Energy planning in Riga

Pathways for a low-carbon energy transformation

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I declare that this document is an original work of my own authorship and that it fulfils all requirements of the Code of Conduct and Good Practices of the Universidade de Lisboa.

Abstract

The city of Riga, being at the forefront of fighting climate change, is in the process of updating their energy planning document, the Riga Smart City Sustainable Energy Action Plan, for the planning period 2020–2030. As Riga surpassed the emission reduction target of the EU for 2030, there is an opportunity for a new ambitious goal and innovative actions to accomplish it. Considering the Intergovernmental Panel on Climate Change’s (IPCC) recommendation of not exceeding a world average temperature increase of 2 °C, suitable targets for Riga are a reduction by 61% (2030) and 70% (2050), respectively, compared to 1990 levels. This paper presents pathways that contain measures that are complementary to the planned actions of Riga and focus on three thematic areas: green hydrogen, solar engagement, and modern transportation. The measures consist of successful European actions modified and applied to the characteristics of Riga. The production of green hydrogen is economically feasible for the city of Riga, achieving a Levelized Cost of Electricity (LCOE) of 0.0395 EUR/kWh and a Levelized Cost of Hydrogen (LCOH) of 3.62 EUR/kg_{H2}. While rooftop solar PV systems are an attractive option for the citizens of Riga if a feed-in tariff of 0.1 EUR/kWh is granted, the employment of solar thermal collectors is not advisable due to the high breakeven duration. Including citizens in renewable projects in the form of voucher return packages is a welcomed alternative loan scheme benefiting both the municipality and the citizens. Furthermore, the development of a microalgae carbon capture pilot project could leverage Riga’s role as an innovation hub. The creation of a fossil-free last-mile delivery zone in the city centre would tackle the challenge of reducing road emissions as electric cargo bicycles have the potential of decreasing emissions by around 99% per trip.

Keywords: Urban energy planning, Emission reduction, Pathways, Renewable energy measures

Resumo

A cidade de Riga, estando na vanguarda da luta contra as alterações climáticas, está a atualizar o seu plano energético (Plano de Ação para a Sustentabilidade Energética), para o período 2020–2030. Como Riga não tem respeitado a meta de redução de emissões da UE até 2030, a cidade tem que definir uma nova e ambiciosa meta e as ações inovadoras para alcançá-la. Considerando a recomendação do Intergovernmental Panel on Climate Change (IPCC) de não exceder um aumento da temperatura média mundial em 2 °C, as metas adequadas para Riga são uma redução de emissões de 61% e 70% até 2030 e 2050, respetivamente, em comparação com os níveis de 1990. As recomendações e perspetivas apresentados nesta dissertação contêm medidas que são complementares às ações já planeadas para Riga e concentram-se em três áreas temáticas: hidrogénio verde, aproveitamento da energia solar e modernização do sistema de transportes. As medidas consistem em ações concretas combinadas com estudos de viabilidade. A produção de hidrogénio verde é economicamente viável para a cidade de Riga, alcançando um Levelized Cost of Electricity (LCOE) de 0,0395 EUR/kWh e um (Levelized Cost of hydrogen) LCOH de 3,62 EUR/kg_{H2}. Embora os sistemas solares fotovoltaicos possam constituir uma opção economicamente viável para os cidadãos de Riga se a tarifa for de 0,1 EUR/kWh, o emprego de coletores solares térmicos não é aconselhável devido ao tempo necessário para recuperar o investimento. Envolver os cidadãos nos projetos de energias renováveis e estabelecer soluções para compensações financeiras pela adoção de soluções energeticamente sustentáveis beneficia tanto o município quanto os cidadãos. Além disso, o desenvolvimento de um projeto piloto de captura de carbono por microalgas poderia alavancar o papel de Riga do ponto de vista da inovação. A criação de uma zona livre de combustíveis fósseis no centro da cidade e o fomento de uso de bicicletas contribuiria para reduzir as emissões poluentes devidas aos transportes, incluindo o uso de bicicletas elétricas que têm potencial para diminuir as emissões em cerca de 99% por viagem.

Palavras-chave: Plano energético, Redução de emissões gasosas, Sustentabilidade, Energia renovável

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List of Acronyms

Acronym	Description
AC	Alternating current
ALK	Alkaline
ATELIER	Amsterdam Bilbao citizen driven smart cities
BAU	Business-as-usual
BEI	Baseline Emission Inventory
CEMR	Council of European Municipalities and Regions
CGET	General Commission for Territorial Equality
CHP	Combined heat and power
CHPP	Combined heat and power plant
CO_2	Carbon dioxide
COP21	Conference of the Parties 21
CoM	Covenant of Mayors
CSS	Carbon capture and storage
DC	Direct current
DH	District heating
DSO	Distribution system operator
DTU	Technical University of Denmark
EC	European Commission
ERDF	European Regional Development Fund
ESO	Electricity system operator
ETS	Emission Trading Scheme
EU	European Union
EUI	European Urban Initiative
FCH JU	Fuel Cells and Hydrogen Joint Undertaking's
FES	Future Energy Scenario
GDP	Gross Domestic Product
GHG	Greenhouse gases
GHI	Global horizontal irradiation
HP	Heat plant
HPP	Hydropower plant
ICT	Information and Communication Technologies
IPCC	Intergovernmental Panel on Climate Change
IRENA	International Renewable Energy Agency
JRC	Joint Research Centre Directorate-General
JSC	Joint-Stock Company
LCOE	Levelized Cost of Electricity
LCOH	Levelized Cost of Hydrogen
LPG	Liquefied petroleum gas

Ltd	Limited company
NRA	National Regulatory Authority
NREL	National Renewable Energy Laboratory
O&M	Operation and maintenance
PBR	Photobioreactor
PEM	Proton exchange membrane
PPM	Parts per million
PV	Photovoltaic
REA	Riga Energy Agency
REPLICATE	REnaissance of PLaces with Innovative Citizenship And TEchnology
RVA	Risk and Vulnerability Assessment
SEAP	Sustainable Energy Action Plan
SECAP	Sustainable Energy and Climate Action Plan
SMR	Steam reforming
STP	Standard temperature and pressure conditions
TEC	Termoelektrocentrāle (Latvian for thermal power plant)
TSO	Transmission system operator
UAEU	Urban Agenda of the EU
UIA	Urban Innovative Action
UDN	Urban Development Network

List of Symbols

Symbol	Description	Unit
A	Annual total cost consisting of fixed and variable operating costs	EUR/year
$A_{aperture}$	Aperture area	m^2
$A_{collector}$	Gross area of the solar collector	m^2
$A_{install}$	Installed collector area	m^2
A_{fixed}	Fixed annual cost	EUR/year
A_{panel}	PV panel module size	m^2
A_{roof}	Roof area including chimneys and other obstacles	m^2
A_{useful}	Total useful roof area that can be used for PV panels	m^2
A_{var}	Variable annual cost	EUR/year
$c_{inv,j}$	Investment cost of component j per installed power	EUR/kW
$c_{inv,k}$	Investment cost per installed power of technology k	EUR/kW
$C_{inv,k}$	Total investment cost of technology k	EUR
$c_{O\&M,j}$	Annual O&M costs of component j	EUR/kW*year
$c_{O\&M,k}$	Annual O&M cost per installed power of technology k	EUR/kW*year
$C_{O\&M,k}$	Total annual O&M cost per installed power of technology k	EUR/year
$C_{savings,k}$	Total savings per year of technology k	EUR/year
c_{water}	Water price	EUR/l
CF_{wind}	Capacity factor of the wind turbine	-
γ	Ratio of specific heat	-
d_{hydro}	Hydrogen density at STP	kg/m^3
E_{com}	Energy input of the compressor	kWh
E_{el}	Annual produced electricity	kWh/year
E_{ELY}	Energy input of the electrolyser	kWh
E_{grid}	Energy delivered to the grid	kWh
E_{hydro}	Energy used for hydrogen production	kWh
E_{PV}	Energy output of the installed PV system	kWh/year
E_{wind}	Energy output of the wind farm	kWh
E_x	Amount of energy of energy carrier x	MWh/year
EF_{grid}	Latvian average electricity emission factor	kg CO_2/kWh_{el}
EF_{NG}	Emission factor of natural gas burning	kg CO_2/kWh_{th}
EF_x	Emission factor of energy carrier x	t CO_2/MWh
$EM_{savings}$	CO_2 emission savings	t CO_2/year
GHI	Global Horizontal Irradiation	kWh/m^2
HHV_{hydro}	Higher Heating Value of hydrogen	kWh/kg
i	Discount/real interest rate	%
I_0	Investment expenditure	EUR
$I_{0,com}$	Investment expenditure of the compressor	EUR
$I_{0,ELY}$	Investment expenditure of the electrolyser	EUR

$I_{0,PC}$	Investment expenditure of the power converter	EUR
$I_{0,stor}$	Investment expenditure of the storage tank	EUR
$I_{0,j}$	Investment expenditure of component j	EUR
K	Investment by the citizen (voucher price)	EUR
k	Indicator of technology used	-
l	Year of time horizon	years
LCOE	Levelized Cost of Electricity	EUR/kWh
LCOH	Levelized Cost of Hydrogen	EUR/kg
$\lambda_{surface}$	Degree of insolation	%
m	Time horizon	years
m_{hydro}	Annual produced hydrogen	kg/year
$\dot{m}_{hydro}$	Hydrogen mass flow rate	kg/s
μ	Share of self-consumption	%
n	Economic lifetime	years
ns	Number of stages	-
η_{com}	Compressor efficiency	%
P_{com}	Compressor power	kW
p_{elec}	Electricity price	EUR/kWh_{el}
P_{ELY}	Power input of the electrolyser	kW
p_{feed}	Feed-in tariff	EUR/kWh_{el}
p_{in}	Input pressure of first compression stage	Pa
$P_{install}$	Installed PV capacity	kW
P_{isen}	Isentropic compressor power	W
P_j	Installed power of component j	kW
p_{NG}	Natural gas price	EUR/kWh_{th}
p_{ns+1}	Output pressure of last compression stage	Pa
P_{panel}	PV panel power output	kW
P_{PC}	Power of the power converter	kW
PV_{out}	Practical PV potential (PV power output)	kWh/kW*year
q	Space holder for (1 + ρ/100)	-
Q_{solar}	Heat delivered by the solar system assuming 15% pipe losses	kWh/year
R	Yearly return voucher	EUR
R_{spec}	Specific gas constant for hydrogen	J/kg*K
ρ	Interest rate granted by the city	%
$S_{baseline}$	Emission share of the base year	%
$S_{int.target}(\tau)$	Emission share of the intermediate target year τ	%
S_{target}	Emission share of the target year	%
SPC_{ELY}	Specific power consumption of the electrolyser	kWh/Nm^3_{H2}
SWC	Specific water consumption of the electrolyser	l/Nm^3_{H2}
t	Year of lifetime (1,2 ... n)	years
$t_{breakeven}$	Breakeven time	years

$t_{oper.life}$	Operational lifetime	years
T_{in}	Input temperature of hydrogen	K
τ	Intermediate target year	years
$\tau_{baseline}$	Baseline year	years
τ_{target}	Target year	years
V_{hydro}	Yearly hydrogen output	Nm^3
$\dot{V}_{hydro}$	Nominal hydrogen flow of the electrolyser	Nm^3/h
V_{stor}	Hydrogen tank capacity	Nm^3
χ_{cover}	Share of roof that can be used for PV panels	%
$\chi_{install}$	Share of area that remains after taking into account spacing of PV panels	%

1 Introduction

The following chapter describes the motivation in choosing the topic for the thesis, the approach, and structure employed to achieve the research goals.

1.1 Motivation

Cities occupy only 2% of the world's landmass but account for over two-thirds of the global energy consumption and more than 70% of the world's CO_2 emissions, making them the main contributor to climate change while simultaneously being at high risk from corresponding impacts such as rising sea levels (90% of urban areas are situated on coastlines) [1]. Considering the big impact cities have and potential they hold, it could be assumed that urban energy planning has been a central topic for the European Union (EU) ever since, but it was not until the 2014–2020 funding period where EU policymakers placed it at the heart of the cohesion policy[1] [2].

A substantial step, underlining the importance of urban energy planning, was the launch of the Covenant of Mayors (CoM) in 2008. The initiative focuses on gathering and supporting local and regional authorities voluntarily committing to achieving and exceeding the EU climate and energy targets [3]. The city of Riga was one of the first European capitals to sign the CoM in 2008 [4]. At the CoM's core is the Sustainable Energy Action Plan (SEAP), a key document where the commitments of the local authority and measures to reach those commitments are outlined [3]. Currently, many authorities, including Riga, are in the process of updating their SEAP to the Sustainable Energy and Climate Action Plan (SECAP), the planning document for the 2020–2030 period.

The city of Riga, being at the forefront of fighting climate change, already passed the emission reduction targets for the SEAP and SECAP planning period, offering the opportunity for a new more ambitious goal supported by innovative actions.

1.2 The impact of COVID-19

The global pandemic due to the coronavirus affected and changed various parts of daily life. While many countries, especially in the European Union, are trying to restore life to normality, others are still fighting the virus unable to decrease the daily cases. The master thesis, like many other people and sectors, was affected heavily by the coronavirus. The cooperation between the Riga Energy Agency (REA) and the author of the thesis started just before the global outbreak of the virus. What followed were months of national lockdowns in whole Europe and therefore as well in Latvia. The lockdown started on March 13th and ended on June 9th. Both supervisors of this thesis and the author agreed that returning to his home country until the pandemic cools down would be the best option. Like many other businesses, the Riga Energy Agency closed its office and switched to remote work.

[1] Cohesion policy seeks a harmonious development of the EU by enhancing its economic, social and territorial coherence [2].

The initial idea was to continue the cooperation remotely and back in the office after the pandemic allowed to. Unfortunately, the agency had to stop its work on the Sustainable Energy and Climate Action Plan for 2030, the project in which REA and author of this thesis were cooperating in. The project was postponed to 2021, which had an extensive impact on the thesis as the cooperation was heavily disrupted. Therefore, the scope of the thesis had to be changed multiple times to adjust to the circumstances both hindering the work process and resulting in considerable downtime. The cooperation was tried to be maintained as good as possible considering the difficult situation of the REA and the postponement of the project. The university supervisor agreed on a more theoretical thesis structure, opposing the initial idea of a practical thesis in close cooperation with the REA. Thanks to the thesis period prolongment of the Instituto Superior Técnico, it was possible to make up for the lost time and finish the thesis without the need of an additional semester. The next sub-chapter describes the final research hypothesis and goals. Previous versions of the scope are not included.

1.3 Research hypothesis and goals

As referred before, the REA is working on an energy planning outlook for the period of 2020–2030. While various aspects of the already designed Sustainable Energy Action Plan (2014–2020) can be reused and updated to fit the purpose of the new planning track, there is a need for new ideas to further reduce greenhouse gas emissions in the city of Riga. Therefore, the research goals of this thesis are as follows:

- Characterise the energy planning structure and the energy system in Riga acquiring the latest data on energy consumption, production, and GHG emissions.
- Set a suitable target for the year 2030 that the city of Riga can use for designing their energy planning document while outlining pathways that help to achieve that target.
- Research on successful emission reduction measures in the European Union, modifying and applying advisable approaches to the city of Riga, while analysing the feasibility of the proposed measures and included energy technologies, ultimately recommending actions for the planning period of 2020–2030.

1.4 Methodology

The methodology used in this thesis can be seen in Figure 1. To conceptualize beneficial measures for the city of Riga, first, the overall situation of energy planning and the existing energy system have to be assessed. The baseline of the characterization is the year 2016, the latest year of obtainable data. With the acquired information, a suitable emission reduction target for 2030 is recommended. To achieve the set goal, different pathways, which reflect distinct measures, are created. A pathway alone does not reduce the emissions enough to attain the desirable reduction. Rather, a mixture of different measures presented additional to the existing pursuit of the city of Riga might do so. The methodologies used for specific parts of the thesis, for instance, the pathways, are described within the corresponding chapter.

Figure 1: Graphical summary of the methodology used.

The measures presented in this thesis serve the purpose to demonstrate useful planning actions for the city of Riga while analysing the feasibility of the technologies involved. The recommendations derive as a result of the calculations performed while characterising the measures of the different pathways.

1.5 Thesis structure

The thesis is organized as follows:

- Chapter 2 provides the political framework of the thesis covering the European climate strategies and targets as well as the importance of urban energy planning;
- Chapter 3 addresses energy planning in Riga. The city characteristics are presented focusing on general information, governance, development plans, the energy system and its emissions, and finally the already implemented reduction measures by the city;
- In chapter 4, the pathway methodology is outlined including the emission target setting for 2030. Furthermore, three distinctive pathways are introduced and compared;
- Chapter 5 specifies the measures of the three pathways, which include the production of green hydrogen, the usage of solar technologies to drive citizen engagement, and the modernisation of urban transportation. The actions are described and feasibility calculations performed;
- Chapter 6 contains recommendations for the city of Riga obtained by the calculations in chapter 5. Additionally, the thesis approach is critically reviewed, and a future work outlook is given;
- Chapter 7 presents the conclusions.

2 Political framework

Chapter 2 sets the political framework for the thesis. The European climate strategies and targets are covered, and the importance of urban energy planning is shown. The relevant European Union's initiatives on urban development are presented with a high emphasis on the Covenant of Mayors.

2.1 European Union climate strategies and targets

The 2020 climate & energy package, a set of binding legislation, introduces three key targets in the European Union's pursuit of addressing climate change. Those targets for the year 2020, set in 2007 and enacted in 2009, are shown in Table 1. The EU is aiming at a 20% greenhouse gas (GHG) emission reduction compared to 1990 levels, 20% renewable energy sources in the EU's energy mix, and a 20% energy efficiency target which limits the consumption of primary and final energy [5].

Table 1: EU energy and climate targets for the years 2020 and 2030. Adapted from [5], [6].

EU package	Target year	Greenhouse gas emissions[2] [%]	Renewable energy share [%]	Energy efficiency [%]
2020 climate & energy	2020	- 20	20	20
Clean energy for all Europeans	2030	- 40	32	32.5

As the year 2020 is reached, new targets apply for the period of 2021 to 2030, which are set in the Clean energy for all Europeans package, proposed by the European Commission (EC) in 2016 and completed in 2019 (see Table 1). This package consists of eight legislative acts which aim at bringing considerable benefits from a consumer, environmental, and economic perspective. The EU countries have one to two years to transpose the new directive into national law. In the light of the Paris Agreement, the EU pledges to strive in the fight of climate change and sets ambitious targets [6].

The directives for renewable energy and energy efficiency contain a clause for a possible upwards revision of the respective targets by 2023. Although those targets are fixed at EU levels, each country has to outline how they plan to achieve their respective targets by drafting a 10-year National Energy and Climate Plan [6].

The EU vision beyond 2030 is to become climate-neutral by 2050. The proposal for the first European Climate Law (March 2020), as part of the European Green Deal[3], aims to write this goal into law and turn it into a legally binding target [8].

Figure 2 shows the progress towards the 2020 and 2030 targets set by the EU. The yellow line represents the share of renewable energy reaching 18.9% in 2018 [9]. The EU is on track to attain the target of 20% in 2020, but current deployment remains insufficient to achieve the 32% target in 2030.

[2] Compared to 1990 levels.
[3] The European Green Deal is a roadmap for making the EU's economy sustainable and turning Europe into the first climate-neutral continent [7].

The present annual growth rate, the proportion of renewables to gross final energy consumption, is 0.7 percentage points per year while one of 1.1 is needed to meet the 2030 target [10].

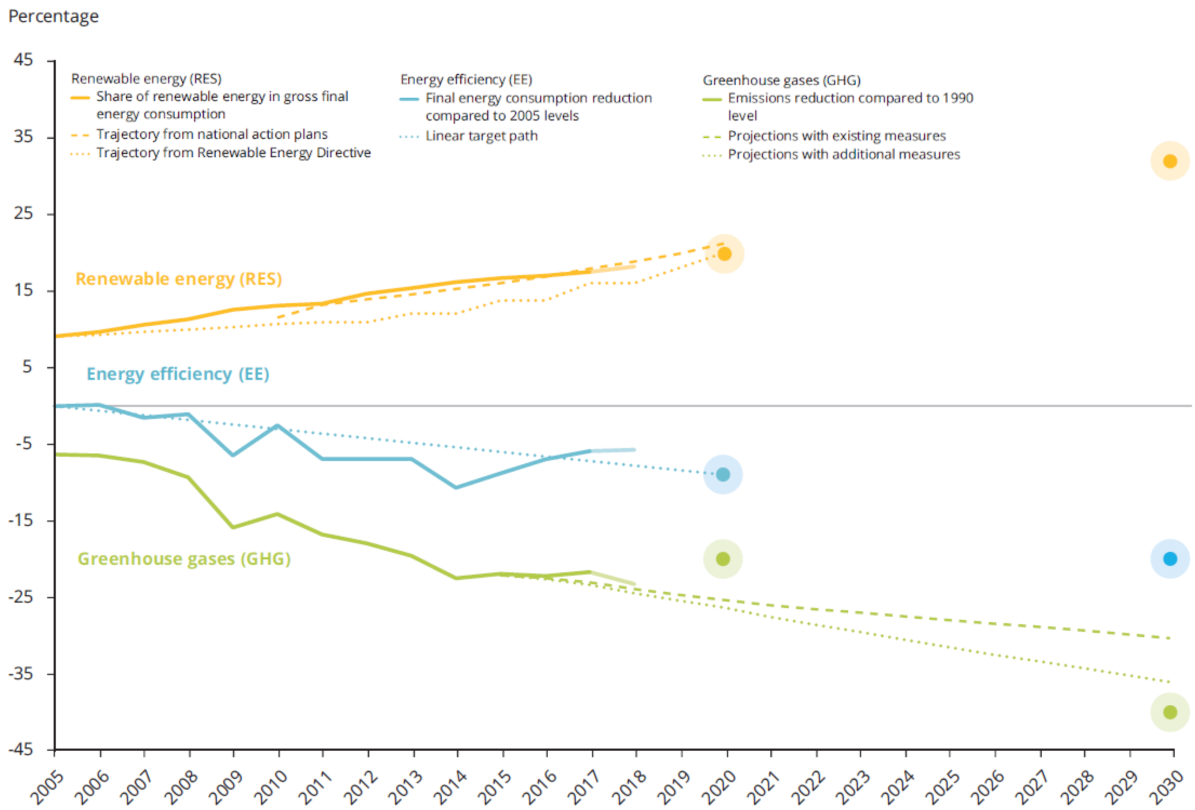

Figure 2: EU progress towards 2020 and 2030 climate and energy targets [10].

The blue line shows the energy efficiency targets and progress expressed as final energy consumption reduction compared to 2005. Both the targets for 2020 and 2030 are not expected to be met. One of the reasons is the increase in energy consumption in buildings (8.3%) and the transport sector (5.8%) between 2014 and 2017 [10]. The GHG emission target (green line) of 20% reduction compared to 1990 levels is expected to be reached, being already at 21.7% in 2017 and being estimated to drop another 2.0% by 2018. Meeting the 2030 target requires further efforts as the current policies and additional measures fail to reach the target by 10% and 4%, respectively [10].

2.2 Importance of urban energy planning

More than half of the world's population (55% in 2018) lives in urban areas. This ratio is expected to grow to 68% in 2050 and 85% (9 billion) in 2100, representing an increase of 8 billion from 1950. The European level of urbanization is higher than the world's average, being at 75% in 2020 and expected to rise to around 84% in 2050 [11]. Already today, buildings in the EU represent 40% of the energy consumption and 36% of the CO_2 emissions, making it the single largest energy consumer in Europe [6].

As described before, cities occupy only 2% of the world's landmass but account for over two-thirds of the global energy consumption and more than 70% of the world's CO_2 emissions [1].

The great carbon footprint created by cities is linked to poor planning and layout. For instance, low-density suburban areas have little public transport in addition to distant workplaces and shops, increasing the usage of cars. Nevertheless, given their role as hubs of innovation and creativity, cities have the potential to gain importance in fighting climate change by adjusting the way of planning, building, managing and powering their territory [12]. An estimated 80% of all economic growth is generated in cities, offering the capability of applying modern technologies and infrastructure to better use scarce resources [11].

The importance of local involvement to achieve climate targets was pointed out at the Conference of the Parties 21 (COP21) where for the first time more than 400 mayors came together for the Climate Summit for Local Leaders. This inclusion of cities showed the recognition of their important role in climate change response and ended the prejudice of cities being just massive polluters and intensive resource consumers. Nowadays, European cities are perceived as leaders in the field of climate change adaptation and mitigation, with many being early adopters of climate goals and policies [13].

2.3 Urban development in the EU policy context

Despite the importance of urban areas mentioned in the previous section, there was a lack of policy initiatives in the EU dealing with urban development. One of the reasons might be that there is no legal basis for urban policy in the EU treaties [14]. First modest steps were taken after the reform of Structural Funds and the revision of the Treaty of Rome[4] (1958) by introducing the first initiatives, the Urban Pilot Projects (1989–1994) followed by the Urban I Program (1994–1999) focussing on anti-poverty policies [15]. While the urban dimensions of European spatial policy grew over the years, a significant step was taken during the 2014–2020 funding period, where European policymakers recognised the importance of urban development policy and placed it at the heart of the cohesion policy[5] directing at least half of the resources of the European Regional Development Fund (ERDF)[6] to it [2]. For the funding period, an agenda was created, a network was established, and an initiative started to support the new urban dimension of the cohesion policy.

Launched in May 2016 with the Pact of Amsterdam, the Urban Agenda of the EU (UAEU) is a new multi-level working approach which aims at maximising the growth potential of cities while tackling social urban challenges. Through the creation of partnerships between the EC, national governments, local authorities, and stakeholders, the UAEU seeks to promote the involvement of cities in EU policymaking, assure better access to and utilisation of funds and foster knowledge exchange [2].

The Urban Development Network (UDN) consists of the urban authorities involved in implementing integrated actions in line with ERDF Article 7 (sustainable urban development) and Article 8 (urban innovative actions).

[4] The Treaty of Rome, addressing the objective of "harmonious development", can be considered the first time in which the urban dimension entered the debate [15].
[5] Cohesion policy is delivered through the ERDF and the cohesion fund [2].
[6] The ERDF focuses on innovation and research, the digital agenda, support for small and medium-sized enterprises and the low-carbon economy [2].

The main objective is to review the implementation of the funds in the involved cities, support information exchange between those, and encourage direct dialogue with the EC. Currently, a minimum of 5% of the ERDF must be invested in integrated sustainable urban development[7] [17].

The Urban Innovative Action (UIA) is an initiative which provides funding for identifying and testing new approaches to present urban challenges based on Article 8. The UIA co-finances 80% of the project's activities (up to 5 million euro) and supports knowledge exchange across urban policymakers and practitioners [18].

Additional to the mentioned instruments of the 2014–2020 cohesion policy, there is URBACT, the European Territorial Cooperation programme which focuses as well on integrated sustainable urban development, established 15 years ago and currently in the third deployment (URBACT III). The programme is organised around the following objectives: the improvement of cities' capacity for policy delivery, policy design plus implementation, and knowledge exchange [19].

The governance structure of the current initiatives (see Table 2) as well as the representation of the stakeholders is highly fragmented. In general, the EC is greatly involved either as a management instance (with different approaches) or as a supervisor while the member states and cities are mostly not represented.

Table 2: Governance structure of the current initiatives[8] (2014–2020 period) and EUI proposal [20].

Roles	Cities	Member States	European Commission	Management
URBACT (shared management)	Not represented	Strategy steering. Management by one Member State	Supervision	Managing authority – secretariat CGET
Urban Innovative Actions (UIA) (indirect management)	Not represented	Not represented	Management	Entrusted entity Secretariat
Urban Agenda of the EU (UAEU) (intergovernmental process, direct management of administration)	Represented by CEMR and cities network	Supervision	Management	EC - Framework contract
Urban Development Network (UDN) (direct management)	Not represented	Not represented	Management	EC - Framework contract
EUI based on the Commission proposal (indirect management)	Strategy steering	Strategy steering	Strategy steering and management	Entrusted entity Secretariat

[7] As urban life has various dimensions (environmental, economic, social and cultural) which are interwoven, the EU believes that urban development can only be successful through an integrated approach combing physical urban renewal with measures promoting the various dimensions in the cities [16].
[8] CGET: General Commission for Territorial Equality; CEMR: Council of European Municipalities and Regions.

For the next long-term EU budget (2021–2027), the EC proposes to modernise the cohesion policy and identifies five investment priorities [21]:

- a smarter,
- greener and carbon-free,
- more connected,
- more social Europe,
- closer to citizens.

65 to 85% of the ERDF and cohesion fund resources are dedicated to the first two objectives. Additionally, the allocation method[9] is reworked including new criteria such as climate change or youth unemployment. To strengthen the urban dimension of cohesion policy, 6% of the ERDF is dedicated to sustainable urban development and a new programme for urban authorities, the European Urban Initiative (EUI), is proposed [21].

The EUI builds on the thematic priorities[10] of the Urban Agenda and aims at strengthening integrated and participatory approaches to sustainable urban development supporting and facilitating the cooperation and capacity building of urban actors. The emphasis lies on the involvement of a substantial number of relevant stakeholders and rapid execution of tasks through efficient and effective operational management [20].

2.4 Covenant of Mayors

A great example of the EC recognising the importance of local-level energy planning to achieve both national and European climate targets is the Covenant of Mayors (2020 target), launched in 2008 by the EC after the adaption of the EU climate and energy package. The initiative concentrates on gathering and supporting local and regional authorities voluntary committing to the implementation of sustainable energy policies on their territories. The CoM provides a harmonised data compilation approach with a methodological and reporting framework to translate the signatories' political commitment, to achieve and exceed the European 20% CO_2 emission reduction target, into practical measures and projects outlined in the signatory's Sustainable Energy Action Plan [3].

A separate initiative called Mayors Adapt, launched in 2014 by the EC in the context of the EU strategy on adaptation to climate change, is based on the same principles as the CoM and supports local authorities in the development and implementation of local adaptation strategies [3].

[9] Mainly based on GDP per capita.
[10] Air quality, circular economy, climate adaptation, culture, digital transition, energy transition, housing, innovative and responsible public procurement, inclusion of migrants and refugees, jobs and skills in the local economy, sustainable use of land and nature-based solutions, urban mobility, and urban poverty.

The Covenant of Mayors for Climate & Energy (2030 target), launched in October 2015, is the unification of the Covenant of Mayors and Mayors Adapt initiatives. It raises the initial GHG emission reduction commitments, integrates adaptation to climate change, and is built around three pillars:

- mitigation (at least 40% emission reduction target by 2030);
- adaptation to climate change;
- secure, sustainable, and affordable energy.

The commitments of the local authority and actions to reach those commitments are outlined in an action plan called the Sustainable Energy and Climate Action Plan. In case a signatory has already developed a SEAP in the past, their previous commitments remain valid.

Joining the new CoM (for Climate & Energy) requires signing up to a new initiative with post-2020 commitments which are included in the SECAP, functioning as a natural extension of the existing SEAP [3].

Both the SEAP and SECAP require a Baseline Emission Inventory (BEI) as a prerequisite which quantifies the amount of CO_2 emitted in the signatories' territory due to the energy consumption in the baseline year. The recommended baseline year is 1990 as used in the Kyoto Protocol and the EU reduction commitments [22].

Currently, the covenant network consists of 10 072 active signatories in over 60 countries covering a population of around 320 million inhabitants. 66.64% of those signatories have less than 10 000 inhabitants, while only 0.96% have over 500 000. In 2008, 239 communities signed the covenant including the city of Riga. Around 64% of the active signatories have submitted an action plan [23]. Furthermore, the commitments made by the signatories on reducing CO_2 emissions are on average higher than the European Union's targets: 31% by 2020 and 47% by 2030 compared to 20% and 40%, respectively [24].

2.4.1 Sustainable Energy Action Plan

The Sustainable Energy Action Plan is the key document outlining how the signatory intends to reach its commitment by 2020. It defines the concrete reduction measures, time frames, and assigned responsibilities, using the BEI to identify actions and opportunities for achieving the local authority's reduction target. The measures should aim at reducing CO_2 emissions and final energy consumption covering the whole geographical area of the local authority concerning both public and private sectors. The main target sectors are buildings, equipment/facilities, and urban transport, but the SEAP may include other areas such as local electricity production, local heat/cooling generation, long-term energy consumption, or markets for energy-efficient products and services. The industrial sector is not considered a key sector but can be embedded by the signatory. Plants covered by the European CO_2 Emission Trading Scheme (ETS) should be excluded [22].

2.4.2 Sustainable Energy and Climate Action Plan

As described in the previous sections, the SECAP is the key document of the joint initiatives CoM (2020 target) and Mayors Adapt. The framework is similar to the SEAP having updated emission reduction targets and a new time frame horizon. Furthermore, a Risk and Vulnerability Assessment (RVA) is included which determines the most relevant climate hazards and vulnerabilities influencing the local authority. The RVA facilitates the process of addressing those risks through adaptation measures and is of great importance as vulnerable sectors differ inimitably within urban parameters [3].

Figure 3 presents the different steps that the signatory undertakes in the SECAP process. After the submission of the SECAP, the signatory must not only implement the proposed actions but monitor them and report to the Joint Research Centre Directorate-General (JRC) of the EC. The JRC is in charge of the evaluation and hands out feedback assessing the SEAP's eligibility and presenting improvement suggestions [3].

Figure 3: The SECAP process [3].

3 Energy planning in the city of Riga

The following chapter focuses on energy planning in the city of Riga. First, the city characteristics are presented focusing on general information, governance, and the Riga Energy Agency. Next, the development plans of the city are reviewed. The planning document focusing on energy planning is the Riga Smart City SEAP in which the main measures to decrease CO_2 emissions are presented. Then, the energy system of the city and its emissions are analysed. Finally, the planned actions of the city are listed.

