Networks for Nuclear Innovation

A Magazine containing the results achieved in the Network for Nuclear Innovation projects during the WNU Summer Institute 2019

FROM WORLD NUCLEAR UNIVERSITY PRESIDENT

Nuclear electricity generation is growing globally, but it needs to grow faster if the world is to meet future energy demand and mitigate the effects of climate change. The major goal that we have set to achieve by 2050 is to generate 25% of global electricity with nuclear power. Challenges in the technological, regulatory, economic, and social levels of our industry must all be addressed to achieve this growth. In such an international industry, this requires strong international collaboration. Networking is a vital component of international collaboration, and I am delighted to see the central role the Networks for Nuclear Innovation has played in this year's Summer Institute.

Fellows are selected to participate in the Summer Institute in part due to their ambition and enthusiasm for the future of nuclear. The Networks for Nuclear Innovation groups this year produced high quality reports with serious recommendations for diverse aspects of the nuclear future. Information does not respect national boundaries, and I anticipate that the innovative ideas generated during the NNI will be carried forward by the Fellows into their 39 countries. I support the endeavours of these future leaders, and fully believe in their future successes.

Agneta Rising
President
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ACKNOWLEDGEMENTS

The first edition of the Networks for Nuclear Innovations (NNI) magazine was completed at the Summer Institute 2016. The main concept is to compile the ideas that emerge from the Fellows collaborative work in a publication that could inspire future innovations and serve as reference for the continuous development of important topics in the nuclear area.

We are extremely impressed by the efforts the Fellows and Mentors dedicated to finalize the text within the Summer Institute timeframe, at the same time they were preparing their impactful oral presentation.

We are grateful for the NNI Magazine Editor, Alina Constantin, who made sure all the pieces were correct and in place for its timely publication. The digital version of the NNI magazines can be found at: www.world-nuclear-university.org

Patricia Wieland
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FOREWORD

This year the Summer Institute attracted 82 Fellows representing 39 countries. They bonded in Romania and then gathered in Switzerland, under the close guidance of their mentors, to intensively work on the dedicated projects of the programme – the Networks for Nuclear Innovation. The thematic chosen reflects actual aspects of nuclear industry, which are or have to be driven even more by innovation, to cope with the global context of climate change and accelerated digitalization.

The Fellows developed ideas, concepts and practical solutions to promote innovation in their area chosen while addressing the Sustainable Development Goals. The presentation of their results achieved, during the closing day of the Summer Institute, called for reflection, adaptability and international cooperation. Institutional changes needed, short term, mid-term and long term perspectives, economical aspects and implementation ways were carefully studied by the teams. Some of the messages derived are captured in this brief introduction, being in the same time an invitation for the reader to carefully consider each of the projects described, engage in dialogue and disseminate the most feasible proposals.

Innovative nuclear reactors, the Gen IV and the small modular reactors can be the ingredients of a nuclear renaissance, having increased safety capabilities and ability to target specific customer needs.

In order to encourage the development of Gen IV reactors, it is needed to collaborate at international to consolidate the fundamental features of Gen IV design and simplify the process of validation.

When communicated nuclear energy outside the industry, the Fellows highlighted how important is to come from the same shared values to the social and ethical level in order to be understood and build solid partnerships based on trust. This is key in gaining more acceptance for nuclear and going towards the goals of the Harmony programme.

Different aspects and criteria have to be considered when assessing the feasibility of a nuclear project, this being the base of creating openness and support, as every country has its own particularities. A forum for providing technical advice on feasibility studies and sharing of information has been proposed by one of the teams.

People are a company's most important resource. Even with the most expensive and safest equipment and systems, high-performing organizations shall invest in their people and culture to truly achieve their vision and mission. In order to maintain a proper organizational environment, favourable to development and progress, periodical checks and assessments of the organizational health and state of the culture in the organization have to be performed.

Another message strongly reinforced was that creating and maintaining a valuable and well prepared human capital is crucial for nuclear but has also to keep the pace with the technology infusing now all aspects of people's life. Organizations have to be aware and prepared to allocate the needed resources while having a sound and adaptive strategy. Governments, academia, and nuclear industry stakeholders can join efforts to create an internationally connected nuclear industry network where individuals possessing qualifications needed are much easier identified, as well as shortages or surpluses of particular skills.

We hope that the reader will enjoy the content and find value in it.

