TALLINN UNIVERSITY OF TECHNOLOGY
SCHOOL OF ENGINEERING
Department of Mechanical and Industrial Engineering

HYDROGEN TRANSITION AT TALTECH CAMPUS

VESINIKUPÖÖRE TALTECH LINNAKUS

MASTER THESIS

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Tallinn 2022

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Department of Mechanical and Industrial Engineering

THESIS TASK

Student: Kätlin Värno, 192556

Study programme: MADM, Design and Technology Futures

main speciality: Design & Engineering

Supervisors: Martin Pärn

Hardi Koduvere

Thesis topic:

HYDROGEN TRANSITION AT TALTECH CAMPUS

VESINIKUPÖÖRE TALTECH LINNAKUS

Thesis main objectives:

1. Research the nowadays situation and green hydrogen opportunities;
2. Finding ways to design the TalTech campus climate-neutral with the help of the green hydrogen technology - solution space;
3. Developing a concept that supports the university's climate-neutral vision until 2035.

Thesis tasks and time schedule:

No	Task description	Deadline
1.	The theoretical first draft is ready	31.03.2022
2.	Practical part is ready	29.04.2022
3.	Thesis is reviewed	29.04.2022
4.	First pre-defence	5.05.2022
5.	Thesis is ready and submitted to reviewer	18.05.2022
6.	Sending the thesis for University	23.05.2022
7.	Thesis defence	30.05.2022

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Student: Kätlin Värno .... "......." 05.2022

Supervisor: Hardi Koduvere .... "......." 05.2022

Head of study programme and supervisor: Martin Pärn .... "......." 05.2022

CONTENTS

Eessõna

Põhiidee sündis koostöös TalTech Energeetika ja Mehhatroonika Instituudiga ning Eleringiga, kes võimaldas stipendiumi magistritöö teemal “Kohaliku võrgu kliima neutraalseks muutmine”.

Magistritöö on kirjutatud TalTechis. Lõputöö autor osales vesinikuenergia ja innovaatiliste tehnoloogiate kursustel Taani Tehnikaülikoolis. Tehnilised vesinikuteadmised on töös põimitud disainmõtlemise praktikatega.

Hardi Koduvere on energeetika ja mehhatroonika instituudi doktorant, kes aitas koguda TalTechi ülikoolilinnaku energiasüsteemist olemasolevaid andmeid ja juhendas lõputöö praktilist modelleerimise osa. Professor Martin Pärn aitas integreerida ning mõtestada lahti disainmõtlemise lähenemisviisi töösse. Tänan rohepöörde prorektorit Helen Sooväli-Seppingut, kes tutvustas TalTechi kliimaneutraalsuse saavutamise eesmärki aastaks 2035 ja oli abivalmis tõstatama vesiniku teemat laiemalt ülikooli tasandil. Suur tänu Tauno Ottole, kes aitas korraldada TalTech vesiniku esimese töötoa ülikooli tasemel, aidates kaasata koostööpartnereid.

Märksõnad: TalTech, rohevesinik, süsteemidisain, magistritöö.

Preface

Thesis main idea was developed through cooperation with TalTech Energetics and Mechatronics Institute and the Elering company, who provided the scholarship on making the grid network climate-neutral locally.

The master thesis is written in TalTech. The author participated in hydrogen energy and innovative technology courses in the Denmark University of Technology. Technical hydrogen knowledge is embedded with design thinking practices.

Hardi Koduvere is a researcher in the Energetic and mechatronic institute who helped gather existing data from the TalTech campus energy system and guided the practical part. The excellent support was also from professor Martin Pärn who helped integrate the design thinking approach into work. Also, TalTech's green transformation vice-rector Helen Sooväli-Sepping supported the insights about the TalTech strategy and future campus climate ambition. A big thanks also to Tauno Otto, who helped gather hydrogen companies and specialists into workshops.

Keywords: TalTech, green hydrogen, system design, master thesis.

List of abbreviations and symbols

AEC - alkaline electrolyser

APS - Announced Pledges Scenario

CAPEX - capital expense

CCS - carbon capture and storage

CHP - combined heat and power

CO_2 – carbon dioxide

DSO - distribution system operator

EU - European Union

EC - European Commission

IEA – International Energy Agency

IoT - ethernet of the things

IRENA- International Renewable Energy Agency

LCOE - levelised cost of electricity

LCOH - levelized cost of hydrogen

NZE – Net Zero Emissions by 2050 Scenario

O&M - operation and maintenance

OPEX - operating expense

PEMEC - polymer electrolyte membrane electrolyser

PESTEL - political, economical, social, technological, environmental, legal model

PV - photovoltaics

SDS - Sustainable Development Scenario

SOEC - solid oxide electrolyser

STEPS - Stated Policies Scenario

TSO - transmission system operator

1. INTRODUCTION

The world's most critical problem today is climate change, which is highlighted as one of the main problems in the International Energy Agency (IEA) and European Commission (EC) strategies. It is critical to develop and provide new solutions for reducing CO_2 emissions to reduce the temperature rise worldwide. There are ongoing development initiatives, well-communicated strategies, and paths. For instance, IEA's World Energy Outlook 2021 and Net Zero Emission (NZE) 2050 reports see a tremendous potential solution in hydrogen. Additionally, the European Commission has set restrictions with the "Fit for 55" strategy that pursues businesses to change their priorities in Europe to achieve agreed hydrogen goals globally. Nowadays, the energy industry is under high pressure from climate change. [1, 2, 3]

The share of fossil fuels in the energy sector is around 80%. With the energy transitions, the aim is to replace carbon-intensive fuels consumption with low-carbon energy sources. Low-carbon energy sources support the major shift of reducing the greenhouse gases to a minimum to achieve climate-neutrality. However, challenges appear through all green energy and hydrogen value chains. [4]

- How to adapt the current electricity and gas grids to clean energy production, distribution, and storage technology to achieve climate neutrality?
- How to design systems that do not pollute the environment as fossil fuel-based energy production does?

The world needs to gain a common understanding of climate-neutral, circular, safe, and regenerative energy. [4]

This thesis will look into different approaches to achieving clean energy production locally from renewable energy sources, considering integrated hydrogen-based solutions and the related costs.

The analysis and formulation of each approach rely on the design thinking methodology. Concepts are designed and visualised with the Energy Pro software that helps to analyse the energy system and technology behaviour (energy production, storage, and consumption) and related costs.

The work supports the long-term strategy of TalTech campus by providing theoretical case study analyses for making the TalTech campus's energy system climate-neutral.

1.1 Field justification

When planning for the future energy system, switching to a more environmentally friendly economic model, hydrogen as a clean energy and storage source creates interdependence between different sectors. Hydrogen energy makes the energy system more flexible, helps to reduce system inefficiency, and supports reducing carbon emissions. Hydrogen supports other socio-economic benefits such as economic growth, job creation, and industrial competitiveness. [5]

1.1.1 The problem area

TalTech's existing energy system is based on natural gas fuel and non-renewable electricity. The carbon footprint of the energy supply of buildings is evaluated at 1.5 tons of CO_2 equivalent per person per year. The existing energy system has no flexibility and alternative opportunities to produce, store, or export energy. Hydrogen has a significant potential to cover the previously stated functionalities. [6]

Hydrogen infrastructure in Estonia is insignificant. Elering is doing the research studies on the goals set by the European Commission in the summer of 2020 to set the concept of transition to a hydrogen-reliant energy system. Likewise, Estonia does not have a hydrogen roadmap, but the Stockholm Environment Institution prepares draft legislation for the Estonian Environmental ministry. The latter document includes three key areas on how to produce and store the hydrogen and what might be the hydrogen consumption methods in Estonia. [7]

While looking at the aspects of education and knowledge of hydrogen, it has not been abundantly addressed in the TalTech's curriculum. There is no significant working experimental, measuring, nor sample equipment.

1.1.2 Hypothesis

There is an opportunity to create a vision for the TalTech campus-based hydrogen power system by 2035. TalTech can produce, store and consume electricity efficiently, cost-effectively and gain flexibility through installing hydrogen technology. The vision of the TalTech Hydrogen Campus can be the basis of the first hydrogen energy integration research projects in Estonia. The TalTech Hydrogen Campus and the related research projects enable fostering a qualified workforce for developing the currently next to nonexistent hydrogen sector in the greater economy.

1.1.3 Research questions

1. What are TalTech campus's environmental ambitions, and what role does hydrogen have in the long-term strategy?
2. How can a hydrogen-reliant energy system bring economic benefits to the TalTech campus?
3. How does the concept of hydrogen campus help create value for teaching and research?

1.2 Methodology

The purpose of this master thesis is to provide concepts for a TalTech campus that could be more cost-effective and climate-neutral by 2035.

Firstly, a thesis desktop study is necessary to get insights into how the future might be for the TalTech campus. Besides the IEA sources, there are already several other scenarios such as NZE, APS, STEPS, and policies from International Renewable Energy Agency IRENA and EU ongoing hydrogen projects where the main insights for the thesis are collected. Through the desktop research, the holistic picture of the transition to hydrogen-based systems, including the renewable energy for buildings is done.

The strategy from the design thinking and tools implementation will be practised throughout the thesis. The thesis analysis relies on the following parts.

1. Empathising the topic with users;
2. Defining the users' needs, problems, and insights via workshops and consultations;
3. Ideating how to approach challenges and create ideas for concepts;
4. Prototyping and reiterating the concepts;
5. Proposing the final concept;
6. Testing the proposed concept;
7. Making conclusions and defining the further works.

The "Zooming-in and zooming-out" technique is applied during the work process to understand the holistic picture of users' perspectives and the essential details of the related challenge. The "Zooming-in" helps to understand green hydrogen and the TalTech campus at a detailed level. To this end, interviews and workshops have been made with the TalTech green transformation Vice-Rector, professors, students, and energy companies. The "Zooming-out" happens through stepping back and judging the concepts made and gathering the feedback through user testing or trying to see new perspectives.

Furthermore, a PESTEL model helps to understand the current situation surrounding the integration of hydrogen into energy system by analysing political, economic, social, technical, environmental, and legal topics. The advantages of a PESTEL analysis are that it can warn of potential threats and opportunities, encourage businesses to consider the external environment, and helps organisations understand external trends. The disadvantages occur from the perspective of the model’s simplicity. The most significant disadvantage of the PESTEL model is that it is only based on assessing the external environment. However, in the analyses in this thesis, there are considered micro forces, where organisations; TalTech campus, and its end users. Therefore, the disadvantage is mitigated. [8, 9]

Gathering all the knowledge together, highlighting and concluding the essential parts of the system design helps to analyse the pain points, relationships, and opportunities between the technical approach and end-users people's attitudes, knowledge, and openness that might influence the proposed further work. Process and context maps are made through the work to highlight the main questions, pain points, opportunities, and stakeholders. Mappings help to understand the root causes and prepare for the ideation and prototype phase.

Finally, concepts are created and tested with Energy Pro software. The fundamental interactions between energy demands, availability and relevant energy technologies have been considered. A designed model with the Energy Pro software solves the energy system. After the testing, a finalised concept is proposed with further discussion. [10]

2. THEORY

The theoretical part will give a holistic understanding of TalTech's current situation and hydrogen. The analysis is made through different lenses as political-legal, economic-social, technological, and environmental perspectives considering the EU, Estonia's, especially TalTech context. The last part gathers information and considers approaching TalTechs' existing energy infrastructure with hydrogen concepts. **Fig. 1** shows the analysis process approach and questions.

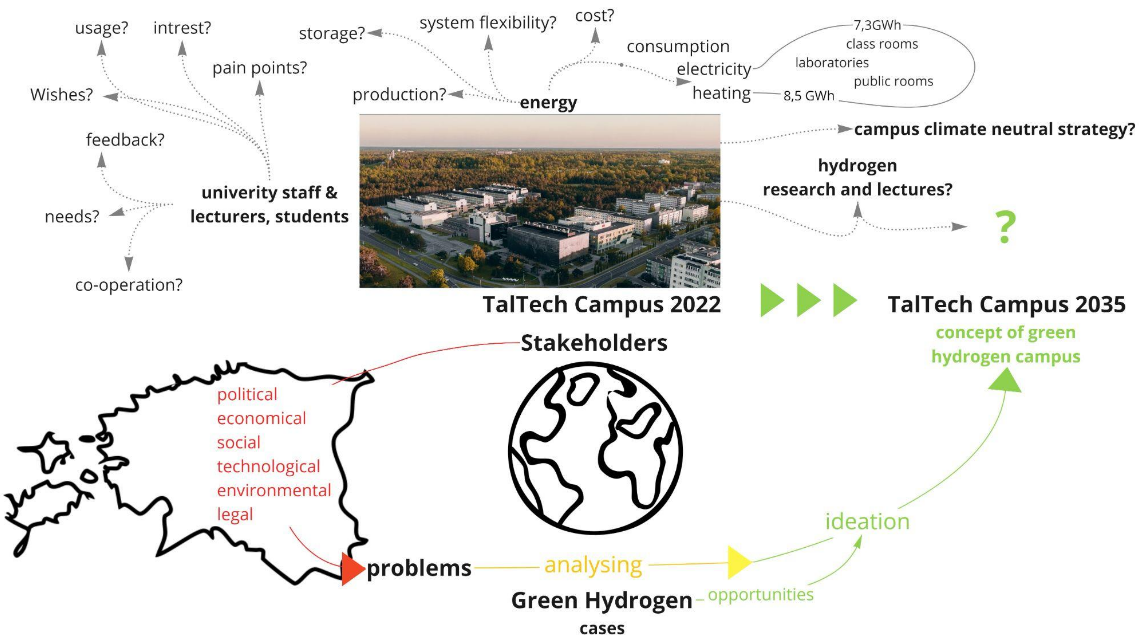

Fig. 1 Analysing process

2.1 Emphasising

Fig. 1 helps to systematically approach questions and topics around green hydrogen and main-user TalTech campus. There is a need to discover the root causes and highlight them with the opportunities to design the concept of a green hydrogen campus.

2.1.1 TalTech campus

In this thesis, the focus has been set on the main building complex of TalTech's campus in Tallinn. Building sections are referred to as SOC, LIB, NRG/STU, U01, U02-U2B, U03-U03B, U04-U04B, U05-U05B, U06-U06A. Overall, there are 34 buildings on the campus - lecture halls, laboratories, restaurants, library, and common areas constructed starting from the 1960s. [11]

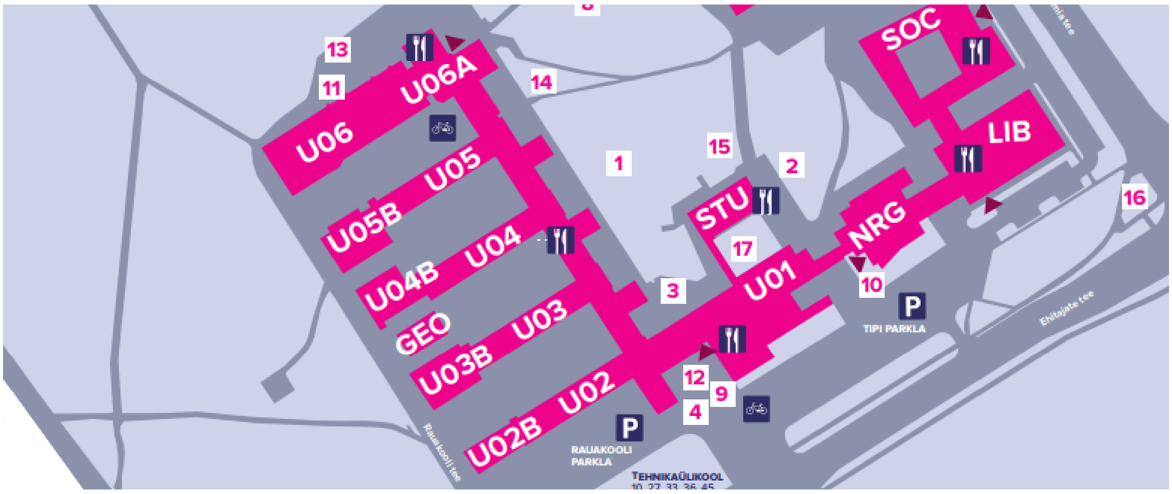

Fig. 2 TalTech main building complex

Considering the end-users of an energy system, the TalTech campus serves 10 000 students and about 1000 academic university employees. [12]

TalTech climate strategy

TalTech's primary strategy is *"Smart and energy-efficient environments - creation, development, and implementation of internationally breakthrough smart and energy-efficient environments in areas important to the Estonian economy."*

TalTech campus has a 2021-2025 development plan wherein the university rector Tiit Land has stated, *"The mission is to be a leading provider of technical and economic education, a leader in technical science and smart technologies. The University of Technology is distinguished by its climate and energy efficiency and is the future city* *as a test centre. Regardless of location, the university forms a whole. One of the goals will be that TalTech develops a smart and environmentally friendly university."* [13]

TalTech strategic goals align with the thesis's aim insofar as the future-oriented approach is represented. The study case could raise the transparency and knowledge about hydrogen as a future opportunity at university level. The question here is how might the hydrogen study case create value for campus on the level of energy management and in research and teaching?

Interview - 1 - [2021 October]
The first interview was held with a former Administrative Director of TalTech. He stated, *" The university's plan to achieve climate neutrality by 2035 is still valid, and I took responsibility for this year and said roughly the campus CO_2 footprint. The big plan has been to make different pilots and demos and create a LivingLab with the people in the town. For example, a digital audit of university-based buildings with the Smart City Centre of Excellence is already underway. The DigiAudit platform develops scientific tools to analyse buildings' energy use and indoor climate, visualise results, and diagnose and renovate renovations and renewables.*

The area of responsibility has been the physical environment and energy of the entire university. From the autumn, the university's green topics and sustainability issues are vice-rector Helen's area of responsibility. He hopes that Helen will offer substantive points of cooperation that will be useful both in the scientific key and in the key to urban development. "

Interview - 2 - [2021 November]
The second interview was held with the green transformation vice-rector. The main questions were:

Question 1: What are the campus pain points?
Answer: "*The campus footprint is an essential topic that needs to be defined methodically. The second one is that the TalTech campus is now like a closed city; there is no fixed walking structure. How do we start opening the town to the town so that people can stay here? How to make the campus attractive and lively so that the space supports being on campus?"*

Question 2: How does TalTech move forward with the green transmission as a campus?

Answer: *"The climate smartness is represented through digitization, green transformation, and campus circular economy. The first phase is to map the TalTech campus data and opportunities. TalTech campus does not have a strategic plan with clear actions by 2035 on establishing a climate-neutral campus. The Council of TalTech expects to get insight into today's campus footprint. The Year 2035 should be over-controlled as well as the communicated CO2 footprint. While looking at other universities in the Nordic countries and what has come with opening a new EU budget that has a mission of 100 climate-neutral cities by 2030 where cities should become climate-neutral in 9 years, Tartu has applied. It is necessary to review how and why universities reduce their carbon footprint scientifically."*

Question 3: Have there been discussions about hydrogen at the university level, including it in campus strategy and lectures?
Answer: *"The hydrogen topic has been on the table very briefly. Overall in a long-term vision, there is no hydrogen topic in the Council of TalTech."*

Question 4: What about if the study case provides the insights for the campus climate-neutral strategy actions?
Answer: *"If we get an overview of the possibilities that would be possible in the campus context, then we could take it into the discussion because no substantive solutions have been devised yet for spring 2022."*

Question 5: To what extent would the projects be feasible in a manner of helping to achieve campus climate goals while the value for university research and teaching is represented?
Answer: "*University Council dictates the budget for TalTech. There is an issue with the lecturer's low wages; this is a priority for university to raise wages. University is seeing that the laboratories and equipment are getting more expensive. Making a world-class investment on campus is not the main priority. It is different from Nordic universities, where they rent buildings. TalTech has its building, so the opportunity to decide remains.*
If there are scientists interested in doing science, then there is support from the university."

The discussion clarified that hydrogen relevance needs to be enhanced in university. First of all, hydrogen is expected to have a critical role in achieving climate neutrality. Moreover, universities have a substantial role as higher education institutions and should be leading the initiative in Estonia on hydrogen topics. Furthermore, if a university wants to be seen on an international level, the further integration of new hydrogen-related technology study cases, student groups, lectures, cooperation with other hydrogen research thriving universities, new ideas, and visions are essential and should be covered.

Stakeholder workshop - [2022 March]
The workshop was on 09.03.2022. Participants were selected from TalTech university's different colleges and companies working with TalTech on the research aims. Four student hydrogen enthusiasts, Vice-vector of green transformation, electrical engineering lectors and specialists, Estonian Hydrogen Association representative, Elering, and Federation of Estonian Engineering Industry insights.

The main agenda for the meeting was to look into existing works, problems and ideate how TalTech could move forward from that point where all stakeholders will work together towards one aim to integrate and get new knowledge from each other in the hydrogen field. The main aim was to collect all stakeholder's perspectives.

Overview of ongoing activities

- The Vice-Rector of the green transformation sees that it is positive if students show interest and take initiative. Research in the hydrogen area should be prioritised, including introducing an international element through collaboration with other European universities.
- The active group of four students has already been researching hydrogen electrolysis processes and organising the hydrogen conference in TalTech, where they have been in contact with other fellow students interested.
- ViDRIK is the Taltech Ida-Virumaa college hydrogen project where different solutions and opportunities are being considered for education and training. The ViDRIK project creates a demo centre or factory. Mainly with smaller wind turbines and solar panels to generate electricity. Using the hydrogen solutions in college in smaller buildings is the one goal. From the technical side, they have said that there is a choice of equipment and systems: small scale wind turbine, electrolyzer, high-pressure pump, fuel cell (providers: PM Module 58, PowerUp); energy management system toolkit Enapter EMS, engineer Turnkey solution UMSTRO GmbH and others.
- There was also a survey from the Federation of Estonian Engineering Industry where companies pointed out the importance of the topic of hydrogen and the need for training.

