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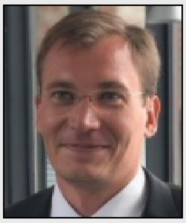

Gas Decarbonisation in Europe: Clean Hydrogen as the New Prospective Area for Russia-EU Cooperation

A. Konoplyanik[*]

Introduction

Active decarbonization of the EU economy, including decarbonization of the gas industry, creates new opportunities for Russia-EU cooperation in gas. This can also be a new type of cooperation – based not only on Russian gas supplies to the EU destined for energy end-use of natural gas in industry, power generation, and households, but as well as a feedstock for the chemical industry, on the joint participation of the parties in developing a new technological pathway based on, inter alia, clean hydrogen from natural gas.

Achieving EU carbon neutrality by 2050 is a priority under the New Green Deal of the European Commission. Significant EU resources are aimed at achieving this goal. The stake is placed on electricity from renewable energy sources (RES) and decarbonized gases, primarily hydrogen (H2). Moreover, the EU considers hydrogen both as an energy carrier and a means of storing excess RES-electricity.

It is clear that post-pandemic EU economic recovery will not return to the old energy supply-demand structure, but will be based on the new low-carbon energy model, even more "green" than was planned in the pre-pandemic time. Thus the market niche for fossil fuels, even for natural gas as the lowest-carbon among them all, including Russian gas, can narrow (in relative terms) in some traditional sectors of their consumption. But it can be expanded within the new sectors of prospective gas demand, in particular, as a feedstock for hydrogen production, especially if the latter is produced from natural gas without CO2 emissions (clean H2 from natural gas). In this context, Russia has a potential competitive niche for export-oriented decarbonization of the gas sector on the joint with the EU basis which will be mutually beneficial for both parties. Since 80% of the GHG (green-house-gases) emissions through Russia-EU cross-border gas supply chain took place downstream of this chain (in the EU end-use)[1], such decarbonization based on clean hydrogen production shall be first organized downstream the EU.[2]

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The views presented in this article do not necessarily present official position of Gazprom Group and/or Russian authorities and are the sole responsibility of this author.
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[1] A. Semenov. Looking for a rational solution for all along the cross-border gas supply chain. Presentation at the 27th Meeting of the EU-Russia Gas Advisory Council's Work Stream on Internal Market Issues (GAC WS2), 07/12/2018, Brussels (https://minenergo.gov.ru/node/14646; www.fief.ru/GAC)
[2] Dr. Oleg Aksyutin, Dr. Alexander Ishkov, Dr. Konstantin Romanov. Potential of natural gas decarbonization: Russian view of the cross-border gas value. // Presentation at the 27th Meeting of the EU-Russia Gas Advisory Council's Work Stream on Internal Market Issues (GAC WS2), 07/12/2018, Brussels (https://minenergo.gov.ru/node/14646; www.fief.ru/GAC)

Two vs. Three H2 Technological Avenues

Today, there are three main avenues of hydrogen production which have reached different stages of their life-cycles (technological curves) and are characterized with different energy intensities and energy costs (see **Box 1**).

<u>**Box 1. To consider cost-figures with care…**</u>

From this author's view, all specific individual and comparative cost-figures of different hydrogen technologies should be taken/used very cautiously and in most cases as illustrative only (this refers in full to **Figure 1**). They demonstrate in most cases just general order/correlation of the orders of such figures. One should bear in mind very approximate character of all today's comparative cost-figures related to hydrogen production by different technologies provided by different authors, firstly, due to the fact that in most cases methodologies behind these figures are either not fully transparent or differs from each other and thus not fully compatible as well as their results.

Secondly, all these technologies today are placed at the different stages of technological curve and characterized by different technology readiness levels (TRL) within almost its full range (from 1 to 9), which means different levels (proportions) of already reached technological improvements (resulted in cost decrease) and further expected to be reached technological improvements (costs further to be decreased).

Thirdly, costs for energy inputs vary substantially across the globe, so the same energy intensities of technologies provide different cost results in different states.

Fourth, figures for different periods, measured in different currencies are adjusted by use of different deflators by different authors, etc.

In result, I would assume that the full and transparent picture does not exist (and it is next to impossible to expect that it can exist today) of the comparable specific costs of different technologies of hydrogen production, which means calculated with the same methodology, based on the same assumptions (where they are necessary/unavoidable) and adjusted to the same TRL levels.

So it would have been very difficult to expect that such figures are available which could have present clear transparent and well-justified picture of comparative competitiveness of different hydrogen production technologies in cost terms. This is why the use of cost-terminology further in the paper is based mostly not on a quantitative analysis of the specific cost-figures, but on the qualitative analysis influencing economic cost in this or that direction.

Firstly, water electrolysis (resulted with a "green" H2 in EU terminology, or "renewable" H2 if RES-electricity is used). It is considered as the most promising avenue in the import-dependent EU. But electrolysis is much more energy intensive, thus, all other conditions being equal, 3-4 times more costly (see **Box 1**), compared to hydrogen production from methane, if IEA figures are considered (see **Figure 1**). According to Gazprom, production of one cubic meter of hydrogen using water electrolysis requires 2.5–8.0 kWh, while methane pyrolysis just

0.7–3.3 kWh[3], so the average difference in energy intensity of technologies is 2.5 times. According to BASF, the gap is even bigger – almost 10 times (286 kJ/mol H2 under water electrolysis against 27 under methane steam reforming (MSR) and 37 under methane pyrolysis).[4] These BASF figures are rather broadly used in different studies by other experts in the international community.[5]

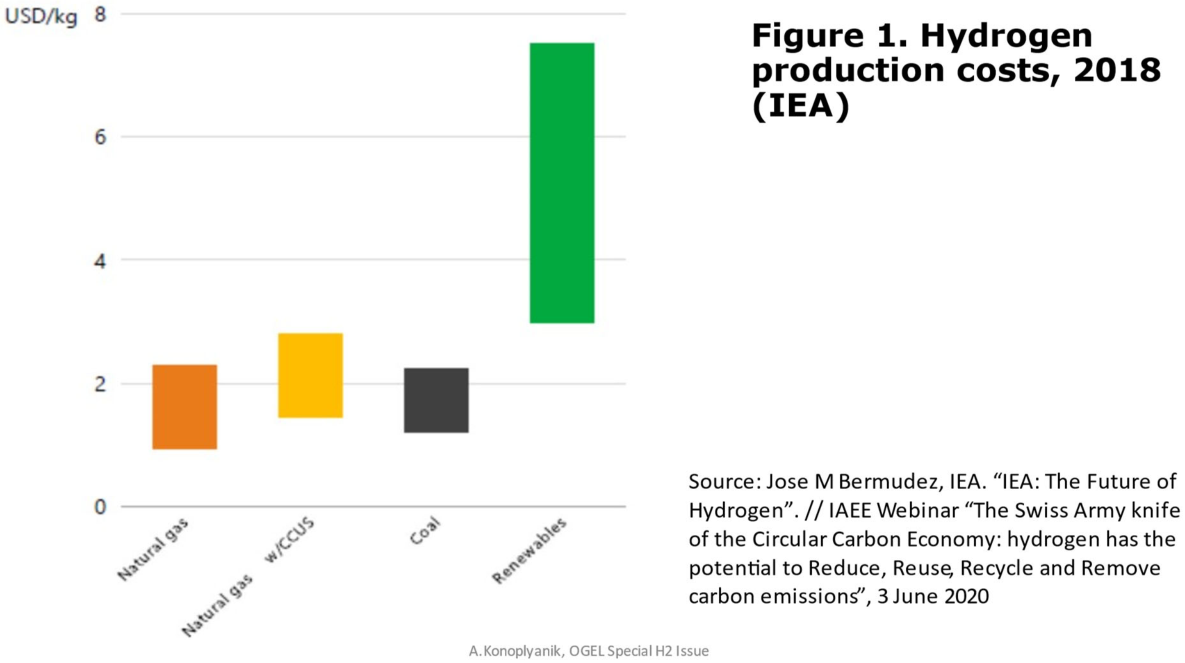


Figure 1. Hydrogen production costs, 2018 (IEA)

In order to reduce H2 production costs by electrolysis (and to compensate intermittency of wind/solar electricity production in its peak volumes) it is desired to use excessive RES-electricity with zero- or negative prices, and to scale up unit capacities of industrial-size electrolysers to GW level ("economy of scale" as a driver of unit cost decrease).