3.1 The city of Riga

Riga, the capital of Latvia, is considered to have been founded in 1201 and is known for its culture, architecture, precisely the art nouveau, and geographical position. In fact, its historical centre is included in the list of world's cultural heritage. The city attracts many tourists and transients, making Riga an influential air, sea, and rail transport hub [4].

Figure 4 displays the geographical position as well as the territorial division of the city. Riga is situated in the north-eastern part of Europe at the coast of the Gulf of Riga of the Baltic Sea, underlining its importance as a Hanseatic city. The city is divided into 58 localities within six districts and suburbs.

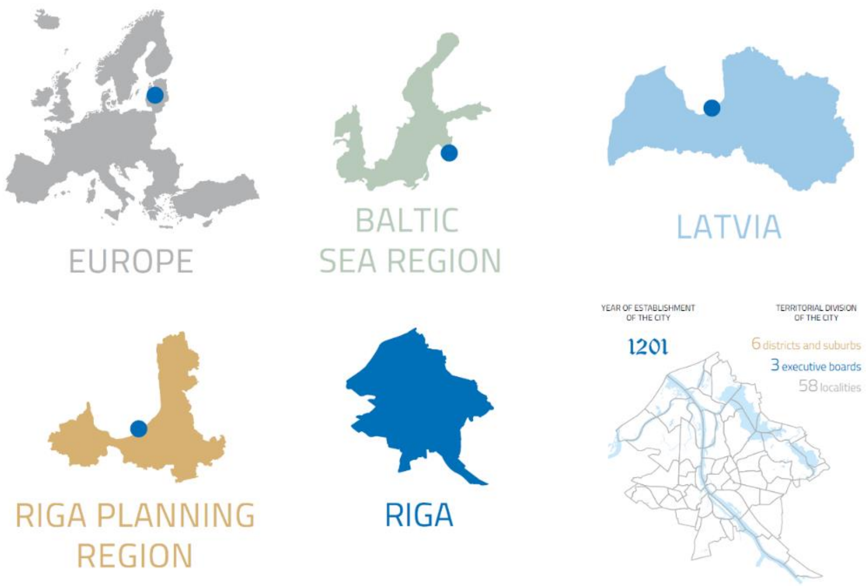

Figure 4: Geographical position of the city of Riga. Adapted from [25].

The current population[11] is 632 614, being 33% of the total inhabitants of Latvia[12] and making it the biggest city of the Baltic states[13] [26]. Riga is of great importance for the Latvian economy, creating 53.6% of the total National Gross Domestic Product (GDP) in 2017 [27].

[11] At the beginning of 2019.
[12] 1 919 968 (2019) [26].
[13] Estonia, Latvia, and Lithuania.

Due to the geographical position, economic power, and touristic attractiveness, Riga is not only an important location for Latvia but the whole Baltic Sea Region.

3.1.1 Governance

The highest political entity in Riga is the City Council, consisting of 60 councillors with its head the Chairman of the City Council. The council forms the subordinate administration deciding its structure and competence [28]. Commitments are taken centrally, applying to the whole city, but implementation is scattered among the municipal structures such as city departments. The structure can be seen in Figure 5, where the colour blue represents elected entities, round boxes refer to persons, and squares to bodies of the government.

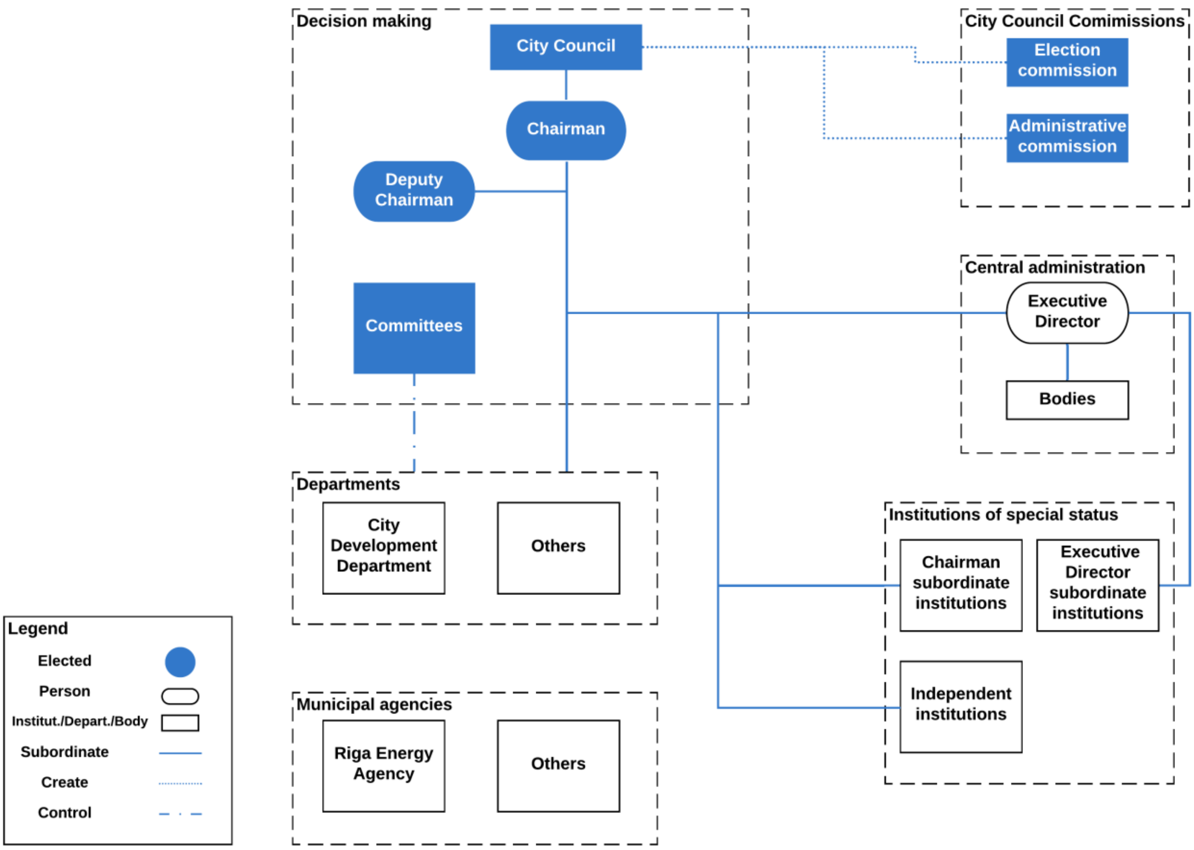

Figure 5: Structure of the Riga municipality administration. Adapted from [28].

The municipality administration organization can be split into six main groups: Decision making, City Council Commissions, Central administration, Departments, Institutions of special status, and Municipal agencies [28].

The committees, part of the decision making, control their respective departments which carry out municipal functions. There are seven departments of the City Council. One of those is the City Development Department, the leading municipality institution in the field of territorial planning, which pursues a lawful, balanced, and efficient development of the city. The department's vision, goals, and main objectives are set in strategic development plans such as the Sustainable Development Strategy of Riga [29].

The City Development Department is in close cooperation with other departments, institutions of special status, and independent municipal agencies which also belong to the municipal administration. The agencies are neither controlled by nor subordinated to any other entity underlining their independent status. The Riga Energy Agency is one of these five municipal agencies and of utmost importance in the pursuit of the development of a resource-efficient, renewable, and low-emission city.

3.1.2 Riga Energy Agency

The REA is an independent, non-profit municipal institution created in a project co-financed by the Intelligent Energy Europe Programme, and established by the Riga City Council in 2007. Its purpose is to plan, manage, monitor, and coordinate the long-term energy supply and consumption in the city of Riga as well as promoting energy efficiency and renewable energy sources. Furthermore, the agency enhances the shift to sustainable transportation, promotes energy-efficient renovation projects of the city's housing stock and public buildings, and raises awareness amongst the local population on energy efficiency issues. The REA participates in the development of laws, policies, and regulations within its competence and is involved in international projects with European countries fostering knowledge transfer, innovation, and pilot activities [4].

3.2 Development plans

The crucial planning document of the city of Riga is the Sustainable Development Strategy of Riga until 2030, which sets the vision, priorities, and strategic objectives for a long-term territory development of Riga. This development is not only affecting the inhabitants of the municipality but as well the whole country, as its capital and economic driving force, and Northern Europe, as of the ambition to become an internationally recognisable Northern European metropolis [25].

Riga of 2030 is a compact city with a distinctive atmosphere, creating diverse opportunities for its inhabitants while being smart and resource-efficient. One of the biggest challenges of the city, the decrease in the number of the city's population[14], is to be overcome and turned into growth by the long-term objectives set by the municipality of Riga.

Those objectives aim at developing [25]:

- a skilful, provided and active society;
- an innovative and open economy;
- a convenient, pleasant, and safe urban environment;
- an internationally recognisable and competitive North-Eastern metropolis.

[14] - 9.96% from 2007 to 2019. Calculated from [26].

Riga’s current Sustainable Energy Action Plan is the Riga Smart City SEAP 2014–2020, a follow-up to the first document, the Riga City SEAP 2010–2020 launched in 2010. In the first version of the action plan, the city of Riga commits itself to exceeding the goals of the 20-20-20 by 2020 formulation of the EU, thus reducing CO_2 emissions by at least 20% which is to be achieved through a 20% gain in energy efficiency and utilization of renewable energy sources accounting for 20% of the volume of energy consumed. The revised document is the result of achieving a CO_2 emission reduction of 50.69% compared to the baseline year 1990, already by 2011 and the subsequent opportunity for new, more ambitious goals [30].

The Smart City SEAP focuses on bringing the city closer to achieving the status of a smart city following the initiative of the EC on the European Innovation Partnership on Smart Cities and Communities. The emphasis lies on the integration of innovative information and communication technologies (ICT) into the energy and transportation sectors, fostering sustainable energy supply and an emission-free transportation system [30].

Figure 6 presents the interaction between the mentioned plans. All strategies are in alignment with the strategic main vision. The REA is in the process of updating and extending its SEAP to the SECAP by adjusting the climate goals and including climate adaptation, RVA, and relevant indicators [31].

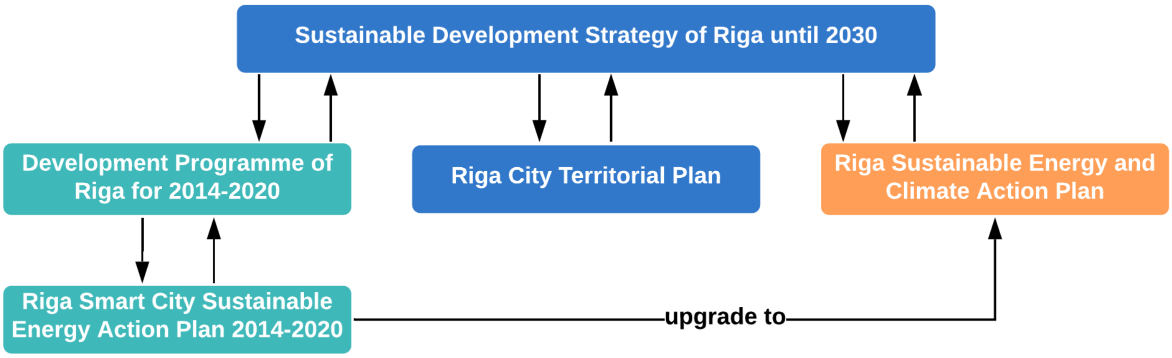

Figure 6: Interaction between current development plans. Adapted from [25], [30].

The various programs have varying time horizons which can be seen in Figure 7. The plans in turquoise are ending in 2020 which in the case of the SEAP created the need to update the strategy to achieve the ambitious goals set for Riga in 2030.

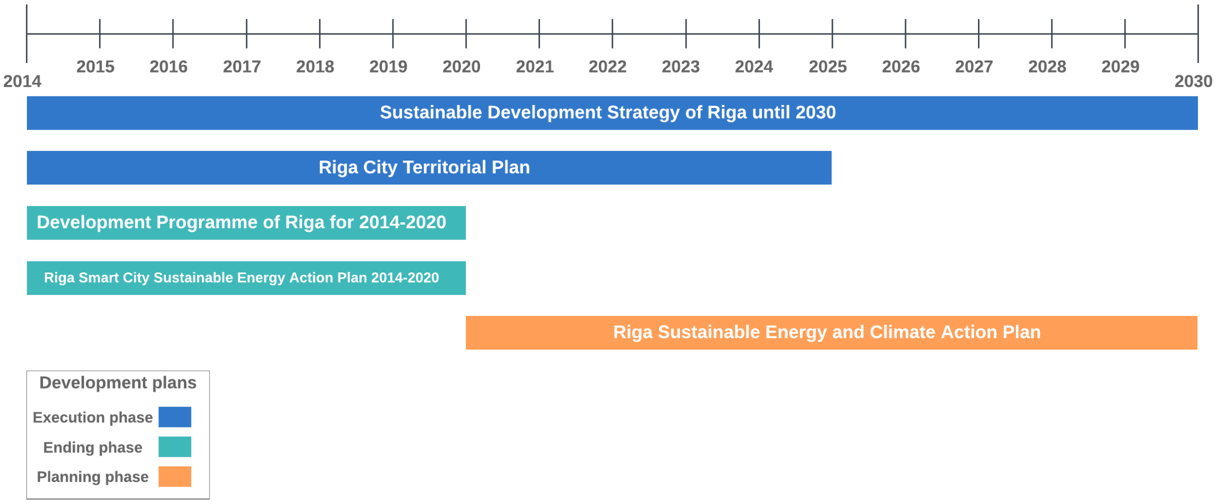

Figure 7: Time horizon of the current development plans. Adapted from [25], [30].

Riga recently joined the smart city project ATELIER (AmsTErdam BiLbao cItizen drivEn smaRt cities) to acquire new knowledge about strategic energy planning processes. This project focuses on creating and replicating so-called positive energy districts as well as fostering knowledge exchange, stakeholder involvement, and energy planning. The participation of the REA, as the representative of Riga, in this project aims to develop a “Bold City Vision 2050” as a guide for the city’s energy transition challenges. This vision should be integrated into all urban planning processes. Nevertheless, the emphasis lies on updating the SEAP to SECAP. The REA intends to increase stakeholder engagement and raise awareness amongst the population in the field of smart city concepts [32].

3.3 Riga’s energy system characteristics

The energy system characteristics of a country (or in this case of a city) depend on a set of factors, such as available resources, climatic circumstances, politics, and more. In Latvia, being located in the cold climatic zone of Europe, heating is a particularly important field as the number of heating degree days[15] is over 4 000 and the winter period lasts for approximately 200 calendar days. In fact, over 60% of the energy resources consumed are used as thermal energy. In Riga, heating is mainly provided through a district heating (DH) system covering around 76% of the consumed volume of heat. DH is provided by the Joint-Stock Company (JSC) Rīgas Siltums which produces around 31% of the heat in its facilities and purchases the rest of JSC Latvenergo’s combined heat and power plants (CHPP). A small amount is bought from private producers, such as the co-generation station of the limited company (Ltd) Juglas Jauda (11.8 MW_{el}). JSC Rīgas Siltums operates boiler houses and heat plants (HP) of which some have co-generation units enabling the production of heat and electricity. The main fuels used are natural gas and woodchips [30].

[15] Heating degree days (HDD) refer to the heating demand in buildings obtained from daily temperature observation and defined relative to a base temperature representing the outside temperature above which a building needs no heating. The HDD is the difference between that base temperature and the actual measured temperature. Over a year the daily HDDs are added resulting in the case of Latvia in a number higher than 4 000 [22].

The amount of heat delivered is profoundly linked to the outdoor air temperature during the heating season. The mean ambient temperature during the heating season (of the fiscal year[16] 2018/2019) was by 0.9 °C higher than in the corresponding period last year, resulting in a 2.2% lower transfer to costumers (3 100 GWh in the fiscal year 2017/2018 [33]) of 3 032 GWh. In the fiscal year 2018/2019, JSC Rīgas Siltums purchased 2 400 GWh (69.9%) of heat and had transmission losses of 11.65% (0.33 percentage points lower than 2017/2018) being the lowest during the company existence. The total amount of produced heat added up to 3 432 GWh. In the co-generation stations 95 GWh of electricity was produced, 11% less than the fiscal year before. Around 12 GWh was self-consumed while 83 GWh was sold [34].

The previously mentioned facilities of JSC Rīgas Siltums contribute to local heat production. Furthermore, the usage of heat pumps (mostly air-source type) in buildings is widely used in Riga. Renewable means of providing heat such as solar collectors and wood pellet boilers are increasingly installed in the building sector. Unfortunately, there is no inventory for listing neither heat pumps nor pellet boilers. The biogas created at the landfill of Ltd Getliņi EKO is used in a co-generation facility with a capacity of 6.8 MW_{th} [26].

Natural gas as one of the main fuels used in Riga is supplied by JSC Latvijas Gaze using the Inčukalns underground gas storage facility, transmission pipelines (4.5 MPa) and a two-level distribution network (1.6/0.3 MPa) [30].

The electricity grid in Riga consists of a 110/330 kV network with 28 110/10 kV substations and 75 distribution points of 10 kV covering the city on both banks of the Daugava river and interconnecting the power production plants. The largest electricity producers are the three major power stations of the state-owned JSC Latvenergo: Riga TEC[17]-1, TEC-2, and hydropower plant (HPP) [30].

Riga TEC-1 and TEC-2 are CHPPs mostly operated in highly efficient co-generation mode. Operation is flexible according to the thermal energy demand and electricity market conditions. Both CHPPs, which are operating on natural gas, play an important role to cover the national power demand. TEC-1 and TEC-2 have generation capacities of 144 MW_{el}/493 MW_{th} and 832[18] MW_{el}/1124 MW_{th}, respectively. The generated heat is sold to JSC Rīgas Siltums at regulated tariffs. In 2019, the amount of generated thermal energy decreased by 20% compared to 2018 as five new heat producers started operating in the thermal zone of JSC Latvenergo. Combined, the CHPPs generated 2 780 GWh_{el} electrical and 1 603 GWh_{th} thermal energy in 2019. The Daugava HPPs, consisting of Kegums, Plavinas and Riga HPP, are the biggest hydropower plants in the country. Riga HPP has a generating capacity of 402 MW_{el} and generated 491 GWh in 2019 [35].

[16] The fiscal year of JSC Rīgas Siltums starts on the 1st of October and ends the 30th of September.
[17] Termoelektrocentrāle; Latvian for thermal power plant.
[18] The plant can operate in co-generation and condensation mode. In condensation mode, the capacity is 881 MW_{el}.

Locally, electricity is generated using co-generation units operating on natural gas, biogas, or wood chips which are mostly owned by JSC Rīgas Siltums such as HP Imanta with a 47.7 MW_{el} generating capacity. The assets of JSC Rīgas Siltums are operating on natural gas and wood chips.

Other producers using biogas are Ltd Rigens at the municipal wastewater treatment plant (2.1 MW_{el}) and Ltd Getliņi EKO at the municipal landfill (5.3 MW_{el}). The largest solar cell structure with an area of 1 200 m^2 is located on the roof of Ltd Zaļā Latvija's hazardous waste treatment plant (120 kW_{el}) [30].

3.4 CO_2 emissions of the city of Riga

Figure 8 shows the emissions of the city of Riga from 1990 to 2016. The methodology used for calculating the emissions, which can be found in Annex A.1, follows the recommendations of the guidelines of the Intergovernmental Panel on Climate Change (IPCC) and the SEAP guidebook and is carried out by Institute of Physical Energetics (Fizikālās enerģētikas institūts). The figure indicates a clear trend of an emission reduction from 1990 to 2016, achieving a decrease of 54.5% and 19.2% compared to 1990[19] and 2008[20], respectively. From 2008, the biggest reduction within a sector (46.9%) is achieved by the end-use fuel consumption, followed by the transport sector (15.1%) and the district heating system (13.9%). The changes in the electricity sector can be regarded as insignificant (0.4%). In 2016, road transportation accounted for the biggest share of emissions (39%), followed by DH with 30%, end-use fuel consumption with 17%, and power consumption with 14% [36].

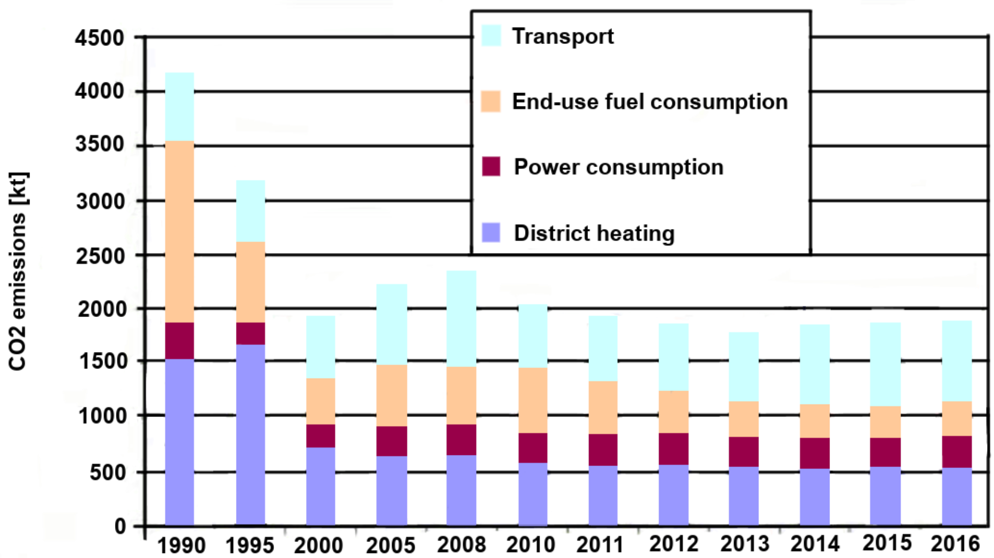

Figure 8: Calculated CO_2 emissions of the city of Riga by main sectors (1990–2016). Adapted from [36].

To better understand the origin of the emissions, each sector is regarded separately. In the transport sector, a reduction of 15.1% of CO_2 emissions was achieved compared to 2008. As represented in Figure 9, not only the total fuel consumption decreased but its structure changed as well. The usage of petrol decreased while diesel consumption raised markedly.

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[19] In the source, no absolute values are given, in the Riga SEAP the emissions of 1990 are stated as 4 295 kt CO_2.

[20] The graph in Figure 8 shows smaller emissions for the years 1990-2012 compared to the SEAP. The numbers for the transport sector differ (but no reason was identified). Furthermore, the power consumption emissions are calculated with an emission factor of 0.109 t/MWh instead of 0.143 t/MWh as in the SEAP.

The structure became more diversified having increased shares of unusual energy carriers such as bio-based fuels and liquefied petroleum gas (LPG). The main reason for the fuel composition change is the shift of light cargo and freight transport from petrol to diesel engines and the overall increase in diesel cars. The high emissions of 2008 can be explained by the rapid increase in the number of passenger cars after 2000. The decrease in 2009 and 2010 was caused by an economic downturn affecting car traffic which rebounded in the following years, resulting in a steady growth until 2015/2016 [36].

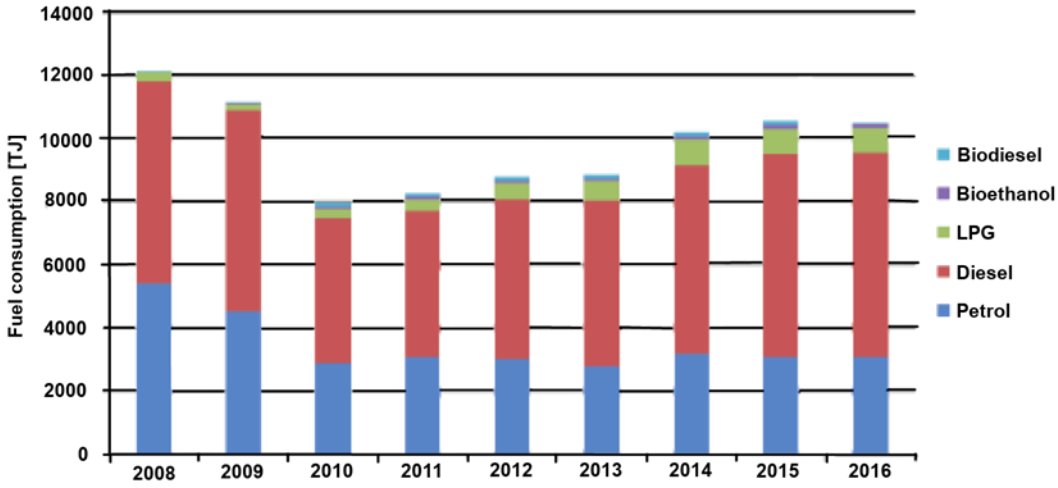

Figure 9: Fuel consumption and its structure in road transport (2008–2016). Adapted from [36].

Figure 10 shows the end-use fuel consumption by different consumer groups. Households represent the largest group with 35% of the total share, followed by the industry (31%), the service sector (25%), and municipal institutions (9%) [36].

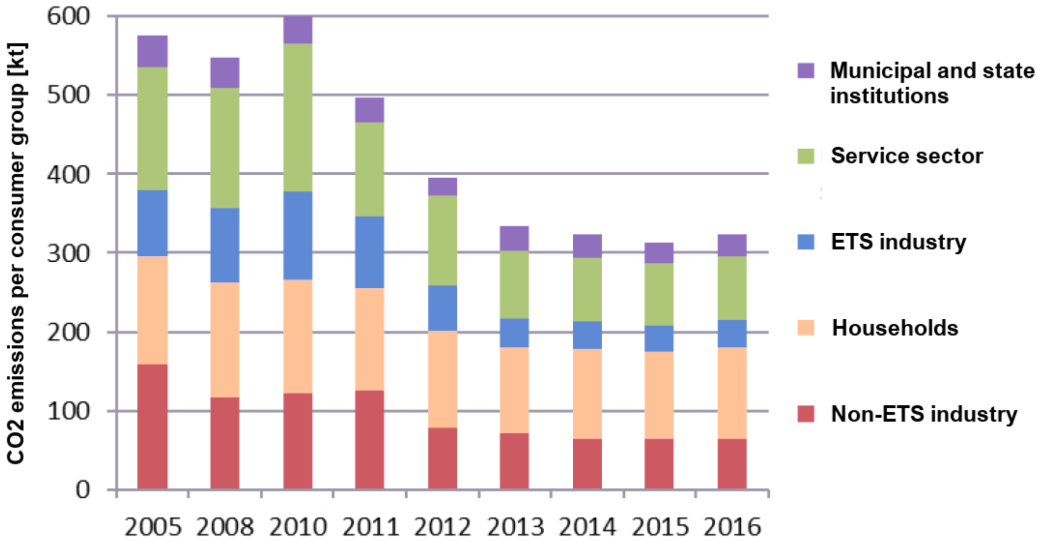

Figure 10: CO_2 emissions from final consumption of fuels by consumer groups (2005–2016). Adapted from [36].

The decline of the end-use fuel sector is mainly related to the replacement of fossil fuels with woody biomass in ETS and non-ETS industrial plants. The increase of RES (mainly biomass) in final energy consumption advanced from 11% in 2010 to 38.3% in 2016 (as seen in Figure 11) [36].

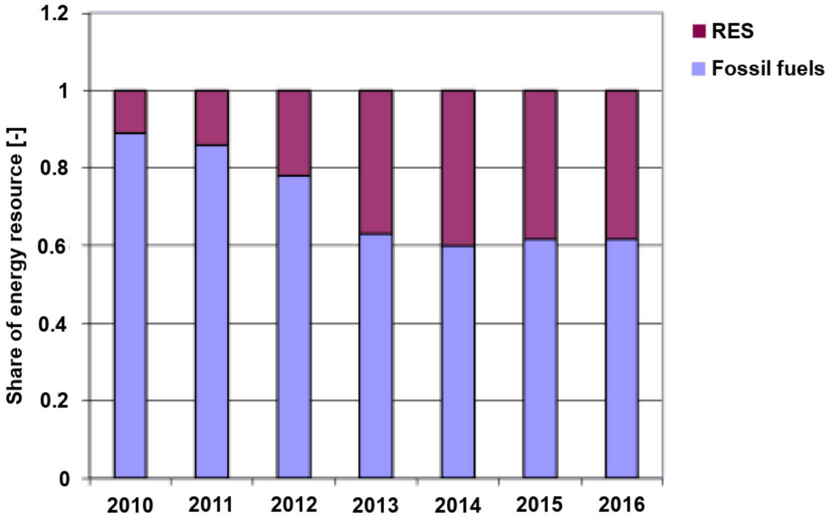

Figure 11: Share of RES and fossil fuels in the final fuel consumption (2010–2016). Adapted from [36].

The largest electricity consumers in 2016 were the service sector (54.1%), followed by households (22.1%) and industry (20.1%). Street lighting and urban transport accounted for the rest. Figure 12 displays the progression of the electricity consumption of the different consumer groups over the years. Compared to 1990, the commercial and service sector increased the most, nearly by 50%. Both the household sector and street lighting grew slightly. However, urban transportation and industry decreased their emissions remarkably by around 50 and 60%, respectively [36].

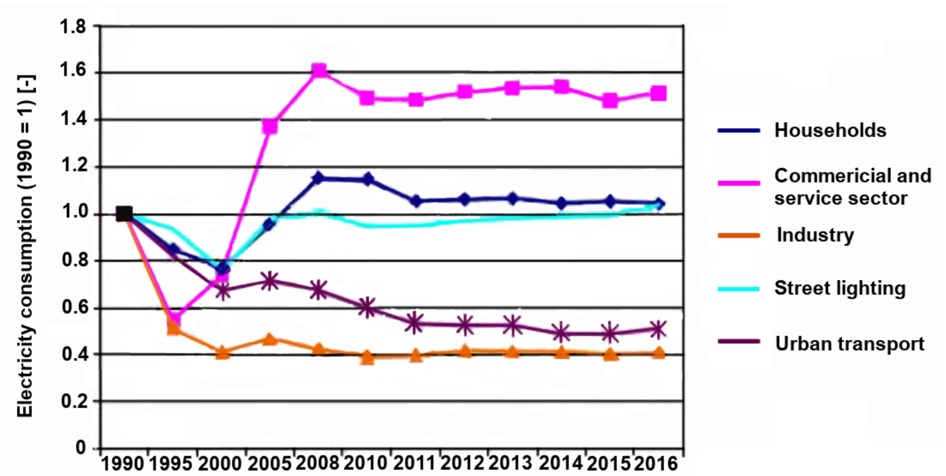

Figure 12: Electricity consumption per consumer group (1990 – 2016, 1990 = 1). Adapted from [36].

From 2008 to 2016, emissions of the district heating system fell by 13.9%. The key factors for the reduction are the modernization of the heat supply system, reducing transmission losses, increasing the usage of co-generation technology and the utilization of wood biomass in the production sites of JSC Rīgas Siltums (from 3% of total fuel in 2008 to 35.4% in 2016 as seen in Figure 13) [36].

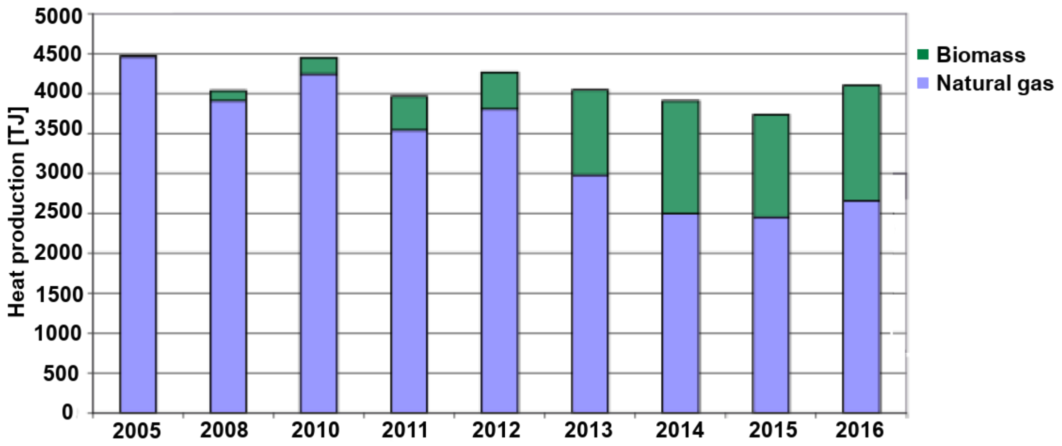

Figure 13: DH heat production per fuel type by Rīgas Siltums' production facilities (2005–2016). Adapted from [36].

3.5 Measures of the city of Riga

To reduce emissions, the city of Riga identified measures in various sectors of energy planning. Their impact is calculated using a so-called "bottom-up" method based on the calculated or measured amount of energy saved or replaced adjusted by the respective energy emission factor. The following formula is used [30]:

$$EM_{savings} = E_x \cdot EF_x \qquad \text{(Eq. 1)}$$

where:

$EM_{savings}$ = CO_2 emission savings [t CO_2/year];

E_x = amount of energy of energy carrier x [MWh/year];

EF_x = emission factor of energy carrier x [t CO_2/MWh].

3.5.1 Main measures of the Riga Smart City SEAP

The main quantifiable measures of the SEAP planning document are listed in Table 3. The measures are organised into three categories: energy efficiency, use of renewable energy, and transport. Their impact is measured as forecasted emission reduction potential expressed in thousand tons per year and is divided into a minimum, optimum, and maximum contribution, reflecting both the complexity and uncertainty of forecasting.

Table 3: Main measures for the period 2013–2020 presented in Riga's SEAP. Adapted from [30].