Yours sincerely,

Alina Constantin

Editor-in-Chief

RECOMMENDATIONS ON THE USE OF CLEAN HYDROGEN TO ACHIEVE DEEP DECARBONISATION

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Abstract

Among various Zero Emission Technology (ZET), Nuclear and Intermittent Renewables are considered as important to achieve deep carbonisation. The public and decision-makers have high expectations for Intermittent Renewables and its share is rapidly growing globally. According to OECD IEA, hydropower remains the largest renewable generation source, meeting 16% of global electricity demand by 2023, followed by wind (6%), solar PV (4%), and bioenergy (3%). The recent expansion of intermittent (or non-dispatchable) renewables, assisted by such policy tools as FIT (Feed-In-Tariff) or PTC (Production Tax Credit), is remarkable, but requires additional system costs for backup power, flexibility of power generating sources, storage/hybrid production and grid management, and does not necessarily translate to low gCO2/kWh nor affordability. In some countries, operation and economics of conventional base-load power generating sources including nuclear power are threatened by increased share of intermittent renewables. However, complementary use of nuclear and intermittent renewables contributes to security (increased GHG emission reduction, increased domestic energy supply) and better economics for both since both are capital-intensive and a high capacity factor is required for economic operation. Looking beyond the complementary use of nuclear and intermittent renewables, there will be many technological (by use of ZET [Zero Emission Technology] and even NET [Negative Emission Technology]) and institutional innovations conceivable for deep decarbonization.

The work conducted for this project aimed to develop technological and institutional options to achieve deep decarbonization by 2050 with minimum cost burden to society. The present report demonstrates a new approach and provides recommendations on accomplishing carbon neutrality in OECD countries by 2050 using hydrogen storage for the most carbon-intense areas of human activity - energy production, industry and transport. The proposed hydrogen-based energy system includes diverse facilities, such as a very high temperature reactor (VHTR), Iodine-Sulphur (IS) conversion facility, electrolysis facility, compressed air storage and Brayton cycle gas turbine, ensuring grid stability, as well as price stability, which can be affected by the prompt ingress of intermittent renewables.

1. Introduction

At the G8 meeting in L'Aquila in 2009, leaders of the world's major industrialized nations agreed to achieve at least 50% reductions of GHG emissions by 2050. The UK is the first major economy that institutionalized by law a target to cut greenhouse gas emissions to net zero by 2050 and legislated to the end its contribution to global warming. Few years later, at the COP 21 in Paris in 2015, 195 countries adopted the first-ever universal, legally binding global climate deal to avoid dangerous climate change by limiting global warming to well below 2°C. In order to accomplish the Paris Agreement, Sweden introduced a climate policy framework with a climate act. By 2045, Sweden is to have zero net emissions of greenhouse gases into the atmosphere.

Climate change is the biggest challenge that society faces today and urgent actions are required by the most developed countries in order to mitigate its effects for future generations. UK and Sweden have started to do more in these terms, however the biggest questions is how to develop technological and institutional options to achieve deep decarbonisation with minimum cost burden to society. Succeeding in that will bring carbon neutrality in OECD countries by 2050. At the same time, that would help to achieve the SDG 7 (Sustainable Development Goals 7 - Affordable and Clean Energy) because our proposal will ensure access to affordable, reliable, clean, sustainable and modern energy, and SDG 3 (Good Health and Well-Being), SDG 13 (Climate actions) and SDG 11 (Sustainable Cities and Communities) because to achieve what we propose takes urgent action to fight climate change and air pollution (especially in the cities).

According to the OECDs Statistical Data Base, 89% of GHG emissions are produced by the Energy, Transport and Industry sectors, so focusing on those three sectors will definitely make changes in achieving decarbonisation. The purpose of this report is to propose to OECD policy makers a new approach on how to accomplish carbon neutrality in OECD countries by 2050. The aim of the new electricity system will be hydrogen production cells that will be used for hydrogen storage that will be used for energy production, industry and transport as needed. Hydrogen is the fuel of the sustainable future because it generates zero emissions and can be produced from low-carbon electricity or from carbon-abated fossil fuels. This report demonstrates that using hydrogen storage to achieve decarbonisation is possible with today’s available technology and implementation of reasonable institutional options.

2. Energy

2.1. Overview

In order to achieve deep decarbonisation in the OECD countries, roughly 60% of electricity supply that today comes from coal, gas and oil should be replaced with renewables and nuclear power [1]. With the introduction of such a high percentage of renewables some kind of storage system is necessary in order to ensure grid stability. Our proposal is to use hydrogen storage.

2.2. Hydrogen Production Cells

The building blocks of this new electricity system are hydrogen production cells. Several of these hydrogen production cells are envisioned as a part of the new electricity system. The idea of the hydrogen production cell is to ensure network stability and reduce the price volatility at the time of a large ingress of renewable energy which is necessary in order to replace 60% of CO_2-intenssive energy sources. It accomplishes these aims by storing energy when electricity supply is abundant (e.g. sunny and windy days) and produces electricity when electricity supply is scarce (e.g. days without wind).

