SANKEY-DIAGRAM- BASED INSIGHTS INTO THE HYDROGEN ECONOMY OF TODAY

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ABSTRACT

Many posit a distinct role for hydrogen within the purview of a future low-carbon, renewables-based transportation system. However, hydrogen is already established as an important energy resource and industrial product displaying versatility of uses and roles in the energy system. In this work, we develop and present an original Sankey-Diagram-based analytical framework aiming at identifying and characterizing key structural aspects of the real hydrogen economy as it exists today (2004 - 2015). We include global hydrogen demand and supply, assorted energy flows, as well as the costs of production and we consider value flows. We suggest that potentially evolutionary trends can be insightfully elucidated via a systems perspective on the existing global hydrogen economy. Perhaps counterintuitively, we build upon suggestions that the best prospects for the evolutionary emergence of a robust hydrogen economy could arise in a world of cheap and abundant oil rather than in a world of oil scarcity and rising fossil fuel prices. Furthermore, in the long term (2050), if global oil supply continues to be ample and environmental pressures intensify, then there will be a need for new and more aggressive energy policies and enhanced pressure for rapid technological innovation including in the domain of hydrogen. The information presented in this paper, however, reminds us of the situation as it applies today. Approximately 96% of global hydrogen is a product of fossil fuel, while 35% is required by the fossil fuel industry for its own purposes. This indirect connection between hydrogen economy and global fossil fuel industry will continue to shape the future of hydrogen economy for decades to come. Currently, over $107 billion/annum is spent globally by the petrochemical industry in producing hydrogen, suggesting the scale as well as the irreducible aspects and inherent synergies associated with the aforementioned connection

Keywords: *Hydrogen economy, Sankey-Diagram, energy policy, global fossil fuel industry.*

INTRODUCTION

Energy policy relies on addressing issues pertaining to energy economy, energy security as well as the impact of energy production state on the state of the environment. Moreover, an economy based heavily on fossil energy is an unsustainable economy, which can lead to an irreversible environmental impact. Therefore the world economy is increasingly focusing on reducing carbon dioxide (CO_2) emissions and tackling the limited and unstable supply of fossil fuels by prioritizing the diversification of energy resources. Global climate is a concern of all citizens and in the UK there is policy pressure to increase greatly the share of renewables in the total energy mix. Indeed, there is a target level of 15% of British total energy supply to come from renewables by 2020 [1] under the recognition that clean energy production modalities using renewables contribute to a healthier environment.

Hydrogen is an abundant element and it can be found in many substances in nature (i.e. hydrogen sulfide, fresh water, biomass and fossil fuels) [2, 3]. It is an energy carrier, like electricity, which is produced and can be transported. In particular, hydrogen is produced from primary energy sources such as nuclear, wind, solar, biomass, geothermal, natural gas, oil, coal, although associated production costs vary , and thus motivate different technological choices [2, 4-6]. In other to produce hydrogen with zero or low impact on the environment, the carbon dioxide (CO_2) and other pollutants must be separated and processed.

Approximately 50 million metric tons of hydrogen is produced globally per annum [5, 7, 8] and used for petroleum refining, fertilizer production, methanol production, metallurgy and food hydrogenation purposes. Notice that 90-95% of the current global hydrogen production relates to the needs of the petrochemical industries. The other 5-10% of the global hydrogen produced is consumed by merchant/consumers. Hydrogen consumption is anticipated to increase by 5-7% annually up to the year 2018 [9, 10]. It should be also pointed out that hydrogen plays an essential and growing role in producing low carbon transportation fuels. It is expected hydrogen will play a key role especially in decarbonisation of the transport sector and elimination of the tailpipe emissions from vehicle [11], but so far this component is small in comparison to the established hydrogen economy. The plans for hydrogen use in fuel cell applications is widely publicised, however the full scale commercialization of hydrogen as an energy carrier has not been achieved since the introduction of the phrase "hydrogen economy" more than 40 years ago. In light of the above considerations, the time has come for a more open transparent and holistic assessment of the real hydrogen value.

The consumption of fossil fuel have been significantly increasing in the last decade, as shown in the Figure 1, global production of crude oil have been increasing constantly since 2002 due to increasing demand/consumption. However, there was a decrease from 2007-2010, due to global credit crunch and since 2010, the production of oil and gas have being rising. Consequently leading to more demand of hydrogen by the petrochemical industry for cleaning crude oil.

[FIGURE 1 below]

Less than 10% is used for low carbon energy carrier purposes, we seek to understand the traditional demand for hydrogen which are shaping today's production methods and market pricing and which will continue to be very important in the future. It is important to note that the hydrogen economy exist today, in the sense that hydrogen is available, at a price, in a market. Supply chain exists and it is these supply chains that will evolve in the future. In that regard we seek to understand better traditional uses of hydrogen and the importance of fossil fuel technology, which itself is evolving rapidly.

The proposed methodological approach is based on Sankey Diagrams. A Sankey Diagram is a graphic illustration of flows, such as energy, money, supply and demand flows etc. It is a better way to illustrate which flows are responsible for benefits or advantages, and what flows represent disadvantages, waste or emission. Key structural aspects of the real hydrogen economy are identified and analysed, including current (2004 - 2015) global hydrogen supply and demand, energy flows, and cost of production (considering various technologies). In particular, the present study aims at: I) revealing useful insight into opportunities for the development of a robust well-functioning hydrogen economy at a larger scale, and II) informing policy makers on future trends and hydrogen commercialization prospects.

