Energy planning in Riga
Pathways for a low-carbon energy transformation

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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

1. Introduction

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 voluntary 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.

2. Political framework

2.1 European Union climate strategies and targets

The 2020 climate & energy package, a set of binding legislation, introduces three key targets in the EU's pursuit of addressing climate change. Those targets for the year 2020, set in 2007 and enacted in 2009, aim at reducing greenhouse gas emissions (GHG), increasing renewable energy sources, and limiting the consumption of primary and final energy [4].

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 [5].

The share of renewable energy reached 18.9% in 2018 [6], thus the EU is on track to attain the target of 20% in 2020, but the current deployment remains insufficient to achieve the 32% target in 2030. Both energy efficiency targets for 2020 (20%) and 2030 (32.5%) are not expected to be met. The GHG target of 20% reduction[2] is expected to be reached, being already at 21.7% in 2017 and being estimated to drop another 2.0% by 2018.

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

[2] Compared to 1990 levels.

Meeting the 2030 target (40%) requires further effort as the current policies and additional measures fail to reach the target by 10% and 4%, respectively [7].

2.2 Urban development in the EU policy context

Despite the importance of urban areas, 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 [8]. First modest steps were taken after the reform of Structural Funds and the revision of the Treaty of Rome[3] (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 [9].

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 and placed it at the heart of the cohesion policy directing at least half of the resources of the European Regional Development Fund (ERDF)[4] to it [2].

For the next long-term EU budget (2021–2027), the EC proposes to modernise the cohesion policy with a new program for urban authorities, the European Urban Initiative [10].

3. Energy planning in the city of Riga

3.1 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 [11]. Commitments are taken centrally, applying to the whole city, but implementation is scattered among the municipal structures such as city departments.

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 [11].

The City Development Department, the leading municipality institution in the field of territorial planning, 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 until 2030, the crucial planning document for a long-term territory development of Riga [12], [13].

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 (REA) is of utmost importance in the pursuit of the development of a resource-efficient, renewable, and low-emission city.

3.2 Development plans

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. 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 [14].

Figure 1 presents the interaction between the mentioned plans. All strategies are in alignment with the strategic main vision.

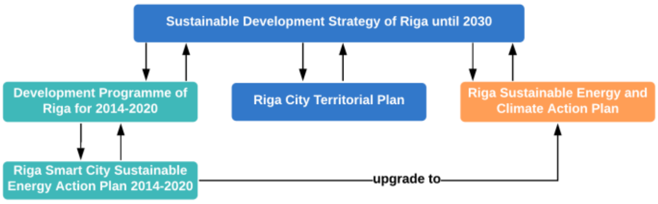

Figure 1: Interaction between current development plans. Adapted from [13], [14].

3.3 CO_2 emissions of the city of Riga

Figure 2 shows the emissions of the city of Riga from 1990 to 2016 and indicates a clear trend of emission reduction, achieving a decrease of 54.5% and 19.2% compared to 1990 and 2008, 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% [15].

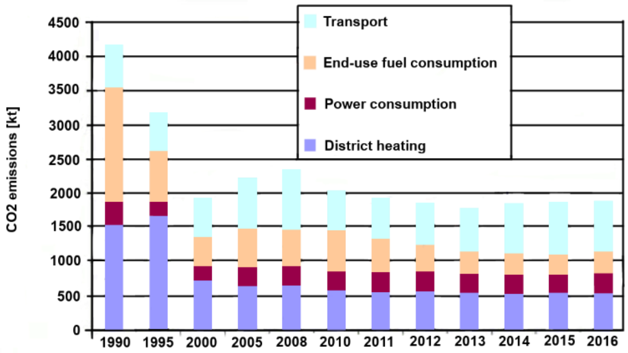

Figure 2: Calculated CO_2 emissions of the city of Riga by main sectors (1990–2016). Adapted from [15].

3.4 Measures of the city of Riga

The actions planned by the city of Riga are summarized in the Riga Smart City SEAP. They are a set of quantifiable and qualitative measures aiming at reducing emissions and fostering smart technologies.

The main measures, such as the installation of a condensation economizer in the district heating system, are forecasted to achieve an emission reduction of 154.8 to 225.5 kt/year by 2020 [14].

An estimation for the year 2016 of the implemented measures shows an emission decrease of 131.6 kt. This impact is mainly achieved through the deployment of renewable energy sources accounting for 86% of the reduction [15].