The hydrogen production cell will contain a very high temperature reactor (VHTR) with accompanying Iodine-Sulphur (IS) conversion facility, electrolysis facility, compressed air storage (if available) and Brayton cycle gas turbine. The facility will be continuously powered by the VHTR and intermittently by the excess renewable energy or outside electricity from nuclear power when the electricity demand is low. The power will be used to produce hydrogen and fill up compressed air storage. Hydrogen storage will have two input streams of hydrogen: Hydrogen from curtailed or low-cost renewable/conventional electricity produced by electrolysis and hydrogen from the VHTR (very high temperature reactor) produced by Iodine-Sulphur (IS) cycle. Figure 1 presents schematic the hydrogen production cell.

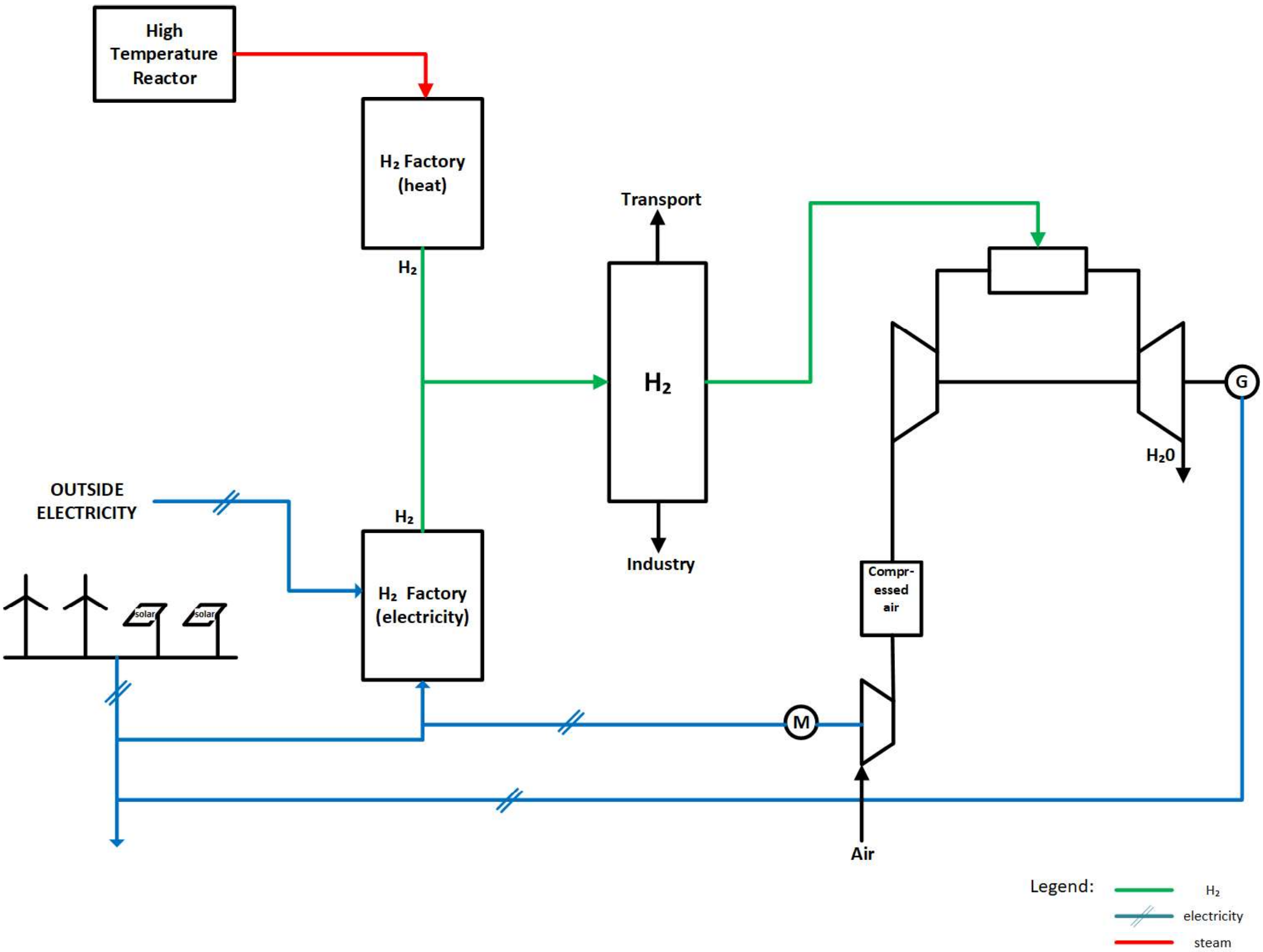

FIG. 1. Hydrogen Production Cell Schematic.

