV recycling were calculated, and the energy and CO_2 reductions were assessed, valuing 52.8 MJ and 2.80 kg CO_2 per kilogram of a vehicle, respectively. Finally, Yi and Lee (2021) investigated the costs and revenues of each ELV treatment process in Korea, using data from operators to estimate their economic feasibility. The results revealed that ELV dismantling accounts for the largest part of the total cost of the ELV recycling process, pointing to the need for policies that provide financial support to ELV dismantlers to enhance the overall ELV recycling rate.

Despite these studies, no studies have yet been performed on the economic assessment of electric, hybrid, and conventional passenger car treatments in Lithuania. Lithuania was chosen as a representative country because it fulfils the recycling and recovery targets stated in Directive 2000/53/EC, and has initiated the integration of EVs into city transport systems which corresponds to both the national and the EU goals to become climate-neutral by 2050. Lithuania has an old car fleet, with an average age of 16 years, and thus has immense potential to achieve the circular economic goals by promoting the reuse, repair, and remanufacturing of old vehicles and their parts. Furthermore, Lithuanian car dismantling companies rely on the International Dismantling Information System (IDIS), which provides information on car parts, their safe dismantling, and composition.

The aim of the present research is to assess and compare the economic and environmental benefits of waste treatment and upcycling of battery electric vehicles (BEVs), hybrid electric vehicles (HEVs), and internal combustion engine vehicles (ICEVs). By using an MFA, CO_2 equivalents for different car parts materials, and a life cycle assessment methodology, this study aims to assess the economic and environmental aspects of ELVs of each engine type after dismantling. In addition, practical research was performed to reveal the prices if the car owners bought all the necessary car parts from dismantling companies for further reuse. Following this, the prices of the used car parts from the dismantlers were compared with the prices of the new ones placed on the market with an aim of showing the economic benefit this may present. Supplementary practical research was then conducted in order to assess the financial benefit for the dismantlers who generate revenue from the used car parts when sold to car owners, and from waste sold to waste management companies.

This study is novel as it provides a comprehensive and comparative environmental and economic analysis of various types of ELV passenger cars. Furthermore, it applies directly to Lithuanian conditions, and focuses on the analysis of CO_2 emission savings when reusing car parts after ELV dismantling. Finally, the analysis adds a comparison of LCA results focusing on the production and end-of-life phases of the BEV, HEV, and ICEVs powered by diesel and petrol.

2. Methodology

Various methodologies were employed to assess the environmental and economic benefits of electric, hybrid, and conventional vehicle treatment; and the study can be divided into four parts as follows: 1) using the MFA, which helps in understanding the ELV material flow movements; 2) performing an economic assessment of each type of car and evaluating the economic benefits of used car parts for ELV dismantlers and consumers; 3) using CO_2 equivalents per kilogram of a substance emitted during its production to estimate and present CO_2 emissions savings per vehicle; the generated amount of CO_2 emissions from the production of each car component allows the assessment and comparison of the environmental benefits of reusing car parts; and 4) applying an LCA methodology to assess the environmental impact throughout the production of the end-of-life stages of the selected vehicles. The methodology is presented in Fig. 1.

2.1. Inventory analysis

The study aimed to show the current situation in Lithuania according to existing technologies, information, and available databases. As reported by the State Enterprise "Regitra" (2020), the most popular used BEV, HEV, and ICEVs registered in Lithuania are the Nissan Leaf 2011–2013, the Toyota Prius 2003–2009, and the Volkswagen Golf Plus 2005–2008. These car models were selected for the comparative analysis, and an inventory analysis is provided in Appendices A–D, which show all the car components, composite materials, and weights.