Measure	Forecasted CO_2 emission reduction by 2020 [kt/year]		
	Minimum	Optimum	Maximum
Energy efficiency measures			
Additional heat production by JSC Rīgas Siltums through installing a condensation economizer	8.5	9.8	10.7
Additional heat production using an absorption heat pump in the cogeneration unit of HP Imanta	0.5	0.8	1.1
Use of wood chips for energy production in the heat sources of JSC Rīgas Siltums	66	83	111
Renovate buildings connected to the district heating system to achieve a 1.5% yearly reduction in heat consumption[21].		62.50	
Measures for the use of renewable energy			
Use of solar collectors for hot water preparation in buildings	0.6	0.9	1.1
Use of geothermal heat pumps for heat supply in buildings	3.5	4.8	6.2
Local use of boiler equipment operating on pellets	4.5	6.1	7.9
Measures in the transport system			
Increase extent of biofuel use in municipal public transport	7.8	15.6	23
Increase number of hydrogen powered vehicles replacing city busses	0.9	1.5	2
Total	**154.8**	**185**	**225.5**

Additional to the presented measures in Table 3, Riga's SEAP presents multiple qualitative measures which can be summarised as follows. The city of Riga aims at increasing the use of decentralised RES for heat and electricity production by facilitating the installation process. On the same time, the removal of coal-fired operated boiler houses in the private housing sector is fostered. In the public building and urban housing sector, the measures target large-scale renovations, e.g., 100% of municipal educational establishments, energy audits as well as better energy consumption management, increased monitoring and data collection, and the introduction of smart metering and technologies. Concerning transport, the city intends to increase the usage of bicycles and emission-free vehicles by providing structural improvements in bicycle lanes, a network of smart and slow charging infrastructure, and free parking possibilities for those vehicles. Meanwhile, citizens should be informed through campaigns, events, and other means of knowledge exchange about on-going projects, energy efficiency, renewables sources, and energy-saving advises [30].

To quantify the final CO_2 emission forecast for 2020, a business-as-usual scenario (BAU) is created and the assessed impact of the three scenarios applied. The BAU is based on the projected heat, electrical power, and fuel consumption by end-users. The econometric method is applied as the access to data on specific consumer groups, technological and technical development can be limited. This method uses several macroeconomic indicators as inputs and postulates a hypothetic relationship between energy consumption and external parameters.

[21] Compared to the average heat energy sold over 2010, 2011 and 2012.

As the amount of energy required is directly related to economic development, the most important parameters are population number, GDP, added value by sector, and changes in private consumption. For every energy service and use, a set of economic, technical, and social factors are identified [30].

The results can be seen in Table 4. With the implementation of all measures listed in Table 3, an emission reduction compared to 1990 of 53–56% can be achieved. As seen in the previous chapter 3.4, in 2016 a reduction of 54.5% compared to the reference year was reached.

Table 4: Assessed impact of the measures in three different scenarios[22]. Adapted from [30].

Scenario	CO_2 emissions in the reference year (1990) [kt]	Projected CO_2 emissions in 2020 [kt]	Reduction against reference year [%]
Minimum	4 295	2 005	53.32
Optimum		1 956	54.46
Maximum		1 880	56.23

3.5.2 Estimated reduction potential of measures in 2016

Table 5 shows the estimated CO_2 emission reduction in 2016 of the implemented measures. The reduction is calculated with the “bottom-up” method described by (Eq. 1). The share of implemented measures compared to the total reduction can be seen in Figure 14. The usage of new renewable resources accounts for 86% of the impact.

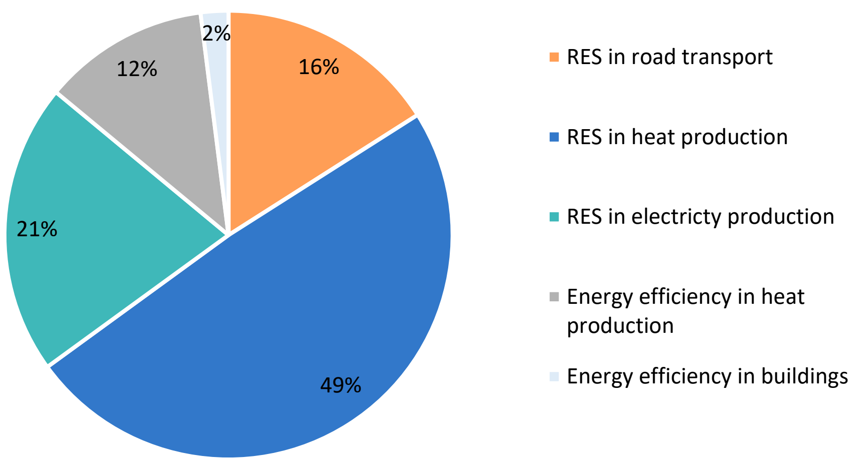

Figure 14: Distribution of the impact of implemented measures[23]. Adapted from [36].

[22] The assessment was performed in 2012.
[23] The impact of the use of electric transportation in municipal institutions is excluded as it represents only 0.05%.

Table 5: Estimated CO_2 emission reduction of implemented measures. Adapted from [36][24].

Measure taken	Estimated reduction of CO_2 emissions in 2016 [t]
Additional heat production by JSC Rīgas Siltums through installing a condensation economizer	15 026
Use of biomass for energy production in the heat sources of JSC Rīgas Siltums	65 030
Additional heat production by JSC Rīgas Siltums through installing an absorption heat pump	741
Renovation of municipal educational institutions and social houses reducing heat consumption	2 291
Renovation of apartment houses reducing heat consumption	457
Use of biofuels in motor vehicles	21 000
Use of electric transport in municipal institutions	68
Electricity generation in biomass co-generation plants	10 597
Electricity generation from biogas Ltd„Rigens municipal wastewater treatment plant Daugavgriva	3 582
Electricity generation from biogas (Ltd Getliņi EKO)	12 795
Electricity generation with solar PV (Ltd Zaļā Latvija)	20
Total	**131 607**

[24] The source is in Latvian. A translating program was used to obtain information.

4 Pathways for 2030

Chapter 4 presents three different pathways for the city of Riga to achieve a reduction of CO_2 emissions. First, the methodology is covered indicating the definition of the pathways representing the different means to realize the emission reduction. Then, a target for 2030 is recommended which will work as the basis for all actions. Finally, three distinct pathways are introduced. The measures, which support fulfilling the target, are shown in chapter 5.

4.1 Methodology

In energy planning, future energy systems are often described by scenarios or forecasts showing the modelled outlook. While scenarios rather explore a range of outcomes resulting from uncertainty, forecasts try to identify the most apparent pathway being most effective when extensive information is available [37].

The Cambridge Dictionary gives the word pathway a second definition as “a series of actions that can be taken in order to achieve something” [38]. In this thesis, this definition is used and slightly changed to fit the purpose of the thesis objective, resulting in the following definition:

A pathway is characterized by the measures employed to achieve a set target.

No predictions of the future development of the city in terms of growth (demographic and economic), policy changes, or similar are taken. The pathways show measures to achieve the target set in chapter 4.2. A renewable energy course would be defined by measures increasing the usage of renewable sources, e.g., the enlarged utilization of biomass as a fuel. To simplify the characterisation and comparison of the pathways, a graphic method is carried out (see Figure 15). This approach is adapted from the Future Energy Scenarios (FES) of the National Grid ESO, the electricity system operator of Great Britain. The FES are a range of credible scenarios exploring the uncertainties and opportunities in energy utilization for the next 30 years. The future is modelled using different pathways that are characterised by the development across five overarching external factors (e.g., policy support) [39]. The methodology is taken from the framework of FES approach with some major changes. First, the pathways used here are not part of a scenario modelling. Second, the factors displayed in Figure 15 are not external factors but indicators of the measures employed. For instance, building a new solar farm requires low citizen engagement, while installing solar thermal collectors on apartment roofs calls for higher involvement. The five different indicators used are derived from the FES framework and the EU project REPLICATE (REnaissance of PLaces with Innovative Citizenship And TEchnology) replication and scalability potential scheme [40]. A scale displaying the score from low to high in five grade steps is applied (see Figure 15).

The definition of the indicators is as follows:

- **Policy support:** The extent of policy assistance, for instance, in form of incentives or subsidies, that is needed to carry out the proposed measures. A high score represents the need of high policy involvement to execute the actions.
- **Stakeholder involvement:** The degree of stakeholder involvement is characterized by the number of stakeholders and their association with the project. A high score indicates crucial involvement of the stakeholder for the success of the measure.
- **Citizen engagement:** The level of citizen engagement and commitment necessary to implement the planned actions. A low mark indicates no needed involvement. Although citizens are normally counted to the stakeholders, an own indicator is created to show the importance of inhabitants in city planning.
- **Trialability:** The degree to which the solution(s) in the pathway can be experimented with on a limited basis before full implementation. A high score displays full trialability on a local scale.
- **Market demand:** The extent to which there is a general market demand for the solution(s) proposed. A low mark shows no market interest.

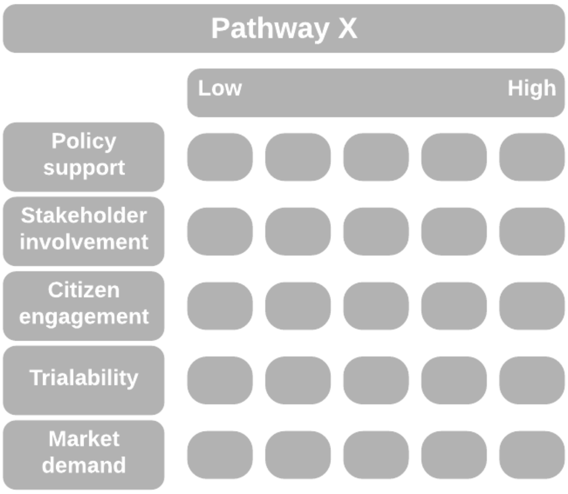

Figure 15: Pathway graphic displaying the pathways' indicators on a scale from low to high.

To define suitable pathways, a target for 2030 has to be set. The concept of backcasting is used, meaning that a desirable future (here: an emission reduction goal) is defined. Actions to achieve this future are identified by working backwards towards the starting point. Furthermore, the new target should be ambition raising, meaning that it must challenge current targets [41].

4.2 Target setting

Setting long-term targets demonstrates a clear commitment of the jurisdiction (e.g., of a city) and sets a clear sign to stakeholders about the long-term opportunities in a given market. Time-intensive processes such as network planning or building the required human capacities are favoured. Commitment helps to anchor stakeholder expectations and to establish a broader support base towards achieving the target [42].

Currently, the city of Riga is missing an emission target for 2030. As seen in chapter 3.4, the city already surpassed the target of the Covenant of Mayors for 2020 and 2030. Therefore, a new challenging goal is needed. The target set in this passage is the basis for the pathways created in the subsequent chapters.

For a target to be effective, it should be SMART (i.e., Specific, Measurable, Achievable, Realistic, and Time-bound). A target must be precise and clear to be measurable. Stakeholders have to understand the target to work with and for it. Furthermore, well-designed targets must be achievable and realistic, which is linked to the time horizon and the level of effort needed to accomplish the target. Although targets should stimulate stakeholders to go beyond business-as-usual, too ambitious goals can lead to nonachievement. Targets need to be set in a time frame, otherwise, there could be a lack of motivation to reach them. Both short- and long-term settings offer certain advantages and disadvantages so that long-term targets with intermediate goals are used to unite both approaches [42].

According to [43], there are five features to describe the characteristics of target setting: (1) motivating goal, (2) target's object, (3) scope, (4) unit of the target and (5) goal type. The motivating goal describes the objective behind the target. As Riga surpassed already the targets of the Covenant of Mayors, a new more ambitious goal to underline Riga's forefront role in fighting climate change is needed. The object of the target determines what the target refers to, in this case, the reduction of GHG emissions. The scope sets the target boundaries, e.g., the sectors which are included. The unit of the target, as the name suggests, indicates the evaluation in terms of absolute or normalized indicators. The last feature, the goal type, shows if a target is absolute or relative to a previous state. Table 6 summarizes the characteristics of the recommended target for Riga in comparison to the proposition of the Covenant of Mayors. As Riga is part of the CoM, the approach of achieving the new target is based on the principles and recommendations of the SECAP guidebook.

Table 6: Summary of the target setting of the Covenant of Mayors in comparison to the proposed new target for Riga. Adapted from [3], [43].

	Target description	Motivating goal	Object	Scope	Unit	Type
CoM	At least 40% reduction of GHG emissions compared to the base year	EU climate & energy targets	GHG emission	Buildings, transport, others (e.g., local electricity production)	Total or per capita	Relative to base year
Riga	61% reduction compared to base year	Set an example for fighting climate change	GHG emission	Same as CoM	Total	Relative to base year

Finding a new reduction objective for the city of Riga is both a challenging and encouraging task. Riga, that already achieved a reduction of 54.5% (compared to 1990) in 2016, surpassed the 2030 goal of the CoM by 15.4% and 14 years earlier. To keep its forefront position in fighting climate change, a target must be chosen that underlines Riga's willingness and pursuit in creating a sustainable city.

The IPCC estimated that to avoid catastrophic climate change, the world average temperature increase should not exceed 2 °C above pre-industrial levels. The panel recommends keeping the temperature well below 2 °C at a 1.5 °C limit. To stay under the 2 °C change, the concentration of GHG emissions in the atmosphere must be limited to 450 parts per million (ppm), corresponding to a 60% reduction in 2050 compared to 2010 levels equalling a level of 20 Gt CO_2-eq. per year[25]. With a forecasted world's population of 9.3 billion habitants by 2050, the limit would translate to a level of around 2 t CO_2-eq per capita. In 2010, the average emissions of the world were 4.9 t CO_2-eq per capita and 7.4 t CO_2-eq per capita for the EU. The 2-ton-limit is taken as the basis for the target setting in Riga, even though the limit refers to overall GHG emissions and not only the ones associated with energy use and does not factor the scale differences between supralocal and small services and activities [43]. Assuming a constant population of Riga for the next 30 years (632 614 inhabitants), the total emission goal of 2050 would amount to 1 266 kt CO_2-eq being around 30% of 1990 emissions, representing a reduction of 70% in 60 years.

As described before, setting long-term objectives is important for all involved stakeholders, but local energy plans usually aim at short or medium terms (e.g., 3 to 5 years) as they allow for more effective implementation and rapid learning from the policy process. Furthermore, they can coincide with electoral cycles. Long-term targets could provide less guidance in terms of concrete implementation, therefore setting intermediate targets can facilitate monitoring [42]. A methodology of setting intermediate targets, backcasting from the long-term target, is using linear progression following the subsequent formula [43]:

$$S_{int.target}(\tau) = S_{baseline} + \frac{S_{target} - S_{baseline}}{\tau_{target} - \tau_{baseline}} \cdot (\tau - \tau_{baseline}) \qquad \text{(Eq. 2)}$$

where:

$S_{int.target}(\tau)$ = emission share of the intermediate target year τ [%];

$S_{baseline}$= emission share of the base year[26] [%];

S_{target} = emission share of the target year [%];

τ = intermediate target year [years];

τ_{target} = target year [years];

$\tau_{baseline}$= baseline year [years].

Using (Eq. 2) results in an intermediate reduction target of 61% in 2030 compared to 1990 levels. Figure 16 shows the visual representation of the recommended targets (in orange) relative to the base year 1990 (in grey) and the most recent calculated year 2016 (in blue). The orange line represents a simple linear progression over the time horizon.

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[25] There are many models applied in climate science to predict the future concentrations and limits needed to slow down climate change. Multiple pathways are being modelled and changed on a yearly basis. Therefore, other sources might indicate different values. As this thesis is not about climate modelling, only one source is used.

[26] Note: For the figure, the base year was set to 2016 using (Eq. 2). The target, 61% reduction, nevertheless is set to the base year 1990.

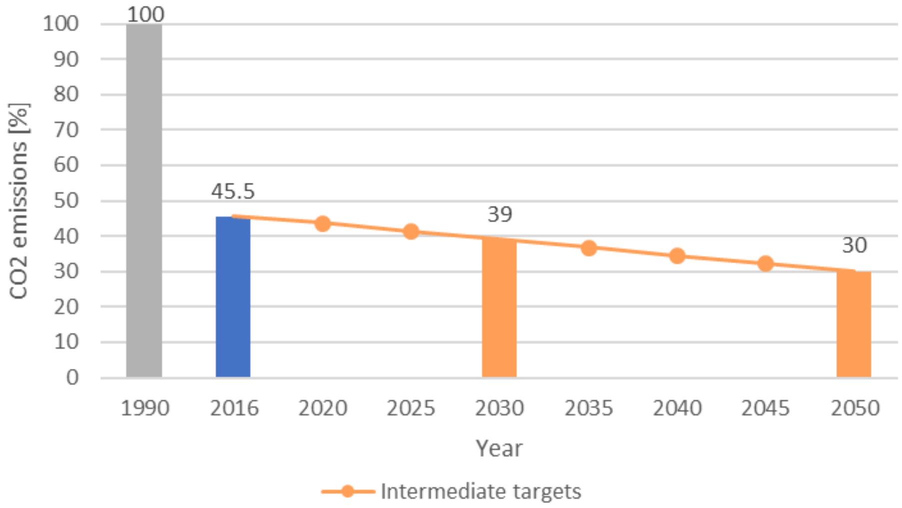


Figure 16: Visual representation of Riga's emissions in the baseline year 1990 (grey) and 2016 (blue), including the target (orange) for 2030 and 2050.

4.3 Pathway A: Green hydrogen

The production of hydrogen is generally characterized into three groups: fossil fuel-based hydrogen (grey hydrogen), fossil fuel-based hydrogen with carbon capture, utilisation and storage (blue hydrogen), and hydrogen from renewables (green hydrogen) [44]. Hydrogen is considered the missing link in the energy transition, providing energy to sectors which are otherwise difficult to decarbonise through electrification. These sectors include industries, building sector, power production in which hydrogen could be injected into existing natural gas grids, and transportation by, for instance, fuel cell electric vehicles. Currently, around 65% of the global hydrogen demand is used by the chemical industry, while the rest is distributed among refineries, iron and steel production, and other general industries. Of the total hydrogen demand, only 4% is produced by electrolysis, while the rest is provided by fossil fuels with natural gas having the biggest share of 48%. Although green hydrogen is gaining more attention, the reality shows that hydrogen production is primarily dominated by fossil fuels and used in the industry sector [45]. Hydrogen usage at industrial scale across the globe results in annual CO_2 emissions equivalent to those of Indonesia and the United Kingdom combined. Nevertheless, green hydrogen is projected to grow rapidly in the coming years as multiple ongoing and planned projects point in that direction. Renewable hydrogen is technically viable and approaching economic competitiveness. Falling costs of renewables, system integration challenges due to rising shares of intermittent power supply, dropping costs of electrolysers, and supply chain logistics favour the development of hydrogen projects. Still, funding and legislative frameworks are needed to facilitate development [44].

According to Latvia's National Energy and Climate Plan, hydrogen is considered as a long-term alternative fuel for the transportation sector. Latvia intends taking further steps to facilitate its development, including the adaptation of its gas network, the deployment of hydrogen infrastructure, and purchase incentives for hydrogen vehicles. Nevertheless, no comprehensive framework has been set up yet. The reality is that there are no pilot projects planned or in execution (see Figure 17). Currently, there is one fuelling station in operation (in Riga) [46].

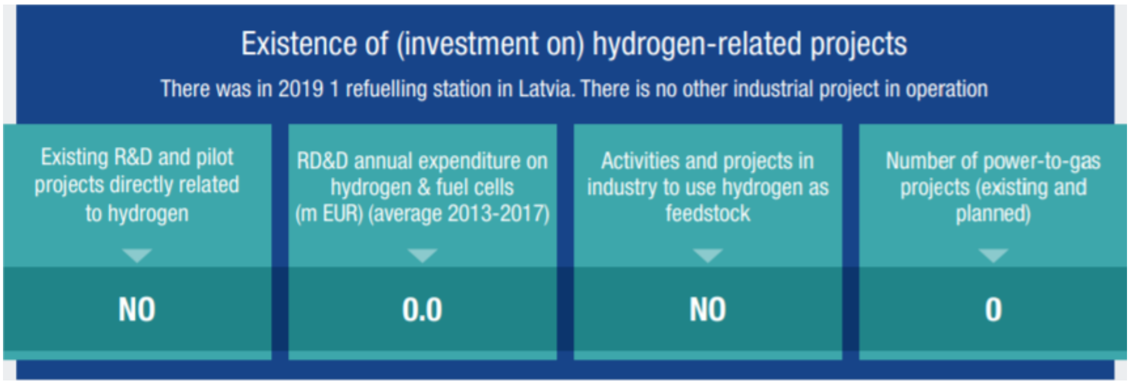


Figure 17: Overview of existing hydrogen-related projects [46].

According to the Fuel Cells and Hydrogen Joint Undertaking's (FCH JU) scenario analysis for Latvia in 2030, there is 46 GWh/year (low scenario) to 210 GWh/year (high scenario) hydrogen demand based on different levels of ambition linked to the national context. The hydrogen, delivered by renewable electrolysis (17 to 76 MW), will be used in four different sectors: industry, building, transport, and power. The analysis estimates the biggest demand in the transport sector (39–135 GWh/year) [46].

The city of Riga understood the potential of hydrogen as an energy carrier and already included measures in their SEAP to gradually replace public service busses with emission-free vehicles, foster the construction of publicly accessible hydrogen charging stations and facilitate the use of hydrogen for creating local energy sources [30]. The only hydrogen filling station in Latvia (and in the Baltics) is situated in Riga. In March 2020, Rīgas Satiksme, the public transport operator, informed that ten hydrogen-driven trolleybuses are now operational, carrying passengers on route 4 [47].

Both Latvia and Riga recognise the importance of hydrogen as a stepping stone in the energy transition. The absence of pilot projects is a perfect opportunity for Riga to develop the measure presented in this pathway. With the first filling station and bus route completely operated by hydrogen, Riga demonstrated the willingness to invest in hydrogen projects. To further improve the deployment and to decrease the dependency on hydrogen import, the presented measure in 5.1 is applicable. Figure 18 displays the indicator score of pathway A. An indicator matrix for all three pathways showing the reasoning of each score can be found in Annex A.2, Table A.1.

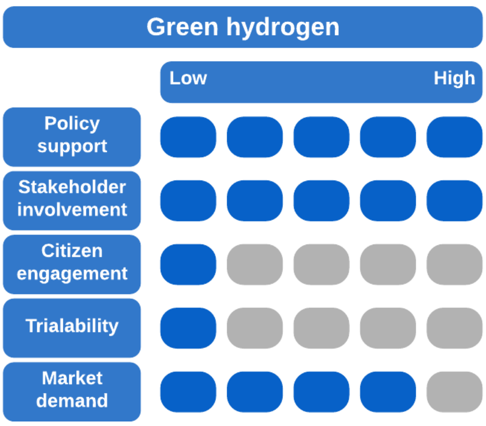


Figure 18: Indicator score pathway A: Green hydrogen.

4.4 Pathway B: Solar engagement

In 2019, 2 107 of the 3 190 GWh gross electricity produced in Latvia was covered by hydropower with an installed capacity of 1 558 MW. In comparison, solar technologies contributed 3 GWh with an installed capacity of 3 MW [48]. The electricity generation in Latvia is characterised by its high hydro share. Although the importance of solar deployment is recognised, the reality shows only an increase of 2.32 MW in the last 5 years (0.68 MW in 2014). An estimation of 2015 by the Baltic transmission system operators (TSO) anticipates an increase up to 8 MW by 2030 [49]. Nevertheless, the city of Riga recognised the crucial role of solar systems in reducing emissions on an urban planning scale. The city aims at facilitating the installation of solar thermal and photovoltaic (PV) systems as well as so-called solar pumps, a combination of solar collectors and a heat pump. Furthermore, a register of local installations such as solar thermal collectors is planned to be set up [30].

Including citizens in urban energy planning is a common feature of modern governance and is gaining more importance as cities acknowledge the crucial role that residents can play in the energy transition. Having a continuous exchange between the city and its habitants fosters customized solutions that are tailored to the needs of the city. Involving and engaging citizens into taking an active role in energy planning should be one of the main points while designing an energy action plan. The city of Riga understood this principle and tries to stimulate exchange through various channels. The most activities aim at transferring knowledge to the citizens in programs like the Riga Energy Days where the REA organizes an exhibition with additional thematic seminars. The REA intends to involve multiple stakeholders in policymaking focusing both on residents and professional societies. Furthermore, the engagement of pupils and students is promoted to ensure future-oriented energy planning [30].

As seen, the city of Riga with the help of the REA is taking citizen engagement seriously, nevertheless, there are always ways to improve such cooperation. While citizens are engaged to foster their knowledge and take part in seminars to express their opinion and visions, tools to individually partake in the energy transition are missing. The proposed pathway should support citizens to take informed actions to help the city reach their emission goals by investing in solar technologies. The residents need tailored solutions that might convince them to take the initiative. Often inhabitants understand the concepts and ideas behind energy measures but see no linkage to their situation (except when the measures include actions such as housing refurbishments). Giving citizens tools to grasp their situation, including the energy and financial context, might lead to increased interest and deployment of renewable technologies. The proposed measures focus on facilitating the investment in solar technologies. The aim is to transmit to the people that they can actively take part in the energy transition not only by getting informed, expressing their opinions, or changing their behaviour but by investing their own money. The pathway intends to show that renewable investments have both energetic and monetary benefits for the citizens. The indicator score of this pathway is shown in Figure 19.

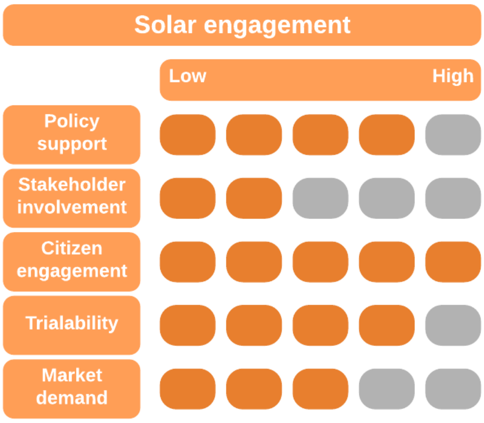


Figure 19: Indicator score pathway B: Solar engagement.

4.5 Pathway C: Modern transportation

Pathway C differs from the other two pathways both in the purpose and extent of the analysis. The measures do not include any economic evaluation and are presented as a thought-provoking impulse. Two measures are shown that could shape future transportation.

Transport is one of Europe's biggest source of CO_2, responsible for the emissions of over a quarter[27] of all greenhouse gases and increased by a quarter[28] since 1990. Unless transport emissions are tackled and brought under control, 2030 climate goals will be missed [51]. Emissions (of the complete transport sector) need to be decreased by around two-thirds by 2050 (compared to 1990 levels) to meet the long-term 60% emission reduction target set out in the 2011 Transport White Paper [50]. To meet the 2050 Paris climate commitments, cars and vans must be entirely[29] decarbonised, requiring the end of sales of cars with internal combustion engines by 2035. Unfortunately, current measures to tackle emissions from cars and vans have largely been a failure. Additionally, with proper lifecycle accounting of biofuels, emissions would be on average 10% higher than official statistics. The big three underlying reasons for failure are: Governments that are unwilling to constrain demand for mobility, car use, and ownership; the car industry which circumvents emission regulation by all possible means; and the unhealthy political influence the industry exercises over some member states with important car industries. Keys to achieving emission reductions are to accelerate the shift to electro-mobility, creating an ambitious new car CO_2 target for 2025, and policy development in the field of road pricing and reform of vehicle taxation [51].

Latvia experienced an increase of 15.1% in total greenhouse gas emissions from the transport sector in the period from 1990 to 2017 [50]. In 2016, road transportation accounted for the biggest share of emissions in Riga with 39% [36]. The city of Riga understood the urgency and potential of reduction measures in this sector and achieved a reduction of 15.1% of CO_2 emissions compared to 2008 [36].

[27] In 2017, 27% of total EU-28 greenhouse gas emissions (22% if international aviation and maritime emissions are excluded) came from the transport sector [50].
[28] In 2017, emissions from transport (including international aviation but excluding international shipping) were 28% above 1990 levels [50].
[29] Transport emissions must be reduced by more than 90% by 2050 [51].

Actions such as enlarging the network of bicycle lanes, increasing bicycle hire stations, and promoting the usage of bicycles were planned and implemented. Furthermore, the city increased the number of emission-free vehicles used by the municipality, raised the share of biofuels in municipal public transport, and deployed a hydrogen bus fleet [30]. Despite the efforts, decarbonizing the transport sector remains a tough challenge calling for new innovative actions and policy changes. Figure 20 presents the indicator score of pathway C.

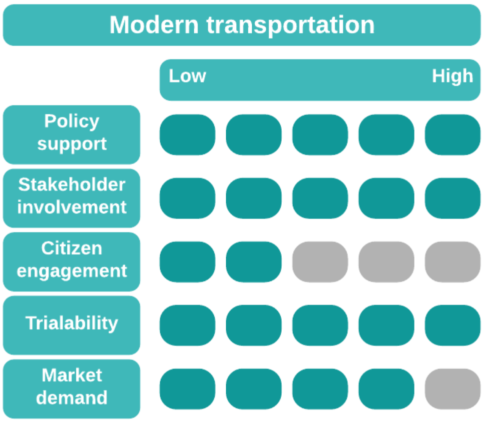


Figure 20: Indicator score pathway C: Modern transportation.

4.6 Comparison of pathways

Reducing emissions (as shown in Figure 16) will not be a matter of choosing one pathway but combining the different measures with the existing solutions planned by the city of Riga. The pathways are not exclusive and not all measures (pathway B and C contain two measures each) must be applied.

All approaches require essential policy support as, for instance, cooperation between stakeholders has to be organised or even laws changed. While pathways A and C are stakeholder intensive, pathway B focuses entirely on citizen engagement. Pathway A, which focuses on the creation of green hydrogen, represents a multi-million-euro project with nearly no trialability. The measures presented in pathways B and C can be tested on a small scale and then upscaled. The market demand for all three is high as both transportation and district heating are crucial sectors for the city of Riga in which multiple efforts were made to reduce emissions up to date. The score for pathway B is lower as solar awareness in the public is just raising and solar power undeveloped in Latvia. An increase in the market demand for solar technologies over the next years is nevertheless expected.

5 Measures

The following chapter specifies the measures of the three distinct pathways. Pathway A describes the production of green hydrogen using wind power. The measure consists of the sizing of a wind farm and the hydrogen production facility. Pathway B is characterized by the usage of solar technologies. An online solar map is conceptualized showing the PV and solar thermal potential of Riga. Additionally, a financing scheme for citizens is presented. The measures in pathway C introduce modern transportation. They show an innovative way of obtaining biodiesel, and new last-mile delivery modes.

5.1 Pathway A: Green hydrogen

The following pathway consists of only one measure, the production of hydrogen via electrolysis of renewable energy. The measure includes many different technologies and stakeholders, thus creating a certain complexity. The produced hydrogen can be used for purposes such as sustainable transportation modes or heat generation. In the subsequent passages, the measure will be explained, starting with a project of Enertrag AG which serves as a basis for this measure. After showing the draft of the measure, the chapter is split into two parts: the wind farm outline and the hydrogen cycle.

The Enertrag Hybrid Power Plant is a project designed to showcase a safe and sustainable energy supply based on renewable sources. Operational since 2011, the hybrid plant with its innovative approach (the first one of this kind worldwide) produces hydrogen from wind energy and reconverts it on demand into electricity using two combined heat and power (CHP) units. The system contains three wind turbines with a nominal power of 2 MW, a 500-kW electrolyser and CHP units (350 kW each) that use a minimum of 30% biogas (up to 100 %) and a maximum of 70% hydrogen. For the measure of this thesis, three turbines and one 500-kW electrolyser are taken as the basis as well. As Riga already possess an extensive DH system with multiple cogeneration heat sources, no new units must be purchased, which reduces the overall system cost and indicates the fitting purpose of this measure. The Enertrag hybrid plant can operate in four different modes: hydrogen production, baseload, wind forecast, and generation against peak demand. In the hydrogen production mode, the power plant operates as a hydrogen factory with the goal to maximize hydrogen production, including the usage of electricity by the CHP units during low wind periods. The baseload mode ensures a constant electrical power output independent from the wind conditions delivered by the wind turbines and the CHP units. Excess wind power is used to run the electrolyser. The other two modes, focusing on wind forecasting and tariff focused production, are not of interest for the pathway [52].

The measure presented in the following paragraphs purely serves as a hydrogen production facility, therefore there is no direct coupling between the production and usage of hydrogen, thus it is not a hybrid power plant. The goal is to maximize hydrogen production, so the hydrogen facility is prioritised over grid injection. It is assumed that the facility runs with the same capacity factor as the turbines. As shown in the subsequent paragraph, the ideal usage of hydrogen in the case of Riga would be as substitute for natural gas or the usage for fuel cell electric transport.

Figure 21 presents a graphical scheme of the proposed measure. Electricity is produced by a wind farm that can either be directly fed into the grid or be used as input to an electrolyser to produce hydrogen. The produced hydrogen is stored in a hydrogen tank and can be used to fill hydrogen cars or in a co-generation plant as a substitute for natural gas. The hydrogen can be transported using trucks, a hydrogen pipeline network, or blended in the natural gas network. As there as specific laws on hydrogen blending in Latvia (see 5.1.1), the most probable transportation mode will be by truck.

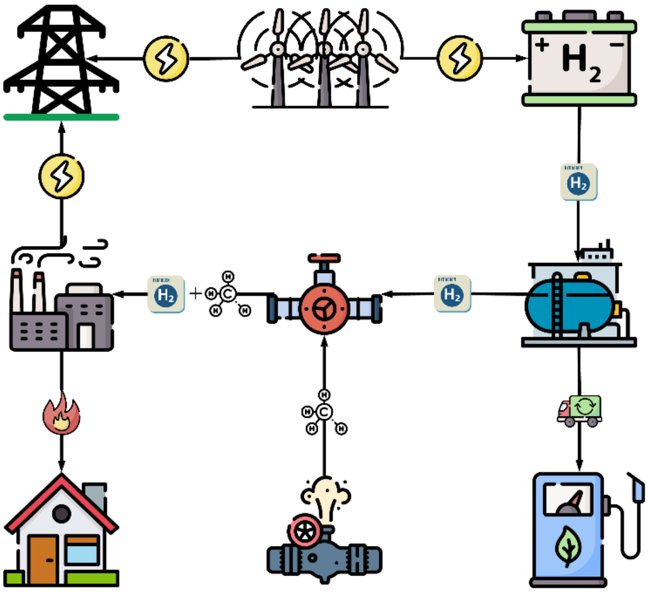


Figure 21: Graphical scheme of the renewable hydrogen production project[30].