At the time of high demand the gas turbine will activate to support the electricity network. Stored energy in form of hydrogen and compressed air will be used.

The proposed system is practical: All the proposed components have been implemented on full or experimental scale and their further development is being actively pursued [2], [3], [4], [5].

The proposed system is economical if the externalities of fossil fuels are reflected in the price of fossil fuels: Utilization of VHTR reduces the price of produced hydrogen to under 28 US¢ /Nm^3 by the year 2030 and 19 US¢ /Nm^3 by the year 2050. This is twice the price of natural gas in Europe per generated power unit meaning that some support mechanism is needed [6], [7].

2.3. Additional Applications

The produced hydrogen will be distributed to the industry and transportation in order to facilitate decarbonisation in these sectors.

In order to guarantee the stable supply and reasonable cost of hydrogen, which is precondition for its acceptance in other sectors such as industry or transportation, a VHTR is an important component. This is because hydrogen produced by this method is cheaper [8] compared to hydrogen produced using only renewable energy and dispatchable.

3. Transport

3.1. Overview

The transport sector consists primarily of road, air, and water based transportation methods, which combined, accounted for almost one quarter of total global CO_2 emissions in 2016, a 71% increase on 1990 levels [9].

Road transportation is the most significant contributor to the sector's emissions. Figure 2 shows the global transport CO_2 emissions by sub-sector [9].

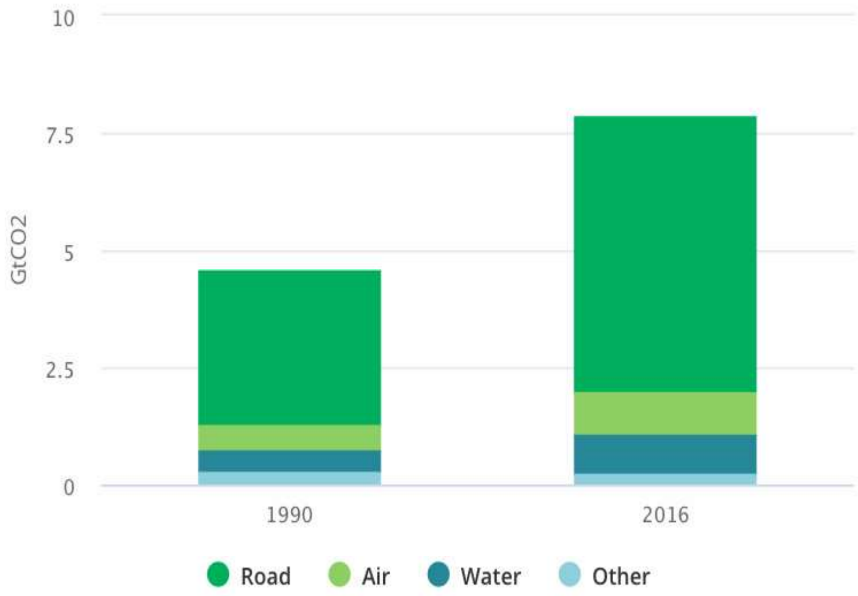

FIG. 2. Global Transport CO_2 Emissions by Sub-Sector.

Given this, and projections of future global trade it is clear the road transport sector in developed countries has an important role to play, alongside other sectors, in providing technological and institutional innovations to reduce CO_2 emissions [10].
One such innovation is the use of Hydrogen powered vehicles throughout the road transport sector.

3.2. Fuel Cell Electric Vehicles for Road Transport

The vast majority of road transport falls into 3 main categories: passenger cars, road freight vehicles (lorries), and public road transport (buses). The decarbonisation of these methods of transportation would account for the almost complete decarbonisation of the road transport sector. All of the above vehicles are compatible with Hydrogen and Fuel Cell technology.

Our proposal is based in the use of FCEVs (Fuel Cell Electric Vehicles), together with BEVs (Battery Electric Vehicles) in substitution of Internal Combustion Engines (ICE) or even Hybrid solutions to get deep decarbonization.

According to the Shell Hydrogen Study, the maturity, requirements, advantages, disadvantages and alternatives can be seen for each vehicle type as indicated in Table 1 [11].

TABLE 1. Factors in FCEVs of Various Types.