2.2. Material flow analysis of ELVs management

An MFA is a systematic assessment of the flows and stocks of materials within a system (Brunner and Rechberger, 2016), where the system is defined in space and time, and connects the sources, pathways, and intermediate and final sinks of a material. The MFA method is a practical decision-support tool for waste, resources, and environmental management. The results are represented using the substance flow analysis (STAN) software, which performs the MFA according to the Austrian ÖNORM S 2096 standard taking into consideration data uncertainties. Having built a graphical model with predefined components (flows, subsystems, system boundaries, and text fields), the known data (mass flows, stocks, concentration, and transfer coefficients) for different hierarchical layers (good, substance, energy) and time periods with their corresponding physical units can either be entered or imported. A graph of the model is shown in the form of a Sankey diagram where the width of a flow is proportional to its value (TU WIEN, 2012). The MFA for ELV management was performed using statistical information from the State enterprise "Regitra" (2021), and information regarding car parts, such as mass, composite and hazardous substances, can be found from the website of the International Dismantling Information System (IDIS) (2021). IDIS is an advanced and comprehensive information system which provides access to an extensive database with practical information on pre-treatment, dismantling and other elements of ELVs. It was developed in compliance with the requirements in Directive 2000/53/EC which state that vehicle manufacturers are required to provide information on vehicle dismantling, thus facilitating the availability of information to dismantlers. The system also provides information on the safe removal, storage, and recycling of parts from the vehicle.

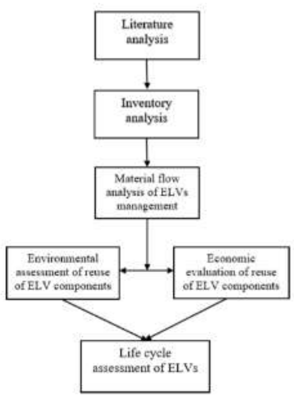

Fig. 1. Methodology scheme.

ELV dismantling companies have provided the necessary information to clarify the path of material flows of ELV parts and waste; the boundaries of the MFA system range from the entry of the ELV into the dismantling company, to the entry of the materials into recycling, energy recovery, export, disposal, and preparation of reuse activities. The main processes in ELV management are visual inspection, dismantling, and the sorting of parts into hazardous and non-hazardous waste, and reusable parts. Hazardous and non-hazardous waste is transported to waste management companies, while car parts that are suitable for reuse are sold to consumers.

2.3. Economic evaluation of reuse of ELV components based on material flow analysis

Various e-shops selling car parts were checked to obtain car part pricing information to conduct the economic assessment. Webpages such as https://autoplius.lt, https://skelbiu.lt, https://autodoc.lt, https://autoaibe.lt, and https://srotas24.lt, were checked, where it is possible to select and match the prices of the car parts according to the exact model of the car. Additionally, car part distributors in Lithuania were interviewed to verify the prices of some rarer new parts, and five local ELV dismantling companies were also interviewed about each part's demand in the Lithuanian market. The prices were then compared with various e-shops and averaged, with the average price being used in the analysis. The economic benefit for dismantlers was evaluated by calculating the prices of the used parts, waste management costs, and the economic value of secondary materials. Human labour, and maintenance of equipment and premises were not evaluated as part of the economic analysis.

2.4. Environmental assessment of reuse of ELV components based on material flow analysis and CO_2 equivalents

The environmental assessment focused on CO_2 savings that were estimated using CO_2 equivalents per kilogram of each car material emitted during the production of the car parts and components. In this manner, it was possible to assess the environmental benefits of reusing car parts after ELV dismantling, as the reuse saves 100% of energy and necessary materials for the production of new parts. This methodology was chosen based on the studies performed by Rovinaru et al. (2019) and Sato et al. (2018), who used the MFA method and CO_2 equivalents defined per car material production. As not all parts are reusable, only reusable parts were assessed, with the car parts with a high and medium probability of reuse being assessed with a 100% and 50% reduction in kg CO_2 emissions, respectively, while parts with a low probability of reuse were not assessed.

The ecological footprint of certain materials was calculated according to the formulas presented in a previous study Sato et al. (2018). The ecological footprint in the production of plastics, rubber, aluminium, steel, and fluids was calculated according to Formula (1):

$$EF_{materials} = E1 \times m, \quad (1)$$

where:

$EF_{materials}$ is the ecological footprint, kg CO_2
E1 is the ecological footprint in production, kg CO_2/kg, and
m is the mass of material, kg.

