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ICEs in the future energy landscape with increased renewables

Operators Perspective

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ABSTRACT

The intermittency of renewables drives the need for more balancing power at zero or very low emissions because the sun doesn't always shine, and the wind doesn't always blow. There is also a steady growing demand for energy as we are transforming to an “electric way of life” including transports sectors, and the internet of things requires more and more data centers. According to the IAE, electricity generation is expected to grow with a factor of three and renewables by eight. So, the shift to renewables is driven by demand, and there will be gradual replacement of coal and other fossil-fueled energy generation.

As a result, the power systems are becoming increasingly complex with different types of generation assets.

To respond to this challenge, sustainable fuels will be part of the balancing journey going forward, and digitalisation will create opportunities to optimise energy costs. Hydrogen, as a feedstock for sustainable fuels or used directly in internal combustion engines is a promising solution for the energy sector decarbonation, especially with the development of peaking power plants along the large interconnected international hydrogen valleys and pipelines with increasing intercountry distribution grids.

Hydrogen can be also a local production solution via electrolysers, for energy storage and redistribution in the grid via hydrogen engines power plants.

We will go through the narrative of a Wärtsilä design typical hydrogen ICE peaking power plant concept and briefly evocate a typical Power-to-X-to-Power pilot project in Finland. A detailed Plexos analysis of Finland grid and the inclusion of renewables will be presented, with conclusions and evidences of the need for balancing power plants.

In addition, it will be introduced the difficulties met when using pure or multi sustainable fuels in ICE. In particular, the hydrogen usage will be presented, in liaison with the Hydrogen Ready TÜV SÜD certification. The safety aspects and the performances will be discussed, with the solutions we adopt. Some operational feedback will be shared.

1 INTRODUCTION

1.1 Energy is moving towards a 100% renewable energy future

The intermittency of renewables drives the need for more balancing power at zero or very low emissions. There is also a steady growing demand for energy as we are transforming to an “electric way of life” including transports sector and internet of things requires more and more data centers. According to the IAE electricity generation is expected to grow with a factor of three and renewables by eight. So, the shift to renewables is driven by demand, and there will be gradual replacement of coal and other fossil fuelled energy generation.

In countries where wind and solar are expected to play a dominant role in the energy transition, integration of these intermittent energy sources with the power grid place significant pressure on the grid operation as the supply of the power especially from wind cannot be controlled or rapidly predicted.

Furthermore, the renewable electricity from wind or solar is often provided in times when demand is low and the electricity has to be stored or wasted. There is a need to create solutions for industrial scale, cost effective and sustainable balancing power plants.

Integration of sustainable balancing power plants with the grid will open new application areas for sustainable fuels such as green hydrogen ranging from operation during peak demand to other services needed to maintain a reliable and secure renewable power supply with no environmental impact. Fundamental technical barriers are not expected to arise.

1.2 Wärtsilä Energy introduction

Wärtsilä Energy leads the transition towards a 100% renewable energy future, helping our partners to accelerate their decarbonisation journeys through our market-leading technologies and power system modelling expertise. These cover decarbonisation services, future-fuel enabled balancing power plants, hybrid solutions, energy storage and optimisation technology, including the GEMS Digital Energy Platform. Wärtsilä Energy’s lifecycle services are designed to increase efficiency, promote reliability and guarantee operational performance. Our track record comprises 79 GW of power plant capacity and 115 energy storage systems delivered to 180 countries around the world.

1.3 Policies and emissions regulations

Regulatory frameworks and policies are accelerating the move to a low-carbon society

- EU has set the climate neutrality target to be reached by 2050 and an agreement on 55% GHG reductions by 2030.
- In United States, many of the states have set targets to have all their electricity produced from 100% renewable energy sources by 2035. Net zero emissions target by 2050
- China has its carbon neutrality target by 2060.
- 46 countries pledged for coal phase-out at COP26 conference held in 2021. Country climate pledges are still likely to evolve and become more progressive.
- REPowerEU is the European Commission’s plan to make Europe independent from Russian fossil fuels well before 2030, in light of Russia's invasion of Ukraine.

A notable step forward in climate policy was the Inflation Reduction Act in the USA, which allocates substantial incentives to renewables, battery energy storage, and other clean energy technologies. The first Just Energy Transition partnership was announced at COP26, between South Africa and France, Germany, the United Kingdom, the United States, and the European Union. The aim of the partnerships is to help a selection of heavily coal-dependent emerging economies make a just energy transition.

At COP28, the involved parties declared their intent to commit to work together to triple the world’s installed renewable energy generation capacity to at least 11 TW by 2030” among other things, such as doubling energy efficiency improvements from 2% to 4% until 2030.

China and India did not sign the pledge but are key countries in achieving this goal. In the Sunnylands Statement with the US, China did “support pursuing efforts” to the same objective. The final decision also “calls on Parties to contribute” to these same targets.

The goal is consistent with pathways to net zero by 2050. According to BNEF, solar is already on that trajectory, but the wind outlook is behind the target. It is important to double down on wind investment due to its complementary profile and higher capacity factor. Figure 1 shows the IEA and BNEF forecast on installed capacity.

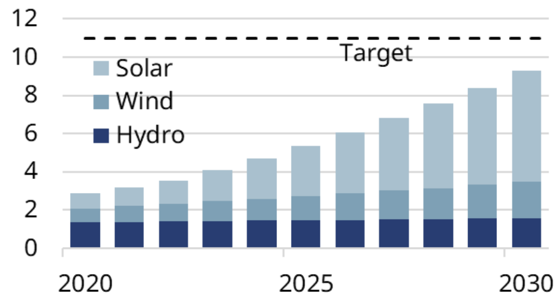

Figure 1. Forecast inst. capacity, TW (BNEF and IEA)

Key bottlenecks for tripling renewables in seven years are grid investment, complex permitting processes, and improving revenue certainty for renewable generators.

1.4 Technologies

Technologies are scaling up to meet the demand:

- Wind and solar growing rapidly as the dominant source of energy
- Intermittent sources requiring balancing power
- Sustainable fuels for balancing power
- Digitalisation will create opportunities for optimising energy costs
- Cyber security growing in importance

If we look at the technology side, the share of wind and solar in the baseload generation is growing rapidly. The intermittency of renewables drives the need for balancing power. Sustainable fuels will also be part of the balancing journey going forward, and digitalisation will create opportunities to optimise energy costs. Also, the importance of cyber security is growing. But these technologies are already commercially available and applied at various size ranges and locations. ENGINE POWER PLANTS

1.5 The place of engine power plants in the power market with renewables

The engine power plants are needed for flexibility, efficiently and reliable power generation. The range of such power plants extend from balancing renewables such as wind and solar to flexible baseload production. They are optimally used in balancing the variability of power systems caused by renewables and weather.

1.6 Flexible power generation

Engines can start and stop quickly, adjust power rapidly, and operate at various loads and extreme conditions. They can generate megawatts to the grid in less than thirty seconds from start up and reach full load in less than two minutes; They are able to ramp down from 100% load to zero within a minute. Engines are designed to start and sto time after time without any impact on maintenance.

1.7 Balancing definition

Balancing can be roughly divided into two time periods. Most of the variability in load and variable generation is balanced by committing generation units to dispatch. This is mid-term balancing. Short-term balancing is mainly about correcting forecast errors in the original dispatch. This is achieved with intra-day and balancing markets and finally, in real time by activating frequency reserves either automatically or manually. Both midterm and short-term balancing are affected by long term decisions on investments and retirements of generation and consumption units. Seasonality, meaning energy demand fluctuations in the winter and summer seasons, is one of the key challenges for future smart energy system management, which will have various consequences for optimization in various parts of Europe and globally. As an example, photovoltaic power production goes down dramatically in winter time, especially in northern countries, while electricity consumption grows for heat pumps.

1.8 Balancing ICE power plant

As renewables increasingly displace the traditional baseload generation there is a growing need ensuring the grid stability with balancing capacity. Balancing power can be scaled up to the share of the power system increase. A balancing ICE power plant can quickly ramp up whenever renewables don’t generate enough electricity in order to provide the necessary balancing power to keep the grid stability.

1.9 Flexible baseload power plant

The energy transition would speed up the decline in inflexible baseload coal and oil power plants. However, ICE flexible baseload provide steady and continuous power supply ensuring the industries a continuous access to a reliable energy.

1.10 Grid stability management

Utilities, system operators, and regulators are increasingly faced with the challenge of balancing power systems in an optimal way. Power grids typically see significant load variations during the day and between seasons. The system capacity is typically a mix of power plants dedicated for base load, intermediate load and peak load. Flexible engine power plants are, however, able to handle many functions in power systems, which have traditionally been managed by separate dedicated power plants applying different technologies. The wide load range, in combination with the high efficiency at different loads and the fast starts and stops, that combustion engine power plants can offer, make them highly valuable assets to a system dispatcher. To date there are more than 1000 Wärtsilä power plants installed operating as grid stability, peaking and stand-by power plants.