Main insights from companies' view

- Urgent need to take action on hydrogen to bring green energy, storage capacities, that provides flexibility and lower energy prices into the energy system. Could not wait until enough renewable energy is available to transition to green hydrogen immediately.
- One place for discussion with the Federation of Estonian Engineering Industry would be the use of hydrogen in the industrial sector. The issue on a large scale and in competition needs to be addressed. The crucial topics were: future fuels and energy production in manufacturing plants.
- Elering looks at the energy system as a whole. The critical question for them is how to ensure energy security and the security of supply. While creating wind farms, the energy system needs to be complemented by storage in order to ensure a continuous energy supply - hydrogen would be one option to consider. Elering will not produce hydrogen itself.

Brainstorming, how to proceed together? Answers and questions.

- There could be an initiative where these issues could be encountered in an emerging and ongoing way.
- Include the topic of hydrogen in curricula, including a laboratory setup for experimental studies.
- The onset of distributed renewable energy production highlights the maturity of the autonomous microgrid concept. TalTech as a university is ideally placed on studying both the related theoretical and practical aspects of implementing a microgrid involving hydrogen-based technology.
- The critical question is what is the bigger picture of the hydrogen revolution and the bigger picture of the campus. What are the missing gaps that should be acknowledged with the hydrogen campus concept?
- The university will undoubtedly play an essential role in generating hydrogen know-how and training engineers.
- It is important to support creating a competitive environment in which the energy industry would build the hydrogen-based energy production and storage units in Estonia. The basis for such an environment is a comprehensive strategy outlining actions related to a transition to hydrogen. This would increase the competitiveness of the Estonian energy sector in comparison to the energy sectors in connected markets.

The active group of students at the workshop asked for a space where anyone interested in hydrogen could visit the laboratory and study; therefore, creating the hydrogen organisation in TalTech is an opportunity primarily for students interested in hydrogen topics and research projects.

If the university's hydrogen research group deals with new ideas and systems development. How and where to start?

- The Faculty of Engineering supports the formalisation of this initiative. It is necessary to create an action plan and determine whether to create an NGO or a student organisation.
- It is essential to make hydrogen topics and new organisation visible at university level while visiting hydrogen conferences but creating the space in a website where possible partners can find the TalTech hydrogen research group/organisation, research projects, etc.
- Lastly, establishing contacts with international student clubs, and NGOs.

In conclusion, the workshop brought hydrogen obstacles and ideas to tackle. After a month of the workshop, the hydrogen organisation in TalTech has been established by a hydrogen active group of students - called TiVo - TalTech Engineering Department Hydrogen Organisation. TiVo started to establish contacts while connecting students, companies, and partners; investigating possible research projects; and wanting to raise the hydrogen knowledge in the society.

The essential questions that were asked were:

- "What is the bigger picture of the hydrogen revolution and the bigger picture of the TalTech campus for achieving climate neutrality?"
- “What are the missing gaps in TalTech that should be acknowledged with the hydrogen campus concept?”

2.1.2 Hydrogen

Hydrogen H is a chemical element with an atomic mass unit of 1, 008 u. A hydrogen atom consists most commonly of one proton and one electron. The hydrogen molecule H_2 is the smallest molecule, consisting of two hydrogen atoms. Hydrogen higher and lower heating value is 142 MJ/kg and 120 MJ/kg. [14]

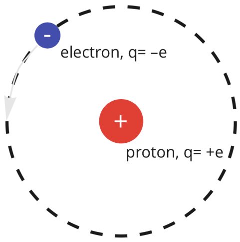

Fig 3. Bohr Model of the hydrogen atom

Why hydrogen?

Hydrogen can be used to store and release energy. Also, hydrogen has chemical-physical advantages compared to other fuels

- High heating value per hydrogen weight;
- Clean emissions while using the water electrolysis technology.

Other chemical-physical characteristics carry intrinsic challenges

- A low density means low heating value per volume;
- Difficulties with compressing and storing the hydrogen due to low density;
- The liquefying process consumes much energy, mainly because of the hydrogen's low evaporation temperature (-250,15 ∘C). [14]

The trend from the NZE report predicts that natural gas use in the power sector will decline globally by more than 80% in the 2030s. Natural gas will be used for power generation in 2050, accounting for around 1% of electricity generation worldwide (compared with almost a quarter today), mostly from facilities equipped with carbon capture and storage (CCS). Energy demand in buildings also transitions quickly away from natural gas. It gives hydrogen fuels and technologies an opportunity because of the demand for low emission energy and heat production. Hydrogen can cover a large amount of energy demand while taking over the existing natural gas share of energy provision by meeting new demand for low emissions fuels and industrial feedstocks; and converting electricity to a storable fuel to assist with the system integration of renewables. [4]

The most significant hydrogen usage growth is predicted for the transport and industrial sector, but hydrogen importance is growing in the building sector over the decade. **Fig. 4** shows the NZE report about global hydrogen demand through different sectors. [14, 15]

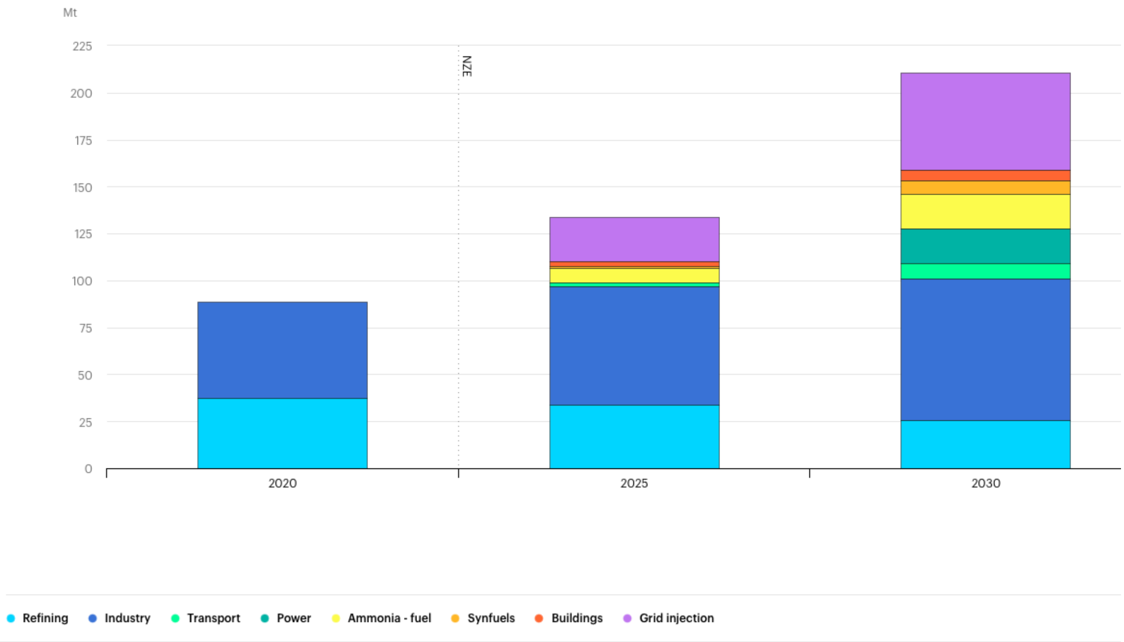

Fig. 4 Global hydrogen demand by sectors 2020-2030, (IEA) [15]

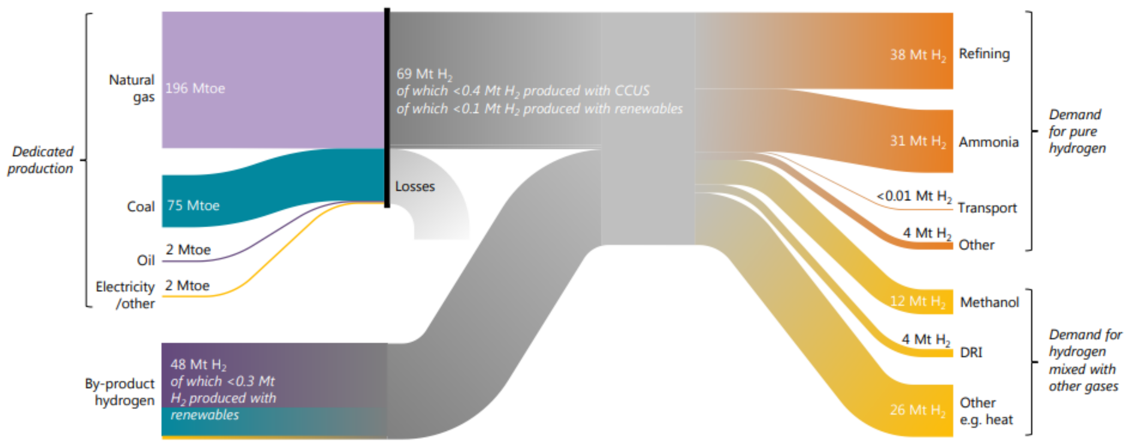

Fig. 5 Nowadays hydrogen value chain [16]

Fig. 5 illustrates today's hydrogen value chain. The dedicated energy production is based mainly on natural gas, coal, and oil fossil fuel resources. Today, demand for pure hydrogen is represented in the refining, transport, and ammonia industry. Demand for hydrogen mixed with other gases is methanol and heat. [16]

In 2020, 80% of all hydrogen produced was based on natural gas and coal because the related production methods were the most cost-effective in scale. While considering the year 2030, there are predictions from the NZE scenario wherein total clean hydrogen production reaches 200 Mt H_2, 70% is produced using low-carbon technologies (electrolysis or fossil fuels with CCS). For instance, the EU project

CertifHy is developing hydrogen certification schemes in Europe to set a better base for green hydrogen preference. [16]

Fig. 6 shows different types of hydrogen production possibilities. The thesis is focused on green hydrogen which is produced via the electrolysis process.

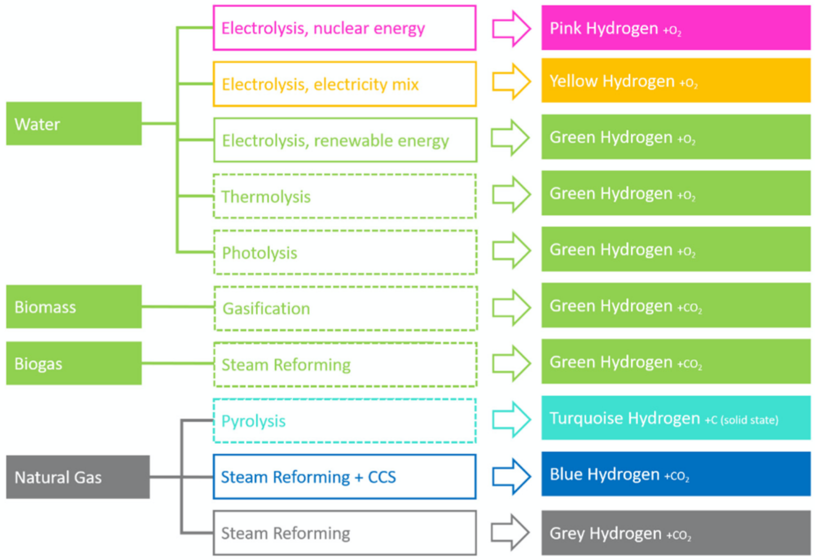

Fig 6. Hydrogen production types - dashed boxes are not commercialised processes [17]

Green hydrogen in TalTech buildings

It is proven that green hydrogen can be stored and transported, which gives the possibility to convert and store renewable electricity to cover energy demands all around the year. Hydrogen-based storage systems can be combined with buildings' energy management systems to lower the buildings' operating costs and carbon intensity. 25-year-old buildings have energy-intensive heating loads (IEA). TalTech building is already 60 years old; therefore, large-scale peak power or energy storage capacity is needed. More favourable are large-scale cogeneration hydrogen concepts because they can be more cost-effective in both CAPEX and OPEX (IEA). [16]

Hydrogen demand in buildings includes existing natural gas infrastructure, heat densities, other building energy needs and safety considerations, cost and consumer acceptance, and various policy-legal challenges. The demonstration projects with solid public and private participation can help overcome the barriers. The decision-making for energy use in buildings is complex and depends on building type, location, ownership, customer preferences, equipment costs, energy prices, and overall convenience, amongst other factors. [16]

2.2 Political and legal view

This chapter assesses the policies of legislative bodies and political groups responsible for hydrogen integration success through the political and legal lenses. It gives insights into the political environment that sets the base strategies for hydrogen. The legislation occurs at several levels with international - EU - Estonian and the Estonian local government measures.

In recent years, Estonia has taken several strategic steps to support a transition to hydrogen (for example, in the Association of Hydrogen Technologies in 2016, various working groups have been formed at the level of government and ministries). However, the use of hydrogen has not yet been reflected in Estonian sectoral strategies and legislation. [19]

2.2.1 EU

The EU objective is to reduce greenhouse gas emissions by a minimum of 55% by 2030 and reach net zero emissions by 2050 compared with the year 1999.

In order to reach these ambitions, European countries need to work on large-scale deployment of hydrogen use (EC). The focus should prioritise the production and use of green hydrogen, relying on wind and solar energy. In addition to the ambitious 2050 climate neutrality target, the European Union launched its Hydrogen strategy in 2020. The report says that there are many reasons why hydrogen is a crucial priority to achieve the European Green Deal and Europe's clean energy transition. *"Hydrogen has a potential to be the bridge of the gap, as a vector for renewable energy storage, alongside batteries, ensuring backup for seasonal variations and connecting production locations to more distant demand centres,"* (EC). The EU published a climate-neutral vision in November 2018, saying that Europe has a competitive position with clean hydrogen technologies manufacturing and is also well-positioned in a global context of development where clean hydrogen is an energy carrier. [20, 21]

The European Commission has created the European Clean Hydrogen Alliance, which brings together over 1500 stakeholders of the industry, civil society, research bodies, investors, and public authorities in the value chain. The Alliance has mapped out the barriers to the large-scale deployment of hydrogen and has proposed mitigating measures. More than 750 hydrogen energy projects have been launched in the coming years all over Europe. [20, 21]

What are the main steps to consider next?

1. The supply side needs to address the availability and affordability of renewable electricity and low carbon hydrogen. The renewable energy usage ambitions have to be raised, solving the administrative barriers that now slow down hydrogen implementation to the existing grid.
2. On the demand side, who can influence hydrogen usage; in the market and provide visibility while facing the additional operational expenditures generated by the high hydrogen costs.
3. The coherent green procurement creation that the countries are missing.
4. CO2 pricing mechanisms correlations, because the CO_2 market today is not satisfying.

These might be the approaches that will make the hydrogen more attractive to get to the hydrogen field more investments and make the hydrogen more approachable to other fuels. The goal is to simplify the hydrogen scale-up processes and technology implementations. [22]

Today using hydrogen to stabilise the residual load in the power system is non-competitive compared to natural gas. There is also a need to revise electricity markets to ensure that the flexibility and electrolyzer can manage congestion and provide balancing reserves. [22]

Hydrogen infrastructure

The natural gas infrastructure exists, but it is not widely used and designed for hydrogen transport and storage infrastructure that could enable large-scale deployment of hydrogen across the energy system. Any investment in gas infrastructure should be hydrogen-ready to avoid carbon lock-in. In 2022 April the EU came out with the help of the European Hydrogen Backbone initiative with the vision of infrastructure that covers 28 countries **Fig. 7**. [22, 23]

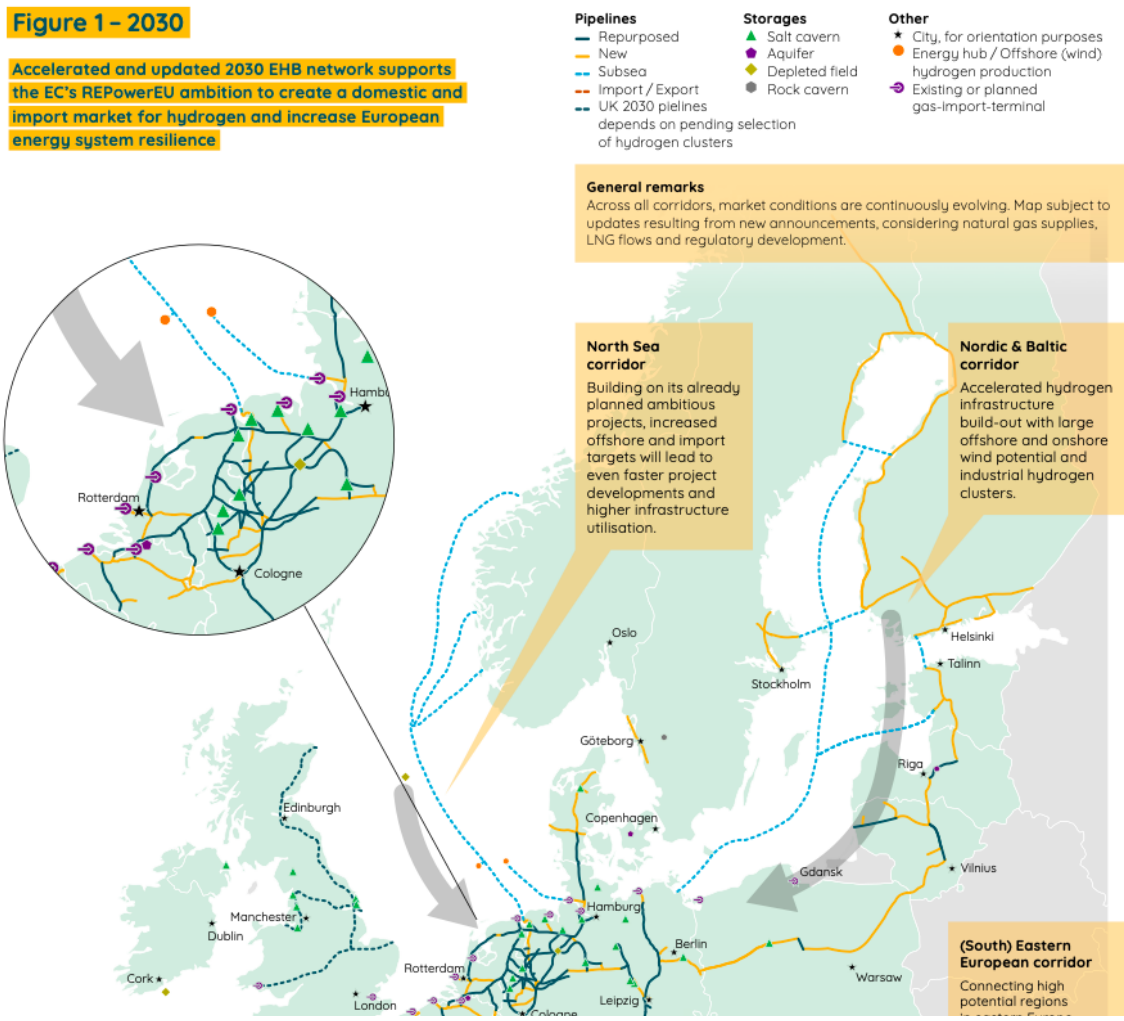

Fig. 7 Hydrogen infrastructure proposal for Baltics and Nordic region by 2030 [23]

The vision covers the economic and technical aspects of building the hydrogen infrastructure. In contrast, the European Commission's hydrogen and the decarbonized gas package has an essential role in fostering the market competition and security of supply hydrogen pipeline infrastructure (published in December 2021). The length of the hydrogen pipelines is planned to be around 53 000 km by 2040, which is based mainly on repurposed existing natural gas infrastructure. The average cost of 0.11-0.21 € per kg of hydrogen is cost-effective for large-scale and long-distance hydrogen transport. [22, 23]

European climate protection, energy system resilience, and supply security are prioritised. The Ukraine invasion by Russia makes it straightforward for the EU countries to have a more urgent transition to clean energy to maintain energy independence. The EU made the REPowerEU plan consisting of renewable hydrogen production and import plans while reducing the use of fossil fuels in buildings and power systems by boosting energy efficiency, increasing renewables and electrification, and addressing infrastructure bottlenecks. [23, 24]

Hydrogen in buildings

While the policy framework set up in the EU and its member states concern themselves with large-scale systems, they are to be operated through strictly local solutions. This thesis studies the building's energy and heat challenge in the context of green hydrogen transition, production, distribution, and consumption. From the sight of the EU building strategy: *"EU buildings are responsible for 40% of energy consumption and 36% of greenhouse gas emissions. EU scenarios for a climate-neutral 2050 show that the share of direct electricity in heating for residential buildings is expected to grow to 34%."* [23]

There is an understanding that hydrogen is an integrated energy system that combines electrification and other renewable and fossilised energy sources. However, in terms of market, regulation, funding, and financing, technology and supply chain are the barriers slowing down hydrogen deployment in the buildings. Mainly, insufficient level of synchronisation across the hydrogen value chain. There is a lack of coordination between

- sourcing green hydrogen
- investments in hydrogen-ready infrastructures and
- investments in hydrogen end-use equipment. [22]

To solve the barriers, creating an effective European market for hydrogen, as indicated by the EU Hydrogen Strategy, is needed as soon as possible. Moreover, the pathway for clean hydrogen is required in order to be understandable for the consumers; otherwise, unknowingness holds back consumer demand for hydrogen technologies. As the current policy framework offers limited technological openness, the direct use of (green) electricity-based technologies has advantages. The "Electrification" approach does not seem feasible in the long term, neither at the system nor at the consumer level in the time frame required by the EU climate targets, as mentioned in the EU Commission scenarios for climate-neutral 2050. [22]

Legalisation

From the perspective of the legal landscape, the renewable energy projects that were successfully implemented a few decades ago have set the tone for future projects and the pace for new regulatory foundations. It is essential to start also with the hydrogen projects. While the legal landscape where hydrogen currently exists differs from jurisdiction to jurisdiction, there are no hydrogen laws in many countries because it is challenging to navigate compared to the other energy source treatments. Some of the laws are applicable for hydrogen if it suits methane, but the risks of leakage and flammability are different. It means further safety regulations for significant dangers.