The ecological footprint in the production of lead and lithium-ion batteries was calculated according to Formula (2):

$$EF_{Li-ionbatteries} = (E1 \times m) + (E2 \times e), \quad (2)$$

where:

$EF_{Li\text{-}ion\ batteries}$ is the ecological footprint of the battery, kg CO_2
E1 is the ecological footprint in production, kg CO_2/kg
m is the battery mass, kg
E2 is the ecological footprint of the battery, kg CO_2/kWh, and
e is the maximum amount of battery power that can be disposed of, kWh.

The ecological footprint in the production of NiMH batteries was calculated according to Formula (3):

$$EF_{NiMH batteries} = E2 \times e \tag{3}$$

where:

E2 is the ecological footprint in production, kg CO_2/kWh, and
e is the maximum amount of battery power that can be disposed of, kWh

When determining the CO_2 saving potential, the values of CO_2 emitted per type of material in the vehicle production process were used from the studies performed by Baumann et al. (2017), Majeau-Bettez et al. (2011), and Sato et al. (2018). These are presented in Appendix E.

2.5. Life cycle assessment of ELVs

An LCA was used for the environmental analysis of selected passenger cars. According to Hauschild et al. (2018), the LCA is an effective tool that can be used in the field of electric mobility to answer questions regarding comparisons between different engine types of vehicles, and investigate various end-of-life scenarios, mainly regarding the treatment of the main components, especially car body, electric motors, and batteries.

The LCA of BEV, HEV, and diesel and petrol ICEVs was carried out following the procedure and recommendations indicated in the European standards series ISO 14040 (2006), and ISO 14044 (2006). The aim of this LCA was to evaluate environmental impacts throughout the production and end-of-life stages of each type of vehicle. The production stage includes the manufacture of the vehicle and the batteries. The end-of-life stage involves the manual dismantling of a vehicle; treatment (shredding) of the used powertrain, glider, and internal combustion engine; treatment of the used Ni-metal hydride and Li-ion batteries through a pyrometallurgical and hydrometallurgical process, respectively; and sorting and remelting of the lead contained in the lead acid battery. Due to the limitations of the database, it was not possible to select individual automotive parts at the production stage or a greater variety of automotive parts' treatment in the end-of-life stage.

The environmental emissions of the selected vehicles were based on a functional unit of "1 km driving distance" and the environmental burden was assessed for a 150,000 km driving distance. The environmental impacts were calculated for the life cycle, considering that no battery replacement was required for the electric vehicle; in this analysis, one battery was used during the total mileage of the BEV. As the average age of passenger cars in the Lithuanian vehicle fleet is 16 years, it should be noted that a mileage of 150,000 km may not lead to the end-of-life stage in all vehicles types in the current practice (State enterprise "Regitra", 2021). Therefore, the study assumed that the BEV, HEV, and ICEVs could drive 150,000 km as the baseline for the life cycle analysis.

The ReCiPe method was used at the midpoint level, and the environmental impact categories were determined as those with the greatest values identified in the study: global warming (kg CO_2 eq), fossil resource scarcity (kg oil eq), human non-carcinogenic toxicity (kg 1,4-DCB), and human carcinogenic toxicity (kg 1,4-DCB) (National Institute for Public Health and the Environment, 2017). For the life cycle impact assessment and interpretation, database Ecoinvent 3.5 (Ecoinvent v3, 2019) and SimaPro 9.1 software were used (PRé Sustainability, 2021).

3. Results and discussion

3.1. The results of material flow analysis

The results are presented in Table 1, which shows the material composition of the vehicles. The weights of the ICEV parts differed slightly, with the largest differences being observed in the weight of steel, owing to the different weights of the engines and body. Electric cars contain the most electronics, as they require high-voltage batteries weighing 292 kg and other electronics to operate. In addition, an electric car has fewer parts made of mixed plastic, with most plastic parts made of polypropylene. This can be attributed to the fact that electric cars are newer and follow the provisions of Directive 2000/53/EC on ELVs, which states that passenger cars must be easier to recycle. As the manufacturer is responsible for complying with the directive, the use of non-recyclable mixed plastics is therefore restricted.

