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ELECTRIC CONSUMPTION ASSESSMENT USING SMART METER DATA AND KPI METHODOLOGY

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In the modern world, many cities make use of state-of-the-art technologies for a diversity of applications. A field with very specific needs is the electric power system that deals with both large entities that govern themselves (grid operators) and the citizens. For both and all actors in between, there is an increased need for information. Steps to provide these data are always taken and several initiatives are ongoing across the world to equip residential users with last generation smart meters. However, a full deployment is still not possible. Considering this aspect, the authors propose KPIs for the specific situation when some information is available from the meters and other sources, but some is not. The study case is based on a residential area occupied mainly by university students and after an extensive measurement campaign the results have been studied and analysis methods proposed.

Keywords: *electric energy, key performance indicator (KPI), load profiles, modelling approach, smart city*

1. INTRODUCTION

People living in cities nowadays progressively take advantage of more communication technologies and multiple opportunities based on solution implementation across various sectors (e.g., transportation, services, infrastructures etc.), thus transforming their environment in a *smarter* one. These advanced cities are called smart cities, which can be defined in multiple ways [1]. The collected definitions slightly differ but share overarching features – advanced connectivity using ICT, improved service system, low impact on the environment and prosperity of citizens. Although the concept of a smart city is fairly similar between definitions as well as implementation, the individual smart city solutions are unique for the individual city. This means that a solution carried out for one city cannot be adopted without any adjustment for another, because solutions are usually specifically designed and developed to address the local situation regarding its inhabitants, environment, infrastructure etc. [2].

The large number of the developed smart city solutions has created a need for solution evaluation and comparison. It is a challenge to provide entirely equal solution comparison. The author in [3] has provided an examination of solution evaluation through modelling approaches. One of the approaches is based on Key Performance Indicator (KPI) methodology, which is one of today's frequently used performance evaluation methods. The KPI method provides the ability to observe, adapt and improve process development through selected parameter monitoring while introducing changes. The change in key parameters is evaluated for a certain selected period to determine growth or decline in the target process. Furthermore, a hasty or inaccurate parameter selection can create a misleading KPI and develop dysfunctional behaviours and/or conclusions. To help mitigate unfavourable KPI creation, authors in [4]–[6] have detailed the process of successful KPI creation and selection.

After KPIs are defined, data are collected and comparison is made between the previously and currently collected data to determine the change over time. Furthermore, if multiple KPIs after examination can be categorised based on common features, the KPIs in question are collected under a specific category, formed as the assembly of different KPIs with similar characteristics. This provides the evaluation method with a large diversity and the KPI method, in general, serves as a powerful tool, which is branching into many areas of human activities.

In this paper, the KPI evaluation method is used to assess the electric energy consumption and related behaviour of student dorms located on the UPB campus in Bucharest, Romania [7]. The dorms represent a part of the city through the role of dorm inhabitants and their effects towards energy consumption based on individual user awareness [8]. The data of dorm KPI evaluation are taken from the smart meter deployment, where each dorm has a smart meter, monitoring consumption per floor. Details about this deployment can be found in [9].

To perform the KPI evaluation, the correct and altered dorm consumption situation must be compared, but considering user privacy, the exact consumption pattern cannot be used. To tackle this situation, building consumption modelling is performed using multiple information sources – user consumption surveys, yearly smart meter measurements and additional information (in Section 2.3). The created model calibrated to represent the real situation is used to test alternative scenarios impacted by user awareness and examine the feasibility of renewable energy solutions.

2. DATA COLLECTION

2.1. Student Dorm

The UPB campus contains multiple student dorms. Four of which have been improved, while working under ITCity project, through smart meter system deployment, providing three-phase electric consumption monitoring of each floor individually.

Table 1 provides general information on the involved dorms. This information includes the number of floors per building, approximate number of inhabitants per floor and room, estimated size of inhabitant living space per floor and room, degree of renewable energy consumption share (estimated from national information [10]), the available roof space area and yearly energy consumption. The yearly energy consumption has been obtained aggregating the smart meter data, while other information is based on statistics.

Table 1. Dorm General Overview

	No. floors	Users		Living space		RES, %	Available roof area, m^2	Yearly energy consumption, kWh
		Floor, no.	Room, no.	Floor, m^2	Room, m^2			
Dorm 1	5	60	5	360	30	42.7	430	109440
Dorm 2	5	80	2	480	12	42.7	600	253635
Dorm 3	5	80	2	480	12	42.7	600	246097
Dorm 4	5	80	2	480	12	42.7	600	321194

Across the involved dorms, situation of approximately 1500 dorm inhabitants is reflected through the data in Table 1. This information is used to derive the consumption model and is used as a guideline for the analysis presented in Section 3.

2.2. Consumer Habits

The inhabitants of student dorms shape the building energy consumption, thereby their individual habits, daily activities and preferences are necessary for a proper consumption assessment. The necessary information is deducted using a statistical approach to information from Electrical Engineering Faculty webpage [11], containing 48 study group schedule, and the results of user consumption surveys filled by students.

University study group schedule provides the essential information of dorm inhabitant work day occupation that is used in the present study as a baseline. This occupation depicts the moment when the inhabitants should be at the university and not contribute to the actual building energy consumption. The study schedules provide a large occupation period variety for the inhabitants, depicting in an accurate way the diversity of the occupancy patterns in the monitored building.

A consumption survey has been carried out to address the individual user consumption in an environment with no smart meter information. The survey results provide an insight into the individual user appliance list as well as their unique use preferences and habits. In Fig. 1, the snapshot of the conducted survey table is presented. The survey table can be divided into two main axes, the top horizontal axis representing the time divided into increments of 15 minutes, adding up to a 24-hour range, and the vertical axis provides a comprehensive list of appliances and their average rated power (in watts). This survey is filled out using values from 1 to N, while the value addresses certain appliance use in a particular time period. If a value larger than 1 is used, it can indicate that the appliance power is larger than the one given in the list or that multiple similar appliances work simultaneously.

#	Device	Average Power [W]	0:00	0:15	0:30	0:45	1:00	1:15	1:30	1:45	2:00	2:15	2:30	2:45	3:00	3:15	3:30
01	Stereo	60															
02	Air conditioning up to 7,500 B	1200															
03	Air conditioning of 10,000 BT	1600															
04	Air conditioning of 12,000 BT	1760															
05	Air conditioning of 18,000 BT	2590															
06	Hot tub	180															
07	Food mixer	60															
08	Gas Boiler	30															
09	Boiler up to 80 liters	1500															
10	Boiler from 100 up to 150 liter	2500															
11	Water pump up to 3/4 HP	1159															
12	1 HP Water Pump	1398															
13	Electric coffee maker	1000															
14	Centrifuge for juices	100															
15	Air circulator	80															
16	Computer	250	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
17	Foam wrapper	65															
18	Fax	100															
19	Clothes iron	1000															
20	Electric oven	2500															
21	Microwave oven	2000															
22	Freezer	100															
23	Refrigerator	40	1			1			1			1			1		
24	Grill	500															
25	Blender	100															
26	Lawn mower	250															
27	Sewing machine	50															
28	Washing machine dishes	1500															
29	Washing machine	1500															
30	Mixer	100															
31	Hair dryer	800															
32	Clothes dryer	600															
33	Sauna up to 5,000 W	5000															
34	12,000 W Sauna	12000															

#	Device	3:45	4:00	4:15	4:30	4:45	5:00	5:15	5:30	5:45	6:00	6:15	6:30	6:45	7:00	7:15	7:3
01	Stereo																
02	Air conditioning up to 7,500 B																
03	Air conditioning of 10,000 BT																
04	Air conditioning of 12,000 BT																
05	Air conditioning of 18,000 BT																
06	Hot tub																
07	Food mixer																
08	Gas Boiler																
09	Boiler up to 80 liters																
10	Boiler from 100 up to 150 liter																
11	Water pump up to 3/4 HP																
12	1 HP Water Pump																
13	Electric coffee maker																
14	Centrifuge for juices																
15	Air circulator																
16	Computer	1	1	1	1	1	1	1	1	1	1	1	1	1	2	2	2
17	Foam wrapper																
18	Fax																
19	Clothes iron																
20	Electric oven																
21	Microwave oven																
22	Freezer																
23	Refrigerator	1			1			1			1			1			1
24	Grill																
25	Blender																
26	Lawn mower																
27	Sewing machine																
28	Washing machine dishes																
29	Washing machine																
30	Mixer																
31	Hair dryer														1	1	
32	Clothes dryer																
33	Sauna up to 5,000 W																
34	12,000 W Sauna																

Fig. 1. Consumption survey snapshot.

The filled out surveys depict the self-assumed user consumption, thereby the user's actual consumption can differ. This information does not include detailed day-to-day habit changes, but provides essential information on the user appliances, user habits and preferences. Even more, it does not completely consider appliances that are used for shorter time periods than 15 min. (e.g., coffee machine, microware used not for cooking but warming up food, hairdryers etc.) or appliances that have a very specific consumption patterns with an average consumption far from the rated power (e.g., fridge, boilers, most of small electronics). However, the consumption survey can be used as a baseline for the analysis, providing a maximal load curve that can be considered for comparison purposes.

Around 100 consumption surveys have been collected and individually analysed, assessing user indicated habits for day-to-day consumption changes. There changes based on user habits provide a variety in daily consumption and this information is used as the guideline for appliance model operation in Section 3.1.

2.3. Additional Information

To properly analyse the consumption model of the target group, a more general approach is needed to describe the micro-environment. Consequently, several other information sources have been identified.

One of these sources is the local weather forecast for the UPB dorm location in Bucharest. The workgroup developing the consumption model has determined two local situation information necessities required for the dorm evaluation:

- Local natural lighting – in order to simulate a natural lighting situation. Information on the natural lighting in Bucharest has been taken from an online source [12]. The information on this weather website divides the intensity of natural lighting into five shares – night, astronomical twilight, nautical twilight, civil twilight and daylight. For the purposes of sufficient natural lighting, the "daylight" data have been taken as the sufficient natural lighting moment. This provides the information of the natural lighting potential for a whole year and is important when modelling the lightning part of the load profile.

- Solar generation – the examined student dorms do not (yet) possess a PV panel solution, but in theory are capable to withstand PV panel deployment. This assumption is made based on the fact that faculty buildings built as part of the same architectural project already have this capability [13]. The solar generation information serves as the guideline of the potential PV panel generation, based on the local situation. The information on solar generation is collected from archived measurements using a 15-minute resolution and the data are available for locations near Romania [14].

3. MODEL DEVELOPMENT

3.1. Auxiliary Models

Auxiliary models use basic information and convert it into specific data, which then can be utilised as the key information for user consumption modelling.

User Behaviour Model

The user behaviour model generates the necessary reference of user daily activity. This information contains data on sleep periods, outdoor and home activity moment. Activity labelled “outside” refers to any activity the user engages in outside of his living space (including time spent at work or lectures), while label “home” indicates user availability at home, thereby potential contribution in overall building consumption.

The generation of individual user behaviour is based on their activities outside of their living space and combined with their sleep period, other moment is assumed as home activities and contribute to energy consumption. First, workday daily occupation is derived as the previously mentioned from the faculty schedule. Second, weekend occupation is generated by a randomized algorithm, selecting a random activity starting time and length. Through these solutions basic user daily activities are created. Additionally, it is assumed that every activity requires up to 1 hour additional time before and after every activity, (hour spent in transit or doing something else (e.g., grocery shopping, eating outside etc.). This additional activity is generated through a randomized algorithm. Last, a user sleep schedule is created and added. The daily sleep schedule is generated by an algorithm randomly selecting length between 6–9 hours and the selected period is analysed if it does not meet other daily activity posed limitations. Other time periods are marked as home activities and are used to model user consumption.

Table 2 shows an example of user behaviour. Top row represents the hours of a day, while the bottom row represents the activity’s code. In the model, this information is generated by increments of 15 minutes, but for the example shown on a smaller resolution. The generated numerical values represent the actual data produced by the model and each value represents a different activity. Value “0” represents the sleep periods, “1” represents the home activity and “2” refers to the outside activity moments, color-coded blue, red and grey, respectively.

Table 2. Hourly Activity Sample

9:00	10:00	11:00	12:00	13:00	14:00	15:00	16:00	17:00	18:00	19:00	20:00	21:00	22:00
0	1	2	2	2	2	2	2	2	1	1	1	1	0

Daylight Model

Daylight model organises the provided weather data regarding local natural lighting. The information gathered from online weather source is primarily divided into natural lighting degrees by their intensity. The portion that is used in the daylight model operation is the "daylight" portion, which occupies most of every day and is a sufficient lighting source. The result of this model is used to examine the energy savings provided by natural lighting prioritization over artificial lighting as a user awareness change.

The daylight model generates a data array with two values for each day of the year. These values depict the starting moment and the final moment the daylight period can be utilised as a lighting solution. In Table 3, an example of a single week and corresponding daylight period times are collected. The top values, in red, represent the starting time and the bottom ones, in blue, depict the ending time. These values have been converted into 24-hour form with hour and minute division, but in the model itself, these values are represented in minute form.

Table 3. Daylight Period Sample

Mon.	Tue.	Wen.	Thu.	Fri.	Sat.	Sun.
8:15	8:14	8:13	8:12	8:11	8:10	8:09
16:30	16:32	16:34	16:36	16:38	16:40	16:42

Appliance Model

The appliance model is the most important user consumption part, which creates the user energy consumption individuality. The individuality is created by alteration in electrical appliance use, specified by the analysed users. Based on the conducted survey data, 24 appliance models have been developed. These models have been made using similar operation and control bases due to the survey data limitations, thereby models operate in 15-minute time steps.

The appliance model operates in two time periods – morning and evening, depicted in Fig. 2. These periods represent the time periods between sleep time and outside activities, and are divided into two in order to modify appliance operation habits. The periods are considered concrete for appliances that require direct user interaction – TV, PC etc., but can also be flexible for appliances that do require user interaction but can operate beyond any restrictions – washing machine, phone charger etc. Furthermore, appliances operating in 24/7 schedule are not limited.

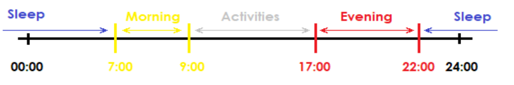

Fig. 2. Day period division.

Every appliance model uses a similar control setup and by control utilisation individual user appliance use habits can be depicted on a greater degree. There are 11 parameters for every appliance model, except 24/7 operation appliances using reduced power throughout the day:

1. Appliance consumption – separated setting for morning/evening period. Sets appliance nominal operation power.
2. Minimum operation time – separated setting for morning/evening period with 15-minute step. Setting is used to set the minimal length the appliance is used.
3. Maximum operation time – separated setting for morning/evening period with 15-minute step. Setting is used to set the maximum length the appliance is used.
4. Appliance use chance – separated for morning/evening period. Sets appliance use frequency in the exact period.
5. Window of operation – separated settings for morning/evening period. Sets appliance operation limitation, due to a lack of available time.
6. Use period preference – combined morning/evening setting. Sets user preference in which period appliance is more likely to be used.

3.2. Conclusive Models

The conclusive models use generated information from all auxiliary models, providing the result of different information interaction. The developed models model individual user consumption, user awareness impact on consumption reduction and simulate renewable energy setup feasibility.

User Consumption Model

The user consumption model designs the individual user energy consumption by generating the energy consumption pattern. The pattern is generated taking into consideration user behaviour model information and appliance model information, which uses the individual user appliance use preferences.

The model operation combines multiple information sources, creating 48 unique user consumption patterns by using single consumption survey data combined with 48 university study schedules. This provides multiple users with similar appliance use preferences, but greatly different daily occupation times and in general impacts the overall user consumption. Furthermore, the modelled user consumption generated from similar preferences is not the same because of the changes in individual activities and different appliance daily use (operation window, utilisation start/end moments and chance of using the appliance). The definition of unique outcomes from a single data source is done with randomized values. In the appliance settings, first, each appliance has a chance of being used; this chance impacts each user individually producing different outcomes. Second, each appliance has minimum and maximum operation time, which is selected randomly each time appliance is used; this is unique for every single time an appliance is used unless maximum and minimum values are the same. Last, each appliance has a randomly selected moment when a user starts to use it. This moment is made unique by two things: user availability, i.e., unique for each individual schedule and the random selected time, making the appliance operation times diverse between even the same settings.

Through a user consumption model, over 3000 unique user consumption patterns have been simulated. The simulated patterns are exclusive, since each generated pattern uses one combination of user behaviour and appliance preferences. This results in a large array of total consumption fluctuations among the user patterns with the smallest total consumption contributing to a six time smaller consumption than the largest total consumption contributor. This diversity is necessary to provide a greater variety of consumption, which will be used to represent an actual consumer group.

Following the user simulations, a randomized selection algorithm is used to choose a certain number of users matching a certain dorm inhabitant number (see Table 1). The users are randomly reselected until the simulated total user consumption practically matches the real student dorm consumption provided in Table 1. The final user selection closely reflects the actual inhabitants and is used in the test cases and the real consumer depiction.

Appliance Consumption Reduction Model

The appliance consumption reduction model tackles the task of exploring user awareness charge through simulation of energy use awareness increase in the form of consumption reduction of selected appliances. The consumption reduction algorithm can be divided into three distinct operation models that can address many appliances.

The first algorithm operation model for consumption reduction is for appliances that are used 24/7 but should not be used in such an extended period of time. It means that it is necessary to use sleep mode or shut down appliances when they are not in use. The use mode is considered the one when the user is at the student dorm and is not sleeping, and periods of sleep and outside activity are the moments when the sleep mode or appliance shutdown is simulated.

The second algorithm operation model assumes that, by increased user awareness, the user will try to use certain appliances less, but without any reduction with regard to the comfort level, but the sleep mode or shutdown of an appliance is used when, for instance, two entertainment appliances are active or an appliance is not used for extended periods by taking breaks from time to time.

This last part of the algorithm is normally only used for lighting solutions, but is not limited to only this solution. This algorithm combines the daylight model and artificial lighting use with a goal to simulate user awareness change impacting users to use natural lighting over an artificial lighting solution when possible.

All algorithms work based on the same user awareness principles and explore user awareness impact on energy use by a gradual increase in awareness from 0 to 100 % of the user involved. The gradual awareness increase is examined with a 5 % step, giving the opportunity to see how each % of population impacted would provide benefit because a 5 % increase in awareness does not directly mean a 5 % consumption reduction because of user activities, i.e., in one situation awareness might give a greater reduction than in another.

PV Panel and Storage Unit Selection Model

In order to achieve higher energy efficiency by consumption and carbon emission reduction, a feasibility study is performed by simulating the impact of the potential PV panel and energy storage (ES) solutions on an individual dorm situation.