A Sankey Diagram is a tool used to illustrate, or map, value flows (energy, material, or cost etc.) in systems at operational level or along global value chains [12, 13]. There are many possible ways of preparing a Sankey chart; it can be adapted flexibly to various needs and to empirical conditions. The essential future is the representation of flow sizes by quantified arrows. The thickness of the arrow directly reflects the relative flow volume, i.e., a flow with twice the volume as another is indicated by an arrow twice as wide. Sankey Diagrams are becoming increasingly important, especially in the context of growing demand for efficient technology. They can also be a helpful instrument in the business sector, since production systems, including their technical and economical interrelationships, are becoming increasingly complex and therefore must be represented in an intelligible way [12]. For example, the data representing the United States' daily petroleum consumption of 23 million barrels/day can be depicted in an insightful way, as shown in the Figure 2.

In this work, the authors capitalised on the existence of the Sankey Diagram as a tool which has become very useful over the years to many including scientists, engineers and economists. It was tailored to the specific needs and aim of this research study – issues related to the structural characterization of key aspects of the hydrogen economy. Within such a context, Figures 3, 4, 6, 7 represent original work produced by the authors, whose content will be discussed in the sequel.

[Figure 2 below]

GLOBAL HYDROGEN SUPPLY AND DEMAND FLOWS

An average of 50 million metric tons of hydrogen are produced globally per annum, and countries like the United States (US) and China are amongst the largest producers of hydrogen [5, 6, 14-18] as shown in Figure 3.

[Figure 3 below]

Approximately 76-77% of hydrogen produced is derived from natural gas and oil (Naphtha), while 19-20% is produced from coal and only a small fraction (3-4%) is produced from renewable sources [9, 17]. Over the last decade there has been significant academic and broader intellectual interest in the prospects of a future hydrogen economy. In the meantime, the current hydrogen economy serves primarily the needs of the petroleum and chemical industries. Indeed, currently the dominant uses of hydrogen are directed towards the removal of sulfur from "sour" crude oil, the cracking of heavy hydrocarbons and the needs of ammonia production for agricultural fertilizers as shown in Figure 4. The primary drivers for growth in the hydrogen demand by the refining industry are the increasingly stringent legislation concerning the regulation of the maximum sulfur content in fuels and the growth of low quality heavy crude oils in the upstream petroleum industry (requiring hydrogen for "hydrocracking" before downstream use). All this comes in the context of increasing oil consumption in developing economies (i.e. China, India etc.)

[Figure 4 below]

[Figure 5 below]

In Japan, most of the fossil fuels consumed are imported, and there is little refining. As a result 97% of the hydrogen produced is used for fertilizer production, as shown in Figure 5. Other Asian countries (e.g. China, India etc.), as well as countries in Africa/Middle East, and CIS are also known for their emphasis on fertilizer production. There is of course a heavy presence of refineries in North America, Central South America and Europe; and therefore, in these regions most of the hydrogen is used at refineries to make reformulated gasoline.

GLOBAL HYDROGEN ENERGY FLOWS

The world population is increasing daily, consequently leading to growth in world energy demand. The current global energy consumption is over 493 EJ/year (EJ = exajoule = 10^{18}J). The United Nations estimates that global population will be 9-10 billion in 2050, and the global annual energy

consumption is likely to be at least 1000 EJ [19-21], with some envisaging even a higher value later in the century. Increase in global energy demand is partly due to emerging countries with growing economies and populations i.e. China and India. In 2004, the International Energy Agency (IEA) suggested that energy demand is expected to increase by 60% by 2030, without any change in policy [22]. In light of the above considerations, the world needs to ensure security of energy supply at affordable prices.

The oil and gas business is of considerable scale and significance, and the global oil and gas market is valued at $3,700 billion at the end of 2015 [23]. The Middle East is the major producer of crude oil, supplying 65% of the global oil demand. According to Jonathan Porritt a leading UK environmentalist, engaging the major fossil fuel companies on climate change has been futile [24]. Convincing them to divert their hydrogen production for energy use in support of climate change mitigation rather than the established use of hydrogen in cleaning crude oil, is relatively impossible, simply due to the profit they stand to lose and the widely unknown terrain of green energy technology efficiency. Mr. Porritt has argued that for the IOCs "doing renewables as Corporate Social Responsibility was fine, but anything that threatened to go seriously 'beyond petroleum' was deemed to be deviant heresy". In this paper we challenge the idea of an inevitable IOC aversion to change in all foreseeable circumstances. We see the prospect for radical strategy changes, especially low oil price scenarios. Orthodox environmental thinking suggests that the IOCs (international oil companies i.e Shell, BP, Total etc.) stand to lose a great deal amount of money by shifting away from traditional activities, but we suggest that the economic context will be key to shaping IOC strategy.

Perhaps counterintuitively we suggest that the best prospects for the commercialization of a significant hydrogen economy will be achieved in a scenario of cheap abundant oil rather than in a world of oil scarcity and high fossil fuel prices. The scenario we envisage is one in which International Oil Companies (IOCs) from the Organisation of Economic Cooperation and Development (OECD) energy consuming countries face a global market crude oil price falling below their costs of production. In such a scenario global oil abundance is dominated by the production from National Oil Companies (NOCs) whose costs of production are generally far lower than the IOCs. In such a sustained scenario the IOCs and OECD states can start to see some advantages in blocking cheap polluting fossil fuel imports. High carbon emission charges could be added to retail fossil fuel prices favouring a shift to low and ultra-low carbon technologies led by the IOCs who generally have higher levels of technological knowledge and competence than their NOC competitors. It is the IOCs together with established vehicle manufacturers and industrial gases companies who could lead us to a true hydrogen economy via an evolutionary path driven by low global oil prices.