"Hydrogen Europe" has presented the fundamental study "Green Hydrogen for a European Green Deal: A 2x40GW Initiative"[6] with the objective to promote massive development of GW-scale electrolysers within and beyond the EU (together with North Africa, Ukraine and

[3] PJSC GAZPROM'S PROPOSALS for the Roadmap on the EU Hydrogen Strategy (discussion paper), June 2020, p. 5 (https://ec.europa.eu/info/law/better-regulation/have-your-say/initiatives/12407-A-EU-hydrogen-strategy/F523992)

[4] Dr. Andreas Bode (Program leader Carbon Management R&D). New process for clean hydrogen. // BASF Research Press Conference on January 10, 2019 (https://www.basf.com/global/en/media/events/2019/basf-research-press-conference.html)

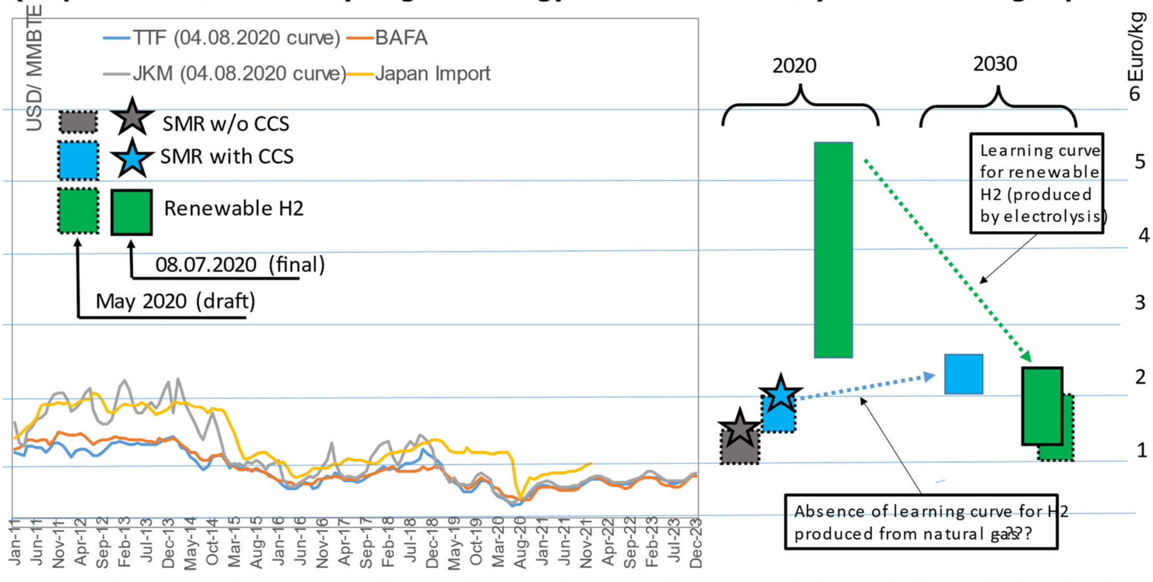
[5] Methane pyrolysis –Key findings of study. // AFRY Report, July 2020, p.9; Litvinenko V.S., Tsvetkov P.S., Dvoynikov M.V., Buslaev G.V., Eichlseder W. Barriers to implementation of hydrogen initiatives in the context of global energy sustainable development. // Journal of Mining Institute. 2020. Vol. 244, p. 428-438 (431). DOI: 10.31897/PMI.2020.4.5

[6] Prof. Dr. Ad van Wijk, Jorgo Chatzimarkakis. "Green Hydrogen for a European Green Deal. A 2x40 GW Initiative". // Hydrogen Europe, 15/04/2020 (https://hydrogeneurope.eu/sites/default/files/Hydrogen%20Europe_2x40%20GW%20Green%20H2%20Initative%20Paper.pdf).

other neighboring countries) in order to support green H2 production. It considers that GW-scale electrolysers at wind and solar hydrogen production sites will produce renewable hydrogen cost competitively with low-carbon hydrogen production (1.5-2.0 €/kg) in 2025 and with grey hydrogen (1.0-1.5 €/kg) in 2030.

The EU policy appears to be "betting" on this kind of hydrogen that it is yet much costlier to be produced compared to other available H2 production technologies generally and, in particular, compared to natural gas prices, even at historical highs of the latter (see **Figure 2**). And, what is strange (if not illogical, from my view), the EU Hydrogen Strategy applies economy of scale principle in regard to renewable H2 production (specifically mentioning its multiplying cost-decrease effect) by electrolysis and completely denies it in regard to H2 production from natural gas technologies by demonstrating their cost-increase with no clear explanation of such future trend. Thus, de facto denying further technological progress in H2 production technologies from natural gas and relying on increase of gas prices as feedstock for H2 production. It seems that such a perception of future growth of natural gas prices can be the only possible explanation. But within the duration of the forward curve period (2 years) such perception is not proven by the available forward curve (see Figure 3). For the rest of the period to 2030 a perception of expected natural gas price growth can be based on the assumption of its overall deficit (diminishing availability) which I cannot share considering overall gas market trends under development from "peak supply" to "peak demand" paradigm and related consequences.

Figure 2. European Commission's estimated costs of H2 production by the key technologies (as presented in the EU Hydrogen Strategy as of 08.08.2020) – and natural gas prices



Source: natural gas prices –Gazprom export; H2 costs – European Commission (EU Hydrogen strategy: dotted lines – draft version, May 2020; solid - final document, 08.07.2020)
A.Konoplyanik, OGEL Special H2 Issue

Figure 2. European Commission's estimated costs of H2 production by the key technologies (as presented in the EU Hydrogen Strategy as of 08.08.2020) – and natural gas prices

Coming back to hydrogen costs, first in its draft Communication "Towards a hydrogen economy in Europe: a strategic outlook" [7], and then in the final version of this Communication "A hydrogen strategy for a climate-neutral Europe"[8], the EU Commission looks for a significant increase in volumes to bring down the price of hydrogen to a range of 1-2 €/kg as quickly as possible (though the particular future cost figures, presented in the draft Communication, are omitted from the main text in the final version of the Strategy though are left in the footnote with the reference to IEA, IRENA, BNEF). It refers to the above mentioned 2x40GW initiative as a driver (moreover, this 2X40GW Initiative of the "Hydrogen Europe" was de facto incorporated into the EU Hydrogen Strategy): a roll-out of green hydrogen production, mainly in dedicated green hydrogen factories with integrated solar or wind renewable facility.

But this will require the development of either a special long-distance hydrogen transportation grid (such plans do exist[9]), or, if the existing gas transmission grid is aimed to be used (such plans do exist as well[10]), to mix hydrogen with methane upstream, to transport the methane-hydrogen mix (MHM) to final destinations, and to separate H2 from methane there before end-use of hydrogen. Both options are costly (if not technically & economically questionable[11], especially in case of proposed repurposing of existing high-pressure long-distance natural gas cross-border infrastructure for H2/MHM export supplies) and will add significantly to the cost of hydrogen for the end-users compared with H2 production downstream, at the or close to consumption sites (areas of advanced H2 consumption, so-called "hydrogen valleys").

According to Gazprom, hydrogen produced from renewable electricity will be significantly more expensive than low and/or zero-carbon hydrogen produced from natural gas, certainly up to 2050 and probably beyond.[12] Such a diversity of opinions means that the cost of hydrogen production is still an open issue and deserves further analysis, but it is clear that hydrogen by

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[7] (Draft) COMMUNICATION FROM THE COMMISSION TO THE EUROPEAN PARLIAMENT, THE COUNCIL, THE EUROPEAN ECONOMIC AND SOCIAL COMMITTEE AND THE COMMITTEE OF THE REGIONS. Towards a hydrogen economy in Europe: a strategic outlook, p.2

[8] COMMUNICATION FROM THE COMMISSION TO THE EUROPEAN PARLIAMENT, THE COUNCIL, THE EUROPEAN ECONOMIC AND SOCIAL COMMITTEE AND THE COMMITTEE OF THE REGIONS. A hydrogen strategy for a climate-neutral Europe, Brussels, 8.7.2020, COM(2020) 301 final, p.4-5 (https://ec.europa.eu/energy/sites/ener/files/hydrogen_strategy.pdf)

[9] Prof. Dr. Ad van Wijk, Jorgo Chatzimarkakis. "Green Hydrogen for a European Green Deal. A 2x40 GW Initiative". // Hydrogen Europe, 15/04/2020 (https://hydrogeneurope.eu/sites/default/files/Hydrogen%20Europe_2x40%20GW%20Green%20H2%20Initative%20Paper.pdf); European Hydrogen Backbone. How a Dedicated Hydrogen Infrastructure Can Be Created. // Enagás, Energinet, Fluxys Belgium, Gasunie, GRTgaz, NET4GAS, OGE, ONTRAS, Snam, Swedegas, Teréga, July 2020, 29 pp. (https://gasforclimate2050.eu/sdm_downloads/european-hydrogen-backbone/); Remarks by Commissioner Simson on the Commission's proposal for a revised TEN-E Regulation at the European Parliament's ITRE Committee meeting, Brussels, 15 December 2020 (https://ec.europa.eu/commission/commissioners/2019-2024/simson/announcements/opening-remarks-commissioner-simson-itre-committee-energy-related-elements-european-green-deal-2020_en)

[10] Peter Adam, Frank Heunemann, Christoph von dem Bussche, Stefan Engelshove, Thomas Thiemann. Hydrogen infrastructure – the pillar of energy transition The practical conversion of long-distance gas networks to hydrogen operation. // Siemens Energy, Gascade Gastransport GmbH, Nowega GmbH, Whitepaper, 2020, 32 pp. (https://assets.siemens-energy.com/siemens/assets/api/uuid:3d4339dc-434e-4692-81a0-a55adbcaa92e/200915-whitepaper-h2-infrastructure-en.pdf)

[11] Litvinenko V.S., Tsvetkov P.S., Dvoynikov M.V., Buslaev G.V., Eichlseder W. Barriers to implementation of hydrogen initiatives in the context of global energy sustainable development. // Journal of Mining Institute. 2020. Vol. 244, p. 428-438 (431). DOl: 10.31897/PMI.2020.4.5

[12] PJSC GAZPROM'S PROPOSALS for the Roadmap on the EU Hydrogen Strategy (discussion paper), June 2020, p. 4

electrolysis is much more costly (taking into consideration explanations in **Box 1**) than hydrogen from natural gas, bearing in mind different energy use per unit of H2 produced. And all future trends are mostly perceptions favouring this type of H2 production as most (only) preferable within the EU.