The model of PV panel and storage unit selection carries out its calculations taking into account three boundaries. First, energy storage units are charged only by the PV panel over-generation. Second, the injection of excess PV panel generation towards the main grid is restricted. Last boundary is a physical limitation of area limited by the available roof space of individual dorm that is used for PV panel deployment.

The model simulates the added PV panel and energy storage achieved benefit by taking the consumption of a whole dorm, a sum of individual user consumption patterns, and reduced by the PV panel generation and storage unit, calculated based on solar generation reference. The consumption pattern and solar generation both use a 15-minute time step and the PV panel power generation overall efficiency is assumed to be 15 %, based on local PV panel generation reference. The goal of using PV panels and energy storage is to reduce the overall consumption; in the model, this is done through simulation of increasing PV panel generation and energy storage capacity. The model increases the PV panel generation by increased coverage, which is increased by 1 square meter per test and the increase in storage system is done by increasing the maximum capacity by 1 kWh per test. The model tests every possible variation of PV panel size and storage capacity, with the main limitation being the available dorm roof area. Without additional boundaries the model will try to maximise the reduction of consumption by occupying all of the available roof space, which provides the result, but not efficiency. To achieve an appropriate result, one of the elements – PV panel or storage – is bound to a value beforehand, thereby the model is required to only simulate the other non-specified element, limiting the non-realistic results. In the dorm testing, a dorm peak consumption value is used as the predetermined value for the bound element, providing a singular best result.

4. NUMERICAL RESULTS

4.1. Power Energy Analysis

The renewable energy solution feasibility of the student dorm building has been tested through the developed model. The solutions include the examination of optimal PV panel and ES system deployment based on peak energy consumption data, and they are aimed at increasing renewable energy share and reducing the building carbon emissions.

The feasibility of renewable energy setup is addressed for each dorm individually (see Table 4). In the process, the main three limitations are taken into account as well as the individual dorm peak consumption, which represents the size of the primarily chosen element in the two examined setup types:

- Type A – prioritization of PV panel peak generation. This type primarily selects PV panel peak generation and afterwards, through the model, selects the most appropriate ES capacity matching this generation.
- Type B – prioritization of ES capacity size. This type primarily selects the ES capacity and afterwards, through the model, selects the most appropriate PV panel size to match this storage capacity.

The modelled outcomes in Table 4 are depicted in percentage from original yearly consumption metered by the smart meter system. In the modelling process, two setup types have been examined and it has been concluded that Type B setup utilisation would provide the most optimal benefit, achieving around 58 % consumption reduction with a margin of ~1 %. All results show that a significant part of the PV panel generation is stored in the ES system, highlighting the necessity of this system.

In the following KPI evaluation regarding the tested renewable setup feasibility, setup Type B is used as the compared solution in Section 4.3.

Table 4. Renewable Energy Setup

Dorm 1 (Peak 15.65 kW)	Type A PV 16 kW & ES 20 kWh	Type B PV 15.45 kW & ES 16 kWh
	Reduced: 60.278 % 26.645 % (Direct PV*) 33.633 % (Storage)	Reduced: 59.129 % 26.264 % (Direct PV*) 32.865 % (Storage)
Dorm 2 (Peak 27,29 kW)	Type A PV 27 kW & ES 13 kWh	Type B PV 3.25 kW & ES 27 kWh
	Reduced: 48.5628 % 24.444 % (Direct PV*) 24.118 % (Storage)	Reduced: 58.005 % 26.096 % (Direct PV*) 31.909 % (Storage)
Dorm 3 (Peak 26.52 kW)	Type A PV 27 kW & ES 14 kWh	Type B PV 31.20 kW & ES 27 kWh
	Reduced: 50.124 % 25.069 % (Direct PV*) 25.055 % (Storage)	Reduced: 57.921 % 26.363 % (Direct PV*) 31.558 % (Storage)
Dorm 4 (Peak 32.70 kW)	Type A PV 33 kW & ES 15 kWh	Type B PV 40.5 kW & ES 33 kWh
	Reduced: 46.772 % 24.178 % (Direct PV*) 22.594 % (Storage)	Reduced: 57.402 % 26.074 % (Direct PV*) 31.328 % (Storage)

*Direct PV – generation from PV panels used when generated.

4.2. User Awareness Analysis

Regarding user awareness, the appliances examined by the developed model have been selected based on the potential to be impacted by user awareness changes. These selected appliances and cases can be seen in Table 5, depicting the situation of Dorm 4. The values, after user awareness column, represent the test case consumption share of the dorm total consumption taken from Table 1.

Test cases addressing user awareness are carried out for each dorm on an increasing 5 % user awareness increments. This step size clearly depicts non-linear consumption impact due to high diversity in user appliance use habits. In Table 5, the main three degrees of user awareness are presented – 0 %; 50 %; 100 %. The 0 % degree represents the original consumption share without user awareness impact, while 100 % degree represents the over-exaggerated awareness, depicting the potential maximum consumption reduction in a certain case. The 50 % degree of user awareness is assumed as the achievable average awareness degree and the results at this degree are used in the evaluation (see Section 4.3).

Table 5. Appliance Cases – Dorm 4

Equipment / User Awareness, %	Fluo.* 25W (Natural lighting)	LED 10W (Natural lighting)	Fluo.* to LED	PC sleep mode	PC red. 20 %	TV red. 20 %	Kettle red. 30 %
0 %	11.9 %	4.8 %	11.9 %	33.4 %	33.4 %	15.1 %	3.7 %
50 %	8.5 %	3.4 %	8.3 %	30.4 %	30.3 %	13.5 %	3.1 %
100 %	5.1 %	2.0 %	4.8 %	26.5 %	26.7 %	12.1 %	2.6 %

*Fluo. – Fluorescent light bulb.

Across all dorms, some similarities can be addressed. Some interchangeable results are "Natural lighting over Fluorescent" and "Fluorescent to LED conversion"; these are the results of any table in the 1st and 3rd column. The interesting result that can be highlighted is the conversion to LED lighting that provides a slightly larger consumption reduction than user's more efficient use of natural lighting. It provides valuable information that a user can provide sufficient saving only by using more efficient lighting without thinking of behaviour changes themselves. Furthermore, achieving a plausible 50 % user awareness provides a theoretical 100 % achievement, which can be made by the reduction created by some users converting to LED solution and other user behaviour changes to use natural lighting more efficiently. The end result of the combined different efforts provides around the same as 100 % of the users switching to natural lighting use or 100 % of the users converting to LED solution. Another major assessment is the inefficiency of optimised kettle use; although the appliance has a large consumption while operating, the total consumption over time is quite small and across all dorms the total consumption reduction of optimised use provides only half a percentage. This result indicates that in the tested cases the optimised kettle use does not provide large consumption savings and the solution will not be included in the final assessment. Column No. 2 "Natural lighting over LED" will also not be addressed in the final assessment because these results serve a means to the lighting solution efficiency comparison and highlight the best practice outcome.

Examination of appliance efficiency impact at 50 % user awareness, 5 of the 7 simulated cases are listed by their overall consumption impact severity:

- Lighting solutions – lighting solution across all test cases provides most reduction in consumption. The largest reduction can be achieved (3.6–7.9 %) by converting to more efficient LED solutions, followed by the second largest reduction (3.4–7.6 %) through increased utilisation of natural lighting.
- PC solutions – PCs nowadays are widely used and this is especially true for university students. From the two tested cases, the most efficient reduction in PC consumption is the third best overall reduction (1.9–3.3 %) – reduced PC overall use by up to 20 %. Slightly less consumption reduction (0–3 %) is provided by the PC sleep mode use, but this solution in the overall reduction rates fourth. Sleep mode in Dorm 1 provides a 0 % change due to the lack of excessive unattended PC usage by the model users.
- TV solution – many of the conducted surveys have indicated users having not only PCs as a frequently used appliance, but also TVs. The reduced consumption for this appliance ranks last – fifth, in the overall consumption reduction, but provides an optimal reduction of around 1.5 %.

4.3. Dorm Cross-Examination

In the final examination, all four dorms are compared side by side. The comparison is observed through the selected KPIs, collected in Table 6. These selected KPIs represent the results with the largest impact on total consumption as well as give a general view. Table includes the KPI name, definition, calculation formula and represented units.

KPI resulting values are presented in Figs. 3 and 4. First five KPIs are based on the assumed achievable 50 % degree of user awareness and the 7th KPI related to renewable energy assumes the best practice from the two available setup types.

Table 6. Compared KPIs

No.	KPI	Definition	Metrics
1.	Daylight Fluorescent	User's maximum utilisation of natural lighting to substitute Fluorescent electrical lighting solutions. Action impacted by User Awareness increases the efficient energy use.	%
2.	Fluorescent to LED conversion	Improvement of efficiency through the use of a more efficient electrical lighting solution. Action impacted by User Awareness increases the efficient energy use.	%
3.	PC sleep mode	Continuous unoccupied operation of PC creates a large increase in consumption, when user does not use the PC directly. Increase in User Awareness motivates user to switch to automatic sleep mode when PC is unoccupied.	%
4.	PC use reduction	PC load can contribute to a large part of user's total consumption. Increase in User Awareness regarding energy use may lead to reduction of appliance use by prioritization of other activities or sleep mode utilisation while PC is not directly used.	%
5.	TV use reduction	TV load can contribute to a large part of user's total consumption. Increase in User Awareness regarding energy use may lead to reduction of appliance use by prioritization of other activities or appliance shutdown while TV is not directly used.	%
6.	Energy consumption [15]	This indicator corresponds to the amount of energy consumed by the end user. This consumption is calculated for a period of a single year and used to assess end user energy efficiency.	%
7.	Increase of RES share [16]	This indicator represents the degree at which household self-supplies energy by renewable energy sources. Parameter provides the ratio of self-supplied energy and total consumed, highlighting the degree of independence.	%
8.*	Carbon dioxide emissions [17]	This indicator represents the CO2 emission share of Greenhouse Gas emissions. Parameter reflects the amount of pollution.	%

* Value is assumed similar to the 7th KPI

In Fig. 3 – Dorm 1, there is a unique singled out outcome of the four involved dorms. By achieving a degree of 50 % user awareness, the overall dorm consumption from only changes in lighting solution reduces the total consumption by 15.5 %. It is a greater impact in comparison with the same solution savings of other dorms. More than half of these savings are achieved by converting current lighting solution with more efficient LED solutions (7.9 %); the other half is represented by user utilisation of natural lighting when possible (7.6 %). Additionally, unlike other dorm results, enabling PC sleep mode does not provide any consumption reduction; this does not limit the potential benefit, but in this case it is assumed that users are efficient, thereby PC sleep mode is enabled prior and no further changes can be applied. Although lighting solutions in Dorm 1 have a large potential of reducing the overall dorm consumption, the PC and TV solutions show a very low impact based on (from PC solution there is a 1.9 % reduction contribution and from TV up to 1.7 %) the dorm total yearly consumption. The percentage is large enough to provide a small impact, but in real consumption values Dorm 1 (in comparison with other three dorms) has from two to four times less consumption in a specific solution consumption reduction. The total dorm consumption reduction made by an increase in user awareness to 50 % is equal to 19 %; this is the largest reduction share, but in actual consumption values the overall reduction of Dorm 1 is two – three times smaller than the results of other dorms. Dorm 1 is also the only dorm with the highest share of increased renewable energy share (34.5 %), where the lowest result is only 1.6 % less for Dorm 4. This result (like the previous mentioned) is the largest one in share, but the smallest one in actual power, with other renewable share size being two – three times larger. Similar change in carbon emissions can be expected as the increase in renewable energy share.

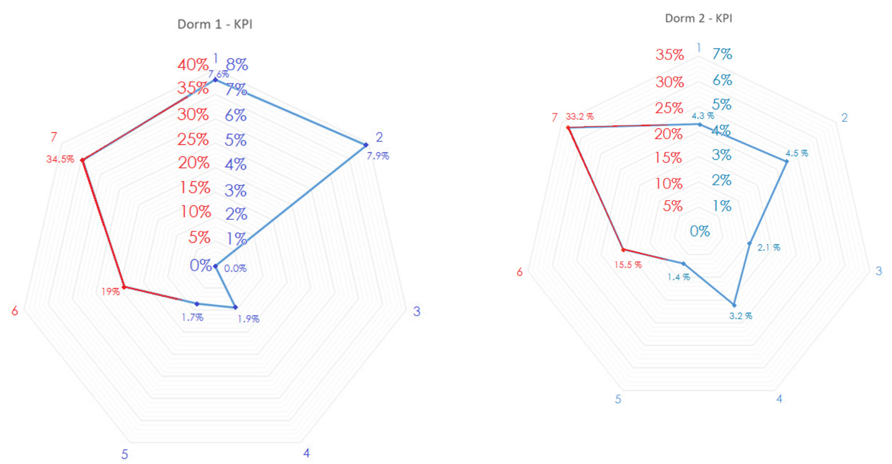

Fig. 3. KPI spider-web representation of Dorm 1 & 2.

In Figs. 3 and 4, Dorm 2 and Dorm 3 respectively represent a very similar situation. Similarities can be seen easily by the shape of the diagram itself; the two dorms share the same outline with a very small margin in values. By looking at yearly energy consumption (Table 1), more similarities can be seen with a ~3 % difference in dorm total consumption. The two situations label the middle results with no specific unique outcomes. Comparing Dorm 2 and Dorm 3, the ~3 % difference can also be seen in values 1–5, where Dorm 3 has a slightly higher percentage, but the overall yearly consumption is slightly lower as well. In the end, Dorm 2 achieves an individual consumption reduction of 15.5 % and Dorm 3 achieves 16.5 %. Although Dorm 3 achieves a 1 % larger consumption reduction, this 1 % share is equal to ~3 % in comparison with Dorm 2 in actual consumption. Thus, we can deduce that both dorms are very similar and all results have a difference of around ~3 % in actual power values. The only value that is greater for Dorm 2 is renewable energy share increase. Both dorms have the same 33.2 % increase in renewable energy share; however, Dorm 2 has slightly greater consumption that is why this share in actual values is slightly greater. The expected change in the reduced carbon emissions is around 33.2 % for each dorm.

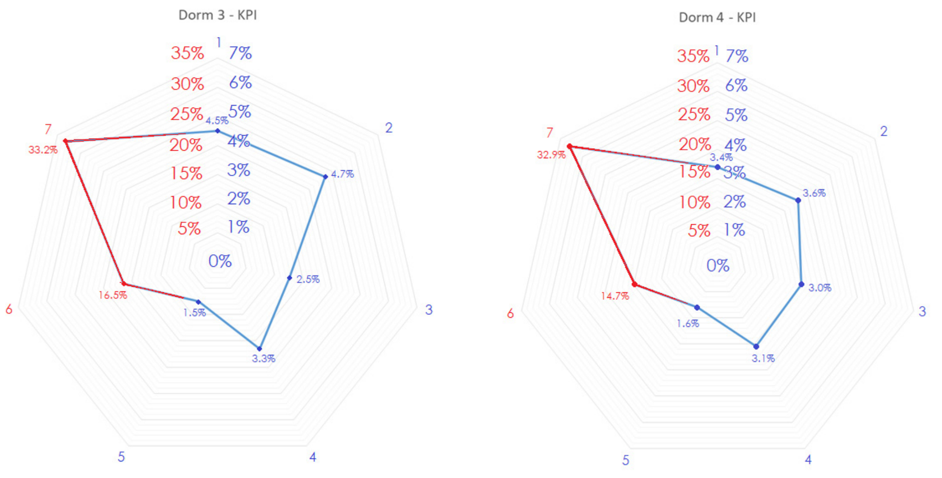

Fig. 4. KPI spider-web representation of Dorm 3 & 4.

In Fig. 4, Dorm 4 presents another unique outcome due to its large overall consumption. Dorm 4 is unique by providing some of the lowest values in categories where Dorm 1 thrives. Examining Dorm 4 lighting solutions, the largest benefit similar to other solutions is by efficient lighting solution utilisation – LED, with a 3.6 % dorm consumption reduction; this is the lowest value in share, but per user it is similar to other dorms. For prioritization of natural lighting, the dorm can achieve a consumption reduction of 3.4 %, which as prior is also the lowest of any shares, but in actual value per person the result is fairly similar. Most impressive savings in Dorm 4 are provided by utilisation of PC sleep mode with the largest share of any dorm (3 %) in dorm total consumption reduction. This value in dorm share is only 3 %, but taking into account actual consumption, where Dorm 4 consumption is three times larger than Dorm 1 or 50 % larger than Dorm 2 or Dorm 3, the value achieved provides large saving in overall consumption. The total reduction in the solutions used provides a 14.7 % overall consumption reduction, which in share values is the lowest one, but in actual power values it is the greatest value of all four dorms. Additionally, in renewable share increase, Dorm 4 has scored 32.9 %, which similarly to other share results is the lowest one among the dorms, but it is 0.5–3 times larger in actual power values. It indicates that the performed savings generated by user awareness increase and renewable energy solution provides a very large reduction in consumption in comparison with dorm large consumption and in general. The reduction in carbon emissions will be similar to the increased renewable share and due to dorm large overall consumption, it provides the greatest reduction in carbon emission in volume.

Across all four dorms, the renewable share has increased by around 33.5 % with a margin of 1 %. This share increase is based on the calculated best outcome of the two setup types concluded in Section 4.1. This "best outcome" is based on individual dorm peak load, which is assumed as the value of PV panel size or ES capacity, depending on the setup type. In general, across all dorms the overall consumption reduction of around 58 % with a margin of 1% has been achieved using prior determined superior "Type B" setup. Due to the resulting renewable energy consumption reduction, the prior known 42.7 % (Table 1) renewable share for each dorm has increased by around 33.5 %, resulting in a very large theoretical renewable energy share. Additionally, each dorm has the potential to achieve around 14–19 % reduction in the overall consumption by implementing 50 % degree of user awareness, which provides significant power savings on the part of end user. From all examined user awareness potential impact factors, the biggest power saving can be achieved in lighting solution modification, primarily from converting to more efficient light bulbs and secondly by wider utilisation of natural lighting.

5. CONCLUSION

The paper has addressed the topic of KPI evaluation on UPB student dorms through utilisation of the high-end smart meter system installed at the floor level. Taking into account the time constraints, KPI evaluation has been performed through energy consumption modelling means, and the comprehensive model has been developed using a multisource approach that has higher flexibility with its modular structure. This model is able to generate multiple individual user consumption patterns based on the information taken from consumption surveys and real smart meter measurements as a guideline. Using models flexibility has allowed simulating the impact of user awareness changes regarding a specific tested consumption case.