1.11 Introducing sustainable fuels

The use of green hydrogen as fuel and derived (ammonia and methanol) produced with surplus of electricity contributes to the decarbonization of electricity generation.

The continued viability of thermal plants will increasingly be determined by their ability to operate with (rather than instead of) renewable generation. The ability to ramp power production up and down rapidly will become critical, as will operating costs during extended periods where cheap renewable power predominates. As a conclusion, in the energy sector, sustainable fuels will play a major role in the decarbonization.

However, fuel flexibility is seen as an insurance against future risks. When demand for sustainable fuels picks up, supply will follow.

2 ENERGY MIX MODELIZATION STUDIES

2.1 Introduction

The idea is to demonstrate through a PLEXOS ® simulation study the need for balancing power plants in the future sustainable energy mix. For such a demonstration, we selected Finland as a representative country of the average European energy mix.

2.2 PLEXOS study

Wärtsilä has delivered more than 200 countries and systems studies with PLEXOS software.

The benefits from such study are:

- Understanding operations and fundamentals of increasingly complex power and energy systems.
- Quantifying system level benefits of different generation and storage technologies.
- Understand and promote high quality modelling.

3 MODELLING THE FINNISH ENERGY SYSTEM IN 2027 & 2030

3.1 PLEXOS Finland case study

For many years in the past, there was no real need for Finland’s grid to be studied thanks to the large amount of hydroelectricity. However recently, with the renewables that are now incorporated in the system, Finland starts to see similar issues than in the US for example. On top of that, despite recent baseload nuclear addition to the grid, it is not really supporting renewables in a way as renewables need flexible firm capacities to be balanced, so a different type of technology is still needed today.

Finland can become a leading country in clean energy and climate footprint, attracting investments in both clean energy production and industry accelerating the green transition.

If production investments and hydrogen projects are realised, Finland's need for electricity will increase. One of the prerequisites for industrial production investments is to ensure the availability of reliable, low-emission and reasonably priced energy. Wärtsilä modelling shows that this requires rapid changes to the Finnish energy system and the construction of new reliable production capacity to support renewable energy sources and curb the rise in energy costs.

Wärtsilä modelling examines the development of electricity prices and system reliability in Finland over the next few years, until 2030. The modeling looks like:

- the price of electricity and its dependence on weather should rise sharply; In 2027, the price will be about 30% higher than in 2023
- The reliability of the power system is already tight in normal circumstances. During a prolonged period of windless and cold weather, there may be a power shortage in Finland
- The average price of electricity reducing 2 GW of flexible and reliable additional capacity by 10% already under normal circumstances, which corresponds to annual savings of EUR 1.3 billion for Finnish electricity users
- Increasing flexible and reliable capacity will have a significant impact on the reliability of the electricity system

3.2 Inputs

The Model type is a fundamental dispatch model. It is an optimized heat and power, including reserve markets. It has 1-hour resolution as a chronological model.

We have selected modelling years 2027 and 2030 and 35 weather years based on historical climate data.

3.3 Costs and bidding

Cost-driven dispatch of available resources based on total cost minimisation and hourly price formation for each price area based on the short-run marginal costs of the marginal unit (marginal pricing).

3.4 Assumptions and inputs

Type	Source
Power generation fleet	entsoe ERAA by ENTSO-E (2022)
Renewable profiles	
Demand side response	
Electricity demand	
District heating demand	Tilastokeskus
Hourly district heating	HELEN
District heating fleet	Energiateollisuus
Fuel costs	Bloomberg
CO_2 cost	

Table 1: list of input sources

3.5 Load growth and capacity mix in Finland

According to ERAA 2022 & Fingrid ® the prediction is described as below:

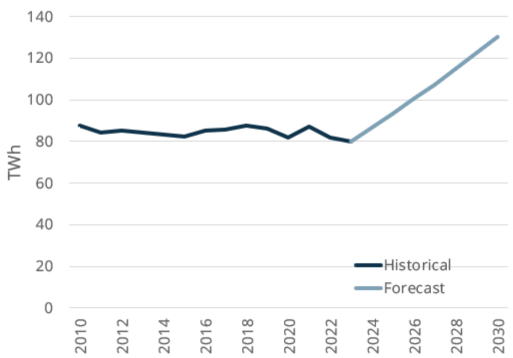

Figure 1. Energy consumption variation

The energy consumption has been stable until now, but things as are moving with the introduction of more renewables; a huge increase u to 2030.

According to the study, electricity prices and wind capture prices are highly dependent on load growth.

Without load growth, electricity prices remain the same in 2027 and will decrease sharply in the future. Wind capture assets price needs to be 30-40 €/MWh in order for them to get financed and built.

Regarding the capacity in the system, in 2023 we had 7GW of Wind, neglectable Solar, and the increase of both is dramatic, as during the same period the firm capacity is decreasing drastically.

3.6 Example week from the model

If we take from the model a week in 2030, we have the demand as below:

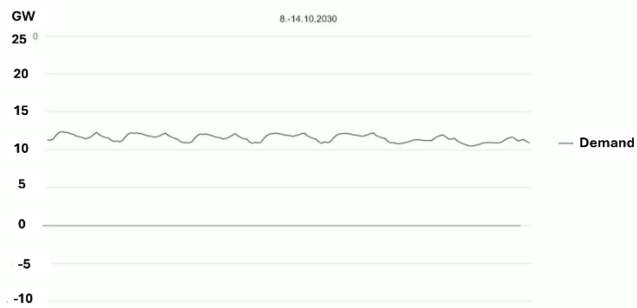

Figure 2. Daily consumption curve

This graph shows what the country is consuming day and night (fluctuating). Consumption is around 12 to 13 GW.

Then the model puts on top of the consumption line where the production is coming from:

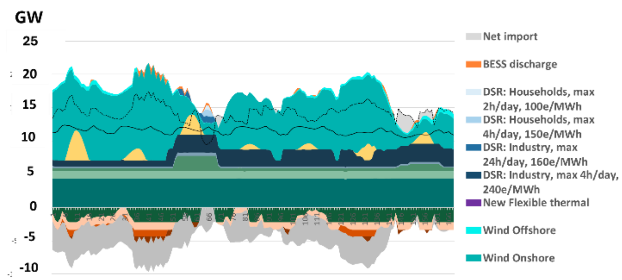

Figure 3. Consumption curves 6 Example week from the model. Average week in October (8.-14.10.2030), weather year 1991

On the base load are the nuclear, the bio thermal, which is partly dispatchable, then the hydroelectricity which has also a bit of flexibility, The solar energy is depicted as peaks, the wind is added, and some batteries storage is discharging on the top.

There is more power produced than the actual demand. But we need to take into account the new consumers, such as electrolysers, the heat pumps for electric district heating, and the batteries need to be recharged. The dotted line is then the total demand. But there is still a difference between what is produced and the total demand. The "grey" surfaces represent what is sold to Finland neighbours, and at some period of time some electricity is bought from Sweden or Norway.

If we look at a more difficult situation such as a typical week below:

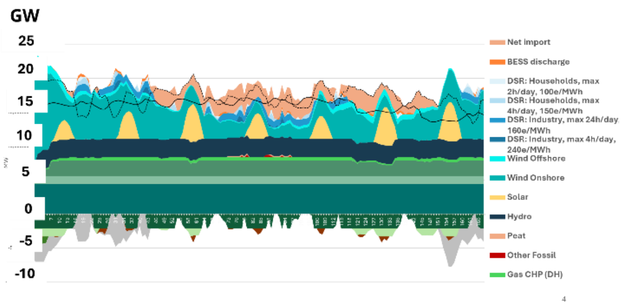

Figure 4 One-week consumption & production sources graph - High demand & low wind week in February (12.-18.2.2030), weather year 2011

We see a high demand and low wind week in February. The weather is much colder than in October, so many days it is necessary to buy electricity from the neighbours. But due to general shortage of wind in the neighbourhood either the price of imported electricity will be important.

Finland area electricity price in 2027 will depend on the weather conditions. Yearly average price can be low or very high depending on wind and hydro conditions on the given year. The price depicted in the figure x below was calculated based on 35 different years with different types of weather.