	Cars	Lorries	Buses
Market Maturity	Technology proven worldwide (Europe, North America, Asia) through prototypes/small fleets, first production vehicles in moderate numbers. Incentive schemes for passenger car purchase still necessary	Vehicles mostly in the USA (around 50), with individual examples in Germany/EU. Concepts and prototypes primarily for smaller lorries in urban areas with air quality issues, but also first concepts/prototypes for heavy goods vehicles.	Technology tried and tested in numerous small fleets worldwide (Europe, North America, Asia), larger projects with several hundred buses at the planning stage; currently only in publicly funded transport projects, studies on commercial use.

Requirements	Comparable to internal combustion engine vehicles in terms of equipment, performance, range; sufficiently dense hydrogen refuelling infrastructure.	Space-saving hydrogen storage; reliable supply; reduction in total cost of ownership.	Flexible, reliable use in scheduled services with short downtimes (for refuelling/charging); ideally no space and weight restrictions for passenger transport.
Advantages	Pollutant-free driving; range and performance close to petrol cars.	Higher efficiency, no air pollutants, low noise emissions.	Range 300 to 450 km, no public infrastructure needed for municipal buses, range still too short for coaches; no air pollutants, low noise emissions, little additional weight from hydrogen tanks.
Disadvantages	Still much more expensive than internal combustion engine cars; poor refuelling station infrastructure.	Expensive drive technology/fuel; still shorter range than diesel; low density of refuelling stations.	Vehicles still more expensive than the reference technology of diesel buses.
Alternatives	CO_2=0:BEV CO_2: ICE	CO_2=0:BEV CO_2: ICE diesel, LNG/CNG	CO_2=0:BEV CO_2: Gas buses, diesel hybrid buses

FCEVs together with BEVs are necessary to achieve a deep decarbonization of the transportation sector. Both make use of similar and complementary technologies suitable for different segments and customers. They are not competitive but complementary.

According to the specific requirements on weight and range for each method of transportation, FCEVs are particularly important for technologies where electrification, or the use of batteries, is not practical, such as long distance freight trains. Figure 3 shows [12] transport technologies most suited to either FCEVs or BEVs, as a function of vehicle range and weight.

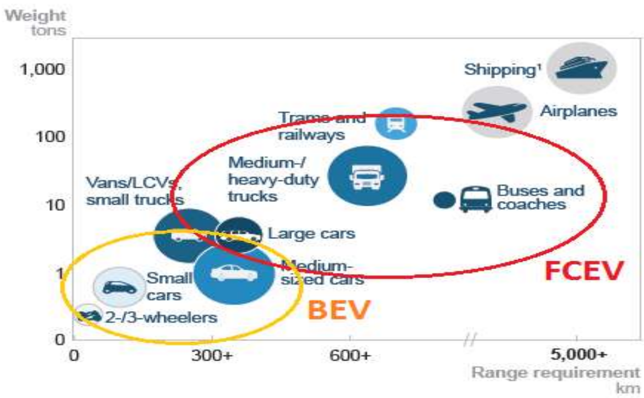

FIG. 3. FCEV and BEV Transport Technology Applicability.

Taking into account the current cost projections of FCEVs and BEVs, mainly for long range or heavy payloads, FCEVs become more competitive, due to the lower associated costs of adding hydrogen storage versus adding batteries. It is expected that by 2030, the cost of a typical powertrain with a 55 kWh battery, with a 300 km range will be comparable between BEV and FCEV [12]. With regards to future projections of technology range, it is estimated that the range to weight ratio of

FCEVs will, by 2030, bring the technology in line with comparable Internal Combustion Engine (ICE) vehicles available today [12].

According to the energy model of green H_2 production, the emissions of the whole FCEV lifecycle are comparable to those of BEVs running on green electricity [12].

3.3. Infrastructure

If hydrogen technology is to be deployed for the decarbonisation of the road transport sector in the future, significant additional infrastructure will be required.

3.4. Filling Stations

There are three different location solutions for hydrogen refuelling stations:

1. Integration into an existing refuelling station
2. New standalone facility
3. Mobile refuelling stations when a small amount of hydrogen is needed

Which of these are chosen depends on different priorities. Our proposal consists on integration into existing refuelling stations to preserve local jobs and capital assets. In case of new standalone facilities, the proposal includes greater possibility of standardization of key components and minimising of investments.

3.5. Transport of H_2

While transporting electricity over long distances can cause energy losses, pipeline transportation of hydrogen reaches almost 100% efficiency. This benefit makes hydrogen an economically attractive option when transporting clean energy at scale and over large distances.

Our proposal recommends the use of current gas transport pipelines to transport. Some experiences, as the H21 project [13] in which gas distributer company in Leeds concluded than it was possible technically and economically viable to decarbonise Leeds' gas distribution networks by converting them to 100% hydrogen.