Still, if there is a lack of legalisation, ongoing policy development will set the base for the hydrogen economy. Firstly the hydrogen market needs to take more shape than the national strategies, and new emerging laws will also be made. [25]

2.2.2 Estonia

In recent years, Estonia has taken several strategic steps to support the use of hydrogen. Organization-wise, the Estonian Association of Hydrogen was established in 2016. Also, other working groups are formed on the governmental level. However, the use of hydrogen has not yet been reflected in several relevant sectoral strategies and legislation in Estonia.

Besides the hydrogen roadmap, the Estonian parliament accepted on the 12th of May 2021 the strategy "Eesti 2035", where the main message for the energy sector is to move to climate-neutral energy production while ensuring energy security. Under the planned activities, the focus areas are the following:

1. regarding future hydrogen integration about the transition to climate-neutral energy production that covers the gradual reduction of the share of oil shale energy and the development and deployment of new climate-neutral energy production and storage solutions;
2. alternative energy supply consideration and selection;
3. growing the renewable energy contribution and balance in the field of security, environmental protection,
4. the population's interests on land and sea while allowing a favourable regulatory environment. [26]

Estonia’s readiness for hydrogen

Hydrogen is not used widely in Estonia. However, some industrial production units are in Estonia, such as Narva power plants wherein heat exchangers are hydrogen. While evaluating the potential usage of hydrogen in Estonia’s context, the transport sector is the most favourable, where hydrogen can reduce emissions immediately. One example is Tartu city planning to integrate three hydrogen buses into its public city bus transportation system. Hydrogen is planned to be produced from green electricity through an electrolysis process. If the hydrogen is leftover from buses, the remaining hydrogen will be diverted to a public service station, giving rise to additional customers. The hydrogen bus project would be the first public hydrogen filling station in Estonia. The green hydrogen project partners are AS Alexela, Eesti Energia AS, and AS GoBus, ensuring buses’ production, refuelling, and procurement. [19, 27]

Besides the transport sector, natural gas accounts for most of the buildings in Estonia in the building sector. In particular, micro-cogeneration plants could potentially be installed in the building sector, as the addition of hydrogen to the existing natural gas network should be replaced or mixed with the hydrogen. From the point of view of electricity generation, it would be reasonable to produce hydrogen primarily to generate backup energy to cover off-grid areas and provide backup energy to vital services such as telecommunications and medical services. [19]

2.3 Economic and social view

The economic forces could affect hydrogen integration while looking into trends, taxation, and technology costs. Society's views, beliefs, and values should be discussed to consider how people think about hydrogen and its integration.

Green hydrogen price

Interest in low-carbon hydrogen production is increasing slowly due to high hydrogen production costs, significantly depending on the region produced by the hydrogen. In Europe and China, the prices are higher compared to the other parts of the world (IEA). There are two concurrent price trends in Europe in the upcoming decades. On the one hand, fossil fuel-related costs are expected to rise due to growing scarcity and CO_2 emission quota prices. In the second part, we anticipate a reduction of green hydrogen prices due to expected long-term electricity and electrolyser costs. [18]

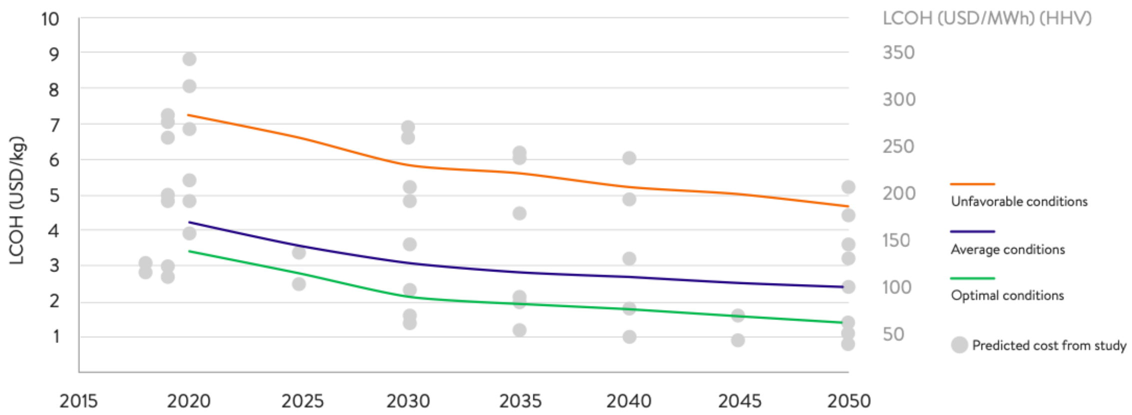

Fig. 8 Green hydrogen cost over the decades [28] LCOH - Levelized Cost of Hydrogen.

Fig. 8 shows that on average conditions, green hydrogen price by the year 2035 will be projected at 2,8 euros per kg, 110 EUR/MWh. Today's natural gas price is around 100 EUR/MWh; according to a trading price, it is predicted that natural gas price is increasing because of CO_2 taxation and the availability of natural gas. According to Trading Economics' global macro models and analysts expectations, EU Natural Gas is expected to trade at 110,92 EUR/MWh by the second quarter of 2022. They estimate it to trade at 150,47 EUR/MWh within 12 months. [28, 29]

The overall cost of hydrogen production is determined in the range of 50%-90% by energy and electrolyser costs. [17, 28]

Electrolysers costs

The expected reduction of electrolyser prices of electrolyer NZE and APS scenarios can be seen in **Fig. 9.** According to NZE and APS, it is expected that electrolyser costs will drop by 65-70% by the year 2035. [17]

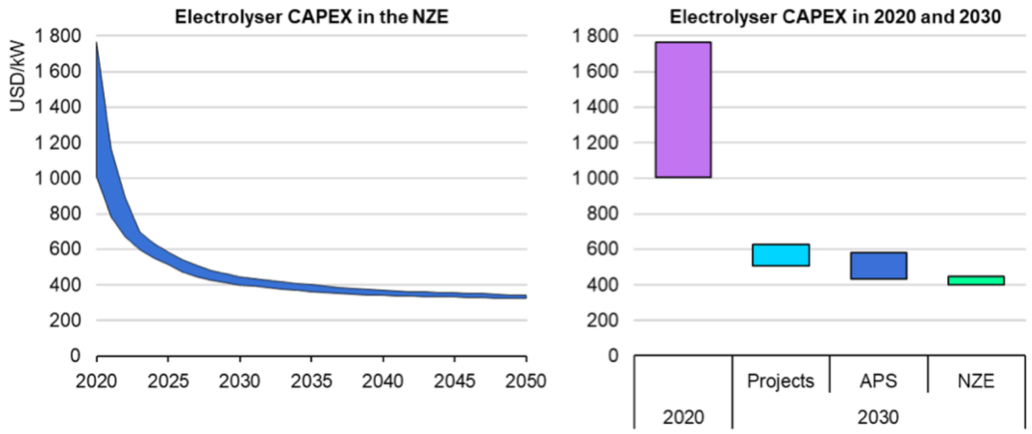

Fig. 9 Evolution of electrolyser capital costs. Data from the Hydrogen Council (IEA) [17]

Renewable energy cost

Solar PV has become one of the most affordable energy sources. As **Fig. 10** shows, the cost of renewable energy will decrease over the decades. [17]

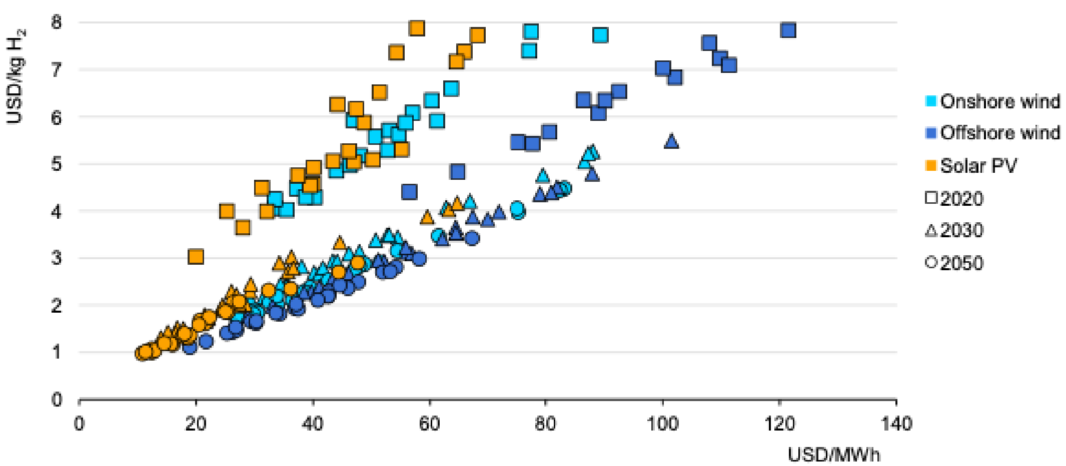

Fig. 10 Renewable electricity costs. Data from the Hydrogen Council and IRENA 2020 (IEA) [17]

From the perspective of costs, 100% hydrogen use in buildings where the fuel cells and hydrogen boilers are used is most attractive for large commercial buildings or buildings complexes and district energy networks. Hydrogen competes with natural gas boilers and electric heat pumps. If 100% hydrogen is ultimately able to compete in terms of CAPEX and OPEX (capital and operational costs), the market potential in buildings is enormous. Today natural gas is used for space and water heating. [16]

Strategy	Advantages	Requirements	Examples
100% hydrogen	Full decarbonisation of gas if low-carbon hydrogen. Lower efficiency losses than synthetic methane	Investment to upgrade gas network and equipment. Co-ordination between gas suppliers and distributors if various networks coexist	The H21 Leeds City Gate (> 2025) and the H21 Network Innovation Competition (NIC-2018) projects in the United Kingdom
Use of fuel cells and co-generation	Multiple energy services (e.g. heat and electricity). Demand-side response potential	Investment in fuel cell or co-generation technology. R&D to improve the efficiency of equipment	ENE-FARM programme in Japan (2009).* Energy Efficiency Incentive Programme in Germany (2016)**

Fig. 11 Hydrogen use for buildings heat supply [19]

Social aspects

Social acceptance is a critical factor for implementing new energy technologies—social acceptance is based on perceptions of risks and benefits that are sometimes subjective. From 43 research studies, mainly from Western Europe, Asia, and America, nearly 30 000 stakeholders answered different questionnaires. The stakeholders are divided into the general public, experts/early adopters, and end-users. Mainly, the studies focused on urban areas where they handled socio-economic, market, and community acceptance. The main factors in nudging public acceptance are trust in the government, industry, and relevant public engagement. There are also different roles of local cultures, social equity, land availability, and proximity for hydrogen units that could affect acceptance. [30]

Experts' noted that public engagement, policy stability, land, and infrastructure availability, and source of hydrogen production are vital for societal acceptance of hydrogen technologies. On the other hand, potential end-users prefer hydrogen facilities near them, have partial ownership of the hydrogen facility, and want social equity. [30]

The location also influences the acceptance where people who live in rural areas are more likely to adopt that hydrogen is produced on-site and not transported from other sites. They also prefer a partial ownership structure for hydrogen projects. Demographic indicators are also playing an important role. Acceptance of hydrogen for cooking and heating at home was affected mainly by land availability, preference for renewable hydrogen, water security, partial ownership structure, and distributive benefits. [30]

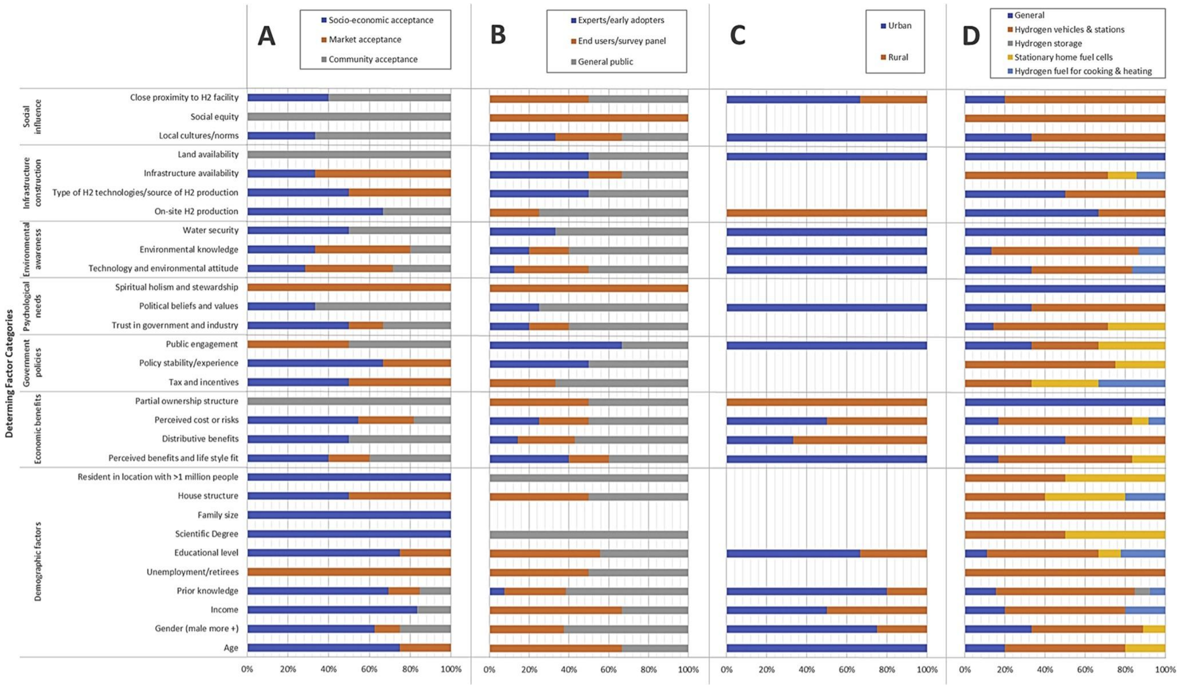

Fig. 12 Quantitative results of societal acceptance (A: types of acceptance, B: by stakeholders' group, C: by location, D: by hydrogen technologies). [30]

Hydrogen technologies were primarily evaluated neutrally to positive, while participants' knowledge of, familiarity, and experience with these technologies was relatively low. There are differences between public perceptions, knowledge, opinion, and attitude on how the hydrogen industry may directly or indirectly impact. For example, hydrogen might be accepted by policymakers. However, the community might object to plant and infrastructure installation, while consumers may be concerned about the cost or safety of hydrogen use. [30]

While considering demographic aspects, the younger people with ages under 30 years had already been in touch with hydrogen technology, known hydrogen, and higher degrees are more supportive. [30]

The general public believes that supporting hydrogen energy technology is an advantage as it improves the country's brand and technological competitiveness. The general public and end-user groups were supportive of the installation of hydrogen infrastructure but wanted more information. End users indicated that their attachment to the community they live in affected their level of support for hydrogen technology. [30]

The studies reported that participants in the general public group supported the idea of hydrogen exports and the hydrogen industry in general. It presents opportunities for direct and indirect job creation in their locality. The European Union adopted the European Hydrogen Strategy, accounting for 13-14% of the Union's total energy portfolio by 2050 and employing around one million highly skilled workers by 2030, reaching 5.4 million. Most of those jobs will come from hydrogen production and distribution-related economic activities. It is assumed that manufacturing fuel cells, electrolysis, and fuel cell-based micro-CHPs will be undertaken locally after 2030; thus, manufacturing-based jobs will complement maintenance and operations jobs. The general public stated a need to ensure that the hydrogen industry benefits the domestic market and prioritises locals. [19, 30]

The local legislative authorities have a key role in the transitional phase. For example, establishing policies that mandate the installation of boilers suitable for hydrogen gas in new homes provides incentives for hydrogen technology demonstration programs. The interests were in the scale of the hydrogen facility and land required for renewables to power hydrogen production plants. On the other hand, experts were concerned over the size of necessary infrastructure needed to export hydrogen and its impact on biodiversity. Experts recommended strengthening environmental legislation as a supportive pre-condition for hydrogen development. Due to environmental concerns, stakeholders supported hydrogen as an environmentally friendly alternative to fossil fuel. The stakeholders agreed that hydrogen can be used to combat climate change if produced from renewables and can serve as a renewable fuel to power other technologies. [30]

In developing community trust and disseminating vital information regarding the hydrogen industry, the general population wanted clear timeframes that would show the evolution of the hydrogen industry to ensure that the community is informed about the development of the industry. Universities were seen as respected knowledge brokers for disseminating information to the communities. The end-user group highlighted the need for more information about the hydrogen industry, but the information should be balanced, open, and honest. The end-users also recommend endorsement by highly respected public figures to promote hydrogen. Experts recommended engaging with indigenous groups while respecting their culture and building a relationship early with industry. [30]

Building coordinated networks between the scientific community, industry, and local and public authorities can improve societal acceptance of the hydrogen industry. [30]

2.4 Environmental view

The atmospheric level of CO_2 has been steadily rising since the 1960s. Atmospheric carbon dioxide levels reached a high of 416.45 parts per million in 2021 compared with the 1960 levels of about 316.91 parts per million. CO_2 emissions are the primary driver causing climate changes, especially the global average temperature rise. [31]

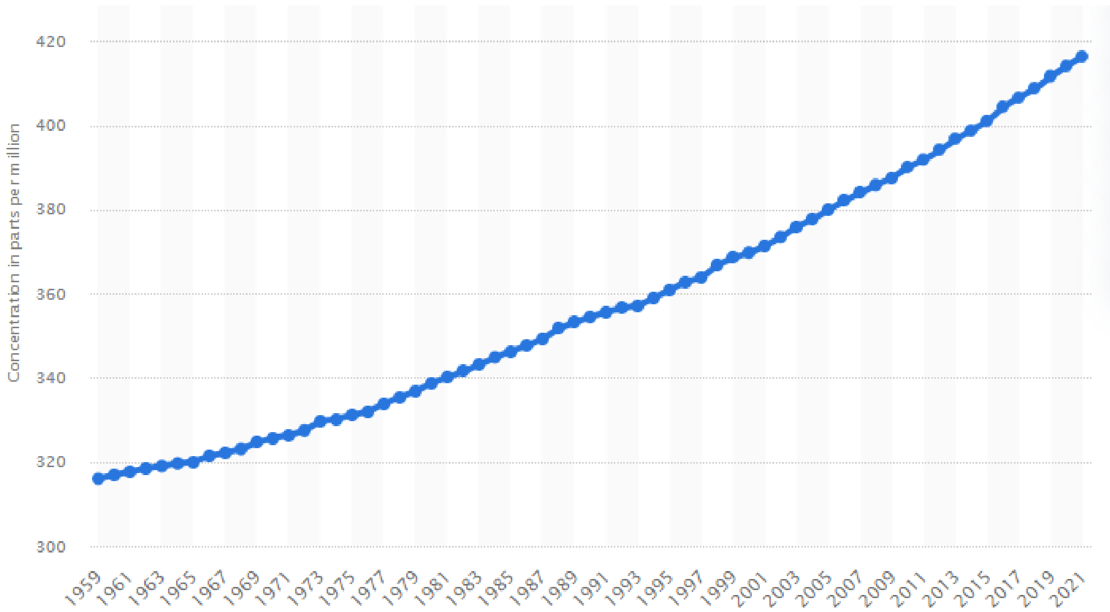

Fig. 13 Historic average carbon dioxide (CO2) levels worldwide [31]

Estonia's average temperature has risen by 0.2-0.3°C per decade since 1951. The rate of warming has exceeded the global average in the past two decades. Estonia's temperatures show an increase of 2.6°C from 2041 to 2071 and 4.3°C from 2071 to 2100. [32]

Fig. 14 Temperature in Estonia, 2000-2020 [32]

There will be changes in electricity demand patterns because Estonian summers will be even hotter. The cooling consumption becomes greater than heating. [32]

Hydrogen has mainly been produced using the cheapest production process: steam reforming of natural gas. Currently accounts for most of the hydrogen produced, resulting in a decidedly undesirable side effect of around 900 million tons of CO_2 emissions per year. On the technical side, green hydrogen is produced through electrolysis of water, and water consumption is an aspect that is often overlooked. Pure water consumption is in the range of 15 L per kg of hydrogen output. However, when comparing embodied water based on a life cycle inventory, the water consumption for steam reforming could be about 24 L per kg of H_2. In the case of coal gasification, water consumption could be even higher, about 38 L per kg of H_2. [18]

Electrolysis can balance fluctuations in the power supply. Moreover, increase electrolysis's value as a clean energy carrier by further conversion into chemicals. Alkaline electrolysers (AEC) technology is usually nickel-based which is not a scarce resource. PEMEC electrolyzers consist of fluoropolymers that need to be disposed of or recycled after use. [33]

2.5 Technological view

2.5.1 Green hydrogen production, storage, and transportation

Green hydrogen production

The only way to produce green hydrogen is through the water electrolysis process, where the input electricity is from renewable sources. The electrolysis of water is described with the following reaction $2H_2O \rightarrow 2H_2 + O_2$.