The developed consumption model has been used to simulate various users based on the available information of electric appliances, appliance use frequency and other preferences as well as individual user activities. Diversity in preferences and individual activity randomization has provided a large number of unique energy consumers and further grouped them together, representing the inhabitants of each dorm. The chosen group of representing inhabitants has been determined based on smart meter measurements. The representatives have been selected once and used in user awareness tests, as well as in the renewable energy setup feasibility study.

The UPB student dorm feasibility has been conducted from the user awareness perspective and renewable energy setup utilisation and depicted using KPI values. As a result of testing of renewable energy setups, it has been concluded that the superiority of "Type B" setup that prioritizes ES capacity selection is based on dorm peak load by providing most consumption reduction across all dorms. The utilisation of renewable energy setup, across all dorms, has provided an average of 58 % in energy consumption reduction and increased the individual dorm renewable share by an average of 33.5 %. Similar percentage to increase renewable share can be expected in regards to carbon emission reduction. Furthermore, by achieving degree of 50 % user awareness, the dorms have the potential to reduce their total yearly consumption by 14–19 %. The largest benefactor of user impact is lighting solutions with 3.6–7.9 % overall consumption reduction by using LED lighting and 3.4–7.6 % reduction by prioritizing natural lighting over artificial solutions.

Based on the evaluation of eight KPIs using a model approach, it has been concluded that great consumption reduction can be made on the user part and that every dorm has a great potential for reducing its individual total consumption and at the same time for increasing renewable energy share and reducing dorm carbon footprint by PV panel and ES system implementation.

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PUMPED-STORAGE HYDROPOWER PLANTS AS ENABLERS FOR TRANSITION TO CIRCULAR ECONOMY IN ENERGY SECTOR: A CASE OF LATVIA

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Nowadays the planet is facing emerging global issues related to climate change, pollution, deforestation, desertification and the number of challenges is expected to grow as the global population is forecasted to reach 10 billion margin by 2050. A concept of circular economy can have a positive contribution to the current development trajectories. In order to implement it, preferably all the energy should be produced by using renewable energy sources, but there has always been a challenge for storage of renewable energy. Therefore, considering technical and economical parameters, construction options for a pumped storage hydropower plant in Latvia have been evaluated using the desk research methodology. Results have shown that Daugavpils PSHP is the most attractive project from the technological point of view, but it requires the greatest amount of investment and construction of Daugavpils HPP. At present all the construction options for PSHP in Latvia are economically disadvantageous and would not be viable without co-financing from European or national funds. Considering both technical and economical parameters, the authors emphasise Plavinas PSHP construction option.

Keywords: *circular economy, electricity price, pumped storage hydropower plant, renewable energy*

1. INTRODUCTION

In the 21st century, the role of environment and ecology is becoming increasingly important. Climate change, water and air pollution, deforestation, desertification are problems that are directly and indirectly influencing the standard of living for a huge part of population worldwide [1]. The global population is growing and the demand for such basic needs as food, housing and transportation is also increasing. For a long time, our economy has been linear, which is characterised by a 'take-make-dispose' approach. In the long-term, it has converted the planet Earth into a landfill, as 60 % of global waste is disposed. Current development trajectories raise serious questions about the sustainability of the planet Earth and require urgent action.

A promising concept in the scientific and governmental environment on which a more sustainable world can be built is a circular economy. In 1966, American economist Kenneth Ewart Boulding drew an analogy regarding rather circular than linear flow of material resources. It reflected transformation from 'cowboy economy' characterised by endless resources and the ability to abandon problems to 'spaceship economy', where limited resources had to be reused and recycled as a precondition to sustainable life-support systems [2]. The concept aims at increasing the resource efficiency, closing resource and material loops, designing out waste, sharing products, extending the life time of products and services, decreasing the demand for resources and products and sustainable consumption. Stable national economy, favourable political environment, competitive business, intensive cooperation between the academy and business, secure social environment and other factors are governed by the regulatory framework implemented by the state, which enables the government to promote, restrict and hinder the development of the national economy [3]. Additionally, the research and development (R&D) level and the development of innovations are crucial factors for any economy that follows global trends [4]. Great emphasis regarding the development of economy is placed on the energy sector. Within the concept of circular economy, preferably all the energy should be produced from renewable energy sources. It is in accordance with the aims of the Blue Growth concept developed by the European Commission [5]. Kurzeme Region contains the greatest potential for renewable energy resource development as it has more than 350 km long Baltic Sea coast [6]. However, there are great challenges related to the storage of renewable energy. Nowadays there are such common storage technologies as electric batteries [16], electric flywheels, compressed air energy storage, superconductors, superconducting magnetic energy storage systems, as well as pumped-storage hydropower plants (PSHPs). New ways of electric energy storage, such as using electric batteries of electric vehicles are considered [17]. As long as the PSHPs are linked to 99 % of the globally installed capacity of energy storage facilities, they have the greatest influence on the energy sector and the greatest potential in providing benefits [7; 18].

If major trends in the era of energy transition, which determine the pathways for technological development, are being discussed, then decarbonisation, increased share of intermittent renewables and changing role of conventional fossil generation should be noted. As a result, there is an urgent need for efficient and competitive storage technologies. Solutions for these challenges are developed via sector coupling and power-to-X. Sector coupling refers to the idea of interconnecting the energy consuming sectors – buildings (heating and cooling), transport, and industry – with the power producing sector via increased electrification, e-hydrogen (power-to-gas) and e-fuels (power-to-fuel) [8]. In the power-to-X equation, X can refer to a number of things: power-to-ammonia, power-to-chemicals, power-to-heat, power-to-hydrogen, power-to-liquid, power-to-fuel and power-to-gas, etc. [9]. At this point, the greatest emphasis is placed on power-to-fuel and power-to-gas to decarbonise global economy. This is a great example of circular economy.

Developing the energy sector, especially its core industry electricity, new tasks are emerging, including integration of renewable energy resources into power systems. Performing these tasks ensures more efficient and stable electricity generation, transmission and distribution. A significant part of these tasks can be carried out by pumped-storage hydropower plants (PSHPs), thus removing load from production facilities.

The most important renewable energy resources for electricity supply are solar and wind energy, as they have already proven to be the most appropriate among other renewable energy sources. Surplus power from wind farms and solar power plants could be used to pump water from the lower reservoir to the upper reservoir, so that during periods of power shortage PSHP could operate in turbine mode and generate electrical power covering the demand. However, these two types of renewable energy in terms of their unpredictable and unstable nature create challenges for power systems.

Electricity demand is uneven every 24 hours. The greatest electricity demand is in daylight and in the evening. Night is the time when most businesses do not work and electricity demand is not so great. Based on economic demand and supply law, it follows that electricity is relatively more expensive during the daytime compared to the night hours. The difference in the electricity price can be used by PSHPs.

PSHPs consume relatively cheap electricity during the night to pump water from the lower reservoir to the upper reservoir. However, during the day when electricity is relatively expensive, water flows from upper reservoir to lower reservoir through the turbine and produces electricity that can be delivered to consumers. In this way, PSHPs equalize daily load schedule and, based on electricity price difference at different times of the day, obtain economic benefits. Additionally, PSHPs play a major role in power regulation of nuclear power plants. Power generation in nuclear power plants cannot be easily stopped. Power capacity of nuclear power plants could not be reduced easily even in night time when electric demand of power system is lower. Excess power could be used to drive pumps of PSHPs. During the day when demand is growing, stored water in an upper pool of PSHP could be used to produce electricity in turbine mode. Therefore, the PSHP is used to provide the base mode for nuclear power plants. For example, Kruonis PSHP, which is closest to Latvia, was built as support for the Ignalina nuclear power plant.

Use of PSHPs for various applications in many cases could be more economically viable than if the same tasks were performed by conventional power plants. The use of storage technologies would also reduce the environmental impact of power plants, which is currently one of the priorities in a large part of the world.

The main goal of the paper is to evaluate possible construction of a pumped-storage hydropower plant in Latvia and its contribution to Latvia.

The construction of PSHPs requires large investment, and the payback period is approximately 30 years. Considering these factors and the fact that economic growth of Latvia is limited, implementation of all projects would be impossible, so the authors of the article using the desk research methodology will compare the options of PSHPs and recommend one of the previously investigated projects (Daugavpils, Plavinas or Riga) that would be most beneficial to implement. Analysis of technological indicators will be carried out based on the developed projects. Economic indicators will be analysed based on the Nord Pool electricity prices.

2. PUMPED-STORAGE HYDROPOWER PLANTS

In the beginning, the authors would like to provide a review of the advantages and disadvantages of PSHPs (see Table 1). Advantages of PSHPs are long service life, low losses of energy storage, relatively high efficiency (70–85 %) comparing to other energy storage technologies and the ability to install very large storage capacity. The main efficiency losses are related to gravity force, which needs to be overcome when pumping water from lower reservoir to upper reservoir. On the other hand, implementing a PSHP project takes long planning and construction time, specific geographical conditions that may be limited according to environmental constraints. Large amount of initial investment and long payback period are PSHP development hindering factors as well.

Table 1. Advantages and Disadvantages of Pumped-Storage Hydropower Plants (developed by the authors)

Advantages	Disadvantages
Long service life	Long planning and construction time
Low losses	Specific geographical conditions for upper reservoir and lower reservoir
Relatively high efficiency	Low power and energy density
Ability to install very large storage capacity	Large amount of initial investment
	Long payback period

In order to exploit the benefits of advantages of PSHPs, it is important to understand if electricity prices can ensure profitability of PSHPs.

3. WIND POWER GENERATION AND ELECTRICITY PRICE ANALYSIS

Produced energy by solar panels and wind generators, which are installed in the territory of Latvia, is directly dependent on the number of sunny and windy days during the year. It is hard to forecast the amount of energy produced by these technologies, especially with the increasing influence of climate change.

Figure 1 shows the estimated wind power and actual wind power from 8 July 2019 to 14 July 2019, which confirms the unpredictability (average relative error – 50.6 %; maximum relative error – 200 %) of this renewable energy source and proves the need of the energy storage system. It would be useful to use PSHPs, and the Daugava River with its hydroelectric power plants has good potential for the development of PSHP in Latvia.

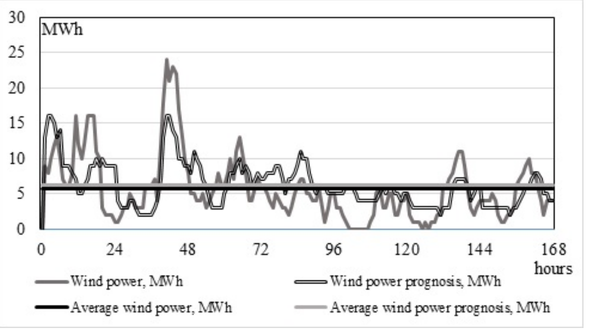

Fig. 1. Wind power and wind power forecast from 8 July 2019 to 14 July 2019 (created by the authors from [10] and [11]).

Based on average electricity prices in Latvia in different times around the clock, the construction of PSHP in Latvia is supportable. Taking into account that average efficiency of PSHP is 77.5 %, the price difference should be at least 22.5 % to make the use of PSHP profitable. This price difference will be sufficient to cover operational expenses of PSHP. In reality the price variation shall be even higher to cover investment costs. Figure 2 illustrates that the lowest average price in 2018 has been between 3 am and 4 am (37.39 EUR/MWh), but the highest average price has been observed between 9 am and 10 am (60.07 EUR/MWh). The 37.8 % difference between these prices can be used by PHSPs. Considering the fact that PSHPs would need more than 1 hour in turbine and pump mode, the authors have calculated the price difference between average price at night (from 11 pm to 6 am) – 39.07 EUR/MWh and average price during the day time (from 7 am to 9 pm) – 56.09 EUR/MWh. Calculations have shown the price difference of 30.3 %.

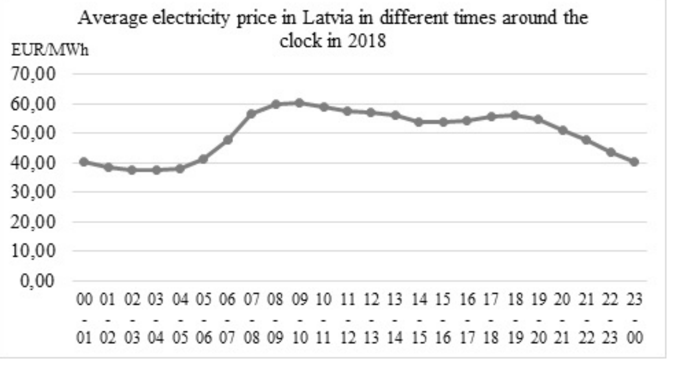

Fig. 2. Average electricity price in Latvia in different times around the clock in 2018 (created by the authors from [12]).

Considering electricity prices and the expected development of wind and solar energy systems, the authors can state that during periods of high wind power and solar power, electricity prices could be very low, but during cloudy and windless days electricity prices could be high.

Taking into account the unpredictability of wind power and average electricity prices in Latvia, further research regarding construction options of PSHP in Latvia has been carried out.

4. RESULTS AND DISCUSSION

The authors have compared 3 PSHP construction options in Latvia – Daugavpils PSHP, Pump station combined with planned emergency spillways of Plavinas HPP (Hydroelectric Power Plant) (Plavinas PSHP) and Pump station near Riga HPP (Riga PSHP).

1) Daugavpils PSHP

In 1986, the proposal for Daugavpils PSHP was made by project institute 'Hydroproject'. The idea for the construction of the PSHP was related to the Daugavpils hydro HPP construction, which was already underway. It allowed using a construction base located near Daugavpils, equipment and personnel after commissioning of Daugavpils HPP in 1990. These conditions allowed starting construction close to HPP. The construction location (see Fig. 3) was picked 8 km from Daugavpils HPP, which provided conditions to use the reservoir of Daugavpils HPP as lower reservoir of Daugavpils PSHP. The two following Daugavpils PSHP options were presented: 1) installed power of 1574 MW and 10 Francis (reverse) hydro units; and 2) installed power of 1260 MW and 8 Francis hydro units [13].

However, the authors offer construction options with 5 or 4 hydro units, which are technologically and economically more feasible under current conditions of the Latvian energy sector.

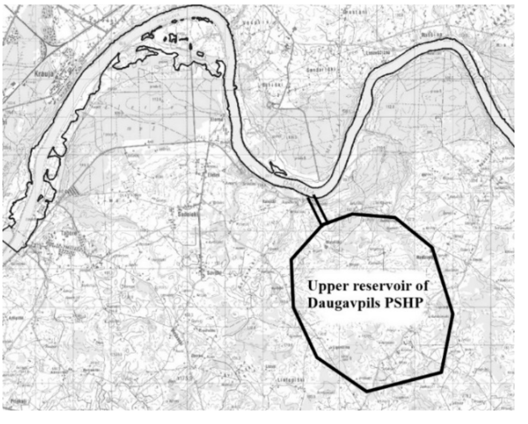

Fig. 3. Planned location of Daugavpils PSHP.

It should be stated that the planned location of Daugavpils PSHP is within the territory of Nature Park "Daugavas loki", where the construction and other economic activities are limited.

2) Pump Station combined with planned emergency spillways of Plavinas HPP (Plavinas PSHP)

Plavinas PSHP is designed to store potential energy by pumping water from Kegums HPP reservoir (lower reservoir) to Plavinas HPP (upper reservoir). Plavinas PSHP is based on a pump station built into emergency spillways of Plavinas hydroelectric power plant [14]. The necessity of emergency spillways at Plavinas HPP was emphasised already in 1994 and its main objective would be to increase the dam safety level of Plavinas HPP. Probable Maximum Flood (PMF) flow in the dam of Plavinas HPP with the probability of 1 in every 10000 years is 12600 m^3/s. Existing spillways of Plavinas HPP dam has the throughput of 8640 m^3/s at the highest permissible level in the reservoir (73.3 m above sea level). In this case, there is a 3960 m^3/s shortage in the throughput of the Plavinas HPP dam that justifies the construction necessity of emergency spillways. It could also be used if smaller floods need to be drained and it can operate independently.

Figure 4 illustrates optimal deployment of the emergency spillways of Plavinas HPP.

Fig. 4. Optimal deployment of the emergency spillways of Plavinas HPP [14].

The main environmental impacts from Plavinas PSHP project implementation are linked to migration disturbance of living organisms to certain areas and creation of additional erosion in the Daugava. Overall, no significant negative environmental impacts were identified that could prohibit the planned construction [14].

3) Pump Station near Riga HPP (Riga PSHP)

According to the Latvenergo Riga PSHP assessment in 2012, the construction of a separate pumping station is considered to be the most efficient option. Hydro units of Riga hydroelectric power plant would be used to generate electricity [15].

Figure 5 shows the potential locations of the pumping station – 1) the left side of Riga HPP reservoir, near the Dry Daugava (Pumping station 1); 2) near the dam of Riga HPP, right coast of the Daugava (Pumping station 2).

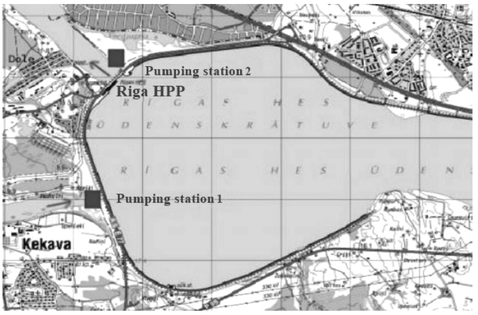

Fig. 5. Potential location of Riga PSHP pump stations [15].

In case of constructing pumping station 1 on the left coast of the Daugava, water pumping would be done for 8 km via Dry Daugava, which is the left tributary of the Daugava, separated from the water course by Dole Island. This pump station construction option would require 8 km deepening of the water course, which would significantly increase the required investment of the Riga PSHP project. However, if the pumping station were built on the right coast of the Daugava (Pumping station 2), the amount of water available for pumping would be over 20 million m^3, which could provide a pumping station with a flow rate of 160 m^3/s for more than 24 hours, allowing to conclude that the flow of water would compensate the pumping of water [15].

The potential Riga PSHP pump station deployment is close to the territory of Nature Park “Doles sala”, where the construction and other economic activities are limited. Construction of pump station could create adverse effects on coastal erosion, biodiversity, geological processes and safety of current hydrotechnics [15].

4) Overview

The authors have compared technical and economic parameters of 3 PSHP construction options in Latvia – Daugavpils PSHP, Pump station combined with planned emergency spillways of Plavinas HPP and Pump station near Riga HPP.