Secondly, methane steam reforming (MSR) and/or auto-thermal reforming (ATR) which is the most advanced technology of hydrogen production and much more cheaper today than "green" H2 (see **Figures 1 & 2**). But it is accompanied by CO2 emissions and therefore requires the use of CO2 capture and sequestration technologies (CCS), which adds 20-40%[13] to the cost and even more (according to EU Hydrogen Strategy – almost twice as much, i.e. adds almost 100%[14]) to the cost budget of H2 produced by MSR (MSR+CCS is a "blue" or "low-carbon" H2 in EU terminology).

And I would like to underline that letter "S" in abbreviation CCS means not "storage" (how it is usually decoded in the EU), but "sequestration", which has totally different economic meaning and thus creates different perception (more favorable at least for general public if not also for prospective investors): cost of storage can be paid-back in economic terms, which is not the case for the cost of sequestration. The EU Commission underlines that in the context of decarbonisation it has clear priority on "green" hydrogen ASAP, accepting that "blue' hydrogen (which means: MSR+CCS) will play a role in the transition.[15]

Thirdly, a set of technical solutions to produce hydrogen from methane without access of oxygen (pyrolysis, plasma-chemical method, etc.), and, hence, without direct CO2 emissions at the H2 productions stage (similar to hydrogen with no-CO2 effect from electrolysis).[16]

This means, all other conditions being equal, methane pyrolysis (and related technologies of hydrogen production from natural gas without CO2 emissions) will be cheaper per unit of H2 produced and more financeable compared both to electrolysis (2.5 to 10 times less energy intensive) and MSR/ATR+CCS (no need in CCS). Moreover, marketing of solid carbon (which is climate-neutral contrary to CO2/CO which are emitted under SMR/ATR) produced as by-product with clean H2 under pyrolysis/plasma-chemical method, will add not to the costs, but to the revenues of this hydrogen production avenue when it will reach its stage of commercialization (top TRL level) (see **Figure 3**).

[13] René Schutte, N.V. Nederlandse Gasunie. Production of Hydrogen. // Masterclass in Hydrogen, Skolkovo – Energy Delta Institute, Moscow, May 23, 2019 (https://drive.google.com/open?id=1g_4TiiKAKGaJziXG8TWjTdpncfipj9x1)

[14] COMMUNICATION FROM THE COMMISSION TO THE EUROPEAN PARLIAMENT, THE COUNCIL, THE EUROPEAN ECONOMIC AND SOCIAL COMMITTEE AND THE COMMITTEE OF THE REGIONS. A hydrogen strategy for a climate-neutral Europe, Brussels, 8.7.2020, COM(2020) 301 final, p.4-5, footnote 26

[15] (Draft) COMMUNICATION FROM THE COMMISSION TO THE EUROPEAN PARLIAMENT, THE COUNCIL, THE EUROPEAN ECONOMIC AND SOCIAL COMMITTEE AND THE COMMITTEE OF THE REGIONS. Towards a hydrogen economy in Europe: a strategic outlook, p.1

[16] Hydrogen from natural gas – The key to deep decarbonisation. Discussion Paper commissioned by Zukunft ERDGAS. // Pöyry Management Consulting, July 2019 (https://www.poyry.com/sites/default/files/zukunft_erdgas_key_to_deep_decarbonisation_0.pdf); Methane pyrolysis –Key findings of study. // AFRY Report, July 2020, p.10; О.Аксютин, А.Ишков, К.Романов, Р.Тетеревлев. Метан, водород, углерод: новые рынки, новые возможности. // «Нефтегазовая Вертикаль», 2021, № 1-2, с. 40-47 (44). (O. Aksyutin, A. Ishkov, K. Romanov, R. Teterevlev. Methane, Hydrogen, Carbon: New Markets, New Prospects. // "Oil & Gas Vertical", 2021, N 1-2, pp. 40-47 (44)).

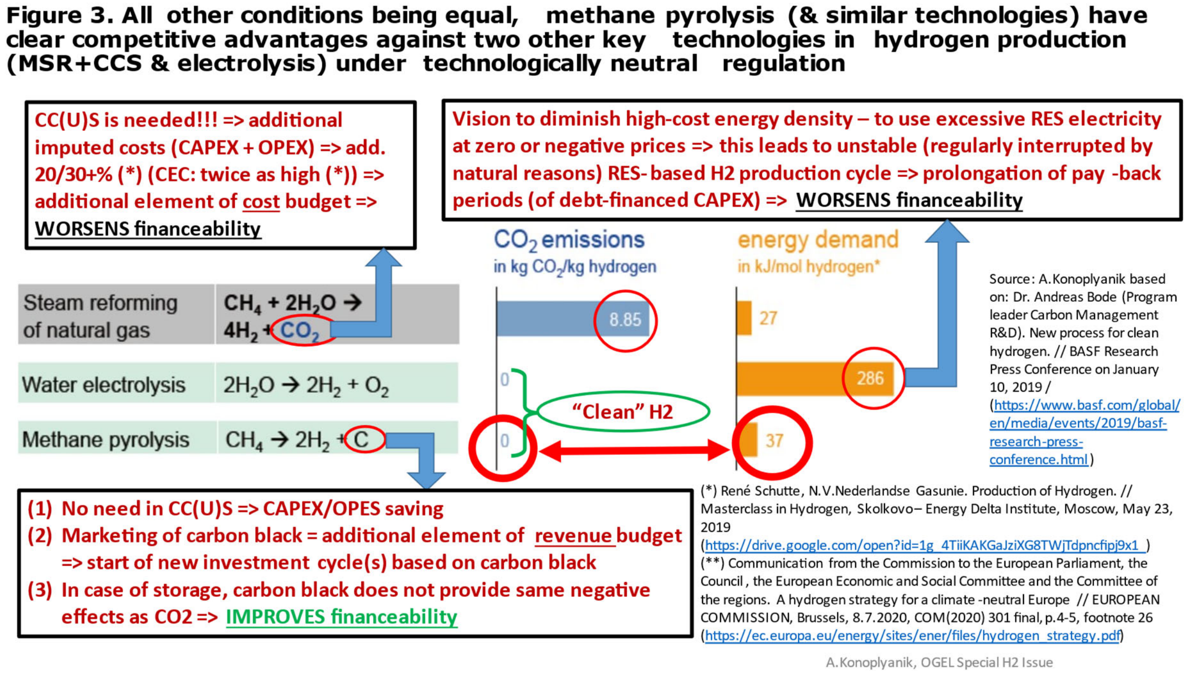

Figure 3. All other conditions being equal, methane pyrolysis (& similar technologies) have clear competitive advantages against two other key technologies in hydrogen production (MSR+CCS & electrolysis) under technologically neutral regulation

There is an understanding in the EU that "renewable" hydrogen (produced by electrolysis) is the ultimate goal, but achieving this by 2050 is impossible without parallel production and use of hydrogen based on natural gas.[17] But in the EU public debate, the latter normally means/understood as only MSR/ATR+CCS. The third group of technical solutions is almost not covered in the media (except maybe in very technical and/or pure academic publications) compared to the first two, and even in the EU Hydrogen Strategy.

For example, the fundamental and very much detailed on the H2-consumption/end-use side "Hydrogen Roadmap Europe" states that "hydrogen production will be a mix of mostly electrolysis and SMR/ATR with CCS in Europe".[18] Moreover, it said that "in locations where CCS is technically not feasible, biomethane reforming, water electrolysis, and longer-term biomass gasification will be the only ultra-low-carbon hydrogen production methods."[19] Clean H2 from natural gas is not even mentioned.

[17] Ralf Dickel. Blue hydrogen as an enabler of green hydrogen: the case of Germany. // OIES, OIES Paper: NG 159 (https://www.oxfordenergy.org/wpcms/wp-content/uploads/2020/06/Blue-hydrogen-as-an-enabler-of-green-hydrogen-the-case-of-Germany-NG-159.pdf#page=17&zoom=100,92,440)

[18] Hydrogen Roadmap Europe. A Sustainable Pathway for the European Energy Transition. Keynote presentation. // Fuel Cells and Hydrogen Joint Undertaking, February 6, 2019, p. 22 (https://www.fch.europa.eu/sites/default/files/20190206_Hydrogen%20Roadmap%20Europe_Keynote_Final.pdf)

[19] Hydrogen Roadmap Europe. A Sustainable Pathway for the European Energy Transition. Full report. // Fuel Cells and Hydrogen Joint Undertaking, February 6, 2019, p. 51 (https://www.fch.europa.eu/sites/default/files/Hydrogen%20Roadmap%20Europe_Report.pdf)

The title "Green Hydrogen for a European Green Deal: A 2x40 GW Initiative" of "Hydrogen Europe"[20] speaks by itself: this initiative (incorporated into EU Hydrogen Strategy) is fully devoted to green H2 only.

In the EU Hydrogen Strategy[21] itself the term "pyrolysis" is mentioned only twice within a 23-pages policy paper. The first time (on page 4) it is mentioned incorrectly, as a synonym of the SMR+CCS which is not the case, the second time (on page 17) as just one among other technologies in R&D section which, said, should be upgraded to the higher TRL levels.

The first time that all three key groups of H2 production technologies were presented on equal basis, was a Discussion Paper by Pöyry commissioned by Zukunft Erdgas.[22]

"Green" H2 vs. "Clean" H2

EU policy documents appear to use "clean" and "green" H2 as synonyms. However, this does not reflect the reality very well.

It is generally accepted in the EU that "green" H2 is a "clean" one and based on this perception it is taken for granted that the reverse observation is true/correct as well. Though it is definitely not the case if not only RES electricity production, which is to be localized inside the EU, is taken into account but the whole value chain of manufacturing RES equipment (which is mostly localized far beyond the EU, mostly in China). So only the internal EU energy-production part of the whole international RES value chain can be considered to be "green" within the still global nature of the environmental problem of GHG emissions (see **Figure 4**[23]). Manufacturing of equipment for RES electricity production is still quite an ecologically dirty chain of production processes started with rare earth materials extraction stage, while most of "dirty" upstream part of full value chain for as if "clean" RES-electricity production is located, as was mentioned, far beyond the EU, mostly in developing countries, particularly in China.