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[3] The Treaty of Rome, addressing the objective of "harmonious development", can be considered the first time in which the urban dimension entered the debate [9].

[4] Cohesion policy is delivered through the ERDF and the cohesion fund [2].

4. Pathways for 2030

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 [16].

The Cambridge Dictionary gives the word pathway a second definition as “a series of actions that can be taken in order to achieve something” [17]. In this paper, this definition is used and slightly changed to fit the purpose of the paper objective, resulting in the following definition:

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

To simplify the characterisation and comparison of the pathways, a graphic indicator method is carried out, adapted from the Future Energy Scenarios of the National Grid ESO, the electricity operator of Great Britain, and the replication and scalability potential scheme of EU project REPLICATE [18], [19].

4.2 Target setting

Currently, the city of Riga is missing an emission target for 2030. The city already achieved a reduction of 54.5% (compared to 1990) in 2016 and surpassed the 2030 goal of the CoM by 15.4% and 14 years earlier.

Figure 3 presents 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. The targets are obtained by following the recommendation of the IPCC to keep the world average temperature increase below 2 °C above pre-industrial levels. This is achievable by limiting GHG emissions in the atmosphere to 450 parts per million, translating to a limit of 2 t CO_2-eq per capita in 2050 [20].

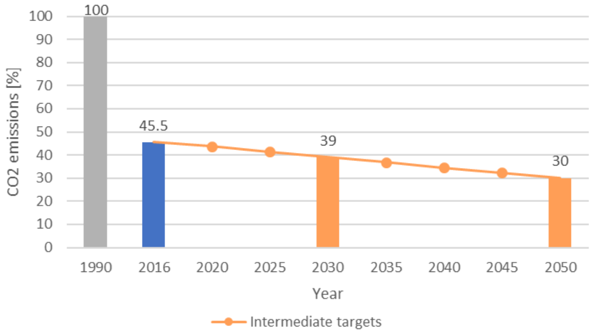

Figure 3: Visual representation of Riga’s emissions in the baseline year 1990 (grey) and 2016 (blue), including the target (orange) for 2030 and 2050.

4.3 Pathway A: Green hydrogen

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. There are no pilot projects planned or in execution [21].

The city of Riga 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 [14].

The absence of hydrogen production projects is a perfect opportunity for Riga to develop the measure presented in this pathway. Figure 4 displays the indicator score of pathway A.

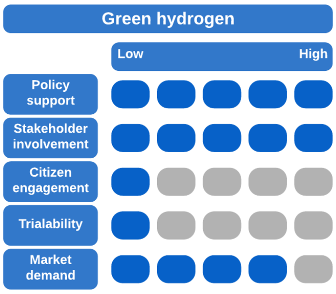

Figure 4: Indicator score pathway A: Green hydrogen.

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 [22]. Although the importance of solar deployment is recognised, the reality shows only an increase of 2.32 MW in the last 5 years [23].

Including citizens in urban energy planning is a common feature of modern governance and is gaining more importance as cities acknowledge the central role that residents can play in the energy transition. The city of Riga with the help of the REA is taking citizen engagement seriously. 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 indicator score of this pathway is shown in Figure 5.

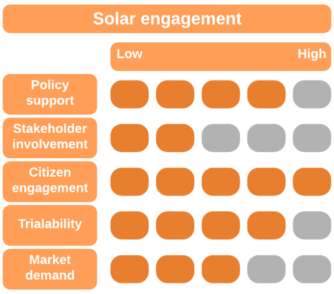

Figure 5: Indicator score pathway B: Solar engagement.

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.

Transport is one of Europe’s biggest source of CO_2, responsible for the emissions of over a quarter of all GHG and increased by a quarter since 1990. Unless transport emissions are tackled and brought under control, 2030 climate goals will be missed [24]. Figure 6 presents the indicator score.

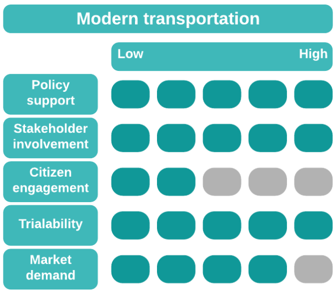

Figure 6: Indicator score pathway C: Modern transportation.