Fig. 2 shows the distribution of mass flows of each car type according to different treatment areas based on the 2019 data published by the Environmental Protection Agency of Lithuania and the information provided by waste management companies. The obtained data show that the recycling of materials (53–68%) and reuse (27–38%) predominate, while the smallest proportion of materials is directed to energy recovery (0.6–2.71%). The majority of the recyclable materials came from ICEVs, whereas the majority of reused parts were from electric-powered cars. Exports of materials were fairly even, amounting to approximately 2% by weight of each car. Landfilling was also fairly even, but hybrid cars contributed the largest share of materials transported to landfills at 3.6%, as these cars contain the most hazardous waste that cannot be reused or recycled. The share from other cars varies between 0.8% and 1.8%. Hybrid cars also contributed the largest share of combustible materials at 2.7%, whereas the share of combustible materials from other cars varies between 0.6% and 1.3%. The high amount of waste from hybrid cars is used for energy recovery as it has the largest proportion of mixed plastic that cannot be recycled.

Based on information regarding ELV treatment in Lithuania and the data on deregistered cars by fuel type (Appendix F), the MFA of the petrol, diesel, hybrid, and electric ELV passenger car treatment was performed and presented in a Sankey diagram, which graphically displays the material flows (Fig. 3). Here, the number of deregistered cars

Table 1
Composition of the analysed passenger cars by materials.

Material	Mass of material, kg			
	Volkswagen Golf (petrol)	Volkswagen Golf (diesel)	Toyota Prius (electricity + petrol)	Nissan Leaf (electricity)
Polypropylene	10.95	10.95	71.24	52.90
Acrylonitrile butadiene styrene	0.88	0.88	1.64	0.00
High density polyethylene	0.00	0.00	2.23	0.00
Polyurethane	7.49	7.49	7.80	10.47
Polyethylene terephthalate	3.22	3.22	9.57	8.27
Mixed plastics	16.93	16.93	43.76	8.14
Steel	933.20	1,116.90	891.45	1,058.45
Electronics	22.75	23.25	79.20	306.14
Glass with polyvinyl butyral	29.20	29.20	34.84	28.12
Aluminium	16.10	15.75	57.28	0.75
Fluids	16.93	16.93	16.06	14.14
Hazardous materials	49.33	49.33	39.61	31.01
Other mixed materials	6.55	3.40	3.50	2.92
Rubber	33.20	33.20	37.95	22.80
Total	**1,147.57**	**1,327.44**	**1,296.12**	**1,544.11**

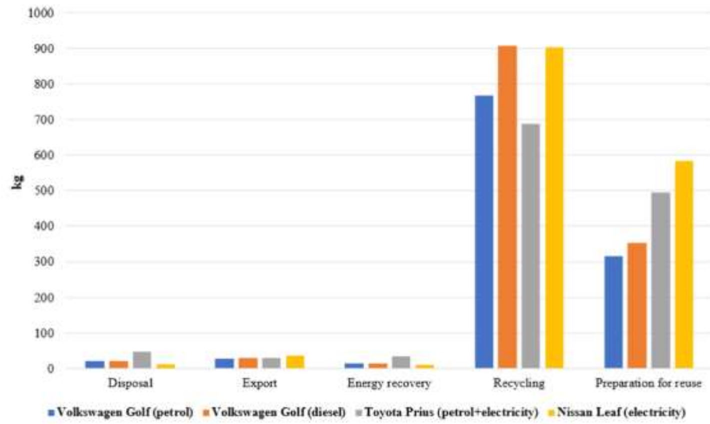

Fig. 2. Treatment of the ELVs in Lithuania (Environmental Protection Agency of Lithuania, 2020).

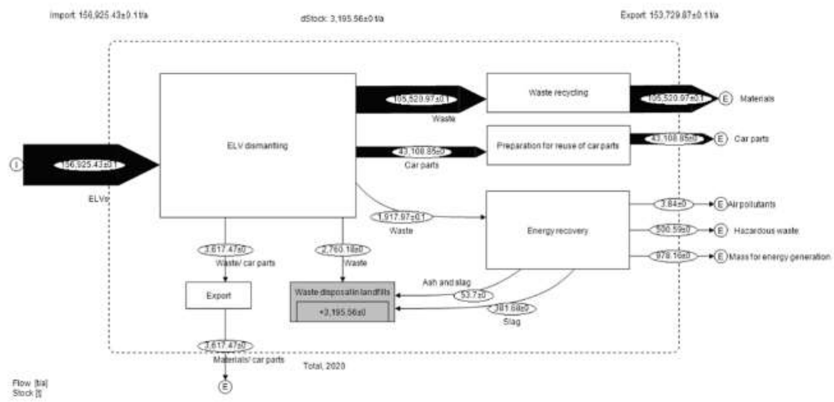

Fig. 3. Flow diagram of materials/waste of ELVs after dismantling.