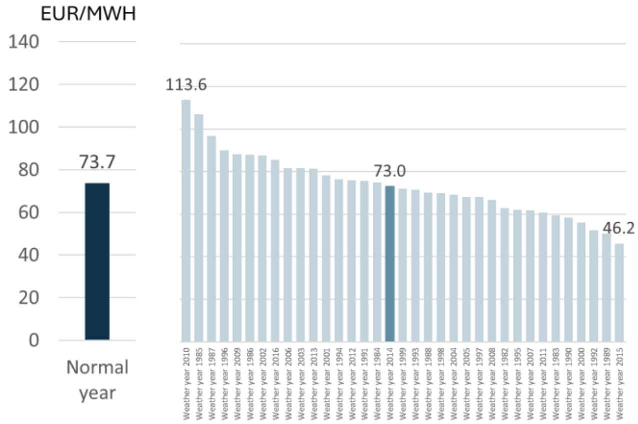

Figure 5: price variation graph - Yearly average of 35 weather years

The Finnish system with this amount of renewable becomes very weather dependant. Worse weather year (1985) with low wind and low temperature the electricity price would have been around115 €/MWh when the best weather year (2017) with a warm winter and high wind would have been around 35 €/MWh.

Furthermore, with the average year (1991), we can see below the price duration:

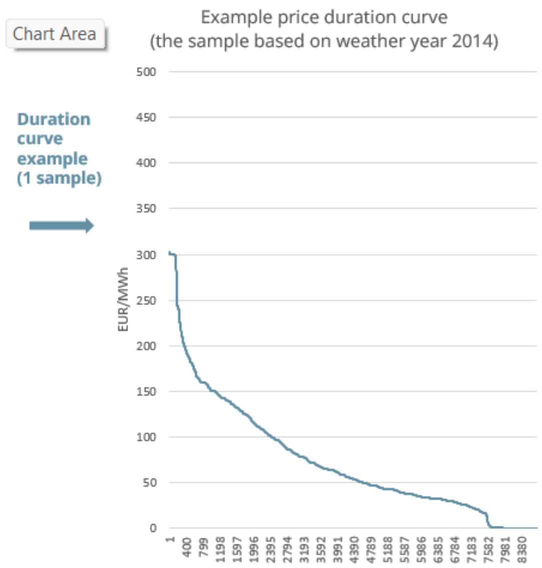

Figure 6: price duration

We can see that a few days extend up to 400 €/kWh and other extreme situations where prices are negatives. The spread is found in a normal year but high prices around 400 €/MWh will become predominant if a worse weather year like 1985 happen again.

3.7 Flexible firm capacity

We would look at the system when we add firm flexible capacity, ie capacity that can be turn on and turn off without any impact on maintenance or operating costs.

The study then modelized 2 GW flexible capacities with Wärtsilä engines in the system, the average price for the consumer drops from 73.7 to 66.6 €/MWh.

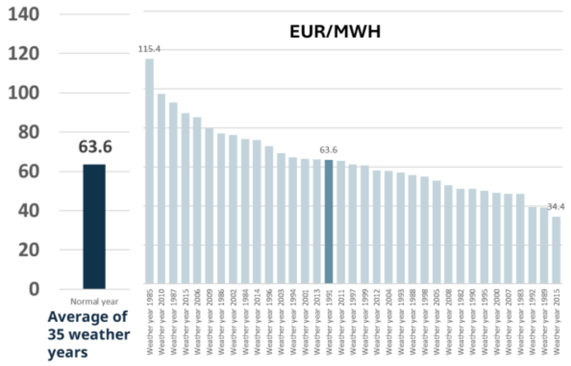

Figure 7: price variation graph

It is interesting to see that the most important impact is happening on the hardest and most difficult years.

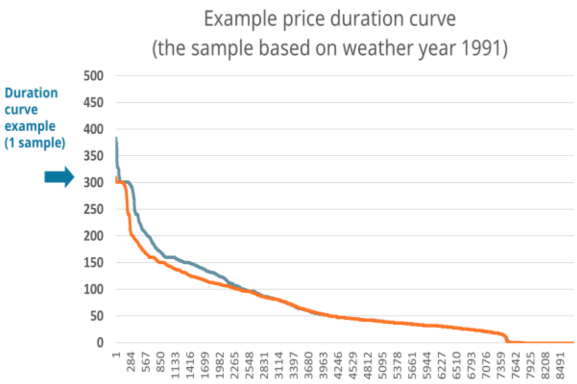

Figure 8. example of price duration curve

When we look on a duration period for the year example 2014, peak is well reduced, reduce the average but no increase of the bottom prices either.

From a consumer perspective, on a week basis, this is the spot prices evolution along that given week (February week weather year 2011):

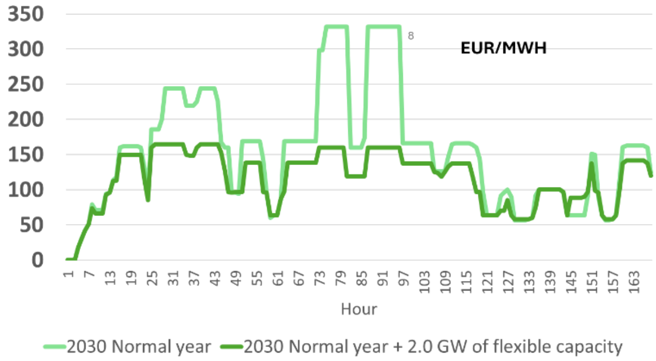

Figure 9. spot prices evolution graph - hourly Finland's marginal price on a February week in 2030, weather year 2011

In blue line the spot prices without the 2GW and in red line the spot prices with 2GW of Wärtsilä firm flexible capacity. The average price for the studies week in Feb weather year 2011 are:

- Normal year = 155 €/MWh
- Normal year with additional 2 GW of firm flexible capacity = 116 €/MWh

3.8 System reliability

In 2027, Finnish power system can handle one crisis but two simultaneous crises would cause problems to system reliability. In years later, Finnish power system can operate normally in the absence of a crisis but cannot handle a disruption in the nuclear power plant Olkiluoto or in the nuclear power plant Fennoskan.

3.9 Adding energy crisis scenarios

- Scenario 1: Nuclear power plant Olkiluoto 3 is unavailable, lost of 1.6 GW
- Scenario 2: Interconnections (Sweden and Finland grids) Fennoskan 1 and 2 out: loss of 1.2 GW
- Scenario 3: both are out, lost of 2.8 GW.

When we add different flexible capacities to the grid (0.5 GW, 1 GW, 1.5 GW, 2 GW) we simulate what will be electricity prices in these three different scenarios.

3.10 Electricity price in different scenarios

Additional firm flexible capacity increases the system reliability and lower the electricity price as shown below:

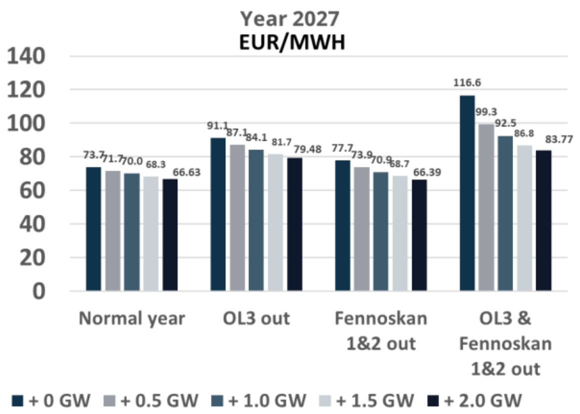

Figure 10. Year 2027 impact of additional firm flexible capacity

3.11 Cost saving

Additional firm flexible capacity decreases electricity prices significantly as shown below:

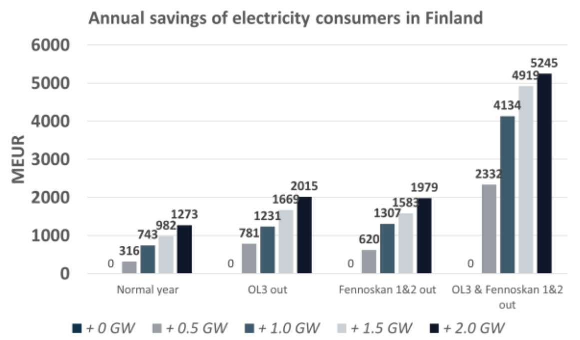

Figure 11. Annual saving of electricity consumers in Finland

On a normal year, additional 1.0 GW or 2.0 GW of firm flexible capacity would lower the cost of electricity by 743 MEUR or 1273 MEUR, respectively, in 2030. From electricity consumers' perspective, the simple payback time for an investment into firm flexible capacity is less than two years.

3.12 Improving system reliability and prevent outages

Unserved energy in the Finnish power system decreases significantly due to new firm flexible capacity especially during a crisis as per above-described scenarios

In a normal year, Finland could have 5 hours of outage with the recent addition of renewables. If on top of that the nuclear power plant Olkiluoto 3 is unavailable, the country will reach a number of 21 hours of outages. If firm capacity is added up to +2 GW, the number of outage hours is zero.