The basis to our argument relies in seeing the future from the perspective of an IOC. IOCs are in competition with national oil companies (NOCs) for the upstream supply of crude oil. 75-80% of crude oil globally is sourced from the NOCs [25]. These companies can typically extract crude oil at rates far lower than the IOCs. Production costs for NOCs can be below $5-6 per barrel, while for the IOCs the equivalent cost can be of the order of $45 [25, 26]. In a world of strong (and rising) global crude oil prices at, say, $100 per barrel both IOCs and NOCs can be highly profitable and the IOCs will be averse to any major shift in strategy. Looking ahead in such a context, the IOCs have multiple ideas for new production sources that can be invoked at costs of $46, $47 and $48 per barrel again maintaining profitability. The motive for a radical shift in IOC strategy comes in a scenario of low (and falling) global oil prices. At a global oil price of $39 per barrel IOCs are typically losing money on their production while the NOCs remain profitable. It is in such a scenario that IOCs might collectively conclude that their best strategy would be to develop a radical low carbon fuel such as hydrogen while lobbying to apply carbon charges that would impact negatively on the activities of the NOCs. In such a scenario of a low-oil-price-motivated shift to hydrogen it will be part of the politics of the transition that the hydrogen production techniques should be of minimal environmental impact.

It is interesting to note that market size is essentially decoupled from commodity price, although we note economies of scale can act to reduce prices for larger market volumes. We have posited that the global oil market could decline as a consequence of falling wholesale prices prompting market exit by the IOCs, rather than as might more conventionally be expected: that rising prices would squeeze out demand. So we can see the prospect of a declining fossil fuel industry in both high and low prices contexts. Whatever the future for fossil fuel prices, drastic greenhouse gas reduction will be needed globally. That driver will drive a shift to Renewable energy and Nuclear (REN), Steam methane reforming (SMR) or coal with Carbon Capture and Sequestration (CCS) as competing options. CCS

could be either by capture of CO_2 from the large power stations and industrial plants or directly from the air [27].

It has been posited that the production of hydrogen globally will be 4.6 EJ in 2030 and it will rise 48.3 EJ by 2050 compared with the total primary energy production in 2050 of 800 EJ [19]. Key to our thinking are a set of energy future considerations including the proportion of renewables in the total energy system and the scale of the future energy system. The future for transport between further electrification or the shift to low carbon fluid fuels (such as hydrogen) represents an additional scenario uncertainty. We are drawn to imagine evolutionary shifts by industry incumbents such as the IOCs and major vehicle manufacturers that will preserve existing supply chains and vehicle production facilities. That scenario is closer to today's fossil fuel economy than scenarios based upon RE growth, transport electrification and the displacement of today's vehicle manufacturers by emergent new companies, such as Tesla. It is not our intention in this paper to explore these scenarios, it is merely our intention to introduce our thinking and describe the current starting position from which any hydrogen future must emerge. We start from where we are.

There could be substantial development in nuclear fission technology and fusion could become a reality from 2050 onwards [28]. Over the period of 2004-2030, the contribution of renewable and nuclear (non-carbon) sources of energy production to the global energy production is expected to keep increasing gradually even though the large portion of energy sources are from coal, gas and oil. In 2006, the IEA shows 54% and 209% increase in the use of oil and coal respectively, over the period of 2004-2030 [28]. If reliance on fossil fuel continues to increase, there will be an increase in atmospheric concentration of greenhouse gases. Before our work takes us towards a fuller examination of future scenarios, we suggest it is useful to present a more detailed picture of how global energy generated is consumed and the corresponding technological influences need to be given (as shown in Figure 6).

[Figure 6 below]

GLOBAL HYDROGEN PRODUCTION COST

Hydrogen can be produced from various technologies; there are several comprehensive studies of production cost structures associated with these technologies, but in this work, a comparative assessment of hydrogen production methods (Table 1) was considered between the years 2004-2020. The assessment shows that the steam methane reforming (SMR), nuclear, coal, and biomass gasification are the most cost effective hydrogen production methods.

The SMR method is a widely known process used in producing hydrogen, with an estimated cost of $0.75 - 2.33/kg H_2, $1.92 - 5/kg H_2 without and with CCS respectively. Nuclear thermochemical cycles (both Cu-Cl and S-I) are competitive to SMR and biomass-derived price while solar technology is the most expensive with an estimated cost of $6.9 – 19.4/kg H_2. Electrolysis derived from renewable energy sources is the cleanest process and it can be applied if high purity hydrogen is required, but it is very expensive [29]. If natural gas becomes expensive, coal gasification becomes the most economical option. It is suggested that these hydrogen production methods (SMR and coal gasification) will become cheaper in the nearest future (2020 - 2040), as global circumstances change i.e. pertaining to climate change, less dependency on fossil fuel, cheaper energy sources, and development of new or more advanced technology options. If more advanced technology options are demonstrated that improve the scalability of hydrogen production, the actual cost comparison between different hydrogen production technologies could be reached earlier than predicted.

[Table 1]

The global hydrogen market is currently valued at approximately $420-500 billion annually with a 20% yearly growth rate [16, 30]. Currently, approximately $107 billion per annum is spent globally by the petrochemical industry in producing hydrogen as shown in Figure 7. Looking ahead, if there is a global drive for hydrogen as an on-vehicle fuel, then huge quantities of additional affordable hydrogen must be provided in order to sustain the future hydrogen energy economy.

