Key Aspects of the Seventh Energy Transition And Its Point of Divergence and Mutually Acceptable International Economic Solutions For Russia

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***Abstract* — In this author's view, current energy transition is the seventh one in human's history. But it is the first one triggered from the demand-side by climatic considerations aimed at decrease of GHG emissions to reach their net-zero level. And it will not end up with another one dominant energy, as in the past, but with competitive energy mix of both renewable and non-renewable energies based on economic, ecologic & climatic considerations. EU decarbonisation is based on "renewable electricity plus decarbonized gases" political concept. Renewable hydrogen is politically predetermined choice in the EU (though within the distorted frame of reference, as this author proves) and hydrogen from natural gas is given only temporary future in the EU. But EU will not manage to produce all hydrogen needed domestically and looks for its import from neighboring states, including Russia. Two concepts of how to organize Russia-EU hydrogen cooperation are debated. EU/German concept is to produce green and blue hydrogen in Russia and to export it to the EU. This means through the existing Russia-EU gas transportation system which will predetermine its costly deep modernization up to full reconstruction/replacement. The author proves why this concept is counterproductive for Russia. He proposes alternative concept: to continue with natural gas supplies from Russia to the EU and to produce hydrogen in the "hydrogen valleys" inside the EU: in continental Europe - by pyrolysis (without CO_2 emissions), and in the coastal areas of North-West Europe – also by methane steam reforming with CO_2 capture and sequestration in the depleted fields in the North Sea.**

***Index Terms*: *renewable energy sources, hydrogen energy, renewable hydrogen, energy transition, hydrogen international cooperation, European Union, Russia, technological neutrality*.**

Highlights

- Not the first or fourth but the seventh energy transition;
- Economic vs climate competition between non-renewable and renewable energies;
- Renewable hydrogen (water electrolysis with renewable electricity) vs non-renewable hydrogen (methane pyrolysis without direct CO2 emissions and/or methane steam reforming with CO2 capture and sequestration) vs technological neutrality principle in the EU;
- Renewable hydrogen in the EU vs three Scopes of GHG emissions;
- The EU-Germany concept of hydrogen cooperation with Russia and controversial Russia's position on hydrogen export;
- The alternative win-win concept based on Russian natural gas supplies to the EU and hydrogen production inside the EU by pyrolysis and methane steam reforming with CO2 capture and sequestration.

I. Introduction

Today, the main publicly discussed topics in the international energy industry are, perhaps, various aspects of the current "energy transition" or "green revolution", that is, a change in the social and technological order and the basic paradigm of the world energy development towards reducing the negative impact on the environment, primarily by reducing greenhouse gas emissions and thereby curbing global warming and its negative consequences. Already at this point, there are very significant differences of opinions, beginning with which energy transition is the current one.

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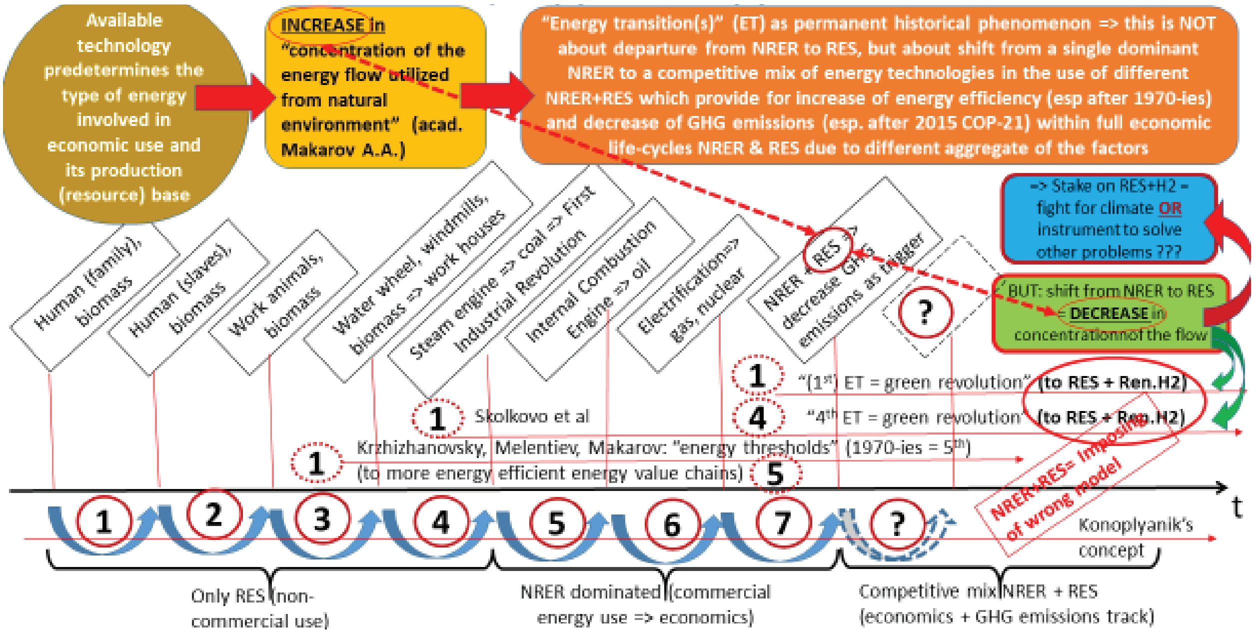

Fig. 1. "Energy Transition(s)" (ET): duration of considered historical time period does matter (Konoplyanik's concept).