3.13 Path toward a zero-carbon system

Finland is on the path to a zero-carbon system:

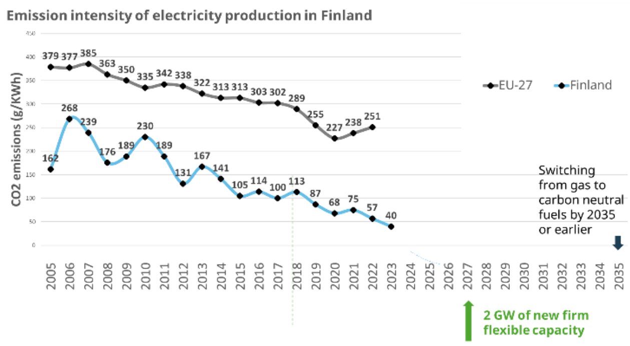

Figure 12. Emission intensity of electricity production in Finland:

On the graph we can read that 2 GW of new firm flexible capacity have been added to the grid.

4 FLEXIBLE POWER GENERATION

4.1 Introduction

As demonstrated in the study above, firm flexible capacities are much needed in the new grid configuration with added renewables. Flexibility such as grid balancing engines and energy storage, can balance the intermittency of wind and solar power, to ensure that power supply always match the demand. There are different ranges of flexibility:

- Flexibility in hours, minutes or even milliseconds:
    - Batteries, PEM fuel cells and flexible engine power can react fast to the smallest changes in power generation
- Daily:
    - Variations in generation are handled by batteries, PEM fuel cells and flexible power generation
- Weekly
    - Flexible engine power ensures longer duration energy balance and system reliability
- Seasonal
    - Power-to-X fuels, such as green hydrogen, will act as long-term energy storage to balance seasonal variation

4.2 Datacenter backup decarbonization

The datacenter market is booming thanks to IA fast track development and the need to decarbonize the sector is crucial.

As an example, Microsoft ® has seen its emissions increase by nearly a third since 2020, primarily driven by the expansion of data centers required for AI and cloud computing, as reported in its annual sustainability report. Despite a 6.3% reduction in direct and energy-related emissions in 2023 compared to its 2020 baseline, emissions from Microsoft overall increase by +29.1% in 2024,

The use of gas engines to decarbonize datacenters has the advantage of maintaining or even improve reliability and very high availability rate. The further development of natural gas retrofitted to hydrogen and the development of new hydrogen network will endeavour the advantage of hydrogen ready gas engines as a back up for Data Centers.

4.3 Flexible power generation advantages

Flexible power generation brings agility in deployment and lower the risks, since engines power plant are modular and can be deployed in consecutive phases.

Flexible power generation plants are adaptable and can be optimized to load. Engines Power plant are faster to ramp-up and down. They higher efficiency at partial load. Starts and stops don't affect the lifecycle of the plant. Engine power plants are also eliminating the primary fuel supply risks since Dual Fuel engines can switch from one fuel to another and Engines Power plant can run at low gas pressure.

4.4 Rapid start-up

Thanks to quick start-up dispatch decisions can be postponed getting latest weather forecast data. It enables reacting to sudden changes in the demand. Quick responses are provided to forced outages of other power plants. In addition, quick start-up can provide back-up for renewables in non-spinning mode. There is a low fuel consumption during the start-up and there is no impact on the cost for engines compare to gas turbines.

Wärtsilä engines can ramp up at over 100%/minute, much faster than gas turbines, providing ultra-responsive power that is needed to maintain the stability of the grid and to integrate renewable energy.

4.5 Switching off engines

Engine power plants can be switched off immediately after the wind starts blowing or the sun starts shining. It enables reacting to sudden changes in the demand and allows for several start-ups and stops per day. There is no fuel is wasted when power is not needed.

Wärtsilä engines can be switched off almost immediately, providing ultra-responsive power that is needed to integrate renewable energy and maintain the stability of the grid.

4.6 Sustainable fuels flexible power plants

Reciprocating internal combustion engines can combine a variety of fuels. Multi-fuel engines can switch fuels under operation without disruption. The approach is now to develop on a common platform different combinations of fuels and combustion processes.

The use of hydrogen as fuel produced with surplus electricity contributes to the decarbonization of electricity generation.

5 INTRODUCING SUSTAINABLE FUELS

5.1 General

From hydrogen to biofuels to biogas made from waste, there is a wide array of different potential future fuels that can help to phase out fossil fuels in favour of renewable energy as part of the final push in decarbonising energy systems. These different types of sustainable fuels for future use can be broadly defined into three main categories based on source of energy.

5.2 Power-to-X (P2X)

P2X (e-fuels) includes hydrogen (H2) and its derivatives such as ammonia (NH3), methanol (MeOH), methane (CH4) and Fischer-Tropsch (FT) diesel/ kerosene. Green hydrogen is produced through electrolysis of water utilising renewable electricity. Hydrogen can then be further processed to its derivatives. Some of the hydrogen derivatives also need CO2, which is provided by CO2 capture, preferably from a biogenic origin. Each conversion step from hydrogen to other synthetic fuels adds energy losses to the value chain. With time there will be excess renewable electricity and thus costs will decrease, which will accelerate the production of P2X fuels.

5.3 Bio-to-X (B2X)

B2X includes biofuels such as biomethane, -methanol or -ethanol, and liquid biofuels such as crude or hydrotreated vegetable oils (HVO) and fatty acid methyl ester (FAME). Biofuels are typically produced from agricultural and forestry side-products and residues or sustainable energy crops grown on “surplus land”, meaning land that is not used for the production of food, feed or fibres.

If biomass is not utilised it will rot in nature or landfills and release methane, which will have a stronger greenhouse effect than the CO_2 emitted in combustion. Therefore, these fuels are carbon neutral or even negative.

Biofuels are already commonly used as blends. The fuel volumes required for power plants are so large that there is seldom adequate amounts of biofuels therefore blending is foreseen to continue. The high transportation costs will push the biofuel production towards local solutions. Biomethane distribution, on the other hand, can widely benefit from existing gas grids which connect local smaller-scale production to large-scale consumers. Biomethane production also has the advantage of being able to utilise various watery sources such as, municipality waste, sewage and sludges. Decarbonising the existing gas grid is a smart and simple solution for decarbonising target of urban society – without conversion needs for existing assets. Furthermore, mixing biofuels into the conventional fuel supply does not need to wait for future development as the whole value chain and commercial industrial-scale fuel production is already in place and mature.

5.4 Waste-to-X (W2X)

W2X fuels or recycled carbon free fuels include e.g. plastic or tyre pyrolysis oils or gasified municipality waste. Converting waste to fuels reduces or eliminates challenges in biodiversity, environmental and health issues of the waste fractions. For instance, pollution of rivers and oceans by plastic waste, uncontrolled fires and formation of malaria mosquito colonies in the tyre piles. These fuels support circular economy in societies and therefore they have value for sustainability and decarbonisation.

5.5 Sustainability and availability of future fuels

All fuels will emit greenhouse gases in their different processing stages including extraction, production, handling and transportation. These upstream emissions are related to, for example, how much energy is required in each step and whether this energy is from renewable sources. If the fuel contains carbon, its combustion will emit CO_2, whereas carbon-free fuels have no direct CO_2 emissions during combustion. As described above, it is not only about the exhaust when discussing global emissions; the whole value chain needs to be evaluated. If the production of fuel has captured CO_2 or prevented CH_4 leaks, the overall emissions of such fuels become carbon neutral or even negative.

The cost of transport and storage of a fuel will be an important factor of the total cost of the fuel and should be an integral part for power generation assets to consider. The cost and space requirements of fuel storage at a power plant will be determined by the volumetric energy density of the fuel and the storage conditions. All conventional fuels have high energy densities and heating values, which made them attractive initially for combustion. With sustainable fuels, and P2X fuels especially, the fuels need to be compressed or liquefied but even so more storage space needs to be reserved.

Although it seems that development today is focused on P2X fuels (hydrogen, ammonia and methanol), many alternative sustainable fuels such as bio/e-methane or liquid biofuels are promising and even more readily available for the energy sector. These fuels are similar in their chemical composition to fossil fuels and can therefore be used with current engine portfolios. These fuels can already today be used on their own or as blends with fossil fuels and are likely to play an important role in the coming 15 years before P2X fuels can be produced in the necessary volumes for the energy sector.

When it comes to which fuel will be used, availability and cost are of course important, but there are other parameters to consider such as footprint of production and storage, and operational safety. A natural gas blend with up to a maximum of 25 vol% hydrogen is still considered to be natural gas and thus rules and regulations for use are already in place. With higher hydrogen blends or pure hydrogen more attention is needed on material selections and designing the overall safety of the power plant solution.