was multiplied by their mass, and the mass flows showing ELV treatment (disposal, recycling, preparation for reuse, export, energy recovery) were distributed accordingly, showing the total material flows resulting from ELV dismantling in 2020. The material flows generated after the energy recovery process were based on proportionate calculations from the environmental impact assessment reports of waste incineration plants (Environmental Protection Agency of Lithuania, 2016; JSC "AF-Consult" and JSC "Toksika", 2014).

3.2. The results of economic and environmental assessment of the reuse of ELV components

3.2.1. The results of economic assessment

An economic analysis was performed to investigate which parts of an ELV could be reused for the same purpose. Similar to the environmental assessment, the data showing the car part demand on the market (Appendices A–D), were used. In-demand parts and average in-demand parts were rated as 100% reusable and 50% of the total weight of the part, respectively, whereas parts not in-demand were not evaluated. Next, the cost of the used and new parts, and waste treatment were analysed, with results showing that a significant proportion of ELVs could be reused (Table 2).

Table 2
Economic benefit of the selected vehicles to the car users and waste treatment companies/dismantlers, and the proportion of car mass that can be reused.

Passenger car	The share of passenger cars mass that can be sold as parts for reuse after dismantling, %	Price of used parts, Eur	Price of new parts, Eur	Economic benefit for consumers, Eur	Economic benefit for dismantlers, Eur
Volkswagen Golf (petrol)	28	2,640	13,460	10,815	1,753
Volkswagen Golf (diesel)	27	2,845	17,480	14,635	1,997
Toyota Prius (petrol + electricity)	38	4,001	21,429	17,428	3,471
Nissan Leaf (electricity)	38	8,334	16,737	8,403	5,518

The results revealed that the Nissan Leaf and Toyota Prius accounted for the largest share of car parts reuse (38%). Simultaneously, the lowest share of parts reuse belonged to the diesel (27%) and petrol (28%) VW Golf. The economic benefits for the car dismantling companies range from 1753 Eur to 5518 Eur, from the petrol VW Golf to the electric Nissan Leaf, respectively. In terms of the economic benefits to users of the car parts, the Toyota Prius provided users benefits of up to 17,428 Eur, and the Nissan Leaf provided the least benefits, at 8403 Eur. As a result, Toyota Prius owners may feel much more motivated to look for alternatives instead of buying a new part. Similarly, buying used car parts of the diesel and petrol VW Golf also provided an economic benefit of 14,635 Eur and 10,815 Eur, respectively, to users.

Referring to the numbers of passenger cars deregistered in 2020 by the type of fuel (Appendix F), and assuming they were dismantled in Lithuania, the total economic benefit to consumers, and dismantlers in Lithuania would amount to 1.64 billion EUR and 0.24 billion EUR, respectively. According to the surveyed dismantling companies, not many electric cars are reaching their end-of-life stage as they are newer than 16 years and still convenient to use, except in the event of an accident. This explains the small price difference between the new and used parts of the Nissan Leaf—the small supply of these parts leads to a higher price in the used parts market.

When assessing the economic benefits, the cost of treatment of car parts that are not in demand on the market was also assessed (Appendix G). The table reveals the economic situation when ELV dismantling companies (as ELV receivers) have to deliver unnecessary car parts to waste management companies for further waste treatment. Some car parts incur costs for dismantling companies, such as filters, cloths, coolants, brake fluids, glass, rubber, tires, plastics, and oil, while they generate revenue for batteries, shock absorbers, ferrous and non-ferrous metal.

3.2.2. *The results of CO_2 emission reduction from reusable parts*

The study assessed and compared the environmental benefits of reusing ELV components by estimating how many kg of CO_2 emissions would be saved if car owners choose to purchase used car parts. Appendices A–D and Table 3 show the estimated potential CO_2 emission savings from the production of various car parts.