II. Which energy transition: the first or the seventh?

In the narrowest sense, the term "energy transition" is interpreted by a number of authors as a phenomenon of modern history only. It is believed that the German term "Energiewende," which can be translated as "energy transition," "energy turn," "energy revolution," in the sense of changing the entire global energy industry, first appeared in 1980 as the title of a publication by the German Öko-Institut [1] and became widely used in Germany in the early 2010s [2]. S. Griffits notes that "although the term 'energy transition' has no single meaning, it usually means the gradual replacement of the use of fossil fuels by renewable energy sources" (RES) [3]. Some authors were quick to call such comments about increasing the share of renewables in the global energy balance "the theory of the global energy transition" [4].

There is also a broader dimension available to the energy transition in the modern world – the transition from one dominant non-renewable energy resource (NRER) to another, and then the transition from NRER dominance to RES dominance. Adopting this approach, some researchers suggest that the current energy transition is the fourth one, "from biomass (firewood) to coal, then to oil, then to gas, and now to renewables" [5]; others, with a similar approach, think of it as only the third one (apparently: coal, hydrocarbons, renewables), also considering only the "modern history of industrial and technological development," while talking about "the transition to a new 'electric world'" [6].

In this author's broader understanding, the "energy transition" is a progressive shift in social development from one technological order to another, in which one or another energy resource dominates (as it did in the past) or a competitive (without an obvious dominant energy resource) energy consumption structure is formed (as it is happening now and, in the author's opinion, will happen in the future), throughout the development of human civilization, not only from the beginning of industrialization period to the present. In this author's opinion, the basis of this or that "technological order" (the term coined by D.S. Lvov and S.Yu. Glazyev [7]) is the overcoming of the corresponding "energy threshold" (if we follow the terminology of Academician G.M. Krzhizhanovsky [8]), that is the transition to a qualitatively new level of energy consumption, not so much with respect to the volume of energy consumption, as by its qualitative structure.

If one is to follow the conceptual vision advocated by Acad. G.M. Krzhizhanovsky, L.A. Melentiev, and A.A. Makarov, then the authors refer to the first "energy threshold" as that of the creation of the water wheel (and then the use of wind energy in mobile and stationary energy as well), which effectively replaced human and animal muscle power, and then the transition to the use of coal (along with firewood) after the appearance of the Watt steam engine. According to L.A. Melentiev's view as of mid-1970-ies, "currently developed market economies are placed within conditions characteristic for the fifth energy threshold which is finalization of forming united energy systems, which they have approached to approximately within 1950-ies/1960-ies" [9]. He also considered that the then "USSR in the last quarter of the XXth century has been slowly approaching the sixth energy threshold" [10].

However, if we look even more broadly, energy transitions did not begin with the first industrial revolution or with the preceding use of the water wheel (the time of development of workhouses) and wind power in pre-industrial time, but much earlier – with the primitive-communal system, when the struggle began for access to material and energy resources and/or for their mastery through various engineering tricks, the achievements of scientific and technological progress (STP) (see Fig. 1).

The first energy resources to provide a minimum level of consumption by human beings (their families) within the framework of simple reproduction were renewable energy sources – the muscle power of human beings themselves and their family members and biomass/wood (after mastering fire). If we count back from this time, then the first energy transition, in this author's opinion, was the expansion of the use of human's physical strength through the additional use of the physical strength of other people – prisoners of war being converted into slaves. This happened in the transition to expanded reproductive performance. That is, the energy resource remained the same (human muscle power), but its source changed: not only the expansion of energy sources within the family by means of fertility and family bonds but also from outside the family by means of slave labor (there was, in fact, the first diversification of energy sources, though not on a commercial basis since the muscle power of slaves was not purchased but conquered).

The second energy transition is the involvement in the energy balance of the muscle power of tame and thus becoming domesticated work animals (draught cattle).

The third is the expansion of the use of RES (wind and water energy) after the invention of wind and water mills (the beginning of the "energy thresholds" of Acad. G.M. Krzhizhanovsky). The use of the latter ensured the development of textile factories (work houses) and was the forerunner of the First Industrial Revolution. However, these RES were mainly suitable only for stationary use along with the use of wind energy in mobile energy by the sailing fleet. And it was only the steam engine that gave rise to the development of mobile energy (at sea and on land) and the coal industry as a source of fuel for steam plants (in stationary and/or mobile applications).

Thus, in this author's frame of reference, the transition to coal is the fourth energy transition (rather than the first one [5, 6]), and the current one, therefore, is the seventh one (rather than the fourth if we divide the period of hydrocarbon dominance into separate periods of oil and gas dominance, as in [5], or the third if we merge them, as, apparently, is done in [6]).

This provides few valid additional arguments to the debate on the substance of energy transition. Those who began the count from the First Industrial Revolution and thus trying to prove the shift from NRER to RES as the very substance of "energy transition" further to their interpretations of the previous historical trends, just either forgot (or intentionally exclude) the previous "energy transition" from pre-industrial to industrial time which was a transition from RES to NRER (see Fig. 1). And that was a reverse process to the imposed vision of the current energy transition as if from NRER to RES. All previous energy transitions were characterized, according to academician A.A. Makarov, by clear and definite trend: "consequent passing through the energy thresholds was accompanied by increasing concentration of the energy flow utilized from natural environment" [11], including through the involvement of NRER of higher and higher quality (first coal, then oil, then natural gas). The imposed shift from NRER to RES as if current "energy transition" leads to decrease of the above mentioned "concentration of the energy flow utilized from natural environment".