On islands and other remote locations with no space to build dedicated renewable energy for hydrogen production, or locations that are not in the vicinity of gas networks, it’s likely that other renewable energy sources will be used, such as liquid biofuels that are easy to transport and can be stored on site. Ammonia or methanol are also possible choices, especially when it comes to transportation.

During the transition period to P2X fuels, biomethane and biofuels can already be blended into their fossil twins, which takes off some of the pressure having the fuels in adequate amounts for the energy sector. As natural gas has the lowest GHG emissions of the fossil fuels it is the clear transition fuel especially as biomethane can be blended into the gas grid.

5.6 Emerging regulations and rules

Regulations and rules for sustainable fuels are being drafted and will play a central role in how quickly the production and utilisation of these fuels will ramp up. For example, in the EU the aim is to have regulations in place so that both the production and use of sustainable fuels can be viable technically and financially in a sustainable manner. Key legislation in the EU for hydrogen production will be the renewable energy directive (RED II and III), which targets high renewable fuel shares especially in the mobility sector.

While many of the details in the EU taxonomy and other regulations are still to be solved, the EU is clearly pushing for the decarbonisation of energy systems. The challenge is to cover the transition period in order to reach 2050 net zero scenarios in time. Many of the details – such as calculation methods and piloting/investment incentives – still need to be solved. This leaves some uncertainty on a national level over how power plant projects can be planned and financed. What is clear is that everybody agrees that decarbonisation is needed, and the regulation/financing rules will push for this change.

5.7 Hydrogen production

Hydrogen can be produced in many ways, each one labelled with different colours:

- Green hydrogen is produced through electrolysis of water utilizing renewable electricity.
- Pink hydrogen is otherwise the same, but the electricity used in the electrolysis is generated by nuclear power.
- Blue hydrogen is produced by splitting fossil natural gas into hydrogen and CO2 and then capturing and storing or utilising the CO2.
- Grey hydrogen is created in the same way as blue hydrogen, except the carbon dioxide is not captured but released into the atmosphere. This is how the majority of hydrogen is produced today.
- White hydrogen is related to natural hydrogen accumulated in the soils and underground usually mixed with some methane content. It has the advantage of being potentially cost competitive and is very low carbon intensive. But the reserves are today unknown and the extraction and recuperation from the ground is still a challenge due to the size of th molecules.

6 HYDROGEN AS FUEL PERSPECTIVES

For a spark-ignited gas engine to use 100% hydrogen, modification to the fuel injection and combustion chamber is required as well as ensuring hydrogen-compliant materials. The modifications are not expected to increase plant costs by more than 30%, which is in line with the EUGINE Hydrogen-Readiness Concept*. The power density is expected to be reduced to 73%. Our test results show that efficiency is expected to remain on same level as for natural gas, while CO2eq emissions will be close to zero.

6.1 Low carbon hydrogen production forecasts

Low-carbon hydrogen supply is expected to be between 7-22 Mt per year by 2030. All sources agree that most of this will be produced by electrolysis, and fossil fuels with CCS generate 23-44% of low-carbon H_2 by that time.

6.2 Hydrogen demand in power and heat **generation**

Power and heat is expected to consume around 10% of low-carbon hydrogen supply. In DNV's forecast, it reaches 2% by 2030 and 11% by 2035, while S&P Global begins from 20% today, decreasing to 9% in 2030. By 2035, S&P and DNV expect 7-8 Mt of hydrogen to be used in power and heat, compared to total H_2 supply of ca. 100 Mt today.

6.3 Implied capacity additions of hydrogen-fuelled power generation

Annual capacity additions required to burn the implied amount of H_2 in power and geat is expected to reach 2-4 GW by 2030 and around 8-15 GW by 2035. However, only two of the used reports give an implication for beyond 2030, reducing the reliability of the estimate. Common assumptions are made as follow:

- 50% of hydrogen is used in existing installations by blending
- New hydrogen-fired capacity operates at 50% capacity factor
- Capacity additions estimated as required installed capacity less previous highest installed capacity

6.4 Risk related to hydrogen balancing in power sector

The most efficient engines run on gas today but are ready to be converted to sustainable fuels such as hydrogen when they will be available at scale. With sustainable fuel production forecast to reach 38 million tonnes by 2030 (a third more than current demand) this transition is expected to be possible within the next decade.

Hydrogen engine pilot power plants will accelerate readiness and decrease technology adoption risk related to hydrogen balancing in power sector. However, the first projects are more likely to be plants that are hydrogen-ready and will be converted to hydrogen after the hydrogen is available. This will decrease partly the investment risk.

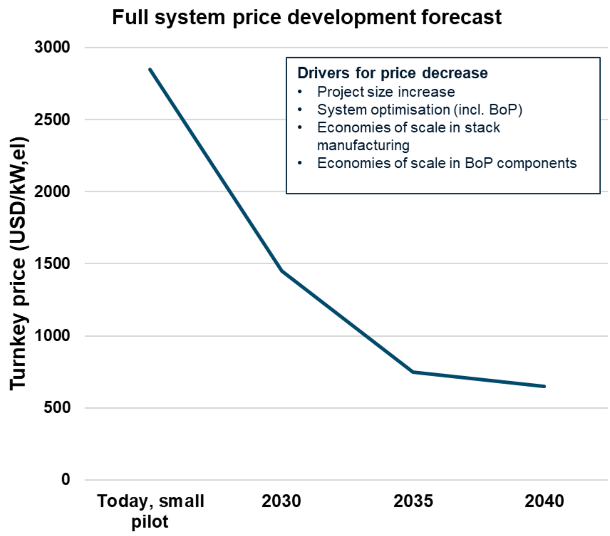

Figure 13: Hydrogen turnkey system prices evolution

Full system price and hydrogen price is expected to significantly decrease in the future.

6.5 Leverage cost of hydrogen

Hydrogen price will dominate the levelized cost of electricity and define the business case to a large extent. For early adopters, green economy subsidies may be necessary to help deployment.

7 SUSTAINABLE FUELS ENGINES PORTFOLIO

7.1 Methanol & ethanol engines

In 2015 was the first engine conversion ZA40S to methanol fuel onboard the ferry Stena ® Germanica. In 2023 was the delivery of first W32 methanol engines. Sales release of additional marine engines and engine conversion packages.

7.2 Ammonia engines

In 2022 were the first combustion and performance testing, optimization with different engine concepts and different engines platforms. In 2023: sales release of the first ammonia W25DF marine engine, delivery 2024. Other dual furls such as ammonia W34DF or other ammonia combustion concepts with direct liquid injection are still under consideration, studied and tested in parallel.

7.3 Hydrogen engines

it started early in the years 2020 and continues in 2024 on the combustion testing on H2 blends and 100% hydrogen. In 2023 hydrogen blend capability was achieved for all SG-engines. In 2025 the 100% hydrogen concept ready for Sales and in 2026 the first industrialized 100% Hydrogen product W31H to be delivered.

8 HYDROGEN AS FUEL FOR POWER GENERATION

8.1 Generalities

At the moment, hydrogen is the most promising candidate of the P2X fuel for power plants. Hydrogen is carbon-free, has the highest production energy efficiency of the P2X fuels and with time it is predicted to become the most cost competitive due to low renewable electricity prices. Of course, there are several issues still to be tackled.

Important for green hydrogen production is access to renewable electricity and clean water. Locations with favourable conditions for these will become hydrogen production hubs.

For a sustainable power plant the access to the fuel is crucial. Mode of fuel transport and distance will have a strong impact on costs and distribution emissions. Likewise, the storage volumes and capabilities need viable solutions. Hydrogen, being a gas, can be distributed via a gas grid which is the best option for both costs and distribution emissions. Hydrogen can be blended with natural gas. However, many industrial users (early adopters) prefer pure hydrogen, which pushes for dedicated hydrogen grids or on-site P2X production. One key concern with green hydrogen is how long it will take to build the needed infrastructure and ensure green hydrogen in adequate amounts.

8.2 ICE vs Pure hydrogen gas turbines power generation

Hydrogen consumed in Gas Turbines produces high level of nitrogen oxides (NOx) during combustion. This could have a significant impact on local air pollution unless the emissions are controlled, which would require costly controls. Hydrogen slippage from Gas Turbines also has an indirect impact on climate change that is the subject of continued research. Hydrogen's global warming potential is 11.6 times stronger than CO2 over a 100-year time frame when accounting for impacts on other gases (compared to 28 times for methane).

9 TÛV SÛD HYDROGEN READY CERTIFICATION

TÜV SÜD has developed a guideline for assessing the hydrogen readiness of gas power plants. This serves as a basis for the certification of concepts of original equipment manufacturers.