Table 2 reflects technical parameters of Daugavpils, Plavinas and Riga PSHP construction options. The greatest installed power in the pump (826 MW) and turbine (630 MW) mode is linked to the Daugavpils PSHP construction option, which can be justified by the fact that water head (73 m) in this option is the greatest as well. Plavinas PSHP installed power in turbine mode is 8 MW higher than the installed power of Riga PSHP in turbine mode. Water consumption in turbine mode is lower than water consumption in pump mode for all construction options due to gravitational force that must be overcome when pumping water. In the option of Daugavpils PSHP, it is planned to build a pumped-storage hydropower plant with an upper reservoir and 4 reverse hydro units, but in the case of Plavinas and Riga PSHP construction options it is planned to build a pumping station with 2 and 5–7 pumps, respectively. The lowest specific water consumption is in the case of Daugavpils PSHP. It is explaned by the highest water head.

Table 2. Comparison of Technical Parameters of PSHP Construction Options in Latvia (developed by the authors)

	Daugavpils PSHP	**Pump station combined with planned emergency spillways of Plavinas HPP**	**Pump station near Riga HPP**
Installed power in pump mode (MW)	826	36.2	28.2
Installed power in turbine mode (MW)	630	90	64.7
Number of hydro units/ pumps	4 hydro units	2 pumps	5–7 pumps
Water head (m)	73	35	14
Efficient water volume (million m^3)	20.76	25.23	41
Water consumption in pump mode (m^3/s)	960	80	159.3
Water consumption in turbine mode (m^3/s)	968	262	478
Specific water consumption in pump mode ($m^3/MW*s$)	1.16	2.21	5.65
Specific water consumption in turbine mode ($m^3/MW*s$)	1.54	2.91	7.39

Table 3 reflects economic indicators of PSHP construction options in Latvia. Daugavpils PSHP construction option has the largest consumed and produced amount of electricity, which also generates the highest profit, but the investment is more than 30 times greater than the planned investment for Plavinas PSHP, where only the construction of a pumping station is planned. The operating costs for the Daugavpils PSHP construction option are also the highest ones. If 85 % of the investment were to be covered by co-financing from European or national funds, Daugavpils PSHP construction option would pay off in 27 years, Plavinas – in 26 years, but Riga – would not pay off even in 50 years. Electricity consumption and production volumes of different PSHP options were estimated based on simulation of PSHP hourly operating modes. For evaluation of annual revenue values Nord Pool electricity price variations were taken into account.

Table 3. Comparison of Economical Parameters of PSHP Construction Options in Latvia (developed by the authors)

Economic indicator	**Daugavpils PSHP**	**Pump station combined with planned emergency spillways of Plavinas HPP**	**Pump station near Riga HPP**
Consumed electricity in pump mode (GWh)	2205	107	69
Produced electricity in turbine mode (GWh)	1695	85	52
Annual electricity generation costs (million EUR)	74.471	3.665	2.310
Annual revenue (million EUR)	87.014	4.343	2.679
Annual profit (million EUR)	12.543	0.678	0.369
Approximate volume of investment (million EUR)	740.516	23.136	28.227
Investment if 85 % is financed by the government or the European Union (million EUR)	111.077	3.47	4.23
Operating costs (million EUR)	3.7	0.4	0.2
NPV (million EUR)	14.16	0.493	-1.203
IRR (%)	9.1	9.2	5.5
Payback period, if 85 % of investment is subsidized (years)	27	26	>50

The authors have carried out the comparison of advantages and disadvantages of PSHP construction options in Latvia (see Table 4). Advantages of Daugavpils PSHP construction option are the most appropriate water head of 73 metres and planned reverse aggregates, which are common all over world. However, the construction of Daugavpils PSHP construction option can be carried out only if Daugavpils HPP is built before that. Additionally, 85 % co-financing from the Latvian government or the EU is required to ensure the payback period of 27 years. Implementation of pump station near Riga HPP (Riga PSHP) would require smaller investment volumes compared to Daugavpils PSHP, but there would be several disadvantages – the lowest water head of all 3 construction options, lack of global practices where PSHP is constructed as a pump station that is built next to the HPP, potential higher required investment if a pump station is constructed near Dry Daugava and possible Riga HPP level restrictions related to the operation of Riga port. Taking into account projected energy prices, all three PSHP construction options are economically disadvantageous.

Table 4. Comparison of Advantages and Disadvantages of PSHP Construction Options in Latvia

Construction option	**Advantages**	**Disadvantages**
Daugavpils PSHP	• The most appropriate water head for PSHP construction in Latvia (73 m) • Construction of PSHP is planned with reverse aggregates, which are common all over world • The lowest specific water consumption, which is explained by the highest water head	• To implement Daugavpils PSHP construction project, there is a necessity to build Daugavpils HPP before that • 85 % of co-financing from Latvia and the EU is required to ensure the payback period of 27 years • Taking into account the estimated energy prices, Daugavpils PSHP construction is economically disadvantageous without co-financing
Pump station combined with planned emergency spillways of Plavinas HPP	• Smaller investment volumes compared to Daugavpils PSHP • Water head is 2 times greater compared to Riga HPP • Efficient use of emergency spillways	• To build a pump station combined with planned emergency spillways of Plavinas HPP, there is a necessity to build emergency spillways of Plavinas HPP • There is a lack of global practices where PSHP is constructed as a pump station that is built next to the HPP • Taking into account the estimated energy prices, Plavinas PSHP construction is economically disadvantageous without co-financing
Pump station near Riga HPP	• Smaller investment volumes compared to Daugavpils PSHP	• Lowest water head out of all 3 construction options • There is a lack of global practices where PSHP is constructed as a pump station that is built next to the HPP • Pump station construction option near Dry Daugava would require 8 km deepening of the water course, which would significantly increase the required investment • Possible Riga HPP level restrictions related to the operation of Riga port • Taking into account the estimated energy prices, Riga PSHP construction is economically disadvantageous even with co-financing

Considering the advantages and disadvantages of PSHP construction options in Latvia, the authors would recommend the construction of Plavinas PSHP.

4. CONCLUSIONS

Having conducted the present research, the authors have come to the following conclusions:

1. Latvia currently does not have cheap base power sources that can be used for night-time pumping, so this power would have to be imported. In the future with growth of solar and wind capacity, this source of cheap electricity for water pumping will appear.
2. During peak hours, the existing Daugava HPP cascade could be used in Latvia. Therefore, the capacity of the Latvian PSHP should be offered in the Baltic market, competing with the Kruonis PSHP.
3. The need for Latvian PSHP in the future could be determined by the increasing capacity of wind and solar power plants.
4. None of the PSHP projects (Daugavpils PSHP, Pump station combined with planned emergency spillways of Plavinas HPP, Pump station near Riga HPP) is economically advantageous taking into account the current market situation. The EU or national co-financing of 85 % is required for projects to be viable.
5. From the technical point of view, taking into account the most appropriate water head, the best option is the construction of a new Daugavpils PSHP. However, this construction option is feasible only in case if the Daugavpils HPP is built. Daugavpils PSHP construction option is the most expensive one (740.5 million EUR), but the PSHP would have the largest installed power (630 MW).
6. The construction of a pump station at the emergency spillways of Plavinas HPP is the best construction option from the economic point of view and the authors recommend this option as the most suitable one for construction of the Latvian PSHP. Plavinas PSHP construction option has the lowest amount of investment, average (among 3 construction options) water head, and it provides opportunity for efficient use of emergency spillways. However, this project could be implemented only if emergency spillways are constructed.
7. The construction of a pump station at Riga HPP could make operation of the Port of Riga more difficult and could cause ecological problems for the Dry Daugava. Water head of this construction option is also the smallest, which determines the largest amount of water that needs to be pumped in order to obtain the same generator power (compared to Daugavpils PSHP).
8. Even though the case of Latvia for construction of PSHP has proven to be economically disadvantageous, the construction of PSHP in other countries worldwide should be considered in order to create opportunities for integration of renewable energy sources into energy systems and promote transition to circular economy.

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ELECTROCHEMICAL DETECTION OF SMALL VOLUMES OF GLYPHOSATE WITH MASS-PRODUCED NON-MODIFIED GOLD CHIPS

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Mass-produced printed circuit board (PCB) electrodes were used as electrochemical cells to detect the widely-used herbicide glyphosate. Square wave voltammetry (SWV) was used to determine the presence of glyphosate in aqueous $Cu(NO_3)_2$ solution. Optimal measurement conditions for the detection of glyphosate with PCB electrodes were found. It was determined that glyphosate was able to soak into the growing plants from the substrate. Glyphosate-contaminated plant juice was distinguished from control samples using the PCB electrode. Glyphosate-contaminated plants were found to have DNA mutations.

Keywords: *electrochemical, glyphosate, printed circuit board, sensor, square wave voltammetry*

1. INTRODUCTION

Glyphosate is the widely-used herbicide considered to have low toxicity, and it is widely used in agriculture [1]. However, ingestion of glyphosate leads to a large number of health issues, including respiratory malfunction, altered consciousness, increased cancer risk, and death [2]–[4].

It is necessary to develop reliable glyphosate detection methods since modern laboratories frequently fail to detect glyphosate in food products [5]. Electrochemical methods are widely used to determine various chemical substances present in solutions, ranging from simple ion detection [6] to complex biological molecule detection [7]. Several electrochemical approaches have been developed in the past two decades [8]. Copper electrodes have shown potential for selective detection of glyphosate in liquids [9]–[11]. Several researchers have suggested that glyphosate can form water-soluble complexes with copper ions

[12]–[13]. Since copper ions by themselves can be detected with electrochemical methods, it is possible to use Cu^{2+} containing buffer solutions to indirectly detect glyphosate from the change in copper ions electrochemical activity.

Since glyphosate is a widely-used herbicide, it is necessary to develop an easy-to-use and cheap method for controlling glyphosate levels at farming sites. An easily available approach for electrode mass production is printed circuit boards (PCBs) since they can be produced at factories throughout the world in large quantities for low cost, and most of the factories can offer electrode-surface coating with gold, making them chemically neutral. PCB electrodes can also be suitable for small liquid volumes, making it possible to run an electrochemical analysis of a 10-µL drop. This greatly reduces the number of the necessary sample preparation steps and the amount of chemicals used in the analysis. There is no need for electrode-surface modification since glyphosate can be detected indirectly by electrochemical quantification of Cu^{2+} ions. In this paper, PCB gold-coated electrodes were used to indirectly detect glyphosate in solution using the described method.

2. EXPERIMENTAL

2.1. Reagents and Materials

Reagents used in the research were the following: copper nitrate trihydrate (99.9 % pure, purchased from Lach-Ner), commercial glyphosate-based herbicide (containing 360 g/L of glyphosate izopropylamine), 97 % ethanol, and distilled water.

2.2. Mass-Produced Au Chip

In place of an electrochemical cell, a mass-produced PCB chip was used. The working area of the chip consisted of 8 copper electrodes covered in gold via the ENIG process, on an FR-4 glass-reinforced epoxy laminate. Each of the electrodes had an individual copper track connected to it, allowing for versatile electrode configuration. All tracks were covered in a protective dielectric polymer. The final product can be seen in Fig. 1. The electrodes were designed to each have a rectangular-shaped 150 x 125-µm exposed gold-covered area. The electrochemical measurements were made using a Zanher Zennium Electrochemical Workstation in square wave voltammetry (SWV) mode, using chip as a three-electrode electrochemical cell.

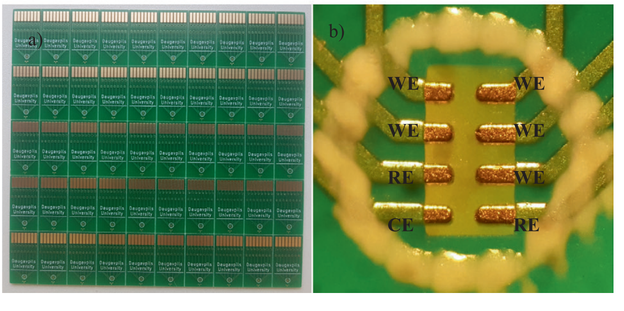

Fig. 1. a) Mass-produced PCB chips with Au-coated electrodes. b) Chip electrode configuration. WE=working electrode, CE=counter electrode, and RE=reference electrode. The diameter of the white ring is 1 mm.

2.3. Sample Preparation

Prior to electrochemical measurements, PCB chips were washed in ethanol and cleaned with a nitrogen jet to free the working surface of any production-process residue. In the first experiment, commercial glyphosate was mixed in copper nitrate buffer to the desired concentration. Then, after a delay of 30 minutes, 10 µL drops of the resulting solution were placed on the chip working-area and measured via SWV. A new chip was used for each separate drop; however, all used chips were from the same batch. In the second experiment, plant juice was extracted by crushing plant tissue and filtering the resulting mass through coarse mesh. The extracted juice was then mixed with copper nitrate buffer, centrifuged after a 30-minute delay, and the resulting solution was separated from the solid residue. This solution was then placed on the chip working area in 10-µL drops and measured via SWV.

2.4. Molecular Studies

Genomic DNA was extracted from samples (n=60) of fresh, 7-day-old rye plant seedlings treated with 1/10 of the working concentration of glyphosate (n=30) and without it (n=30). Extraction was done with slight modification using the purification of total DNA from plant tissue Mini Protocol (DNeasy Plant Mini Kit, Qiagen GmbH, Hilden, Germany). The genomic DNA was quantified using a spectrophotometer (NanoDrop 1000, Thermo Scientific, Waltham, the USA) to measure absorbance at 260 nm, and the purity of the DNA was determined. Stock DNA was diluted to make a working solution of 50 ng/μL for further PCR analysis.

Five random amplified polymorphic DNA (RAPD) primers, OPA-02, OPA-07, OPA-11, OPD-18, and OPN-15 (Table 1), were selected for the study. PCR reactions were carried out in a thermocycler (Veriti 96-WellThermal Cycler, Applied Biosystems, Foster City, the USA). All PCR reactions were prepared as described in [14]. RAPD fragments were separated, and the product length was detected using the QIAxcel (Qiagen GmbH, Hilden, Germany) capillary automated electrophoresis system. The amplification reaction for each primer was repeated twice for each sample to ensure reproducibility. Only clear and reproducible bands were considered for the analysis.

Table 1. Sequences of the 10-mer Primers (5'–3') Used in the Experiments

Primer ID	**Sequence (5'–3')**
OPA-02	5'- TGCCGAGCTG-3'
OPA-07	5'-GAAACGGGTG-3'
OPA-11	5'-CAATCGCCGT-3'
OPD-18	5'-GAGAGCCAAC-3'
OPN-15	5'-CAGCGACTGT-3'

3. RESULTS AND DISCUSSION

3.1. Glyphosate Detection in Copper Nitrate Buffer Solution

Due to the extremely small electrode surface area (approximately 1.88×10^{-8} m^2 for a single electrode), to obtain significant current through the cell, a buffer with relatively high copper nitrate concentration is required. However, higher copper nitrate concentration leads to a higher glyphosate detection threshold since a less relative change in Cu^{2+} ion concentration is induced by the same glyphosate concentration. The optimal buffer was determined to be a 15 mmol/L $Cu(NO_3)_2$ solution in deionized water.

The SWV results for the detection of glyphosate in 15 mmol/L $Cu(NO_3)_2$ buffer can be seen in Fig. 2. It should be noted that the current was normalised to the maximum current value. As the measurements have shown, the maximum-current peak-amplitude corresponds to the 0 mmol/L glyphosate control solution. The potential of the main peak from the SWV curve drifts with changes in glyphosate concentration. This could be caused by the change in the pH value of the solution, as the glyphosate is acidic, and measurements are done in a non-controlled pH environment. The peak at 50–300 mV is reported to be caused by the reduction of Cu^{2+} ions [9], and it is easy to notice since this peak has the biggest amplitude. Figure 2b shows the main peak amplitude versus glyphosate concentration. In the 0–1.5 mmol/L range, the peak amplitude drops linearly as the concentration increases and the cell becomes saturated. There is no change in the peak amplitude for concentrations greater than 1.5 mmol/L. This behaviour is approximated by the line in Fig. 2b. The reduction in the main-peak amplitude can be explained by passivation of the electrode surface by the glyphosate/Cu^{2+} complex [9].

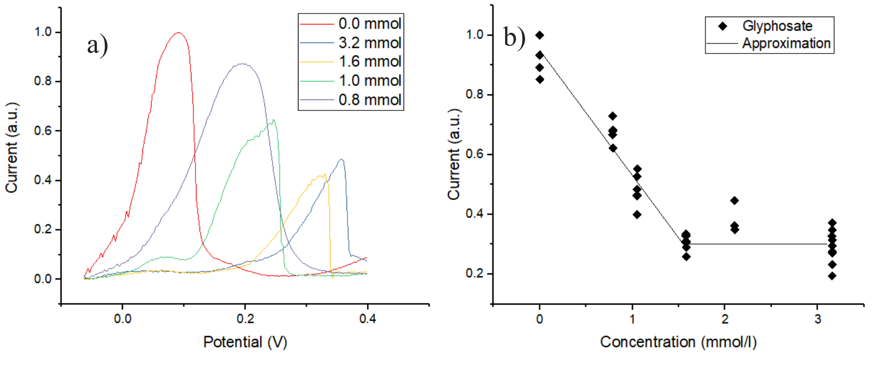

Fig. 2. a) The square wave voltammetry (SWV) results for the detection of glyphosate in copper nitrate solution. b) The main-peak maximum from SWV versus glyphosate concentration. The potential was measured relative to the on-chip Au reference electrode.

3.2. Glyphosate Detection in Grown Plants

Rye, wheat, and barley plants were grown to 6-cm long grass, then treated with a 1:10 dose of glyphosate and allowed to grow for additional 5 days. Plant juice was collected and mixed with a small amount of highly-concentrated copper nitrate buffer to achieve 15 mmol/L resulting copper nitrate concentration in the solution. The SWV measurement results of the samples can be seen in Fig. 3. The control plant juice did not change the SWV curve shape, and the SWV curve for the control plants with no glyphosate treatment was similar to the curve obtained from copper nitrate solution in deionized water. However, plants that underwent glyphosate treatment showed a slight reduction in the main-peak amplitude of the SWV curve. As can be seen from Fig. 3b, samples from the control and glyphosate groups formed two distinct distribution clouds. It is possible to distinguish glyphosate-containing plant juice since the main peak value is less than 0.9 a.u.

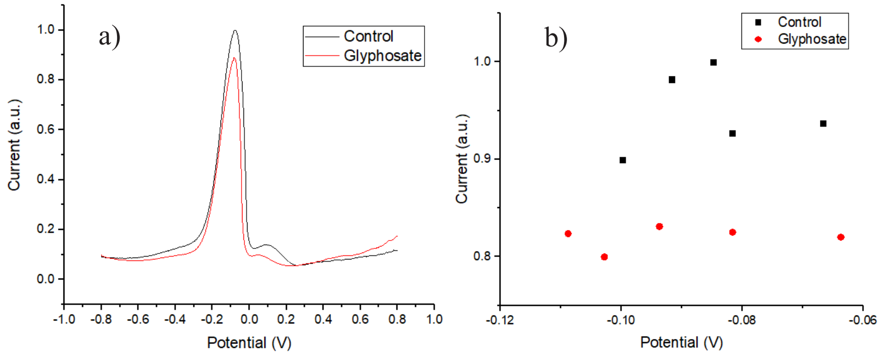

Fig. 3. a) Averaged SWV curve for rye samples.
b) The main-peak potential and current for rye samples.