This is why I do consider "energy transitions" as permanent historical phenomenon which is NOT about departure from NRER to RES today or in the longer trend, but it is nowadays about shift from a single dominant NRER to a competitive mix of energy technologies in the use of different NRER+RES which provide for increase of energy efficiency (especially after the 1970-ies) and decrease of GHG emissions (especially after 2015 COP-21) within full economic life-cycles NRER & RES due to different aggregate of the factors. And it is not energy resource per se that does matter, but it is available technology which predetermines the type of energy involved in economic use (now both energy and climate efficient) and its production (resource) base.

All previous energy transitions were determined by the introduction of new energy sources into the energy balance due to the achievements of the revolutionary STP, and mainly on the supply side. In contrast, the current energy transition is caused by man-made restrictions on demand for primary and final energy in connection with the climate agenda. Therefore, it is accompanied by containment and even contraction of supply of NRER that have been dominant to date and maintain its dominant position in their "conventional version", that is, without restrictions on emissions.

In Russia, the questions of what place this country should take in the current energy transition and how to build international cooperation in it, primarily with Europe as our main export market, are certainly added to this discussion with much practical consequences.

III. NRER and RES: economic vs. climate competition, before and after the Paris Agreement

For the EU, the severity of the climate problem is obvious and is largely the result of the industrial model of development. Industrialization began earlier in the Old World than in other parts of the globe, so it is there that its negative effects, in particular the growth of greenhouse gas emissions from energy, industry, and transport, have first manifested themselves. The climate agenda is often given exaggerated importance, which means that it is given such an excessive attention that it can overshadow other equally urgent problems of the current stage of human development.

In its most radical, and therefore highly politicized, version, the current energy transition is seen by many, and, alas, not only in Europe, as a rejection of the use of NRER and a transition to the widest possible, if not exclusive, use of RES. The politicization of debate leads to the politicization of climate models. This approach is telling of an unexecting perception of the STP, which provides an opportunity to reduce emissions through the improvement and application of new technologies of production and use (through the whole value chain) of NRER. Thus, there is an artificial (deliberate?) narrowing of the zone of the search for optimal solutions to ensure low-emission development, including the use of NRER, but on a new – low-emission – technological basis.

After the cumulative effects of the world economy's response to the oil price surge of the 1970s came into action, the demand curve for primary and end-use energy began to flatten as a result of the broken correlation between energy consumption and economic growth. As a result, there has been an expansion of supply on the one hand, and a restraint on the growth of energy demand on the other. There was an objectively determined transition from anticipation of "peak supply" to anticipation of "peak demand".

Under these conditions, an additional man-made demand restriction has emerged in the form of the "Paris Agreement," whose stated goal is to fight for climate protection by reducing greenhouse gas emissions, and thus to impose targeted restrictions on conventional global energy development on the basis of NRER. It is generally accepted by many that such energy is the main human-induced pollutant. Therefore, the fight for the climate made it the top priority. More precisely, its rejection.

Before the Paris Agreement, it were economic factors that dominated, which worked within the expanding set of NRER/RES and led to a redistribution of competitive market shares between different NRER/RES, their "economic substitution" was taking place. The Paris Agreement factor introduced a new dimension that became the dominant criterion of preference over the economic one – the climate or "carbon footprint" dimension (cumulative emissions along the entire value chain, thus it would be more correct – terminology does matter – to speak not about "carbon footprint" but about "GHG emissions footprint").

Hence the surge of attention to RES as sources of not only "electrons" – renewable electricity, but also "molecules" – decarbonized gases, primarily so-called "renewable" hydrogen (H_2), produced by electrolysis of water using RES electricity. This has brought to a new level the issues of competition between NRER and RES, where the key question is how to correctly calculate emissions and the length of value chains taken into account in these calculations.

The experience of previous energy transitions and, more generally, the patterns of the evolution of energy markets show that there can be no complete replacement of the conventional energy resources that form the existing structure of the energy balance by a new energy carrier, introduced for one reason or another into the economic turnover. Each successive dominant energy resource occupied a smaller share of the energy balance than its dominant predecessor because substitution of incumbent energy sources by the new ones has been done not on "instead of" but on "in addition to" basis. There is a kind of "equalization" of the competitive shares of "new" and "incumbent" energy resources in consumption: each eventually finds its optimal competitive niche (which can be distorted in favour this or that energy by non-technologically-neutral state regulation providing preferences to this or that energy for whatever reasons). That is, we cannot consider any new energy resource as a possible universal solution or the next dominant energy source (whether RES or H_2 obtained from them).

There will continue to be another redistribution of competitive niches between "incumbent" (in this case, various types of NRER, including nuclear energy, and conventional RES, such as hydropower) and "new" energy resources (solar, wind, and other "new" RES that appear exotic today, hydrogen, and, perhaps, even energy sources unknown today) taking into account new, additionally introduced criteria and man-made restrictions (in this case, under the framework of the climate agenda – such as the "emission footprint", etc.) and the achievements of the STP in response to these new man-made (and, apparently, not final) restrictions (next, this author supposes, could be the "water intensity" of material production).