5. Measures

5.1 Pathway A: Green hydrogen

The Enertrag Hybrid Power Plant, a project producing hydrogen from wind energy and reconverting it on demand into electricity using two combined heat and power (CHP) units, serves as basis for the proposed measure, which can be seen in Figure 7 [25]. 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. As there as specific laws on hydrogen blending in natural gas networks in Latvia, the hydrogen most likely would be transported by trucks.

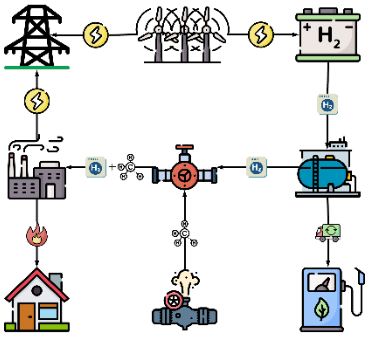

Figure 7: Graphical scheme of the renewable hydrogen production project[5].

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. Figure 8 shows an exemplary location and 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)[26].

Figure 8: Exemplary position of the project wind farm. Adapted from [27].

To determine the wind speed characteristics, the DTU (Technical University of Denmark) Global Wind Atlas is used. The average wind speed of the city of Riga ranges around 6 m/s to 8 m/s, which corresponds to the IEC wind class IIIa [26], [28].

To calculate the yearly energy output of the turbine, Enercon E-82 with a rated power of 2 300 kW, the wind speed profile and the power output are used [26], [29]. The yearly energy output of the E-82 at the project location is 8.64 GWh with a capacity factor of 0.43.

The Levelized Cost of Electricity 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 [30]:

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

where LCOE is the Levelized Cost of Electricity [EUR/kWh], I_0 is the investment expenditure [EUR], A is the annual total cost consisting of fixed and variable operating costs [EUR/year], E_{el} is the annual produced electricity [kWh/year], i is the discount/real interest rate [%], n is economic lifetime [years], and t is the 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 discount rate for the whole measure is set to 5%. The LCOE ranks around the global weighted average for wind farm projects and shows economic competitiveness [31].

5.1.2 Hydrogen cycle

For the energetic and monetary calculations, it is assumed that the hydrogen production facility operates with the same capacity factor as the wind turbine. If excess electricity is produced, it is injected to the grid. For the sizing approach, an example alkaline electrolyser of the company Hydrogenics with a nominal power input of 500 kW is chosen [32]. To calculate the energy need of the electrolyser, the following equation can be used:

$$E_{ELY} = CF_{wind} \cdot 8760 \cdot P_{ELY} \qquad \text{(Eq. 2)}$$

where E_{ELY} is the energy input of the electrolyser [kWh], CF_{wind} is the capacity factor of the wind turbine [-], and P_{ELY} is the power input of the electrolyser [kW].

The produced amount of hydrogen can be derived by using:

$$V_{hydro} = \frac{E_{ELY}}{SPC_{ELY}} \qquad \text{(Eq. 3)}$$

where V_{hydro} is the yearly hydrogen output [Nm^3], and SPC_{ELY} is the 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. The power needed for a multistage process (here: 3 stages) is as follows [33]:

$$P_{isen} = ns \cdot \frac{\gamma}{\gamma - 1} \cdot \dot{m}_{hydro} \cdot R_{spec} \cdot T_{in} \cdot \left[\left(\frac{p_{ns+1}}{p_{in}} \right)^{\frac{\gamma-1}{\gamma} \cdot \frac{1}{ns}} - 1 \right] \qquad \text{(Eq. 4)}$$

$$P_{com} = \frac{P_{isen}}{\eta_{com}} \cdot \frac{1}{1000} \qquad \text{(Eq. 5)}$$

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

where P_{isen} is the isentropic compressor power [W], ns is the number of stages [-], γ is the ratio of specific heat [-], $\dot{m}_{hydro}$ is the hydrogen mass flow rate [kg/s], R_{spec} is the specific gas constant for hydrogen [J/kg*K], T_{in} is the input temperature of hydrogen [K], p_{ns+1} is the output pressure of last compression stage [Pa], p_{in} is the input pressure of first compression stage [Pa], P_{com} is the compressor power [kW], and η_{com} is the compressor efficiency [%].

The mass flow rate of hydrogen, needed for (Eq. 4), 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.

To obtain the energy consumed by the compressor, (Eq. 2) can be used as the compressor operates the same amount of time as the electrolyser. As the electrolyser and compression unit operate with direct current (DC), a 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. 6):

$$P_{PC} = P_{ELY} + P_{com} \qquad \text{(Eq. 6)}$$

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

Note that the power converter efficiency is not regarded as the power calculations for the electrolyser and compressor are carried out on AC current basis.