5.1.1 Wind farm outline

Selecting a suitable site for a wind farm is a manifold process including various technical, economic, environmental, and social factors. A wind farm project has to be economically feasible to be developed, meaning that both technical and economic factors have to favourable. Technical factors include aspects such as wind speed, land topography and geology, and grid structure. The proximity of a grid line reduces the cost to connect the wind farm to the said grid. Having paved roads leading to the site facilitates the transportation of the components. Economic considerations include capital, operational and maintenance (O&M), and land cost. Another important aspect is the environmental impact of the wind farm that has to be kept as low as possible. The wind farm will have a visual impact on the landscape and generates noise that can affect both wildlife and the public if built too close to residential areas. Furthermore, wind turbines can affect birds through collision, disturbances, or habitat loss. Additionally, a wind farm can cause electromagnetic disturbances. As the last point, the wind farm should be accepted by the public involved. Residents in the proximity of the site should be integrated into the project development ensuring no adverse effects for the community [53].

[30] Icons made by Freepik and Nhor Phai from www.flaticon.com.

Figure 22 indicates a suitable location for the project considering the presented site selection criteria and the characteristics of the city area. Most of the land area of Riga is either used as residential area or covered by forest and water. Finding a suitable location is therefore a rather challenging task that has to consider local laws and the occurrence of natural reserves. The proposed location is just an example of a convenient site as most of the site selection criteria can be fulfilled. Both a country road and transmission line are within one-kilometre distance. Residential areas are further than one kilometre such that the noise of the wind farm will cause no disturbance. Nevertheless, the wind farm would be a visually prominent feature. The only deficit of the location is the relatively close airport Lidosta Spilve (around 3 km) that is used for leisure aviation. The relatively small size of the wind farm should not cause any aerodynamic or space disruption. Riga International Airport, outside the city border, is roughly 8 km away. A concise study must be conducted to determine if the three wind turbines could cause any disturbance for the air traffic. If more locations, for example, in the planning region of Riga, are considered, a site that does not disturb the airport can be found. Staying in the city boundaries, the selected location still represents the best option.

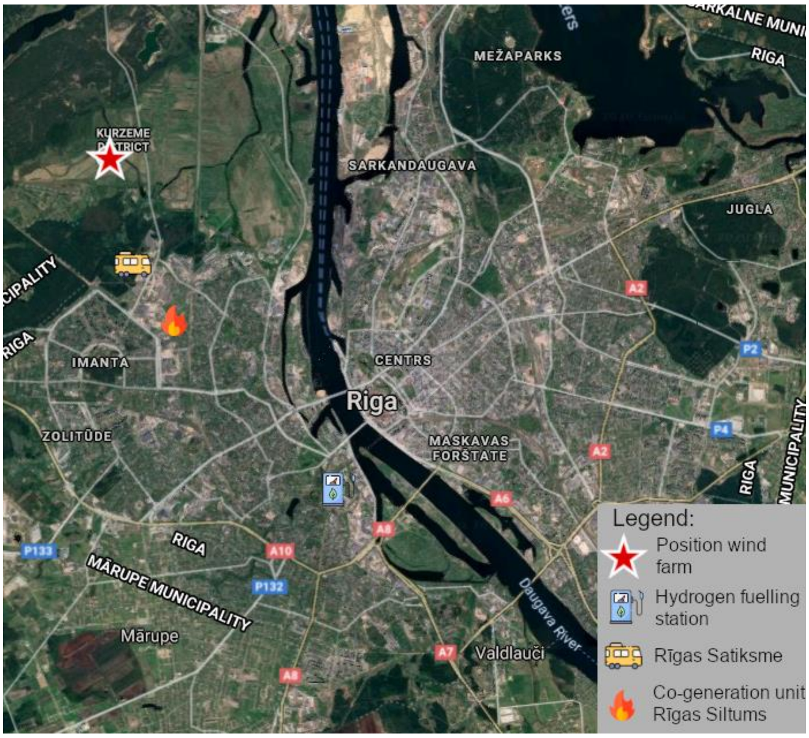


Figure 22: Proposed project site (star symbol), hydrogen fuelling station (fuelling station symbol), Rīgas Satiksme (bus symbol) and HP Imanta (fire symbol). Adapted from [54].

Good features of the site are the proximity to Rīgas Satiksme, the local bus fleet operator and the location where the buses are parked and the HP Imanta, the co-generation unit of Rīgas Siltums. As described before, the city of Riga is increasing their hydrogen-powered bus fleet that could be fuelled at the parking location of the bus operator indicated by the bus sign in Figure 22. Currently, one fuelling station is operated by Rīgas Satiksme for the operation of bus line No. 4. The station is open to the public as well. Furthermore, the produced hydrogen can easily be transported to HP Imanta using trucks or a pipeline connection.

To determine the wind speed characteristics, the DTU (Technical University of Denmark) Global Wind Atlas in cooperation with the International Renewable Energy Agency (IRENA) is used. The average wind speed of the city of Riga can be seen in Figure 23 and ranges around 6 m/s to 8 m/s, which corresponds to the IEC wind class IIIa [55].

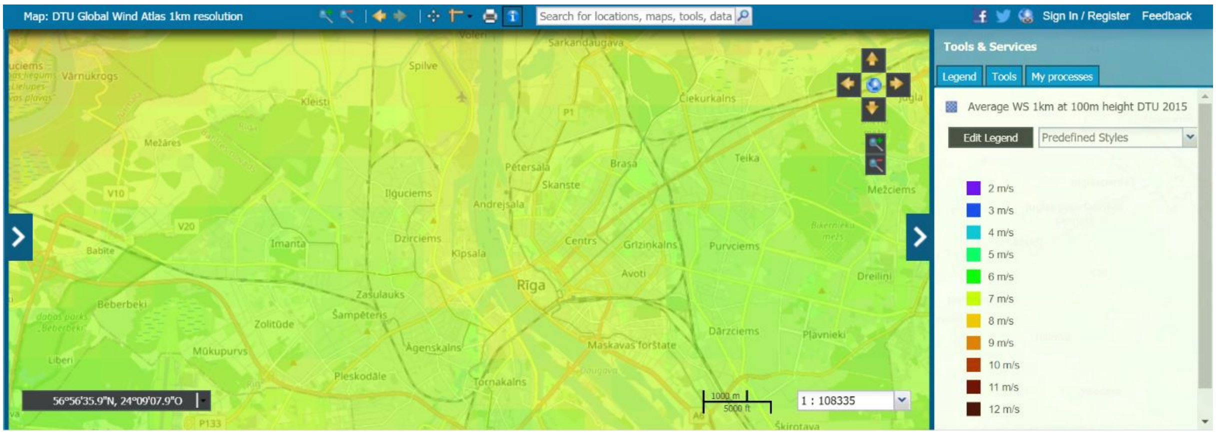


Figure 23: Average wind speed at 100 m height in Riga [56].

Knowing the wind class, a suitable wind turbine can be found. Unfortunately, wind class IIa is considered standard and more turbines of this type are offered. In this thesis, an IIa turbine of the German manufacturer Enercon is chosen. For the selection, following criteria are regarded: the manufacturer and their factory should be European to minimise logistics cost and the power profile of the turbine has to be available. The second point turns out to be limiting, which results in the choice of the Enercon E-82. The turbine has a rated power of 2 300 kW, a rotor diameter of 82 metres, a design life of 20 years, a cut-in speed of 2.5 m/s, and a cut-off speed of 34 m/s. The hub height can be adjusted from 78 to 138 metres, as the parameters of the wind map are set at 100 metres, thus the hub height is chosen to be 98 metres [57]. The investment cost for wind projects installed in the European Union in 2016 was 1 564 EUR/kW, while the O&M cost was set to 23 EUR/kW*year [58]. The biggest cost component is the turbine. The National Renewable Energy Laboratory (NREL) ascribed around 68% of the total capital cost to the turbine for a land-based reference wind power plant project in 2017. The cost for the balance of the system covers roughly 22%, including the electrical infrastructure, foundation, and others. Other financial aspects account for the last 10% [59]. The cost breakdown changes depending on the project characteristics, nevertheless, the turbine remains the highest investment.

Figure 24 shows an exemplary positioning of the wind farm. The location's coordinates are 56°59' N, 24°00' E. The prevailing wind direction is west-southwest (around 13% frequency of occurrence). The location demonstrates a wind speed index close to 1 over the whole year indicating a rather constant annual energy output (Annex A.3.1, Figure A.3) [56]. The turbines are facing towards the predominant wind direction being placed 330 metres (= four times the diameter) and 500 (= six times the diameter) apart. Wind turbines need to be positioned so that the distances in between are 3 to 10 rotor diameters. The exact spacing depends on the individual circumstances of the site. The exemplary layout of this measure represents a compromise between compactness, which minimises capital cost, and the need for adequate separation to reduce wind shadowing and interferences [60].

Figure 24: Exemplary position of the project wind farm. Adapted from [54].

To calculate the yearly energy output of one turbine, the wind speed profile (Figure 25) and the power output of the turbine (Figure 26) are needed. The calculations can be found in Annex A.3.1, Table A.3. The yearly energy output of the E-82 at the project location is 8.64 GWh with a capacity factor of 0.43.

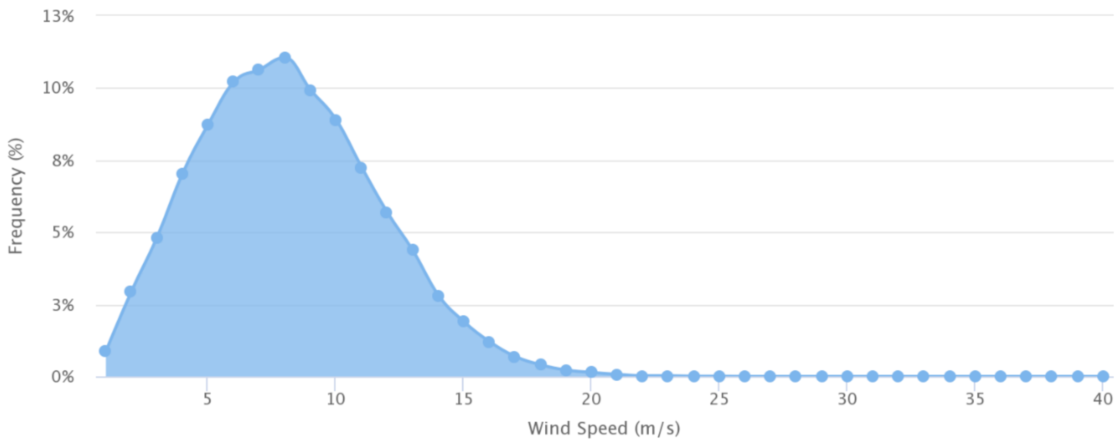


Figure 25: Frequency of certain wind speeds at the project location [56].

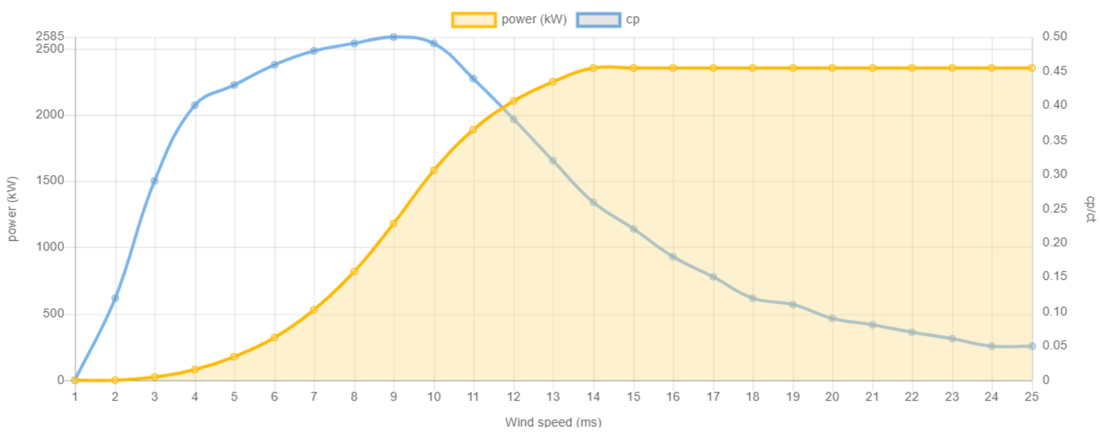


Figure 26: Power output of the turbine Enercon E-82 with a rated power of 2 300 kW [61][31].

[31] The power output curve could not be found on official documents of Enercon. The data is taken from a database of wind turbines done by two private persons. The database comprises more than 2000 turbines. Nevertheless, the data must be treated carefully. A small change to the data was performed by the author.

The Levelized Cost of Electricity (LCOE) is a method to compare power plants with different generating capacities and cost characteristics considering their lifetime costs and generated energy throughout their life cycle. The following formula represents one way of determining the LCOE of a project [62]:

$$LCOE = \frac{I_0 + \sum_{t=1}^{n} \frac{A}{(1+i)^t}}{\sum_{t=1}^{n} \frac{E_{el}}{(1+i)^t}} \qquad \text{(Eq. 3)}$$

where:

LCOE = Levelized Cost of Electricity [EUR/kWh];

I_0 = investment expenditure [EUR];

A = annual total cost consisting of fixed and variable operating costs [EUR/year];

E_{el} = annual produced electricity [kWh/year];

i = discount/real interest rate [%];

n = economic lifetime [years];

t = year of lifetime (1, 2, … n).

Using the formula and the project assumptions result in a LCOE for the wind farm of 0.0395 EUR/kWh. The executed calculations regarding the wind farm can be found in Annex A.3.1. The discount rate for the whole measure is set to 5%. This parameter affects the LCOE, which can be seen in Figure 27. The exact rate is project-specific. The Levelized Cost of Hydrogen (LCOH) is calculated in chapter 5.1.2.

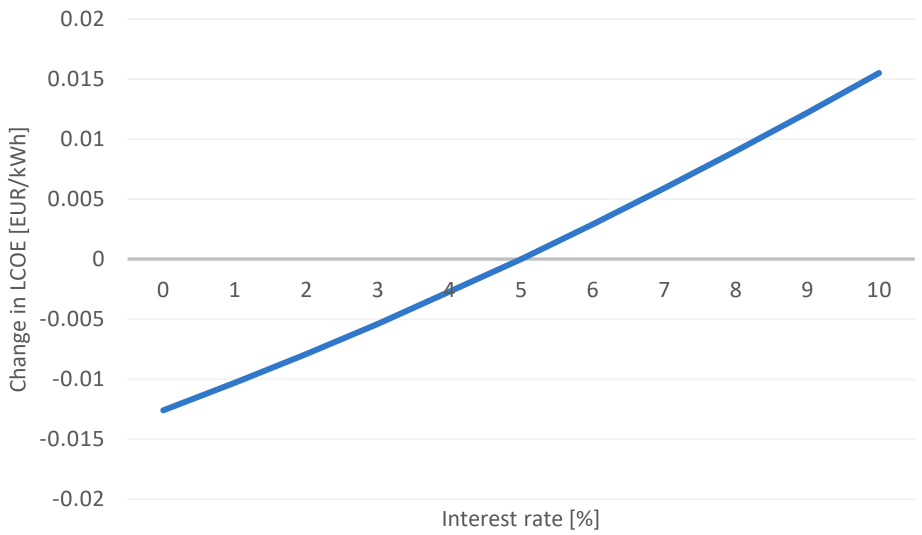


Figure 27: Influence of the interest rate on the LCOE.

Figure 28 shows the LCOE and global weighted average values for onshore wind projects from 2010 until 2020. The blue dots represent project-level LCOE data of the IRENA Renewable Cost Database based on project-specific costs and capacity factors. The orange dots indicate power purchase agreement and auction results and give an outlook for the years 2019 and 2020. The proposed wind farm of this pathway with its LCOE of 0.0395 EUR/kWh ranks around the global weighted average and shows the economic competitiveness of the project.

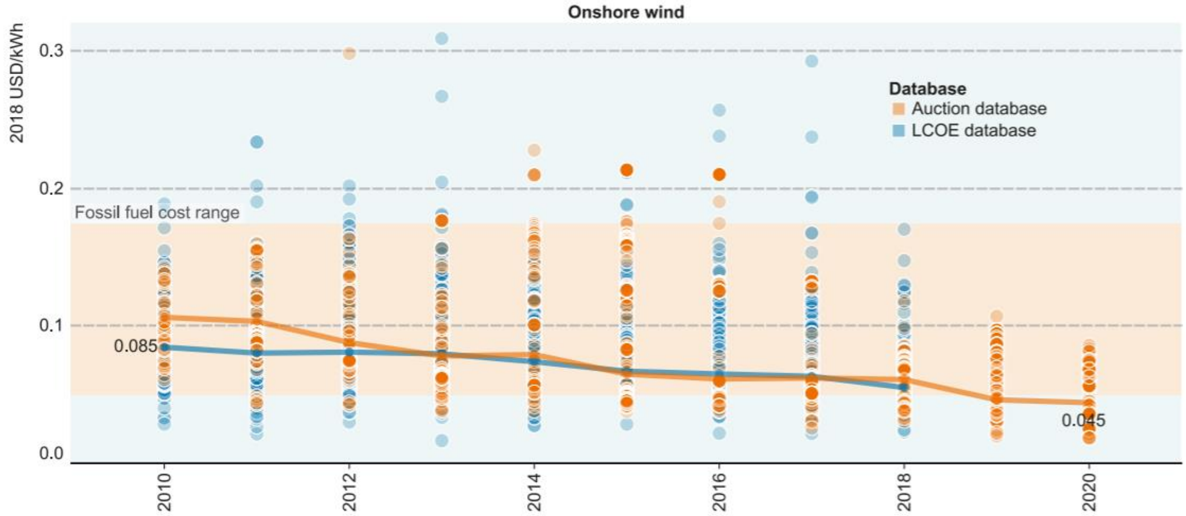


Figure 28: Levelized Cost of Electricity (blue), auction prices (orange), and their respective global weighted average values for onshore wind projects, 2010–2020 [63].

5.1.2 Hydrogen cycle

Electrolysis of water is the process of using direct current (DC) to split water into oxygen and hydrogen. There are three main electrolyser technologies that are used or being developed: alkaline (ALK), proton exchange membrane (PEM), and solid oxide. Solid oxide electrolysers are still in the development phase and therefore not further regarded. ALK electrolysers are the industry standard, while PEM electrolysers are rapidly gaining market traction and are commercially available today. The past development and established production volumes of ALK electrolysers result in lower capital expenditure compared to PEM electrolysers. Additionally, the lifetime of ALK electrolysers is twice as long (80 000 h to 40 000 h). State-of-the-art PEM electrolysers can operate more flexible and reactively than ALK electrolysers which offers a significant advantage in flexible operation [45].

As the electrolyser is just connected to the wind farm with no additional grid connection, high flexibility is needed to follow the intermittent load of the wind turbines which favours the usage of a PEM electrolyser. Nevertheless, the lower initial investment coupled with the longer lifetime was critical for the decision to perform the calculations with an ALK electrolyser. Furthermore, the company Hydrogenics, which provides the example electrolyser data, states that both their electrolyser types have the same response time [64].

For the energetic and monetary calculations, it is assumed that the hydrogen production facility operates with the same capacity factor as the wind turbine, thus the produced electricity by the turbine is first fed to the electrolyser and compressor. If excess electricity is produced, it is injected to the grid. For the sizing approach, an example electrolyser of the company Hydrogenics with a nominal power input of 500 kW is chosen [64]. To calculate the energy need of the electrolyser, the following equation can be used:

$$E_{ELY} = CF_{wind} \cdot 8760 \cdot P_{ELY} \qquad \text{(Eq. 4)}$$

where:

E_{ELY} = energy input of the electrolyser [kWh];

CF_{wind} = capacity factor of the wind turbine [-];

P_{ELY} = power input of the electrolyser [kW].

The produced amount of hydrogen can be derived by using:

$$V_{hydro} = \frac{E_{ELY}}{SPC_{ELY}} \qquad \text{(Eq. 5)}$$

where:

V_{hydro} = yearly hydrogen output [Nm^3];

SPC_{ELY} = specific power consumption of the electrolyser [$kWh/Nm^3{}_{H2}$].

The compressor is sized regarding the hydrogen flow derived from the electrolyser. To obtain the compressor power, isentropic compression is assumed. Generally, the compressed gas has to be cooled down between compression stages to make the process more isothermal and less adiabatic. A single-stage compression would result in a high outlet temperature of the gas, which would be unsuitable for storage. Thus, hydrogen is typically compressed in several stages with intercoolers in between [65]. Perfect intercooling is assumed, meaning that the temperature of the gas leaving the intercooler is the same as that of the gas entering the first compression stage. For this measure, a 3-stage compressor is assumed. The power needed for a multistage process is as follows [66]:

$$P_{isen} = ns \cdot \frac{\gamma}{\gamma - 1} \cdot \dot{m}_{hydro} \cdot R_{spec} \cdot T_{in} \cdot \left[\left(\frac{p_{ns+1}}{p_{in}} \right)^{\frac{\gamma-1}{\gamma} \cdot \frac{1}{ns}} - 1 \right] \qquad \text{(Eq. 6)}$$

$$P_{com} = \frac{P_{isen}}{\eta_{com}} \cdot \frac{1}{1000} \qquad \text{(Eq. 7)}$$

where:

P_{isen} = isentropic compressor power [W];

ns = number of stages [-];

γ = Ratio of specific heat [-];

$\dot{m}_{hydro}$ = hydrogen mass flow rate [kg/s];

R_{spec} = specific gas constant for hydrogen [J/kg*K];

T_{in} = input temperature of hydrogen [K];

p_{ns+1} = output pressure of last compression stage [Pa];

p_{in} = input pressure of first compression stage [Pa];

P_{com} = compressor power [kW];

η_{com} = compressor efficiency [%].

Using a 3-stage compressor reduces the minimum power needed by 36.34% compared to the single-stage process. Cooling after the last stage is still needed after the last compression stage before the gas can enter the storage system. Increasing the number of stages will further reduce the power and after-cooling needed but will increase the mechanical complexity.

Fewer stages generally result in lower purchase and O&M cost at the expense of lower energy efficiency and operation at cooler temperatures [67]. The 3-stage process in this example achieves a temperature reduction (after the last compression step) of 54.99% compared to the single compression (from 970.95 K to 436.98 K).

The mass flow rate of hydrogen, needed for (Eq. 6), is obtained by using the density at standard temperature and pressure conditions (STP) and multiplying by the nominal hydrogen flow. The STP conditions are defined as 101 325 Pa and 0 °C:

$$\dot{m}_{hydro} = d_{hydro} \cdot \dot{V}_{hydro} \qquad \text{(Eq. 8)}$$

where:

d_{hydro} = hydrogen density at STP [kg/m^3];

$\dot{V}_{hydro}$ = nominal hydrogen flow of the electrolyser [Nm^3/h].

To obtain the energy consumed by the compressor, (Eq. 4) can be used as the compressor operates the same amount of time as the electrolyser. As the electrolyser and compression unit operate on DC, a power converter, a so-called rectifier, is needed to convert the alternating current (AC) of the wind turbine to DC. The power of the power converter can be estimated by applying (Eq. 9):

$$P_{PC} = P_{ELY} + P_{com} \qquad \text{(Eq. 9)}$$

where:

P_{PC} = power of the power converter [kW].

Note that the power converter efficiency is not regarded as the power and energy calculations for the electrolyser and compressor are carried out on AC current basis. The datasheet of Hydrogenics presents the specific power consumption and power input on AC basis. It is assumed that their products include a rectifier. In the case of the compressor, the conversion from AC to DC is already considered in the compressor efficiency. The power input of the power converter is needed for the cost analysis as no specific cost of the Hydrogenics system could be retrieved.

The storage unit, a high-pressure cylinder, operates at 700 bar and is sized to store seven times the average daily produced hydrogen. As the electrolyser works at the same pace as the intermittent wind turbine, the oversized tank should ensure that hydrogen must not be transported away from the facility daily. If the discharge frequency should be further reduced, the tank size must be further increased. At 700 bar, high-pressure vessels can store hydrogen with a volumetric density of around 40 kg/m^3 [65]. The daily mass flow rate is obtained by multiplying the mass flow rate with the capacity factor and hours of a day. The results of the hydrogen facility sizing can be found in Table 7. A more detailed view of the results of the hydrogen facility sizing and related calculations can be found in Annex A.3.2.

Table 7: Sizing of the hydrogen production facility.

Electrolyser	$\dot{m}_{hydro}$ [kg/h]	m_{hydro} [t/year]	V_{hydro} [m^3]	$t_{oper,life}$[32] [h]
	8.99	33.86	640.356	75 336

Compressor	P_{isen} [kW]	P_{com} [kW]	**Rectifier**	P_{PC} [kW]	**Storage**	m_{stor} [kg]	V_{stor} [m^3]
	15.42	20.56		520.56		649.44	16.236

Regarding the energy balance, the wind energy generated by the turbines is split into two shares: one transmitted to the grid and one powering the hydrogen cycle. Therefore, the energy balance can be formulated as follows:

$$E_{wind} = E_{grid} + E_{hydro} = E_{grid} + E_{ELY} + E_{com} \tag{Eq. 10}$$

where:

E_{wind} = energy output of the wind farm [kWh];

E_{grid} = energy delivered to the grid [kWh];

E_{hydro} = energy used for hydrogen production [kWh];

E_{com} = energy input of the compressor [kWh].

Assuming that the compressor works with the same capacity factor as the electrolyser, the subsequent energetic values (presented in Table 8) are obtained.

Table 8: Energy balance of hydrogen production facility.

Energy [GWh$_{el}$]	E_{ELY}	E_{com}	E_{hydro}	E_{grid}	E_{wind}
	1.8834	0.0774	1.9608	23.9591	25.9199

The electricity of the wind turbine that is fed directly to the grid replaces electricity created by other sources. The emission reduction is obtained by using the Latvian national average emission factor. The hydrogen produced by the electrolyser is used to reduce the emissions in the district heating system by replacing natural gas. The case of hydrogen substituting gasoline in, e.g., hydrogen buses is not regarded. The total saved emissions can be obtained by applying the following equation:

$$EM_{savings} = E_{grid} \cdot EF_{grid} + m_{hydro} \cdot HHV_{hydro} \cdot EF_{NG} \tag{Eq. 11}$$

where:

EF_{grid} = Latvian average electricity emission factor [kg CO_2/kWh$_{el}$];

m_{hydro} = annual hydrogen production [kg/year];

HHV_{hydro} = Higher Heating Value of hydrogen [kWh/kg];

EF_{NG} = emission factor of natural gas burning [kg CO_2/kWh$_{th}$].

The measure avoids a total of 2 881.05 tons of CO_2 emissions in a year. The emissions avoided by the wind turbines and the usage of hydrogen as a substitute for natural gas can be seen in Figure 29.

[32] Operational lifetime

The figure compares the saved emissions resulting from the different use of electricity delivered by the wind turbines. One share is directly transmitted to the grid, the other share is used to produce hydrogen. The electricity delivered to the grid reduces emissions by 2 611.54 t, while the hydrogen cycle accounts for a decrease of 269.51 t. The hydrogen cycle represents 9.35% of the total emission reduction potential but does have a higher emission factor (0.137 kg CO_2/kWh_{el}) compared to the Latvian average grid factor of 0.109 kg CO_2/kWh_{el}.

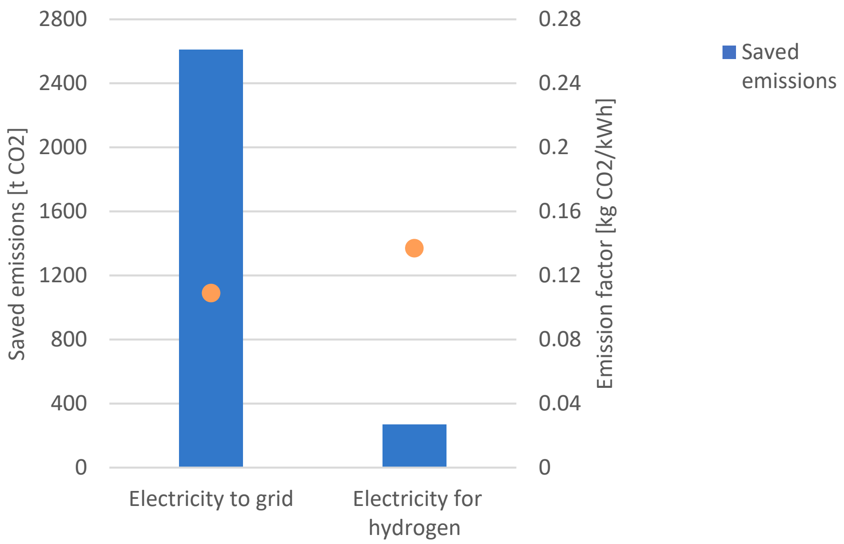


Figure 29: Saved emissions by the measure (in blue) and the respective emission factors (orange).

Figure 30 presents the difference between injecting the total produced electricity by the turbines into the grid ("Only grid") and using a share to produce hydrogen ("Grid + hydro"). The hydrogen cycle measure achieves a higher emission reduction by 55.78 t CO_2 per year.

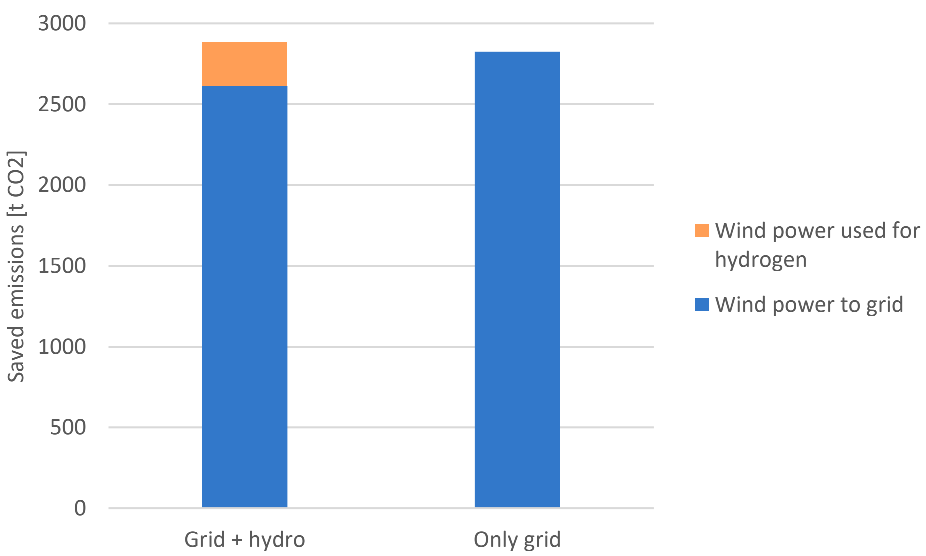


Figure 30: Difference between deploying hydrogen production and pure grid injection.

Like the LCOE, the LCOH can be calculated using a slightly altered version of (Eq. 3):

$$LCOH = \frac{I_0 + \sum_{t=1}^{n} \frac{A}{(1+i)^t}}{\sum_{t=1}^{n} \frac{m_{hydro}}{(1+i)^t}} \qquad \text{(Eq. 12)}$$

where:

LCOH = Levelized Cost of Hydrogen [EUR/kg];

I_0 = total investment expenditure of all components [EUR];

m_{hydro} = annual produced hydrogen [kg/year].

The LCOH, in this example, includes the whole production cycle along with compression and storage of hydrogen. The investment cost for this measure can be calculated with the subsequent formulas:

$$I_0 = I_{0,ELY} + I_{0,com} + I_{0,PC} + I_{0,stor} = \sum_{j=1}^{3} I_{0,j} + I_{0,stor} \qquad \text{(Eq. 13)}$$

$$I_{0,j} = c_{inv,j} \cdot P_j \qquad \text{(Eq. 14)}$$

where:

$I_{0,com}$ = investment expenditure of the compressor [EUR];

$I_{0,ELY}$ = investment expenditure of the electrolyser [EUR];

$I_{0,PC}$ = investment expenditure of the power converter [EUR];

$I_{0,stor}$ = investment expenditure of the storage tank [EUR];

$I_{0,j}$ = investment expenditure of component j (e.g., j = ELY) [EUR];

$c_{inv,j}$ = investment cost of component j per installed power [EUR/kW];

P_j = installed power of component j [kW].

The investment cost for the storage tank does not follow a linear cost assumption as shown in (Eq. 14). To obtain the cost, the following equation is used [68]:

$$I_{0,stor} = €80 \cdot 2500 \cdot \left(\frac{V_{stor}}{2500}\right)^{0.75} \qquad \text{(Eq. 15)}$$

where:

V_{stor} = hydrogen tank capacity [Nm^3].