3.3. Molecular Studies

The RAPD technique, a PCR-based technique, has been shown to successfully detect genotoxicity from DNA in plants [15]–[17]. RAPD analysis is capable of detecting temporary DNA changes and is considered more sensitive than classic genotoxic tests, i.e., the comet or micronucleus assay [18]. Moreover, RAPD profiling is successfully used for evaluating the genetic effects of glyphosate on plants [19], [20]. The evident changes observed in the RAPD profiles, such as disappearance and/or appearance of bands in comparison with untreated control samples, were evaluated and considered to be genotoxic changes. Treatment of rye plant seedlings with 1/10 of the working concentration of glyphosate for 5 days resulted in changes in the RAPD profiles obtained from the exposed plants. RAPD profiles of the plants showed the disappearance of a normal band and the appearance of a new band in comparison with the control. Differences in the DNA banding pattern between control samples and samples treated with glyphosate were significant and were detected at different places with all utilized primers. All obtained DNA bands were polymorphic. The RAPD profiles obtained from the five oligonucleotide primers are presented in Table 2.

In total, among all primers in the control samples, 27 fragments were detected. Samples treated with glyphosate showed 15 new bands, and 12 bands were eliminated in comparison with the samples without treatment. According to the literature, the disappearance of normal bands can probably be designated as DNA damage through modified bases, point and deletion mutations, and single and double strand breaks, whereas new bands generally reveal a change in some oligonucleotide priming sites due to mutations, large deletion, and/or homologous recombination [18], [21], [22]. Overall, the RAPD results indicate that 1/10 of the working concentration of glyphosate caused significant changes in the genome of the rye plant seedlings.

Table 2. RAPD Profiles from Rye Plant Seedlings without Treatment (Control) and Treated with Glyphosate

Primers ID	Fragment length, bp		Primers ID	Fragment length, bp	
	Control	Glyphosate		Control	Glyphosate
OPD-18	– 345 355 424 – 445 – 561 – – 972 – 1203 1217 – – 1314 – – 2612 2716	339 349 358 419 434 441 549 559 827 873 – 1049 1209 – 1275 1290 1305 2573 2590 – –	OPA-11	512 2650 2736	514 – 2740
			OPN-15	– 2741	285 –
			OPA-07	213 276 505 514 – – – 2593	– – 507 524 1264 1280 2762 –
			OPA-02	– 616 659 1060 1094 1449 2911 2924	602 615 659 – 1099 – 2913 –

4. CONCLUSION

Glyphosate can be successfully detected in both distilled water and plant juice indirectly by adding a Cu^{2+} ion source to the solution and detecting changes in ion electrochemical activity. Glyphosate presence in plant juice was also confirmed by investigation of the plant DNA. The described method provides a fast and cheap way to control glyphosate usage in the field. Since PCB electrodes are easy to mass produce, electrochemical analysis can be done in a mobile lab, and required chemicals are common. Due to consistent reduction in the main peak amplitude from the SWV, glyphosate-contaminated samples can be easily distinguished from non-contaminated samples, and the glyphosate tests can be automated.

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THE FABRICATION OF NATURAL ZEOLITE VIA CO-PRECIPITATION METHOD AS Cu, Pb AND Zn METAL ABSORBENT

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Heavy metal waste is very dangerous, which can change the condition of water into a solid substance that can be suspended in water and can reduce the cleanliness level of water consumed by living things. To date, heavy metals can be managed through several processes, namely physics, biology or chemistry. One of the ways to overcome heavy metal pollution is to use natural zeolite applying a co-precipitation method, as it is known that zeolite is a powerful natural material to be used for certain purposes. In order to justify the research results, several analyses have been performed, such as X-Ray Diffraction (XRD), Scanning Electron Microscopy (SEM), Surface Area Analyser (SAA), and Atomic Adsorption Spectrophotometric (AAS). From the XRD results, it has been found out that the size of each zeolite with variations in size of 150 mesh, 200 mesh, and 250 mesh is 29.274 nm, 38.665 nm and 43.863 nm, respectively. Moreover, the SEM-EDX has shown that the zeolite under consideration is a type of Na-Zeolite and that the co-precipitation method successfully removes impurity elements, namely, Fe, Ti, and Cl. The results of SAA testing have indicated that the total surface area for each variation of zeolite sizes is 63.23 m^2/g, 45.14 m^2/g and 59.76 m^2/g. The results of the AAS test analysis have demonstrated that the optimal absorption of metal content is observed in a size of 150 mesh zeolite with adsorption power of 99.6 % for Pb metal, 98 % for Cu metal, and 96 % Zn metal.

Keywords: *Co-precipitation method, metal adsorbent, natural zeolite*

1. INTRODUCTION

Aquatic environment pollution caused by heavy metals is transforming into a serious problem in public health and significant environmental issues. Mining activities, household waste liquids, industrial waste and agricultural waste are reported to be the main contributors to pollute the aquatic environment [1]–[4]. Natural zeolite is formed due to the existence of complex chemical and physical processes from rocks, which experience various kinds of changes in nature. Geochemists and mineralogists estimate that zeolites are frozen volcanic products, which then turn into volcanic rocks, sedimentary rocks and metamorphic rocks. Then, they subsequently undergo weathering due to the effects of heat and cold. Zeolite structures can be divided into three components, namely, alumino silicate frame, empty space interconnected containing metal cations and water molecules in the occluded phase [5].

One way to overcome heavy metal pollution is by applying natural zeolite. Zeolite is commonly used as a catalyst in various acid catalyst reactions [6]–[9]. The adsorption method is an alternative method to minimize the presence of pollutants in the environment [10]–[14]. Moreover, by synthesizing the zeolite via co-precipitation method and combining it with the acid, such as hydrochloric acid (HCl), it can give a significant effect, since hydrochloric acid is known as an acid capable of dissolving inorganic compounds [15], [16].

The co-precipitation method is a bottom up synthesis method that is used to obtain small nanometer sized particles [17]. This method has the principle of removing the continuous bond that is owned by a metal compound in the form of liquid without considering the specific mechanism that occurs. By using the co-precipitation method, a solid material is obtained from its aqueous precipitate [18].

Finally, it is necessary to investigate and research an active natural zeolite to be more optimal and efficient in its performance as an adsorbent. This adsorption property will be focused on removing metals as pollutants such as copper (Cu) and lead (Pb). Adsorption has been chosen as the best method for it is efficient and reliable.

2. EXPERIMENTAL

Concentrated hydrochloric acid, copper metal, lead metal, zync metal and distilled water were purchased from merck and used for the research. Moreover, ball mill and several characterisation and analysis equipment, namely X-ray Diffraction (XRD), Atomic Absorption Spectroscopy (AAS), Surface Area Analyser (SAA) and Scanning Electron Microscopy (SEM) were utilised.

2.1. The Synthesis of Zeolite

Natural zeolite was dried in the furnace with various temperature levels. The first heating was reaching at 200 °C for 30 minutes, then it was increased to 400 °C for 30 minutes. Finally, the heating temperature was increased to 600 °C for 1 hour, which aimed at removing the water content in the zeolite to ease the grinding process.

Zeolite was crushed to break the zeolite stones and then sieved with 200 mesh sieves. Furthermore, zeolite powder was treated with ball mill type planetary ball mill for 2 hours with 400 rpm rotation and sieved with 200 mesh sieve to produce a smoother powder zeolite. Finally, it was characterised by using SEM-EDX and XRD method.

As much as 20 g of zeolite powder from the previous treatment was put into a beaker glass and then dissolved in 100 ml of 12 M HCl, then heated in a magnetic stirrer at the temperature range of 70 °C–90 °C for 120 minutes. Then, it was stirred at 350 rpm, and also heated at the temperature range of 70 °C–90 °C for 120 minutes. The mixture was then neutralized with distilled water.

The mixture was dried in the oven for 5 hours at the temperature of 100 °C. The dried mixture was crushed using a mortar to smoothen and turn it into powder. The zeolite powder was calcined in a furnace at the temperature of 600 °C. After calcination process, zeolite powder was milled using a ball mill at a speed of 100 rpm for 30 minutes, and sieved to produce zeolite. Zeolites combined with HCl solvents were tested by SEM-EDX, XRD, and SAA method.

2.2. The Metal Adsorbent Test

As much as 0.2 g of Pb, Cu and Zn were weighed and then poured into a beaker glass and added with 1200 mL of distilled water. Then, it was stirred at room temperature at a rotation speed of 300 rpm until mixed evenly. After that, as much as 1 g of zeolite combined with HCl with various particle size of 150, 200 and 250 mesh was put in three beaker glasses. Then, as much as 300 mL of the solution containing metals was poured into each of zeolite with various particle size and into one beaker glass that did not contain zeolite (blank).

The solution mixed with zeolite was stirred at a room temperature at a rotation speed of 300 rpm for 1 hour. The mixtures were filtered with Whatman paper to separate the solution and adsorbent materials. Finally, it was characterised by using the AAS method.

3. RESULTS AND DISCUSSION

Zeolites in the form of chunks were first put in the furnace at the temperature of 600 °C for 4 hours. The zeolite chunks were crushed with mortal and then sieved with 150 mesh, 200 mesh, and 250 mesh sieves. The sieve results were milled with the planetary ball mill at a rotation speed of 300 rpm for 2 hours to produce zeolite powder.

Then, the size variations were carried out with the aim of discovering which zeolite would have optimum adsorption of heavy metal ions and have the largest surface area.

3.1. XRD (X-Ray Diffraction) Analysis

X-ray diffraction method is an analytical method based on the interaction between matter with X-ray electromagnetic radiation (having λ = 0.5–2.5 Ǻ and energy ± 107 eV), which is the measurement of diffracted X-ray radiation by the field crystal. Moreover, in the present research, the XRD characterisation used the Shimadzu type XRD tool with Ka wavelength of 1.541862 Å and speed (scan speed) of 2 degree/min. The XRD characterisation results are displayed in Fig. 1.

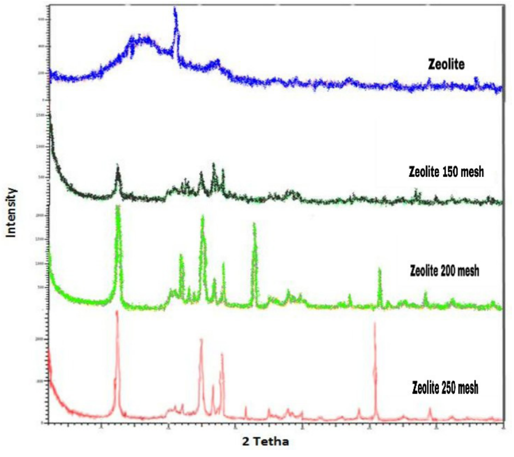

Fig. 1. The XRD result of:
Zeolite after milling process,
zeolite 150 mesh, zeolite 200 mesh
and zeolite 250 mesh.

Based on the XRD results, it can be seen that the size of each zeolite with variations in the size of 150 mesh, 200 mesh, and 250 mesh is 29.274 nm, 38.665 nm and 43.863 nm, respectively. Furthermore, the crystal structure of zeolite after milling process, zeolite 150 mesh, zeolite 200 mesh, zeolite 250 mesh are trigonal, tetragonal and cubical, respectively.

Particle size can affect material properties; a smaller size affects a larger surface area causing greater or more responsive reaction power [19], [20]. Furthermore, changes in material properties (chemical properties and thermal properties) lead to changes in the structure of the material; this structure also illustrates the strength of the material [21].

3.2. Scanning Electron Microscope (SEM) Analysis

The characterisation using Scanning Electron Microscopy (SEM) is expected to determine the morphological structure of a material. Through SEM analysis, the pore particle size can be seen in the sample with a certain magnification; besides, the composition of the material can be determined through an EDX tool that is integrated with the tool.

The smaller the size of the adsorbent pores, the higher the surface area so that the number of molecules adsorbed will increase. From the results of the analysis of the composition of the SEM-EDX compound, it is known that zeolite under consideration was Na-Zeolite type. Zeolite before being co-precipitated had a rough surface and agglomerated, whereas zeolite that was co-precipitated had a smooth surface and less agglomeration. The zeolite synthesis of the co-precipitation method succeeded in removing impurities, namely, Fe.

Table 1. The Element Composition Obtained from the EDX Analysis

Chemical Elements	Mass [%]			
	Zeolite	Zeolite 150 mesh	Zeolite 200 mesh	Zeolite 250
Si	14.40	15.10	18.71	30.65
Al	32.86	15.09	17.49	16.33
Fe	10.04	1.20	0.74	-
Ti	-	0.13	0.34	-
C	4.80	8.73	7.56	4.64
Cl	3.31	0.61	0.84	-
O	34.58	58.91	52.85	48.38

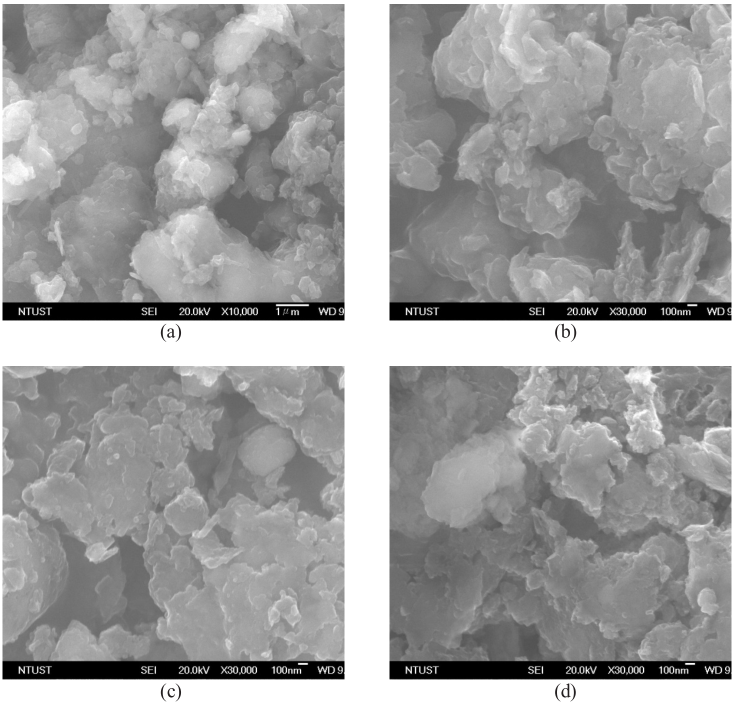

Fig. 2. The SEM result of: (a) zeolite after milling process, (b) zeolite 150 mesh, (c) zeolite 200 mesh and (d) zeolite 250 mesh.

3.3. Analysis of Surface Area Analyser (SAA)

Surface Area Analyser has several methods with one of them in the form of Gas Surface Analyser, which uses gas to analyse the surface area of a porous material with desorption adsorption techniques applying adsorbate inert gases such as nitrogen or helium and adsorbent in the form of porous material. Zeolite is said to be physically adsorbed, which only occurs in the interaction between the molecule adsorbent and the adsorbate.

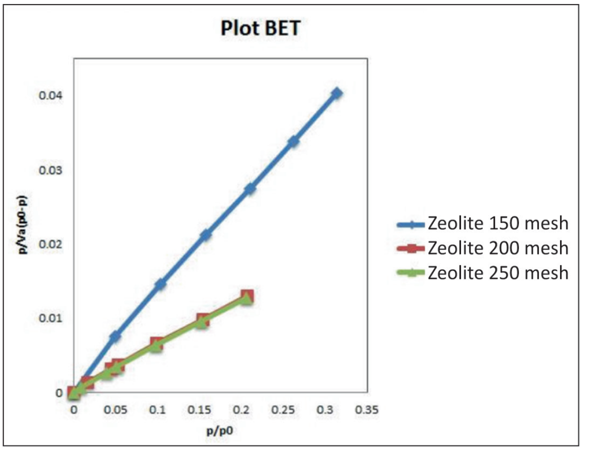

Fig. 3. The BET plot result of zeolite 150 mesh, zeolite 200 mesh and zeolite 250 mesh.

The SAA test results revealed that the total surface area of the zeolite variation of 150 mesh, 200 mesh, 250 mesh were 32.07 m^2/g, 65.36 m^2/g and 65.06 m^2/g, respectively, with specific surface area (BET) variations in each size – 323.95 m^2/g, 660.26 m^2/g and 657.18 m^2/g. Furthermore, the calculation results of BET analysis on the surface area of each zeolite size are as follows (see Table 2).

Table 2. The Calculation Result of BET Analysis

Sample	Zeolite 150 mesh	Zeolite 200 mesh	Zeolite 250 mesh
Slope	1.22×10^{-1}	5.99×10^{-2}	6.05×10^{-2}
Intercept	2.04×10^{-3}	7.07×10^{-4}	4.00×10^{-4}
Surface Area	3.52×10^{1}	7.18×10^{1}	7.15×10^{1}
Wm (m^2/g)	8.09	1.65×10^{1}	1.64×10^{1}
St (m^2/g)	3.21×10^{1}	6.54×10^{1}	6.51×10^{1}
S (m^2/g)	3.24×10^{2}	6.60×10^{2}	6.57×10^{2}
Error (%)	8.9761	8.9718	8.9714

3.4. Atomic Adsorption Spectrophotometric (AAS) Analysis

The results of the AAS analysis showed that the optimum adsorption of metal content was using zeolite variations in size of 150 mesh with adsorption power of 99.6 % for Pb metal, 98 % for Cu metal, and 96 % Zn metal. The zeolite 200 mesh adsorption power was Pb 96.97 %, Zn 99.694 %, and Cu 97.51 %, while zeolite 250 mesh adsorption power was Pb 99.92 %, Zn 99.684 %, and Cu 99.978 %.

At the time of exchange of heavy metal ions with zeolites, it will be confused with zeolite elements which have weak ionization, so that zeolites can absorb the metal ions. The second indicator that causes high absorption results is because the small particle size will increase the surface area, causing higher absorption properties.

Table 3. The Metal Content of Each Size Variation of Zeolite

Sample	Pb (mg/L)	Zn (mg/L)	Cu (mg/L)
Without indicator	591.6	0.5264	0.2709
Zeolite 150 mesh	0.1051	0.1636	<0.006
Zeolite 200 mesh	6.49	0.1611	0.6734
Zeolite 250 mesh	<0.005	0.5880	<0.006

Based on the table above, it can be seen that there is a decrease in metal content when using nano zeolite. The optimal metal absorption uses HCl solvent where there is a decrease in metal content for all Pb, Zn and Cu metals. It can be inferred that the co-precipitation method applied to natural zeolite and converted to several size variations is proven to be able to show a good performance for metal adsorbent.