The storage unit, a high-pressure cylinder, operates at 700 bar and is sized to store seven times the average daily produced hydrogen. The results of the hydrogen facility sizing can be found in Table 1 and Table 2.

Table 1: Sizing of the electrolyser.

$\dot{m}_{hydro}$ [kg/h]	m_{hydro} [t/year]	V_{hydro} [m^3]	$t_{oper,life}$[6] [h]
8.99	33.86	640.356	75 336

Table 2: Sizing of the remaining components.

P_{isen} [kW]	P_{com} [kW]	P_{PC} [kW]	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:

$$E_{wind} = E_{grid} + E_{hydro} = E_{grid} + E_{ELY} + E_{com} \qquad \text{(Eq. 7)}$$

where E_{wind} is the energy output of the wind farm [kWh], E_{grid} is the energy delivered to the grid [kWh], E_{hydro} is the energy used for hydrogen production [kWh], and E_{com} is the 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 3) are obtained.

Table 3: Energy balance of the 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 (0.109 kg CO_2/kWh$_{el}$ [15]). The hydrogen produced is used to reduce the emissions in the district heating system by replacing natural gas (0.202 kg CO_2/kWh$_{th}$ [34]). The total saved emissions can be obtained by applying the following equation:

$$EM_{savings} = E_{grid} \cdot EF_{grid} + m_{hydro} \cdot HHV_{hydro} \cdot EF_{NG} \qquad \text{(Eq. 8)}$$

where EF_{grid} is the Latvian average electricity emission factor [kg CO_2/kWh$_{el}$], m_{hydro} is the annual hydrogen production [kg/year], HHV_{hydro} is the Higher Heating Value of hydrogen [kWh/kg], and EF_{NG} is the 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 (see Figure 9). The electricity delivered to the grid reduces emissions by 2 611.54 t, while the hydrogen circle 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.

The difference between using a share of electricity by the turbines to produce hydrogen and injecting the total produced electricity into the grid is +55.78 t CO_2 per year.

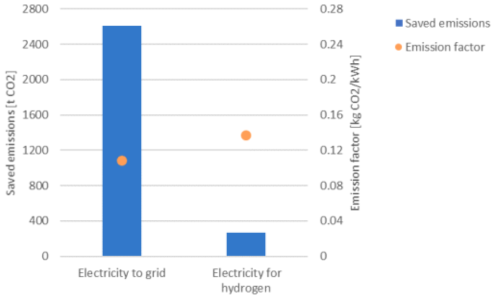

Figure 9: Saved emissions by the measure (in blue) and the respective emission factors (orange).

Like the LCOE, the Levelized Cost of Hydrogen can be calculated using a slightly altered version of (Eq. 1), replacing E_{el} with m_{hydro}, the 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 of the single components follows a linear cost assumption. The storage tank does not follow the said assumption. To obtain the cost, the following equation is used [35]:

$$I_{0,stor} = \text{€}80 \cdot 2500 \cdot \left(\frac{V_{stor}}{2500}\right)^{0.75} \qquad \text{(Eq. 9)}$$

where V_{stor} is the hydrogen tank capacity [Nm^3].

The cost of the wind farm is not directly included in the LCOH but are being considered by using the LCOE as the price for electricity. The annual total cost consists of fixed and variable costs. The fixed cost is described by the operation and maintenance (O&M) cost of the components. The variable cost is as follows:

$$A_{var} = LCOE \cdot E_{hydro} + c_{water} \cdot V_{hydro} \cdot SWC \qquad \text{(Eq. 10)}$$

where A_{var} is the variable annual cost [EUR/year], c_{water} is the water price [EUR/l], and SWC is the specific water consumption of the electrolyser [l/Nm$^3_{H2}$].

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[6] Operational lifetime

The LCOH amounts to 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 International Renewable Energy Agency, 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[7] EUR/kW in the cost model of this paper, the LCOH would drop to 2.81 EUR/kg$_{H2}$ [36].

Considering the total economics, the measure would have an initial investment cost of MEUR 11.26, whereof MEUR 10.8 account for the wind farm and MEUR 0.46 for the hydrogen facility.

5.2 Pathway B: Solar engagement

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.