[Figure 7 below]

RESULTS AND DISCUSSION

Today's hydrogen economy is centered on the petrochemical industry. In order to enhance the commercialization prospects and the use of hydrogen making it widely available for merchant consumption, the cost of producing hydrogen has to be reduced to become competitive. For this the efficiency of existing hydrogen production technologies should be improved. Steam reforming of methane remains the most widely known method of producing hydrogen in large quantities and in a cost-efficient manner. Coal gasification-based hydrogen production seems to be enjoying techno-economic advantages as well, due to the availability of cheap and abundant coal. However, this technology option releases more CO_2 into the atmosphere i.e. 29kg-CO_2/kg-H_2 compared to other methods of production such as SMR which produces 7.33kg-CO2/kg-H_2 [29, 31, 32]. It should be pointed out that co-generation of hydrogen and electricity in centralized integrated gasification combined cycle (IGCC) plants with CCS represents an advanced technology option with enhanced environmental performance for cost effective, hydrogen production from coal [33]. However, a set of proper incentives need to be provided to stimulate an initial fleet of technology demonstration plants on the commercial scale. The authors envisage that in the short term (2016 - 2030), trends and prospects of hydrogen commercialization would be linked to coal- with CCS and SMR-based with CCS hydrogen production systems. Please notice that China has identified coal-based production with CCS as one of its key prospects for hydrogen commercialization in a carbon-constrained world [18]. If fossil fuel prices increase, the pursuit of cost parities in hydrogen production by RE could be hastened, especially if the associated CCS cost is considered. Under these conditions, energy will be generated through coal-gasification with CCS, SMR with CCS, as well as renewables with energy storage and power capabilities. In light of the above remarks and the absence of any accumulated operating experience, more comprehensive studies need to be conducted in order to reliably inform future policy and financing initiatives aiming at accelerating the realization of demonstration plants associated with the aforementioned advanced technology options in the presence of regulatory and fuel market uncertainties.

In this work we focus on today's global realities and as such carbon pricing in most territories is either non-existent or yielding ineffectively low prices. We invite the reader to consider the carbon price assumptions implicit in the various entries of Table 1. The SMR method is a widely known process used in producing hydrogen, with an estimated cost of $0.75 - 2.33/kg H_2, $1.92 - 5/kg H_2 without and with CCS respectively. Coal gasification and Nuclear thermochemical cycles (both Cu-Cl and S-I) are competitive to SMR and biomass-derived price while geothermal, hydropower electrolysis and solar technology are more expensive with an estimated cost of $6.9 – 19.4/kg H_2. Looking ahead to future research work we are interested in the level of carbon pricing that would be sufficient to motivate transitions from one form of hydrogen production to another as well as the transition from gasoline-based vehicular transportation to on-vehicle hydrogen fueling. We also remain very interested in synergies between hydrogen and natural gas production and use [34].

The transformation towards a sustainable energy economy will consistently be a global challenge, until there is a high level of international cooperation, alongside with forward planning and investment courage from companies (the IOC). Rather than aiming at stigmatising the oil and gas industry by persuading investors to dump their fossil fuel shares, investors can engage with IOCs to drive effective and positive change. With the global atmosphere approaching its carbon limit and technological advancement gradually reducing the price of non-fossil fuels, the Bank of England warned that some of the world reserves could become stranded assets with no market value [35]. Abundance of global cheap crude oil could drive the commercialisation of hydrogen production in the long term. It seems likely that there will always be plenty of oil in the ground; the question is how to exploit it in safe and economical ways while on our journey to a low-carbon future.

As a result of diverse policy and business drivers by 2050, energy will be generated from a far wider range of sources, and it will be generated on different scales from domestic, through local and regional to national or international. Hydrogen is likely to play a key role in the emerging markets especially when produced through local electrolysers and biomass gasification, assuming a crucial role in the transportation market. It is anticipated, that under the provision of the right set of behavior-changing incentives, more people are going to be responsible for their own energy generation options

(using micro wind turbine, solar- powered fuel cells etc.) when necessary, while enjoying additional options to purchase energy from a wide range of suppliers. Moreover, large industries could supply additional energy in the form of liquid fuels to power fuel cells. On a global level, a lot of work will be required to design a well-functioning and reliable hydrogen energy economy and also to sustain it in a dynamically changing world and in the presence of irreducible macroeconomic, geopolitical and regulatory uncertainties. We suggest that the IOCs and the industrial gases companies will have key supportive roles to play in that process.

All journeys involve both a destination and a starting point. While we note the rich challenges associated with the destination, this paper seeks to provide a better understanding of our starting point. There is a hydrogen economy today and it is expanding and evolving. As we hope this paper makes clear the hydrogen economy of today looks very different by that posited for a fossil-fuel-free world. In fact the hydrogen economy of today relates strongly to the concerns of the global petroleum industry which remains very much focused on fossil fuels for internal combustion engines. More broadly the hydrogen economy of today is a chemical process industry and we see that reality as fundamental to the evolutionary development of new hydrogen futures.

CONCLUSIONS

In the present research work, we develop and present an original Sankey Diagram-based framework aiming at identifying and characterizing key structural aspects of the real hydrogen economy as it exists today (2004-2015), including global hydrogen demand and supply, assorted energy flows as well as costs of production (considering various technologies). Within the proposed context, useful insights are expected to be gained into evolutionary opportunities for the hydrogen economy at a large scale, and also opportunities to reliably inform policy-makers on future trends in hydrogen commercialization. We suggest that these trends might emerge from a system's perspective relevant to the global hydrogen economy as it actually exists, rather than derived from speculative future policy aspirations. About 96% of global hydrogen is a product of fossil fuel, while 35% is required by the fossil fuel industry for its own purposes. Indeed this inherent connection between the states of the hydrogen economy and global fossil fuel industry will continue to shape the future of hydrogen economy for decades to come.