4. CONCLUSION

The fabrication of natural zeolite via the co-precipitation method has been successfully performed. Furthermore, this material shows an impressive capability as a metal adsorbent, particularly copper, lead and zinc.

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ROLE OF BALANCING MARKETS IN DEALING WITH FUTURE CHALLENGES OF SYSTEM ADEQUACY CAUSED BY ENERGY TRANSMISSION

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The national energy and climate plans developed by the Baltic States for the period up to 2030 foresee a significant increase in the share of renewable energy in final consumption. Therefore, the development of wind, solar and distributed generation in the Baltic electricity system is expected to increase significantly in the next decade and, thus, the need for balancing capacity will increase. The planned synchronisation of the Baltic power system with the power system of Continental Europe in 2025 will also increase the need for frequency restoration and balancing reserves. At the same time, the shutdown of uncompetitive thermal power plants in the Baltics reduces centralized generation capacity. If this trend continues, the risk of electricity supply shortages will increase in the future. Therefore, it is important to identify activities that help mitigate this risk and take timely actions.
Keywords: *Baltic ACE, Baltic balancing market, Baltic power system*

1. RENEWABLE ENERGY SOURCES REPLACE THE FOSSIL ENERGY

During the years, there is a clear trend towards increasing production from renewable energy sources and decreasing production from fossil energy sources in the Baltic States. During the past years, on average around 40 % of the produced electricity has come from renewable sources (mainly hydropower and wind energy), while about 60 % – from fossil fuels (mainly oil shale and natural gas). In 2017 and 2018, the generation of electricity from renewable energy sources exceeded 40 % of total generation threshold for the first time, exceeding 10 TWh and 8 TWh, respectively. However, in 2019 the share of renewable generation exceeded 50 % for the first time.

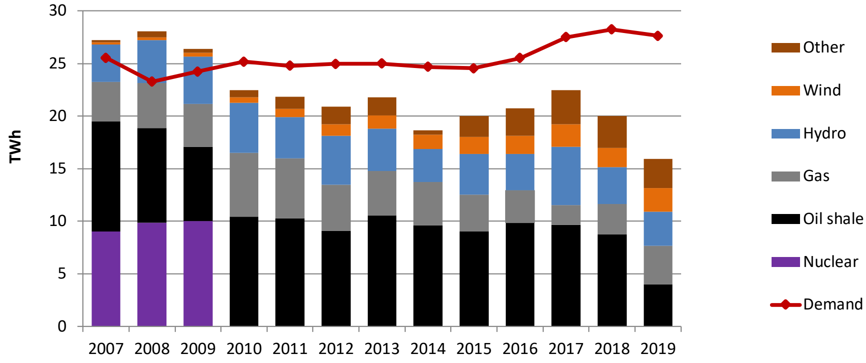

Fig. 1. Electricity production and consumption in the Baltic States.

Source: ENTSO-E

2. LARGEST CO_2 EMITTERS WILL BE PUSHED OUT OF THE MARKET

Estonian oil shale power plants have played an important role in the Baltic power system. In recent years, oil shale power plants have generated around 9–10 TWh of electricity annually, or about half of the total electricity output in the Baltics.

Oil shale combustion generates substantial CO_2 emissions; therefore, the profitability of the operation of these power plants is particularly affected by the price changes in CO_2 emission allowances on the European market. Low and stable CO_2 emission allowance prices have been contributing to stable electricity production at oil shale power plants in recent years (Fig. 2). However, since 2018 CO_2 emission allowance price has experienced a significant rise [1] exceeding EUR 25 [2] per tonne. As a result, electricity generation at oil shale power plants declined significantly reaching record low 4 TWh in 2019. Overall electricity production in the Baltics also reached record low 58 % of demand in 2019, while electricity generation from renewable sources reached record high 50 % in the Baltic electricity generation mix in 2019.

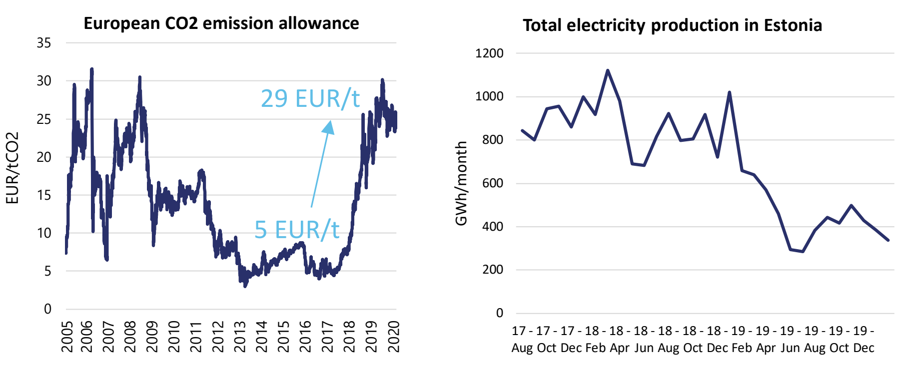

Fig. 2. Price of CO_2 emission allowances in Europe (EUR/t) and electricity production in Estonia.

Source: EEX and Nord Pool market data

3. CENTRALIZED, CONTROLLABLE PRODUCTION CAPACITY IS SHRINKING IN THE REGION

During the past five years, the total installed capacity of power plants in the Baltics has been relatively stable and now exceeds 9000 MW, which is about twice the peak of the Baltic consumption peak.

During the past five years, the installed capacity of gas power plants has decreased by 25 % (or about 1000 MW), mainly due to the closure of the oldest gas power plant units in Lithuania [3]. The most significant increase in production capacity was due to commissioning of new wind [4], [5] and biomass power plants (with a total capacity of 600 MW), as well as commissioning of a new 300 MW Auvere shale power plant (Estonia) in 2015 [6].

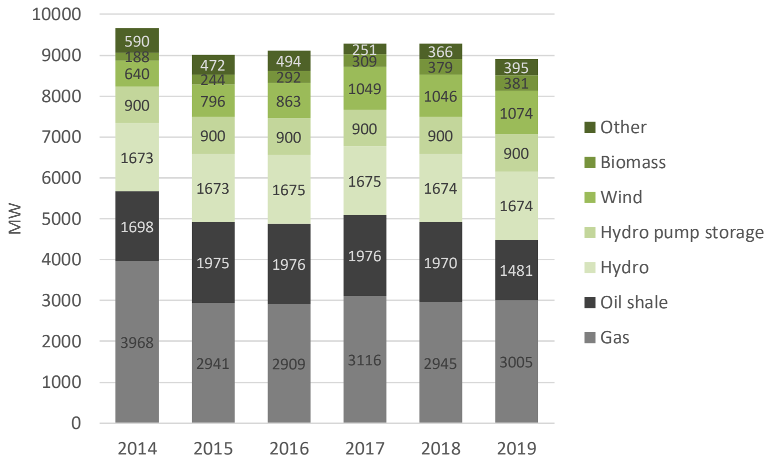

Fig. 3. Installed power capacity in the Baltic States.

Source: ENTSO-E

In 2019, the Baltic mix of installed capacity consists of approximately 50 % of fossil and 50% of renewable capacity. The capacity of centralized power plants in the Baltic countries is expected to decline in the coming years – mainly due to uncompetitive old thermal power plant units in Estonia and Lithuania.

4. GROWING SHARE OF INTERMITTENT GENERATION INCREASE DEMAND FOR BALANCING RESOURCES

Although the overall installed generation capacity is expected to grow in the Baltic region, the proportion of centralized, controllable generation capacity is expected to decrease, while the proportion of intermittent and distributed generation is expected to increase [7]. The biggest increase is expected for wind generation capacity – from approximately 1000 MW in 2020 to 4000 MW by 2034 [8] (Fig. 4).

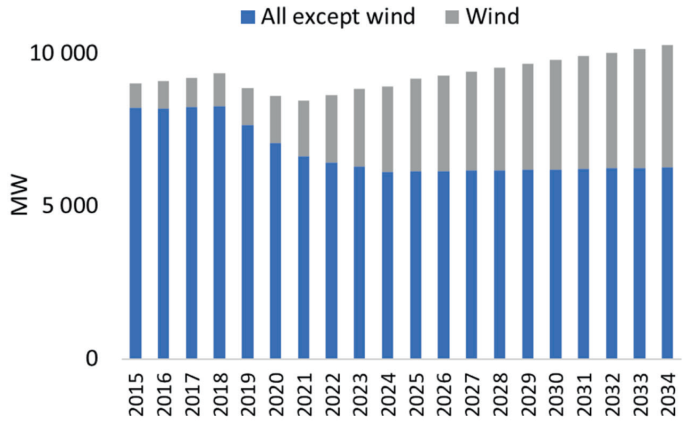

Fig. 4. Forecast of installed generation capacity in the Baltics.

Source: Baltic transmission system operators

While the rising amount of wind power entering the electricity grids greatly contributes to the climate goals [9], [10], it also makes the operation of the power system systematically more complex. Wind is an intermittent energy source [11] and output fluctuations must be offset to maintain continuous power balance in the system. Therefore, demand for balancing resources in the power system is expected to increase [12].

Analysis of data from the Baltic power system indicates the relation between growing wind generation and growing area control error ACE (Figs. 5, 6, 7). Analysis of statistical data for period from 2015 till 2019 suggests that increasing wind generation by 400 % during the next decade could increase the average Baltic ACE by 50 %.

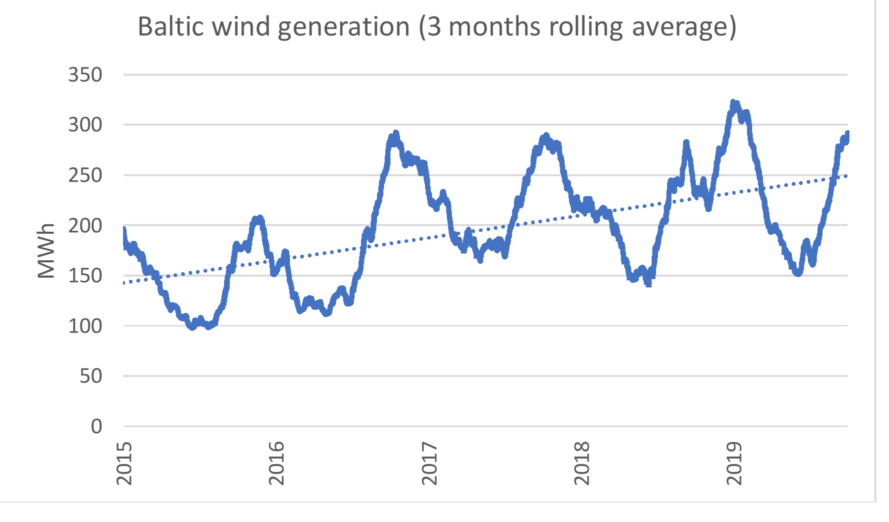

Fig. 5. Baltic wind generation (3 months rolling average).

Source: Baltic transmission system operators

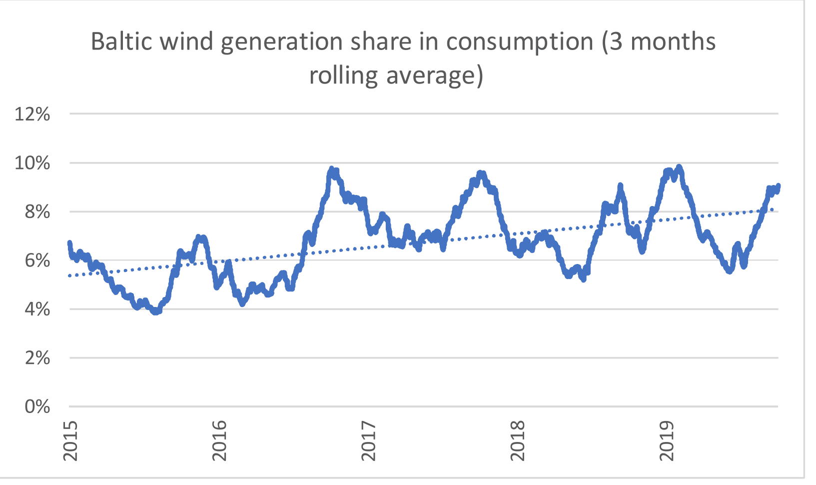

Fig. 6. Baltic wind generation share in consumption (3 months rolling average).

Source: Baltic transmission system operators

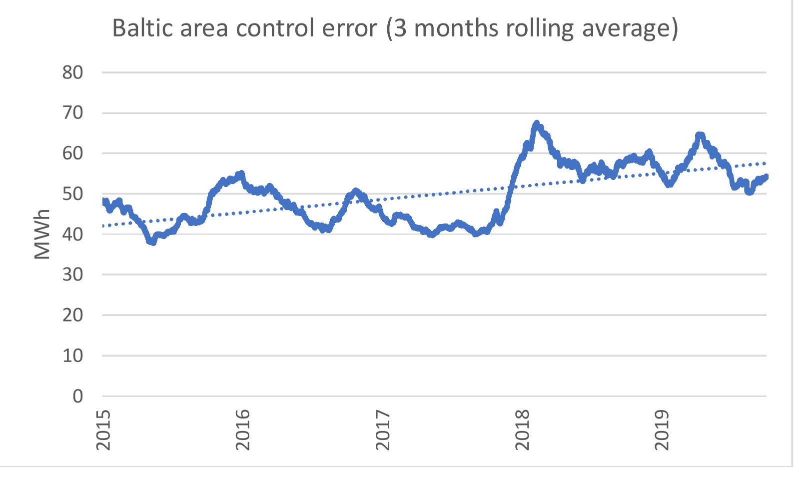

Fig. 7. Baltic area control error (3 months rolling average).

Source: Baltic transmission system operators

5. SUPPLY OF BALANCING RESERVES DECREASES AS CONVENTIONAL, CENTRALIZED POWER PLANTS EXIT THE MARKET

The creation of new Baltic balancing market and more active power system control have been implemented since the beginning of 2018. It has resulted in a more active usage of balancing resources [13], more active balance control and lower ACE after balance control (Table 1). Average Baltic ACE after balance control in 2019 was two times smaller than in 2017 and the number of hours with Baltic ACE after balance control within 50 MWh limit increased from 65 % in 2017 to 94 % in 2019 [14].

Table 1. Indicators of the Baltic Power System Balancing Accuracy and ACE after balance control

Period	2019	2018	2017
Average ACE, MWh	18.81	23.99	41.99
Hours with Baltic ACE inside 50MWh	94 %	89 %	65 %

The oldest conventional, centralized power plants in the Baltics have been gradually decommissioned during the past years. However, 2019 was particularly significant as generation decreased by 29 % in 2019 compared to 2018. Particularly, power generation from oil-shale – the largest source of power generation in the Baltics – decreased by more than a half in 2019. Since the conventional thermal power plants are also a significant source of balancing power, this fact affects the availability of balancing reserves in the Baltic market. Amount of balancing energy from the Baltic balancing reserves decreased by 1/3 in 2019 compared to the previous year (Fig. 8).

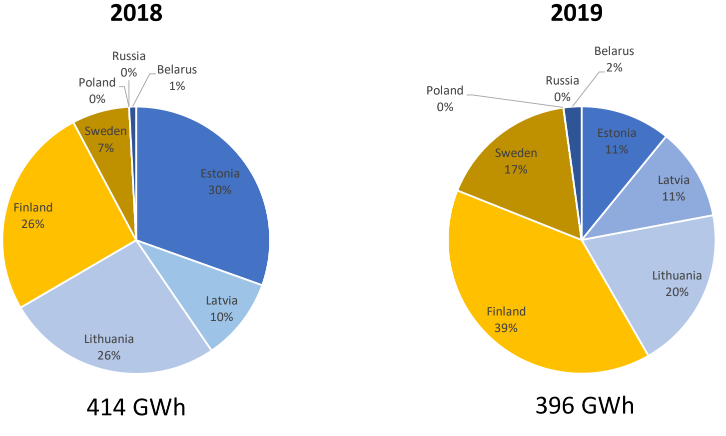

Fig. 8. Origin of used balancing energy in the Baltic market.

Source: Baltic transmission system operators

6. THE RISK OF SHORTAGE OF GENERATION CAPACITIES WILL INCREASE IN THE COMING YEARS

According to the TSO evaluation [8] after 2020, the adequacy of electricity supply in the Baltic States will highly depend on imports through interconnections from neighbouring power systems. The peak load capacity will be significantly reduced after 2025 [5], when the Baltic transmission system will disconnect from the unified Russian power system and start synchronous operation with the continental Europe power system. After 2030, however, generation and import capacities of the Baltic power system are expected to be insufficient to cover peak loads and provide an adequate level of safety in the Baltic electricity system in normal operation, with a capacity deficit of up to 360 MW.

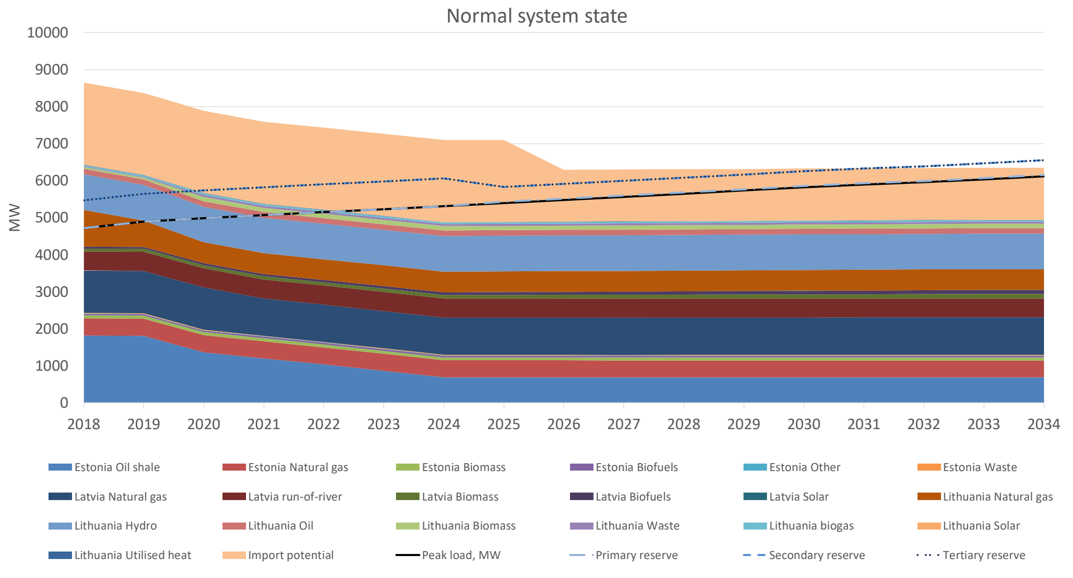

Fig. 9. Capacity adequacy (peak load) evaluation on normal system state.