4. Industry

4.1. Overview

According to a United Kingdom CO_2 emission survey in the industrial sector, the primary emitter is the steel industry and secondary is the chemical industry [14]. So we propose a hydrogen-utilising decarbonisation solution for the steel and chemical industries.

4.2. Steel Industry

Iron and steel are key products for the global economy. The sector is the largest industrial emitter of and second largest industrial user of energy [15]. Although considerable improvements have been made in recent years, the iron and steel sector still has the technical potential to further reduce CO_2 emissions.

The steel making process is illustrated in Figure 4. First, steam the material coal to make a substance called "coke". Next, this coke, iron ore and limestone are put into a furnace called

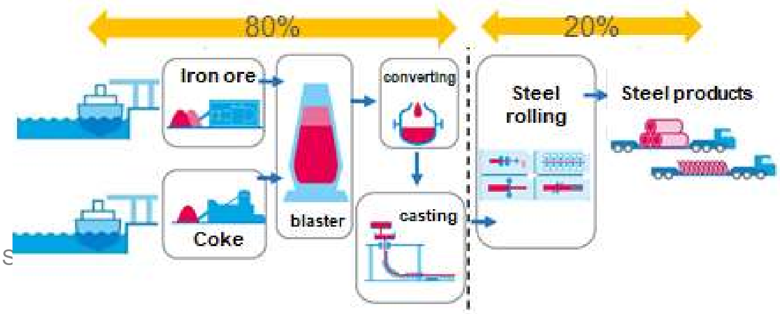

FIG. 4. Typical Steel Production Process.

"Blaster". What we have produced is the "crude iron" which is the raw material for steelmaking. Then, after various processes, it becomes a block called “a slab” and finally it becomes steel.

The coke is a mass of carbon, which is a substance represented by "C" in the elemental symbol. On the other hand, iron ore is represented by "Fe_2O_3". In the blast, the easy-to-burn coke burns, generating very high heat and raising the temperature inside the blast. Iron ore is melted by this heat. Furthermore, since coke is "C", it combines with oxygen "O" contained in iron ore to generate CO_2 and plays a role of removing oxygen from iron ore. This phenomenon is called reduction. This process can prevent the oxidation of iron ore and make strong iron.

The percentage of energy consumption in the entire steelmaking process is approximately 80% of the upper stroke including this blast furnace. If energy saving and CO_2 reduction proceed in this part, it can have a big impact on the CO_2 emissions of the entire steel industry.

To reduce CO_2 emissions in the "upper stroke" including blast furnaces, we propose two methods "Hydrogen reduction technology" and "Carbon dioxide Capture and Storage".

4.3. Hydrogen Reduction Technology

Hydrogen reduction technology is that replace part of the role of coke entering the blast furnace to Hydrogen (H). Hydrogen (H) is combined with oxygen "O" of iron ore "Fe_2O_3" to make water (H_2O), and "reduction" is performed to remove oxygen from iron ore.

The steel industry is trying to use hydrogen produced by reforming the gas which is produced when coke is produced, as for “hydrogen reduction technology" [16]. On the other hand, we, the nuclear industry and the electricity industry, can supply hydrogen using technologies such as HGTR. In other words, collaboration between the steel industry and the nuclear industry are expected to achieve significant reduction of CO_2 emission in the steel industry (Figure 5).

FIG. 5. Proposed Nuclear, Hydrogen and Steel Industry Solution.

4.4. Carbon Dioxide Capture and Storage

In order to burn with high heat, it is necessary to put coke into the blast furnace as well. But then, as mentioned above, CO_2 is generated by "reduction". Therefore, CO_2 is separated and recovered from the gas discharged from the blast furnace. This is Carbon dioxide Capture and Storage (CCS).

4.5. Chemical Industry

The chemical industry is the second largest CO_2 emission sector. The chemical industry consumes a large amount of fossil resources such as naphtha and ethylene as a

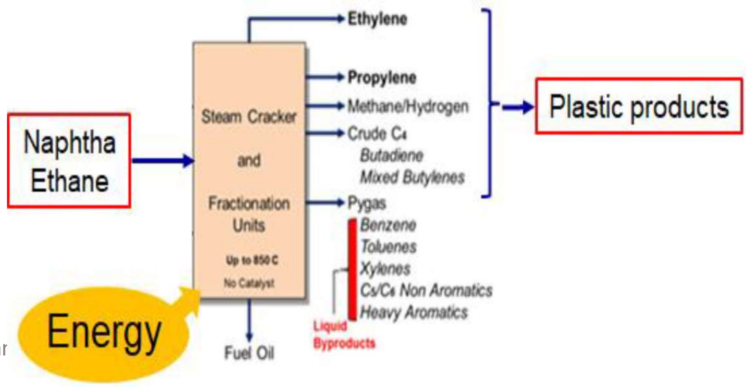

FIG. 6. Typical Plastic Production Process.

raw material for plastic products, and its impact on global warming due to CO_2 emissions is significant.