Perhaps counter-intuitively, we suggest that the best prospects for the emergence of a robust hydrogen economy could be achieved in a world of cheap and abundant oil rather than in a world of oil scarcity and high fossil fuel prices. At the time of writing, oil prices have fallen significantly over the last year, arguably enhancing the realistic prospects of such a scenario. In particular, the authors envisage that in the immediate future (2016 - 2030), trends of hydrogen commercialisation would be linked to coal-based (with CCS) and steam methane reforming (SMR)-based (with CCS) hydrogen production options due to lower production costs and scale-pertinent advantages - compared to other methods of production. Notice that in the long term (2050 upward), if global oil supply continues to be ample and environmental pressures intensify, stricter and more drastic measures will be considered in mitigating climate change impacts. Indeed, with the global atmosphere approaching its carbon limits and in light of renewable energy and nuclear (REN) technological progress, the economics of non-fossil fuels-based options might gradually become more appealing. Moreover, some of the world oil reserves could become stranded assets with low market value as oil remains locked in the ground, while coal-based (with CCS) hydrogen production options could remain popular. Furthermore renewable energy (wind, solar etc.) - based options could progressively become more appealing and biomass gasification-based technology options could be playing a major role in producing cheaper hydrogen in abundance if underpinning policies are sustained around the world.

ACKNOWLEDGEMENT

NOMENCLATURE

EJ	ExaJoule
CCS	Carbon Capture Sequestration
CIS	Countries of former Soviet Republic
CO_2	Carbondioxide
Cu-Cl	Copper-Chlorine
H_2	Hydrogen
HTE	High Temperature Electrolysis
IEA	International Energy Agency
IOC	International Oil Company
IGCC	Integrated gasification combined cycle
NG	Natural Gas
NOC	National Oil Company
OECD	Organisation of Economic Cooperation and Development
PV	Photovoltaic
RE	Renewable Energy
REN	Renewable Energy and Nuclear
S-I	Sulphur-Iodine
SMR	Steam Methane Reforming

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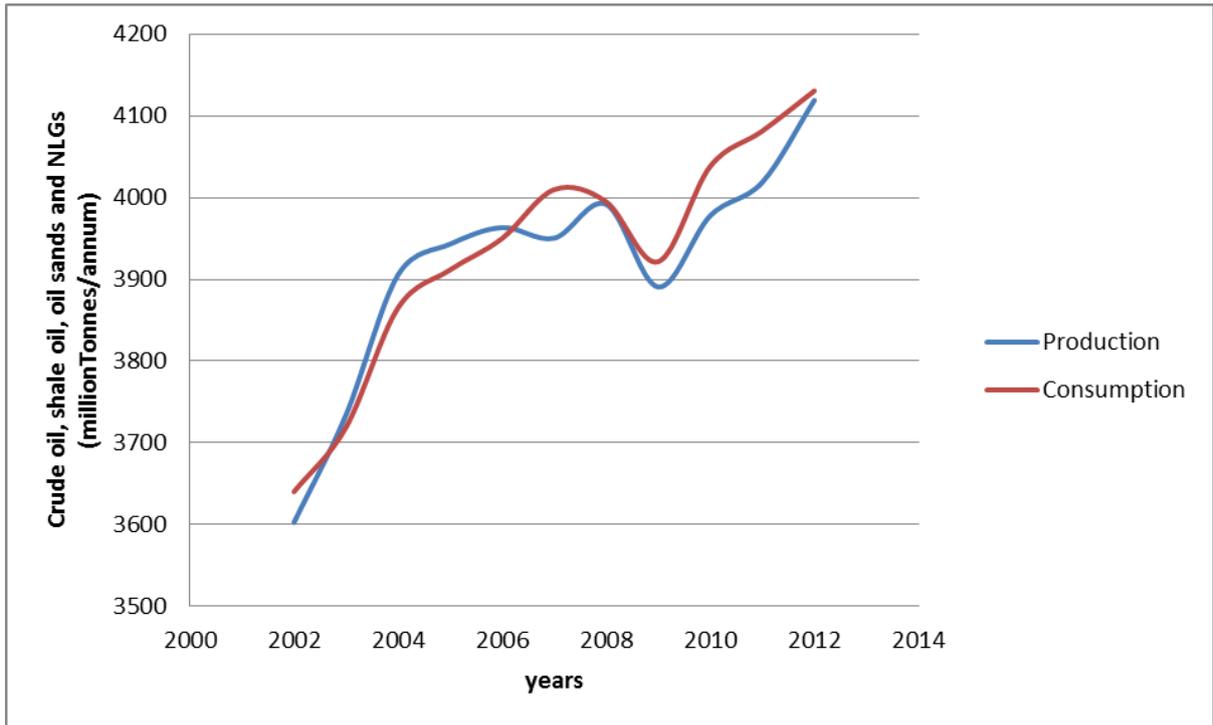
Figure 1 2012-2013 Global world Oil and Gas Production and Consumption (excluding former Soviet Union) – data from 2013 BP statistical review [36]
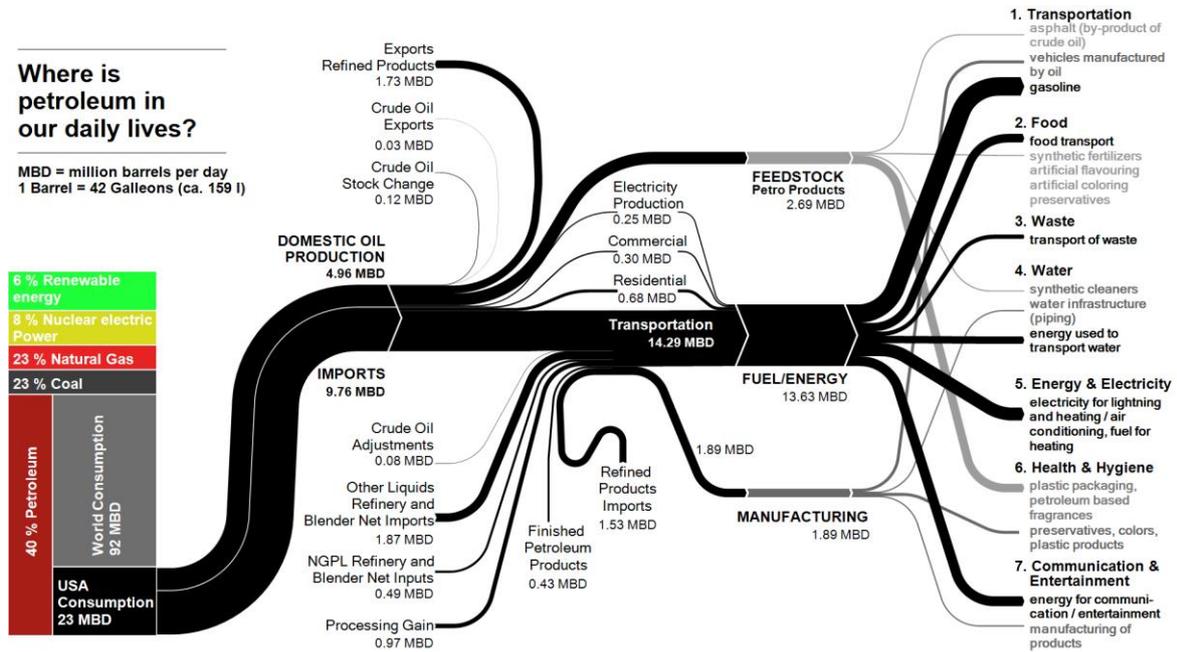