IV. EU: Hydrogen, "renewable" and that obtained from natural gas, and "technological neutrality"

At first, as the universal solution for the future of energy under the framework of its decarbonization policy in the EU, they envisioned a 100% electrification based on renewable energy under "digital, electrical, renewable" EU future energy vision. In January 2018 this vision was publicly reformulated to "RES electricity plus decarbonized gases". I called this EU energy policy maneuvre/adaptation a "Borchardt turn" – by the name of the then Deputy Director General of Energy Directorate (DG ENERGY) of the European Commission Klaus-Dieter Borchardt who has first announced this is his interview to Florence School of Regulation [12]. This opened a window of opportunities for the search for a new balance of interests between Russia and the EU in the energy and, in particular, in the gas sector based on the low-emission agenda. Among the main "decarbonized gases" and, perhaps, the key one in the EU is considered to be hydrogen. At the same time, despite the declared adherence to the principles of "technological neutrality" in its energy regulation, in the EU there is clearly an unconcealed preference for "green" or (which means the same in the EU) "renewable" H_2, that is, the one obtained through electrolysis of water using RES electricity, which is considered to be as if the only "clean" one in the EU. This is clearly prescribed in the EU

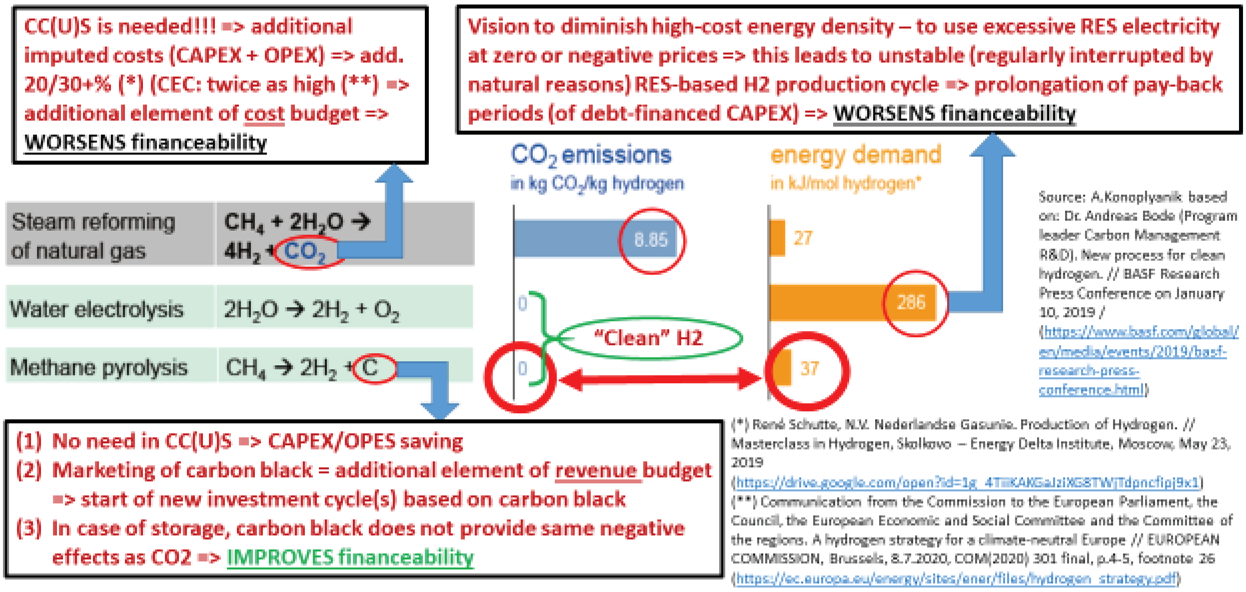

Fig. 2. All other conditions being equal, methane pyrolysis (& similar technologies) have clear competitive advantages against two other key technologies in hydrogen production (MSR+CCS & electrolysis) under technologically neutral regulation.

Hydrogen Strategy [13].

However, there are both obvious disadvantages of "renewable" H_2, and the comparative advantages of H_2 produced from natural gas, both by steam methane reforming (SMR) with the mandatory use of CCUS technology (carbon capture and sequestration and/or commercial use of CO_2 obtained when using the SMR), and methane pyrolysis, in which process CO_2 is not produced (see Fig. 2).

However, at the political level, it is actually already predetermined (as part of the EU Green New Deal unveiled by the European Commission in 2019) that this renewable H_2 is the designated desirable choice in the decarbonization policy. Other technologies of H_2 production are either allowed as temporary companions (unwelcome but involuntary) within the framework of the energy transition for the next ten years or so – until 2030 (SMR + CCUS), or almost (de facto) ignored altogether on one pretext or another (pyrolysis-based group of technologies for obtaining H_2 without CO_2 emissions from natural gas). On this basis a new long-term energy policy of the EU is being built, including in the external economic area, that is, in the relationship with major foreign trade partners. And this transition to "green" ("renewable") H_2 is not only not based on the balance of interests of EU energy consumers and energy suppliers inside and outside the EU, but it is (explicitly or implicitly) imposed on the EU community and its foreign trade partners as the only correct (the only possible) scenario of a hydrogen economy, despite many issues that remain open, questionable, controversial.