Ethylene, one of the raw materials for plastics, is produced by thermal decomposition of naphtha and ethane. Therefore, the production of ethylene requires a large amount of energy and emits a large amount of CO_2. Figure 6 illustrates the typical plastic production process.

CO_2 emissions can be reduced if plastics can be produced using CO_2 as a raw material instead of fossil resources. To reduce CO_2 emissions, we propose "Carbon dioxide derived Key Chemical Production Process technology".

This is a technology that produces plastics using CO_2 and hydrogen as raw materials, not fossil resources [17]. CO_2 is collected from thermal power plants, steelworks and factories, hydrogen production facilities using steam reforming etc. Hydrogen can be supplied by the nuclear industry and the electricity industry using technologies such as HGTR. In other words, collaboration between the chemical industry and the nuclear industry are expected to achieve significant reduction of CO_2 emission in the chemical industry. The proposed nuclear, hydrogen and chemical industry solution is presented in Figure 7.

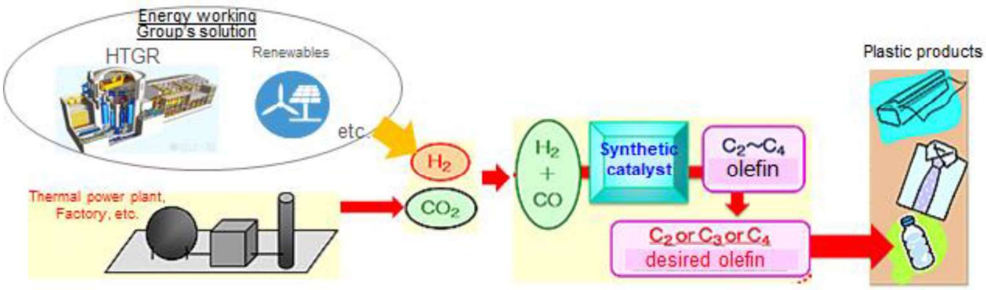

FIG. 7. Proposed Nuclear, Hydrogen and Chemical Industry Solution.

5. Institutional Recommendations

In order to implement the technical vision of the hydrogen society, and to achieve the required target of net zero greenhouse gas emissions by the 2050, innovative and deep institutional policies are needed. We propose comprehensive climate legislation supported by clear global budgetary commitments. Part of the legislation will apply immediately and include, among other proposals, the following main provisions presented in Table 2.

TABLE 2. Immediate term institutional provisions.

Provision	Short Description	Motivation
Hydrogen and clean energy education and research promotion.	Education about hydrogen, climate change, different type of clean energy production and importance of the environment conservation for the general public. Promotion of hydrogen research nationally and internationally (e.g. through OECD)	In order to achieve public acceptance of the proposed measures it is necessary to educate the public about the technology. Promotion of research of hydrogen technology is necessary in order to reduce cost and increase safety and availability of the technology.

Greenhouse gas tax for energy generation	Tax per released amount of greenhouse gas and current CO2 trading system reform (fixed and increased minimum CO_2 €/ton price)	Include society/external cost into the price of generated energy; make hydrogen economically more attractive.
Government subsidy for hydrogen technology	Monetary support for development and introduction of hydrogen-based technologies.	Development of hydrogen-based society requires R&D and investment support that should be provided by the government.

Part of the legislation will apply in the middle to long term and include among other things the harmonized tax policy, the preferential treatment for low-CO_2 products and the ban on carbon combustion (Table 3).

TABLE 3. Mid / long term institutional provisions.

Provision	Short Description	Motivation
Harmonized tax policy	Harmonized tax policy in relation to hydrogen across the OECD.	In order to ensure equal development of the technology across the national borders a common tax policy is needed.
Preferential treatment for low-CO_2 products.	Customs tariff should apply in relation to CO_2 emission resulting from the manufacturing of the product.	Serves to increase economic competitiveness of hydrogen advanced and CO_2-low economies in comparison to countries that have not adopted low CO_2 framework.
Ban on carbon combustion	Total prohibition on combustion of fossil fuels. Year when this measure will be introduced should be agreed and fixed long in advance.	This purpose of this policy is to create the sense of urgency and ensure introduction of CO_2-neutral technologies.