The first level in the certification scheme is called the Concept Certificate. From the point of view of the lifecycle of a power plant it is relevant in the bidding phase, when a conceptual design of the plant is available, including the plant configuration, the specifications of the main systems and components with, amongst others, the material classes, which are planned to be used, as well as the operational and safety concepts. The goal of the TÜV SÜD Concept Certification is to confirm that the hydrogen-readiness concept of the Wärtsilä covers all necessary topics and is technically realizable given the selected boundary conditions. From a process perspective it is also checking that the hydrogen-readiness concepted is integrated in the bidding process. Certification was obtained in June 2024.

10 PURE ICE HYDROGEN POWER PLANT

10.1 Comparison of hydrogen vs other fuels

Fuel	LHV Mass Mj/kW	LHV Vol Mj/L	Laminar flame speed stoichiometric m/s	Minimum ignition energy mJ (in air)	Autoignition temperature K
LFO	43	36	0.87	0.23	483
methane	50	23	0.38	0.29	868
methanol	20	16	0.36	0.14	712
ammonia	19	13	0.07	8	930
hydrogen	120	9	3.5	0.017	858

Table 2: Properties of hydrogen and comparison with other sustainable and fossil fuels

10.2 High Flammability and High Explosivity consequences

Hydrogen is characterised by (see also table 2):

- Very low energy to ignite, much lower than methane or butane
- High flammability range: it is 6 times higher than for methane (and 10 times higher than for propane)
- Flame speed which is 6 times higher than for methane (and 7 times higher than for propane)

It is however to be noted that the laminar flame speed is not really decisive for propagation of a flame, the turbulent speed of combustion is highly larger than the laminar flame speed. Turbulence is a property of the average flow and is not dependent on the gas composition except as far as it is affecting average property such as density and viscosity of the overall air and gas mixture.

There are 3 typical types of consequences which shall be considered when a flammable gas phase pressurised release or leak is ignited:

- Jet fire
- VCE (vapour cloud explosion)
- Flash fire

10.3 Hydrogen temperature increase behavior

Hydrogen is a gas having a negative Joule-Thompson effect above 200 °K, leading to a temperature increased during depressurisation unlike natural gas and propane. However, the temperature increase is considered not be significant as such to be a source of concern by raising hydrogen to its ignition temperature unless it is already near the autoignition temperature of 858 °K.

10.4 Hydrogen embrittlement (HE)

The mechanical properties of metals can undergo significant deterioration upon exposure to hydrogen. Whether used in a structural application or as a sensing element in an instrument, metals selected for hydrogen service should be evaluated against influence factors that arise from their material properties, the degree of exposure from the intended hydrogen environment, and the applied stress required by the application. General guidelines for evaluating the influence factors are noted in ANSI/AIAA G-095A and a comprehensive

Review of experimental data for assessment is provided in NASA TM-2016-218602.

Naming of the different failure mechanisms can vary from one standard to another. Hydrogen blistering, hydrogen induced cracking (HIC) and hydrogen assisted cracking (HAC) are forms of corrosion in which the hydrogen atoms formed by the cathodic reaction are forced to go into metals by the presence of H_2S, HCN etc. It results from hydrogen charging of the metal by corrosion and impurities in the steel. The hydrogen is trapped in these impurities and will build up a very high pressure, resulting in blistering and/or stepwise cracking.

HE embrittles structural metals, lowering strain to failure and fracture toughness-increases fatigue crack growth rate. Example of HE progress are:

- Hydrogen absorption to metal surface,
- dissociation: $H2 \rightarrow 2$ H,
- H-atom diffusion into metal,
- partly to grain / phase boundaries (traps), partly interstitially distributed.

For hydrogen-assisted cracking (HAC), under tension the crack tip attracts hydrogen which lowers the stress intensity threshold for growth and crack grows below nominal tensile strength.

Factors of importance of HE and HAC are:

- strong steels (high strength / hardness) and ferritic microstructure are more sensitive
- austenitic steel is more resistant than ferritic
- higher risk by increased hydrogen pressure
- temperature: there is no HE at temperature above 300°C as temperature affects solubility and diffusion of hydrogen

10.5 High temperature hydrogen attack (HTHA)

Exposure of steels to hot hydrogen, especially at high pressures, may result in an internal attack of the carbides of the steel: hydrogen reacts with carbon which creates methane bubbles which leads to cracks at grain/phase boundaries. In addition, the transformation from carbides into iron causes a drop in mechanical strength. After a certain exposure time the steel component may fail by HTHA.

The Nelson curves in API RP 941 provides guidelines for proper materials selection. These curves are periodically modified based on field experience, therefor the latest revision of API RP 941 shall always be used. The minimum temperature to have HTHA in carbon steels is 210°C.

HTHA is slower or prevented by higher alloying of steel (Cr, Ni, Mo).

Many failures are related to inadvertent mixing of alloy and un-alloyed steels. Positive material identification can help to identify the right material and components.

10.6 Welding

Welds are susceptible to hydrogen embrittlement in all hydrogen environments. The heat-affected weld zone frequently produces hard spots, residual stresses, and a microstructure conducive to embrittlement.

Post-weld annealing may be required to restore a favourable microstructure. Type 347 stainless steel is very sensitive to cracking during welding and should not be used without taking proper welding precautions.

10.7 Material selection

The suitability of the steel material shall be determined. The risk of hydrogen cracking shall be assessed considering the maximum pressure, the composition of hydrogen gas, if the equipment is subject to stress (vibration, pressure cycle etc.), to have proper selection of the material and testing methods, if a liner inside the equipment is needed.

A common rule is that high strength steels require a heat treatment after welding to reduce the hardness below 240 Hv to prevent cracking. The carbon and magnesium content can also be restricted to allow welding without hard zones near the welds. Cast iron pipe and fittings shall not be used. The use of any casting is not recommended due to the permeability of hydrogen and the possibility of porosity in the casting. Other materials to be avoided in hydrogen environment:

- stainless ferritic, martensitic and duplex steels
- aluminum, Al alloys in moist/wet environments, other than oxygen-free coppers
- Ni, Pb, Sn and their alloys
- polymers (plastics)

It is therefore recommended to use stainless steel 316L as much as possible.

10.8 Hydrogen fuel piping

Material selection of a plant is based on process composition, temperature, pressure and environment (for example corrosive atmosphere), so material used for the piping, valves and fitting shall be compatible with hydrogen and thus shall not be subject to hydrogen embrittlement and have proper tightness and permeability. The piping should be compliant with EN 13480. There is a specific ASME code for hydrogen piping: ASME B

31-12 which can also be used. Piping and fitting devices shall be designed so that moisture cannot collect and freeze in a way that would prevent the equipment safe operation.

Like for equipment used by hydrocarbon fuels, flange connections in hydrogen service are likely to catch fire and burn if a leak occurs, therefore welded connections are preferred.

Valves, gaskets, connection systems and their tightening shall be carefully designed, installed and tested. Pure helium or helium and nitrogen mix shall be used for leak testing due its molar mass close to hydrogen.

Specific care shall be given to the fittings type with regards to hydrogen and operating conditions compatibility. The equipment design shall take into consideration and be able to safely operate in the given range of process and environmental conditions.

Outside & inside engine hall, hydrogen piping welds shall be submitted to 100% RT (X ray). Quality level for welding for hydrogen service as per EN ISO 5817 shall be defined.

Where fully welded system is not possible to be located on open air outside any engine hall or confined area, dual wall piping is be used to prevent leak occurrence inside engine hall or any other closed space. For dual wall, consideration shall be given to have inert gas or vacuum condition in the annual space to prevent an explosion in the annular space or explosion scenario shall be handled by design. It is also to prevent large explosion zone area classification complicating the design.

The equipment shall be cautiously flushed before starting to prevent to have particles left in the pipe that could cause a static charge and an explosion in case of leak. Hydrogen gas system shall be bonded and grounded like for a natural gas system.

From NFPA 2 § 6.22.1, cleaning procedures shall be established and reviewed when one or more of the following conditions align:

- The system is installed and prior to being placed into service
- There is a change in service
- There are alterations or repair of the system involving the replacement of parts or addition to the piping system and prior to returning the system to service
- The design standards or written procedures specify cleaning or purging.

The compatibility of the selected cleaning agent with all construction materials should be established prior to its use. Equipment under pure hydrogen service shall be identified by a safety sign as particular operating procedure can apply like the use of non-sparkling tools.

10.9 Fuel Gas Supply Unit

It includes components such as shutoff valve, hydrogen mass flow meter and inert gas connections.