This equation shows the essential ingredients of the chemical process but omits two critical, required components - electricity and the presence of a catalyst. The catalyst modifies the energy consumption or reaction speed of the process. The equation shows that the output is hydrogen, oxygen, and excess heat from the process. **Fig. 14 and Fig. 15** represent widely known electrolysis technologies from the energy balance side. [33]

Electrolyzers can be divided into three standard technologies: Alkaline Electrolyzer (AEC), Polymer Electrolyte Membrane Electrolyzer (PEMEC), and Solid Oxide Electrolyzer (SOEC). In a further discussion, the SOEC would not be included because the estimated investment cost per SOEC unit is over € 2 /W and it has the lowest overall cycle efficiency besides AEC and PEMEC. Also, the cold start-up time is 720 (680-880) minutes, suitable for more extensive energy systems. SOEC systems can be found on the sub-MW scale and are mainly applied for Power-to-X scenarios. From that point, the SOEC technology is excluded from further discussion. [14, 33]

AEC - water is fed to the cathode, wherein OH- ions are transported across the membrane to form hydrogen and oxygen [33].

Advantages

- Systems that operate in the MW power range;
- The cell operates at 65-100 °C and can work at atmospheric pressure at up to 35 bars - (means low operating temperature.);
- The feature is a minimum stable load; they cannot normally operate below 10-40% of maximum power;
- Warm start-up response 240 sec - (A quick response - in grid services, making it suitable for use as grid flexibility asset);
- Lifetime more than 100000 h currently;
- Efficiency is around 60%;

- The price of AEC technology today is about 1 € / W. [14, 33]

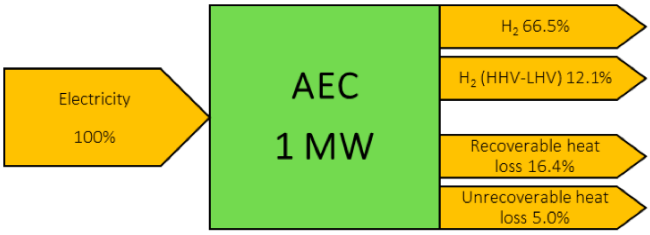

Fig. 14 AEC 1 MW energy balance

Fig. 14 shows that AEC electolyser can produce 70% of hydrogen and 20% recoverable heat from total energy input. Revocable heat can be used for district heating. [14, 33]

Disadvantages

- Less flexibility under atmospheric operation;
- The use of highly caustic electrolytes in AEC;
- Leakage of KOH;
- High membrane resistance;
- Low maximum operational current density. [33]

PEMEC - The reaction occurs by the transport of H+ ions across the membrane. Water is fed at the anode, and hydrogen is formed at the cathode.

Advantages

- MW systems are already developed;
- The operating system temperature is 60-80 °C -(low op. temp);
- Warm start-up time 10 sec (quickest);
- The higher price of 1,9 €/W compared to AEC electrolyzers is due to the freshness of the technology and high cost of the catalyst components. [14, 33]

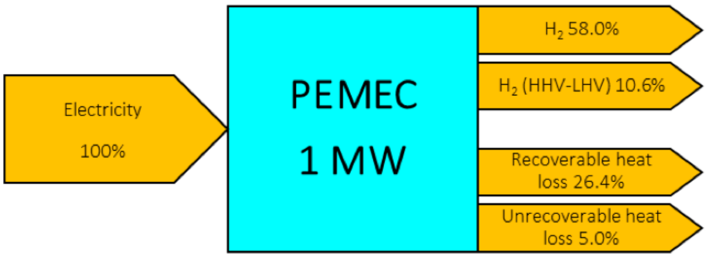

Fig. 15 PEMEC energy balance

Fig. 15 shows that PEMEC electrolyser can produce 60% of hydrogen and 26% of recoverable heat from total energy input. Revocable heat can be used for district heating. [33]

Disadvantages

- Very sensitive to impurities, with a prerequisite of pure water as input;
- The lifetime of the SoA system is still uncertain;
- PEMEC modules are expensive due to catalysts and bipolar plates (oxide-resistant stack elements);
- Cost-efficient water treatment and drying of the hydrogen at high pressure is still a challenge to be addressed. [33]

The example of the AEC and PEM electrolyzers system visualised in **Fig. 16.** The input box shows the required parameters. The middlebox describes the electrolyser system; all the components might be included in the CAPEX. The box on the right gives the output streams and components. [33]

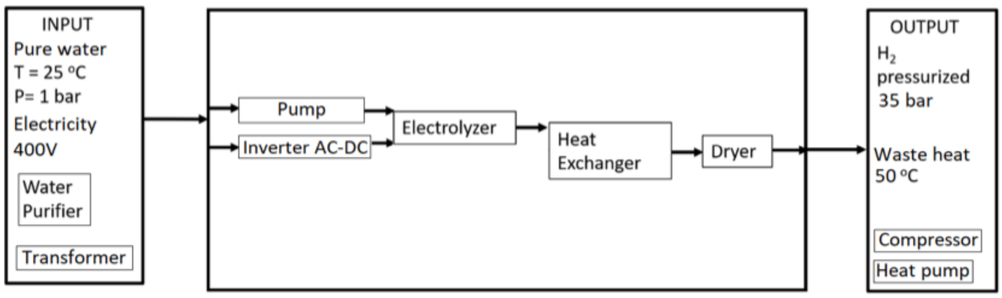

Fig. 16 Systems of AEC and PEM electrolysers [33]

Electrolysis systems can be operated dynamically. The limitations are:

- Heat management,
- The maximum voltage of the rectifier;
- Time coefficients of external components;
- The *cold start-up* time;
- The *warm start-up* time.

A *cold start* is defined as a start-up from ambient temperature after a prolonged shut-down. A *warm start* is defined as a start-up from heated stand-by or idle mode, which means that the system is held at operating temperature and pressure if necessary. The power response signal is the time it takes for the system to adjust to a change in the power input and is measured in seconds. This rapid reaction may allow the system to stabilise power grids when running at operating temperatures. [33]

Table 1. Specifications of electrolysers standard system [33]

Regulation ability	**AEC**	**PEMEC**
Cold start-up time [minutes]	<120	10 (5-10)
Warm start-up time (from 0 to 100%) [seconds]	240 (60-300)	<10
Power response signal [seconds]	<1 (<1-5)	<1(<1-5)

For 1 MW plants, the electrolysis would be connected to a medium voltage grid connection in agreement with a DSO.

Fig. 17 ITM Power PEM electrolyser [34]

Predictions of performance and costs are built on reports from IEA, Europe, IRENA, and input from the industry. For AEC and PEM, operation and maintenance (O&M) are stated between 2-5% of CAPEX per year. Smaller systems have larger O&M and vice versa. The lifetime of the electrolyser plants is expected to increase.

Table. 2 AEC and PEMEC price evaluation [33] 1 USD=0,95 EUR*

	AEC			**PEMEC**		
	2020	**2030**	**Long term**	**2020**	**2030**	**Long term**
Electrical efficiency (%, LHV)	63-70	65-71	70-80	56-60	63-68	67-74
CAPEX (USD/kWe)	500-1400	400-850	200-700	1100-1800	650-1500	200-900

Current and future CAPEX is estimated 50% decrease of 2020 unit price by 2040 for both electrolyser, based on predictions from reports and manufacturers. The predicted expectation is that produced electrolyser units by 2040 will have doubled four times compared to 2020. [33]

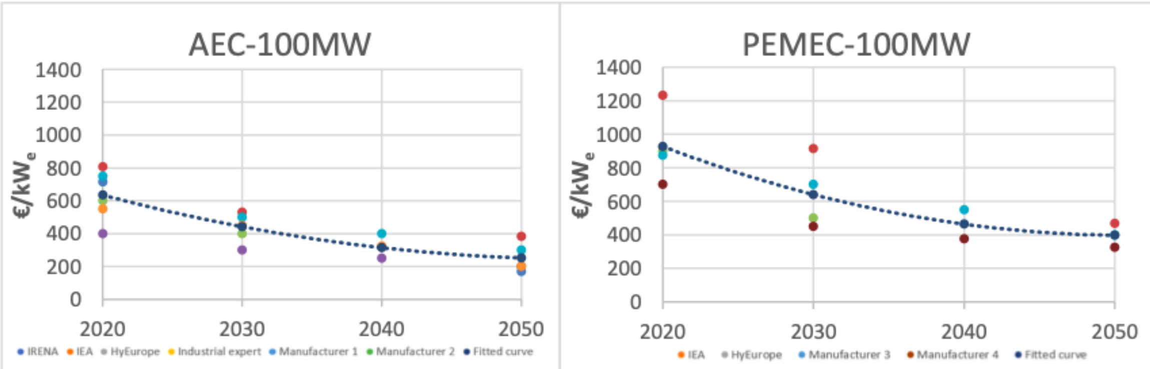

Fig. 18 CAPEX values: 100 MW AEC and PEMEC [33]

The electrolyzer's primary price decrease is expected. However, the price projection is associated with a high level of uncertainty based on the previous lessons from the technology learning curves. Policies for hydrogen infrastructure are decisive commercialization of large-scale electrolysis systems. Furthermore, the cost of scarce materials and economies of scale are also associated with a significant level of uncertainty. [33]

Hydrogen storage

Electrolysers can operate quite flexible to accommodate the variability of renewable electricity supplies; hydrogen storage is likely needed to ensure supply constancy. Typically, hydrogen is stored as hydrogen compressed gas. [17, 35]

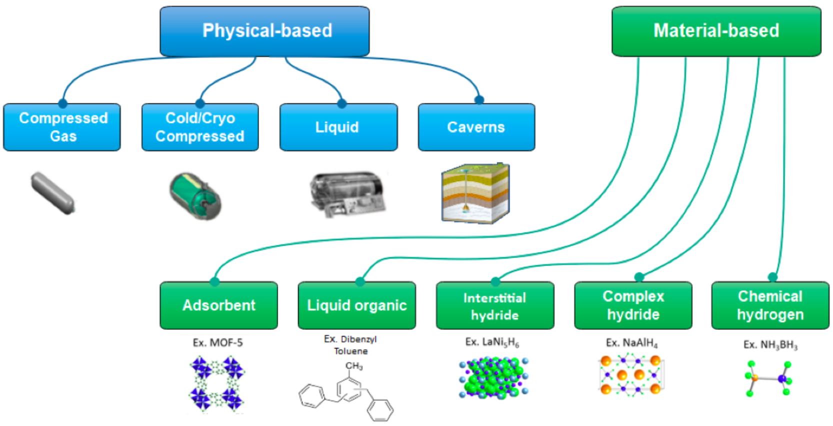

Fig. 19 Hydrogen storage technologies [35]

Hydrogen storage methods and technologies can be divided into two main categories: physical-based and material-based hydrogen storage. Feasible hydrogen storage options are high-pressure tanks, liquefaction, and chemical storage. Hydrogen storage in metals by chemical bonding is one of the most practical solutions for hydrogen storage. [35]

Pressurised hydrogen storage

This technology fits the purpose of hydrogen storage where the production of hydrogen gas is from renewable energy. If hydrogen is used where it is produced, there is no reason to store hydrogen in any other way. In the context of Estonia, due to the short distances, it is most suitable to store gaseous hydrogen in special gas cylinders. [20, 35]

The pressurised hydrogen tanks' input and output of all types are hydrogen gas and energy for its compression, respectively. Hydrogen is generated from PEM electrolysis. [35]

Fig. 20 Hydrogen Energy storage [36]

Storage system components are varying because they depend on the application.
Storage system required components and indications:

- Tank type;
- Tank size;
- Pressure class;
- Compressor size, which is often customised for each application's purpose. [35]

The following assumptions have been made while describing a typical pressurised storage system for a stationary application. Stationary storage system receiving hydrogen produced at low pressures. PEM already delivers hydrogen at elevated pressure, typically 30 bars. Pressurised hydrogen storage systems only store the energy, energy conversion is done by electrolysis to produce hydrogen from electricity. A fuel cell system, for instance, can be utilised to generate electricity after storing hydrogen; hence, only the efficiency of storing the hydrogen is considered. [35]

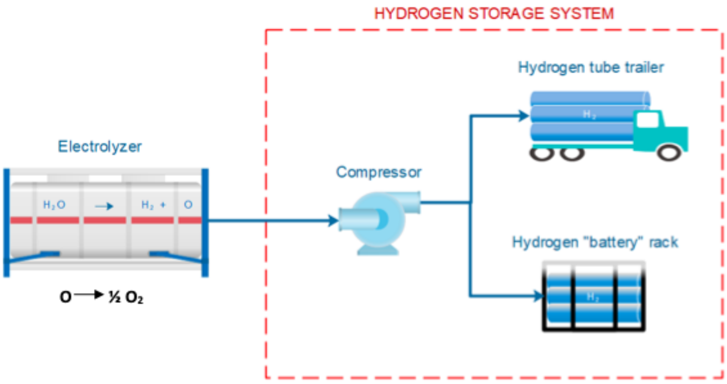

Fig. 21 Hydrogen storage system [35]

The compressor is responsible for raising the pressure from the atmospheric (or low) pressure input to the desired pressure output in the pressurised tanks. It can include one compressor or many compressors in series. [35]

Tanks I and II are most suitable for low-pressure stationary hydrogen storage due to their durability, low permeation characteristics, and low cost. Type II tanks provide a relatively higher-pressure range and more hydrogen capacity than Type I, but their price will be lower. Long-term hydrogen storage in pressurised tanks is performed at ambient temperature. The manufacturer determines the lifetime expectancy when the tank needs to be replaced; otherwise, there is no guarantee for storing hydrogen safely. [35]

Table 3. Hydrogen storage tanks [35]

Type	Working Pressure (bar)	Materials	Usage	Permeation [mol/s/m/MPa$^{1/2}$]	Typical Storage Period [months]	Average cost [€/kg$_{H2\ stored}$]
Type I	< 250	Seamless steel or aluminum	Stationary applications	2.84×10^{-27}	years	500
Type II	450-800	Seamless steel/aluminum with filament windings like glass fiber/aramid or carbon fiber wrap	Stationary applications or short transportation (tube trucks)	2.84×10^{-27}	years	900
Type III	300-700	Seamless or welded aluminum liners fully wrapped with fiber resin composite	Stationary and automotive applications. Used also in hydrogen fueling industry	2.84×10^{-27}	days to months	1,100

Tanks have mainly two types of losses: operational losses - affiliated primarily with the energy losses of the compression, and standby losses.

In conclusion, pressurised hydrogen storage is a proven technology used on any significant scale for hydrogen storage while being cost-efficient compared to other industrialised storage methods. Type I tanks cost predicted to be half of today's price by 2050. The exact prediction is for a compressor component that reduces the cost to one-fourth of today's price by 2050. The cost data of the hydrogen storage system is described in **Table 4.** [35]

Table 4. The cost of hydrogen storage system [35]

System component	**Average cost** (EUR/unit)	**Average operational cost** (EUR/year)	**Lifetime** (years)
Compressor	500 000	6000	25
Hydrogen battery	600 EUR/kg	1250	25
Piping, power electronics, man hours	150 000 /system	1000 /system	25
Overall system for 500 kg H2	950 000	8250	25

Hydrogen transportation

Hydrogen can be fed directly into the natural gas pipelines. As volumes and distances increase, the pipelines become attractive where the hydrogen can be delivered up to 1,500 km very quickly. The existing gas infrastructure that needs reconstruction can be used, but the better case is if it is possible to build an entirely new infrastructure for hydrogen transportation. In some cases, electricity transport for decentralised electrolytic hydrogen production may be the most economical choice, but centralised production relying on hydrogen transport can be preferable. [14, 16, 19, 37]

2.5.2 Renewables - PV

Photovoltaics (PV), also called solar cells, are electronic devices that convert sunlight directly into electricity. Renewable technologies represent the cheapest available source of new electricity generation. The variability of electricity supply will be affected by rising wind and solar PV shares, putting a considerable premium on robust grids and other sources of supply flexibility.

PV generation varies with the weather and the time of day and year, which can cause changes to electricity generation patterns on a daily or weekly basis. A large share of seasonal energy demand is also transferred onto the power system through the increasing use of electric heating and cooling equipment. Electricity storage, demand-side response, and dispatchable low emissions power sources are essential to meet flexibility requirements in clean energy transitions. [28]

Fig. 22 PV roof example from Roofit Solar company - Haapsalu rental house [38]

2.5.3 Heating and electricity - CHP

A combined heat and power plant (CHP) produces electricity and heat from the fuel. CHPs are usually located close to the end-user to avoid transportation and distribution losses.

PEM fuel cell CHP systems are represented in commercial and institutional buildings with space heating and hot water requirements. They are the primary applications for building types with high electric and heat demand; for instance, universities and hospitals. One of the first CHPs to run on total hydrogen is at Berlin Airport in Germany. The hydrogen CHP produces green hydrogen via electrolysis unit AEC 500 kW that can produce more than 200 kg hydrogen per day and is enough to refuel around 50 fuel cell electric vehicles. Being a localised source of power generation can help improve a site's resilience in a power grid failure. Berlin Brandenburg Airport has the world's first 100 percent hydrogen-burning 160 kW system CHP plant. Additionally, the plant can operate with natural gas. Hydrogen is offered at the multi-energy station for refuelling fuel cell electric vehicles.

In conclusion, the examples considered here suggest that fuel cell CHP can be a viable alternative to hydrogen boilers and heat pumps by 2030 when the cost of hydrogen is approximately 1.8 EUR/kg. [39, 40, 41]

2.5.4 Smart grid functionalities - flexibility and security of supply

Managing the imbalances between supply and demand, especially over longer timeframes, requires transforming how energy systems operate. The future energy system consists of more complex interactions between fuels and electricity. The NZE report shows that by 2050, around 40% of primary energy will be converted at least twice before reaching end-users. Energy travels through electrolyzers, converting from electricity to heat or fuels and back again. Conversion processes need to match the supply of variable renewables and demand for electricity at least cost while providing flexibility.

Flexibility, according to NZE, should be achieved by integrating the storage options. *"NZE shows that the utility-scale battery storage increases from less than 20 GW in 2020 to over 3 000 GW by 2050. There are millions of behind-the-metre enablers of flexibility in smart metres, EVs, and charging infrastructure."* [35]

Scaling up energy storage systems will be critical to addressing solar PV's hour-to-hour variability, especially as their share of generation increases and meeting rising flexibility needs while decarbonizing electricity. It is a central challenge for the electricity sector and calls for tapping all sources of flexibility, including power plants, grids, demand-side response, and storage. Apart from direct hydrogen consumption, it is possible to use hydrogen as a source of significant energy system flexibility by storing hydrogen through electrolysis in moments of high renewable energy production and reusing it later. [14, 28]

2.5.5 Safety

The hydrogen flammability range is 4% to 75%, and when hydrogen is mixed with air, there is an explosion danger. Suppose the hydrogen facility is projected to be closed during the operation phase. If safety equipment is installed correctly and the safety tests are run accordingly, the hydrogen facility is safe for residential areas. [30, 35]

2.6 Cases

While looking at the different examples at the university level, the Technical University of Munich (TUM) is opening an international hydrogen Future Lab with researchers from 13 countries. The German Federal Ministry of Education supports their research initiative and will provide five million euros over three years. [42]

The second example is Lancaster University, which brings together: local and global energy and technology firms, local transport companies and heat consumers, clean-air, planning, regeneration, and low-carbon stakeholders, scientists, economists, and engineers. The Hydrogen Hub has three main aims:

- Build and grow local hydrogen production, storage, and transport facilities;
- Decarbonise local industry & transport and heating of building estates;
- Demonstrate a scalable hydrogen economy rolled out via incremental infrastructure investments.

Fig. 23 shows that the surrounding district offers opportunities to showcase hydrogen-based transport on a rail, road, port, and hydrogen-supported heating. [43]

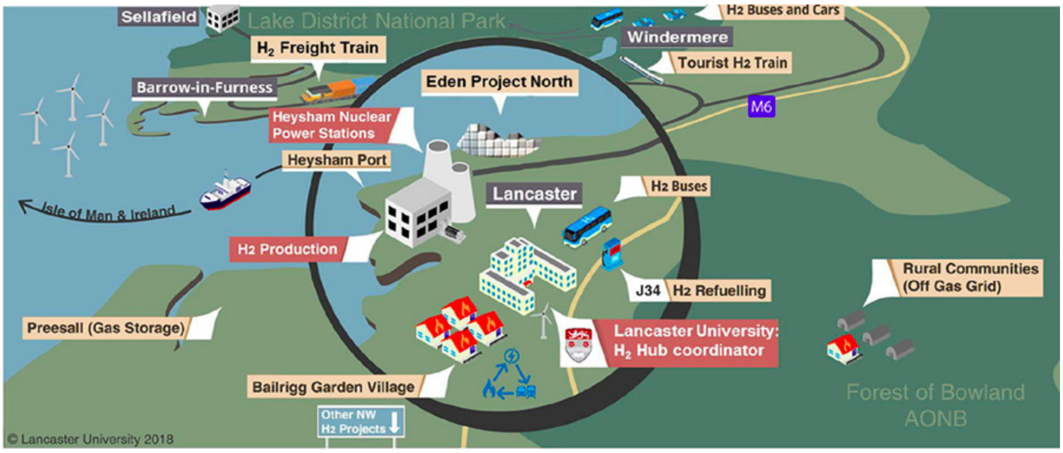

Fig. 23 Lancaster H2 Hub concept [43]

The HyPER project collaborates between Cranfield University, GTI, and Doosan Babcock. During this project, they are designing a pilot project operating a state-of-the-art 1.5 MWh hydrogen production pilot plant at Cranfield University to test an innovative hydrogen production technology that substantially reduces greenhouse gas emissions. [44]

Fig. 24 Construction of hydrogen production facility [44]

An additional good example is from the Technical University of Darmstadt. The interdisciplinary research project is federal government-funded. TU Darmstadt is pursuing the goal of significantly increasing the energy efficiency of its campus premises, considering also building thermal and electrical energy supply and linking it with the internet of things (IoT). The overall goal requires innovative technologies, especially energy supply, load management, and decentralised storage. There were mainly four-campus project-based goals:

Structural goals

- Determining the building efficiency potential through the energetic balancing of structural and technical renovation measures.
- Determining annual load profiles through thermal building simulations, derivations of synergy effects, and flexibility options at the building and campus levels.
- Build a roadmap for the long-term implementation of the energy-related goals for the university.