Figure 2 Sankey Diagram showing the role of petroleum in our daily lives (adopted from knowtheflow.com [37])
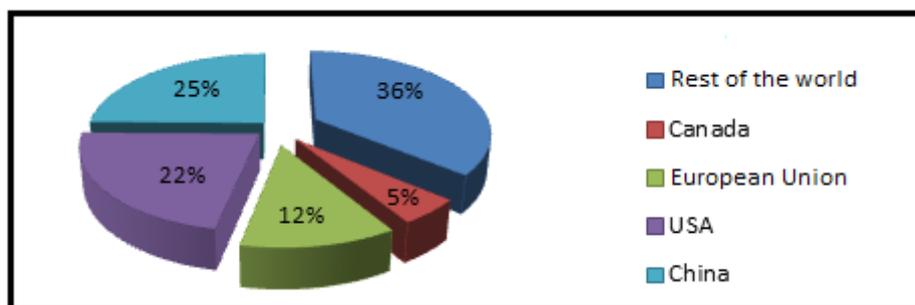
Figure 3 Global hydrogen production per annum (~ 50 million metric tons) adapted from multiple sources [5, 6, 14-17]
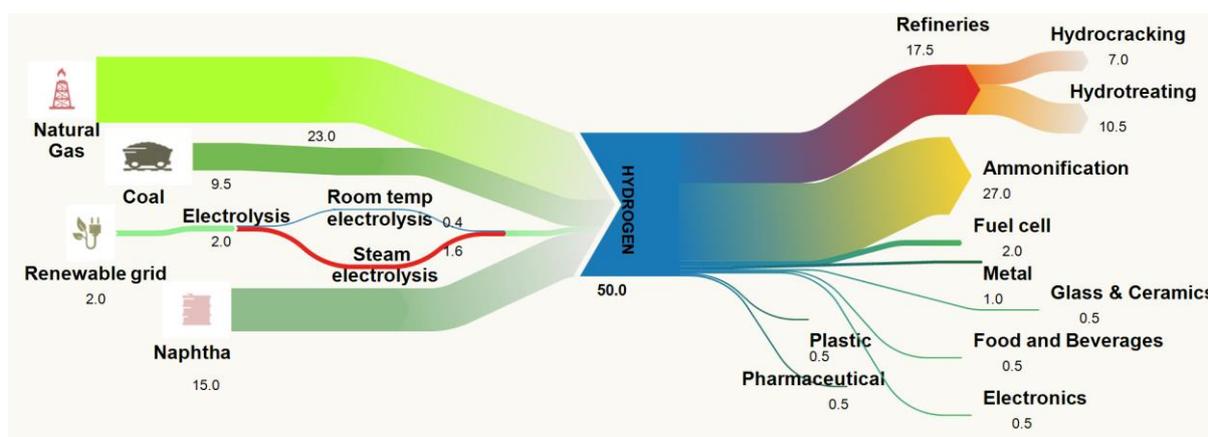

Figure 4 The average global hydrogen supply and demand - unit is million metric tons (assembled from multiple sources (2004-2013) in the references section) [4, 6, 15-17, 19-22, 28-30, 32, 33, 38-57]
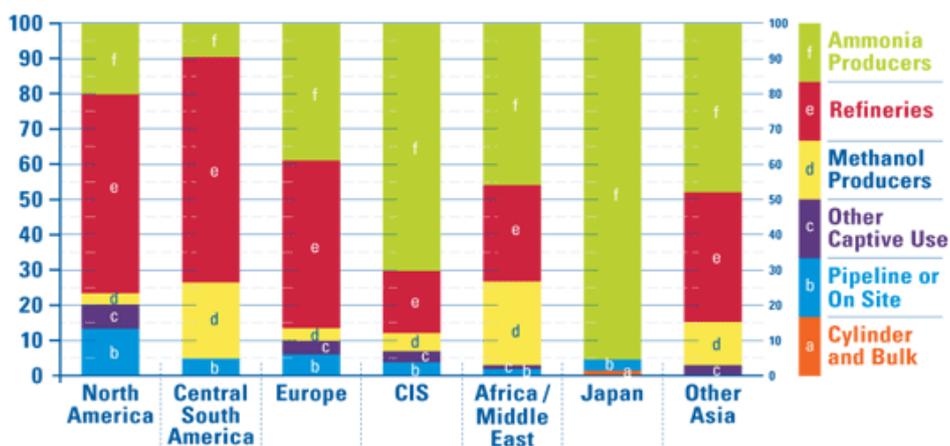