The cost of the wind farm is not directly included in the LCOH but is being considered by using the LCOE as the price for electricity. The annual total cost consists of fixed and variable costs that are as follows:

$$A = A_{fixed} + A_{var} \qquad \text{(Eq. 16)}$$

$$A_{fixed} = \sum_{j=1}^{4} c_{O\&M,j} \cdot P_j \qquad \text{(Eq. 17)}$$

$$A_{var} = LCOE \cdot E_{hydro} + c_{water} \cdot V_{hydro} \cdot SWC \quad \text{(Eq. 18)}$$

where:

A_{fixed} = fixed annual cost [EUR/year];

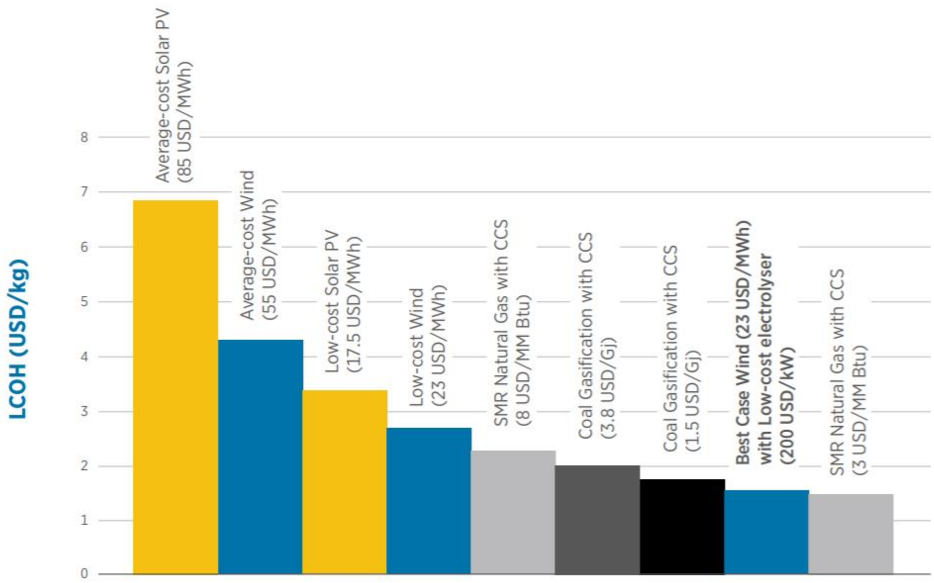
A_{var} = variable annual cost [EUR/year];

$c_{O\&M,j}$ = annual O&M costs of component j [EUR/kW*year];

c_{water} = water price [EUR/l];

SWC = specific water consumption of the electrolyser [l/Nm$^3_{H2}$]

Replacement costs of the components are not regarded in the LCOH calculations. The electrolyser has a lifetime of around 80 000 hours [45]. In the measure, the electrolyser is operated 75 336 h during the project lifetime. Other logistics or transportation costs such as dispenser or hydrogen transport trucks are not considered in the cost analysis. Using the parameters of Table A.6 and the results of the energetic sizing of the hydrogen facility (Table 7), the LCOH amounts to 3.67 EUR/kg$_{H2}$. Figure 31 indicates the cost of producing hydrogen from renewables and fossil fuels. Although the calculation basis of the figure is different from the one used in the thesis, it can be used as a reference for the assessment of the measure. With a LCOH of 3.67 EUR/kg$_{H2}$, the hydrogen produced by the measure ranks around projects with average-cost wind electricity. Steam reforming (SMR) or gasification of fossil fuels with carbon capture and storage (CSS) results in lower production costs. In the analysis carried out by IRENA, only the projects with best-case wind electricity (with a price of 23 USD/MWh) with a low-cost electrolyser (200 USD/kW) are competitive. Changing the electrolyser price from 750 EUR/kW to 168.5[33] EUR/kW in the cost model of the thesis, the LCOH would drop to 2.81 EUR/kg$_{H2}$.



Notes: Electrolyser capex: USD 840/kW; Efficiency: 65%; Electrolyser load factor equals to either solar or wind reference capacity factors. For sake of simplicity, all reference capacity factors are set at 48% for wind farms and 26% for solar PV systems.

Figure 31: Hydrogen production costs from renewables and fossil fuels [44].

[33] Conversion rate of USD 1 to EUR 0.84 as of 16.09.2020.

As Figure 27 displays, the interest rate has a noticeable impact on project economics. For the wind farm calculations (LCOE) and the hydrogen cycle (LCOH), the same interest rate of 5% is applied. The impact of changing the interest rate on the LCOH can be seen in Figure 32. Note that this graph indicates the change of the project interest rate, therefore the LCOE is changed accordingly.

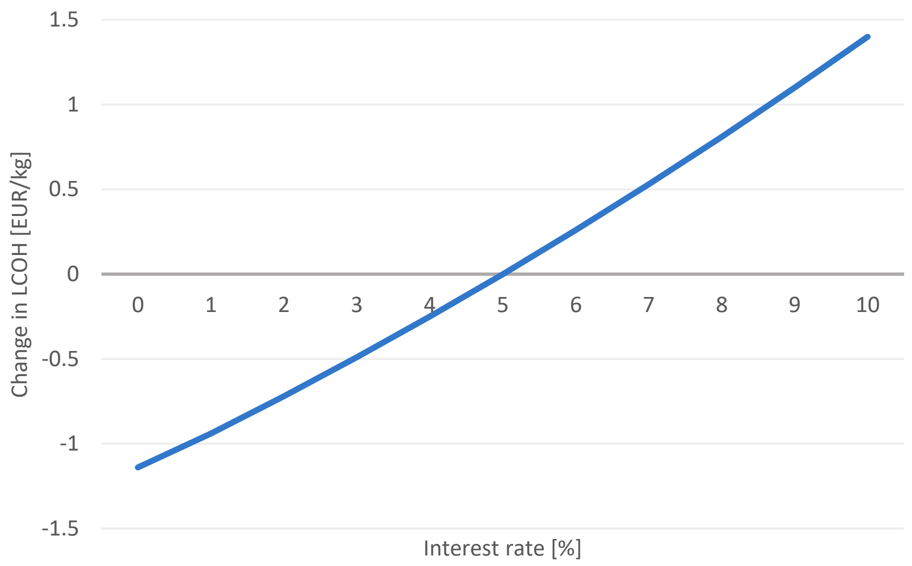


Figure 32: Influence of the interest rate on the LCOH.

The summary of the measure including the total initial investment, saved emissions, LCOE and LCOH can be found in Table 9.

Table 9: Results of the wind farm and hydrogen production sizing.

Wind initial investment [MEUR]	Hydrogen initial investment [MEUR]	Total initial investment [MEUR]	Total saved emissions [t CO_2/year]	LCOE [EUR/kWh]	LCOH [EUR/kg H_2]
10.7916	0.4616	11.2532	2 881.05	0.0395	3.67

As described before, the difference between injecting the electricity delivered by the wind turbines directly into the grid or using a share for hydrogen electrolysis is 55.78 t CO_2 per year. Assuming that the consumption of the electrolyser does not change if upscaling is applied, Figure 33 shows the effect of increasing the power input by 500-kW steps. The increase in the saved emissions is linear with a gradient of 0.112 t CO_2/kW. This raise is linked to an initial investment expansion of around 8.25 EUR/kg CO_2. Note that for the analysis nominal production conditions are assumed. In reality, with bigger electrolyser capacity nominal production is not guaranteed as the three wind turbines do not deliver the needed nominal power input of the electrolyser constantly (as seen in Table A.3). The incline of the saved emission curve would be smaller if the mismatch of turbine power and capacity size for higher capacities would be regarded.

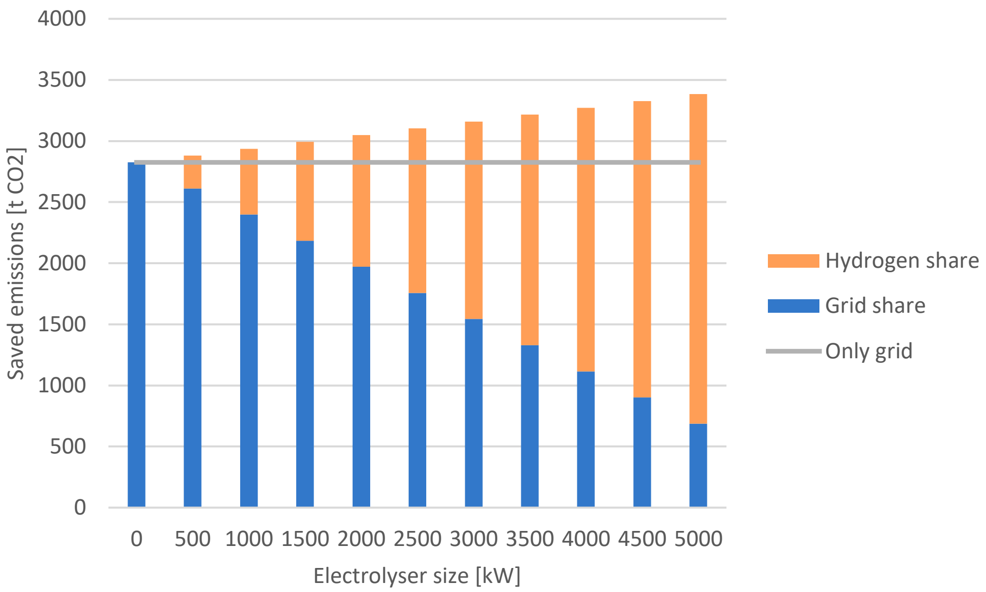


Figure 33: Upscaling of the electrolyser (hydrogen share in orange, grid share in blue, and only grid in grey).

5.1.3 Regulations concerning hydrogen

Blending hydrogen into existing natural pipelines is possible up to a concentration of 5 to 15% depending on the pipeline system and local natural gas composition. To ensure safety, modifications to the pipeline monitoring and maintenance practices might be necessary. Considering the utilization of a hydrogen-methane blend in end-use applications a concentration up to 5 to 20 vol% of hydrogen is feasible. The permitted concentration of hydrogen varies considerably between the EU member states from generally not allowed to between 0.1 vol% up to 10 vol% such as in Germany. There is neither an international nor European standard defining rules for an admissible concentration, therefore a case-by-case analysis is recommended by the European Committee for Standardisation. The absence of such regulations might lead to a fragmentation of the gas market and may create problems at cross-border connection points [69].

Currently, the maximum blending concentration for the transmission gas grid in Latvia is 0.1 vol%, but the National Regulatory Authority (NRA) in Latvia reports the existence of cooperation among the neighbouring states aiming to set coordinated hydrogen limits. Lithuania has a current limit of 2 vol%. Furthermore, direct hydrogen injection at transmission system operator (TSO) level is not possible in Latvia (due to technical features and absence of injection points) [70]. According to HyLaw, a flagship project aiming at boosting the market uptake of hydrogen, injection on TSO and distribution system operator (DSO) level is possible if a system user agreement is concluded [71]. In the case of the pathway, a DSO connection should be sufficient. Additionally, the NRA in Latvia reported that there are plans to increase the hydrogen acceptance into the natural gas networks, but no incentives are planned for developing hydrogen injection projects. In the National Energy and Climate Plan for 2021–2030, a study on the de-carbonization of the gas network and adapting to renewable hydrogen input is planned to be carried out [70].

Regarding the land use, the hydrogen production facility must be located in an area where industrial construction and use of territory is allowed according to the local land-use plan which is issued every 5 to 10 years. A change in the land-use plan must go through public consultation and the overall decision process to change the usability of a specific area can take up to two years [71].

5.2 Pathway B: Solar engagement

As described in 4.4, the measures presented in this chapter focus on convincing the citizens of Riga to invest in solar technologies, both understanding the financial and environmental benefits coming with it. The city of Riga is already actively promoting renewable energy sources during events such as the Riga Energy Days. The following measures should show the financial side of investing in renewables. The first measure describes a solar map indicating the potential of rooftop PV and solar thermal collectors. The second measure describes a financing scheme for citizens that want to actively support the city in the pursuit of fighting climate change.

5.2.1 Riga solar map

The following measure, a solar potential map for the city of Riga, aims at increasing the share of residential solar systems by offering a platform where citizens can understand the solar potential of their roofs. This tool should facilitate the investment decision of the citizens as the energy saved, emissions avoided, and financial aspects are covered. In the subsequent passages, the methodology of the tool, the assumptions, and a calculation example are described. No actual tool is programmed as this would go beyond the scope of the thesis.

Solar maps are a way of helping citizens to make an informed decision on whether to invest in solar technologies or not. Figure 34 presents the solar map of three cities: Barcelona in Spain, Nantes, and Paris in France. These solar maps are the basis of the concept for the solar map of Riga. The cities have different approaches on how to pass knowledge to the citizens. To design an approach for the Riga solar map, the common features and differences are analysed. All three tools show specific data per roof area so that every citizen can obtain information on their assets. While the Parisian map solely shows the solar potential, the interfaces of the city of Nantes and the municipality of Barcelona indicate the potential installed capacity, generated energy, and saved emissions. Furthermore, both tools illustrate the economics behind the purchase of a PV system, although the economic calculations of Nantes are more elaborated considering the rate of return and return time. Unfortunately, the tool of Nantes is lacking the used assumptions for the calculations, which, in contrast, are offered by the municipality of Barcelona in a user guide.

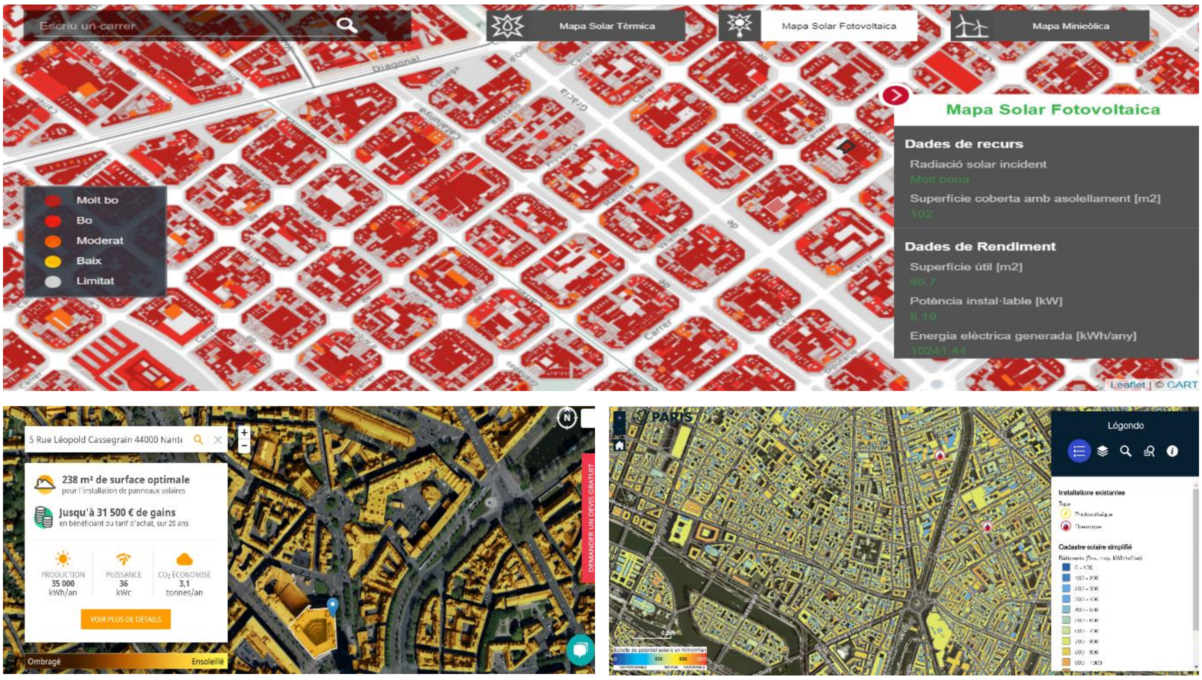


Figure 34: Solar maps deployed by the municipalities of Barcelona (top), Nantes (left), and Paris (right) [72]–[74].

The main difference between the solar maps is how the solar potential is described to the user. All three use a colour grading scheme to show high or low potential. The interface of Nantes shows a scale of insolation going from shady to sunny without giving specific values or measurements. The tool of Paris displays the solar potential in kWh/m^2/year giving the option of a simplified (see Figure 34) or a detailed map. The municipality of Barcelona uses a scale from “limited” (grey) to “very good” (red) with a constant solar potential (for all roofs) to indicate the differences of the areas. The municipality uses the concept of a practical PV potential called the PV power output (PV_{out}). PV_{out} is a specific yield, representing the amount of power generated per unit of installed PV capacity measured in kWh/kW per day. Essentially, it describes the achievable power output of a PV configuration taking into account the theoretical potential, air temperature, system configuration, shading and soling, as well as topographic and land-use constraints [75].

While the approach of Nantes is rather nontransparent, the concept of Paris requires a highly detailed mapping of the solar potential. For the map of Riga, the method of the municipality of Barcelona is chosen. The approach is simple to deploy and understand for both the user and the municipality. Clearly, if the chance is given to get an exact map of the global horizontal irradiation (GHI), the municipality of Riga should consider working with the GHI values and compute the PV power output themselves. As for lack of data, the approach of the municipality of Barcelona is currently the best option.

To obtain the PV_{out} of Riga, the Global Solar Atlas is used (see Figure 35). The Global Solar Atlas is a tool that indicates the world solar potential. It shows indicators such as direct normal irradiation, global horizontal irradiation, and others to describe the solar potential of a specific location. Furthermore, the tool calculates the specific PV_{out} of an area (for instance, the red dotted in Figure 35). The methodology and assumptions that the tool uses are summarised in Annex A.4.1.

Figure 35: Daily solar parameters of the city of Riga provided by the Global Solar Atlas [76].

As the PV$_{out}$ value is chosen to be constant for the selected region another variable (here: $\lambda_{surface}$) is needed to indicate the differences of the roof areas. This variable should include aspects such as orientation, shading, and shape of the roof. Therefore, the variable shows the degree of insolation the roof area receives. The municipality of Barcelona uses a colour grading system to represent this variable. The colour scheme proposed for the Riga solar map is shown in Figure 36.

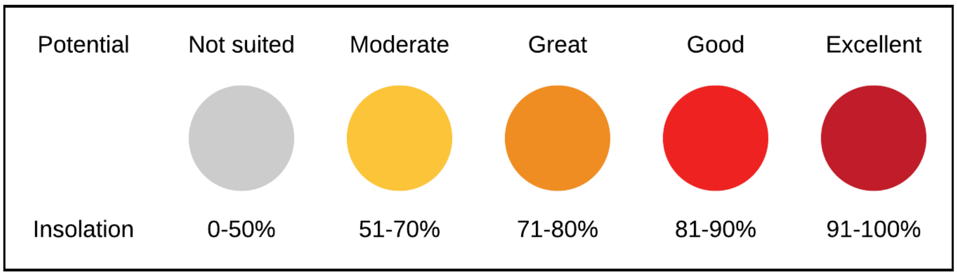


Figure 36: Colour grading representing variable $\lambda_{surface}$.

For the solar performance, two angles of the panel orientation have great importance: the tilt angle and azimuth angle. Regarding the azimuth angle, solar panels should face due south to obtain the maximum yield. The Global Solar Atlas recommends an optimal tilt angle of 39–40° (see Figure 35) equalling approximately the latitude of Riga (56.9496° N) - 15°, the rule of the thumb[34] to maximise the yield in the summer. Figure 37 shows the theoretical solar irradiation at latitude 56° N not considering specific characteristics of the location such as local weather effects. The graphs display the incident power (blue), the power on a horizontal plane (red), and the module power (green) with a certain tilt angle. The angles displayed are 41° (left), 56° (middle), and 71° (right). At a tilt angle of 41°, the module power curve is closely aligned with the incident power curve (96.7% curve coverage) [78].

[34] The rule of the thumb for the tilt angle recommends maximum production in summer: tilt angle = latitude - 15°, max. production in winter: latitude + 15°, overall yearly: latitude [77].

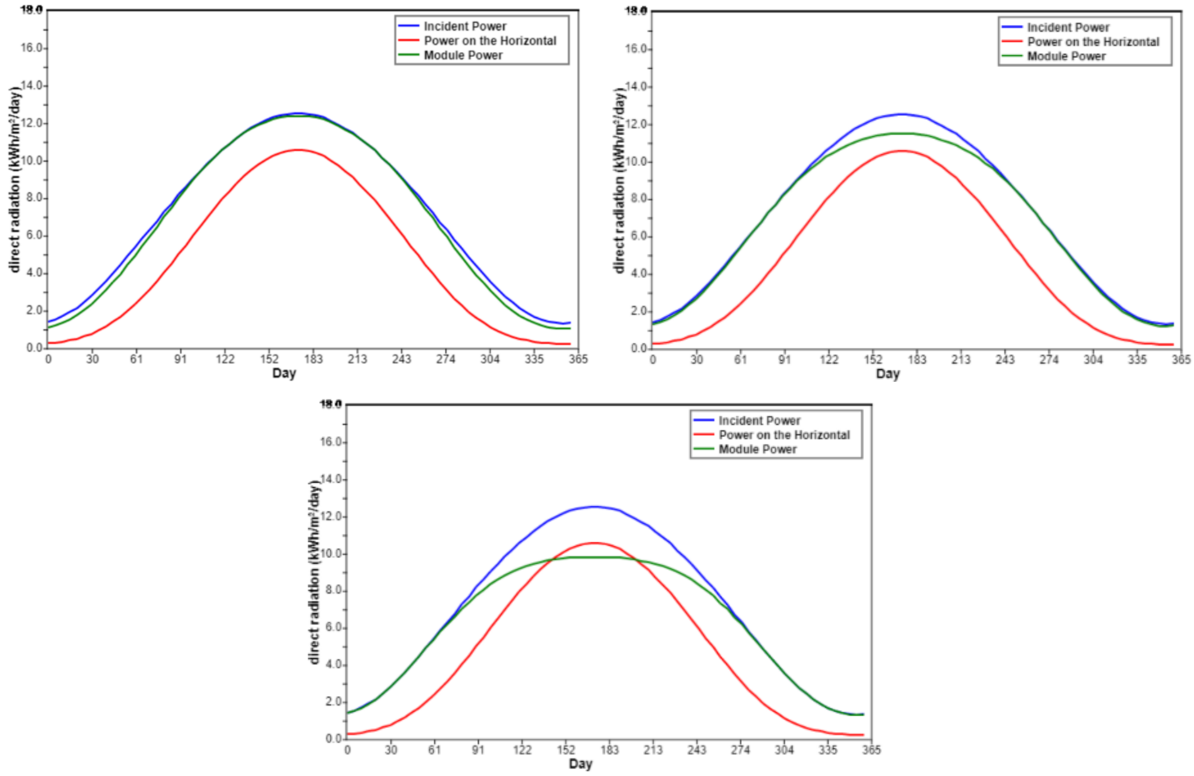


Figure 37: Theoretical solar irradiation at longitude 56° N with three different module tilt angles: 41° (left), 56° (right), and 71° (down) [78].

Using the colour scheme, a schematic overview of the tool for Riga could look as presented in Figure 38. No exact measurements are executed. Using, for instance, Lidar[35], would give an exact representation of the city.

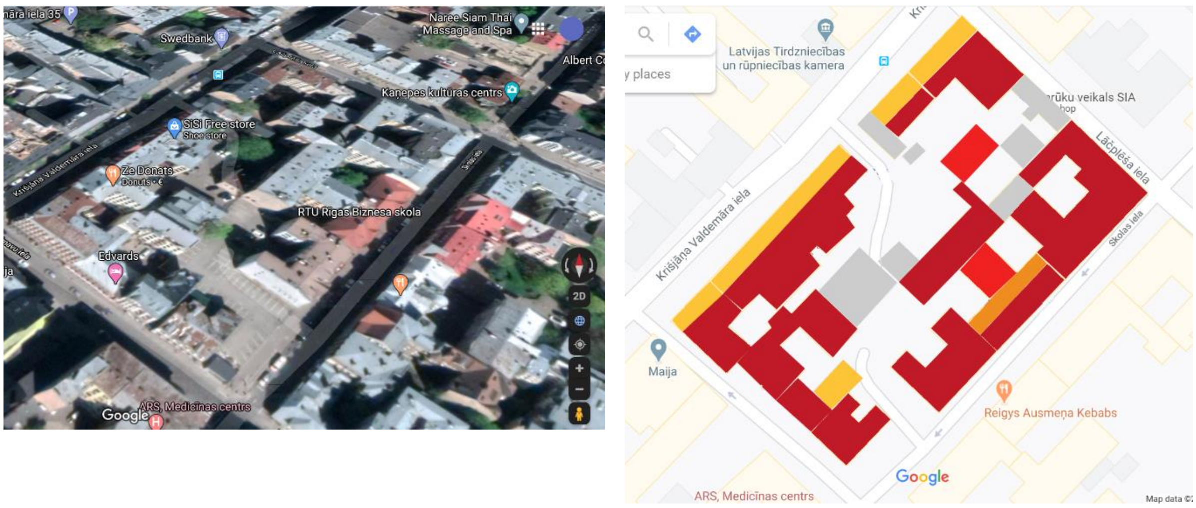


Figure 38: Example area in Riga using Google Maps in satellite view (left) and schematic solar map (right) [79].

As seen in the Parisian map, just giving information about insolation is not valuable for the user. Therefore, extra parameters such as useful roof area, installable PV capacity, generated energy, saved emissions, and economics must be presented.

[35] Lidar is a method for measuring distances by using a laser and deploying 3D representations of the target.

The following formulas are derived from the approach and assumptions used by the municipality of Barcelona [80]:

$$A_{useful} = A_{roof} \cdot \chi_{cover} \cdot \chi_{install} \quad \text{(Eq. 19)}$$

$$E_{PV} = \left\lfloor \frac{A_{useful}}{A_{panel}} \right\rfloor \cdot \lambda_{surface} \cdot P_{panel} \cdot PV_{out} = P_{install} \cdot PV_{out} \quad \text{(Eq. 20)}$$

where:

A_{useful} = total useful roof area that can be used for PV panels [m^2];

A_{roof} = roof area including chimneys and other obstacles [m^2];

χ_{cover} = share of roof that can be used for PV panels (excluding obstacles) [%];

$\chi_{install}$= share of area that remains after taking into account spacing of PV panels [%];

E_{PV} = energy output of the installed PV system [kWh/year];

A_{panel} = PV panel module size [m^2];

$\lambda_{surface}$= degree of insolation [%];

P_{panel} = PV panel power output [kW];

PV_{out} = practical PV potential (PV power output) [kWh/kW*year];

$P_{install}$ = installed PV capacity [kW].

To calculate the saved emissions (Eq. 1) of chapter 3.5 can be used. Another important information undoubtedly is the financial aspect. Crucial parameters are the investment cost, the saved money per year, and the breakeven duration. To keep the calculation simple and comprehensible for non-experts, PV module degradation or loans are not regarded. The equation for estimating the breakeven time, the duration after which the investment is profitable, is derived from the LG solar calculator [81]:

$$t_{breakeven} = \frac{c_{inv,pv} \cdot P_{install}}{E_{PV} \cdot \left(\mu \cdot p_{elec} + (1-\mu) \cdot p_{feed}\right) - c_{O\&M,pv} \cdot P_{install}} = \frac{C_{inv,pv}}{C_{savings,pv} - C_{O\&M,pv}} \quad \text{(Eq. 21)}$$

where:

$t_{breakeven}$ = breakeven time [years];

$c_{inv,k}$ = investment cost per installed power of technology k [EUR/kW];

$C_{inv,k}$ = total investment cost of technology k [EUR];

μ = share of self-consumption [%];

p_{elec} = electricity price [EUR/kWh_{el}];

p_{feed} = feed-in tariff [EUR/kWh_{el}];

$c_{O\&M,k}$ = O&M cost per installed power of technology k per year [EUR/kW*year];

$C_{O\&M,k}$ = total O&M cost of technology k per year [EUR/year];

$C_{savings,k}$ = total savings per year of technology k [EUR/year];

k = indicator of technology used, in this case k = pv (photovoltaic system) [-].

The parameter μ, the share of self-consumption, indicates the intermittent character of solar power. The demand of the building will not match the production of the PV panels. Mostly, when PV production reaches its peak during the day, residents are not at home.

Therefore, it is recommended to incentivize the citizen investment by guaranteeing a feed-in tariff for the electricity which is not self-consumed. On the one hand, the PV installation does not have to be downsized to fit the peak consumption of the building, thus the maximal potential of the installation can be achieved. On the other hand, no electricity will be wasted, benefitting the prosumers and the city of Riga. If no feed-in tariff is granted, the orientation of the PV installation should be shifted towards south-east (higher production in the morning) or south-west (higher production in the late afternoon) to fit the owner's daily routine. This shift will result in a reduced yield. Other possible incentives are, for instance, investment subsidies or value-added tax reductions. Currently, there is no feed-in tariff active in Latvia due to concerns about corruption and lack of transparency in the way it was carried out since 2007, therefore p_{feed} is set to zero [82].

Table 10 displays the assumptions made for the Riga solar map. The values try to represent the current country-specific and technological situation. The specific PV_{out} is obtained by multiplying the average daily output obtained by the Global Solar Map by 365.25. The two parameters χ_{cover} and $\chi_{install}$ describe the circumstance that not the complete roof area is suitable for PV panels. Roofs have obstacles such as windows and chimneys that reduce the usable area expressed by χ_{cover}. The panels themselves need additional space to avoid shadowing as well taking into account the mounting structure and cables. Therefore, an additional factor is needed expressed by $\chi_{install}$.

Table 10: Summary of the assumptions made for calculating the PV potential of roofs.

Parameter	Symbol	Value	Unit	Source
PV module power output per area	P_{panel}	320	W	[83], [84]
PV module area	A_{panel}	1.7	m^2	[83], [84]
Specific PV power output	PV_{out}	1 063	kWh/kW*year	[76]
Percentage of useful roof area	χ_{cover}	85	%	[80]
Percentage of installable area	$\chi_{install}$	70	%	[80]
Latvian average electricity emission factor	EF_{grid}	0.109	kg CO_2/kWh_{el}	[36]
Investment cost	$c_{inv,pv}$	1 331	EUR/kW	[85][36]
O&M cost	$c_{t,main,pv}$	33	EUR/kW*year	[62]
Latvian electricity price (2019)	$p_{elec.}$	0.164	EUR/kWh_{el}	[86]

In the subsequent passage, an example calculation of a building in Riga is shown. To simplify the calculation $\lambda_{surface}$ is chosen to be 100% and μ set to 70%. The roof area is determined using Google Maps. The example building is located on the Ģertrūdes iela 67 and is a multi-apartment complex[37]. Installing PV panels is therefore a decision taken by the landlord. The roof area is 493.21 m^2 (Figure 39).

[36] The investment cost in the source do not include VAT (Value-added tax). The VAT for Latvia (21%) is added.
[37] A multi-apartment complex was chosen to show the applicability to all kind of roofs and not only private owned residential buildings.

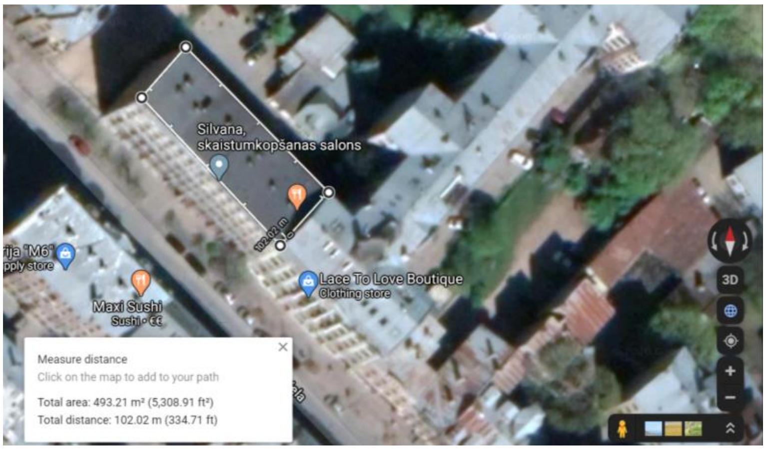


Figure 39: Example roof on Ģertrūdes iela 67 [87].

The results of the calculation example are displayed in Table 11. The PV system would save around 6.4 tons of CO_2 yearly and be paid off after 15 years.

Table 11: Results of the example roof PV calculation.

A_{roof} [m^2]	A_{useful} [m^2]	$P_{install}$ [kW]	E_{PV} [kWh/year]	$EM_{savings}$ [kg CO_2/year]
493.21	293.46	55.04	58 507.52	6 377.32

$C_{inv,pv}$ [EUR]	$C_{t,savings,pv}$ [EUR/year]	$C_{t,main,pv}$ [EUR/year]	$t_{breakeven}$ [years]
73 258.24	6 716.66	1 816.32	14.95

Two variables affect the breakeven duration: the feed-in tariff p_{feed} and the share of self-consumption μ. For the example calculation, the p_{feed} is set to zero and μ to 0.7 to reflect a realistic consumption profile. The impact of those two variables on the duration can be seen in Figure 40. The lower the self-consumption, the bigger the impact of the feed-in tariff. If the feed-in tariff reaches the electricity price, the self-consumption becomes irrelevant. The detailed results can be found in Annex A.4.2, Table A.11.

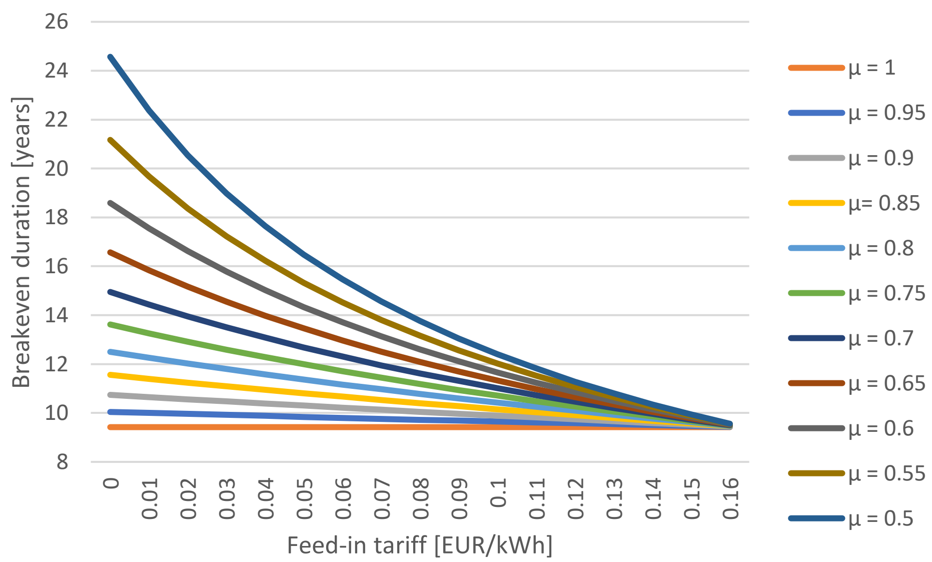


Figure 40: Effect of p_{feed} and μ on the breakeven duration.