Source: Baltic transmission system operators

7. BALTIC SYNCHRONISATION WITH POWER SYSTEM OF CONTINENTAL EUROPE WILL INCREASE DEMAND FOR BALANCING RESERVES

Currently, the Baltic electricity transmission system is integrated into the unified Russian power system BRELL. Due to the planned Baltic desynchronisation from the BRELL system and synchronous operation with the Continental Europe system as from 2025, the Baltic transmission system operators will have to be able to participate in frequency regulation both in normal conditions and in the event of a major generator or cross-border interconnection outage. Synchronisation with Continental Europe grid will require changes in network balancing routines by reacting to changes in quicker and more automatised way by using frequency containment reserves and automated frequency restoration reserves. Desynchronisation from BRELL will require additional balancing reserves to the Baltic transmission system operators. Table 2 shows the indicative reserve requirements, which will be required by the Baltic TSOs in accordance with the operational guidelines of the power system of Continental Europe.

Table 2. Indicative Reserve Requirements for Baltic TSOs after Synchronisation with the Continental European Power System in 2025 (MW)

Reserve type	Baltic	Estonia	Latvia	Lithuania
FCR	30	7	11	12
aFRR upward	100	32	23	45
aFRR downward	100	32	23	45
mFRR upward	600	218	148	234
mFRR downward	600	279	21	300

FCR – *frequency containment reserve*
aFRR – *automated frequency restoration reserve*
mFRR – *manual frequency restoration reserve*

CONCLUSIONS

Supply of balancing reserves is expected to decrease in the Baltic power system in the coming years because the oldest, centralized power plants (mainly oil-shale and natural gas) are expected to exit the market. Rising price of CO_2 emission allowances and low electricity price are important factors.

Demand of balancing reserves is expected to increase in the coming years due to the growing share of intermittent and distributed generation in the Baltic power system. Quadrupling the installed wind generation capacity during the next decade could increase the area control error of the Baltic power system by 50 %.

Synchronisation of the Baltic power system with the grid of Continental Europe will further increase demand for balancing reserves as Baltic TSOs will have to participate in frequency control process and ensure availability of additional frequency containment reserves and automated/manual frequency restoration reserves.

The Baltic power system could face the increased risk of a shortage of generation capacities for covering peak load and shortage of balancing capacities in the next decade if the current trend of capacity decommissioning continues without new adequate, controllable capacities replacing them. One of the activity that help mitigate the risk is implementation of the Balancing capacity market and Capacity remuneration mechanisms.

ACKNOWLEDGEMENTS

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NATURAL GAS AND BIOMETHANE IN THE EUROPEAN ROAD TRANSPORT: THE LATVIAN PERSPECTIVE

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The European Union (hereafter – the EU) takes a strong position in the global fight against climate changes by setting ambitious targets on reduction of greenhouse gas (hereafter – GHG) emissions. A binding target is to reduce those emissions by at least 40 % below 1990 levels till 2030, which would help make Europe the first climate neutral continent by the mid-21st century. Consequently, the expected 2050 emission reduction target for the EU is 80 %–90 % below 1990 levels. The EU's new economy decarbonisation framework – The European Green Deal – outlines and summarises Europe's ambition to become a world's first climate neutral continent by 2050. This supposedly can be achieved by turning climate and environmental challenges into opportunities across all policy areas and making the energy transition just and inclusive for all.

The transport, and particularly road transport, is one of the most significant fossil fuel dependent segments of national economies across the EU. Oil dependency of all segments of the transport sector makes it the single biggest source of GHG emissions in the united Europe as well. Road transport is responsible for about 73 % of total transport GHG emissions, as Europe's more than 308.3 million road vehicles are over 90 % reliant on conventional types of oil-based fuels (diesel, gasoline etc.).

However, there is a wide range of low-emission alternative fuels for all kinds of transport that can reduce overall oil dependence of the EU's transport sector and significantly lower GHG in road transport. Among these alternatives a tandem of the natural gas and biomethane could be named as one of the most promising for short and mid-term transport decarbonisation solutions both in the EU and Latvia.

Keywords: *biomethane, decarbonisation, natural gas, road transport*

1. INTRODUCTION

The EU takes a strong position in the global fight against climate changes by setting ambitious targets on reduction of GHG emissions. A binding target is to reduce those emissions by at least 40 % below 1990 levels till 2030, which would help make Europe the first climate neutral continent by the mid-21st century. Consequently, the expected 2050 emission reduction target for the EU is 80 %–90% below 1990 levels. This supposedly can be achieved by turning climate and environmental challenges into opportunities across all policy areas and making the energy transition just and inclusive for all. And sustainable mobility is given an important role in this process [1].

Road transport is one of the most significant fossil fuel dependent segments of national economies across the EU. Oil dependency of all segments of the transport sector makes it the single biggest source of GHG emissions in the united Europe as well. Road transport is responsible for about 73 % of total transport GHG emissions, as Europe's more than 308.3 million road vehicles [2] are over 95 % reliant on oil-based fuels [3].

Table 1. Road Vehicles by Fuel Types in the EU* (2018; %)

Type of Vehicle	Gasoline	Diesel	Hybrid Electric	Electric**	CNG, LNG, LPG	Other
Passenger cars	54	41.9	0.7	0.2	2.8	0.3
Light commercial vehicles	7.1	91.2	0	0.3	1.3	0.1
Medium and heavy commercial vehicles	1	98.3	0	0	0.4	0.2
Buses	0.8	95.4	0.3	0.3	2.7	0.4

*- including the United Kingdom
* - battery electric + plug-in hybrid
Source: ACEA Report Vehicles in use, Europe 2019

At the same time, there is a wide range of low emission alternative fuels for all kinds of vehicles available that can reduce overall oil dependence of the EU's transport sector and significantly lower GHG in road transport. The very term "alternative fuels" is universally undefined – some explanations emphasise the renewable energy component, while others, including Directive 2014/94/EU of the European Parliament and of the Council on the deployment of alternative fuels infrastructure (Directive 2014/94/EU), focus on all types and kinds of fuel more sustainable than traditional ones. Some other definitions even include coal-derived liquid fuels in a range of alternatives. The following fuels are defined as alternative fuels in the U.S. by the Energy Policy Act of 1992: pure methanol, ethanol, and other alcohols, blends of 85 % or more of alcohol with gasoline, natural gas and liquid fuels domestically produced from natural gas, propane, coal-derived liquid fuels, hydrogen, electricity, pure biodiesel, fuels other than alcohol derived from biological materials. In addition, the U.S. Department of Energy may designate other alternative fuels provided that they are substantially non-petroleum, yield significant energy security benefits, and offer substantial environmental benefits [4]–[5].

In the EU, however, according to Article

2 (1) of Directive 2014/94 /EU, “alternative fuels” are sources of fuel or energy which at least partially replace fossil fuel oil sources in vehicle power supply and which have the potential to contribute to decarbonisation of transport and the environmental performance of the transport sector.

Directive 2014/94 / EU defines, *inter alia*, the following alternative fuels:

- electricity;
- hydrogen;
- liquid biofuels (biodiesel, bioethanol and hydrogenated vegetable oil);
- biomethane;
- compressed natural gas (CNG);
- liquefied natural gas (LNG) [6].

Among these alternatives a tandem of the natural gas and biomethane could be named as one of the most promising for short and mid-term transport decarbonisation solutions both in the EU and Latvia. Currently, transport represents only a minor consumer of the natural gas in the EU, amounting to less than 1 % of its total demand. Despite an increase in registrations in recent years, alternatively powered passenger cars make up only about 3.7 % of the total EU car fleet [2].

Transport accounts for around one third of overall energy consumption, and for achievement of Europe’s climate neutrality by 2050, a fundamental – 90 % – reduction in transport emissions is needed [1]. It is also acknowledged that there will be no single solution for decarbonisation of this sector, with multiple alternative fuels being needed for different modes of transportation. Therefore, there is a potential for growth in demand for quite a few alternative fuel sources, such as natural gas, biomethane and other renewable gases (hereafter – RG), as well as electric mobility solutions, and in more distant future – blue and green hydrogen [1].

This research presents an analytic review of the growth dynamics of the natural gas mobility sector in the EU and Latvia with regard to possible trends of development of the natural gas and biomethane mobility in our country in next ten years and beyond.

2. NATURAL GAS INFRASTRUCTURE AND VEHICLES

Directive 2014/94/EU requires the EU Member States to ensure, by means of their national policy frameworks, that an appropriate number of recharging and refuelling points accessible to the public are put in place, first and foremost, targeting urban and suburban agglomerations, as well as the Core Trans-European Transport Network (hereafter – TEN-T). The alternative fuels that demand specific infrastructure solutions and for which Directive 2014/94/EU requires future targets from the EU Member States are electricity, CNG, LNG, and hydrogen [6].

As for CNG and LNG, Directive 2014/94/EU prescribes that the Member States shall ensure that:

- an appropriate number of refuelling points for LNG accessible to the public are put in place by 31 December 2025, at least along the existing TEN-T Core Network, in order to ensure that LNG heavy duty motor vehicles can circulate throughout the Union, where there is demand, unless the costs are disproportionate to the benefits, including environmental benefits;
- an appropriate number of CNG refuelling points accessible to the public are put in place by 31 December 2020, in

order to ensure, in line with the sixth indent of Article 3(1), that CNG motor vehicles can circulate in urban/suburban agglomerations and other densely populated areas, and, where appropriate, within networks determined by the Member States;
- an appropriate number of CNG refuelling points accessible to the public are put in place by 31 December 2025, at least along the existing TEN-T Core Network, to ensure that CNG motor vehicles can circulate throughout the Union [6].

Today, over 2 million natural gas vehicles (hereafter – NGVs) are in use all over the EU, where they are supported by a network of 4041 CNG and LNG fuelling stations.

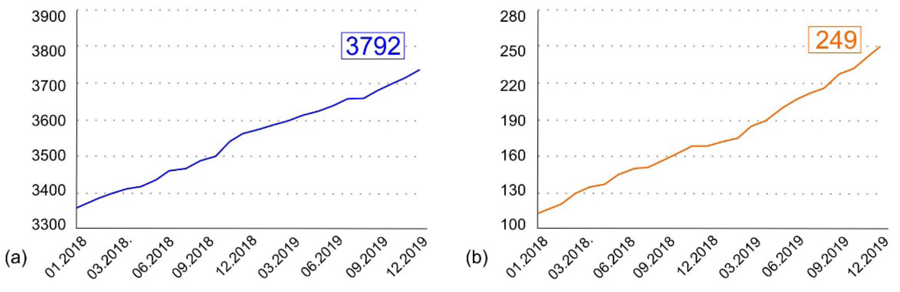


Fig. 1. Dynamics of the European CNG (a) and LNG (b) fuelling stations.

Source: NGVA Europe

CNG passenger cars make up about 0.4 % of the vehicle fleet in the EU, but the largest market share of CNG by far – 4 %, is in Italy. In 2018, the breakdown of CNG vehicles in the EU was as shown in Table 2, and further sector development in general followed the same trend. Significantly enough that CNG heavy duty vehicle registration was rather high in comparison with LNG heavy duty vehicle registration, which was 714 in 2018 [7], [10].

Table 2. EU CNG Fleet by Vehicle Type, 2018

Vehicle Type	CNG Existing Fleet	New CNG Registrations
Passenger Cars	1.150.000	65.835
Light Commercial Vehicles	125.308	9914
Buses	7901	430
Heavy Duty Vehicles	14.163	514

Source: NGVA Europe

NGVs are defined as all land-based motor vehicles, from two wheelers through to off-road. It includes original equipment manufacturers' vehicles, factory-approved conversions and post-sale conversions. Fuels used include CNG, LNG and biomethane or other RGs, which can be in gaseous or liquid form. Comprehensive statistics on NGVs is provided by NGV Global, which estimates that, in middle of 2019, there were around 27.7 million NGVs operating worldwide, with the biggest share – close to 20 million, used in the Asia–Pacific region [8].

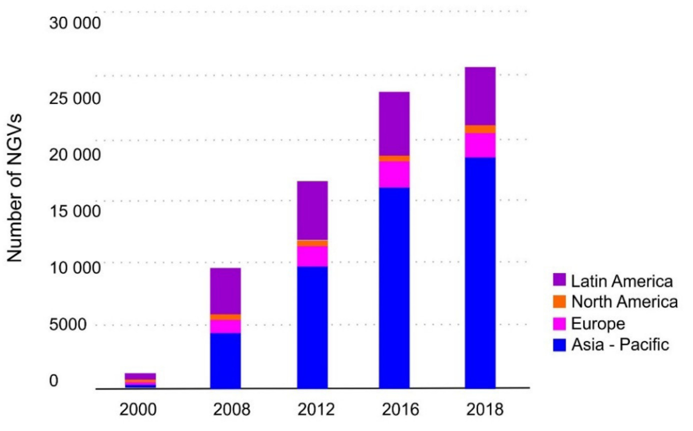


Fig. 2. Global NGV numbers by region, 2000 to 2018.

Source: NGV Global

Both NGV fleet and fuelling station networks are constantly expanding across Europe, too [9], even though currently it is quite challenging to estimate the rate and speed of development in the next few decades, as the European Commission's Summary on National Plans for Alternative Fuel Infrastructure clearly show significant differences in the Member States' political efforts to support CNG and LNG mobility. For instance, Germany already has a relatively dense network of CNG refuelling points, and available infrastructure could probably support more than five times the CNG vehicles on the roads in the country today. The German national policy framework defines a network of nine LNG refuelling points that could guarantee fulfilment of the maximum distance requirement for LNG refuelling points for heavy duty vehicles along the TEN-T Core Network. However, LNG driven heavy duty vehicles may have to deviate from the shortest route in order to refuel when travelling on the TEN-T Core Network [10]. At the same time other EU Member States, like Latvia and Lithuania, are still working on the very initiation of natural gas mobility and trying to find ways to trigger political support and financial incentives for expanding the public CNG filling station network.

Fuel logistics is one of the important points, which also defines future of the natural gas mobility. In the EU, CNG and LNG networks operate on different terms, as their fuel supply chain functions differently [11]. Traditionally, where natural gas distribution network is available, CNG fuelling is made available as well; thus, in locations, where natural gas network is absent, LNG fuelling is almost exclusive. However, availability of regional or national natural gas network is not the only option for development of CNG fuelling infrastructure. It could be installed in locations with local small-scale LNG fed natural gas networks as well. In terms of fuel logistics, availability of the natural gas grid for injection of biomethane is increasingly important [12]. In 2018, in the EU amount of biomethane injected into the grid was rather small – 2BCM, in comparison with 363BCM of imported natural gas resources [13]. Biomethane can also be used in form of CNG as it is in many EU Member States. Biomethane is made available through local CNG filling facilities near biomethane plants. In many states, including Latvia, biomethane injection into regional or national gas transportation of distribution network still is not performed.

In Germany, which is the EU's pioneer in biomethane injection into natural gas grids, in 2014 there were 168 biomethane plants with a total capacity of 204.000 m^3/h, but just a few of them were feeding biomethane into the grid. Currently, Germany has a strong biogas industry with more than 10,000 biogas plants, and it is also the EU leading country in terms of biomethane production [14]. In 2016, the amount of plants feeding the grid was 193 with 940 million m^3 of biomethane fed into system, which contributed to about 1 % of the natural gas consumption in Germany [12]. In 2018, however, 203 biogas plants with upgrading technologies were producing biomethane for natural gas grid injection needs. In total, biogas production was equal to about 10 billion m^3/year, whereof biomethane plants produced 2.7 million m^3/day, or around the same amount of biomethane fed into the grid as two years ago [13].

The objective of Germany and France – other country with clear future vision of centralised distribution of biomethane – is to replace 10 % of their total natural gas consumption with biomethane via the natural gas grids by 2030, which is the most ambitious goal among the EU Member States. But, for the sake of clarity, it must be noted that in France, the legislation defines a target of 10 % that should be represented by biomethane and other "green gases". However, the present stage of development of non-methane RG sector in the country allows only biomethane to be produced on an industrial scale to meet the demand set in the legislation [14].

3. ROLE OF BIOMETHANE

Biomethane is methane produced from biomass, landfill gases or gases acquired from different types of organic waste by means of purification of raw biogas, with chemical characteristics close or equal to natural gas. The initial product is raw biogas that is upgraded to reach a high methane content (usually >96 %), which can then be used as a fuel for transport [15]. The number of biomethane production plants in the EU has nearly tripled between 2011 and 2017, showing the fast development of this sector. By the end of 2017, there were 17,783 biogas plants and 540 biomethane plants in operation Europe-wide. The total installed electric capacity of biogas plants continued to increase in 2017, growing by 5 % to reach a total of 10.532 MW. The electricity produced from biogas amounted to the European total of 65.179 GWh.

Biomethane production also increased, reaching about 1.94 billion cubic meters (BCM) in 2017 [16]. France had the highest growth rate for biomethane plants due to favourable policy conditions for biomethane production. The country is attempting to reach 1000 biomethane plants injecting its gas into the national gas grid by late 2020. To achieve this target, an incentive scheme has been put in place to support biomethane production. In 2017, 18 new biomethane plants were constructed in France and, before the end of 2018, 23 additional plants were installed, reaching a total of 67 biomethane plants.

The rate of increase in the number of European biomethane plants from 2016 to 2017 was half that between 2014 and 2015, but biomethane production nevertheless continued to grow, rising by 12 % in 2017. For biomethane as for biogas, there is a trend towards larger installations [16].

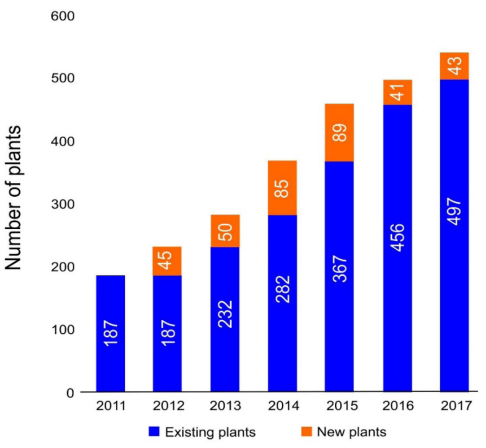


Fig. 3. Biomethane production plant in the EU (2011–2017).