The solar maps of three cities, Barcelona in Spain, Nantes, and Paris in France, serve as a basis for this measure. All three tools show specific data per roof area so that every citizen can obtain information on their assets. The main difference between the solar maps is how the solar potential is calculated and described to the user [37]–[39].

The Riga solar map follows the approach of the municipality of Barcelona using a practical photovoltaic (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 [40].

To obtain the PV_{out} of Riga, the Global Solar Atlas is used [41]. As the PV_{out} value is chosen to be constant for the selected area, 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 and be represented by a colour scheme. A schematic overview of the tool for Riga could look as presented in Figure 10.

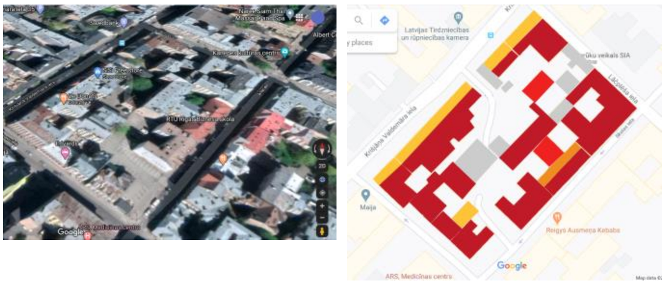

Figure 10: Example area in Riga using Google Maps in satellite view (left) and schematic solar map (right) [42].

The following formulas to obtain the energy output of the PV system are derived from the approach and assumptions used by the municipality of Barcelona [43]:

$$A_{useful} = A_{roof} \cdot \chi_{cover} \cdot \chi_{install} \qquad \text{(Eq. 11)}$$

$$\begin{aligned} E_{PV} &= \left\lfloor \frac{A_{useful}}{A_{panel}} \right\rfloor \cdot \lambda_{surface} \cdot P_{panel} \cdot PV_{out} \\ &= P_{install} \cdot PV_{out} \end{aligned} \qquad \text{(Eq. 12)}$$

where A_{useful} is total useful roof area that can be used for PV panels [m^2], A_{roof} is the roof area including chimneys and other obstacles [m^2], χ_{cover} is the share of roof that can be used for PV panels (excluding obstacles) [%], $\chi_{install}$ is the share of area that remains after taking into account spacing of PV panels [%], E_{PV} is the energy output of the installed PV system [kWh/year], A_{panel} is the PV panel module size [m^2], $\lambda_{surface}$ is the degree of insolation [%], P_{panel} is the PV panel power output [kW], PV_{out} is the practical PV potential (PV power output) [kWh/kW*year], and $P_{install}$ is the installed PV capacity [kW].

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 [44]:

$$\begin{aligned} t_{breakeven} \\ &= \frac{c_{inv,pv} \cdot P_{install}}{E_{PV} \cdot \left(\mu \cdot p_{elec} + (1-\mu) \cdot p_{feed}\right) - c_{O\&M,pv} \cdot P_{install}} \\ &= \frac{C_{inv,pv}}{C_{savings,pv} - C_{O\&M,pv}} \end{aligned} \qquad \text{(Eq. 13)}$$

where $t_{breakeven}$ is the breakeven time [years], $c_{inv,k}$ is the investment cost per installed power of technology k [EUR/kW], $C_{inv,k}$ is the total investment cost of technology k [EUR], μ is the share of self-consumption [%], p_{elec} is the electricity price [EUR/kWh$_{el}$], p_{feed} is the feed-in tariff [EUR/kWh$_{el}$], $c_{O\&M,k}$ is the O&M cost per installed power of technology k per year [EUR/kW*year], $C_{O\&M,k}$ is the total O&M cost of technology k per year [EUR/year], $C_{savings,k}$ is the total savings per year of technology k [EUR/year], and k is the 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. To simplify the calculation $\lambda_{surface}$ is chosen to be 100% and μ set to 70%.

An example roof on the Ģertrūdes iela 67 is taken for the calculation of the solar map. The results are presented in Table 4 and Table 5.

Table 4: 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

Table 5: Economics of the example roof PV calculation.

$C_{inv,pv}$ [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

The PV system would avoid around 6.4 tons of CO$_2$ and has a breakeven duration of 15 years. Two variables affect the breakeven duration: the feed-in tariff p_{feed} and the share of self-consumption μ.

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

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 11. 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.