The overall impact of this measure is not quantifiable as first, the total suitable roof area of Riga is unknown and second, the effectiveness of this approach depends on the citizen engagement and their willingness to invest in residential solar systems. Nevertheless, having a tool that indicates the solar potential of the roofs of the city of Riga will have a positive effect on the citizen decisions and policymaking as stakeholders can easily use the same tool. In Nantes Métropole, the covered roof area by PV panels rose from 85 000 m^2 in 2013 to 130 000 m^2 in 2017 and is expected to grow by 100 000 m^2 between 2018 and 2020. Clearly, not all PV systems are residential. For instance, a project of 31 000 m^2 on the wholesale agricultural-produce market is planned between the 2018–2020 period [88]. Nonetheless, the solar map of Nantes facilitated a considerable increase in both residential and commercial projects. A similar effect, with the right policy support, can be expected for the city of Riga.

If the city decides to implement this measure, the correct approach has to be determined. As described before, the solar map can have two different premises; either using the PV_{out} value combined with a precise scan of the city's roof area by, for instance, using a Lidar scan as done in Barcelona or utilizing exact solar data that shows the irradiation of every point in the city. In the second approach, no Lidar scan is needed, but the calculations of the PV system output have to be done by the city. For this thesis, the first procedure was chosen as it is simple to describe, use, and shows the basic idea of the measure. As seen, Nantes and Paris follow the second approach. Finally, both concepts deliver the same information, deciding on which one to employ could end up being a question of cost.

The approach used for the Riga solar map determining the investment of PV systems can be transferred to understand the economics of solar thermal collectors. Solar thermal collectors provide heat, for instance, in form of hot water. Some adjustments in the calculation methodology and assumptions have to be made to use the solar map for solar thermal energy. The biggest difference is the use of the GHI instead of the PV_{out}. Calculating the annual energy output of a thermal collector is easier than of a PV system, therefore the GHI can be used as a basis and no difficult calculations must be made to receive a parameter such as PV_{out}. It is assumed that the gained heat of the solar system is used for domestic hot water and can either replace a natural gas boiler or be auxiliary to the district heating system to which many buildings are already connected. (Eq. 19) can be used for the solar collector as well. For the produced heat by a glazed solar collector, the equation is as follows [89]:

$$Q_{solar} = 0.38 \cdot GHI \cdot \left\lfloor \frac{A_{useful}}{A_{collector}} \right\rfloor \cdot A_{aperture} \qquad \text{(Eq. 22)}$$

where:

Q_{solar} = heat delivered by the solar system assuming 15% pipe losses [kWh/year]

GHI = Global Horizontal Irradiation [kWh/m^2]

$A_{collector}$ = gross area of the solar collector [m^2]

$A_{aperture}$ = aperture area, net area that collects the sunbeams [m^2].

If no specific GHI values can be obtained, then the degree of insolation factor $\lambda_{surface}$ has to be applied to (Eq. 22) as done for the PV calculations. For the following calculations, this factor is as well set to 100% as done previously.

To determine the finances, a slightly changed version of (Eq. 21) can be used. The costs are not based on the installed capacity but the installed area resulting in the subsequent equations:

$$A_{install} = \left\lfloor \frac{A_{useful}}{A_{collector}} \right\rfloor \cdot A_{collector} \quad \text{(Eq. 23)}$$

$$t_{breakeven} = \frac{c_{inv,sc} \cdot A_{install}}{Q_{out} \cdot p_{ng} - c_{O\&M,sc} \cdot A_{install}} = \frac{C_{inv,sc}}{C_{savings,sc} - C_{O\&M,sc}} \quad \text{(Eq. 24)}$$

where:

$A_{install}$ = installed collector area [m^2];

p_{ng} = natural gas price [EUR/kWh_{th}];

k = indicator of technology used, in this case k = sc (solar thermal collector) [-].

Table 12 displays the assumptions made for the solar thermal approach.

Table 12: Summary of the assumptions made for calculating the solar thermal potential of roofs.

Indicator	Symbol	Value	Unit	Source
Solar collector gross area	$A_{collector}$	2	m^2	[90]
Solar collector aperture area	$A_{aperture}$	1.824	m^2	[90]
Global horizontal irradiation	GHI	1 030	kWh/m^2	[76]
Percentage of useful roof area	χ_{cover}	0.85	%	[80]
Percentage of installable area	$\chi_{install}$	0.7	%	[80]
Emission factor	EF_{NG}	0.202	kg CO_2/kWh_{th}	[91]
Investment cost	$c_{inv,c}$	420	EUR/m^2	[72]
O&M cost	$c_{t,main,c}$	4.2	EUR/m^2*year	[92]
Natural gas price (2019, Latvian households)	$p_{ng.}$	0.0351	EUR/kWh_{th}	[93]

Applying the assumptions and presented equations to the same use case (see Figure 39) leads to the results presented in Table 13.

Table 13: Results of the example roof solar thermal calculation.

A_{roof} [m^2]	A_{useful} [m^2]	$A_{install}$ [m^2]	Q_{solar} [kWh/year]	$EM_{savings}$ [kg CO_2/year]
493.21	293.46	292	104 231.39	21 054.74

$C_{inv,c}$ [EUR]	$C_{t,savings,c}$ [EUR/year]	$C_{t,main,c}$ [EUR/year]	$t_{breakeven}$ [years]
122 640	3 658.52	1 226.4	50.43

The example roof solar collector system would avoid around 21.05 tons of CO_2 per year but has a breakeven duration of 50 years. Only self-consumption is regarded, therefore solar thermal systems should be sized matching the thermal demand of the building. If the building is already connected to the DH system, a solar thermal system could be installed as an auxiliary source of heat. The designed system would most likely not use the full roof area. The approach shows that it is theoretically possible to include solar thermal into the Riga solar map application.

Nevertheless, solar thermal systems require installations of other components such as a storage tank or need to be integrated into the existing heating system (e.g., hot water system). That should be considered when using the Riga solar map for solar thermal sources.

The crucial factors that influence the breakeven duration are the natural gas price and high investment cost. Figure 41 displays the influence of the natural gas price and gives an outlook on how a naturally growing or artificially raised price by means such as tax changes affects the breakeven duration. The change of the price is applied at the start of the project and set constant during the whole duration.

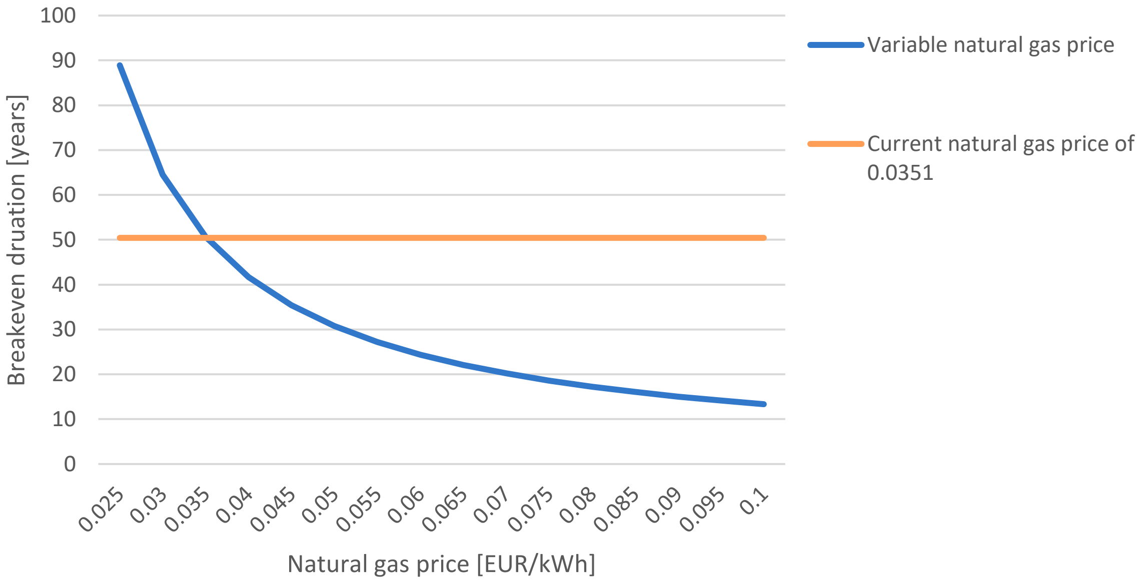


Figure 41: Breakeven duration versus the natural gas price.

The high upfront investment needed to finance a solar collector system raises the breakeven duration. Figure 42 indicates the change in that duration if the investment cost is reduced. This reduction can, for instance, be achieved by actions such as subsidies. Detailed results of both sensitivity calculations can be found in Annex A.4.3.

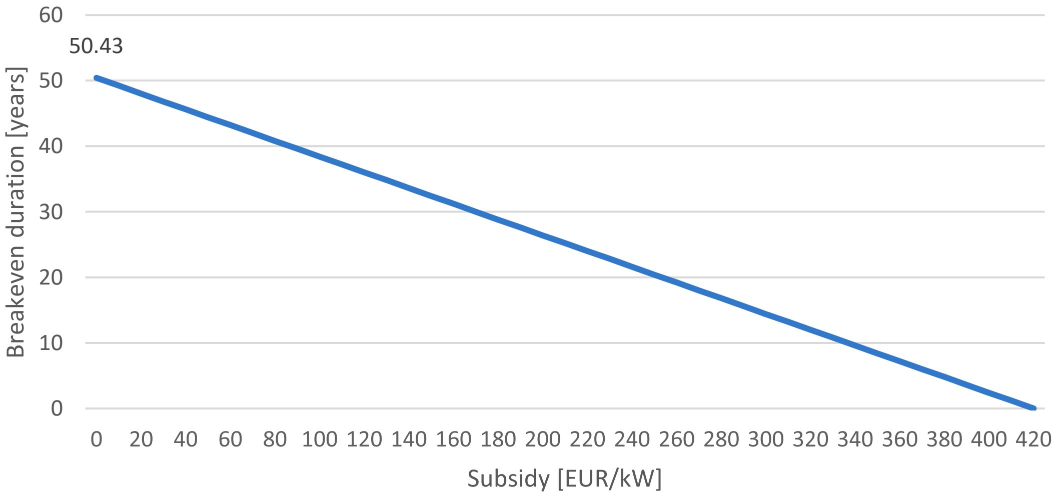


Figure 42: Breakeven duration versus subsidies applied to the investment cost.

Excluding the costs for the website itself (it is assumed the city council can provide a website), the Riga solar map would require an expenditure of EUR 19 720 for programming the needed functionalities. This price presumes that the software engineer receives all data needed and the calculations (and formulas) are already presented. Furthermore, the price estimation is applied only for the PV approach of the solar map [94].

The exact cost breakdown is as follows: EUR 9 800 for the data integration of the solar database, including the transformation of solar data to PV panel demand and transformation of the data for the OpenStreetMap; EUR 4 200 for the OpenStreetMap overlay including the integration of the map into the existing website and the overlay for the PV panel demand; EUR 3 000 for consultation and EUR 2 720 for tax [94].

The solar data has to be obtained separately. For the pathway, the solar data was retrieved from the Global Solar Atlas, which works with data from Solargis. The values for PV_{out} and GHI were set constant for the whole city of Riga, similar to the approach of the City of Barcelona. To receive better results, custom data for each site point should be applied. Solargis offers a package of data for 100 sites for EUR 10 000 per year [95]. Solcast offers a EUR 672[38] per month enterprise package for customers needing data for multiple sites [96]. As data for the whole city of Riga is needed, an individual quote should be requested.

5.2.2 Citizen power plant

As the example roof of Figure 39 demonstrates, not all citizens have the possibility to invest in renewable technologies, for instance, just because they are renting a flat in a multi-apartment complex. Knowing the situation of big cities and especially capitals, this circumstance applies to a fair share of people.

To give all citizens the chance to invest in renewable technologies and help fight climate change, regardless of the housing situation, Wien Energie[39] created the initiative of the BürgerInnen Kraftwerke[40]. In the subsequent passages, the initiative is described, and due to its high replicability applied to Riga.

BürgerInnen Kraftwerke (in the following called citizen power plant) is a financing scheme that lets citizens invest in the development of renewable energy in the city of Vienna. Started in 2012 with the first solar power plant, Wien Energie is offering this financing model already eight years. The citizens of Vienna spent EUR 37 million, helping to build 27 solar power plants and four wind farms [97]. Although each project has its characteristics, the baseline is a voucher concept. Citizens can invest for a certain amount of money, lending Wien Energie capital to develop renewable energy projects. The citizen purchases a voucher package, where the invested money with a fixed interest rate yields a yearly remuneration in the form of a coupon.

[38] Conversion rate of USD 1 to EUR 0.84 as of 16.09.2020.
[39] Wien Energie is the biggest energy provider of Austria and belongs to the Wiener Stadtwerke, the public utility of Vienna, Austria.
[40] German for citizen power plant.

Those coupons will be disbursed for the whole length of the contract period. The parameters, such as interest rate or contract period, differ between projects. A numerical example will be shown in the next passage describing the current project.

The current project is a solar farm connected to a pumping station in Unterlaa, which started operation in May 2020, providing the city with drinking water. The solar power plant of 1.92 MW, the biggest in Vienna, can provide up to 2.05 GWh energy covering 40% of the demand of the pumping station and additionally supplying 600 households with electricity. A CO_2 reduction of 706 tons per year is estimated. 10 000 voucher packages were purchasable for the price of EUR 250, each with a limit of three per person. These packages were rapidly sold out, showing the willingness of the citizen to invest in renewable projects [98]. Wien Energie differentiates between costumers of Wien Energie and other citizens that want to take part in the initiative. Costumers receive a higher interest rate of 6.4% compared to 1.32%. The yearly vouchers can be used to either pay a part of the customer's electricity bill or for shopping at SPAR, a supermarket chain. For costumers, the coupon is worth EUR 60. Table 14 shows the financing scheme with a contract period of 5 years using the methodology presented by Wien Energie [99].

Table 14: Financing scheme for citizens purchasing voucher packages (6.4% interest). Adapted from [99].

	Balance beginning of the year [EUR]	Interest credit [EUR]	Balance + interest [EUR]	Payout [EUR]	Balance end of the year [EUR]
Year 1	250	16	266	60	206
Year 2	206	13.20	219.20	60	159.20
Year 3	159.20	10.20	169.40	60	109.40
Year 4	109.40	7	116.40	60	56.40
Year 5	56.40	3.6	60	60	0

Buying the voucher package will result in a net profit of EUR 50. In comparison, depositing the money in a bank with an interest rate of 2.5% would amount to a profit of EUR 32.85 (without yearly payout). Considering that banks normally offer lower interest rates, investing in the Wien Energie initiative has financial benefits for the citizen. A non-costumer of Wien Energie receives an interest rate of 1.32%, resulting in a net profit of EUR 10.

As described before, the Austrian initiative is a good approach to finance renewable energy projects and involve citizens in the process. The projects do not have to focus on solar energy only but can vary from smaller projects, such as PV panels on a school's roof, to bigger scale as, for instance, the installation of wind power parks. By keeping a website where the projects are shown and their impact measured, the involved citizens can see their contribution.

When applying this measure to Riga, a crucial aspect must be regarded, the relatively low Latvian average gross salary. In 2019, it amounted to EUR 1 076 per month, resulting in an average net value of EUR 793 [100]. The average gross compensation in the city of Riga was on average 12.1% higher than the national average for the reporting year (EUR 1 206) [28].

Investing EUR 250, as in the current project of the BürgerInnen Kraftwerke scheme, might be unfeasible to a big share of citizens. Therefore, for the subsequent concept, the price for the voucher package is reduced to EUR 150.

To apply this approach to Riga, the following equation[41] can be used:

$$K \cdot \left(1 + \frac{\rho}{100}\right)^m - \sum_{l=0}^{m-1} R \cdot \left(1 + \frac{\rho}{100}\right)^l = 0 \qquad \text{(Eq. 25)}$$

$$\Leftrightarrow K \cdot q^m = R \cdot \sum_{x=0}^{m-1} q^l$$

$$\Leftrightarrow K \cdot q^m = R \cdot \frac{1 - q^m}{1 - q}$$

where:

K = investment by the citizen (voucher price) [EUR];
ρ = interest rate granted by the city [%];
m = time horizon [years];
l = year of time horizon (1, 2, … m) [years];
R = (yearly) return voucher [EUR];
q = space holder for (1 + ρ/100).

The equation contains four different variables, therefore three have to be decided beforehand and the equation has to be transposed and solved for the unknown parameter. As mentioned before, the voucher package price is set to EUR 150. For the contract period, 5 years as chosen by Wien Energie seems reasonable. Assuming the same interest rate of 6.4%, using (Eq. 25) results in a yearly coupon payout of EUR 36. The final net profit amounts to EUR 30. The voucher remuneration scheme has to be adjusted to each proposal; thus the used numbers are just for showing the concept.

Regarding the vouchers, the city of Riga could, for instance, acquire a supermarket such as Rimi as a partner or seek cooperation with electricity retailers. The coupon should have benefits for all citizens involved, therefore it should focus on necessary daily expenses such as food.

Using the parameters in Table 10, (Eq. 19) and (Eq. 20) of chapter 5.2.1, an example solar citizen power plant can be calculated using the measuring tool of Google Maps. The example roof can be seen in Figure 43 and is a part of the Riga main station halls. The project would consist of a 168.32 kW rooftop PV system with an investment cost of EUR 224 034. Giving out EUR-150-voucher packages, 1 494 citizens could completely finance the capital needed for the PV system resulting in EUR 44 820 costs for the city (due to the payouts).

[41] No source was used. The equation was obtained by following the example of the approach of Vienna.

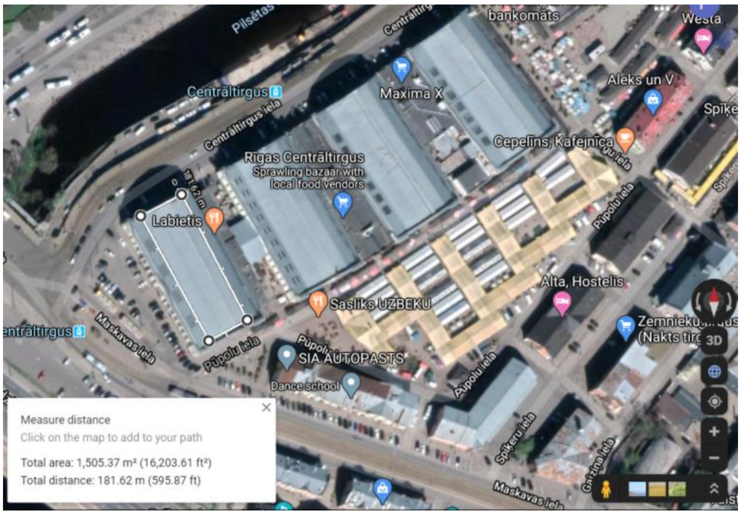


Figure 43: Example PV system on the roof of one of the four Riga main station halls [101].

The initiative benefits both sides. On the one hand, citizens get the chance to actively help their city pursue a renewable energy transition and fight climate change while gaining financial benefits. On the other hand, the city implements an easy and transparent financing scheme that skips the involvement of bank loans while both fostering the interest of people in renewable projects and fulfilling climate goals, making the city an overall more sustainable place.

5.3 Pathway C: Modern transportation

As seen in Figure 8, transportation is the biggest contributor to the city's emissions (around 39%). This is due to the high utilization of fossil fuels such as diesel. Biofuels such as bioethanol and biodiesel contribute insignificantly (2.3%) to the fuel mix (see Figure 9). This leaves the potential to decarbonize the sector. As described in 4.5, this pathway serves a thought-provoking impulse rather than an extensive analysis as performed in the prior chapters. The first measure describes a possibility to increase the production of biofuels using carbon sequestration by microalgae. The following measure outlines the opportunity of revolutionizing last-mile delivery.

5.3.1 Biofuels by algae carbon capture

Microalgae are unicellular photosynthetic microorganisms living in saline or freshwater environments converting sunlight, water, and carbon dioxide into biomass. The growth medium must include inorganic elements, such as nitrogen, that constitute the algal cell. The culture temperature should be around 15 to 30 °C for optimal growth [102]. Many microalgal species can accumulate substantial quantities of lipids, often greater than 60% of their dry biomass. High oil species in optimized growth conditions have the potential to yield 46 950 to 140 850 l of microalgal oil per hectare per year[42]. The oil yield of algae is over 200 times the yield of best-performing plants [103]. Since microalgae contain lipids, carbohydrates, proteins, and some fats, these constituents can be converted into serval commercial applications such as animal feed, cosmetics, fertilisers, biofuels and so on [104].

[42] Converted value, source value: 19 000 to 57 000 l per acre per year.

Biological post-combustion CO_2 capture has attracted attention in recent years, especially the biofixation of CO_2 in microalgae due to particular advantages. Microalgae can grow faster and in harsher conditions than terrestrial plants, having a 10 to 50 times higher CO_2 fixation efficiency. High purity CO_2 gas is not needed, flue gas containing varying amounts of CO_2 can be directly fed to the microalgal culture. Furthermore, some combustion products such as NO_x and SO_x can be used as nutrients, potentially negating the use of flue gas scrubbing systems for power plants [104].

To cultivate microalgae, two types of systems based on open pond and closed photobioreactor (PBR) technologies have been deployed. An example of an open system (here: raceway pond) and a PBR (here: horizontal tubular) can be seen in Figure 44. Open systems are the first choice for microalgae cultivation in industrial applications due to the simple operation, easy scale-up and low operation cost. However, poor light utilisation by the cells, evaporative water loss, diffusion of CO_2 to the atmosphere, and dependency on local weather conditions result in low biomass production and the need of large areas of land. To achieve better biomass productivity, microalgae can be grown in closed photobioreactors that overcome the disadvantages of open systems by providing control over parameters such as pH, temperature, light, and so on. The major drawback of PBRs is the high equipment cost. PBRs can be described as enclosed, illuminated culture vessels with gas exchange performed through a sterilised gas filter. Common types of PBRs include vertical columns, flat plate, and horizontal tubular systems [104]. The advantages and disadvantages of those types can be found in Annex A.5.1, Table A.15.

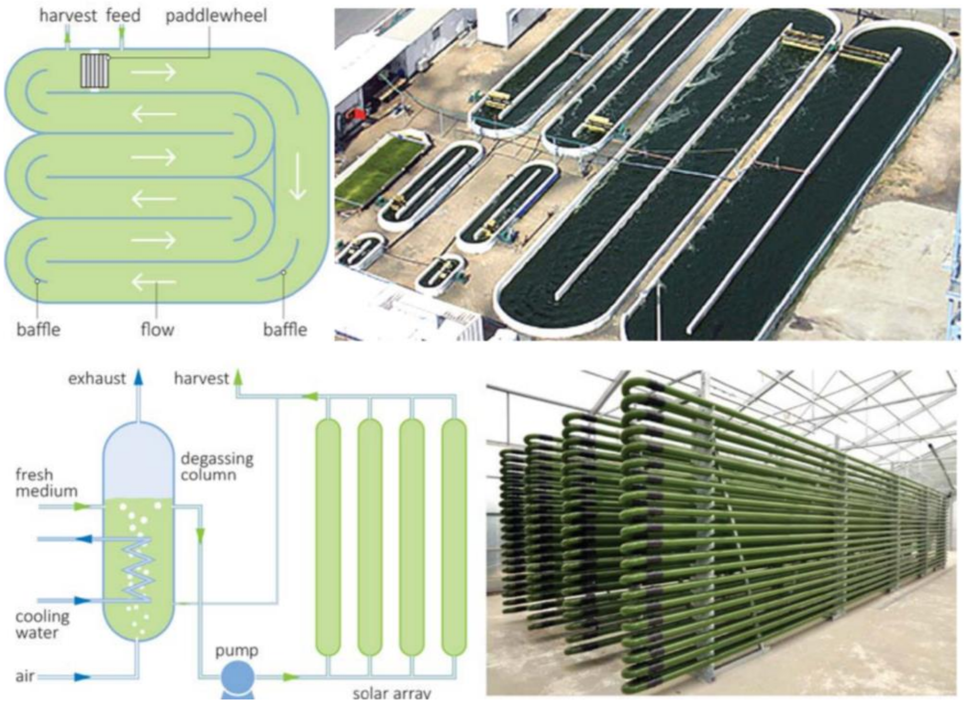


Figure 44: Scheme and picture of microalgae cultivation systems: raceway pond (top), horizontal tubular PBR (bottom) [104].

Figure 45 displays the concept of the measure presented in this chapter. The measure aims at producing biofuels while reducing the emissions of the CHP plants used to deliver heat to the district heating system. The flue gas emitted by the CHP plant is used to cultivate microalgae in a PBR system. To successfully grow microalgae, sunlight and nutrients, of which some can be received by wastewater, are needed. Furthermore, the PBR requires energy that can be delivered by the CHP. The resulting biomass can be harvested and processed into multiple end products such as biodiesel.

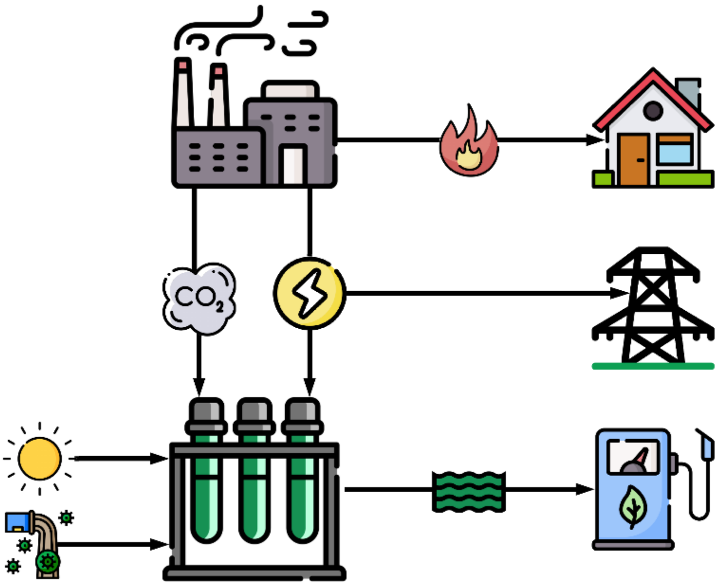


Figure 45: Concept scheme of biofuels creation by algae carbon capture[43].

Figure 46 shows the possible usage of microalgae as a biomass carrier. Although the figure shows a certain complexity, it perfectly displays the various possibilities and vast potential of microalgae. Through different production steps, algae can be turned into multiple energy carriers. In the case of Riga, two biofuels, biogas and biodiesel, are of interest. Biogas can be used to substitute natural gas which dominates the district heating system. Biodiesel, as the name suggests, is the renewable replacement of diesel and used as an example for this measure. Biodiesel is produced by transesterifying the parent oil or fat, such as vegetable oil or animal fat, to achieve a viscosity close to that of diesel. It shows a comparable energy density, depending on the source, to petroleum diesel. Using different extraction techniques, up to 100% of the algal oil can be extracted. The exact conversion from algae biomass to biodiesel is not covered but can be summarized as the mixing of algae oil with alcohol and an acid (or base) to produce the fatty acid methyl esters which make up the biodiesel. Biodiesel from microalgae is similar in properties to the standard biodiesel [103].

[43] Icons made by Freepik and Nhor Phai from www.flaticon.com.

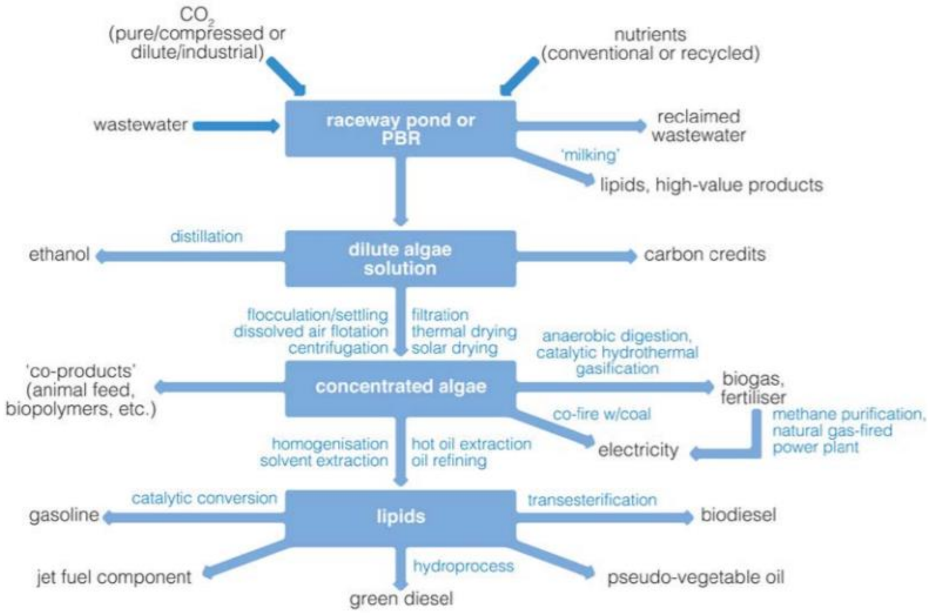


Figure 46: Microalgae production and utilization scheme [104].

As described in chapter 3.3, JSC Rīgas Siltums provides around 31% of the delivered heat in the DH network by their own assets. Interesting for the measure are CHP facilities as they can provide the heat and electricity needed by the carbon capture system. In 2016, the second biggest[44] contributor to the 1 020 GWh produced heat was HP Ziepniekkalns with 153 GWh (15%) [105]. HP Ziepniekkalns is a CHP plant running on natural gas and serves as an example for the impact calculations of this measure. As no emission factor of the plant is given, the weighted average emission factor of the district heating system of 2012 (0.189 t CO_2/MWh_{th}) is taken [30]. The calculated emissions of the CHP facility amount to 28 917 t CO_2. The goal of the measure is to substitute a certain amount of the diesel usage of the transportation sector. In 2016, the utilization was round 6 500 TJ (see Figure 9). The measure aims at a substitution of 0.01% (0.65 TJ). The energy density of the biodiesel is assumed to be 37.3 MJ/kg [104]. Three different microalgae species are regarded to project the current status quo of research: Chlorella sp., a commonly used microalga for carbon capture projects, Chlorella vulgaris, a species with utmost high biomass productivity, and Chlorella sorokiniana, which achieved the highest productivity so far (by 2015) under over-saturating light conditions. Although the system is sorely exposed to natural light conditions, the Chlorella sorokiniana result could be an outlook to future biomass productivity of species. The biomass productivity and CO_2 consumption rate of the species can be seen in Table 15. The parameters refer to the medium that contains the microalgae.

Table 15: Characteristics of three different microalgae species. Adapted from [104].

	Chlorella sp.	Chlorella vulgaris	Chlorella sorokiniana
Biomass productivity (mg/l/d)	1 000	3 219	12 200
CO_2 consumption rate (mg/l/d)[45]	1 880	6 240	22 936

[44] The second biggest contributor was chosen due to the lower scale. If the measure turns out to be effective, it can be upscaled and used at HP Imanta, the biggest emitter.
[45] CO_2 fixation rate = 1.88 times biomass productivity.

Assuming an oil content of 30% (on wet basis) for all three species, an oil extraction efficiency of 100%, and a transformation efficiency from biooil to biodiesel of 100%, 58 088 kg microalgae biomass is needed to produce 0.65 TJ of biodiesel, resulting in a CO_2 capture of 109 205 kg [106]. This corresponds to 0.38% captured CO_2 of the total emissions by HP Ziepniekkalns. Note that for this simplified calculation, no energy penalty is regarded as no system with specific energetic parameters is designed. The carbon capture system requires an energy input by the plant, the facility suffers a so-called efficiency or energy penalty resulting in higher emissions to deliver the same amount of heat (or electricity). The avoided emissions are therefore less than the captured emissions. As shown in Figure 44, the microalgae can be grown in photobioreactors which use a tubular arrangement. For this calculation example, horizontal tubes with a length of 80 m and 0.06 m in diameter are used [106]. The results for the sizing of the three microalgae systems are shown in Table 16. The commonly used species would require 692 PBR tubes. The system size would be reduced by 69.8% for the Chlorella vulgaris and 91.8% for the Chlorella sorokiniana.

Table 16: Results of carbon capture by microalgae.

Biomass needed [kg]	CO_2 captured [kg]	CO_2 captured of CHP [%]
58 088	109 205	0.38

	Chlorella sp.	Chlorella vulgaris	Chlorella sorokiniana
Volume needed [l]	159 144.05	47 947.25	13 044.6
PBR tubes [-]	692	209	57

5.3.2 Decarbonizing last-mile delivery

The ‘last mile’ of a product’s journey from warehouse to customer describes the final delivery act to the customer doorstep. This final step is not only the costliest of the overall shipping process (53% of total cost) but as well inefficient as of multiple stops with low drop size. While in rural areas delivery points could be distant, in urban areas the stop proximity is negated by the constant delays of traffic congestion [107].

If last-mile delivery is performed by fossil fuel-based light-duty trucks, a high environmental burden is created by the inefficient driving strategy. Last-mile delivery is expected to rise by 78% by 2030, followed by an increase of 36% more delivery vehicles resulting in an emission rise of 30% and additional 11 minutes to each passenger’s commute (21% higher traffic congestion) if no effective measures are taken [108].