Thermal goals

- Expansion of the share of combined heat and power through
    - Thermal storage and use of the storage potential of the district heating network and buildings
    - Use of thermal energy for cooling with absorption chillers
- Increasing the thermal energy efficiency by lowering the network temperatures:
    - Reduction of heat losses in the district heating network
    - Increasing the efficiency of the combined heat and power plants

Electrical goals

- Optimization of the interfaces between electrical and thermal networks
- Improved operation of generation (CHP) and storage systems
- Definition of the requirements for the future network structure, taking into account technological developments and infrastructural changes

Digital goals

- The campus energy system's overall virtual model ("digital twin") is created based on comprehensive monitoring that allows optimizations. [45]

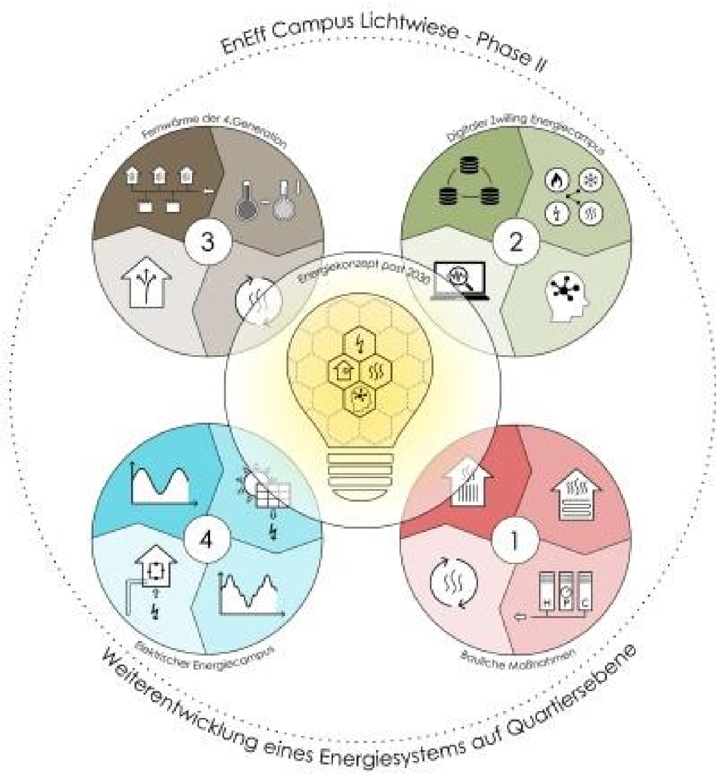

Fig. 25 TU Darmstadt campus concept [45]

2.7 Opportunities

Based on previous research, a holistic overview of political-legal, socio-economic, environmental, and technological insights are considered while designing the concepts. The crucial insights are visualised and connected in the context map **Fig. 26.**

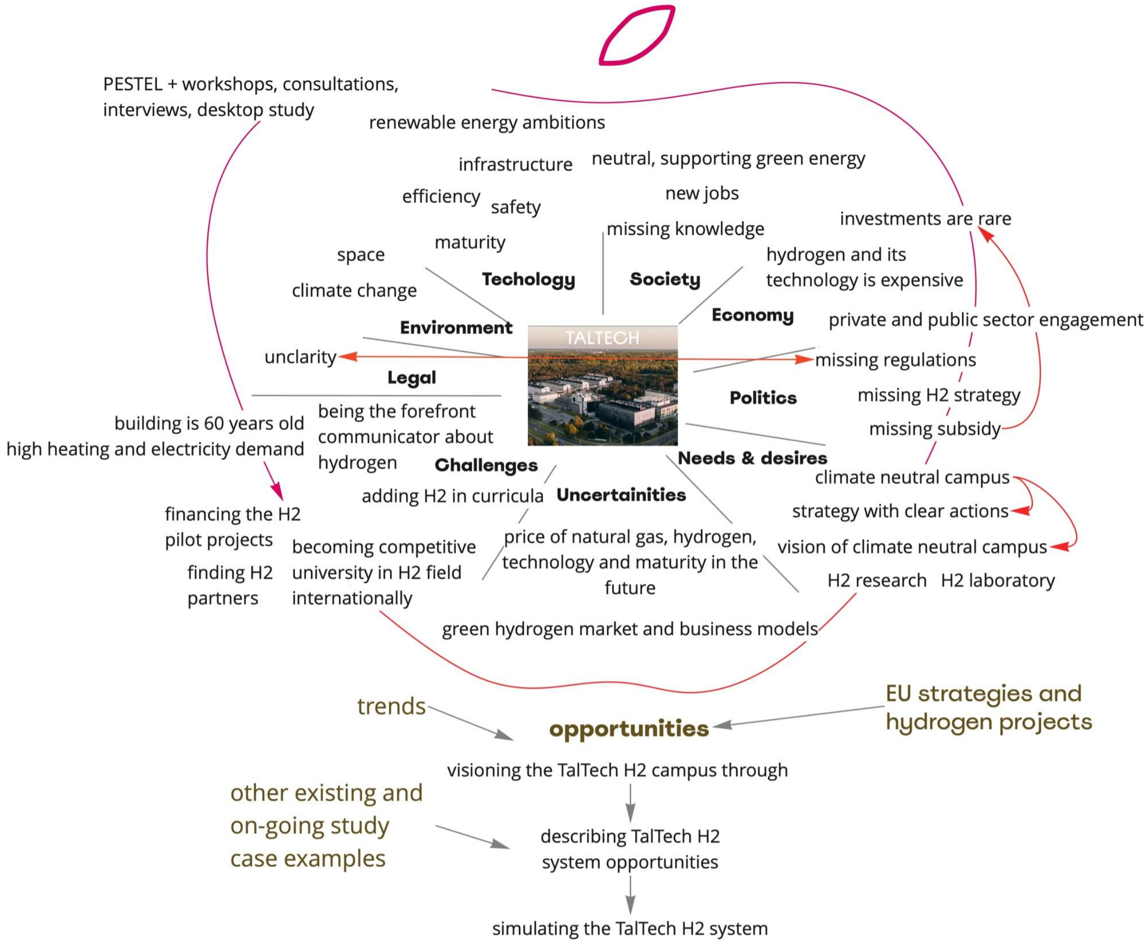

Fig. 26 Challenges and opportunities

While looking at how to guide the TalTech campus journey to zero carbon emission, study cases could help to vision a hydrogen-based system for the year 2035. Study case models can give the first vision and calculations about rethinking the existing system toward a green hydrogen system. The energy system models are helping to understand how the system will behave in certain conditions.

3. CONCEPT

Approach

For efficient development of the 2035 hydrogen system for the TalTech campus main building requires systematic analysis. The concepts will be designed to be flexible and cost-efficient from the perspective of consumption, production, transport, and storage. Concepts will consider the criterias from the energy market, hydrogen technologies, and emerging renewable and hydrogen energy fields trends while considering the campus demands.

Focus

1. Ideating the concepts based on gathered knowledge and defining the first ideas through further analysis and concepts;
2. Providing the strategy for how the technical concepts are created;
3. Modelling the concepts;
4. Specialist interviews to validate concept models;
5. Making the modifications in Energy Pro software to generate hydrogen-based system proposals.

Strategy

Visioning the concepts for the 2035 TalTech campus can create value for teaching and research but also helps to understand alternative opportunities with hydrogen for the journey to zero. Some insights have been collected from the workshop and consultations on the subsequent strategic actions and plan to make the hydrogen transition on campus. However, a further technical discussion will be held through the concept analysis.

The overall modelling strategy

1. Describing the purposes;
2. The Energy Pro software models - plan and goals;
3. Overall model criterias and component descriptions;
4. Assumptions for model concepts;
5. Models descriptions and schemes that are created in software;
6. Analysis - results based on technical and economical aspects.

3.1 Ideation

Before looking at ideas, the point of view needs to be defined. TalTech campus needs climate-neutral actions to achieve a climate-neutral journey.

"How might we design a hydrogen energy system for TalTech that brings economic benefits based on energy consumption?"

It starts with the ideation; the brainstorming technique is used. A 2X2 matrix is a design tool that helps to prioritise ideas. At the same time, it can also be used to change the way of thinking from a 100% idea orientation toward recognizing unfulfilled user needs and strategic opportunities. [46 - Book: The design thinking toolbox, Wiley]

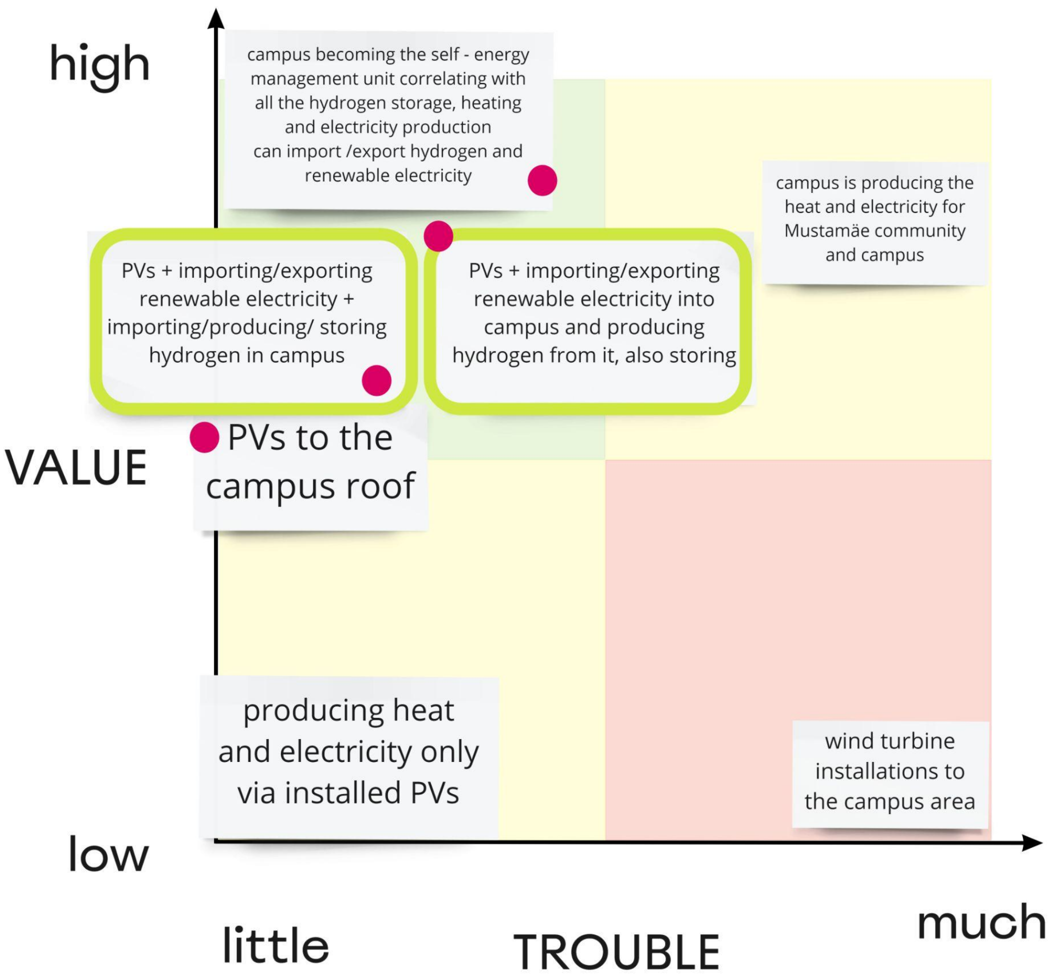

Fig. 27 Ideating first concepts

From **Fig. 28,** two ideas can be analysed through modelling (marked with green boxes).

Concept 1 - importing renewable electricity

The first concept will be that the campus imports a lot of renewable energy into the TalTech energy system. As predicted, renewable energy prices are likely to be lower in the future. This renewable energy can be used to produce hydrogen and cover the electricity demand or be exported to the grid. The campus will produce green hydrogen through PEM electrolysers. Hydrogen from the electrolysis process can be stored in large quantities at the production site in compressed gas storage and will help regulate consumption and production processes.

Concept 2 - importing renewable electricity and hydrogen

The second concept should be that the campus imports hydrogen fuel as needed into the system while also producing hydrogen locally with PEM electrolysers. There is an assumption that for the year 2035, there will be a natural gas infrastructure with hydrogen infrastructure pipelines, and hydrogen fuel is likely to be lower. Campus will also import and export renewable energy. Renewable energy covers the energy demand or is the input for PEM electrolysers. CHP produces heat and electricity while contributing to covering the heat and energy demands together.

The first question is how much renewable energy production capacity - primarily based on PV panels - can be installed into TalTech buildings. Approximate roof surface area was calculated with the following parameters

Table 5. Roof area

Buildings	**S (m²)**	**a (m)**	**b (m)**
SOC	2726	47	58
LIB	1914	33	58
NRG	1023	33	31
ÜE- 5	700	20	35
ÜE - 5/1	735	21	35
Hall	1066	41	26
Wardrobe	480	20	24
Corridors	1488	31	12
U02/3/4/5	6160	110	14
U06	2200	110	20

Roof area (m²)	**17469**
2019 TalTech electricity consumption (GWh)	**7,3**

Roof	flat
Direction of the arc	north-east

Eesti Energia AS, PV calculator. [47]

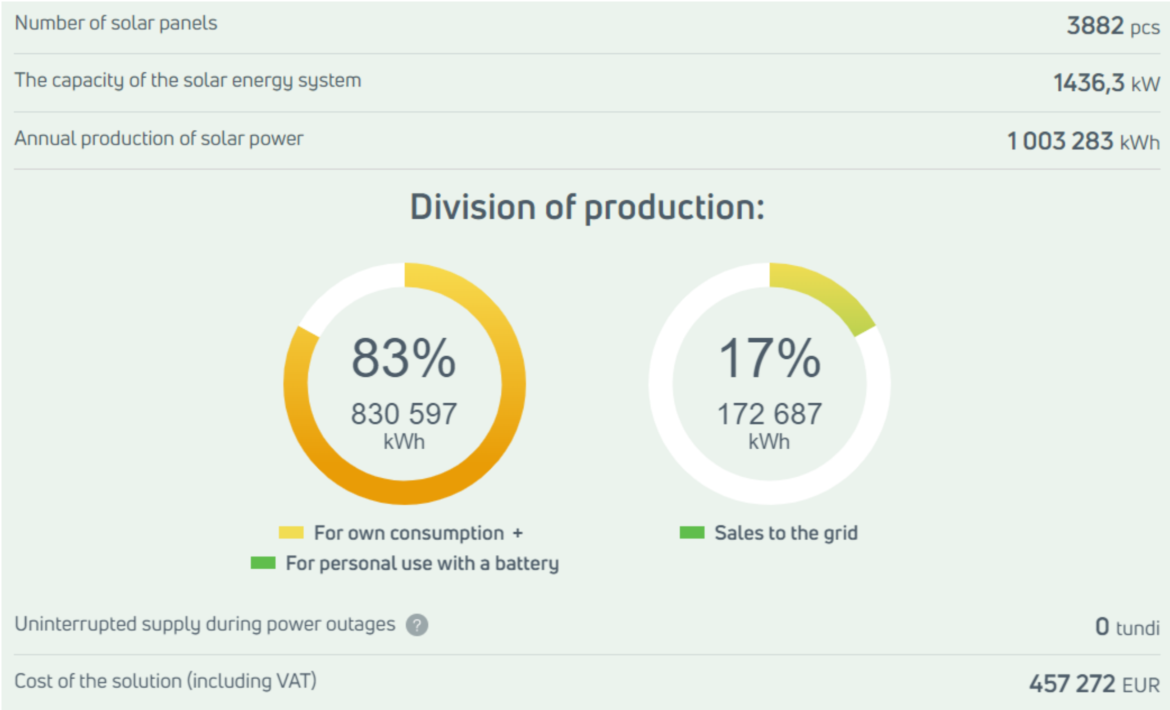

Fig. 29 The total PV production and investment cost for TalTech main building

Solar panels are not a sufficient standalone solution to make the TalTech campus climate-neutral; other technology and capabilities are needed. The modelled PV park can produce 1 GWh of renewable electricity in perfect conditions, but that corresponds to only 13,7 % of the overall annual campus energy demand. It should also acknowledge the investment cost, almost 0,5 mln euros.

The energy and heat demand data is from TalTech real estate administration. The data accuracy is based on 1 - hour campus 2019 consumption for chosen buildings - SOC, LIB, NRG/STU, U01, U02-U2B, U03-U03B, U04-U04B, U05-U05B, U06-U06A.

TalTech main building energy demand

Fig. 30 shows TalTech main building electricity consumption over 2019. In total, the main building consumes 7,3 GWh of electricity per year. The electricity consumption throughout the year is constant.

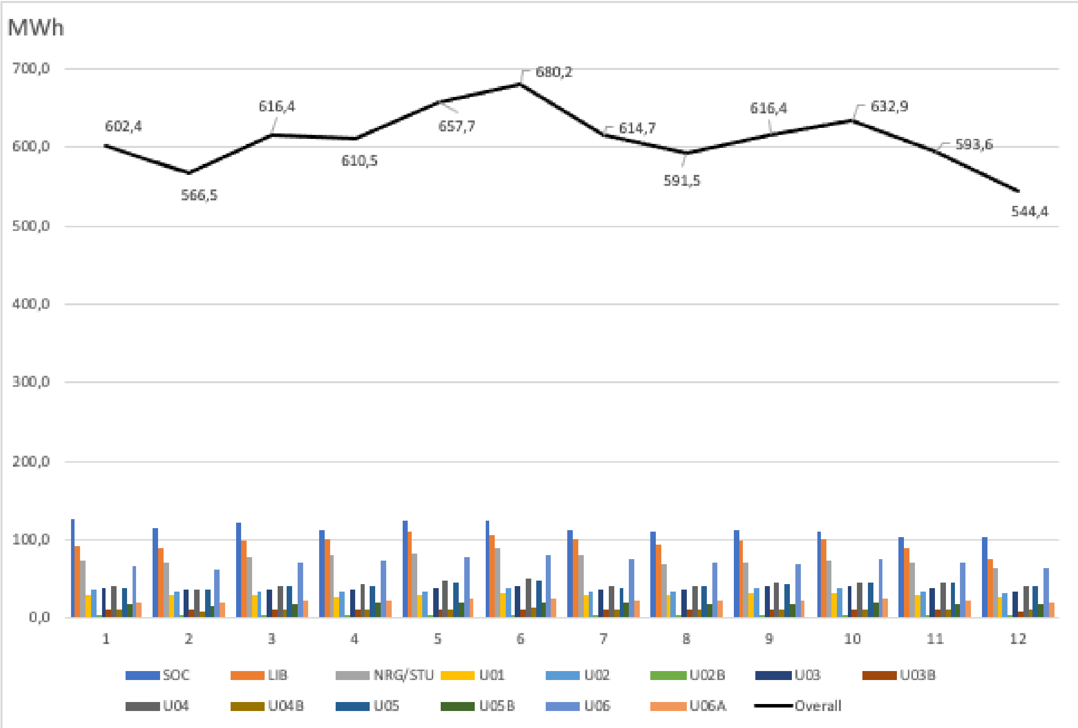

Fig. 30 Total TalTech main building electricity consumption per 12 months in 2019

TalTech main building heat demand

While looking at **Fig. 31**, the TalTech main building energy demand for heating is 8,5 GWh. There is a seasonal need for heating because of summertime. The gas demand data is divided with an efficiency coefficient of 0,9 in order to approximate the effect of heat loss.