Figure 5 Global hydrogen consumption in 2006, CIS (countries of former Soviet Union) taken from SRI consulting [58]
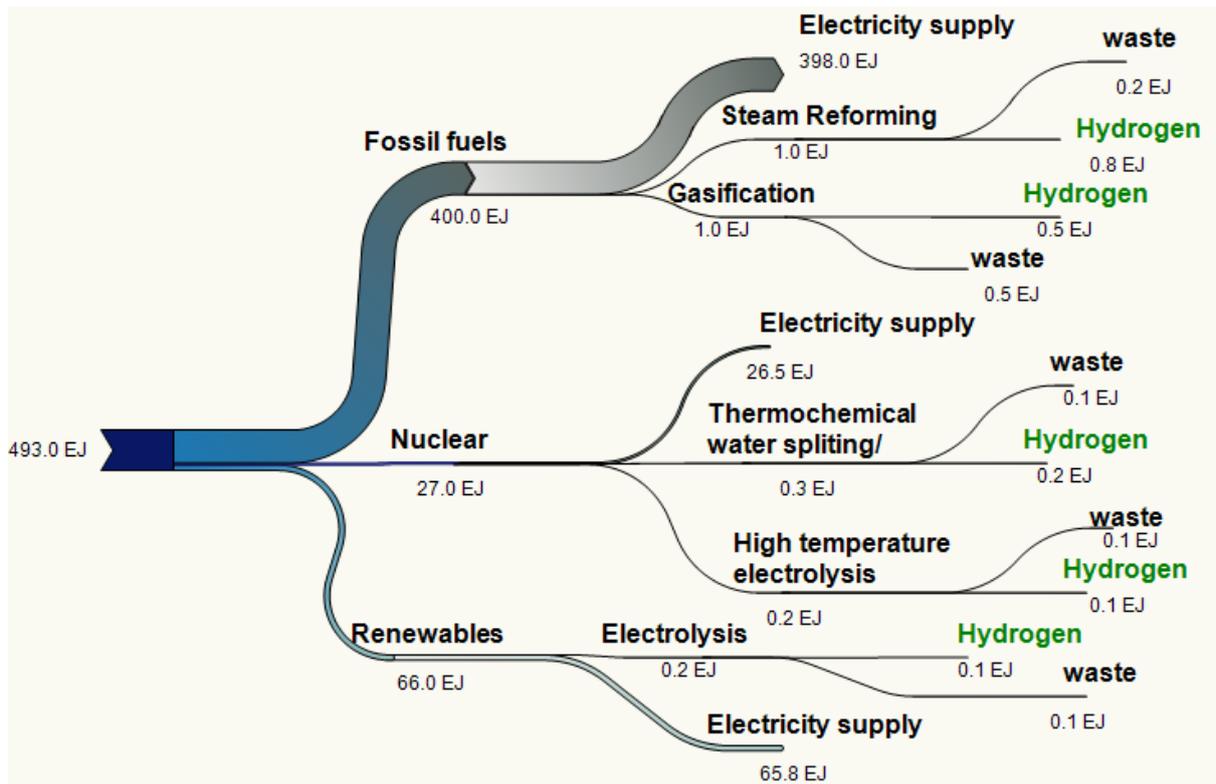
Figure 6 Energy flow scenario for hydrogen and electricity production in a possible near future [21, 40, 43, 48]
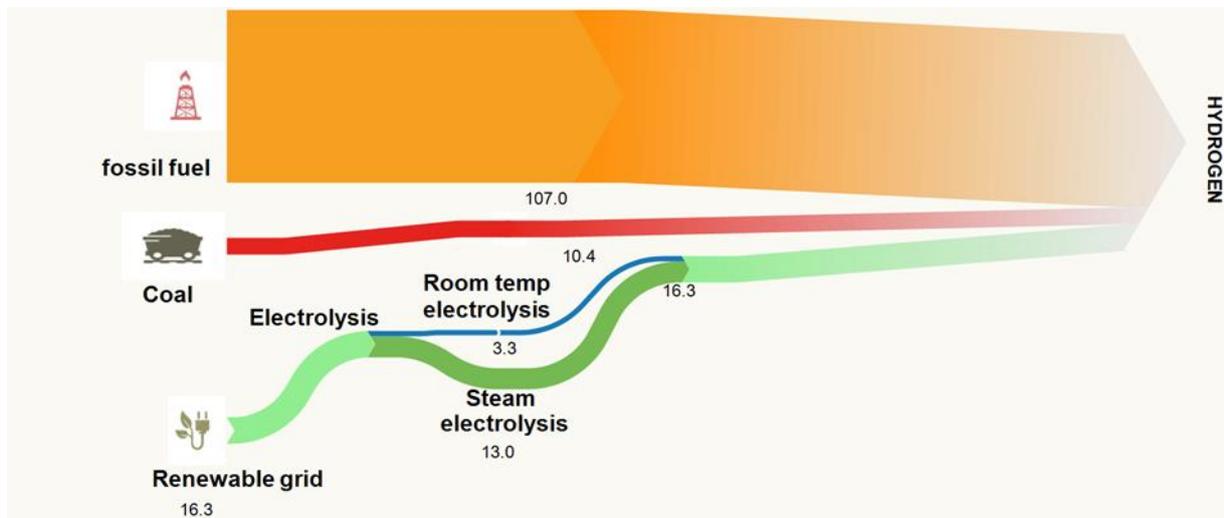