[20] Prof. Dr. Ad van Wijk, Jorgo Chatzimarkakis. "Green Hydrogen for a European Green Deal. A 2x40 GW Initiative". // Hydrogen Europe, 15/04/2020

[21] COMMUNICATION FROM THE COMMISSION TO THE EUROPEAN PARLIAMENT, THE COUNCIL, THE EUROPEAN ECONOMIC AND SOCIAL COMMITTEE AND THE COMMITTEE OF THE REGIONS. A hydrogen strategy for a climate-neutral Europe, Brussels, 8.7.2020, COM(2020) 301 final, pp. 4, 17.

[22] Hydrogen from natural gas – The key to deep decarbonisation. Discussion Paper commissioned by Zukunft ERDGAS. // Pöyry Management Consulting, July 2019

[23] A. Konoplyanik. Hydrogen strategies EU, Germany, Russia: how to correlate different interests & the role of Russia-EU Energy Dialogue. // Presentation at the XIII International Scientific Conference "ENERGETIKA-XXI: Economics, Politics, Ecology" – "World energy after pandemia COVID-19", November 25-27, 2020, FINEC – Gazprom, Saint-Petersburg, online

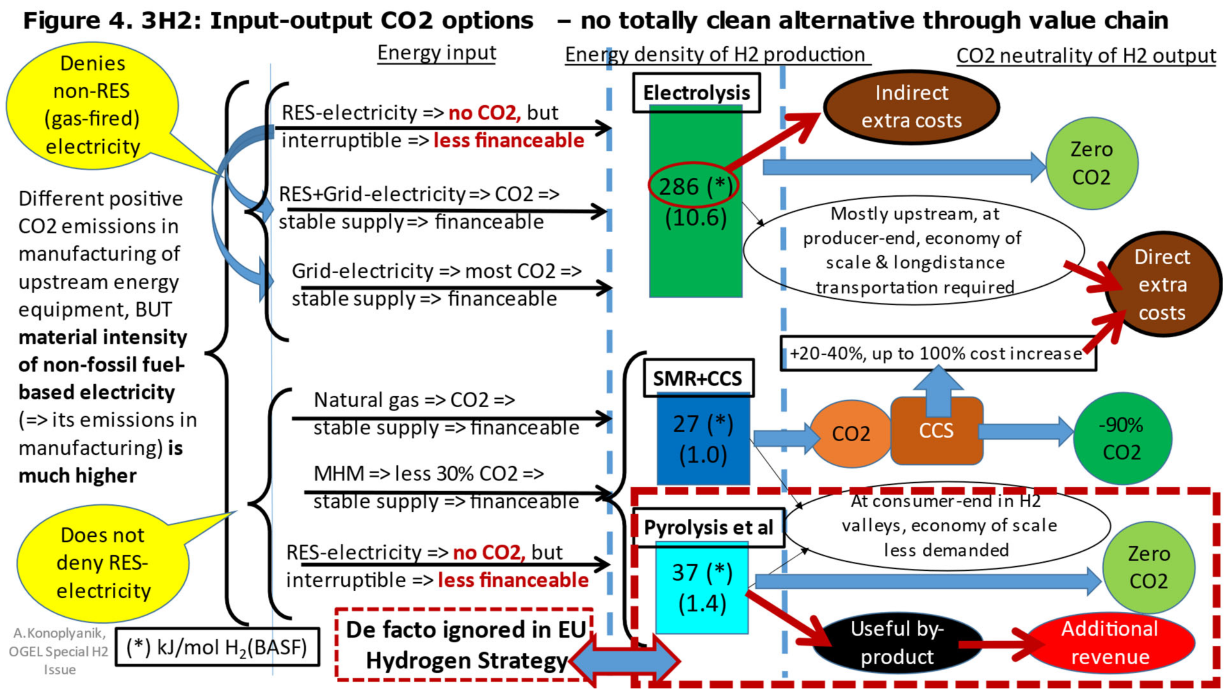

Figure 4. 3H2: Input-output CO2 options – no totally clean alternative through value chain

Moreover, as demonstrated by research of Olivier Vidal,[24] material intensity measured for four structural materials (concrete, steel, aluminium, copper) used to manufacture different power generation infrastructure by 13 different power generation technologies, in case of six based on fossil fuel are much lower that for seven based on RES, both for MW of installed capacity (see **Figure 5**) and for MWh of electricity produced (see **Figure 6**).

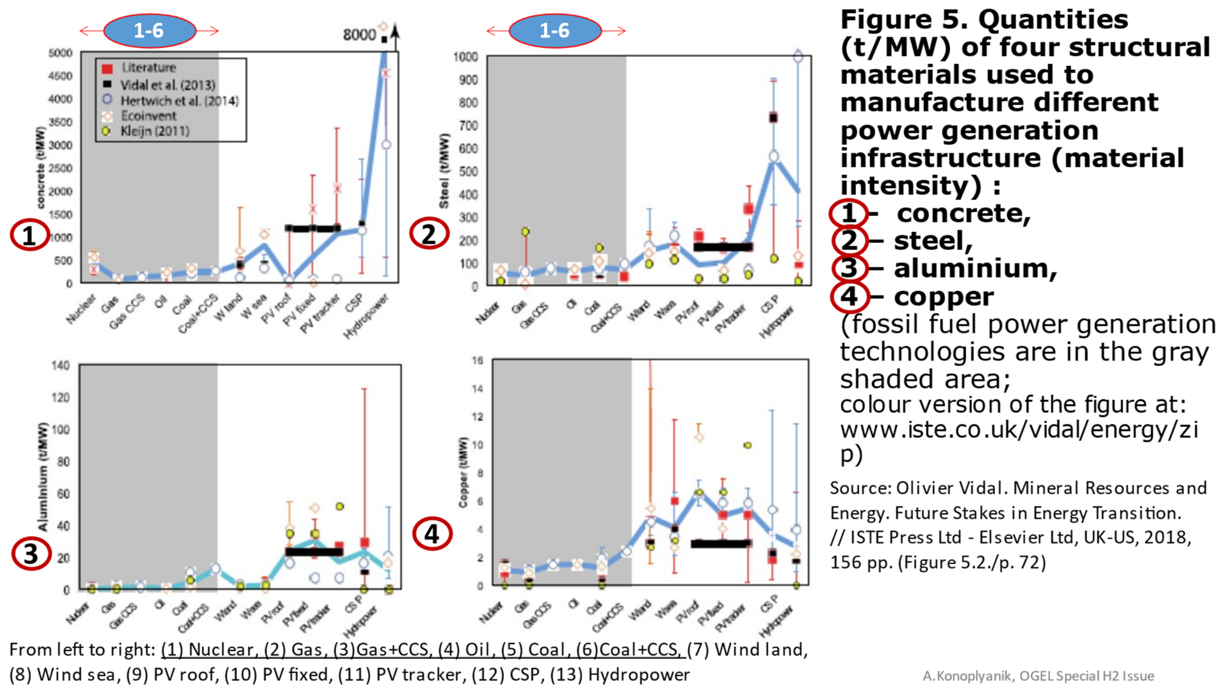

Figure 5. Quantities (t/MW) of four structural materials used to manufacture different power generation infrastructure (material intensity)

[24] Olivier Vidal. Mineral Resources and Energy. Future Stakes in Energy Transition. // ISTE Press Ltd - Elsevier Ltd, UK-US, 2018, 156 pp.

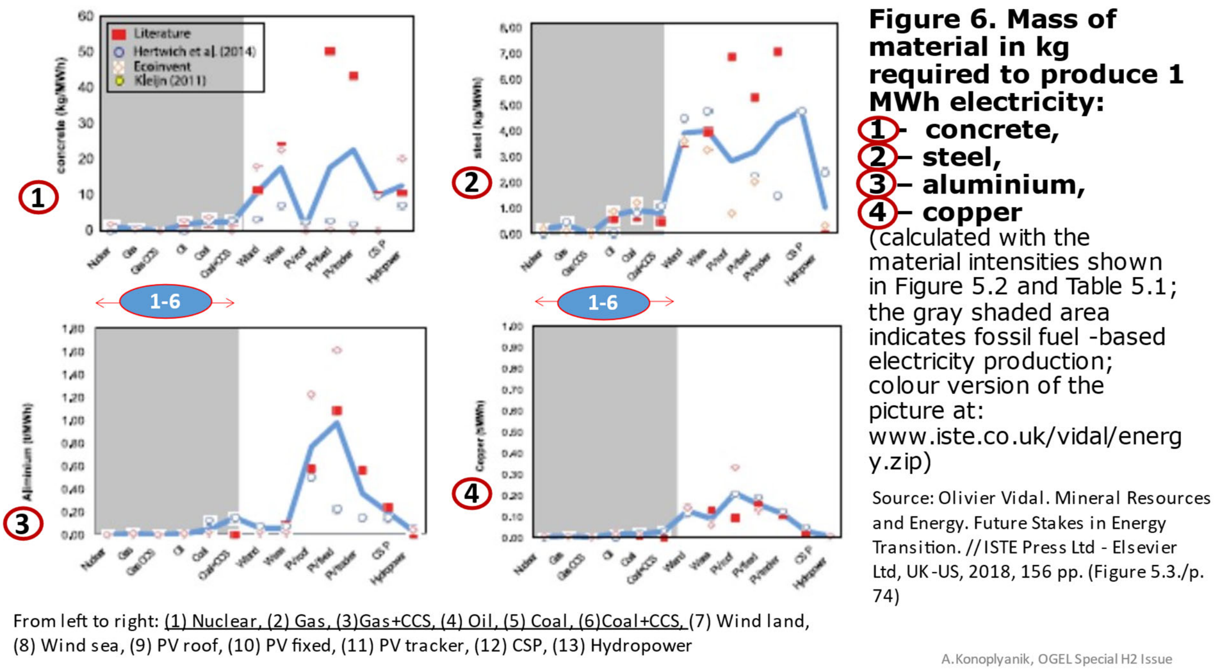

Figure 6. Mass of material in kg required to produce 1 MWh electricity

This means that GHG emissions related to manufacting chains of different power generation infrastructure technologies in case of RES are higher due to their higher material intensity, compared to fossil fuel based power generation technologies, though such higher emissions related to RES electricity production inside the EU are mostly located beyond the EU. And this is not only the case of the EU, but, as I would assume, of a number of other developed market economies…