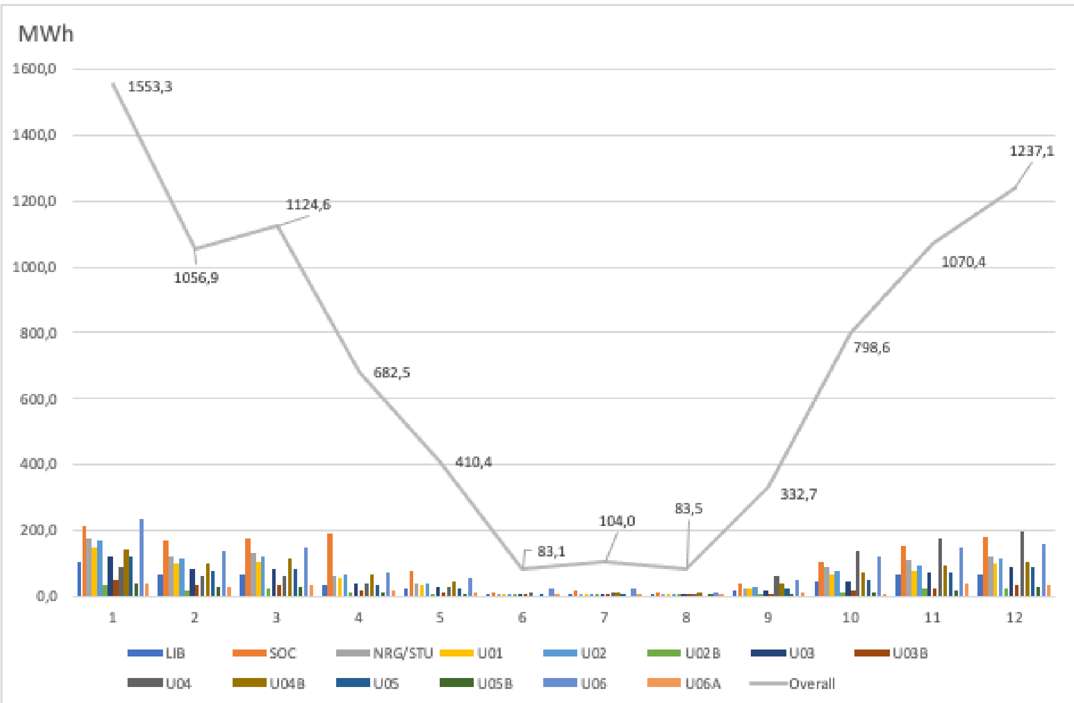

Fig. 31 Total Taltech main building energy consumption per 12 months in 2019

If comparing electricity and heating demand results, they differ by 1,2 GWh per year.

TalTech has a natural gas boiler that heats the water. Boilerhouse power level is 1,12 MW + 5,9 MW = 7,02 MW.

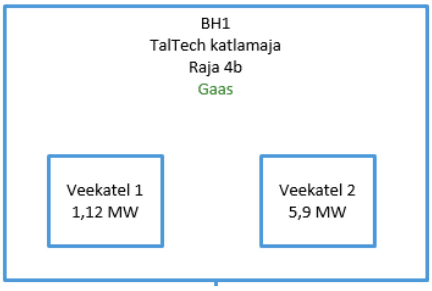

Fig. 31 Natural Gas boiler house

The hydrogen combustion and heat plant (CHP) can replace it. In contrast, electricity and heat consumption graphics were primarily compatible, and renewable energy campus itself could not cover the energy demand.

3.1.1 energyPRO software and models

The energyPRO is used for detailed technical and financial analysis for existing and new energy projects. The energyPRO has been chosen because it offers technical and economic reports, including a graphical presentation of the simulated operation. While running the simulations, a thesis will gather a quick overview and in-depth understanding of the dynamics of a complex energy system. The energyPRO represents different models that are included in the energy system calculations.

These thesis concepts are modelled based on the software financial model that will require price and investment data. After simulation, it will show the cash flows. Energy and economic calculations can be extended by setting the projected lifetime. The finance module provides more detailed investment analyses of proposed energy projects or compares different project options. The further analysis's main aim is to look at what scenario could be the best in energy efficiency and cost perspective.

Furthermore, the design module is also used that primarily consists of calculation and production and operational economics optimization in energy plants. It calculates the optimal energy conversions for heat and electricity for one year based on hourly in a TalTech context. [48]

Plan and goals

- Gathering technical, financial, and regional data required by the program and system-wise;
- Creating the models for proposed concepts in the Energy Pro software;
- Running the model simulations, reiterating and comparing the models;
- Selecting the best case scenario model for further analysis and research.

System design

EnergyPRO provides various system components that can be chosen, for instance, cogeneration plants, hybrid energy systems, storage, CHP plants, and photovoltaics. Additionally, there is an option for making the components by the software user.

The hydrogen and renewable technology, financial indicators, and system operation logic have been explicitly described beforehand. There is a quick overview of required components and data regarding green hydrogen and energy production, transport, and storage.

System components

- External conditions
  - Nord Pool Estonia 1 hour electricity prices in 2021. (chosen because the electricity prices are also in the future more volatile because of renewable energy units that will continue to contribution to the grid)
  - Temperature and radiation - Estonia (Tallinn) 1-hour data by 2019.
- Fuel - Hydrogen
- Demands
  - Electricity demand - TalTech 1 hour data about 2019.
  - Heating demand - TalTech 1-hour data about the 2019 year.
- Energy conversion units
  - Solar photovoltaic
  - CHP - hydrogen
  - Electrolyser - PEM
  - Hydrogen storage - compressed air
- Electricity market - day ahead market
- Hydrogen infrastructure - H2 pipeline

Financial components

- OPEX
  - Tarif

    - CO_2 price
    - Maintenance
    - Water consumption
    - Electricity payment
    - Hydrogen fuel payment
    - Natural gas payment

- CAPEX (investments)
    - PV system cost
    - PEM system cost
    - Hydrogen storage system cost
    - CHP system cost

- Revenues
    - Exported electricity
    - Exported fuel

3.2 Concepts

Under the concepts part, several proposals are discussed that could be opportunities for existing energy systems in TalTech. A significant advantage of hydrogen blends, direct hydrogen use, and indirect hydrogen use for district heating and cooling is using existing infrastructure.

The data is gathered from the TalTech and the open sources as Nord Pool, bigger hydrogen technology manufacturers, and the Danish Energy Agency make the reports with the Energinet to understand general values. These sources are chosen to make specific investment decisions that can lead to further research and hydrogen projects in TalTech.

3.2.1 Existing system

Before going to the first two concepts, for comparison, the existing energy system of TalTech is created. Electricity will be bought from the electricity grid and gas from the gas grid. 90% of the gas will go through Raja 4b - boiler house that consists of two water boilers whose power is 1,12 MW and 5,9 MW, maximum power is 7,02 MW. In the boiler house, while burning natural gas, the two water boilers are heating water, which will be distributed into buildings. Buildings use the heated water from the heating plant for different purposes. For instance, through heating units and heat exchangers, the purpose is to heat the vents and rooms.

Table 6. System criterias for all concepts with 1-hour accuracy

Electricity demand	7,3 GWh
Heat demand	8,5 GWh
Electricity market	Day-ahead market
Electricity prices	EE - Nord Pool

The 2019 Tallinn temperature data is used because buildings' heating depends on it.

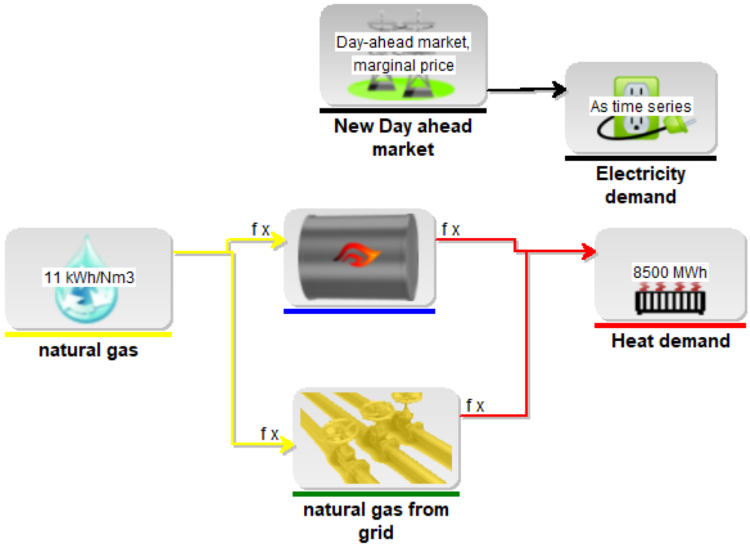

Fig. 32 Existing TalTech energy system

The boiler house was made in 2000, and the amortisation period is over, but the expectation is that it should last at least for 2040. It means that while looking at the year 2035, the residual value of the boiler is 0 euros.

While looking at the operational expenses, the grid fees will not be considered in the other simulations because there is an assumption that the grid's infrastructure will be the same only; while integrating the hydrogen into the grid, there are better seals measuring devices. There might be the same grid fee for hydrogen as natural gas has. Then the conclusion is that grid fees do not add weight to the calculations. However, the CO_2 price will dictate the price of natural gas and hydrogen, which should be considered and added to the operational expenses. The final cost of CO_2 in Europe at 11.05.2022 is 88,83 EUR/ton. While calculating last year's average CO_2 price from 2021 May to 2022 May, the price is 68,7 EUR/ton. Considering today's trend that CO_2 prices will increase, the last price will be inserted. CO_2 price per is 0,195 EUR/MWh. Natural gas prices nowadays in Europe are around 100 EUR/MWh. [49]

From the sight of the maintenance the 0,5-10 MW boiler expenses per year are 2000 euros. [50]

Table 7. Additional input for existing system simulation

OPEX	
Natural gas price	100 EUR/MWh
CO2 price	0, 195 EUR/MWh
O&M	2000 EUR/year

CAPEX	
Boiler investment	0 EUR

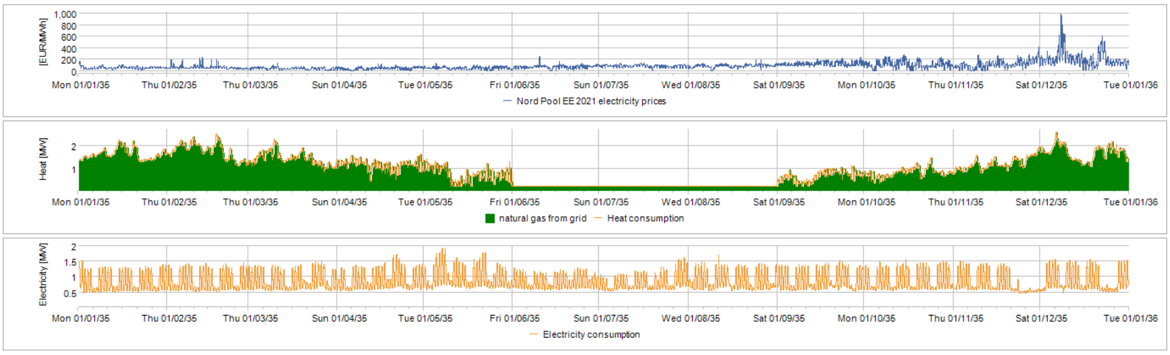

Fig. 33 Existing TalTech main building electricity and heating demand and consumption

From **Fig. 33**, there can be seen that in the summer, the heating demand is much lower. The heat and electricity demand peaks are around 2 MW, represented from December to March. At the end of 2021, the electricity prices (blue graphic) are more volatile. Also, while designing new concepts, there should be tests with more volatile electricity prices to see how the hydrogen system will behave. However, going back to the existing grid, the results are presented in **Table 8.**

Table 8. Existing TalTech main building system simulation results

	Imported	Cash flow
Natural gas	8500 (MWh)	-772 727 EUR
Electricity	7350 (MWh)	-663 998 EUR
CO2 price		-150 682 EUR
Maintenance		-2 000 EUR
Total one year operating expenditures		**-1 589 407 EUR**

In conclusion, the total expenses in 2022 are 1,6 million euros from the modelling results. Here it should be noted that this is not the actual expense; it is the modelling expense result where all the scenarios have been set to common goals. There is no revenue because TalTech does not produce electricity. The only purpose is now to consume energy and pay for consumed energy with the correlation of market and CO_2 prices. Natural gas prices and CO_2 prices will increase. If the grid does not have any flexibility to store the energy in a *"beneficial time,"* then the market's dependency and energy supply are very high. *The "beneficial time"* means when the electricity prices are low, the system will store much energy or import the energy for additional energy and heat production. If the electricity or gas prices are high, it is better to sell the electricity back to the grid from stored energy.

The CO_2 price will not be included for further analysis because there is no CO_2 footprint while importing and exporting renewable energy and green hydrogen.

3.2.2 Concept 1 - importing renewable energy

What to replace and what to add to the existing energy system?
From the side of replacement, gas boilers are old and boilers' fuel input is natural gas; the heat production unit should be replaced with CHP. The existing natural gas pipes should be replaced or redesigned the gas pipes where also hydrogen can be transported. Additional energy production units that will be added are PV, PEM, and compressed hydrogen storage.

What is the background data?
Energy and heating consumption 1-hour data were also in the existing TalTech energy system calculations.

The system will buy and sell renewable energy from the trading perspective. The price used in the analysis is 1 - hour EE - Nord Pool 2021 electricity prices. The one background system is electricity prices, which should stay the same while making the first comparison. EE - Nord Pool prices will be considered renewable energy prices in 2035.

The CAPEX investment data is from the Danish Energy Agency's newest technical reports, where the performance and costs predictions are built on IEA reports.

External conditions considered in the simulation are the 2019 Tallinn temperature and radiation data for the PV system. In Table 6, the other external system criteria for all concepts have already been described.

What are the investments?
The CAPEX investment data is from the Danish Energy Agency's newest technical reports, where the performance and costs predictions are built on IEA reports.

PV system investment is taken from the Eesti Energia PV calculations. Maintenance and lifetime data are taken from [51].

- Overall PV 8,5 MW system cost: 364 748 EUR (without 20% Estonian VAT)
- Maintenance is 10% of the cost

- Lifetime 25 years [51]

PEM system investment is taken from [33, 52].

For 10 MW PEM electrolyser investments 2035

- Specific investment (€ / kW of total input) 450
  - hereof equipment (%) 95
  - hereof installation (%) 5
- Overall 10 MW PEM electrolyser cost: 4,5 M EUR
- Fixed O&M (% of specific investment/year) - 7, it means 0,016 M EUR/year
- Lifetime 20 years
- Water 184 kg/MWh

If taking, for instance, the ITM Power 2 GEP Skid two 5 MW electrolysers, then the system's maximum hydrogen production is 180 kg/h. [53]

PEMEC lifetime now is 25,000 hours (2020), but PEMEC cells' lifetime is expected to increase to 50,000 hours within a few years. By 2035 the expected lifetime will be 50 000 hours. [53]

Hydrogen storage investment is taken from [35]. For the year 2035 the financial data about pressurised hydrogen gas energy storage capacity for 1 (MWh) at 200 bar is next:

- Specific investment (M EUR/MWh): 0,027
- Compressor component (M EUR/MWh): 0,011
- Type I tanks component (M EUR/MWh): 0,01
- Installation, equipment, man hours (M EUR/ MWh): 0,006
- Overall cost 0,054 M EUR
- Fixed O&M (€/MW/year): 500
- Lifetime 25 years

Additional data for the model

- LHV 120 MJ/kg
- Tank hydrogen storage capacity is 5000 kg

Overall storage investment:

- Storage capacity 175 MWh
- Storage investment 9,45 M EUR

- O&M (€/MW/year) = 0,0035 M EUR

CHP system investment is taken from [54]

By the year of 2035 the nominal investment is 1,1 M EUR/ MW

- of which equipment (M EUR/MW): 0.8
- of which installation (M EUR/MW): 0.3
- Overall 7,5 MW CHP system cost: 1,1 x 7,5 = 8,25 M EUR
- fixed O&M (EUR/MW/year) : 55,000 x 7,5/ 10= 0, 41 M EUR
- Lifetime 10 years [54]

In conclusion the system maintenance is Msolar + Mpem + Mstorage + Mchp = 0,002 +0,016+ 0,0035 + 0,041 = 0,06 M EUR

Table 9. Inputs for concept 1 model

OPEX	
Electricity price	EE-Nord Pool 2021 (1-hour data)
Water consumption	184 kg/MWh
Maintenance	0,06 M EUR/year
CAPEX	
PV system investment	0,365 M EUR/ lifetime 25 years
PEM system investment	4,5 M EUR/ lifetime 20 years
Hydrogen storage system investment	9,45 M EUR/MWh/ lifetime 25 years
CHP system investment	8,25 M EUR/MW/ lifetime 10 years

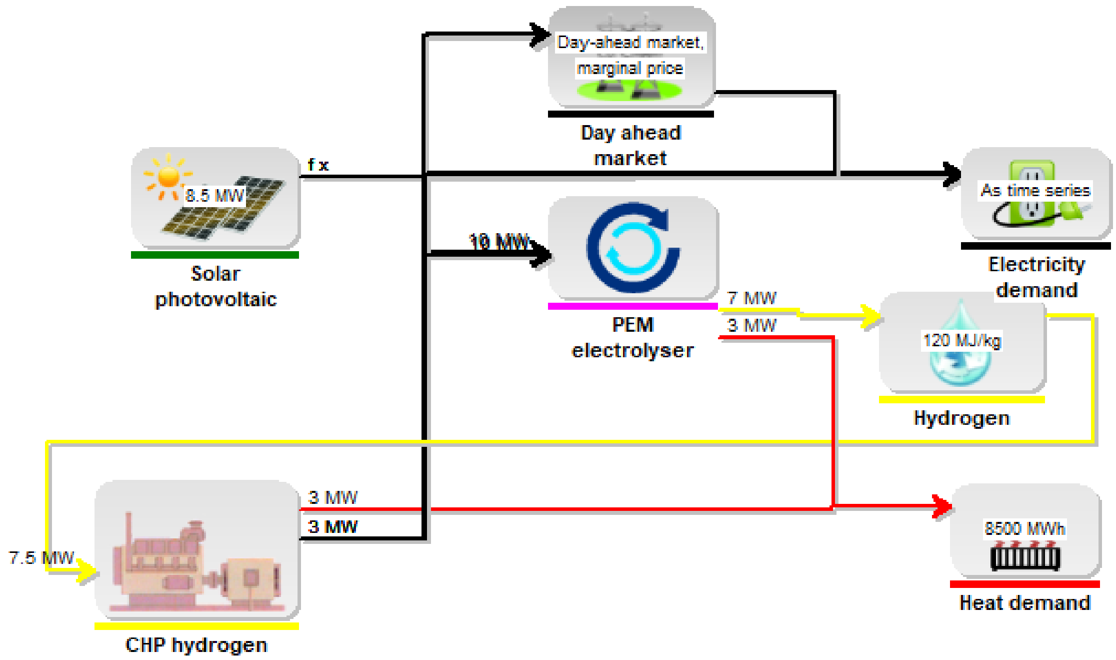

Fig. 34 Concept 1 model - importing renewable energy

The electricity prices are the same throughout all the analyses. **Fig. 35** is good to have here because of the direct comparison with the following model graphics to see the system sensitivity and dependence on electricity prices.

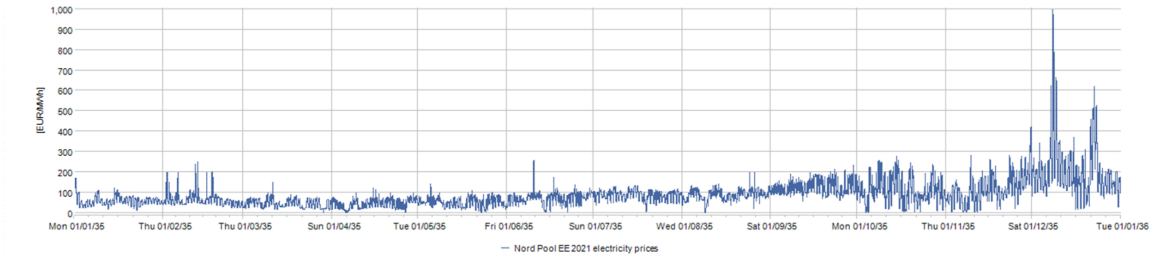

Fig. 35 Electricity prices

Fig. 36 shows the heat consumption. PEM electrolyser (pink) and CHP (yellow) production units are the main contributors to covering the heat demand. The PEM electrolyser covers more heat demand than CHP. This should be in that way because PEM electrolyser is now the only source that is generating the hydrogen and in the perspective of the system, it is more efficient to directly cover the heat demand than distributing the heat for the CHP plant.

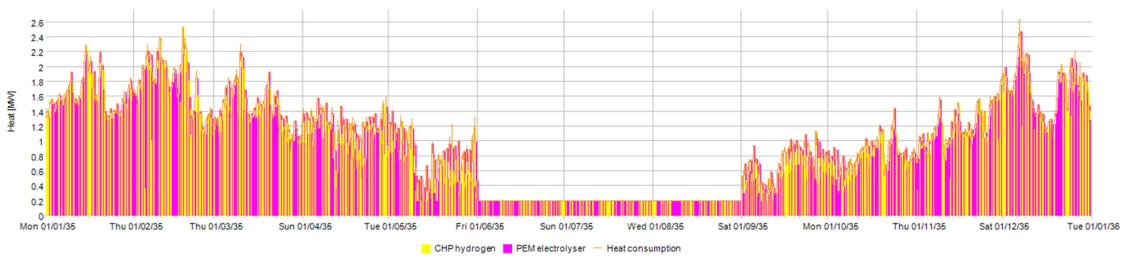

Fig. 36 Concept 1- heat production and consumption

Fig. 37 shows the PV panel's production of renewable energy (green), CHP, and the overall electricity consumption. PV produces electricity mainly in the summer. CHP only supports electricity generation besides the PV because CHP does not work full-time and it is more efficient if PV panels are producing renewable energy and cover the electricity demand directly. Also, importing renewable energy covers beforehand the electricity demand than CHP because CHP is rather now the expense source.