Table 3
The results of the environmental assessment – CO_2 saving potential from reusable car parts.

Passenger car	CO_2 emission savings from reusable car parts, kg (per one unit)	CO_2 emission savings from reusable car parts, kg per year (estimating the total amount of deregistered ELVs)
Volkswagen Golf (petrol)	1,828	101,122,756
Volkswagen Golf (diesel)	1,880	124,629,939
Toyota Prius (electricity + petrol)	2,403	9,983,001
Nissan Leaf (electricity)	6,420	776,871
Total	**12,531**	**236,512,567**

The results revealed the highest CO_2 saving potential is from the electric ELV, at 6,420 kg. This is because the electric car has a high-voltage lithium-ion battery that emits more than 8,241 kg of CO_2 during production. As the probability of resale of these batteries is average, 50% of the CO_2 emissions were taken, amounting to an estimated 4,120.5 kg reduction for the lithium-ion battery alone.

The CO_2 saving potential for petrol and diesel cars differ slightly, at 1,828 kg and 1,880 kg, respectively, with considerably more CO_2 being saved by reusing the hybrid ELV parts, at 2,403 kg. The highest CO_2 savings in these cars are from lead acid batteries, wheels, and tires, which are 100% reusable, with further saving from reuse of the engine, radiator, tailgate, bumper, etc.

The study found that the overall environmental benefit of parts reuse in Lithuania is a saving potential of approximately 236,513 t CO_2 emissions, however, car parts composed of several different components were not evaluated because the exact data on how much and which material was used in the production were not known.

The results of this research were also compared with those of two other studies performed by Rovinaru et al. (2019) in Romania and Sato et al. (2018) in Japan. While each of the selected previous studies selected one petrol or diesel (not specified) car for analysis, this study analysed four different types of cars. Additionally, Rovinaru et al. (2019) only assessed the CO_2 saving potential for steel and aluminium car parts by selecting equivalents but did not assess which parts were in demand in the market and which were not. While the results of the study by Rovinaru et al. (2019) showed twice the CO_2 saving potential compared to this study, a comprehensive comparison was not deemed possible due to the underestimation of the market demand of car parts and the reuse of different materials. Sato et al. (2018) evaluated all the materials of the car and had a comprehensive database of sales of various car parts on the market. They could therefore accurately determine market demand, and obtained a lower CO_2 saving potential compared to Rovinaru et al. (2019), but a similar CO_2 saving potential to that found in this study; perhaps as the same methodology was used, and the market demand for the used car parts was assessed in both studies.

3.2.3. *The results of the life cycle assessment*

The results of the LCA at the midpoint level regarding the analysed environmental impact categories of BEV, HEV, and diesel and petrol ICEVs reveal the impacts of production and end-of-life stages in the categories of global warming, fossil resource scarcity, human non-carcinogenic toxicity, and human carcinogenic toxicity as those with the major values identified in the research (Fig. 4).

For the environmental impact assessment using the available databases, the main vehicle parts, such as the glider, internal combustion engine/powertrain, Li-ion (from BEV), and Ni-metal hydride (from HEV) batteries were analysed. According to Eurostat statistics (2020), automotive batteries are recycled by up to 80%, while the glider and engine/powertrain are made mostly from metal, which can be melted and used for the same purpose an infinite number of times. Therefore, it was assumed that the glider and internal combustion engine/powertrain were recycled at 100%, and batteries at 80%, which means that the recovered amounts of materials can be used in production and save CO_2