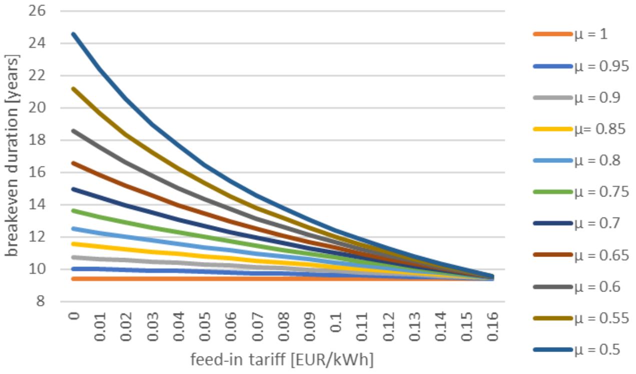

Figure 11: Effect of p_{feed} and μ on the breakeven duration.

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. 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 Global Horizontal Irradiation (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. 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. 11) can be used for the solar collector as well. For the produced heat by a glazed solar collector, the equation is as follows [45]:

$$Q_{solar} = 0.38 \cdot GHI \cdot \left\lfloor \frac{A_{useful}}{A_{collector}} \right\rfloor \cdot A_{aperture} \qquad \text{(Eq. 14)}$$

where Q_{solar} is the heat delivered by the solar system assuming 15% pipe losses [kWh/year], GHI is the Global Horizontal Irradiation [kWh/m^2], $A_{collector}$ is the gross area of the solar collector [m^2], and $A_{aperture}$ is the aperture area, the 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. 14) 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. 13) can be used. The costs are not based on the installed capacity but the installed area resulting in the subsequent equations:

$$A_{install} = \left\lfloor \frac{A_{useful}}{A_{collector}} \right\rfloor \cdot A_{collector} \qquad \text{(Eq. 15)}$$

$$t_{breakeven} = \frac{c_{inv,sc} \cdot A_{install}}{Q_{out} \cdot p_{ng} - c_{O\&M,sc} \cdot A_{install}} \qquad \text{(Eq. 16)}$$

where $A_{install}$ is the installed collector area [m^2], p_{ng} is the natural gas price [EUR/kWh$_{th}$], and k is the indicator of technology used, in this case k = sc (solar thermal collector) [-].

Applying the assumptions and presented equations to the same example roof leads to the results presented in Table 6 and Table 7.

Table 6: 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

Table 7: Economics of the example roof solar thermal calculation.

$C_{inv,c}$ [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. 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.

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 [46]. The solar data has to be obtained separately.

5.2.2 Citizen power plant

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[8] created the initiative of the BürgerInnen Kraftwerke[9], a financing scheme that lets citizens invest in the development of renewable energy in the city of Vienna. 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 [47].

When applying this measure to Riga, a crucial aspect must be regarded, the relatively low Latvian average gross salary, thus setting the voucher package price to EUR 150 is reasonable. For the contract period, 5 years as chosen by Wien Energie seems favourable. Assuming an interest rate of 6.4% results in a yearly coupon payout of EUR 36. The final net profit amounts to EUR 30.

Using (Eq. 11) and (Eq. 12), an example solar citizen power plant can be calculated using the measuring tool of Google Maps. The example roof is part of the Riga main station halls.

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[8] Wien Energie is the biggest energy provider of Austria and belongs to the Wiener Stadtwerke, the public utility of Vienna, Austria.

[9] German for citizen power plant.

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).

5.3 Pathway C: Modern transportation

5.3.1 Biofuels by algae carbon capture

Figure 12 displays the concept of 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 photobioreactor (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.

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[10]. The oil yield of algae is over 200 times the yield of best-performing plants [48].

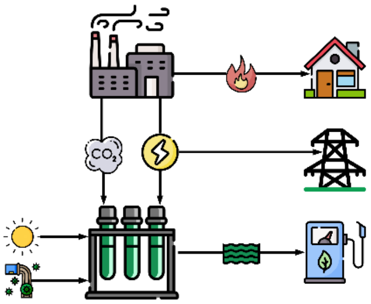

Figure 12: Concept scheme of biofuels creation by algae carbon capture[11].

The measure aims at a substitution of 0.01% (0.65 TJ) of the diesel usage of the transportation sector in Riga [15]. The CO_2 emissions are captured from the heat plant (HP) Ziepniekkalns, which produced 153 GWh heat in 2016 [49]. 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. The biomass productivity and CO_2 consumption rate of the species can be seen in Table 8.

Table 8: Characteristics of three different microalgae species. Adapted from [50].