Although those numbers might not apply perfectly to the city of Riga, growth can still be expected especially due to the popularity of e-commerce in the times of COVID-19. In 2015, light-duty trucks contributed around 100 000 t of CO_2, being the second biggest share after cars with more than 500 000 t [36]. Clearly, not all light-duty trucks are used for last-mile delivery or can be substituted, nevertheless, there is a high potential for alternative delivery modes especially regarding the dense city centre of Riga with narrow roads and blocked access areas for motorized vehicles.

Figure 47 shows a few examples of companies that came up with solutions to the last-mile delivery problems mentioned before. The presented solutions use electricity to facilitate the delivery of high volumes. There are non-electric bike solutions on the market, but due to their lower transportation capacity and the need for high physical work of the operator, they are not regarded. Nevertheless, cargo bicycles can be seen as a complementary concept used for light transport such as mail or fast food delivery as already done in many cities.

Figure 47: Three different last-mile delivery solutions: ONO (left), Scoobic Light (middle), and the Armadillo by Velove (right) [109]–[111].

The ONO is a Vehicle-as-a-Service e-bike with two 125 W engines and two 1400 Wh batteries allowing for a maximum distance of 80 km. The vehicle can reach up to 25 km/h and the container (2 100 litres) is designed in a way that it can be easily removed and swapped to reduce the downtime of the bicycle. The vehicle load capacity, including the cargo unit, is 300 kg [109].

The Scoobic Light is e-scooter which is due to its innovative construction, agile, and easy to manoeuvre through small streets. It has a model range of 100 kilometres with 2 000 life cycles. The lithium battery can be charged in 6 to 8 hours. The load capacity is 419 kg (1 400 litres) [111].

The Armadillo by Velove is an e-bike with a 250 W engine assisting when pedalling up to 25 km/h with a maximum energy consumption of 0.15 to 0.2 kWh/10 km. The battery capacity is 0.6 kWh giving a 25 to 40 km range. The cargo unit is 1 000 litres big and can hold up to 150 kg [112].

To show the difference between the standard delivery mode, a 3.5-ton light-duty truck, and a sustainable vehicle as presented in Figure 47, a simple calculation is executed. The Armadillo represents the sustainable transportation mode. For the standard process, a Mercedes Sprinter with a payload of 3.5 tonnes and fuel consumption of 8.1 l/100 km running on diesel (resulting in emissions of 214 g CO_2/km) is taken [113]. For the calculation example, two example routes are created using Google Maps. On both routes, ten parcels are delivered. The example routes can be seen in Figure 48 (Route 1) and Figure 49 (Route 2).

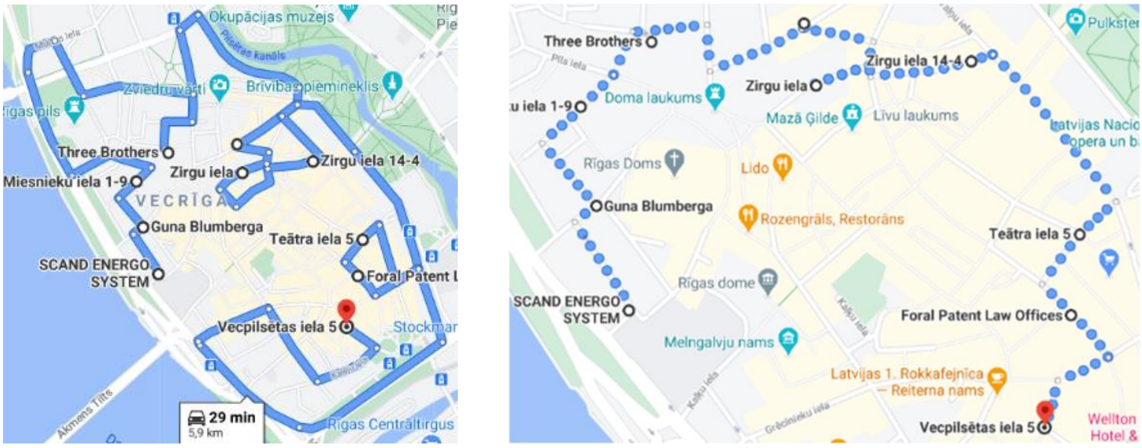


Figure 48: Example route 1: car path (left), walking course (right) [114].

As there is no bicycle route option given for Riga, as, for example, applicable on Google Maps for other cities, it is assumed that the walking route is suitable for bicycle traffic. In route 1, the walking time is 20 minutes, it is assumed that in the city centre a last-mile delivery e-bike can travel twice as fast. On route 2, the e-bike moves with three times the speed of the walking average as the streets are bigger and distances are longer. The stop time to physically delivery the parcel at the doorstep is not considered as no difference between those two modes is assumed.

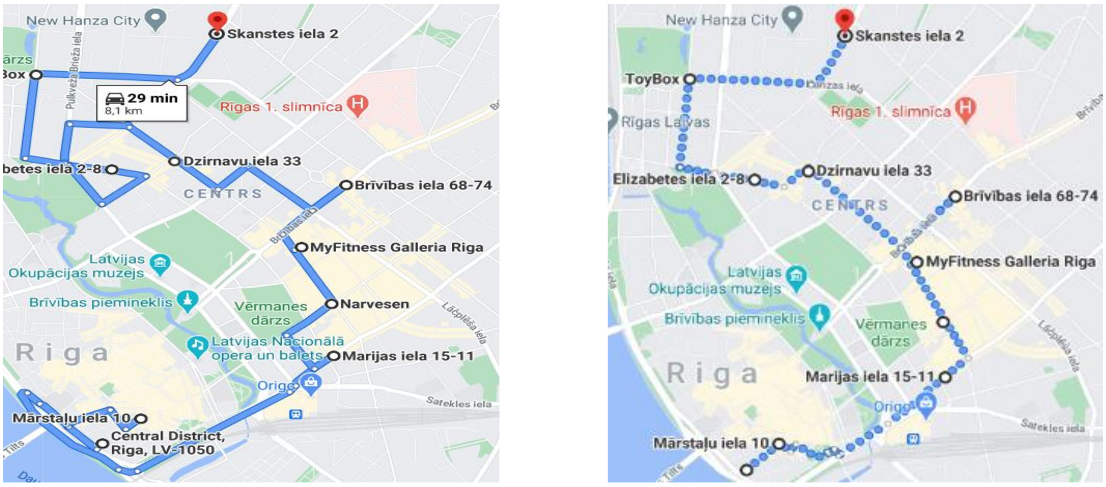


Figure 49: Example route 2: car path (left), walking course (right) [114].

Table 17 presents the results of the simplified comparison of the two last-mile delivery modes. The e-bike saves on both routes 99.7% and 99.4% emissions, respectively. Not considering the time that is needed during the stops, the e-bike operates by 65.5% and 24.1% faster. Neither the maximum payload of the vehicles nor the maximum distance per full battery/tank is considered.

Table 17: Comparison of two last-mile delivery modes on two routes.

	The Armadillo by Velove		Standard light-duty truck	
	Route 1	Route 2	Route 1	Route 2
Distance [km]	1.6	5.2	5.9	8.1
Emissions [g CO_2]	3.5	11.3	1 262.6	1 733.4
Time travelled [min]	10	22	29	29

The city of Barcelona, as part of Grow Smarter, an incentive of cities and industry to integrate and demonstrate 12 smart city solutions, implemented a micro-distribution of freight solution in 2017. The service is offered by the company Vanapedal. The last-mile operator offers different services but foremost the distribution of parcels and packages from other carriers to their final destination. The city of Barcelona leased a public space to the company to establish a micro platform where carriers can bring items to which are then delivered by Vanapedal using electric bicycles and tricycles. During the first three months, 23 000 journeys were performed with an increase in daily numbers, averaging 160 km/day in March [115]. The city reports that this measure resulted in a 95.9% reduction in CO_2 emissions, a 97.5% decline in energy use, and a cutback of 21.7% in noise. As the lessons learnt by this project, the city reports that last-mile delivery could be rolled out more widely with the right support by the city administration by, for instance, designating entire zones only accessible for e-bike delivery, monitoring non-compliance and in the case of Barcelona identifying premises for the micro-consolidation centre [116]. The city administration noticed that reaching the market with a single last-mile operator is difficult as there were competitors and other logistics companies that began operating their own sustainable last-mile delivery fleets without using the service of Vanapedal [115]. The main challenges for the project were identifying a suitable location, agreeing on the terms of operation, and ensuring a suitable installation of sensor units to monitor the project. Nevertheless, a high replication potential was identified with no major technical or economic feasibility problems. The economic feasibility is increased by large volumes of deliveries insured by partnerships with large distributors [116].

6 Recommendations and outlook

The following chapter contains recommendations for the city of Riga obtained by the calculations performed in chapter 5. Additionally, the thesis approach is critically reviewed, and a future work outlook is given.

6.1 Green hydrogen

The measure presented in the Green hydrogen pathway displayed two things: the economic feasibility of wind power and hydrogen production in Riga. The LCOE and LCOH amount to 0.0395 EUR/kWh and 3.67 EUR/kg$_{H2}$, respectively. It is recommended to carry out an environmental impact assessment for the wind farm as site selection can be difficult. As mentioned before, the proximity of the Riga International airport and Lidosta Spilve airport could be problematic for the chosen example location.

Although the production of hydrogen proved to be in the cost range of other projects, the environmental impact can be questioned. As seen in Figure 30, producing and using hydrogen compared to just wind farm electricity fed to the grid results in a difference of 55.78 t CO_2 per year. Despite the fact that the difference is not high, developing a hydrogen project is highly recommended as Riga's future plans aim at fostering the hydrogen transition. Creating an own source of hydrogen increases fuel independence on imports.

One obstacle for Latvia to increase the usage of hydrogen is the low maximum blending limit of 0.1 vol% in the natural gas piping system. This limit, set by the NRA, is based on safety concerns and on the possibility of network components to accept H_2, including the potential impact on Inčukalns underground gas storage facility and the adjustment of end-user equipment [70]. The presented measure in 5.1 can be executed using hydrogen trucks, the DSO gas network, or own hydrogen pipelines as hydrogen transportation modes. Nevertheless, having a higher limit would facilitate the employment of hydrogen and foster the generation of higher quantities which can be transmitted via the DSO or TSO network. The NRA of Latvia should take into consideration the increase of the limit up to 1 or 2 vol%. Figure 50 presents the hydrogen tolerance of gas infrastructure components. Nearly all infrastructure components can easily adapt a single-digit limit. The biggest concern is the Inčukalns underground gas storage facility. The facility uses geological structures including a porous sandstone layer to store natural gas [117]. As seen in Figure 50, porous storage is the only infrastructure where extensive research is needed to quantify a feasible hydrogen blending limit. A feasibility study especially applied to the Inčukalns underground gas storage facility is highly recommended. As being an important storage facility not only for Latvia but Estonia, north-west Russia, and Lithuania as well, the safe operation has the highest priority [117]. If any increase of the blending limit is not feasible, other solutions such as hydrogen truck transportation or hydrogen pipelines have to be applied.

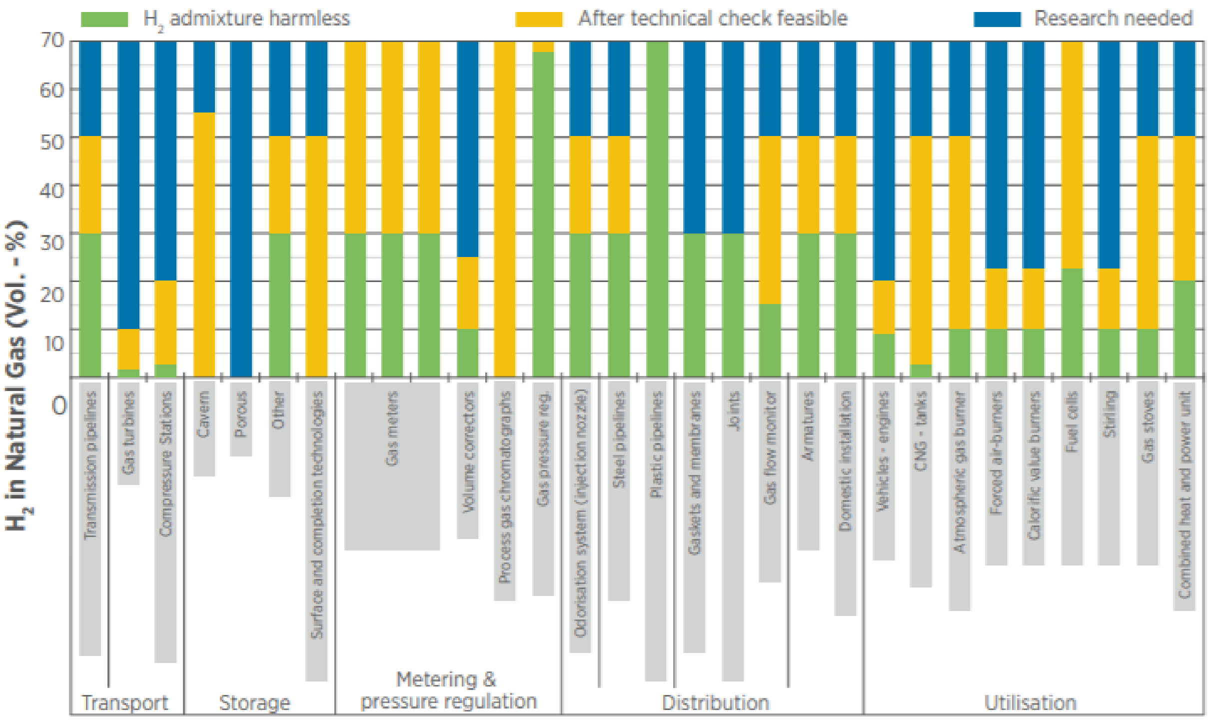


Figure 50: Hydrogen tolerance of gas infrastructure [45].

6.2 Solar engagement

A solar map is not only a great way to create awareness but showing the individual impact the decision of investing in solar technologies can have for citizens. Both private persons and companies can use the application as a first estimation of the economic feasibility of solar projects. The personal feeling of the map, as every roof displays the solar potential, accomplishes the transition from “solar power is good” to “solar power is good for me”.

The analysis indicates that photovoltaic panels are an attractive solution in Riga. The example calculation shows a breakeven duration of less than 15 years. If a feed-in tariff is granted, the time frame can essentially be reduced as seen in Figure 40. The figure shows the influence of a feed-in tariff and the share of self-consumption. If no feed-in tariff is set, PV owners receive no compensation for feeding electricity to the grid, which would result in undersized PV systems to avoid losing money. Considering the perspective of the city of Riga, reducing CO_2 emissions, PV systems should use the full roof area to generate the most electricity possible. It is therefore recommended to grant a feed-in tariff for rooftop PV systems. Figure 51 displays the sample standard deviation (of the breakeven duration for different degrees of self-consumption) as a function of the feed-in tariff of the data used in Figure 40. The standard deviation drops lower than 1 for a feed-in tariff of 0.1 EUR/kWh, indicating that from a customer point of view, the degree of self-consumption at that point does not play a significant role for the breakeven duration. If no feed-in tariff is set, the degree of self-consumption solely determines the breakeven duration, resulting in a high standard deviation. It is recommendable to grant a feed-in tariff of 0.1 EUR/kWh to maximize the solar rooftop potential of the city. For the example roof, applying that feed-in tariff would result in a breakeven time reduction of 4 years. The calculations underlining Figure 51 are presented in Annex A.4.2, Table A.12.

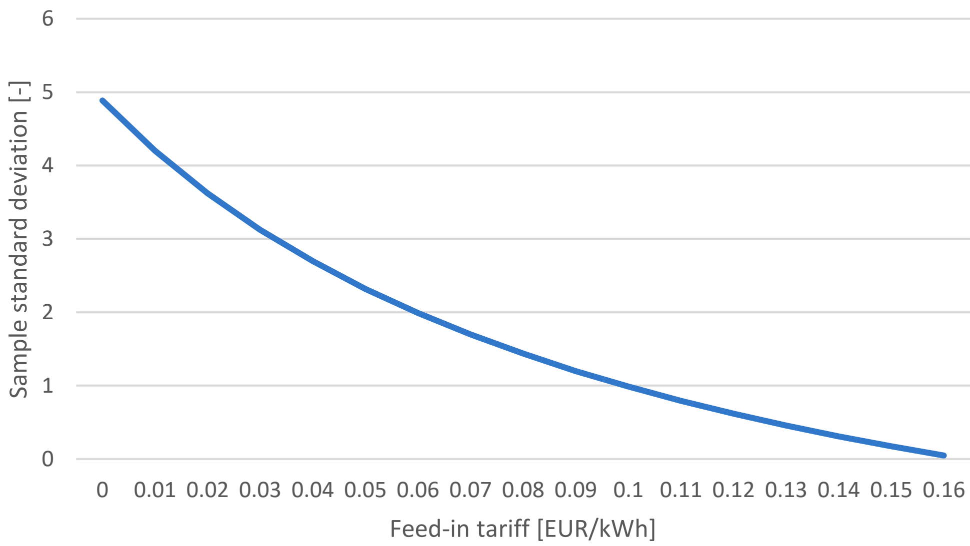


Figure 51: Sample standard deviation as function of feed-in tariff.

Concerning the development of solar thermal collectors, the sample calculations showed that with a breakeven duration of 50 years, it is not an advisable investment for the citizens. The two crucial parameters are the high initial investment cost and the low natural gas price. In Figure 41 and Figure 42 the impact of natural gas price and subsidies on the investment cost, respectively, can be seen. If the city of Riga were to pay an incentive in the form of a bonus to every avoided kWh of natural gas, reducing the breakeven duration by 10 years would result in extra costs of EUR 24 442 for the example roof. A subsidy on the investment cost resulting in the same time reduction would amount to EUR 24 309. Both paying a bonus or a subsidy are not recommendable actions. Furthermore, establishing an additional natural gas tax is not considered an option as it would interfere with operations of the district heating system operator and JSC Latvenergo, which delivers energy to the whole country. As the price of fossil fuels is expected to grow over the years and the costs of solar technologies to fall further, solar thermal might become an attractive technology for the citizens of Riga in the near future.

The financing scheme presented by Wien Energie is a great way to include citizens in shaping the sustainable transformation of the city. The citizen power plant concept can be used for various kinds of projects and presents benefits for both the municipality and the inhabitants. As already described in the measure (see 5.2.2), it is recommended to adjust the voucher price to the project. In the measure, a cost of EUR 150 is advised taking into account the average Latvian wages.

6.3 Modern transportation

Using microalgae to capture CO_2 and produce useful products such as biodiesel is a concept that has sparked interest over the last years resulting in multiple projects all over the world. While technical viability has been demonstrated, the major challenges are the strategic and holistic development of technologies that will improve economic feasibility [118]. Closed systems using photobioreactors exhibit high capital investment. Additionally, harvesting and processing, especially drying, usually have major costs [104]. Current research and development efforts focus on increasing the oil content of existing strains or selecting new strains with great oil content, and enhancing the growth rate [102].

As the calculations in 5.3.1 showed, having a higher biomass productivity can reduce the size of the system and therefore the investment cost vastly. The Chlorella sorokiniana would require just 57 PBR tubes compared to the commonly used strain of Chlorella sp. (692 tubes). The simplified calculation showed that CO_2 capture via microalgae is an interesting topic that will eventually reach economic feasibility. It is advisable to invest in a small-scale pilot project to gain first experience with the concept and used technologies. When microalgae strains reach higher oil contents and biomass productivity, the knowledge gained in the first pilot can be used to upscale to projects with significant impacts on emission reduction. Developing a small-scale project in the near future, followed by upscaling projects in 5 to 10 years from now could result in a leading position of Riga in the carbon capture and sustainable transportation sector.

Decarbonizing last-mile delivery will not happen overnight and without impulses of the city council. Although delivery service providers understood the potential of changing to modern non-fossil transportation modes, as seen in other cities, there is a need for projects or laws coordinated by the city of Riga to fasten and facilitate the change. One indicator that sustainable last-mile delivery is gaining attention in Latvia is the new planned regional DHL[46] shipment processing and logistics centre at the new terminal of Riga airport. As part of its efforts to reduce CO_2 emissions, DHL is planning energy-sufficient solutions including an electric vehicle fleet. Regarding the demonstration project mentioned in 5.3.2, the city of Barcelona successfully demonstrated that using e-cargo bikes is a technical and economic feasible solution with even better prospects of success if supported by the city administration. One of the lessons learnt of their project was that designating entire zones within densely populated areas of the city only accessible for e-bike delivery would boost this emerging market segment [116]. This conclusion could be applied to the city of Riga as well. Figure 52 indicates an example area (with a size of 55.23 km^2) where fossil-based last-mile delivery could be prohibited. As shown in 5.3.2, in this area electrified last-mile delivery is superior to fossil-based vehicles in time and environmental impact. Before creating the prohibition zone, the city of Riga should understand the situation of the stakeholders and consider an incentive scheme to promote fossil-free last-mile delivery. Providing spaces for companies to create micro-consolidation centres close to the fossil-free zone, for instance, on the other side of the Daugava river, could help facilitate the transition. As seen at the pilot project in Barcelona, a single micro-consolidation centre operated by only one company (here: Vanapedal) executing the last-mile delivery for multiple different logistics companies is not recommended, as competitors began using their own sustainable modes instead of using the service by Vanapedal.

[46] DHL (Dalsey, Hillblom and Lynn) International GmbH is a German courier, parcel, and express mail service.

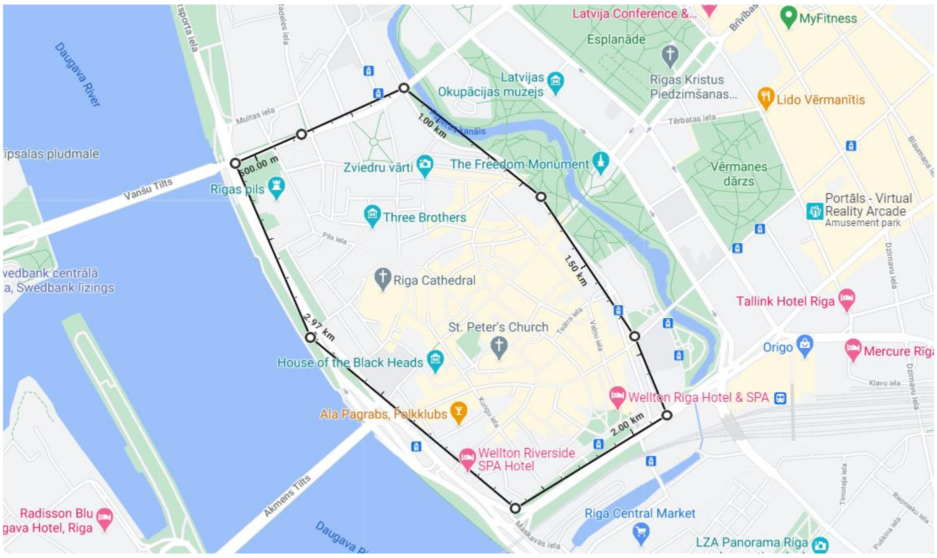


Figure 52: Recommend fossil-free last-mile delivery zone [114].

6.4 Critical review

The recommendations made in the previous chapter are the result of the calculations done in chapter 5. They reflect the reality that is portrayed in the pathways. It has been tried both with the approach and the assumptions made to characterise the situation of the city of Riga as realistic as possible. The results have to be regarded with care as the following aspects have to be taken into account.

The ideas for the measures were obtained by researching on European urban planning platforms and projects trying to find sustainable actions that fit the characteristics of the city of Riga. The presented measures are what was regarded as a good fit, considering the vast amount of urban energy projects. Cities such as Barcelona serve as an example of a modern city open to innovative energy planning. The ideas collected over extensive research were then applied to the city of Riga. Unfortunately, this was done without consulting stakeholders as planned before the outbreak of COVID-19. As a result, specific data are missing such as exact demand curves. For instance, the sizing of the hydrogen facility was executed without knowing the hydrogen demand of the city. The closest to Riga specific data were the outdated data presented in the Riga SEAP and the figures received by the Institute of Physical Energetics in Riga. The report of the institute contains no absolute values, thus the figures just give a general outlook on the situation. For instance, in 5.3.2, the emissions of light-duty trucks were estimated to be around 100 000 t CO_2 which was taken from a figure of the report. Furthermore, besides the amount of data of Riga being little, both the SEAP and the report of the institute exhibited some lack of clarity and errors.

As described before, the measures consist of ideas and projects applied to the case of Riga. The approach differs between the measures. As this thesis did not focus on one specific measure and could describe it in all details, a lack of depth had to be accepted in some parts of the calculations. The measures of this thesis have to be regarded for what they are, feasibility analyses with concrete examples.

For instance, pathway A shows a sustainable way of producing hydrogen but indicates at the same time the economic feasibility of wind power. Pathway B describes a solar map for the citizens of Riga while displaying the economic potential of PV and solar thermal systems. The thesis aims at providing specific measures that not only show the feasibility of the action but of the energy sources included. Therefore, if the Riga Energy Agency is not convinced by the idea of a solar map application, the calculations still show that PV systems should be integrated in another way. Nevertheless, it has to be considered that the data used for the economic calculations are not specific to Riga. Cost and characteristics of the components were taken from certain supplies or estimates performed by other agencies, such as IRENA. The companies displayed in this thesis are gaining no benefit and were chosen purely for academic purposes. For instance, the wind turbine data is taken from Enercon, as it was possible to obtain a data sheet.

Despite the lack of Riga-specific data considering demand, economics, and so on, the presented measures try to resemble reality but often use assumptions and simplifications. Results and recommendations should be regarded with this in mind. Nevertheless, the results carry a great significance as they both show an explicit measure tailored to the city of Riga and a thorough analysis of the energy sources included in the measure.

6.5 Future work

As described in 1.2, the Riga Energy Agency put their work on the new Sustainable Energy and Climate Action Plan document on hold and intends to resume it in 2021. While this is unfortunate considering that the planning document should have been finalized by 2020, it gives the opportunity to incorporate other measures and aspects that had been revealed during the pandemic. This applies as well to the measures presented in this thesis. The future work depends solely on the fact if a certain measure sparks interest and is considered useful by the REA. If so, the next steps that must be taken are as follows and apply to all measures despite the differences they have.

The calculations performed for a certain measure have to be refined by using certain modelling programs and applied with correct, up-to-date data specifically tailored to Riga to obtain more realistic results. Pathway C does not include any economic evaluations, which still have to be carried out if the measures are taken into consideration to be applied. If the calculations confirm economic feasibility, the city of Riga should bring together the involved stakeholders to discuss the possible measures and to gain insights. The measures presented in this thesis were calculated without consultation with the involved stakeholders which might have led to wrong assumptions. If the measure is accepted by all parties involved, the city of Riga can continue the implementation including all necessary steps that have to be taken.

7 Conclusion

The Covenant of Mayors is a great example of the European Commission understanding the importance of urban energy planning. The city of Riga signed the CoM in 2008, being one of the first European capitals. Riga's current SEAP is the Riga Smart City SEAP 2014–2020, a follow-up of the first document launched in 2010. The revised action plan is the result of achieving a CO_2 emission reduction of 50.69% compared to 1990 levels already by 2011, and the subsequent need for new, more ambitious goals. Currently, the city of Riga is updating their SEAP to a SECAP, having the opportunity for setting up an updated emission target with new measures.

Riga, being located in the cold climatic zone of Europe, is characterised by having a large number of heating degree days. The demand for heat is mainly (around 76%) covered by a district heating system operated by JSC Rīgas Siltums. Electricity is provided by three major power stations of the state-owned JSC Latvenergo: two CHPP (Riga TEC-1 and TEC-2) and a hydropower plant. From 1990 to 2016, the city of Riga achieved a 54.5% emission decrease. In 2016, road transportation accounted for the biggest share of emissions (39%), followed by DH with 30%, end-use fuel consumption with 17%, and power consumption (14%). From 2008 to 2016, a total emission decrease of 19.2% was achieved, while the end-use fuel consumption was reduced by 46.9%, the transport sector by 15.1%, and the DH by 13.9%. The electricity sector changed insignificantly (0.4%). The reduction of the last years show the effectiveness of the measures executed by the city. For the year 2016, a total cutback of 131 607 t CO_2 was estimated, whereof around 86% is to be achieved by integrating renewable energy sources.

To underline Riga's leading role in fighting climate change a new emission target and innovative actions to reach the said target are needed as the 2030 goal of the CoM, a 40% emission reduction compared to 1990 levels, was already surpassed by 15.4% in 2016, 14 years earlier. The new recommended targets for Riga are a reduction of 61% in 2030 and 70% in 2050 compared to 1990 levels. The targets are linked to the global effort of staying under a 2° C world average temperature increase.

To achieve this target, three pathways are defined: Green hydrogen, Solar engagement, and Modern transportation. The pathways are identified using an indicator score scheme with the following indicators: Policy support, Stakeholder involvement, Citizen engagement, Trialability and Market demand. All pathways require high policy support. Pathways A and C are stakeholder intensive, while pathway B focuses entirely on citizen engagement.

The Green hydrogen pathway consists of only one measure, the production of renewable hydrogen by using an alkaline electrolyser fed by electricity from a three-turbine-wind farm. The average wind speed of Riga ranges around 6 to 8 m/s, indicating a potential for employing wind power. For the measure, three wind turbines with a rated power of 2 300 kW were selected. The analysis resulted in a LCOE of 0.0395 EUR/kWh, ranking around the global weighted average and showing the competitiveness of the wind farm. The hydrogen production facility consists of a 500-kW electrolyser, a compressor, and a storage tank. The produced hydrogen can be used as a fuel for hydrogen cars or as a substitute for natural gas.

The LCOH of the project amounts to 3.67 EUR/kg_{H2}, ranking around global projects with average-cost wind electricity. The measure avoids 2 881.05 t CO_2 per year, while the electricity to the grid accounts for 2 611.54 t and the hydrogen circle for 269.51 t. If no hydrogen is produced and all electricity generated by the wind farm is fed to the grid, the emission reduction would be decreased by solely 55.78 t CO_2 per year. Although the difference is low, it is highly recommended to develop the hydrogen project. Furthermore, an assessment of the capability of Inčukalns underground gas storage facility to store natural gas with a higher hydrogen blending limit than 0.1 vol% should be carried out.

The Solar engagement pathway includes a solar map and a financing scheme for citizens. The solar map is an application showing the potential of PV and solar thermal as rooftop systems. The analysis showed that without any feed-in tariff PV systems are economically viable for the citizens of Riga. An example roof calculation showed a breakeven time of around 15 years. Nevertheless, a feed-in tariff for rooftop PV systems of 0.1 EUR/kWh is recommended. The breakeven duration of the example roof would be reduced by 4 years. Solar thermal collectors are not an economically feasible option as the example roof calculation showed a breakeven duration of 50 years. Solar thermal might become an attractive technology in the near future considering growing prices of fossil fuels, currently no incentive or bonus scheme is recommended. The citizen power plant financing scheme is an attractive option for both municipality and citizens. Putting a PV rooftop system on one of the four Riga main station halls would require the engagement of 1 494 citizens to completely cover the initial capital cost.

Two measures are presented in the Modern transportation pathway: algae carbon capture, and sustainable last-mile delivery. Algae carbon capture is an emerging technology using microalgae to capture carbon and upgrading the biomass to, for instance, biodiesel. Current biomass productivity and oil contents of microalgae strains are too low for projects to be economically feasible. Nevertheless, research shows promising results to overcome those bottlenecks. A small-scale project is recommended to get familiar with the technology and be at the forefront when microalgae strains show the right characteristics for economically viable projects. E-bike last-mile delivery is a fast and environmentally friendly alternative for current transportation modes. The example calculations showed an emission reduction of around 99%. The city of Riga should consider creating a fossil-free last-mile delivery zone in the city centre.

The future work of this thesis is depending on the fact if the city of Riga considers the presented measures useful for the SECAP. If so, the calculations performed have to be refined using certain modelling programs and up-to-date data specially tailored to Riga to obtain more realistic results.

The proposed measures displayed the economic feasibility of wind electricity, hydrogen production, and rooftop PV systems, while rooftop solar thermal collectors turned out not to be economically viable. While all measures are suitable to be further pursued, the Riga solar map, including a feed-in tariff of 0.1 EUR/kWh, the voucher financing scheme for renewable projects, and the fossil-free last-mile delivery zone show the best fit and greatest potential for the city to achieve the new recommended target of a 61% reduction compared to 1990 levels.

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Annex

A.1 Methodology for calculating CO_2 emissions in Riga's SEAP

The following methodology is used by the Institute of Physical Energetics in Riga to calculate the CO_2 emissions derived from the consumption of all types of energy and fuel in the territory of the city of Riga and presented in the Smart City SEAP. The methodology is based on the guidelines drafted by the Intergovernmental Panel on Climate Change (IPCC) and the recommendations of the SEAP guidebook. Only CO_2 emissions are calculated disregarding other greenhouse gases [30]. The calculation methodology is presented in Figure A.1.

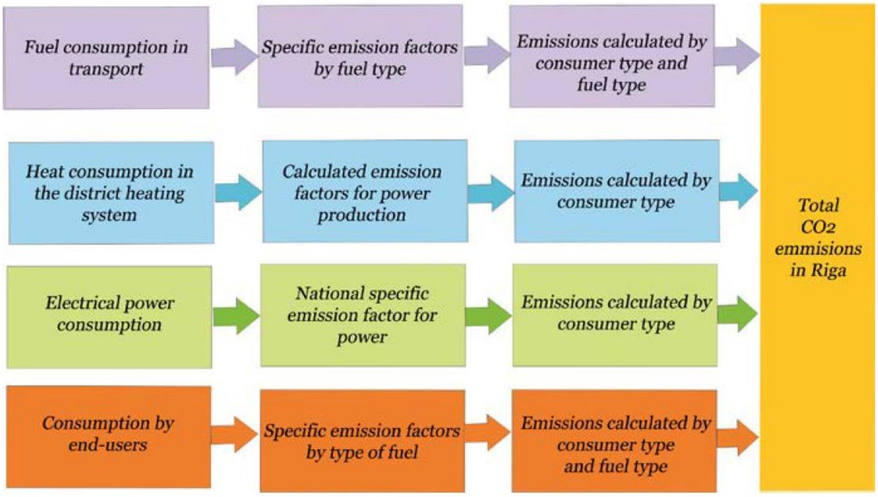

Figure A.1: Scheme of the CO_2 emission calculation methodology [30].