All this gave reason for the well-known energy expert Daniel Yergin, the Pulitzer Prize winner for his world-renowned "The Prize" book, to say at the presentation of his new book "The New Map" at the Atlantic Council last Fall, that "New supply chains for net-zero carbon requires carbon!!! … They require diesel to operate shuttle in mining…"[25]

Moreover, the dominant view in the EU is that such "green" H2 is the only "clean" H2, so both terms are used as the synonyms in the corresponding draft EU regulatory documents and in final EU Hydrogen Strategy paper (which means that it is a long-standing perception), followed by corresponding documentation of different EU industrial associations and in the public media which, on the one hand, interprets them in this particular way, and, on the other hand, business began to act accordingly using such definitions as a guidance for practical actions.

But "clean" or "not-clean" character of H2 shall be considered based not on the presence/absence of carbon molecules in the energy/material input in H2 production, but based on the presence or absence of CO2 emissions in the end result of H2 production technological processes.

[25] A conversation with Pulitzer Prize winner and energy expert Daniel Yergin, Atlantic Council, 25.09.2020 (https://www.youtube.com/watch?v=hWMOU8IjRhI)

So H2 produced by MSR/ATR is not "clean" until/unless CCS is integrated into their production cycle (which demands additional costs). Alternatively, H2 produced by pyrolysis and/or the plasma-chemical method (without O2 access and without direct CO2 emissions) shall be considered to be "clean" without incremental costs in CCS and thus fully corresponds to the EU considerations for decarbonisation and carbon neutrality meaning as reduction (up to full elimination) of CO2 emissions.

Even the very terminology such as "carbon neutrality" (instead, say, of climate neutrality) creates wrong public perceptions since ecologically neutral solid carbon (by-product of pyrolysis et al) under such terminology is being equalized in the meaning with ecologically harmful GHG/CO2 emissions (by-product of SMR/ATR). And thus this further improves invalid public perceptions against clean H2 from natural gas.

I can assume that the background for this perception lies in the geopolitical (means: energy security) area and reflects easy to accept vision/policy (inspired, inter alia, by virtual pains of Jan'2006/2009 gas transit crises and following developments): to substitute *as if dirty foreign* molecules by *as if clean domestic* electrons, non-dependent whether this perception is true in it substance or not true.

In sum total, what I am trying to show is not that the pyrolysis is better than electrolysis for H2 production (or, not that H2 by pyrolysis is less or equally ecologically clean if all stages of energy production involved and manufacturing of such energy equipment is considered), but that it is incorrect, not proven and not economically viable/justified (but it is, more probably, motivated, and even, most probably, politically motivated), to consider that it is only renewable H2 is clean and others are not clean.

Though in the EU Hydrogen strategy it is directly said that "'Clean hydrogen' refers to renewable hydrogen" and that "The full life-cycle greenhouse gas emissions of the production of renewable hydrogen are close to zero" with the reference to IEA in the footnote that "The well-to-gate greenhouse gas emissions for renewable hydrogen from renewable electricity are close to zero (IEA, 2019). "[26] This means that at least indirect emissions of RES (at the stages of manufacturing production with their higher material intensity compared to fossil fuel based power generation technologies) are not considered.

If only the stage of production is considered, both H2 produced by electrolysis and pyrolysis (since both produce zero CO2 without any additional undertakings, like CCS in case of MSR) are clean, i.e. without direct CO2 emissions. But if also the stage of end-use energy production is considered (which is used in production of hydrogen), then the statement that "renewable H2 is the only clean H2" is not valid as well, since pyrolysis can be undertaken (say, under plasma technologies) with renewable electricity and thus both pyrolysis and electrolysis will provide clean CO2 (**Figure 4**).

[26] COMMUNICATION FROM THE COMMISSION TO THE EUROPEAN PARLIAMENT, THE COUNCIL, THE EUROPEAN ECONOMIC AND SOCIAL COMMITTEE AND THE COMMITTEE OF THE REGIONS. A hydrogen strategy for a climate-neutral Europe, Brussels, 8.7.2020, COM(2020) 301 final, pp. 3-4, footnote 20.

But if overall technological (business) cycle is considered, including both:

(i) energy production cycle from primary energy, from the well-head, through transportation, processing, transformation stages to the end-use, where it is finally split into useful work and losses, and
(ii) manufacturing cycle of energy equipment for such different stages of full energy production cycle, bearing in mind different unit energy and material consumption for different technologies,

then the statement (taken as key/fundamental perception, in, say, EU Hydrogen Strategy) that only renewable hydrogen is clean (emission free through its business cycle) is invalid, incorrect. And thus all following EU regulation is based on this improper perception, which limits opportunity for decarbonisation path of the EU and made it more costly by pushing the business into more narrow corridor of opportunities. And thus also narrowing the basis for cooperation with the prospective partners.

Conceptual Basis for Cooperation: "Three-step Aksyutin's Pathway"

Bearing above descriptions in mind, I see the conceptual basis for export-oriented Russian effective participation in EU decarbonization (by producing clean H2) within Gazprom's proposals for the "Strategy for Long-Term EU Greenhouse Gas Emission Reduction by 2050".[27] I call it "Three-step Aksyutin's pathway" as it was developed and first presented by Gazprom Deputy-CEO Oleg Aksyutin within the framework of the Russia-EU Gas Advisory Council (GAC) at July 2018 meeting of its Work Stream 2 "Internal Markets" (WS2) in Saint-Petersburg (see **Figure 7**)[28], as well as in related publications.[29]

[27] PJSC Gazprom's feedback on Strategy for long-term EU greenhouse gas emissions reduction to 2050 // https://ec.europa.eu/info/law/better-regulation/initiatives/ares-2018-3742094/feedback/F13767_en?p_id=265612
[28] Dr. Oleg Aksyutin (Member of the Gazprom Management Committee, Head of Department, Corresponding Member of the Russian Academy of Sciences). FUTURE ROLE OF GAS IN THE EU. GAZPROM'S VISION OF LOW-CARBON ENERGY FUTURE. // Presentation at the 33rd round of Informal Russia-EU Consultations on EU Regulatory Topics (Consultations) & 26th meeting of the EU-Russia Gas Advisory Council's Work Stream on Internal Market Issues (GAC WS2), 10.07.2018, Russia, St. Petersburg (https://minenergo.gov.ru/node/14646; www.fief.ru/GAC)
[29] О.Аксютин, А.Ишков, К.Романов, Р.Тетеревлев. Метано-водородная энергия для низкоэмиссионного развития. // «Газовая промышленность», 2018, № 11, с. 20-25 (O. Aksyutin, A. Ishkov, K. Romanov, R. Teterevlev. Methane-hydrogen energy for low-emission development. // "Gas Industry", 2018, N11, p. 20-25)