Characteristics (mg/l/d)	Chlorella sp.	Chlorella vulgaris	Chlorella sorokiniana
Biomass productivity	1 000	3 319	12 200
CO_2 fixation rate[12]	1 880	6 240	22 936

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 (0.38% of the emissions of HP Ziepniekkalns) [51]. The results for the sizing of the three microalgae systems are shown in Table 9. Note that for this simplified calculation, no energy penalty is regarded as no system with specific energetic parameters is designed. 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 9: Results of carbon capture by microalgae.

	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 [52].

In 2015, light-duty trucks in Riga contributed around 100 000 t of CO_2, being the second biggest share after cars with more than 500 000 t [15]. 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.

To show the difference between the standard delivery mode, a 3.5-ton light-duty truck, and a sustainable vehicle, a simple calculation is executed. The Armadillo by Velove, an e-bike with a 250 W engine assisting when pedalling up to 25 km/h with a maximum energy consumption of 0.2 kWh/10 km, represents the sustainable transportation [53]. For the standard process, a Mercedes Sprinter with a payload of 3.5 tonnes and a fuel consumption of 8.1 l/100 km running on diesel (resulting in emissions of 214 g CO_2/km) is taken [54]. For the calculation example, two example routes are created using Google Maps. On both routes, ten parcels are delivered.

Table 10 presents the results of the 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 10: Comparison of two last-mile delivery modes on two routes.

	The Armadillo		Mercedes Sprinter	
	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

6. Recommendations

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.

Developing a hydrogen project is recommended as Riga's future plans aim at fostering the hydrogen transition.

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. The National Regulatory Authority of Latvia should take into consideration to increase of the limit up to 1 or 2 vol%.

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

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

[12] CO_2 fixation rate = 1.88 times biomass productivity.

The biggest concern is the Inčukalns underground gas storage facility, which uses geological structures including a porous sandstone layer to store natural gas [55]. Porous storage is the only infrastructure where extensive research is needed to quantify a feasible hydrogen blending limit [56]. A feasibility study especially applied to that is advisable.

A solar map is not only a great way to create awareness but showing the individual impact the decision of investing in solar technology can have for citizens. The analysis indicates that PV panels are an attractive solution. 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 11. Setting no feed-in tariff would result in undersized PV systems. It is therefore recommended to grant a feed-in tariff for rooftop PV systems. 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 11 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. 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.

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. 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.

The financing scheme presented by the 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, 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.

The technical viability of using microalgae to capture CO_2 and produce useful products such as biodiesel has been demonstrated, but the major challenges are the strategic and holistic development of technologies that will improve economic feasibility [57]. Closed systems using photobioreactors exhibit high capital investment. Additionally, harvesting and processing, especially drying, usually have high costs [50]. Current research and development efforts focus on increasing the oil content, and enhancing the growth rate [58]. As the calculations showed, having a higher biomass productivity can reduce the size of the system and therefore the investment cost vastly. It is advisable to invest in a small-scale pilot project to gain experience. 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.

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.

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 [59]. Designating an example area where fossil-based last-mile delivery could be prohibited is recommended. The calculations showed that 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.

7. Conclusion

The purpose of this paper was to find suitable measures for the city of Riga to further reduce their CO_2 emissions. Alongside that, the energy planning characteristics of Riga were analysed, as well as new emissions reduction targets for 2030 and 2050 proposed. The presented measures were characterised in unique pathways with an indictor scheme to facilitate comparison.

The paper discovered the economic feasibility for the deployment of a renewable hydrogen production facility with a LCOH of 3.67 EUR/kg$_{H2}$. Additionally, the employment of PV systems for citizens was confirmed as an attractive option. Granting a feed-in tariff of 0.1 EUR/kWh is highly recommended to foster the development of solar technologies in the city of Riga. It was concluded that solar thermal systems are not advisable from an economic point of view. A financing scheme using voucher packages should be considered by the city. Furthermore, the employment of a pilot microalgae carbon capture project is recommended to be at the forefront when microalgae strains reach economic biomass productivity. Creating a fossil-free last-mile delivery zone would tackle the high transport sector emissions of the city.

The proposed measures in this paper were chosen to tackle sectors that need further emission reduction. As future work, the presented results should be discussed with the involved stakeholders. While all measures are suitable to be further pursued, the Riga solar map, including a feed-in tariff, the voucher financing scheme, and the fossil-free last-mile delivery zone show the best fit and greatest potential for the city.

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