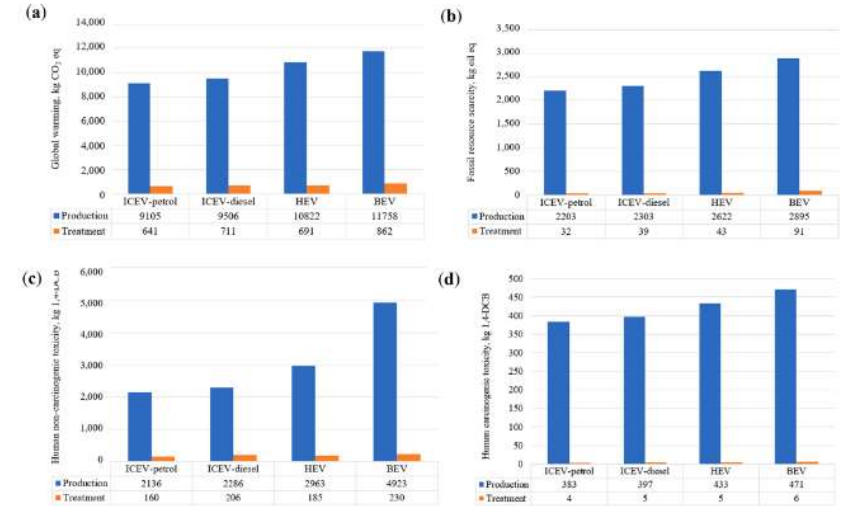

Fig. 4. BEV, HEV, and ICEVs life cycle assessment of the impact categories: (a) global warming; (b) fossil resource scarcity; (c) human non-carcinogenic toxicity; (d) human carcinogenic toxicity.

emissions. The results showed that in the selected impact categories, EVs had the highest impact in both production and end-of-life stages compared to the other analysed vehicles. This is because Li-ion battery production and treatment have a significant impact on environmental evaluation. Furthermore, the LCA results revealed the importance of waste treatment which, for example, in the global warming category, causes only 6–7% of the total CO_2 emissions which are generated during the production stage.

4. Conclusions

This study aimed to reveal the current situation of ELV treatment in Lithuania based on existing information and available databases. The main focus of the economic and environmental assessment was to assess the benefits of the treatment of passenger cars with different engine types. An MFA showed that most of the ELV materials were recycled (53–68%) and reused (27–38%), with only a minority being directed to energy recovery (0.6–2.71%), and the rest to disposal in landfills or exports.

The results of the economic assessment showed that 38% of the mass of electric and hybrid ELVs and 27% and 28% of diesel and petrol powered ELVs, respectively, can be sold as parts (reused), which would save up to 12,739 Eur and 51,281 Eur (of the four ELVs) as an economic benefit for the dismantlers and owners, respectively. Furthermore, when estimating the total amount of deregistered ELVs per year (diesel, petrol, hybrid and electric passenger cars), the annual economic benefit of reuse of car parts in Lithuania for dismantlers and owners would be 0.24 billion EUR and 1.64 billion EUR, respectively.

The results of the environmental analysis of different ELVs using material flows and ecological footprint equivalents for each material showed that electric cars have the greatest potential to contribute to CO_2 emission savings, with 6,420 kg CO_2 saving potential per unit. Hybrid, diesel, and petrol cars follow with 2,403, 1,880, and 1,828 kg CO_2 saving potential per unit, respectively. Furthermore, when estimating the total amount of deregistered ELVs per year, the annual environmental benefit of reuse of car parts in Lithuania would amount to a saving potential of 236,512 t CO_2 emissions.

The results of the LCA showed that the end-of-life stage treatment of the glider, internal combustion engine/powertrain, Li-ion (from BEV), and Ni-metal (from HEV) batteries only account for 6–7% of the environmental impact of the production of the analysed cars. Thus, ELV treatment is a crucial factor for better environmental performance and conservation of raw materials. Owing to Li-ion battery production and treatment, the BEV has the most significant environmental impact in all the selected impact categories compared to the other analysed passenger cars.

This study has confirmed the importance of the vehicle treatment industry and its potential for environmental performance development and economic growth that supports the principles of a circular economy. Such insights can encourage policymakers and other groups of interest to improve policies and strengthen support regarding ELV treatment, which could lead to even greater economic, environmental, and social benefits. Furthermore, improved policies would contribute to the reduction of illegal ELV treatment and their harmful impact within and outside the EU, a reduction in the volume of waste from ELVs generated every year, increase in the efficiency of materials use, and lower use of raw materials. In addition, the companies involved in the dismantling, treatment, recycling, and sale of ELV parts, are expected to be the most affected by the improved policies, which could lead to the development of their activities. This will result in the creation of jobs in these sectors, which are the core of the circular economy.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary material

Supplementary data to this article can be found online at https://doi.org/10.1016/j.wasman.2022.01.009.

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