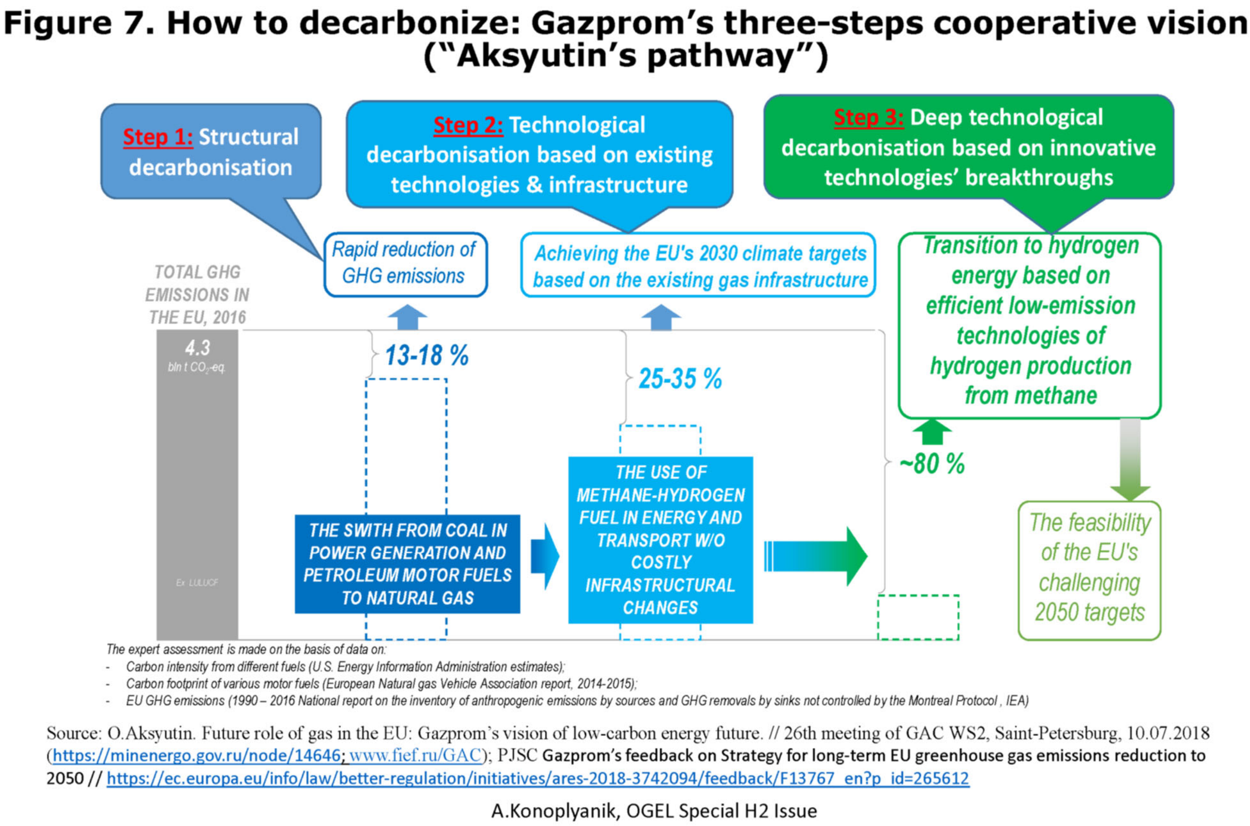

Figure 7. How to decarbonize: Gazprom's three-steps cooperative vision ("Aksyutin's pathway")

The first step is the traditional substitution of coal by gas in power generation and of liquid fuels by both CNG and/or LNG in the transport sector. This is structural decarbonization. The second step is technological decarbonization based on the existing technical solutions and infrastructure, in particular, the production of a methane-hydrogen mix (MHM) at compressor stations of gas pipelines (say, by using adiabatic conversion of methane technology, patented by Gazprom) and its use as fuel gas at these stations instead of methane, which reduces CO2 emissions at such compressor stations by about a third. The third step is deep decarbonization based on innovative solutions, in particular, the transition to hydrogen production from methane without CO2 emissions (by pyrolysis and related technologies), with a view to future use of hydrogen. My vision of potential Russia-EU cooperation in decarbonisation, including in clean H2 production based on "Three-step Aksyutin's pathway", is presented at **Figure 8**.

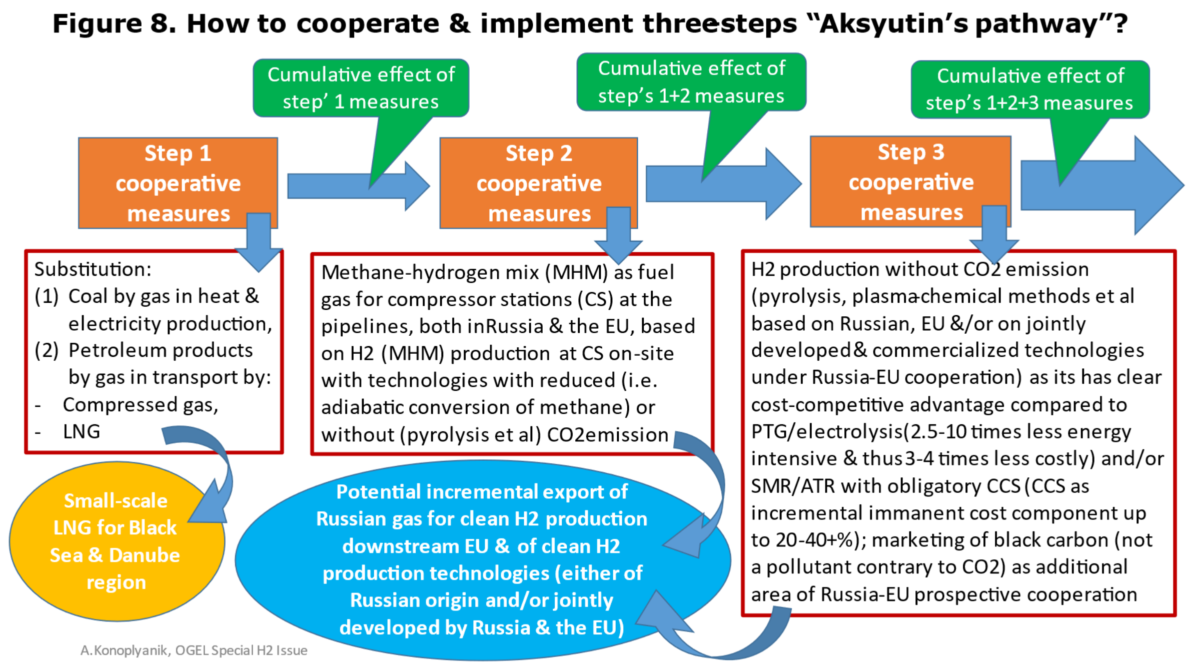

Figure 8. How to cooperate & implement three-steps "Aksyutin's pathway"?

The cooperation of Russian and EU research institutions and companies for the fastest possible commercialization of the latter group of technologies can be a win-win solution for both Russia and the EU. It will expand Russian gas supplies to the EU to be used for clean H2 production and thus will increase monetization of Russian gas resource. It will help to develop innovative clean H2 production facilities on a joint Russia-EU basis to be used within the "Broader Energy Europe" (which includes both the EU and Russia as well as other territories covered by this diversified energy grid) and maybe beyond it at the later stage. And it will reduce the cost of decarbonization for the EU. That is, it will lead to increased welfare of both Russian and European citizens.

"Clean H2 from Natural Gas Alliance"

Such cooperation can be organized in the form of developing a special Russia-EU undertaking (see **Figure 9**) with an open participation similar to "Clean Hydrogen Alliance", say, under the umbrella of WS2 GAC, where this concept was first presented.[30]

[30] A. Konoplyanik. A "Clean Hydrogen from Natural Gas Alliance" Proposal – why it is in mutual benefit for the EU and Russia: proposal for creation of the platform. // Presentation at the 31-th meeting of WS2 GAC, online, 18.09.2020 (https://minenergo.gov.ru/node/14646; www.fief.ru/GAC; http://www.konoplyanik.ru/speeches/200918-Konoplyanik-WS2GAC-final.pdf)

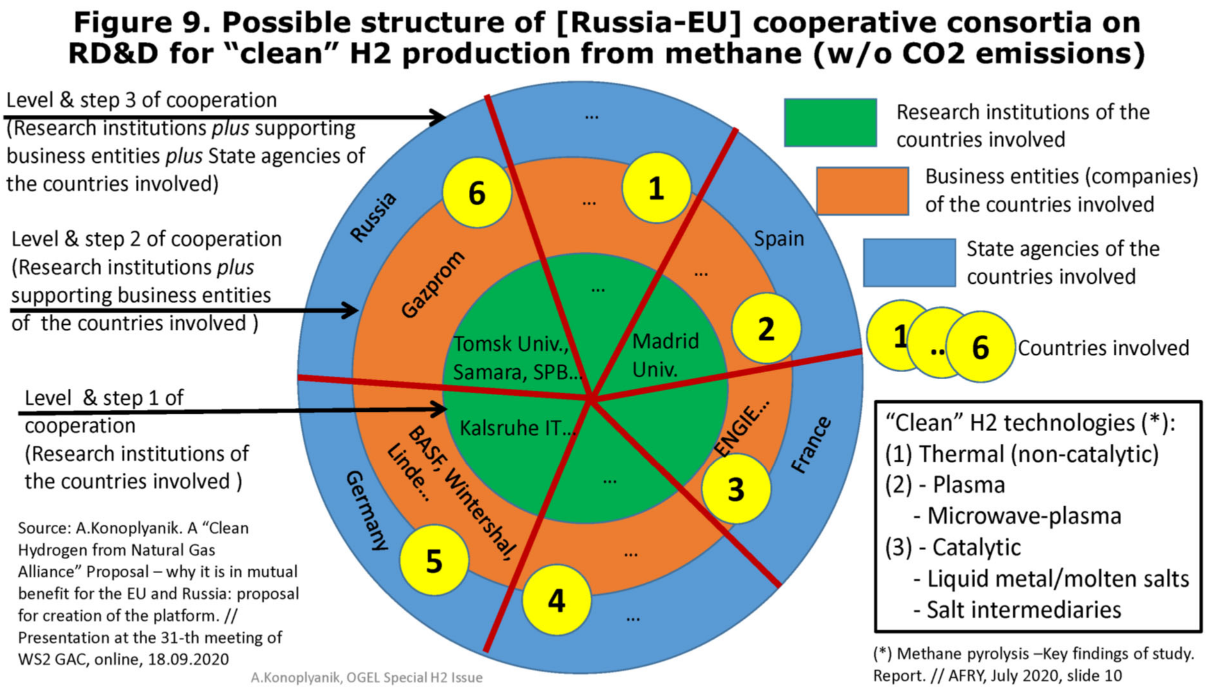

Figure 9. Possible structure of [Russia-EU] cooperative consortia on RD&D for "clean" H2 production from methane (w/o CO2 emissions)

In its Communication on "A New Industrial Strategy for Europe" in March 2020, the EU Commission stated that it will shortly propose to launch the new European Clean Hydrogen Alliance bringing investors together with governmental, institutional and industrial partners. The Alliance will build on existing work to identify technology needs, investment opportunities and regulatory barriers and enablers.[31] According to Hydrogen Europe, this initiative was already supported by the CEOs of at least 90+ European companies[32] even before such "Clean Hydrogen Alliance" was launched with/by the adoption of EU Hydrogen Strategy on 08.07.2020.