However, both within and outside the EU, it is de facto recognized that many aspects of the transition to a hydrogen economy based on "green"/"renewable" H_2 (with respect to its unconditional superiority and priority of such H_2-related decisions, including politically predetermined ones, which have already been taken) are still not elaborated enough. Moreover, much of the hydrogen topic is essentially hype (hard-sell advertising). This is, in fact, acknowledged in the European Commission itself [14] and as part of various high-profile events [15]. There are also more radical views on the current European euphoria regarding the H_2 and its causes, and coming from amongst the professionals. For example, Samuel Furfari, a professional chemical engineer who has worked for 36 years at the European Commission and has spent his entire career in the field of energy and emissions reduction, believes that the "hydrogen illusion" (which is the unambiguous title of his book) that has gripped Europe is among other things a wrong decision used to cover another mistake made earlier – reliance on the advanced development of unstable energy production based on RES. The author believes that the movement along this dead-end path has begun only because it is politically correct, is on-trend, and is secured by money that can be spent on it [16].

"Green" ("renewable") H_2 remains much more expensive than both "blue" H_2 and natural gas (see Fig. 3). Despite the ambiguity of any current estimates (based on different and often unknown assumptions) of the costs of producing H_2 in different countries and their delivery to places of consumption, and the inappropriateness of direct comparisons of such estimates, the gap between the cost levels (order of magnitude of numbers) today is sufficient to assert the absolute economic inefficiency of using technologies for producing "renewable" H_2 as compared to obtaining H_2 from natural gas, and hydrogen technologies – as compared to gas technologies, based on the degree of maturity (commercialization) of these technologies and the price of the energy resource used. And the steps that

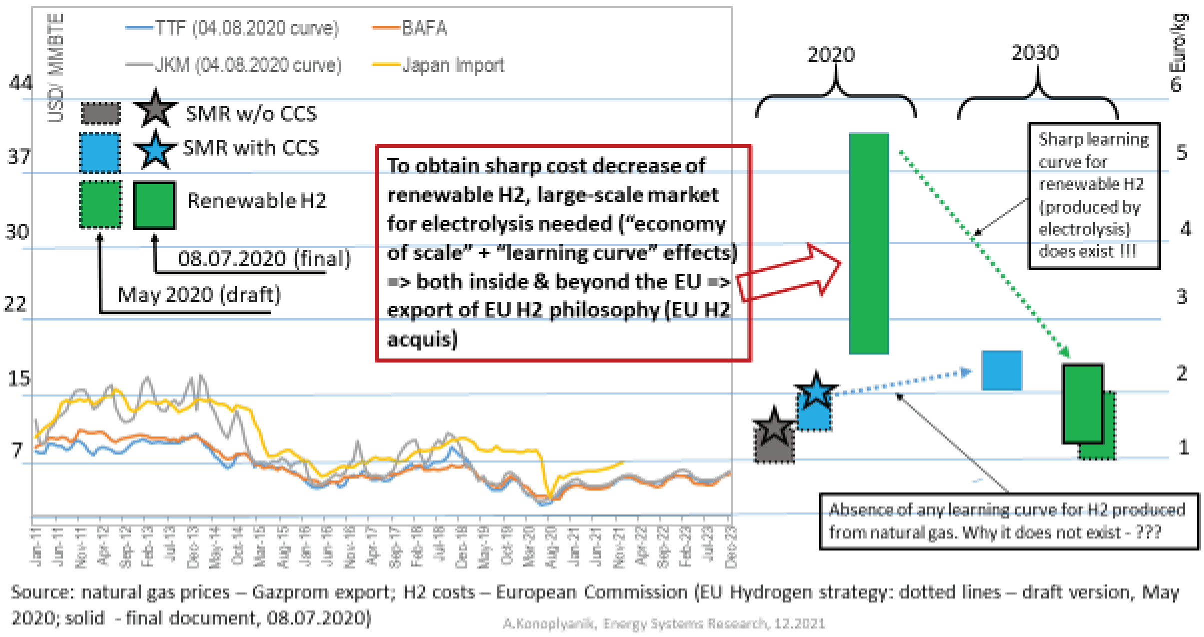

Fig. 3. European Commission's estimated costs of H_2 production by the key technologies (as presented in the EU Hydrogen Strategy as of 08.08.2020) – and natural gas prices.

followed could be characterized by the proverbial "destroy your competitor" and "it does not matter how they voted, it is important how we counted".

This author was unable to get a coherent explanation in the sources of information available to him, or in conversations with European experts (from companies, universities, the European Commission), that would warrant the fact that it is expected (and included in the EU Hydrogen Strategy [13]) to have such a sharp decline in the cost of producing "green" H_2 by 2030, given that the main component of these costs is the price of purchased electricity.

It is clear, and it was repeatedly stated, that the bet is on the purchase of excess RES electricity (otherwise this H_2 ceases to be "green" and "renewable") at zero or negative prices when it is too much sun and/or wind above the demand electricity curve. But in 2019, for example in Germany, the duration of the period of negative prices was only 211 hours of 24 × 365 = 8 760 hours of their annual balance, that is, the electrolyzer will run on excess RES electricity only 2.5% of the time [17, p. 6]. This may explain the prohibitively high production costs of "green" H_2, but it fails to explain why they should fall.

It is also unclear why the European Commission's projections use a "learning curve" for estimating the costs of producing "renewable" H_2, and a steeply declining one for that matter, while for H_2 from natural gas (and the European Commission persists in considering only the SMR+CCUS bundle, continuing to ignore the more economically viable methane pyrolysis), by contrast, it presupposes the rising costs of production of "blue" H_2. In this author's opinion, the remarks that gas prices will grow in the long term (let us leave aside the inevitable market deviations from the trend that take place under any long-term dynamics) are unfounded. In the transition to a supply surplus (the result of the predicted "peak demand" for NRER) instead of the "Hotelling theorem", which ensures that the producer gains the "Hotelling rent" in the case of a supply shortage (due to price equalization with the more expensive substitute energy resource as a benchmark), gas-to-gas competition begins to take place in the market, leading to lower prices. Open questions remain about the price of produced H_2 at the consumer end (by adding the cost of its transport and taxes through the whole hydrogen chain, and what kind of technology is to be used), etc.