Four main sectors are identified for which different approaches are used to calculate the emissions. Energy consumption beyond the control of the municipality, such as maritime and rail transport, cargo transit, aviation, and the use of agricultural and construction machinery is excluded from the calculation. Furthermore, industrial technologies, refrigerators and air conditioning systems, natural putrefaction of organic matter, wastewater treatment reservoirs, storage sites for solid waste, and burning processes are not taken into account [30].

The transport-related emissions are calculated by using the commonly used model of COPERT IV, a computer program designed for determining motor vehicle-related emissions. To characterize the overall traffic flow in Riga, three main groups are formed: cars registered in Riga, public transport vehicles, and cars driving into Riga. The information about the registered cars and public vehicles is obtained from the Road Traffic Safety Directorate and the Transport Department of the Riga City Council. The number of incoming cars is retrieved by analysing the number of cars registered in the Riga region and the data of traffic flow moving into and out of the city boundaries [30].

Figure A.2 shows the calculation methodology for the emissions of the district heating system operated by JSC Rīgas Siltums. Heat is produced at various small installations owned by JSC Rīgas Siltums and at the co-generation plants TEC-1 and TEC-2 owned by JSC Latvenergo.

To obtain a weighted average factor per produced heat the proportion of the heat delivered by the facilities compared to the total amount multiplied by their respective emission factors are used.

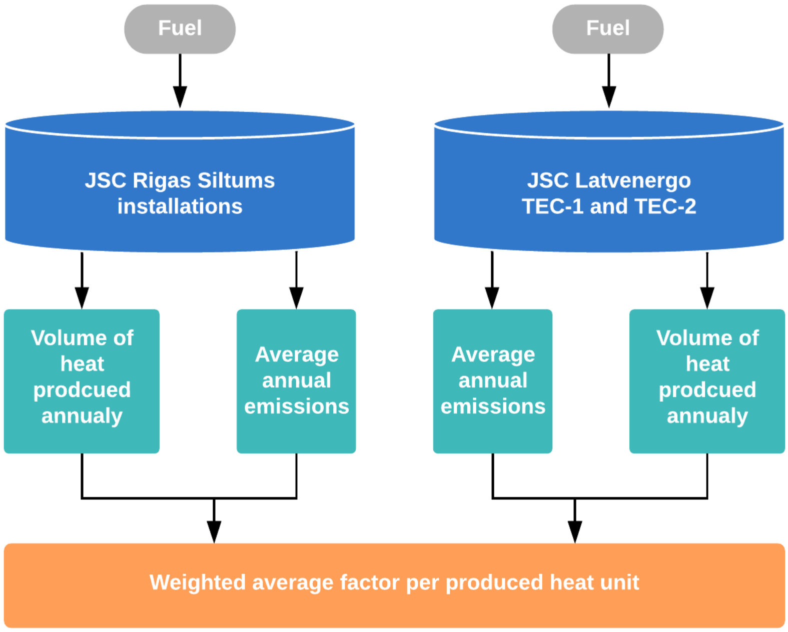

Figure A.2: District heating emission calculation scheme. Adapted from [30].

The power consumption in Riga is ensured by various production recourses, therefore the emission factor used is based on the average structure of the national electrical grid.

The energy end-use consumption covers households, industry, government and municipal institutions, and the service sector. To access the energy usage in the industrial and service sector, a database of the Latvian Environment, Geology and Meteorology Centre is used which contains publicly available information on the amount of fuel used for the production of heat and/or power, filled out by polluting companies or institutions. The data for the household sector were gathered from surveys of the Central Statistical Bureau of the Republic of Latvia [30].

CO_2 emissions from biomass combustion are accounted with a factor of 0 if the criterion of sustainable production is given, stating that the average increase of the country's forest stock is higher than the average deforestation rate. This applies to Latvia having an average growth from 2011 to 2017 of at least 20 million m^3 and an average deforestation rate of about 12.13 million m^3 [36].

A.2 Pathway indicator matrix

Table A.1 shows the reasoning behind the indicator scores for each pathway. The indicators scores (low to high) are translated into a colour scheme with following colours: red – orange – yellow – light green – green.

Table A.1: Pathway indicator matrix.

	Pathway A: Renewable hydrogen	Pathway B: Solar engagement	Pathway C: Modern transportation
Policy support	The measure is complex as it entails many different aspects (components, planning, etc.) and stakeholders. A high degree of policy support is needed to facilitate the project regarding political restrictions and cooperation between the entities.	As the calculations showed, a feed-in tariff is needed to support the investment. Any kind of incentive is crucial to as the investment costs might be too high for many citizens. The citizen power plant needs high policy support as well.	Revolutionizing last-mile delivery is connected to policy changes, prohibitions, incentives, and similar actions. Increasing the share of biofuels requires agreements.
Stakeholder involvement	The pathway includes many stakeholders from the manufacture of plant components to the companies involved in the district heating and transportation system. A high degree of cooperation is needed.	Excluding the citizens, not many stakeholders are involved. Furthermore, they do not possess high influence on both measures.	Changing last-mile delivery concerns many different delivery companies and their day to day operations. Applying biogas capturing must be coordinated with Rīgas Siltums.
Citizen engagement	Citizen engagement is not specifically needed. When choosing a location for the wind turbines, the opinion of the residents should be considered.	The pathway essentially just works with 100% citizen engagement.	Not high engagement is needed. Nevertheless, the public has to accept the usage of biodiesel and the new last-mile delivery modes.
Trialability	The measure represents a multimillion project. A lower scale trial is not beneficial.	As the example calculations showed, a small local trial for both financing schemes can be easily implemented.	Both measures presented in the pathway can be tried on a small-scale basis and upscaled to bigger quantities.
Market demand	Riga recently has implemented a hydrogen fueled bus line and plans on expanding the usage of alternative fuels. Furthermore, there are constant efforts to reduce the emissions of the DH system.	Solar power has gained more popularity in Latvia both on the political and citizen level.	The transportation sector is the biggest emitting sector. While the public is getting more aware of sustainable transportation modes, there is a high potential and need for modernisation.

A.3 Pathway A

A.3.1 Wind farm outline

Figure A.3 shows the wind speed index over a year at the chosen project location in Riga. The index represents the average wind speed for a period compared to the annual wind speed average.

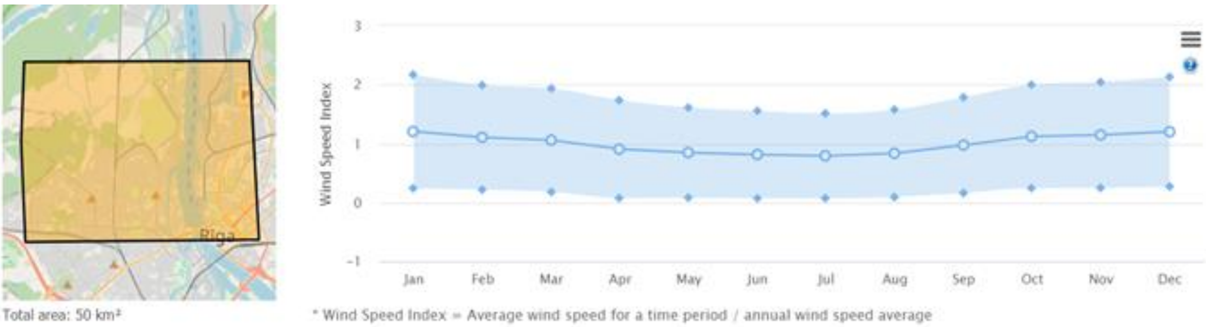

Figure A.3: Wind speed index at project location [56].

Table A.2 indicates the levelized cost calculations of the wind farm. Table A.3 displays the calculations done to receive the energy output of one wind turbine at the project location. The wind speed profile of the location and the specific power curve of the turbine are used to obtain the energy output. Table A.4 shows the results of calculating the LCOE with ten different interest rates. The complete number set is not shown as it would essentially look like the data displayed in Table A.2 but tenfold.

Table A.2: LCOE calculations of the wind farm.

Parameter	Value	Unit				Year	Investment costs [€]	Fixed [€]	Variable [€]	Energy [GWh]
Capital cost	1564	EUR/kW				0	10791600			
Maintenance costs	23	EUR/kW/year				1		151142.86		24.68562
Discount rate	5	%				2		143945.58		23.5101
Life time	20	year				3		137091.03		22.3906
Wind turbine rated power	2300	kW				4		130562.88		21.3244
Number of turbines	3					5		124345.6		20.3089
Installed total power	6900	kW				6		118424.38		19.3418
Total energy	25.9199	GWh				7		112785.13		18.4208
						8		107414.41		17.5436
						9		102299.44		16.7082
						10		97428.03		15.9126
LCOE	0.0395	EUR/kWh				11		92788.6		15.1548
						12		88370.1		14.4332
						13		84162		13.7459
						14		80154.28		13.0913
						15		76337.41		12.4679
						16		72702.3		11.8742
						17		69240.28		11.3088
						18		65943.13		10.7703
						19		62802.98		10.2574
						20		59812.36		9.7689
						SUM	10791600	1977752.78	0	323.01932

Table A.3: Yearly energy output of one turbine at the project location.

Wind speed [m/s]	Frequency [-]	Time [h]	Power [kW]	Energy [GWh]	Capacity factor [-]
1	0.0088	77.088	0	0	0.43
2	0.0296	259.296	0	0	
3	0.0483	423.108	25	0.0105777	
4	0.0705	617.58	82	0.05064156	
5	0.0875	766.5	174	0.133371	
6	0.1021	894.396	321	0.287101116	
7	0.1064	932.064	532	0.495858048	
8	0.1106	968.856	815	0.78961764	
9	0.0994	870.744	1180	1.02747792	
10	0.089	779.64	1580	1.2318312	
11	0.0725	635.1	1890	1.200339	
12	0.0569	498.444	2100	1.0467324	
13	0.0436	381.936	2250	0.859356	
14	0.0281	246.156	2300	0.5661588	
15	0.0189	165.564	2300	0.3807972	
16	0.012	105.12	2300	0.241776	
17	0.0069	60.444	2300	0.1390212	
18	0.004	35.04	2300	0.080592	
19	0.0022	19.272	2300	0.0443256	
20	0.0014	12.264	2300	0.0282072	
21	0.0007	6.132	2300	0.0141036	
22	0.0002	1.752	2300	0.0040296	
23	0.0002	1.752	2300	0.0040296	
24	0.0001	0.876	2300	0.0020148	
25	0.0001	0.876	2300	0.0020148	
26	0	0	0	0	
27	0	0	0	0	
28	0	0	0	0	
29	0	0	0	0	
30	0	0	0	0	
SUM	1	8760		8.64	

Table A.4: Impact of interest rate on the LCOE.

d [%]	LCOE [EUR/kWh]	Change [EUR/kWh]
0	0.0269	-0.0126
1	0.0292	-0.0103
2	0.0316	-0.0079
3	0.0341	-0.0054
4	0.0368	-0.0027
5	0.0395	0
6	0.0424	0.0029
7	0.0454	0.0059
8	0.0485	0.009
9	0.0517	0.0122
10	0.055	0.0155

A.3.2 The hydrogen cycle

Table A.5 shows a selection of hydrogen properties relevant for the calculations performed in 5.1.2. Table A.6 presents the assumptions and their respective sources made to design the hydrogen system.

Table A.5: Properties of hydrogen.

Parameter	Symbol	Value	Unit
Density (at STP)	d_{hydro}	0.0899	Kg/Nm^3
Molar mass	M_{hydro}	2.01588	g/mol
Individual gas constant	R_{spec}	4124.5	J/kg*K
High heating value	HHV	39.4	kWh/kg
Ratio of specific heat	γ	1.405	g/mol

Table A.6: Assumptions made for the components of the hydrogen process.

Parameter	Symbol	Value	Unit	Source
Electrolyser				
Nominal input power	P_{ELY}	500	kW	[64]
Nominal hydrogen flow	$\dot{V}_{hydro}$	100	Nm^3/h	[64]
Specific power consumption	SPC_{ELY}	5	kWh/Nm^3_{H2}	[64]
Specific water consumption	SWC	1.7	l/Nm^3_{H2}	[64]
Output pressure	p_{out}	10	bar(g)[47]	[64]
Operating hours	t_{oper}	80 000	h	[45]
Investment costs	$C_{inv,ELY}$	750	EUR/kW	[45]
O&M cost	$C_{t,main,ELY}$	15	EUR/kW*year	[45]
Lifetime	t_{life}	20	years	[45]
Power converter				
Investment costs	$C_{inv,PC}$	130	EUR/kW	[68]
O&M cost	$C_{t,main,PC}$	2	EUR/kW*year	[68]
Compressor				
Efficiency	η_{com}	75	%	-
Investment costs	$C_{inv,com}$	700	EUR/kW	[68]
O&M cost	$C_{t,main,com}$	28	EUR/kW*year	[68]
Storage				
Storage pressure	p_{stor}	700	bar(g)	[65]
Storage density	d_{stor}	40	kg/m^3	[65]
O&M cost	$C_{t,main,stor}$	2	%[48]	[68]
General				
Water price	C_{water}	0.85	EUR/m^3	[119]
Latvian average electricity emission factor	EF_{grid}	0.109	kg CO_2/kWh_{el}	[36]
Natural gas emission factor	EF_{NG}	0.202	kg CO_2/kWh_{th}	[91]

[47] Bar(g) represents the gauge pressure, meaning the pressure in bars above ambient or atmospheric pressure.
[48] 2% of the total investment costs.

Table A.7 displays the calculations and results of the hydrogen facility sizing. Table A.8 shows the LCOH calculations, while Table A.9 presents the sensitivity analysis of the electrolyser size.

Table A.7: Calculations and results of hydrogen facility sizing.

Electrolyser	Value	Unit						
E_ELY	1883400	kWh						
V_t,hydro	376680	Nm3						
m_t,hydro	33863.532	kg						
V_t,water	640356	l						
t_oper,life	75336	h	replacement?	no				
Compressor								
dm_hydro	8.99	kg/h						
P_isen,single	24218.8135	W	ns/single	63.66	%	T_out,sing	970.95	K
P_isen,ns	15417.4829	W	reduction	36.34	%	T_out,ns	436.98	K
P_com	20.5566438	kW				reduction	54.99	%
E_com	77432.766	kWh						
PC								
P_PC	520.556644	kW						
Storage								
m_stor	649.4376	kg						
V_stor	16.23594	m3						
Energy								
E_hydro	1.96083277	GWh						
E_wind	25.9199	GWh						
E_grid	23.9590672	GWh						
Emissions								
EM_grid	2611.53833	t CO2	90.65	%				
EM_hydro	269.513078	t CO2	9.35	%	7.9588	kg CO2/kg H2	0.137	kg CO2/kWhel
EM_total	2881.05141	t CO2	100	%				
EM_wind	2825.2691	t CO2	98.06	%				

Table A.8: LCOH calculation including sensitivity analysis.

	Investment costs [€]				Fixed [€]				Variable [€]		Hydrogen	
Year	ELY	Com	PC	Stor	ELY	Com	PC	Stor	Electricity	Water	Mass [kg]	
0	375000	14389.65	67672.36	4575.44								
1					7142.86	548.18	991.54	87.15	73764.66	518.38	32250.98	
2					6802.72	522.07	944.32	83	70252.06	493.7	30715.22	
3					6478.78	497.21	899.35	79.05	66906.72	470.19	29252.59	
4					6170.27	473.54	856.53	75.28	63720.69	447.8	27859.61	
5					5876.45	450.99	815.74	71.7	60686.37	426.48	26532.96	
6					5596.62	429.51	776.89	68.29	57796.54	406.17	25269.49	
7					5330.11	409.06	739.9	65.03	55044.33	386.83	24066.18	
8					5076.3	389.58	704.67	61.94	52423.17	368.41	22920.17	
9					4834.57	371.03	671.11	58.99	49926.83	350.86	21828.73	
10					4604.35	353.36	639.15	56.18	47549.36	334.15	20789.27	
11					4385.09	336.53	608.72	53.5	45285.1	318.24	19799.31	
12					4176.28	320.51	579.73	50.96	43128.67	303.09	18856.48	
13					3977.41	305.25	552.12	48.53	41074.92	288.66	17958.55	
14					3788.01	290.71	525.83	46.22	39118.97	274.91	17103.38	
15					3607.63	276.87	500.79	44.02	37256.17	261.82	16288.94	
16					3435.84	263.68	476.95	41.92	35482.06	249.35	15513.27	
17					3272.23	251.13	454.23	39.92	33792.44	237.48	14774.55	
18					3116.4	239.17	432.6	38.02	32183.28	226.17	14071	
19					2968	227.78	412	36.21	30650.74	215.4	13400.95	
20					2826.67	216.93	392.38	34.49	29191.18	205.14	12762.81	
SUM	375000	14389.65	67672.36	4575.44	93466.59	7173.09	12974.55	1140.4	965234.26	6783.23	422014.44	
	Investment SUM	461637.45										
LCOH	3.67	EUR/kg										
Sensitivity												
	interest rate	0	1	2	3	4	5	6	7	8	9	10
	LCOH	2.53	2.73	2.95	3.18	3.42	3.67	3.93	4.2	4.48	4.77	5.07
	Diff.	-1.14	-0.94	-0.72	-0.49	-0.25	0	0.26	0.53	0.81	1.1	1.4

Table A.9: Impact of electrolyser size on emission reduction and costs.

Electrolyser [kW]	0	500	1000	1500	2000	2500	3000	3500	4000	4500	5000
Energy [GWh]											
E_hydro	0	1.96083277	3.92166553	5.8824983	7.84333106	9.80416383	11.7649966	13.7258294	15.6866621	17.6474949	19.6083277
E_wind	25.9199	25.9199	25.9199	25.9199	25.9199	25.9199	25.9199	25.9199	25.9199	25.9199	25.9199
E_grid	25.9199	23.9590672	21.9982345	20.0374017	18.0765689	16.1157362	14.1549034	12.1940706	10.2332379	8.27240511	6.31157234
Emissions [t CO2]											
EM_grid	2825.2691	2611.53833	2397.80756	2184.07679	1970.34601	1756.61524	1542.88447	1329.1537	1115.42293	901.692157	687.961385
EM_hydro	0	269.513078	539.026157	808.539235	1078.05231	1347.56539	1617.07847	1886.59155	2156.10463	2425.61771	2695.13078
EM_total	2825.2691	2881.05141	2936.83371	2992.61602	3048.39833	3104.18063	3159.96294	3215.74525	3271.52756	3327.30986	3383.09217
EM_wind	2825.2691	2825.2691	2825.2691	2825.2691	2825.2691	2825.2691	2825.2691	2825.2691	2825.2691	2825.2691	2825.2691
EM_dif	0	55.782307	111.564614	167.346921	223.129228	278.911535	334.693842	390.476149	446.258456	502.040763	557.82307
EM_step_dif	55.782307	55.782307	55.782307	55.782307	55.782307	55.782307	55.782307	55.782307	55.782307	55.782307	
Costs											
Invest Hydro	0	461637.45	921818.98	1381615.79	1841189.35	2300608.98	2759912.76	3219124.59	3678260.71	4137332.82	4596349.75
Diff	461637.45	460181.53	459796.81	459573.56	459419.63	459303.78	459211.83	459136.12	459072.11	459016.93	
EUR/kg		8.27569663	8.26264662	8.25599767	8.25167266	8.24852576	8.24608169	8.24410044	8.24244485	8.24102967	8.2397986

A.4 Pathway B

A.4.1 Global Solar Atlas methodology and assumptions

The following passages describe a summary of the methodology used by the Global Solar Atlas tool developed by Solargis. The information provided by the Atlas is based on three different models: solar radiation model, air temperature model and PV power simulation model.

The solar radiation model considers the attenuation factors of sun rays on the way through the atmosphere. To calculate the solar resource parameters the model uses data inputs from geostationary satellites and meteorological models. The clear-sky irradiance (absence of clouds) is calculated considering the position of the sun at every instant together with the effect of altitude, concentration of aerosols, water vapour and ozone. To obtain the all-sky irradiance, data from geostationary meteorological satellites is used to quantify the cloud index, which is then coupled with the clear-sky irradiance. The primary calculated global horizontal irradiance (GHI) is further processed by other models to receive direct and diffuse irradiance as well as global irradiance on tilted surfaces [120].

The solar irradiance is a crucial parameter to determine the output of solar technologies. Nevertheless, meteorological parameters are as well important to characterise operating conditions and performance of solar power plants. As meteorological data is mostly not available for a specific site, meteorological models are employed. The resulting data must be post-processed to provide parameters with local representation. The Solar Atlas works with data based on time series of air temperature data [120].

In the last step, the PV power simulation model is used to obtain the PV power output (PV_{out}). As described before, determining the electrical output of PV systems depends on external factors such as solar radiation and air temperature. To obtain the potential electricity output for a selected location several conversion steps concerning factors such as the PV module characteristics have to be regarded. Shading by terrain features is determined by using high-resolution elevation data.

Shading driven by buildings and similar is not considered, but PV field self-shading due to the arrangement of the modules in rows is regarded.

The performance of the PV module uses parameters of a generic crystalline silicon module implemented in a single-diode equivalent circuit simulation with De Soto five-parameter model. The DC to AC conversion is calculated using the Sandia Inverter model, where the inverter efficiency is modelled at the maximum power point of the connected module array [120].

Table A.10 displays the assumptions made to characterize the PV system configuration. The Global Solar Atlas offers the possibility to calculate the PV_{out} for a small residential system with changed assumptions (e.g. losses) that consider roof-mounted PV characteristics such as bad ventilation or shorter cable paths but is only available for point-specific sites. Therefore, the theoretical value (with the assumptions of Table A.10) is chosen for the whole area of Riga. The theoretical value assumes an optimum title angle and can be used as a quick assessment where additional information about the installation is not needed and the electricity output is referenced to 1 kW installed power [120].

Table A.10: Assumption of the PV system configuration to calculate $PV_{out.}$ Adapted from [120].

PV system	Installed power [kW]	Nominal operating cell temp. [°C]	PV field self-shading [%]	Inverter efficiency [%]	DC losses[49] [%]	AC losses[50] [%]	Availability [%]
Theoretical (Site data)	1	46.2	2.0	98	5.8	1.4	100

A.4.2 Results of PV calculations

Table A.11 shows the calculations regarding the breakeven time as a function of the degree of self-consumption and feed-in tariff. Table A.12 presents the standard deviation of the breakeven durations calculated in Table A.11.

Table A.11: Breakeven time analysis as a function of degree of self-consumption and feed-in tariff.

Feed in tariff	C_inv	C_main	μ	1		0.95		0.9		0.85		0.8	
	73258.24	1816.32		C_save	t_break	C_save	t_break	C_save	t_break	C_save	t_break	C_save	t_break
0				9595.23	9.42	9115.47	10.04	8635.71	10.74	8155.95	11.56	7676.19	12.5
0.01				9595.23	9.42	9144.73	10	8694.22	10.65	8243.71	11.4	7793.2	12.26
0.02				9595.23	9.42	9173.98	9.96	8752.72	10.56	8331.47	11.24	7910.22	12.02
0.03				9595.23	9.42	9203.23	9.92	8811.23	10.47	8419.23	11.09	8027.23	11.8
0.04				9595.23	9.42	9232.49	9.88	8869.74	10.39	8506.99	10.95	8144.25	11.58
0.05				9595.23	9.42	9261.74	9.84	8928.25	10.3	8594.75	10.81	8261.26	11.37
0.06				9595.23	9.42	9290.99	9.8	8986.76	10.22	8682.52	10.67	8378.28	11.16
0.07				9595.23	9.42	9320.25	9.76	9045.26	10.13	8770.28	10.53	8495.29	10.97
0.08				9595.23	9.42	9349.5	9.72	9103.77	10.05	8858.04	10.4	8612.31	10.78
0.09				9595.23	9.42	9378.76	9.69	9162.28	9.97	8945.8	10.28	8729.32	10.6
0.1				9595.23	9.42	9408.01	9.65	9220.79	9.89	9033.56	10.15	8846.34	10.42
0.11				9595.23	9.42	9437.26	9.61	9279.29	9.82	9121.32	10.03	8963.35	10.25
0.12				9595.23	9.42	9466.52	9.58	9337.8	9.74	9209.08	9.91	9080.37	10.09
0.13				9595.23	9.42	9495.77	9.54	9396.31	9.66	9296.84	9.79	9197.38	9.93
0.14				9595.23	9.42	9525.02	9.5	9454.82	9.59	9384.61	9.68	9314.4	9.77
0.15				9595.23	9.42	9554.28	9.47	9513.32	9.52	9472.37	9.57	9431.41	9.62
0.16				9595.23	9.42	9583.53	9.43	9571.83	9.45	9560.13	9.46	9548.43	9.47

[49] Soiling, cables, mismatch
[50] Transformer and cables

Table A.11 (continued).

0.75		0.7		0.65		0.6		0.55		0.5	
C_save	t_break	C_save	t_break	C_save	t_break	C_save	t_break	C_save	t_break	C_save	t_break
7196.42	13.62	6716.66	14.95	6236.9	16.57	5757.14	18.59	5277.38	21.17	4797.62	24.57
7342.69	13.26	6892.19	14.43	6441.68	15.84	5991.17	17.55	5540.66	19.67	5090.15	22.38
7488.96	12.91	7067.71	13.95	6646.45	15.17	6225.2	16.62	5803.95	18.37	5382.69	20.54
7635.23	12.59	7243.23	13.5	6851.23	14.55	6459.23	15.78	6067.23	17.23	5675.23	18.98
7781.5	12.28	7418.75	13.08	7056.01	13.98	6693.26	15.02	6330.51	16.23	5967.77	17.65
7927.77	11.99	7594.28	12.68	7260.78	13.46	6927.29	14.33	6593.8	15.33	6260.3	16.48
8074.04	11.71	7769.8	12.31	7465.56	12.97	7161.32	13.71	6857.08	14.53	6552.84	15.47
8220.31	11.44	7945.32	11.95	7670.34	12.51	7395.35	13.13	7120.37	13.81	6845.38	14.57
8366.58	11.18	8120.84	11.62	7875.11	12.09	7629.38	12.6	7383.65	13.16	7137.92	13.77
8512.84	10.94	8296.37	11.31	8079.89	11.7	7863.41	12.11	7646.93	12.56	7430.46	13.05
8659.11	10.71	8471.89	11.01	8284.66	11.33	8097.44	11.66	7910.22	12.02	7722.99	12.4
8805.38	10.48	8647.41	10.72	8489.44	10.98	8331.47	11.24	8173.5	11.52	8015.53	11.82
8951.65	10.27	8822.93	10.46	8694.22	10.65	8565.5	10.85	8436.78	11.07	8308.07	11.28
9097.92	10.06	8998.46	10.2	8898.99	10.34	8799.53	10.49	8700.07	10.64	8600.61	10.8
9244.19	9.86	9173.98	9.96	9103.77	10.05	9033.56	10.15	8963.35	10.25	8893.14	10.35
9390.46	9.67	9349.5	9.72	9308.55	9.78	9267.59	9.83	9226.64	9.89	9185.68	9.94
9536.73	9.49	9525.02	9.5	9513.32	9.52	9501.62	9.53	9489.92	9.55	9478.22	9.56

Table A.12: Standard deviation analysis of the breakeven time depending on feed-in tariff.

Feed in tariff µ		1	0.95	0.9	0.85	0.8	0.75	0.7	0.65	0.6	0.55	0.5		t_break	
		t_break	t_break	t_break	t_break	t_break	t_break	t_break	t_break	t_break	t_break	t_break	Average	Variance	Std. deviation
0		9.42	10.04	10.74	11.56	12.5	13.62	14.95	16.57	18.59	21.17	24.57	14.8845455	23.8736273	4.8860646
0.01		9.42	10	10.65	11.4	12.26	13.26	14.43	15.84	17.55	19.67	22.38	14.26	17.63368	4.199247552
0.02		9.42	9.96	10.56	11.24	12.02	12.91	13.95	15.17	16.62	18.37	20.54	13.7054545	13.1007673	3.619498207
0.03		9.42	9.92	10.47	11.09	11.8	12.59	13.5	14.55	15.78	17.23	18.98	13.2118182	9.75005636	3.122508025
0.04		9.42	9.88	10.39	10.95	11.58	12.28	13.08	13.98	15.02	16.23	17.65	12.7690909	7.26162909	2.694741006
0.05		9.42	9.84	10.3	10.81	11.37	11.99	12.68	13.46	14.33	15.33	16.48	12.3645455	5.37454727	2.318306984
0.06		9.42	9.8	10.22	10.67	11.16	11.71	12.31	12.97	13.71	14.53	15.47	11.9972727	3.96262182	1.990633522
0.07		9.42	9.76	10.13	10.53	10.97	11.44	11.95	12.51	13.13	13.81	14.57	11.6563636	2.88278545	1.697876749
0.08		9.42	9.72	10.05	10.4	10.78	11.18	11.62	12.09	12.6	13.16	13.77	11.3445455	2.06432727	1.436776695
0.09		9.42	9.69	9.97	10.28	10.6	10.94	11.31	11.7	12.11	12.56	13.05	11.0572727	1.43736182	1.198900254
0.1		9.42	9.65	9.89	10.15	10.42	10.71	11.01	11.33	11.66	12.02	12.4	10.7872727	0.97412182	0.986976098
0.11		9.42	9.61	9.82	10.03	10.25	10.48	10.72	10.98	11.24	11.52	11.82	10.5354545	0.63000727	0.793729975
0.12		9.42	9.58	9.74	9.91	10.09	10.27	10.46	10.65	10.85	11.07	11.28	10.3018182	0.38073636	0.617038381
0.13		9.42	9.54	9.66	9.79	9.93	10.06	10.2	10.34	10.49	10.64	10.8	10.0790909	0.20926909	0.457459387
0.14		9.42	9.5	9.59	9.68	9.77	9.86	9.96	10.05	10.15	10.25	10.35	9.87090909	0.09576909	0.309465815
0.15		9.42	9.47	9.52	9.57	9.62	9.67	9.72	9.78	9.83	9.89	9.94	9.67545455	0.02986727	0.172821505
0.16		9.42	9.43	9.45	9.46	9.47	9.49	9.5	9.52	9.53	9.55	9.56	9.48909091	0.00224909	0.047424581

A.4.3 Results of solar thermal calculations

Table A.13 and Table A.14 show the sensitivity analyses of the breakeven duration.

Table A.13: Sensitivity analysis of the breakeven duration as a function of the natural gas price.

NG price	C_inv	C_main		C_save	t_break
	122640	1226.4			
0.01				1042.31	
0.015				1563.47	363.84
0.02				2084.63	142.9
0.025				2605.78	88.91
0.03				3126.94	64.53
0.035				3648.1	50.64
0.04				4169.26	41.67
0.045				4690.41	35.4
0.05				5211.57	30.77
0.055				5732.73	27.22
0.06				6253.88	24.39
0.065				6775.04	22.1
0.07				7296.2	20.2
0.075				7817.35	18.61
0.08				8338.51	17.24
0.085				8859.67	16.07
0.09				9380.83	15.04
0.095				9901.98	14.14
0.1				10423.14	13.34

Table A.14: Sensitivity analysis of the breakeven duration regarding the effect of subsidies.

p_incen	c_inv	A_install	C_main	C_save		C_inv	t_break
	420	292	1226.4	3658.52			
0						122640	50.43
10						119720	49.22
20						116800	48.02
30						113880	46.82
40						110960	45.62
50						108040	44.42
60						105120	43.22
70						102200	42.02
80						99280	40.82
90						96360	39.62
100						93440	38.42
110						90520	37.22
120						87600	36.02
130						84680	34.82
140						81760	33.62
150						78840	32.42
160						75920	31.22
170						73000	30.01
180						70080	28.81
190						67160	27.61
200						64240	26.41
210						61320	25.21
220						58400	24.01
230						55480	22.81
240						52560	21.61
250						49640	20.41
260						46720	19.21
270						43800	18.01
280						40880	16.81
290						37960	15.61
300						35040	14.41
310						32120	13.21
320						29200	12.01
330						26280	10.81
340						23360	9.6
350						20440	8.4
360						17520	7.2
370						14600	6
380						11680	4.8
390						8760	3.6
400						5840	2.4
410						2920	1.2
420						0	0

A.5 Pathway C

A.5.1 Biofuels by algae carbon capture

Table A.15 shows the advantages and disadvantages of three different photobioreactor types for microalgae cultivation.

Table A.15: Comparison of different types of photobioreactors [104].

Photobioreactors	Advantages	Disadvantages
Vertical column (tubular)	Compact, high mass transfer, good mixing with low shear stress, low energy consumption, high potential for scalability, easy to sterilise, readily tempered, good for immobilisation of algae, reduced photoinhibition and photooxidation	Small illumination surface area, construction requires sophisticated materials, stress to algal cultures, decrease of illumination surface area upon scale-up, expensive compared to open ponds
Flat panel	Large illumination surface area, suitable for outdoor cultures, good for immobilisation of algae, good light path, high biomass productivities, relatively cheap, easy to clean up, readily tempered, low oxygen build-up	Scale-up requires many compartments and support materials, difficulty in controlling culture temperature, some degree of wall growth, possibility of hydrodynamic stress to some algal strains
Horizontal tubular	Large illumination surface area, suitable for outdoor cultures, good biomass productivities, relatively cheap	Gradients of pH, dissolved oxygen and CO_2 along the tubes, fouling, some degree of wall growth, requires large land space