The proposed Russia-EU undertaking can be entitled "Clean Hydrogen from Natural Gas Alliance" since as of today the substance of EU "Clean Hydrogen Alliance" seems to address mostly/only the issues of "green" H2 in the terminology dominating in the EU. So both Alliances will be not competing, but complementary to each other (see **Figure 10**). Also, such Russia-EU undertaking cannot be organized just as a section of "Clean Hydrogen Alliance" as the latter is aimed for the EU, the Energy Community and the regional EU partnerships (like with Northern Africa, Ukraine), and the proposed "Clean Hydrogen from Natural Gas Alliance" aimed to cover the broader geographical area.

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[31] COMMUNICATION FROM THE COMMISSION TO THE EUROPEAN PARLIAMENT, THE EUROPEAN COUNCIL, THE COUNCIL, THE EUROPEAN ECONOMIC AND SOCIAL COMMITTEE AND THE COMMITTEE OF THE REGIONS: A New Industrial Strategy for Europe, Brussels, 10.3.2020 COM(2020) 102 final, p.15 (https://ec.europa.eu/info/sites/info/files/communication-eu-industrial-strategy-march-2020_en.pdf)
[32] 90+ Hydrogen Europe CEOs ready to support Clean Hydrogen Alliance. Press Release. // Hydrogen Europe, 02.06.2020 (https://hydrogeneurope.eu/sites/default/files/Hydrogen%20Europe's%20CEOs%20Letter%20to%20EC_final.pdf)

Figure 10. Comparison of two Clean H2 Alliances proposals (with no CO2 emissions in H2 production)

Items	EU Clean H2 Alliance (08.07.2020)	Proposed RF-EU Clean H2 from CH4 Alliance
Targeted H2	Renewable H2 (current EU mainstream)	Clean H2 from natural gas (almost ignored in the EU)
Feedstock & its inland limitation in EU	Water => natural limits	Natural gas => no limitations with diversified multiple import supplies by pipelines & LNG
Energy supply for H2 production Source: A.Konoplyanik. A "Clean Hydrogen from Natural Gas Alliance" Proposal – why it is in mutual benefit for the EU and Russia: proposal for creation of the platform. // Presentation at the 31-th meeting of WS2 GAC, online, 18.09.2020	Renewable electricity (wind, solar): - Interruptible (difficult to finance), - Non-interruptible only with electricity storage (yet non-available) - RES-electricity clean, but its upstream equipment production chain not clean	MHM-fueled CCGT at/close to CS on existing GTS: - non-interruptible (easy financeable) - MHM not as clean as RES-electricity, but 30% less CO2 than in gas-fired turbines, its up-stream equipment production chain not clean - open issue of methane leakages
Location of H2 production units	Where intensive sun & wind => far beyond the EU => far away from EU H2 consumption centers	Close to/in EU H2 consumption centers (H2 valleys)
Triggering effect for H2 cost-reduction	Economy of scale (obligatory) + learning curve (at the production site) => maximum increase of unit production capacity required =>	Adequacy of production capacity to demand levels + learning curve => no need in obligatory economy of scale
H2 unit production capacity	=> Increase to technically achievable maximum (GW-level)! ...from today's kW/100'skW/MW(?)	Selection of optimal sizes close to demand(s) in "H2 valleys" (100'kW to MW-level) ?
Long distance H2 transportation	Badly needed	No need
H2 distribution lines	Needed (in sum-total longer)	Needed (in sum-total shorter)
Existing cross-border GTS (CH4)	Risk to become a stranded asset	Continued to be used, no risk of stranded asset; prolongation of economic life
Scope	Internal EU	Internal 'Broader Energy Europe' (incl.RF-EU)

A.Konoplyanik, OGEL Special H2 Issue

Figure 10. Comparison of two Clean H2 Alliances proposals (with no CO2 emissions in H2 production)

There is no such special undertaking anywhere yet in regard to clean H2 from natural gas which is quite a specific avenue compared to two other technological avenues of H2 production. At least, some time ago I have not managed to find it at the Hydrogen Europe website within its 229 projects mentioned any indications relevant to such specific technological path.

There are not too many companies and/or institutions that are dealing with this "third avenue" of H2 production – from methane without CO2 emissions: there are few from Russia (Gazprom, National Research Tomsk Polytechnic University…), Germany (BASF, Winterschall, Linde, Uniper, Karlsruhe Institute of Technology…), Spain (Madrid Polytechnic University - ETSII), some others… (see **Figure 9**). Some of those have made their presentations at the earlier WS2 GAC meetings.[33] The benefits of cooperation are well-known: it can speed up both the moment of entering "learning curve" referred to this technology and further sliding downwards with cost reduction through it. Cooperation in clean H2 from natural gas can be one of the mainstream of the further work of WS2 GAC which has been reformatting its activity due to pandemia COVID-19 limitations.

"Hydrogen Europe" might be a coordinative body for such undertaking on the EU side. In its latest publication "The EU Hydrogen Strategy: Hydrogen Europe's Top 10 Key Recommendations" under recommendation number 10, this industry association has proposed to "launch the Clean Hydrogen Alliance and establish hydrogen as a key element in global EU climate diplomacy and neighbourhood policy" including to "establish hydrogen as key component of the ongoing EU-Ukraine energy cooperation as well as the EU-Africa and Euro-

[33] See: https://minenergo.gov.ru/node/14646; www.fief.ru/GAC

Mediterranean partnerships.”[34] On a non-conflicting basis with these regional EU cooperative undertakings, the Russia-EU Gas Advisory Council (GAC) can add to its already 10-years-long non-interrupted continued activities the “clean H2 from natural gas” facet as a mutually beneficial new activity.

From the Russian side, one of the prominent prospective participants might be the newly created (in November 2020, by six Universities and Russian Academy of Sciences Research Institutes, at the initiative of Tomsk Politechnic University) Consortium on the Development of Hydrogen Technologies “Technological Hydrogen Valley”[35] which has held its first event – all-Russian scientific and business conference “Hydrogen. Technologies. Future” on 23-24.12.2020, presenting a broad spectrum of multiple technological achievements in the area.[36]

And such a “Clean Hydrogen from Natural Gas Alliance” is proposed to organize not instead of, but in addition to, other technological avenues of low-carbon and/or clean H2 production efforts, based on their geographical complementarity, within a “Broader Energy Europe”.

Cooperation Based on Complementarity of Technological Avenues

There are several geographical areas within “Broader Energy Europe” of prospective competitive advantages for certain H2 production technologies (see **Figure 11**). If technologically neutral regulatory approach is undertaken, as promised, in the EU, all these technologies can find their competitive niches and add to the effective decarbonisation path of the EU.

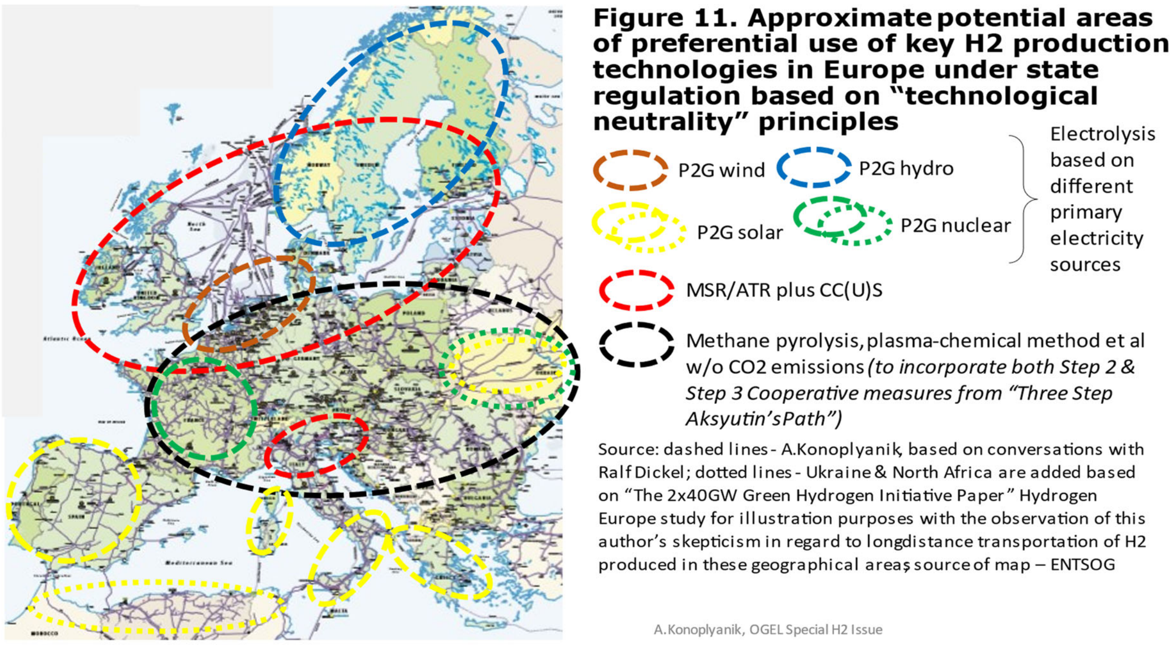

Figure 11. Approximate potential areas of preferential use of key H2 production technologies in Europe under state regulation based on “technological neutrality” principles

[34] The EU Hydrogen Strategy: Hydrogen Europe’s Top 10 Key Recommendations. // Hydrogen Europe, 22/06/2020, pp. 2,19 (https://hydrogeneurope.eu/sites/default/files/The%20EU%20Hydrogen%20Strategy_%20%20Hydrogen%20Europe’s%20top%2010%20key%20recommendations_FINAL.pdf)

[35] В России создали первый научный консорциум по развитию водородных технологий. // ТАСС, 13.11.2020 (First scientific consortium on development of hydrogen technologies is created in Russia. // TASS, 13.11.2020) (https://nauka.tass.ru/nauka/9997227)

[36] https://portal.tpu.ru/portal/page/portal/htf

EU countries with a long active solar radiation (the Iberian Peninsula, Southern Europe, Mediterranean islands, but also non-EU North Africa and Ukraine, according to “A 2x40GW Initiative” of Hydrogen Europe, incorporated in EU Hydrogen Strategy) can use solar energy for electrolysis, and countries of North-Western Europe where wind energy is now actively used already (both onshore and offshore wind farms) can use electrolysis based on excessive wind energy.