There is an overemphasis on H_2 in general and on "green" H_2 in particular, it is overrated as a possible universal solution to the decarbonization problem, which it, in principle, cannot be and will not be – there is no one single "silver bullet". Unrealistic expectations, as we know, can only lead to bigger disappointments in the end. And if the unrealistic expectations regarding H_2 in general and "green" H_2, in particular, are the basis for long-term capital-intensive investment decisions (and there can be no other in this area by definition), the disappointments in the end will be not only and not so much emotional. Much more important will be long-term economic consequences in the form of direct and indirect damage to the EU economy, and – more importantly – to the economy of my own country Russia. Therefore, in order to avoid all sorts of disappointments, to avoid building the country's long-term energy policy on the basis of imported unrealistic or, worse, incorrect expectations related to H_2, it seems necessary to look more carefully and critically at the key arguments regarding H_2 and scenarios of hydrogen cooperation of Russia primarily with the EU.

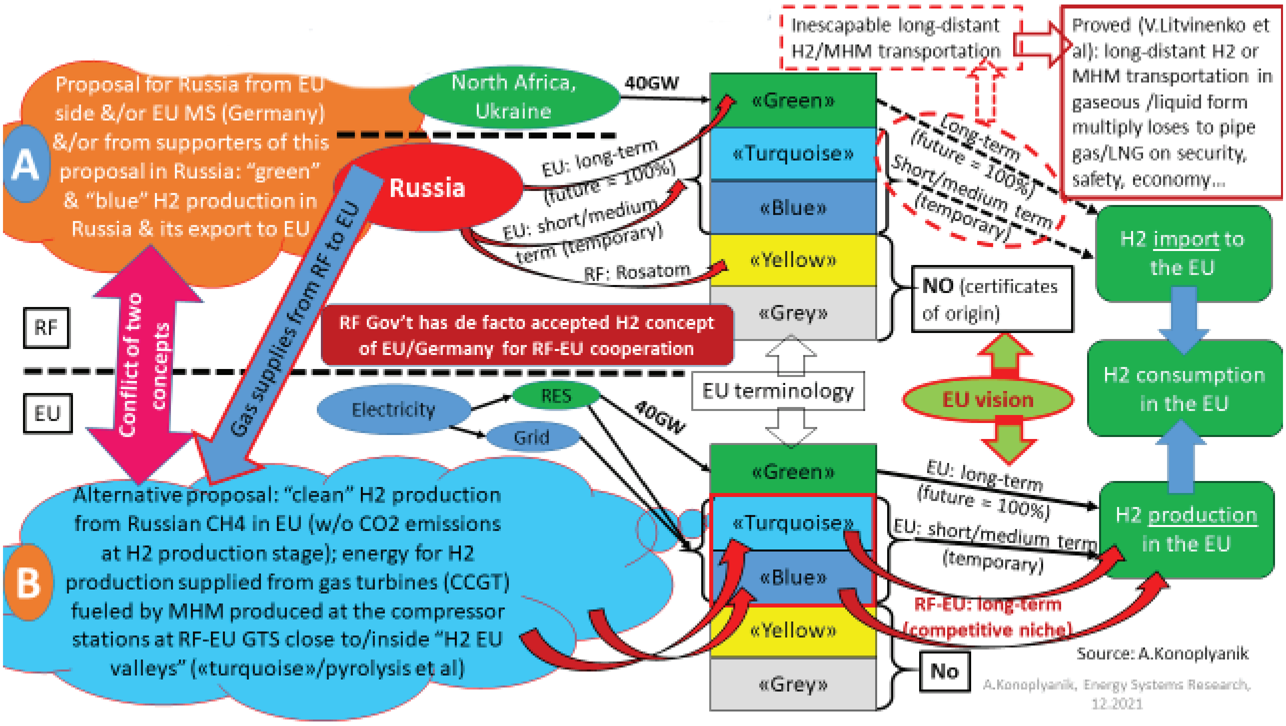

Fig. 4. Russia-EU cooperation prospects in H_2 area as seen by different parties: alternatives for H_2 supply to the EU.

The development of hydrogen technology in Russia will not be able to quickly create sufficient domestic demand for H_2 so as to make it competitive with other energy resources. This author believes that his country is not ready for this today, primarily because of its socio-economic parameters. Therefore, the development of such technologies (considered as zero- or low-emission) as one of the key areas of curbing the growth of global temperature, in this author's opinion, for Russia is not as a priority state task as is for many foreign countries characterized by both higher values of per capita GDP and higher, compared to Russia, levels of energy efficiency in all segments of energy value chains.

So, there is no point in counting on intensive development of hydrogen competences, their rapid scaling based on domestic demand for H_2 (economy of scale and learning curve effect), growth of their not only national but also global competitiveness through the domestic market. But it is also counterproductive to withdraw from global technological competition in this area. Therefore, the initial impetus for the development of hydrogen energy (as one of the components of the country's low-carbon development) should come from the external economic area, using the stated desire of our main trade and investment partners to decarbonize, including the gas industry.