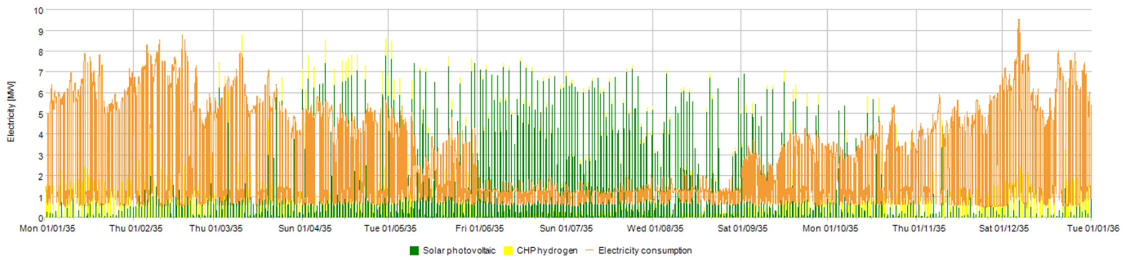

Fig. 37 Concept 1- electricity production and consumption

Fig. 38 is focused on PEM electrolyser production that will cover the hydrogen demand. Hydrogen consumption divided by hydrogen storage and CHP plant needs.

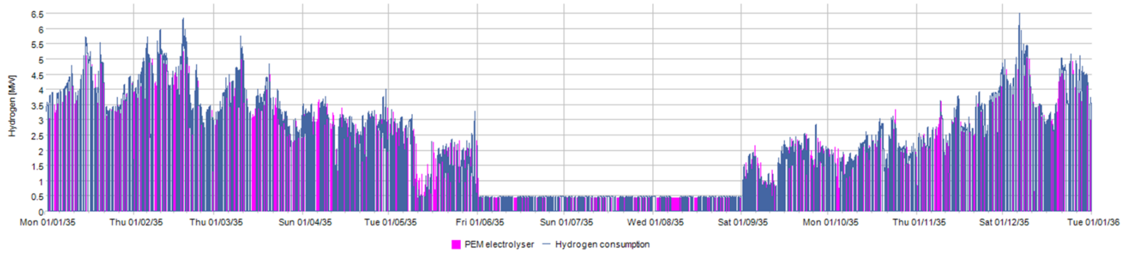

Fig. 38 Concept 1- PEM electrolyser production and hydrogen demand

Fig. 39 shows hydrogen storage behaviour, correlation with electricity prices, PEM production, and CHP hydrogen fuel needs. While looking at more volatile times, there is no long-term storage, but the correlation is that if the energy prices are too high, the storage will lower the storage capacity.

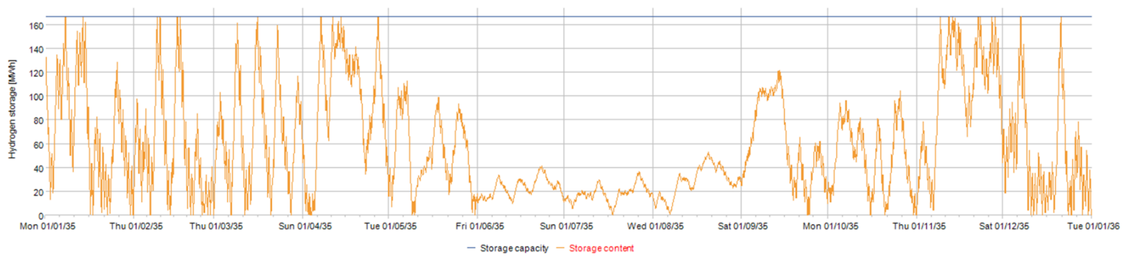

Fig. 39 Concept 1 - storage if H2 is 120 MJ/kg, storage capacity 175 MWh

Fig. 40 Concept 1 - production and consumption graphics

Table 10. Concept 1 simulation results

	Imported	Cash flow EUR
Renewable electricity	15 979 (MWh)	-974 579
	Exported	
Renewable electricity	7 948 (MWh)	740 397
Water consumption		-19 553
Maintenance		-60 000
Net cash from operation		**-313,736 EUR**
PV cost		-14 589
CHP cost		-800 000
PEM cost		-225 000
Storage cost		-378 000
Total investments per year		**-1,417,589 EUR**
Cash surplus		**-1,731,325 EUR**

In conclusion, comparing the solution with the existing natural gas system that has no flexibility in the system, the overall cost is almost the same.

3.2.3 Concept 2 - importing renewable energy and hydrogen

The second concept should be that the campus will buy the hydrogen fuel as much as needed into the system. There is an assumption that for the year 2035, there will be a natural gas infrastructure with hydrogen infrastructure pipelines. Also, the hydrogen fuel prices will be at the same level or lower than natural gas.

Overall, the CAPEX and OPEX will be the same, but the hydrogen fuel price will now be defined under the operational cost. The predicted hydrogen price in 2035 will be 110 EUR/MWh. [23] Then the price will be 110 x 0,011 = 1.21 EUR/kg.

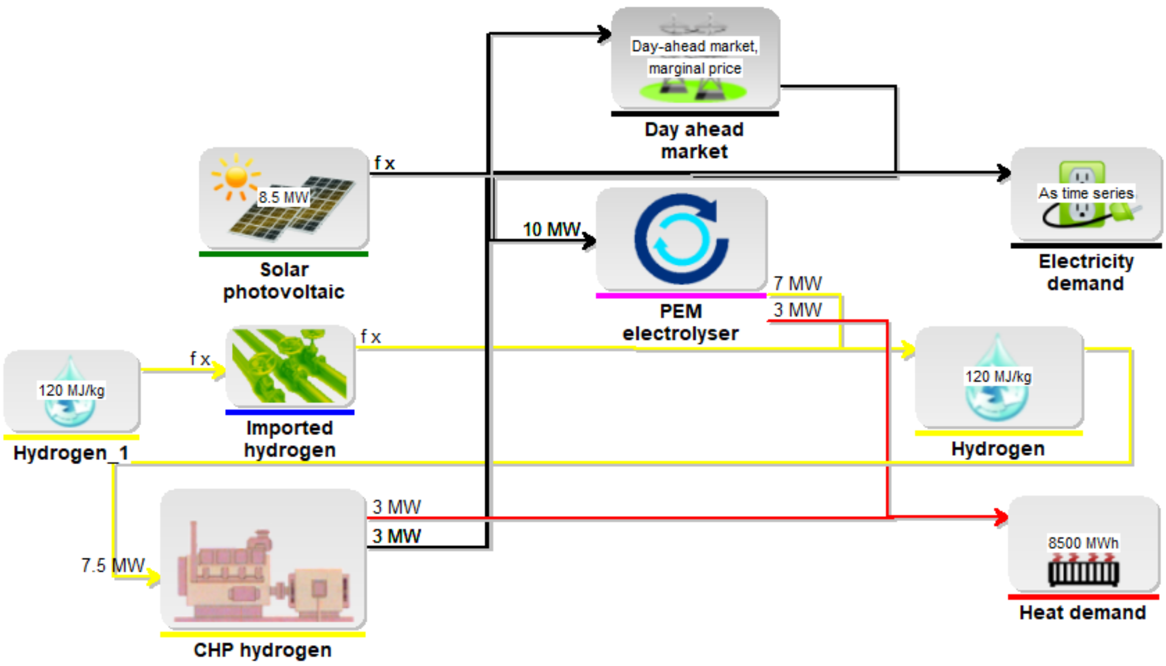

Fig. 41 Concept 2 model

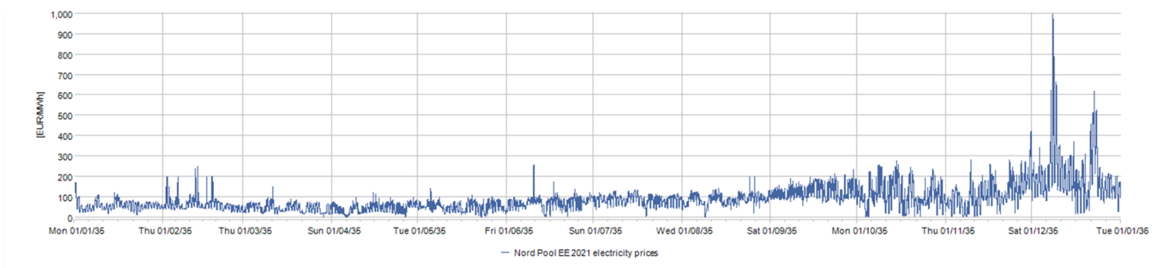

Fig. 42 Electricity prices

Results are showing that with concept 2 the electricity production by energy units is higher in total 14 828 MWh while concept 1 model produces 13 634 MWh electricity. PV park is producing 9400 MWh of renewable electricity per year with both scenarios - concept 1 and concept 2. Concept 1 model units consumed in total 14 544 MWh while the concept 2 model consumed only 10 563 MWh of electricity, which means that PEM electrolyser worked less and there were times if the hydrogen importing was more beneficial for the system in a wise of cost.

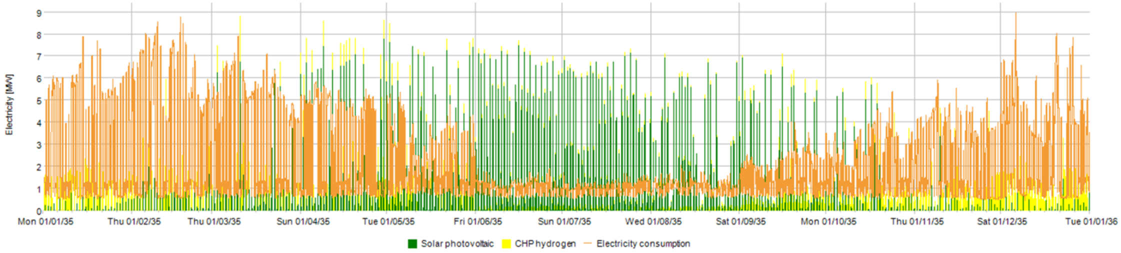

Fig. 43 Electricity production and demand

CHP operating hours were higher if the energy system imported the hydrogen. In concept 1 CHP operated 4300 hours while in concept 2 CHP operated 6600 hours per year. **Fig. 44** is showing a greater amount of CHP heat production 5330 MWh per year.

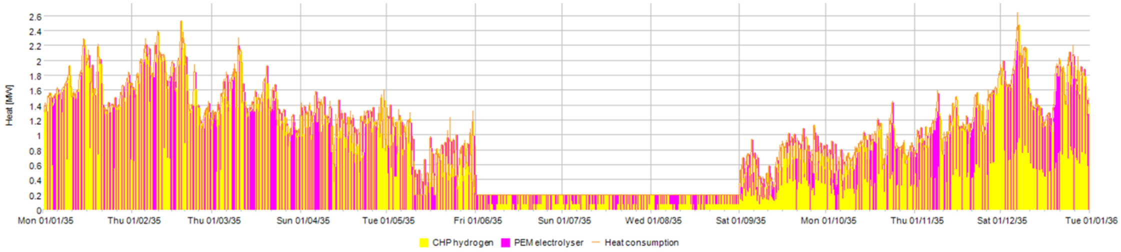

Fig. 44 Heat production and demand

Fig. 45 shows the balance between hydrogen import and production.

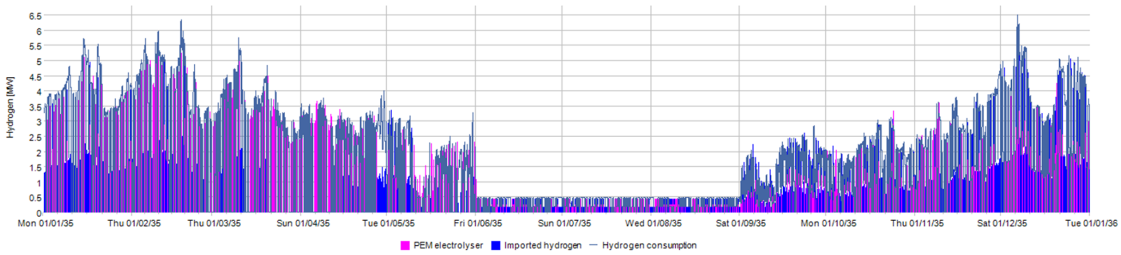

Fig. 45 Hydrogen production and demand

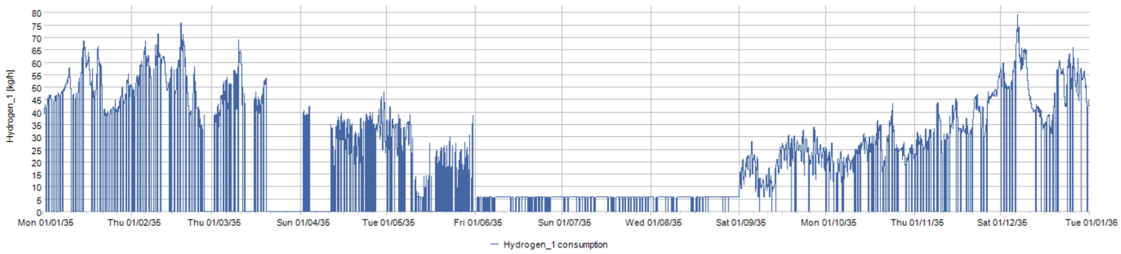

Fig. 46 Imported hydrogen

It seems in **Fig. 47** that storage behaviour is overall the same, the concept 2 model storage is more unstable than concept 1 storage.

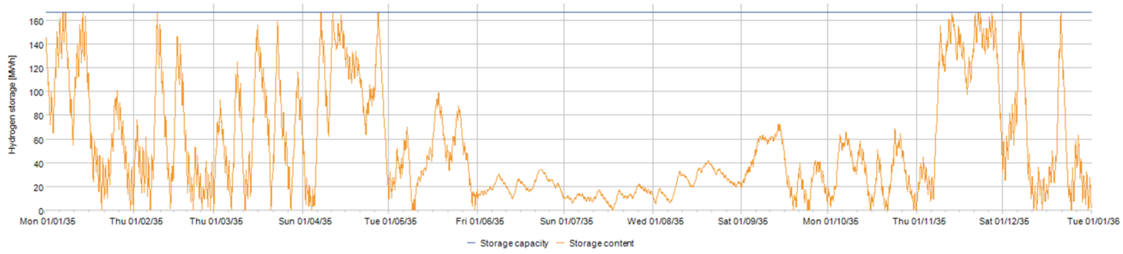

Fig. 47 Storage if H2 is 120 MJ/kg

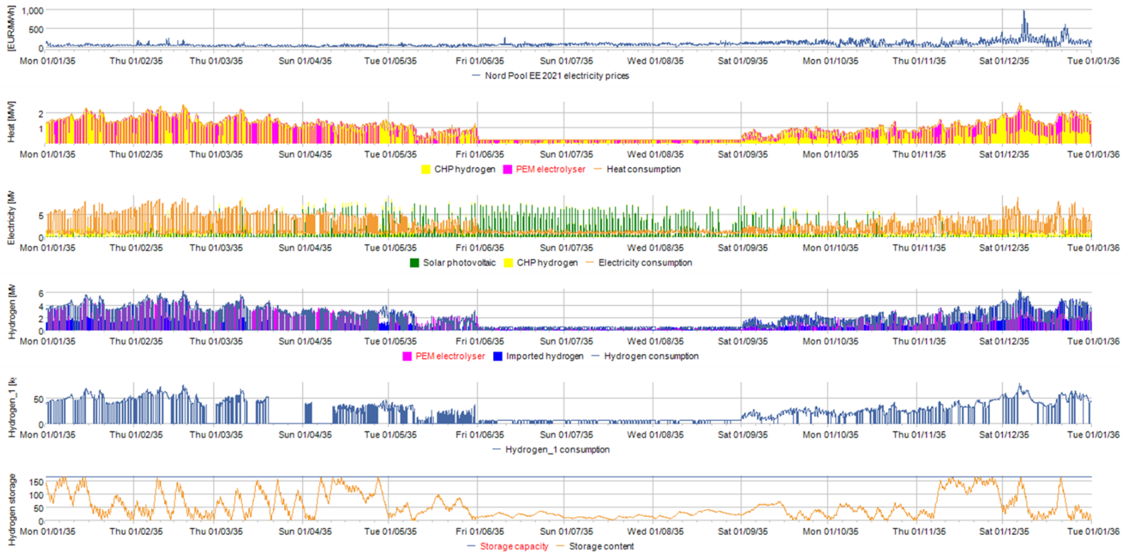

Fig. 48 Concept 2- Electricity, heat, hydrogen production, and consumption graphics

Table 11. Concept 2 simulation results

	Imported	**Cash flow EUR**
Renewable electricity	(MWh)	-591 764
Hydrogen		-209 495
	Exported	
Renewable electricity	(MWh)	793 874
Water consumption		-14 202
Maintenance		-60 000
Net cash from operation		**-81 587**
PV cost		-14 589
CHP cost		-800 000
PEM cost		-225 000
Storage cost		-378 000
Total investments per year		**-1,417,589 EUR**
Cash surplus		**-1,499,176 EUR**

In conclusion, concept two is cost-effective while importing the hydrogen into the grid from the cost side. The overall expense is smaller than the existing system and concept one solution. Here should be noted that this and the previous concept 1 model are sensitive to the hydrogen and natural gas price levels.

3.2.4 Zooming - out

While two of the hydrogen-based system models have been done, there should be some feedback from specialists and considering what else can be done? Stepping back and judging the existing systems will help to see new perspectives or opportunities that could be implemented.

From the consultations with the energy and hydrogen field specialists, they said that the system needs some support, especially the CHP production plant, which is the only unit where it is producing the heat; if this plant is in maintenance or does not have enough power to cover the heating demand, the system will not be resilient. In that sense, the gas boilers are not an option as the existing system has. There should be more significant support from a heating pump that could use renewable energy as input energy for the plant in the new concept. Furthermore, while receiving specialists' feedback and researching heat pump, the IEA strategies have also recommended supporting the hydrogen-based system with heat pumps in building sector energy management.

3.2.5 Concept 3 - adding a heat pump

The idea of adding a heat pump to the system is that it supports and will make the system even more flexible and secure. All the previous data is the same, but the new investment is the heat pump and its specific input and output values. Also, the maintenance price will be a little bit higher because of the new production unit. *"Heat pumps are drawing the heat from a heat source and converting the heat to a higher temperature."* Heat pumps have the ability to provide more heat than the electricity consumed - main advantage. The heat pump's efficiency is defined through coefficient of performance (COP), which is calculated by the formula below. [55]

$$COP = \frac{Delivered\ heat}{Electricity\ consumed}$$

COP for model testing is 2,5.

For systems installed for larger buildings, the cost of equipment is expected to fall 15% in the period 2020-30. For instance, taking the ground-source heat pump, if the overall system heat demand per year is 8,5 MWh, the heat pump total investment cost is around 16 000 euros while annual fixed O&M is 200 EUR. Its lifetime is 18 years. The levelized cost of heating, besides other heat pumps, is the lowest 113 EUR/MWh. The previous heat pump data is from the source [55, 56].

Table 12. Additional inputs for concept 3 model

OPEX	
Maintenance	0,0602 M EUR/year
CAPEX	
Heat pump system investment	0,016 M EUR/ lifetime 18 years

The ground heat pump specifications and the temperatures used. Heat pump inputs: Heating capacity, selected according to consumption; minimum heating capacity; heat factor, heat pump efficiency factor, heating water inlet temperature; heating water outlet temperature.

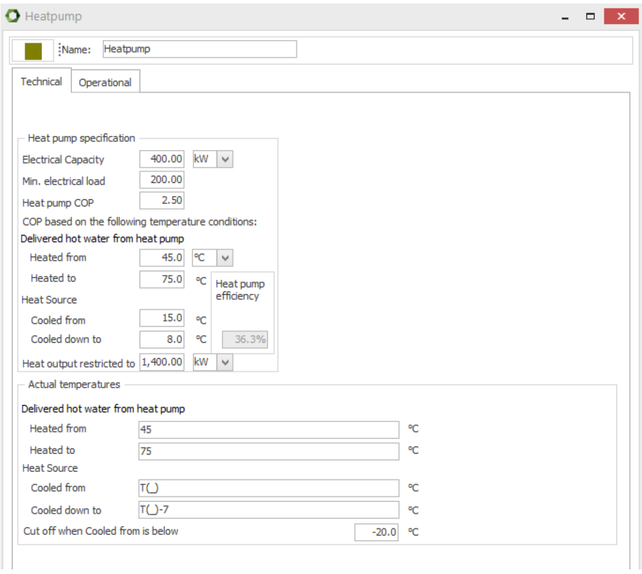

Fig. 49 Heat Pump specification

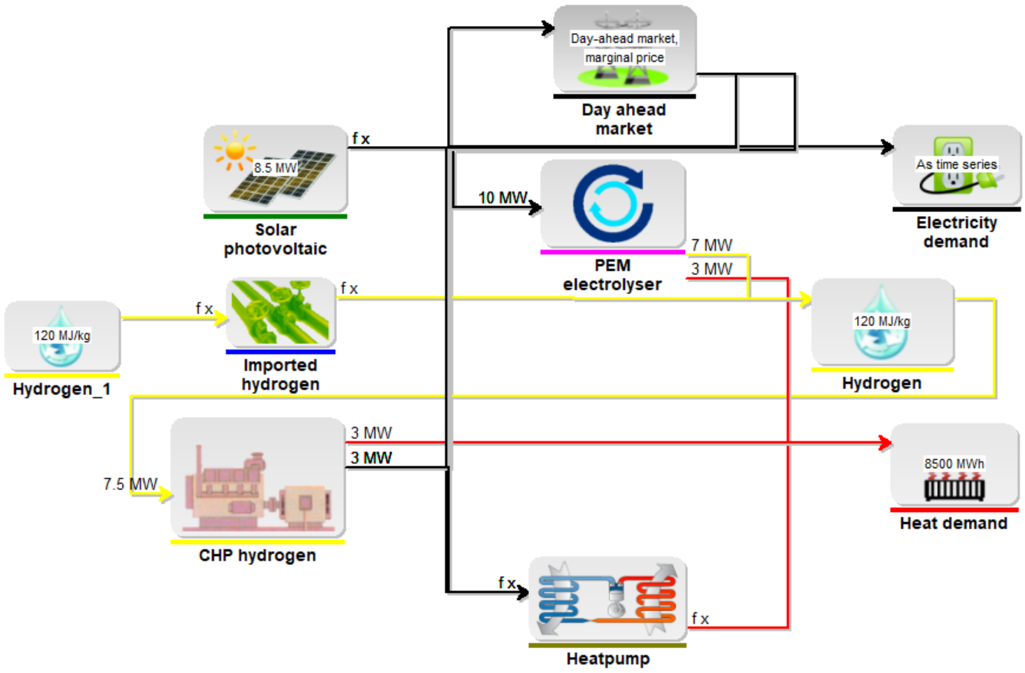

Fig 50. Concept 3 - adding the heat pump to the previous system concept 2.