6. Evaluation

Sustainable development requires a long-term structural strategy for the global economic and social systems, which aims to reduce the burden on the environment and on natural resources to a permanently viable level, while still maintaining economic growth and social cohesion. Only development that manages to balance these three dimensions can be sustained in the long term. Concerns regarding such factors as social, economic and environmental impact have increased interest in the sustainability assessment of energy systems based on hydrogen [18].

International Energy Agency (IEA) Task 36 advances were used to increase the readiness level associated with the life-cycle framework for sustainability assessment of hydrogen energy systems by robustly combining harmonized life-cycle environmental (global warming, cumulative energy demand, and acidification), economic (LCOE) and social (fair salary, health expenditure, etc.) indicators [19].

Three sustainability dimensions are to be taken into account in carbon-intensive areas of industry, energy and transport. Since 2017 energy sector emissions increased by 2.6% and a further by 2.5% in 2018, following three years of decline. In the industry sector direct CO_2 emissions rose 0.3% to reach 8.5 $GtCO_2$ in 2017 (24% of global emissions), a rebound from the 1.5% annual decline during 2014-16. Transportation is responsible for 24% of direct CO_2 emissions from fuel combustion.

Decarbonizing the power, industry and transport sectors is a fundamental step to reduce emissions, especially in an increasingly electrified world [20].

Sustainability assessment of complex energy systems is encumbered by a need to consider a number of important while also competitive parameters reflecting three sustainability dimensions. These parameters are defined quantitatively as indicators to be used in the assessment. No single indicator can fully capture the complexity of an energy system. In this case structured methodologies for assessing energy sustainability are needed. IEA and the International Renewable Energy Agency (IRENA) in their studies [20], [21], provided a set of indicators helping to assess different areas of hydrogen energy systems use. Together, the indicators make up an accessible and comprehensive tracking framework that can help inform effective and well-coordinated policy-making.

Considering advantages and disadvantages of these methods in assessing sustainability of the proposed hydrogen-based energy system is complex, highlighting the need for additional elaboration. In addition to three sustainability dimensions proposed the infrastructure dimension is crucial for development. It provides the services that enable society to function and economies to thrive. This puts infrastructure at the very heart of efforts to meet the Sustainable Development Goals (SDGs) [22]. The proposal developed by the Network for Nuclear Innovation (NNI) Group 1 for sustainability assessment of energy systems involving hydrogen production combines suitable indicators developed by IEA and IRENA and supplements them with ones for infrastructure dimension providing the ground for sustainability enhancements. The assessment indicators for hydrogen energy systems are presented in Figure 8.

Sections	Our key indicators	Measure	Our weight proposal
Environmental	• CO_2 emissions	CO_2	10%
	• Share of low-carbon power generation	%	10%
	• Share of EV in new sales	%	5%
	• Energy savings, CO_2 savings	%	8%
	• Energy consumption per GDP	Energy / $	5%
Economic	• CAPEX	$	10%
	• Discount rate	%	5%
	• Capacity factor	%	7%
	• Lifetime	years	5%
	• Performance, commodity prices	$	5%
	• Operation & Maintenance cost	$	5%
Infrastructural	• Development of Hydrogen and EV charging station	Yes | No	5%
	• Integration of Transmission grid, Storage, Curtailment	Yes | No	5%
Social	• Level of direct human work input	%	5%
	• Level of health expenditures	%	5%
	• Average salary in a Country	Salary / Average	5%

FIG. 8. Assessment Indicators for Hydrogen Energy Systems.

The set of indicators with proposed weighting can be used within the framework of multiple-criteria decision analysis tools to see the progress in the process of sustainability enhancement and gaps identification.

7. Conclusions

In the view of major environmental challenges facing humanity nowadays, the transformation of the global energy sector from fossil-based to zero-carbon by the second half of this century is evident and acknowledged on the international level. The present report demonstrates a new approach and provides recommendations on accomplishing carbon neutrality in OECD countries by 2050 using hydrogen storage for the most carbon-intense areas of human activity - energy production, industry and transport. The proposed hydrogen-based energy system includes diverse facilities such as VHTR, IS conversion facility, electrolysis facility, compressed air storage and Brayton cycle gas turbine, ensuring grid stability, as well as price volatility, which can be affected by the prompt ingress of intermittent renewables. Technological and institutional recommendations developed are aimed at achieving targets stated in the SDG 3 (Good Health and Well-Being), SDG 7 (Affordable and Clean Energy), SDG 11 (Sustainable Cities and Communities) and SDG 13 (Climate Action). The progress on the way to successfully reach CO_2 burden free future can be assessed by means of indicators in each of sustainability dimensions, including infrastructure.

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