And here is where the point of divergence arises: how to build such external economic cooperation. Which model to use: the one offered by our Western partners (the EU, in particular, Germany), which is also advocated by many domestic "experts" and which the Russian Ministry of Energy and the Russian Government seem to intend to follow (judging by the newly adopted Hydrogen Concept of the country [18]), or an alternative model?

V. The EU-Germany concept of hydrogen cooperation with Russia

Adopted in 2019, the European Green Deal aims to achieve carbon neutrality of the EU by 2050, relying on the development of RES and decarbonized gases, primarily H_2. At the same time in the "Hydrogen Strategy of the EU" of July 8, 2020 [13] the emphasis is made on "renewable" ("green") H_2, produced by methods of electrolysis of water using RES electricity. However, the EU recognizes that the projected volumes of "renewable" H_2 produced domestically by 2050 will not be enough to achieve the zero-emission goal. Therefore, imports of H_2 and its production from natural gas are allowed. The latter is to be achieved exclusively by SMR with the mandatory use of CCUS. There is some tough rhetoric on H_2 from natural gas as only a temporary (unwanted, but necessary) companion to "renewable" H_2.

To make "renewable" H_2 in the EU as cost-effective as possible, European equipment manufacturers need to have a large-scale market for high-unit-capacity electrolyzers both inside and outside the EU. The concept of cooperation with neighboring countries on hydrogen, promoted by the EU, its member states (Germany) and their business associations (the Russian-German Chamber of Foreign Trade [19–21]) is aimed at this. The EU (primarily Germany) proposes to build cooperation on the basis of the development of H_2 production inside Russia and its exports – in pure form or as a methane and hydrogen blend (MHB) to the EU.

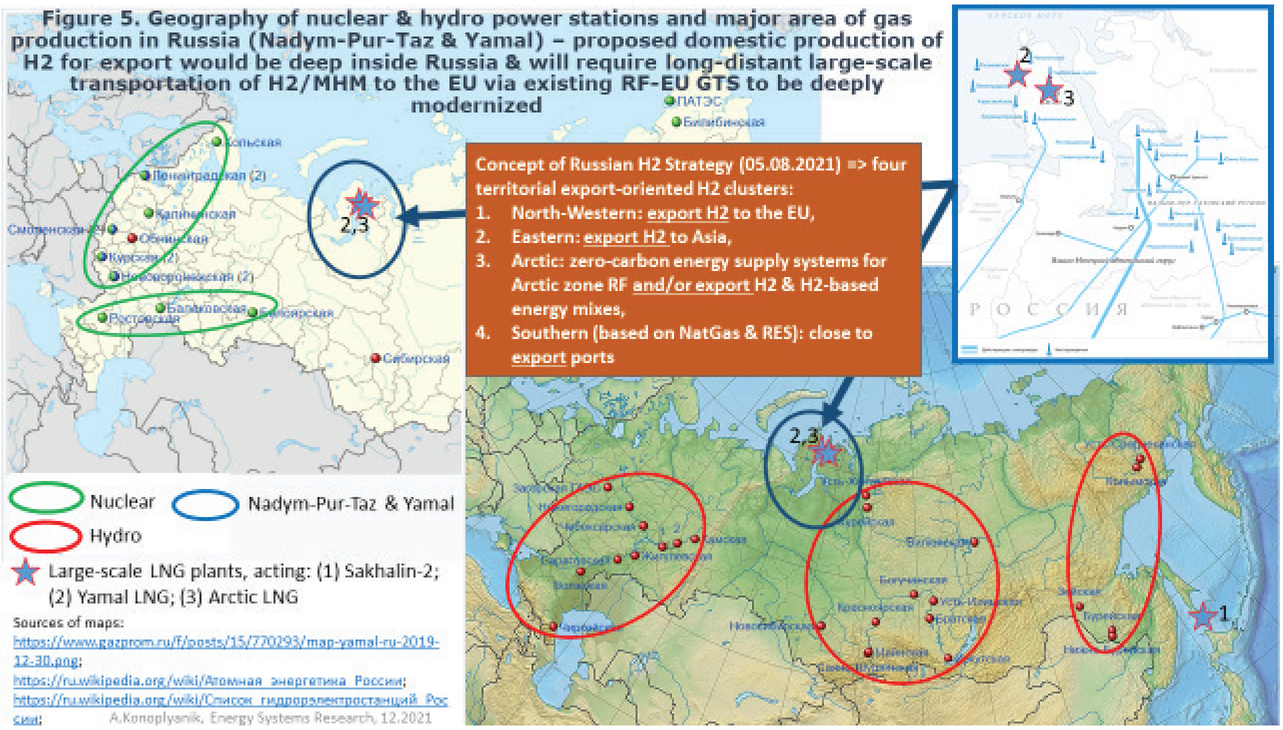

Fig. 5. Geography of nuclear & hydro power stations and major area of gas production in Russia (Nadym-Pur-Taz & Yamal) – proposed domestic production of H_2 for export would be deep inside Russia & will require long-distant large-scale transportation of H_2/MHM to the EU via existing RF-EU GTS to be deeply modernized.

It is proposed to produce H_2 by electrolysis on the basis of excess capacities of Russian hydro power stations (HPPs) and nuclear power stations (NPPs), and by SMR (with CCUS technology) on the basis of Russian gas fields in the main gas production regions (Nadym-Pur-Taz, Yamal) and to inject CO_2 into pay zones of oil fields in Western Siberia to increase oil recovery. Given the location of the proposed H_2 production facilities in the interior of Russia (see Fig. 5), this predetermines the long-distance pipeline transport and deep modernization to make it suitable for H_2/MHB, and in fact complete replacement of the existing cross-border gas transportation system (GTS) Russia-EU throughout its many thousands of kilometers of diversified length.