In **Fig. 51**, the heat pump is covering some of the TalTech heat demand.

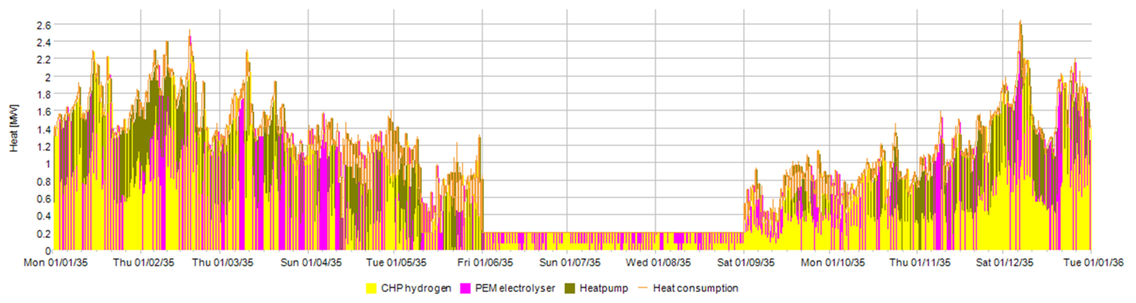

Fig. 51 Heat pump heat production graphic with other units

Additionally, if the heat pump is integrated, now the system is importing 9318 MWh of electricity, but the second concept model is importing 11 518 MWh of electricity. Furthermore, the electricity export is also lower with concept 3. Less electricity is also used by energy units in model 3. The biggest electricity consumer in the system is the PEM electrolyser, where now the heat pump has the role of to balance the system. The CHP operation hours are rising with the concept 3 only 100 hours. While looking at **Fig. 52**, the storage is less sensitive.

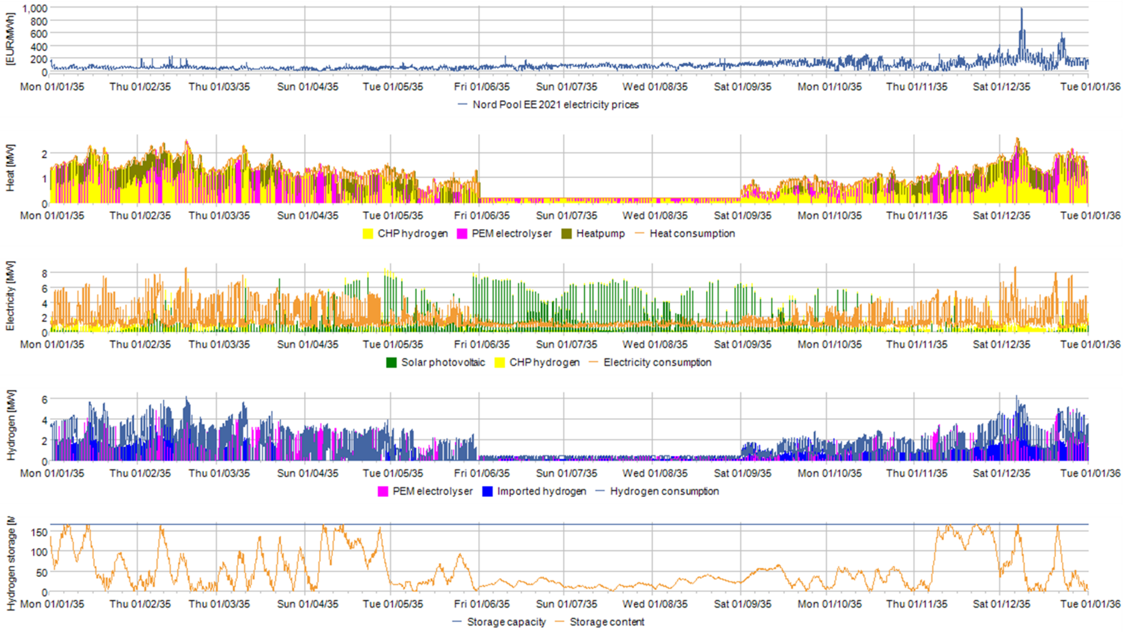

Fig. 52 Concept 3

Table 13. Concept 3 simulation results

	Imported	Cash flow EUR
Renewable electricity	9 319 (MWh)	-461 814
Hydrogen		-192 033
	Exported	
Renewable electricity	7 334 (MWh)	702 415
Water consumption		-9 730
Maintenance		-60 200
Net cash from operation		**-21 363**
PV cost		-14 589
CHP cost		-800 000
PEM cost		-225 000
Storage cost		-378 000
Heat pump cost		-900
Total investments per year		**-1 418 852 EUR**
Cash surplus		**-1 439 852 EUR**

3.3 Concept evaluations

The electricity production/ consumption is about what the units have produced by CHP or consumed by PEM (concepts 1 and 2), PEM and heat pump (concept 3). Electricity import and export mean how much the grid imported or exported the electricity in the excellent time. Hydrogen consumption means how much hydrogen PEM electrolysers have produced and how much CHP is consumed. Hydrogen imports have been calculated by dividing hydrogen's total cost by hydrogen price.

Table 14. Concept evaluations

Concepts	Electricity production/ consumption MWh	Electricity import/ export MWh	Hydrogen consumption	Hydrogen import MWh	OPEX and CAPEX Cost (€/ 2035 y)
Existing case	n.a/ boiler	7 350/ n.a	n.a/n.a	n.a	1 589 407
Concept 1	13 600/ 14 655	16 105/ 7 700	10 342	n.a	1 731 325
Concept 2	14 828/ 10 563	11 518/ 8 432	13 327	1 904,5	1 499 176
Concept 3	13 704 / 8 338	9 319/7 334	10 517	1 745,8	1 439 852

Final concept 3 is the most feasible technically and economically. The system's total cost has the value for investing besides the existing system that has even more significant expenses because the system does not have the flexibility to import, export, and store the energy. In concept three, half of the revenue comes from exporting renewable electricity. That sets into the vital role of renewable energy sources besides hydrogen and proves that local renewable energy production sources are raising the value of the overall energy system with hydrogen-based systems. Additionally, models are price sensitive, which means if the natural price is projected as 150 EUR/MWh shortly, the OPEX expenses are raising the total cost even more.

Also, adaptability is the key value when considering TalTech campus. There is a question of where the hydrogen and electricity production unit should fit on a larger scale. Initially, considering the smaller case, the laboratory should be enough to make the study module interactive, modularized/movable, and practical.

3.4 Tests

Taking the most efficient hydrogen concept 3 and testing the model with different hydrogen prices while comparing the existing model of TalTech, where the total operating expenses per year was -1 589 407 EUR with 100 EUR/MWh natural gas and CO_2 0,195 EUR/Nm³ price level.

Table 15. Hydrogen price comparison

Concept 3	**hydrogen price (EUR/MWh)**	**hydrogen cost per year (EUR)**	**total cost per year OPEX + CAPEX (EUR)**
1	30	69 428	1 255 105
2	60	129 295	1 322 296
3	90	175 334	1 384 237
4	120	192 804	1 437 568
5	150	175 446	1 479 352
6	180	151 486	1 507 765
7	210	150 389	1 529 337
8	240	146 038	1 547 768
9	270	132 698	1 562 017
10	300	130 122	1 575 360

From the results it seems that with hydrogen system TalTech total expenses per one year are still lower if hydrogen price will be 300 EUR/MWh by 2035. The system's total cost will be higher but not with a correlation to the hydrogen price that was ten times higher. It means that electricity prices and exports influence the models a lot. Also, as previously stated, half the revenue is from exported renewable electricity.

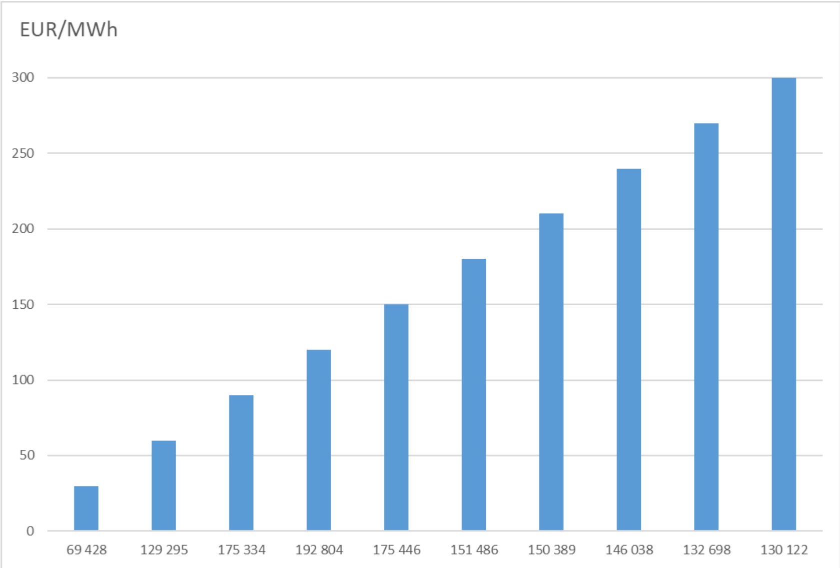

Fig. 53 Hydrogen price test with concept 3 total cost

Besides the changing hydrogen prices, **Table 16.** shows the total cost scenarios whether the gas prices are higher or lower.

Table 16. Natural gas price comparison

Existing system	natural gas price (EUR/MWh)	total cost per year (EUR)
1	50	1 203 043
2	60	1 280 316
3	70	1 357 589
4	90	1 512 134
5	120	1 743 953
6	180	2 207 589
7	210	2 439 407

The existing natural gas-based energy system is cost-effective besides concept 3 hydrogen-based energy system if the natural gas price level is 70 EUR/MWh and lower.

4. DISCUSSION

Concept 3 was about importing hydrogen and renewable energy into the energy system while renewable energy was also exported. Hydrogen was produced from renewable electricity with a PEM electrolyser. Hydrogen was stored in the compressed gas tank or distributed to the CHP that generates the electricity and heat from the hydrogen that can cover heat and electricity demands. Furthermore, a heat pump was added to concept 3 because electricity export was high from the previous system analysis results. The heat pump makes the energy system more flexible and reliable, whereas the CHP unit is not the only production plant that supplies the campus with heat. Concept 3 is the most cost-effective solution while implementing green hydrogen and PV park into the TalTech existing gas and electricity grid if the hydrogen price will be 110 EUR/MWh on the same level as today's natural gas, with the 10% difference being in favour of hydrogen by in the total cost (OPEX + CAPEX). However, it must be noted that this difference factor is expected to grow as the price of natural gas per energy unit is projected to rise. In contrast, the price of hydrogen per energy unit is projected to fall. [23]

It must be stressed that the analyses presented in the thesis were conducted with a relatively high-level model. This model could be improved for further analysis by, for example, allowing the campus energy system to participate in the local balancing markets or arbitrage. Hypothetically, given the hydrogen storage and regeneration capacity, it should be expected that this will further improve the economic performance of a hydrogen-based model compared to a natural gas-based system.
Overall if the distribution grid is flexible and the system has hydrogen energy storage in the future, that solution can help balance the special locations of the distribution grid with the high load peaks.

In addition to improvements made to the analysis model itself, the model's elements can be optimised for different setups. For instance, carrying in mind participation in the balancing markets, one could suppose that a significantly oversized electrical energy storage capacity would outperform a smaller storage capacity despite the expected increase in CAPEX required. This will require further research, as some of the Estonian frequency markets are still unopened due to desynchronization from the BRELL grid area only planned to occur in 2024. [57]

Cost-effectiveness aside, the many uncovered research areas display the necessity of a hydrogen-focused research initiative group. In order to get to actual system integration, several steps will need to be taken in succession. Theoretical studies will be followed by experiments; experiments will be followed by live pilot systems; live pilot systems may be developed into industrially operable systems. Focusing on hydrogen systems research will eventually lead to a climate-neutral TalTech campus.

A growing community of engineers with experience in the hydrogen energy field, who may even have had practice in building experiments on the TalTech campus, will likely lead to a growing hydrogen energy sector in the greater economy. The interest is already there, as seen in the interviews and surveys conducted with Elering and Eesti Energia companies. The hydrogen system is estimated to be economically and ecologically preferable to a natural gas-based system in 2035.

Furthermore, it is inevitable that, for building any necessary large-scale infrastructure for greater involvement of hydrogen in the energy sector, practice models and experiments will need to have been run beforehand. TalTech will be a strategic forerunner and partner for industrial hydrogen projects by including a hydrogen technology testbed on campus. With practical experience, TalTech will also be in the position to provide consultations for properly regulating the field in order to ensure the safety, reliability, and environmental friendliness of the hydrogen sector.

The Estonian economy can benefit from piloting the hydrogen system, but also the knowledge in society will rise, and people will accept the hydrogen sooner. TiVo hydrogen organisation could be in the position of spreading the knowledge, connecting people, universities, and companies.

4.1 Values

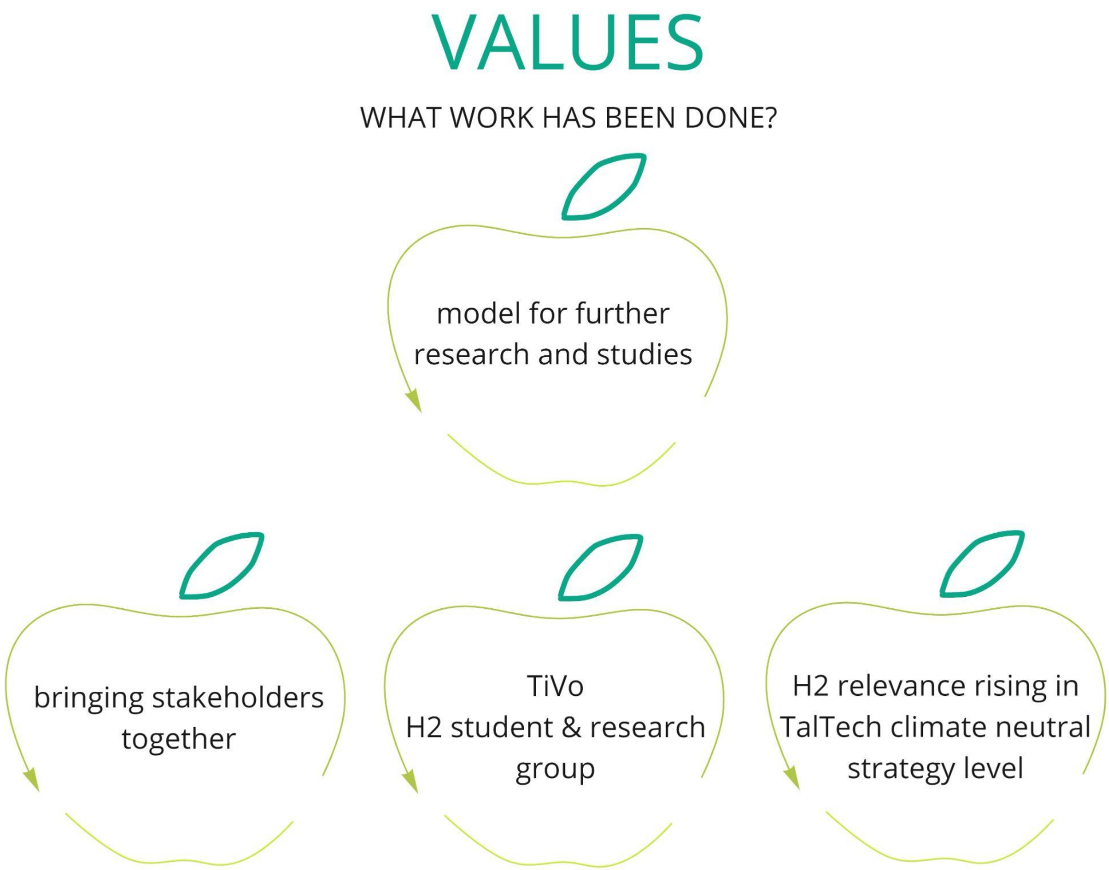

Fig. 54 Thesis values

SUMMARY

TalTech has not fully defined actions on how to achieve a climate-neutral campus by 2035. This thesis supports the one strategic action where hydrogen transition at the TalTech campus should take place by piloting the project. Helen Sooväli-Sepping as a Vice-Rector for green transformation, and the workshop participants were in favour of hydrogen-based energy systems being explored as one potential option. Currently, enrolled students are interested in hydrogen research. The university's greater support has been seen for TiVo, where they made the first organisation introduction event for university-family in May.

A further plan could be for the university to look into the possibility of further hydrogen research and the integration of hydrogen into the Department of Electrical Power Engineering and Mechatronics curricula. TalTech could consider the research work that has justified the importance of integrating hydrogen at the social, economic, technical, political, environmental, and legal levels, based on a vision for the future of campus climate neutrality. IEA and European Commission climate strategies strongly emphasised hydrogen integration.

The proposed model demonstrates the cost-effectiveness and flexibility of local energy and heat production based on renewable energy and clean hydrogen if the hydrogen price achieves the price level of 110 EUR/MWh or natural gas prices rise enormously with CO_2 taxes by 2035. Concept 3 has many benefits on the grid level but also for the end-user TalTech campus. The most valuable is gaining the know-how and contributing to Estonian hydrogen regulations and infrastructure formalisation. On a world level, this would be among the first biggest hydrogen system projects, and the university will benefit from this project as an innovation leader.

KOKKUVÕTE

TalTechil puudub täpsem tegevuste kirjeldus saavutamaks kliimaneutraalset ülikoolilinnakut aastaks 2035. Käesolev lõputöö toetab visiooniloomet vesinikule üleminekust TalTechi ülikoolilinnakus aastaks 2035. Rohepöörde prorektor Helen Sooväli-Sepping on toetava seisukohaga, et vesinik võiks olla üks võimalikest uuritavatest lahendustest. Ülikoolis on sisemine huvi vesiniku uuringute vastu, mis tuli peamiselt välja workshopi korraldamisest. Ülikool toetab loodud TiVo - Tehnikaülikooli Inseneriteaduskonna Vesinikuorganisatsiooni, maikuus esimese tutvustusürituse ülikooliperele, tutvustades organisatsiooni ning küsides teadlikkust vesiniku kohta.

Edasine plaan võiks olla ülikoolil vaadata võimalust vesiniku edasise uurimistööde ja vesiniku integreerimise Elektroenergeetika ja mehhatroonika õppekavasse. TalTech võiks kaalutlusele võtta tehtud uurimusliku töö, mis on põhjendanud vesiniku integreerimise olulisust nii sotsiaalsel, majanduslikul, tehnilisel, poliitilisel, keskkonna ning juriidilisel tasandil, lähtudes tuleviku TalTech linnaku kliimaneutraalsuse saavutamise vajadusest.

Modelleeritud kolmas vesiniku kontseptsioon loob esimese teadmuse kohaliku energiasüsteemi üleminekust vesiniku ja taastuvenergeetika lahendustele. Euroopa Komisjoni ning IEA strateegiad rõhutavad ning toetavad vesinikul baseeruvai süsteeme kui kliimastrateegia eesmärikidele kaasaaitajat.

Loodud mudel 3 tõestab kuluefektiivsust ning paindlikkust taastuvenergial ja puhtal vesinikul põhinevas kohaliku energia ja soojuse tootmises, kui vesiniku hind on võrdsustunud 110 EUR/MWh tänase maagaasi hinnaga või kui maagaasi hind on drastiliselt tõusnud CO_2 maksustamisega aastaks 2035.

Väljapakutud mudelil on eeliseid võrgu tasemel, aga ka lõppkasutaja TalTechi ülikoolilinnaku jaoks. Kõige väärtuslikum on oskusteabe omandamine ja panustamine Eesti vesinikuturu reguleerimisse ja infrastruktuuri rajamisse. Maailma tasandil oleks see üks esimesi suuremaid vesinikusüsteemi projekte ning ülikool on siis kui vesiniku tööstuses üks innovatsiooniliidreid.

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