10.10 Hydrogen Gas Detection

As a colourless, odourless and tasteless gas, hydrogen cannot be detected by human senses, therefore, means should be provided to detect the presence of hydrogen in locations where leaks and/or accumulations may occur. For hydrogen detection, ISO 26142 (Hydrogen detection apparatus — Stationary applications and possible additional standards: Sensors for leak detection of H2 and H2NG) can be considered. Hydrogen is not an hydrocarbon but can be combined with methane detection. The same setpoints than for natural gas are used: 10% vol LFL for alarm and 20% vol LFL for ESD. Standards can give higher setpoints[1], however to have consistency with natural gas and as hydrogen has higher flammability and can even disperse better than natural gas the 10% and 20% setpoints are kept for hydrogen to provide higher coverage of detection. 2 detectors at 10% LFL shall initiate an ESD. The principle regarding default handling and voting of the gas detection shall be the same than in Gas safety concept chart template. Selection of the sensors shall be compliant with the temperature range specification.

10.11 Hydrogen Flame Detection

In contrast to hydrocarbon fuels such as gasoline, which generate most of their radiation as visible light and heat, the hydrogen flame radiates less heat and is practically invisible in broad daylight. Most of the emission is around 311 nm. Chemiluminescence around 350 nm has also been measured. This radiation is just outside the visible range near ultraviolet (UV) spectrum. Light passing through the thermal gradients in the flame or hot products flow sometimes casts a flickering light/dark pattern. For the human senses, these characteristics make detection of small hydrogen flames difficult compared to hydrocarbon flames. Thus, without suitable detection equipment, the first indication of a small flame is likely to be the hissing noise of the gas leak and perhaps the intermittent shadows from the thermal gradients of the flame.

Thermal camera can be used to detect manually a hydrogen fire during commissioning to ensure that the system is tight and during ERP (emergency response plan) to localize a hydrogen fire or confirm that a hydrogen fire has stopped.

10.12 Electrical equipment selection

As per EN 60079-0 chapter 4, electrical equipment for explosive atmospheres is divided into groups. Electrical equipment of Group II is intended for use in places with an explosive gas atmosphere other than mines susceptible to firedamp.

Electrical equipment of Group II is subdivided according to the nature of the explosive gas atmosphere for which it is intended.

Group II subdivisions:

- IIA, a typical gas is methane
- IIB, a typical gas is ethylene
- IIC, a typical gas is hydrogen

This subdivision is based on the maximum experimental safe gap (MESG) or the minimum ignition current ratio (MIC ratio) of the explosive gas atmosphere in which the equipment may be installed (see IEC 60079-20-1).

Equipment marked IIB is suitable for applications requiring Group IIA equipment. Similarly, equipment marked IIC is suitable for applications requiring Group IIA or Group IIB equipment.

10.13 Inerting principle

An inerting philosophy has been developed considering NFPA 56 and other relevant standards. It considers purging out of service and purging into service for engine stops and for maintenance activities for fuel gas system and engine crankcase. The philosophy specifies the quality grade of inert gas and the minimum number of purging rounds. The quality of the inert gas shall be high enough tocontain oxygen below 0.5% vol and the oxygen concentration shall be considered for the LOC calculation. The philosophy shall also specify in which conditions purging with natural gas can be done. For natural gas/hydrogen mixture, LOC will vary based on the hydrogen content. Purging of the inert gas in fuel gas equipment with flammable gas needs to be done prior engine starts.

10.14 Ventilation

The equipment as much as possible shall be in open area in area with free air circulation (no congestion, no confinement).

Inside engine hall, the welded dual wall piping for engine gas header and bellow will prevent leakages. In case of potential leak sources on the engine or other equipment, the leak management shall be handled by proper ventilation of engine hall and/or inerting of equipment.

Crankcase is also carefully ventilated due to oil mist and hydrogen presence; however large amount of condensed water will be also present in the crankcase. So, the ventilation will more be used to prevent water condensation in the oil sump and corrosion.

10.15 Venting

Pure hydrogen sections shall be fitted with a vent pipe system that will divert gas discharged from pressure relief devices to the atmosphere. The vent pipe system shall be constructed of materials compatible for hydrogen service, taking into account associated fluid process parameters (e.g. pressure, temperature, maximum expected flow rate, etc...).

10.16 Exhaust Gas System

Hydrogen combustion in the combustion chamber (engine cylinder) is efficient and the hydrogen slip is considered to be negligeable during normal operation though there is a possibility of unburnt hydrogen gas slipping into exhaust gas system during exhaust stroke of the engine, but actual amount cannot be quantified at this point and will be verified by test engine. In addition to normal operation there are few situations that promote hydrogen slip and increase the amount of unburnt hydrogen in the exhaust gas. The possible cases are listed below with some comments of the probability:

- Failed engine start attempts
- Cold cylinder operation: when combustion in any of the engine cylinder fails during normal operation
- Engine trip
- Engine overloaded: as a general principle system design should be able to withstand 110% design conditions for short term operation

Therefore, likelihood for major amount of hydrogen in exhaust is small.

10.17 Explosion disks and flame arresters

The explosion disks and flame arresters shall be designed and effective for relevant explosion scenario. For equipment in hydrogen service, it shall be designed for hydrogen explosion. Potential for detonation shall be assessed. Simulation was used to this purpose.

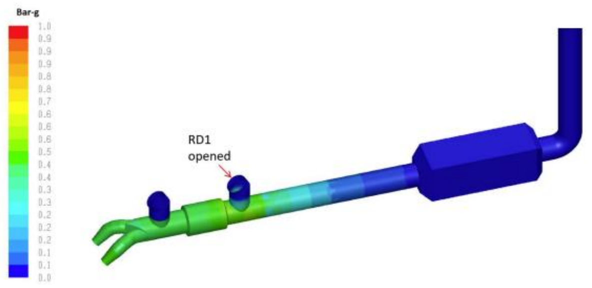

Illustration 2: Maximum pressure observed in with air fuel mixture and two rupture discs.

10.18 Other exhaust safety features

Exhaust ventilation fan will be installed for additional safety. There are no standard applicable for reciprocating engines. Same design will be used as for natural gas engine.

Bellows specification is for the exhaust gas and hydrogen reactivity is not considered askey factor having any impact on specification.

Gasket specification is for the exhaust gas and hydrogen reactivity is not considered as key factor having any impact on specification.

10.19 Main design differences from traditional natural gas power plant

To summarize, from a safety perspective, one of the most important differences between natural gas and hydrogen is the tightness requirements, since hydrogen is much more fugitive and is not odorized. In a typical hydrogen supply line, there are screwed connections, houses, couplings and/or flanges included for various reasons, which may be susceptible to hydrogen emission. In addition, the combustion chamber of an engine is not tight towards other areas of the engine. This leads to the occurrence of hydrogen within not only the combustion system but almost the whole engine. Nevertheless, there are different areas with different concentrations of hydrogen, for example the gas supply with pure hydrogen. In the crank case, there is a hydrogen air mixture with oil mist that may form an explosive atmosphere. In the exhaust system hydrogen is only present after special events like misfiring or during startup, which need a proper explosion protection such as bursting disks.

11 PURE HYDROGEN ENGINE DEVELOPMENT

11.1 History

Since 2015 Wârtsilä has been actively developing hydrogen engine concept.

To that purpose, Single Cylinder Engines and a Rapid Expansion Machine have been used to validate injection and combustion concepts. The primary goal was to demonstrate capability to run on pure hydrogen and to determine maximum power output within combustion limitations.

11.2 Lean Burn SG engine

In a lean-burn gas engine, the mixture of air and gas in the cylinder is lean, i.e. more air is present in the cylinder than is needed for complete combustion. With leaner combustion, the peak temperature is reduced and less NOx is produced. Higher output can be reached while avoiding knocking and the efficiency is increased as well, although a too lean mixture will cause misfiring. Ignition of the lean air-fuel mixture is initiated with a spark plug located in the prechamber, giving a high-energy ignition source for the main fuel charge in the cylinder. To obtain the best efficiency and lowest emissions, every cylinder is individually controlled to ensure operation at the correct air-fuel ratio and with the correct timing of the ignition. Stable and well-controlled combustion also contributes to less mechanical and thermal load on engine components. A specially developed Engine Control System is designed to control the combustion process in each cylinder, and to keep the engine within the operating window, by optimizing the efficiency and emissions level of each cylinder under all conditions.

11.3 Selection of the recent W31 platform

Having in consideration lean burn concept for the pure hydrogen engine, It was then decided to select the W31 engine platform to develop a new generation of multi-fuels engines having the ability to run either on fossil fuels and sustainable fuels (hydrogen, methanol and ammonia) and therefore prepared for upcoming emission legislations.

At first stage, hydrogen as fuel has been set as priority one for the development of a W31 H2 power plant.

11.4 Hydrogen combustion challenges

Engine operation with pure hydrogen imposes a few additional challenges compared to the operation with natural gas.