Source: EBA Statistical Report 2018

The period between 2020 and 2030 will trigger the transformation of the natural gas industry to reduce its CO_2 emissions, which currently represent 25 % of the EU's total CO_2 emissions and 20 % of its power sector emissions. The production of biogas and its upgrade to biomethane is one of the best available options, alongside efforts to reduce methane leakage and gas flaring in the upstream part of the gas supply chain. In the longer perspective, it might be followed by green hydrogen produced from renewable electricity or blue hydrogen from gas combined with carbon capture and storage [13].

The biogas sector is expanding and has experienced many improvements in the past decade in terms of physical and economic efficiency. Germany still remains the European leader in biogas production, even though there has been little slowdown in recent years regarding the implementation of new biogas plants, mainly, due to changes in the national support scheme. On the other hand, the United Kingdom and France have continued to increase the number of new plants in operation, with possibility to overtake Germany in the next decade. Six countries – Austria, Germany, Italy, Portugal, Sweden as well as the United Kingdom – have currently achieved their biogas target for 2020 set in the National Renewable Energy Action Plans. Landfill and sewage gases account for around 24 % of total biogas production, while most of the biogas comes from another source: anaerobic fermentation of agricultural feedstock. In Europe, up to 70 % of the feedstocks used for biogas production come from the agricultural sector such as energy crops, manure, as well as agricultural residues. The utilisation of agricultural residues such as manure is particularly important in countries such as Denmark, France and Italy. This underlying growth in synergy between animal farming and biogas provides a profitable manure management solution. Energy crops are mainly grown and used in Germany and Austria. The municipal and industrial organic waste still has the potential to be developed for use in biogas production, but currently it is underrepresented [17].

Italy is the largest, but not the only EU Member State, that plans to develop a significant biomethane-based transport network around the existing CNG market. Sweden has also reported such an ambition. Even more, it has stated that 91.3 % of its gas for vehicles came from renewable sources in 2018, and 100 % is likely to come in 2030 [18]. In addition, the Natural & bio Gas Vehicle Association's (NGVA Europe) forecast shows that the potential of biomethane production in the EU would reach 45 BCM by 2030, where 19 BCM would come from anaerobic digestion, 13 BCM – from synthetic methane from power to gas and 13 BCM – from gasification. It is anticipated that 9 BCM of this production would be used in transport [19].

However, other estimates show that the potential of biomethane production and, therefore, its abundance across all consumption sectors are limited, and, as it is shown in Fig. 4, there are just a few EU Member States that will have a higher estimated maximum potential of biomethane for all sectors of national economy in 2030 than the estimated percentage of transport energy needs.

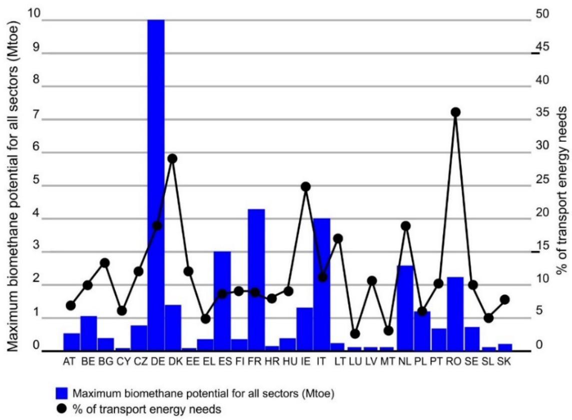


Fig. 4. Maximum biogas production potential by the EU Member States and the UK.

Source: Transport & Environment citing data from CE Delft, 2016

One of the EU Member States, where the natural gas mobility sector is still emerging – Latvia, also has to work at the development of methane use in transport. Currently, there are 59 biogas plants in operation there, and biomethane is mostly used for the production of electricity. However, according to present estimates, transformation of biogas into biomethane for use in transport would be regarded as a more cost-effective option in terms of economy than the combustion of biogas locally [20]. As seen in Fig. 5, the Latvian biogas plants are mostly located in a close vicinity of both natural gas transport and distribution networks, but injection of biogas into those networks is prevented by many private territories and other obstacles, which should be at least partially overcome in the near future.

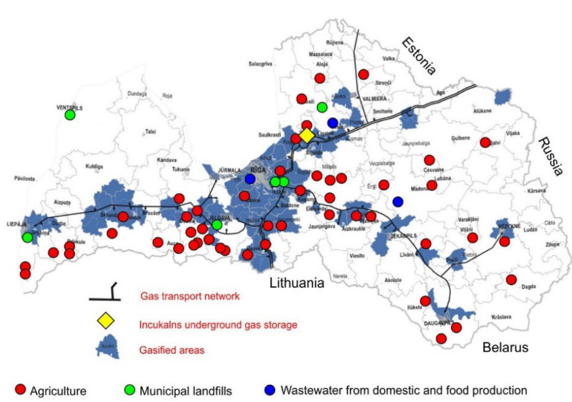


Fig. 5. Location and type of biogas plants in Latvia with respect to the natural gas network.

Source: JSC "Gaso", the Latvian Biogas Association

Establishment of EU-wide quality rules for biomethane injected into the natural gas grids and used as transport fuel was one of the alternative fuel sector standardisation process priorities. Due to differences in existing Member States' legal acts and standards regarding the quality of biomethane for natural gas grid injection purposes, it was decided to prepare actual EU standard in two stages. The standardisation deals with biomethane as a common end product regardless of its production pathways or origin of the substrates.

Part 1 of standard EN 16723–2 "Natural gas and biomethane used in transport as well as biomethane injected into the natural gas network" was published in 2016, and it concerns the requirements of biomethane injected into the natural gas grids [21]. Part 2, published in 2017, specifies the requirements and test methods for natural gas, biomethane and blends of both for use as vehicle fuels (standardisation applies to these fuels irrespective of the storage state (compressed or liquefied)) [22].

The technical requirements and safety conditions for the use of biomethane-powered vehicles are identical to those for CNG vehicles, so also their use must be in compliance with regulations and standards, such as ISO 15403-1:2006(en) Natural gas – Natural gas for use as a compressed fuel for vehicles – Part 1: Designation of the quality [23], [12].

At the national level, where access to the grid infrastructure is equal and non-discriminatory, additional quality requirements have been set for biomethane and regasified LNG for injection into the natural gas grids (both transportation and distribution networks) [24].

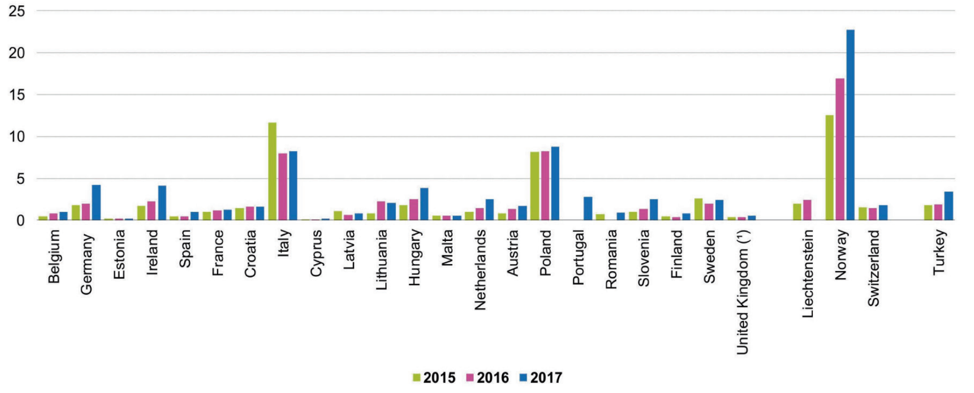
In the long term perspective, injection of biomethane into the natural gas grid brings a valid option for decarbonisation of natural gas supply chain and provides local, renewable resources with wider market accessibility. Positive effects of biomethane injection into the natural gas grid include, but are not limited to:

- sustainable and effective use of biomethane, as using it on-site for electricity-only applications with no local demand for the heat energy would utilise only 30 %–35 % of available energy. Using biomethane in an efficient modern domestic boiler or remote modern CHPs, when it is transported through the natural gas grid, allows improving efficiency of biomethane up to 90 %;
- effective and widespread delivery of renewable heat, as biomethane injection into the natural gas grid enables renewable heat to reach over 444 400 of homes in Latvia, where natural gas is physically available and could be used for heating purposes as well;
- active market participation, as the injection of biomethane into the natural gas grid gives producer direct access to a much larger market of potential clients than if biomethane was to be sold and used only locally. From the perspective of the biogas producer, injecting biomethane into the natural gas grid can, therefore, give access to a higher price than available locally. Depending on commercial factors, including the associated costs, this may mean a higher net price.

With correctly balanced incentives, biomethane is a commercially viable transport fuel as well: it can rely on existing natural gas infrastructure and contribute to reaching European climate targets in reduction of CO_2 and other GHG emissions [17].

4. THE PERSPECTIVE OF LATVIA

Transport sector in Latvia in 2018 accounted for 30.1 % of the total final energy consumption and 78 % of the total final consumption of oil products. More than 92 % of Latvia's road vehicle fleet is made up of vehicles powered by traditional fuels. Alternative fuels – biofuels, biomethane, CNG and LNG – are used in only about 6 % of all vehicles registered in Latvia. As for new passenger cars, between 2015 and 2017 the number of alternatively fuelled vehicles registered did not even reach 1 %.



(1) – Great Britain only; data on Bulgaria, the Czech Republic, Denmark, Greece, Slovakia not available

Fig. 6. New passenger cars with alternative fuel engines (2015–2017, %).

Source: Eurostat

Almost all fuel used for transport is imported, except for a small share of biofuel. In 2018, road transport accounted for 82.6 % of total transport energy, 11.9 % for international air transport, 4.8 % for rail, 0.5 % for river and maritime transport, and the remaining 0.2 % for inland air transport and energy used in pipeline transport. Transport accounted for 28.5 % of GHG emissions [20].

In order to promote decarbonisation of the transport sector and reduce the negative environmental impact of its GHG emissions, as well as to transpose the requirements of Directive 2014/94/EU, "The Development Plan for Alternative Fuels 2017–2020" (hereafter – Plan) was adopted. Its aim was to identify the necessary trends of research and analysis that would lead to the development of further policies on the introduction of alternative fuels in certain transport sectors to ensure their sustainability. The task of the plan was to identify the current situation in the field of alternative fuels and to determine further steps for the introduction and promotion of alternative fuels in Latvia [25].

The plan requires, for example, that by 31 December 2020, at least five publicly available CNG filling stations be established in Latvia, and by 31 December 2019, a review of tax policy, including the level of excise duty on natural gas as transport fuel, be performed. Concerning the CNG filling station target, it is likely that this could be achieved as there are already two public

CNG filling stations operating in Latvia and at least one more is planned to be opened in summer 2020. However, the agreement on the excise duty rate reduction for the natural gas as transport fuel has not been reached yet.

The excise duty on natural gas as transport fuel in Latvia is 99.6 EUR/1000 m^3 [29], while excise duty on natural gas used for heating is 17.07 EUR/1000 m^3. However, in 2019, as a result of negotiations between industry and policy makers, the Cabinet of Ministers of the Republic of Latvia drafted an order "Amendments to Cabinet Order No. 202 of 25 April 2017 "On Alternative Fuels Development Plan 2017–2020"", which, *inter alia*, provides an assessment of possible solutions to ensure the application of a reduction in excise duty on natural gas used as fuel in transport, if biomethane is added [20]. In the most optimistic case of the alternative fuel development in Latvia reflected in the plan, CNG and LNG combined would account for more than any other transport fuel in fleet, including diesel and gasoline, by 2050, but for fulfilment of such a high ambition much stronger and politically coordinated support to RG industry, first and foremost domestic biomethane production and its end use both locally and by means of natural gas grid, must be provided.

Table 3. Possible Alternative Fuel Development in the Latvian Transport Sector (2025-2050, %)

Fuel	Year			
	2025	2030	2040	2050
Diesel	67.2	64	34.4	23.1
Gasoline	20.4	12.1	12.8	10.6
LPG	7.1	13.9	7	6.4
LNG	0.5	0.7	2	2.1
CNG	2.5	4.5	19.9	30.2
Biodiesel	0.2	0.2	10.4	12.9
Bioethanol	0.7	0.4	0.5	0.4
Biomethane	0	1	1.9	0
Hydrogen	0	0	0	0
Electric cars	1	2.5	10.2	13.2
Electric public transport	0.5	0.6	0.9	1

Latvia admits that the absence of a national policy plan has jeopardized the use of natural gas in transport. It has established targets for the deployment of CNG refuelling points accessible to the public. The targeted number of CNG refuelling points could support a significant increase in CNG vehicles. As indicated in the national policy framework, Latvia also has no plans for the deployment of LNG refuelling points in its ports [10].

As for the beginning of 2020, there were two public CNG filling stations, one closed filling station and three natural gas filling points available in Latvia. In our country, the current annual consumption of CNG is 0.2 million m^3/year, while in neighbouring Lithuania and Estonia – 13 and 14 million m^3/year, respectively. A study by the Ministry of Transport on the Development of Alternative Fuels concludes that natural gas, including CNG, will be a transition fuel in a way to transport sector decarbonisation, so in next fifteen years, according to the most ambitious scenario of CNG filling station expansion along the Latvian natural gas distribution network, 172 CNG (69 of them along Core TEN-T network roads in 9 municipalities) and 6 LNG stations could be installed [25]. However, as Directive 2014/94/EU requires, distance between CNG filling stations in the TEN-T Core network should be150 km maximum; it is highly likely that the actual number of CNG filling stations will be smaller.

Design and construction costs of CNG filling stations range from 100.000 EUR up to 300.000 EUR or even more, depending on the installed equipment and filling capacity. As the Estonian experience shows, a medium-sized station with a capacity of about 100–150 cars/day costs around 150.000 EUR to build [26].

In Latvia, CNG vehicles could potentially be suitable not only for private use, but also for taxi companies, freight transport, public buses and minibuses. In part, it could be appropriate for inland water transport and light-weight agricultural vehicles, too. Good stimulus for development of the domestic CNG mobility sector would be the addition of modern CNG-powered buses to public transportation fleets in cities, as it is already done in Jekabpils, with economic benefits of running 7 CNG buses on the municipal lines – 35 % in fuel costs alone [27]. For example, in the Nordic countries, including Sweden, the share of CNG buses in individual municipal bus fleets is as high as 80 %, while in Italy, the number of CNG public buses exceeds that of conventionally fuelled buses [28]. However, as there is no sufficient CNG filling station network established in Latvia yet, many companies, including large municipalities with their own public transportation companies, are choosing a more convenient alternative for the near future. It is expected, however, that the requirements of Directive 2014/94/EU and possible synergy between natural gas and biomethane in transport will facilitate faster growth of CNG sector in Latvia in next ten years, and, as a result, large car fleet owners will be made more aware of the potential benefits of transition to CNG as a traditional fuel alternative.

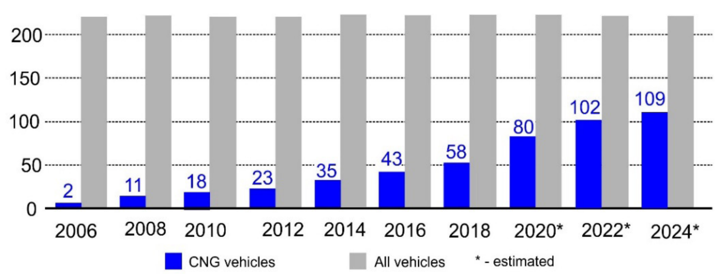


Fig. 7. Share of CNG vehicles in JSC "Gaso" car fleet.

Economic calculations for 59 CNG cars currently used by the natural gas distribution system operator JSC "Gaso" (by 2024 it is estimated to reach 109) – the owner of Latvia's largest commercial CNG vehicle fleet dating back to 2006 – show that if the car travels about 12.000 km/year, CNG engine pays off in about 7 years, but if it has a mileage of 30.000 km/year, then the payback period decreases to 2–3 years. Of course, each car manufacturer has its own models and the payback periods of CNG engines vary accordingly [9], [25]–[26].

However, given the current realities, it is expected that in the mid-term perspective oil-based fuels will remain the main source of transport energy in the EU and Latvia, although their importance will decrease already in the present decade. It is estimated that by 2030 oil resources and its products will still account for about 88 % of the EU's transport sector energy needs compared to around 84 % in 2050 [20]. Situation in the Latvian road transport sector will most likely follow the same trend with expected minor deviations, and there is a possibility that these deviations, with both political and industrial support, would bring long awaited growth and prosperity to one of the alternatives: natural gas – biomethane mobility.

5. CONCLUSION

The EU is about to significantly increase production and deployment of sustainable alternative transport fuels, as by 2025, about 1 million public recharging and refuelling stations will be needed for the 13 million alternatively fuelled low emission vehicles expected on European roads [1]. Transport should become drastically less polluting, especially in cities. A combination of measures should address emissions, urban congestion, and improved public transport. In addition, considerations regarding European emission trading for road transport are voiced, as a complement to existing and future CO_2 emission performance standards for road vehicles. It includes natural gas and RG mobility as well, where many differences in the national policies of the EU Member States still exist. Further and more effective blending of CNG and LNG, as well as biomethane into the European and Latvian road transport sector decarbonisation agenda is the only viable option foreseeable for overall gas mobility development in upcoming decades.

As for Latvia, the following conclusions on the matter could be drawn and recommendations presented:

- draft proposal of legislative regulation regarding development of the natural gas and RG mobility in Latvia should be drawn, focusing on a step-by-step strategy of road transport decarbonisation by means of natural gas as a) transitional fuel, b) fuel that at once could be sustainably used together with other RG, mostly biomethane;
- revision of excise duty for the natural gas as transport fuel should be performed with at least 50 % reduction of the duty for at least 5 years for natural gas and for undetermined period for biomethane (as biomethane is not currently used as the transport fuel in Latvia);
- extensive cross-sectoral study should be initiated and carried out in order to determine the actual stage of development of the Latvian biogas and biomethane production sectors with regard to investments into potential natural gas grid connections in locations of the highest and most effective biogas/biomethane production plant concentration with the most appropriate access to the natural gas transport and distribution grids;
- technical and economical case study should be proposed in order to establish technical options and financial investments needed for creation of a single natural gas injection point for one or several biogas plants (with estimated connecting infrastructure capital costs included and project financing breakdown presented);

- technically sound and economically justified estimates should be made for evaluating the effectiveness of biomethane plant *en masse* connections to the natural gas grid with regard to mid-term development plans of grid operators' infrastructure;
- study should be initiated and carried out in order to establish the incentives that would be needed to reach the maximum percentage of NGVs in the Latvian road transport fleet by 2050, and the measures to be taken in order to reach at least 1 % of NGV in the Latvian road transport by 2025. Prospects regarding setting up CNG fuelling stations in the areas without coverage of natural gas grid could be examined with possibilities to couple local, LNG fed natural gas grids with public CNG fuelling station infrastructure.

ACKNOWLEDGEMENTS

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