Figure 7 The global value flows for hydrogen production (unit = Billion US $). The values were calculated by multiplying the average global hydrogen supply and demand (Figure 3) by the average cost of producing hydrogen (Table 1): 2004-2013

Table 1 Studies of hydrogen production cost parities (HTE: high temperature electrolysis, Cu-Cl: Copper-Chlorine, S-I: Sulfur-Iodine, PV: Photovoltaic, NG: natural gas**)**

Energy source	Process	Cost ($/kgH$_2$)	Study	Year
Natural gas	SMR	1.99	NRC [59]	2004
Natural gas	SMR	1.74 – 2.33	Kim & Moon [46]	2005
Natural gas	SMR	1.75	Richard et al [56]	2006
Natural gas	SMR	1.5	Wang et al [53]	2010
Natural gas	SMR	0.75	Cannan & Parthasarathy [60, 61]	2014
Natural gas	SMR	0.4 – 0.7	Winter [54]	2020
Natural gas	SMR + CCS	2.18	NRC [59]	2004
Natural gas	SMR + CCS	1.92 – 2.55	Kim & Moon [46]	2005
Natural gas	SMR + CCS	2.5	Richa et al [32]	2006
Natural gas	SMR + CCS	4-5	Lattin&Utgikar [15]	2007
Natural gas	SMR + CCS	2.4 -2.7	Naterer et al [16]	2008
Natural gas	SMR + CCS	2.67	Dincer [42, 52]	2010 - 2012
Natural gas	SMR + CCS	1 – 1.6	Winter [54]	2020
Nuclear	Electrolysis	4.6 – 6.4	DoE [62]	2008
Nuclear	Electrolysis	2.4	Dincer [42, 52]	2010 - 2012
Nuclear	Electrolysis	3.6	DoE [62]	2020
Nuclear	HTE	3.5	Acar & Dincer [29]	2014
Nuclear	Cu-Cl	2 -3.5	Naterer et al [16]	2008
Nuclear	Cu-Cl	1.7	Wang et al [53]	2010
Nuclear	Cu-Cl (small plant)	2.71	Dincer [42, 52]	2010 - 2012
Nuclear	S-I cycle	2.92	Kim & Moon [46]	2005
Nuclear	S-I cycle	4 – 5.5	Khamis [45]	2008
Nuclear	S-I cycle	1.9	Wang et al [53]	2010
Nuclear	S-I (HTGR)	1.4 – 3.6	Winter [54]	2020
Nuclear	S-I cycle	2.1 – 2.9	Winter [54]	2020
Coal	Gasification	1.88	Kim & Moon [46]	2004
Coal	Gasification +CCS	1.89	Kim & Moon [46]	2004
Coal	Gasification +CCS	1.8	Wang et al [53]	2010
Coal	Gasification +CCS	1.1 – 1.6	Winter [54]	2020
Solar	Electrolysis	6.91	Kim & Moon [46]	2005
Solar	Electrolysis	19.4	Richa et al [32]	2006
Solar + NG	S-I cycle	7.53	Giaconia et al [44]	2007
Solar	Electrolysis	9	Wang et al [53]	2010
Solar	Electrolysis	7.7	Nowotny & Nejat [51]	2011
Solar	PV electrolysis	10.3	Ngoh & Njomo [63]	2012
Solar	PV electrolysis	9.1	Bhandari & Hwang [64, 65]	2013 - 2014
Solar	PV electrolysis	6.7 – 10.7	Winter [54]	2020
Solar	Thermochemical	3.9 - 5	Winter [54]	2020
Solar	Photoelectrochmical	3.5	Canan et al [60]	2014
Wind	Electrolysis	3.8	Kim & Moon [46]	2005
Wind	Electrolysis	3.3	Richa et al [32]	2006
Wind + electricity	Electrolysis	6.6	Muradov & Nejat [50]	2008
Wind	Electrolysis	7.2	Wang et al [53]	2010
Wind	Electrolysis	7.3	Hwang [65]	2013
Wind	Electrolysis	3.6	DoE [62]	2019
Onshore wind	Electrolysis	2.4 – 3.3	Winter [54]	2020
Offshore wind	Electrolysis	3.1 – 4.3	Winter [54]	2020
Biomass	Gasification	3 - 4.5	Ogden [38]	2004
Biomass	Gasification	2.18 – 3.39	Kim & Moon [46]	2005
Biomass	Gasification	1.4	Wang et al [53]	2010
Biomass	Gasification	1.65	Ngoh & Njomo [63]	2012
Biomass	Gasification	1.4 - 2	Kalamaras [31]	2013
Biomass	Gasification	1.4 – 2.6	Winter [54]	2020
Biomass	Gasification	1.9 – 2.4	DoE [62]	2030
Biomass	Pyrolysis	1.3 – 2.2	Kalamaras [31]	2013
Geothermal	Electrolysis	10.8	Ewan et al [43, 49]	2007
Geothermal	Steam electrolysis	1 – 2.6	Yilmaz et al [55]	2012
Hydropower	Electrolysis	6.4 – 9.4	Ewan et al [43, 49]	2007
Tidal	Electrolysis	7.6	Mueller et al [49]	2007