Abnormal combustion is an important factor in the development process of gas engines. This includes mainly pre-ignition, backfire, and knocking. When using hydrogen as a fuel these phenomena must be considered even more than with other gaseous fuels due to the fuel's high reactivity, flammability, and low ignitability limits. In gas engines, pre-ignition can be caused by different effects. Potential ignition mechanisms are oil droplets or other hot particles in the cylinder and hot components such as the spark plug or the exhaust valves.

Hydrogen has high risk for autoignition, meaning that an hydrogen/air mixture can ignite spontaneously at sufficiently high temperatures without a dedicated ignition source. Typically, the combustion stability will decrease at higher load since the elevated pressure and temperature will foster abnormal combustion events.

In particular, the high laminar flame speed in stoichiometric mixtures combined with the very low minimum ignition energy increase the difficulty. It is therefore necessary to mitigate the hydrogen combustion velocity and prevent unacceptable peak cylinder pressures and pressure rise rates.

11.5 Lube oil pre ignition issue

Operation on hydrogen can lead to lube oil pre ignition. Using the lubricating oil with a formula adapted for hydrogen operation is sensible. It is also necessary to change the design of traditional valve train and cylinder head in order to minimise the risk of oil droplets.

Improved valve sealing goes along with an optimised ring pack for low lub oil consumption and increased blow-by in order to reduce lube oil in the combustion chamber.

- Hydrogen combustion might generate some amount of water in the combustion chamber as a product of the combustion. Therefore sampling of water amount in lube oil is recommended.
- High Temperature Hydrogen Attack: hydrogen might react with carbon is steel. This might happen when hydrogen is above 300°C.
- Dry friction wear: as hydrogen is a reducing gas, it makes oxidation more difficult on surface, giving poor tribology performance and can create dry friction wear.

11.6 Emissions

Some emissions values from pure hydrogen engine W31 are given here below as indicative:

- CO_2 = zero
- NOx = between 45 to 90 ppm at 15% ppm-vol dry
- Efficiency: = +5% to +10% higher energy consumption
- Some traces of CO emissions
- THC = zero

12 TESTING HYDROGEN ENGINE

12.1 Generalities

Several combustion process options exist for pure hydrogen internal combustion engine. From Otto thermodynamic cycle to Diesel, using different injection concepts, such as Direct Injection or Port side Injection.

Each concept has its own ignition concept based on a Pre-Combustion Chamber (PCC). The prechamber should be as small as possible to give low NOx values, but big enough to give rapid and reliable combustion ignition. Some of the design parameters considered are: shape and size, mixing of air and fuel, gas velocities and turbulence at the spark plug, cooling of the prechamber and the spark plug and choice of material.

In addition, different piston shapes have been tested in order to select the more efficient one.

The idea is to vary different compression ratios, turbulence level (burn duration) and spark plug layout in order to evaluate effect on engine efficiency and peak firing pressure.

12.2 Single Cylinder engine

A SCE was designed for the hydrogen testing. The test cell has been provided with hydrogen fuel supply and safety assessment made. It benefits from unique Infrastructure for gaseous and liquid fuels of all kinds (Hydrogen, ammonia, methanol, LNG, LPG, bio fuels) installed at STH in Vaasa central office of Wärtsilä.

Objectives were to investigate injector vs spark plug position, optimization of hydrogen nozzle and test of dedicated piston design for hydrogen combustion.

All the different configurations will be tested for the selection of the final configuration, that will be further tested then on the V10 multi cylinder W31 in Bermeo laboratory. It is necessary to test the hydrogen piping tightness as well and all the auxiliaries in a sufficient number of hours before final validation.

12.3 Multi Cylinders V10 W31H pure hydrogen

test engine

A dedicated multi cylinder engine is developed featuring most of the W31H components. Improved valve train is one of the components that will ease the hydrogen combustion process amongst other innovations. The testing engine is be tested at Bermeo Testing Center in Spain from late 2025.

Specific W31H Fuel Gas Supply Unit has been designed and is part of the innovative features needed for the new hydrogen power plant. It will be tested as well with the lab engine.

12.4 New multi cylinders V20 W31H pure Hydrogen engine

In general, the new hydrogen engine platform is directly derived from the existing W31SG natural gas variant. The idea is to minimise the design changes and so easing a future hydrogen conversion of a natural gas variant engine. There are two variants to be produced: W31H2 pure hydrogen engine capable to run again on gas, if necessary, with minor hardware modification, and W31SG Hydrogen Ready, easy to retrofit on site as it is delivered with a conversion kit to hydrogen. It gives then a flexibility for adopting hydrogen, ie use full hydrogen and then to decide to use natural gas again in case of running out of hydrogen (the case applies literally to local H2 production and storage and does not really apply to connection to hydrogen grid network).

The target for hydrogen engine W31H developed for the power generation sector is to achieve a power output with limited derating compared to natural gas-fuelled power plants.

Regarding automation effort is paid due to new functionalities needed. As much as possible same sensors location and nature than in W31SG are used unless specific requirements such as material compatibility occur.

Piston head and connecting rod upper part are designed specifically for new hydrogen combustion and compression ratio. New cylinder head is designed for hydrogen compatibility and also to accept updated design valve train.

Mainly material compatibility drives the metallic parts for change.

12.5 Argon Hydrogen Power Cycle engine iHAPC

As a next step towards highest efficiency and zero emissions, Wärtsilä is part of a new research project exploring innovative technology for cleaner, more energy-efficient engines utilising a closed loop combustion cycle. The research will focus on the use of argon – a non-toxic ideal gas present in the atmosphere – to increase efficiency of balancing engines. The co-innovation project is run by the Integrated Hydrogen-Argon Power Cycle (iHAPC) consortium, led by the University of Vaasa, in partnership with Business Finland and a wide network of partners.

In an internal combustion engine, the energy supplied by combusting fuel is directly converted into mechanical power by the controlled combustion of the fuel in an enclosed space. In the Argon Power Cycle, air, which is normally used to combust the fuel in an internal combustion engine, is now replaced by argon and oxygen. The research focuses on scaling up the Argon Power Cycle to medium speed engines with full argon recovery. Argon enables a considerably higher thermodynamic efficiency due to its properties.

When using hydrogen, oxygen and argon as input the only product from the process is water and the inert argon. Argon is recycled from exhaust to inlet forming a closed loop combustion cycle. Hydrogen and oxygen, the only inputs in the integrated Hydrogen Argon Power Cycle, are both products of electrolysis, which increases the overall efficiency of the power-to-hydrogen-to-power process.

The three-year project is part of the WISE (Wide and Intelligent Sustainable Energy) programme, led by Wärtsilä and funded by Business Finland, the official government agency for trade, investment promotion and innovation funding. The partners of the iHAPC project are University of Vaasa, University of Oulu, VTT Technical Research Centre of Finland, Parker Hannifin Manufacturing Finland Oy, Vahterus Oy, Vaisala Oyj and TotalEnergies.

13 CONCLUSIONS

An energy system PLEXOS modeling was applied to investigate the conditions under which engine flexible power plants hydrogen ready or fueled with hydrogen would act as a cost reduction factor in the transition of the electricity system of Finland a case study. From the modeling results, it can be concluded that hydrogen ready engine flexible power plants followed or at first stage pure hydrogen fueled engine flexible power plants can act strongly as cost and emissions reduction factor when there is a strong penetration of renewables in the local grid.

It can also be concluded that when pure hydrogen engine power plants become commercially available at scale it is likely that the cost difference will be very limited since design changes have limited impacts and given that the level of complexity is not increased drastically. However, at this point of time slight derating of delivered power is still an option that may be taken into account at first stage when envisaging Hydrogen Ready power plant future conversion to 100% hydrogen operations. Regarding efficiency tests have shown a slight efficiency difference from natural gas to hydrogen which is in his way to be arranged by additional testing on multicylinder engine with different arrangement.

The only remaining question left open is related to the hydrogen market development readiness and the green hydrogen availability and pricing. It is the bottle neck for a large market adoption of green hydrogen for power generation. Wârtsilâ has taken the reality of the market drive into account and has included the development of Hydrogen Ready W31SG variant in the W31H engine product development: a gas engine directly retrofittable to pure hydrogen flexible power plant when it is time for change to pure hydrogen as fuel.

14 DEFINITIONS, ACRONYMS, ABBREVIATIONS

CO_2: Carbon dioxide.

CO_{2eq}: Equivalent Carbon dioxide.

CH_4: Methane.

CR: Compression ratio.

ICE: Internal Combustion Engine.

LCOE: Levelized Cost of Electricity

LEL: Lower Explosive Limit

LFS: Laminar Flame Speed

LHV: Lower Heating Value

NO_x: Nitrogen oxides.

NG: Natural Gas

PM: Particulate Matter.

SCR: Selective Catalytic Reduction

SI: Spark Ignition.

THC: Total Hydrocarbons