The Scandinavian countries known as the “hydropower states” due to a high percentage of hydropower in their electricity production, will have the groundwork ready for competitive use of electrolysis based on hydroelectricity (to smooth out the night-time fall of the load curve).

Similarly (based on operational considerations – smoothing out the night-time fall of the load curve in nuclear power generation), electrolysis for H2 production can be used in France, a country with a high share of nuclear power plants in electricity production since nuclear stations requires stable load-curve and can work only in the base-load (and, maybe, also in Ukraine – if the logic of the above-mentioned “A 2X40GW Initiative” it to be followed).

SMR with CCS is now being actively developed by Equinor with its partners (including CO2 capture from the coastal industrial plants in the North and Baltic Seas and transportation for sequestration in the North Sea depleted fields); in particular, the Norwegian Petroleum Directorate offers a wide program for using the depleted oil and gas reservoirs to dispose of CO2.[37] Therefore, I believe that a zone covering the water areas and coastal states of the North and Baltic Seas will/might be a zone of competitive application of the SMR/ATR with CCS technology.

Finally, the methane pyrolysis and similar technologies will spread (in case of their accelerated transition from the stage of laboratory testing and pilot units to the stage of industrial application, including through cooperation between Russia and the EU in this sphere) in Continental Europe based on the extensive well-diversified cross-border gas transmission grid, with reliance on the second and third steps of the aforementioned “three-step Aksyutin’s pathway”.

What Can Be an Action Plan?

At the 29th WS2 GAC meeting in Berlin in October 2019 the co-chairs have initiated discussions on a potential joint research/investigation on key decarbonization issues of mutual Russia-EU interest.[38] One of the line of thoughts for further consideration might be the following, as it was presented at the 31st, the first online, WS2 GAC meeting.[39]

[37] Jasminka Mujezinović, Van Pham. Evaluation of Norwegian Shelf for CO2 Storage. // Presentations at XI International Scientific Conference Energetika XXI, 14th-16th November 2018, St. Petersburg

[38] Discussion on potential joint research on key decarbonization issues of mutual interest, Leaded by Co-chairs Work Stream 2 “Internal Markets”, Russia-EU Gas Advisory Council. // 29th meeting of the EU-Russia Gas Advisory Council’s Work Stream on Internal markets Issues (GAC WS2), Berlin, Germany, 21 October 2019 (https://minenergo.gov.ru/node/14646; www.fief.ru/GAC; http://www.konoplyanik.ru/speeches/ab191021-Berlin%20WS2-Konoplyanik-Boltz-v3-191016.pdf)

[39] A. Konoplyanik. A “Clean Hydrogen from Natural Gas Alliance” Proposal – why it is in mutual benefit for the EU and Russia: proposal for creation of the platform. // Presentation at the 31-th meeting of WS2 GAC, online, 18.09.2020 (https://minenergo.gov.ru/node/14646; www.fief.ru/GAC; http://www.konoplyanik.ru/speeches/200918-Konoplyanik-WS2GAC-final.pdf)

Clean H2 from methane is to be produced downstream EU, close to demand centers for H2, at locations close to existing compressor stations (CS) at cross-border gas transmission grid within "Broader Energy Europe" (see **Figure 12**). Natural gas transported through this grid is to be used:

(1) on-site of corresponding gas-fueled CS for production of MHM to be used as fuel gas (instead of methane) at this compressor stations for further transportation of gas through the grid, but also as energy input for clean H2 production at the plants to be built nearby such CS at scale adequate to prospective H2 demand from the neighboring area (this is my proposed alternate interpretation of "hydrogen valleys" term), and

(2) as a feedstock at the new clean H2 from methane production plants to be located near-by such CS. The scale of such plants shall not be determined by the scaling-up effect to maximum possible technical production capacity within GW range (as proposed in EU Hydrogen Strategy to use "economy of scale" approach to diminish unit cost of H2 production at the location of resource) since it will require development of more extensive and diversified H2 transportation grid from resource to the end-users. And then cost savings at production stage can be easily "eaten" by incremental costs of development H2 transportation grid.

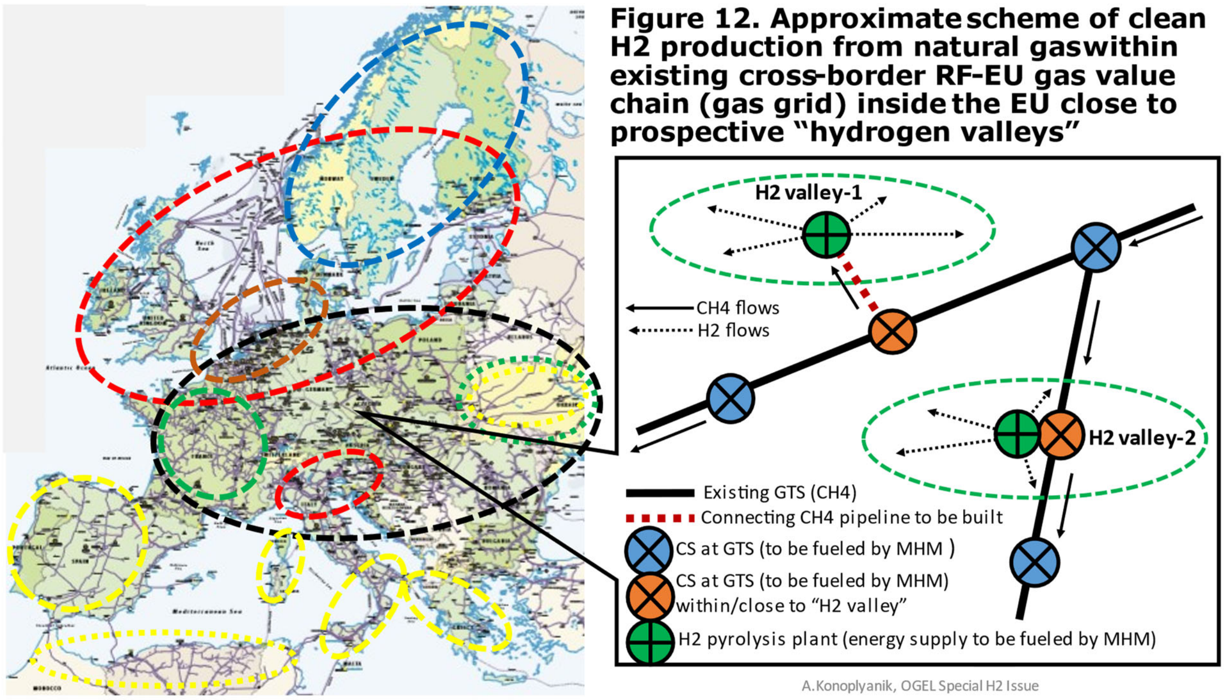

Figure 12. Approximate scheme of clean H2 production from natural gas within existing cross-border RF-EU gas value chain (gas grid) inside the EU close to prospective "hydrogen valleys"

Unit capacities of clean H2 production plants located close to existing CS shall be determined by their adequacy to prospective demand for H2 from local areas (within local hydrogen valleys). In such model the costly needs for H2 transportation through newly developed hydrogen grid and/or existing gas grid to be adapted to the transportation of MXM, or pure hydrogen, will be downgraded to the reasonable minimum. Inversely, such decarbonisation path extends the economically proven life of existing cross-border capital-intensive immobile gas infrastructure within "Broader Energy Europe".

At the coming WS2 GAC meetings (which are now reorganized into online format for the time-being due to pandemic COVID-19 limitations) we plan to continue discussing this avenue of Russia-EU cooperation in "clean H2 from natural gas" area within the framework of the EU Hydrogen Strategy so both parties will manage to materialize mutual benefit of their cooperation in the clean hydrogen area.

List of Abbreviations

ASAP	as soon as possible	**IEA**	International Energy Agency
ATR	auto thermal reforming	**IRENA**	International Renewable Energy Agency
BNEF	Bloomberg Nerw Energy Finance	**kW (kWh)**	kilowatt (kilowatt-hour)
CCS	carbon capture and sequestration	**LLC**	Limited Liability Company
CNG	ompressed natural gas	**LNG**	liquefied natural gas
CO2	carbon dioxide	**MHM**	methane hydrogen mix (mixture)
CS	compressor station	**MSR/SMR**	methane steam reforming (steam methane reforming)
EU	European Union	**MW**	Megawatt
GHG	green house gases	**R&D**	research and development
GTS	gas transportation system	**RES**	renewable energy sources
GW	Gigawatt	**WS2 GAC**	Work Stream 2 "Internal markets" of the Russia-EU Gas Advisory Council
H2	hydrogen		