The main beneficiaries of such a decision will be the European machine-manufacturing industries. First of all, the German electrolyzer manufacturing industry. It needs a thick sales market to reduce unit costs (economies of scale). Within Europe this market is limited. So neighboring countries should be encouraged to produce "renewable" H_2 at home (based on electrolyzers labeled "Made in Germany") and transport it to Europe from there. To support this international model of hydrogen cooperation, the Federal Republic of Germany has allocated 2 billion euros in its national hydrogen strategy [22, p. 3]. It is directly mentioned in the German National Hydrogen Strategy, that among its goals and ambitions are: "Developing a domestic market for hydrogen technology in Germany, paving the way for imports", "Enhancing transport and distribution infrastructure", and especially "Strengthening German industry and securing global market opportunities for German firms", and for this "Establishing international markets and cooperation for hydrogen", "Building up and securing the quality assurance infrastructure for hydrogen production, transport, storage and use, and building trust" and "Regarding global cooperation as an opportunity" [22, pp. 5–7]. Such a model (production of "renewable" hydrogen abroad and importing it from there in the form of H_2, MHB or ammonia) is promoted by Germany with respect to Russia and other countries, such as Saudi Arabia (the German industrial giant Thyssenkrupp is to become the supplier of 20 MW electrolyzers for this \$5 billion initiative) [23], Morocco [24], some other African states [25]. This model underpins the EU Hydrogen Strategy, which explicitly mentions three regions – North Africa, the Western Balkans, and Ukraine within the framework of the EU Southern and Eastern Neighborhood Policy [13].

Such an external economic concept is completely in line with the national interests of the EU and individual EU countries and is completely, in this author's opinion, contrary to the national interests of Russia.

VI. Hydrogen cooperation with the EU: mutually exclusive Russian approaches

However, some Russian "experts" voice their support for the EU/Germany vision of establishing hydrogen cooperation with Russia, almost in unison with that for the hydrogen philosophy of Germany (June 2020 [22]) and the EU (July 2020 [13]). Moreover, in this very direction,

Export, mln tonnes	2024 г.	2025 г.	2030 г.	2035 г.	2050 г.
(1) Russian Energy Strategy (June 2020)	0.2			2	-
(2) Governmental Road Map (October 2020)	-			-	-
(3) Draft Concept Russian Hydrogen Energy Development (April 2021)	0.2-1.0		-	2-7	7.9-33.4
(4) Yu.Dobrovolsky(*) («We with Minenergo... acc. to conservative forecast») (O&GV, June 2021)	-	2-3	20-30 & more	-	-
(5) Concept of Russian Hydrogen Energy Development (August 2021)	0.2-1.0			2-12	15-50

Risk of counterproductive decision to inject H2/MHM into acting GTS for export to EU

16 Mt in 2031 in RF MinPromTorg Atlas

Fig. 6. Russian Ministry of Energy/Government: increasingly ambitious bet on hydrogen exports, but the issue of getting it to export markets is technically unsolved, and the solutions voiced by "experts" are counterproductive, unprofessional, and ruinous...

which is counterproductive for Russia, in this author's opinion, the vector of hydrogen energy development has already been formed, which was first unambiguously outlined in the hydrogen section of Russia's Energy Strategy as of June 2020. It says that "an indicator of the solution to the hydrogen energy problem is the export of hydrogen" [26, p. 47]. And later the focus on H_2 exports was strengthened in the Concept of Hydrogen Strategy of the country approved by the Russian government in August 2021 [18]. This explicitly stated the plans for domestic export-oriented H_2 production in the four planned "territorial export-oriented hydrogen clusters" (see Fig. 5) which thus predetermines (and this is how it is explicitly understood in public in Russia and internationally) long-distance transport of H_2 or MHB abroad. And the plans for H_2 exports become more and more ambitious with each revision of the government document without any obvious reason or explanation: from Energy Strategy (June 2020) [26, p. 47] – to the draft Hydrogen Strategy (April 2021 [27, slide 7]) – to the approved Concept of Hydrogen Strategy (August 2021) [18, paragraph 26] (see Fig. 6). Despite the fact that the same source [18, paragraph18] says that "the technologies of transport and storage of H_2 currently used, haven't been tested enough in the industry, have unsatisfactory technical and economic performance, and lead to a significant increase in the cost of H_2".

Nevertheless, many "experts" look at the problem of H_2 transport differently. A.B. Chubais, Special Representative of the President of Russia for relations with international organizations for achieving sustainable development goals, publicly stated three times during June-July 2021 [28–30] that "Russia is able to set the goal of maintaining the status of a "great energy power" with the substitution of hydrocarbon exports with H_2 exports. There is a figure in the European Hydrogen Strategy: in 2030 the H_2 market volume in Europe is 10 million tons. Europe says frankly: this entire volume cannot be generated in Europe alone. We need imports. Its volume is up to about 50%." That means 5 million tons. And now the figures for "potential" Russian H_2 export for 2030 have been increased from about 1.5 million tons in the Hydrogen Section of the Energy Strategy of Russia [26, p. 47] to 4 million tons in the draft [27, slide 7] and to 6.5 million tons (although at maximum) in the Concept of Hydrogen Strategy of Russia [18, paragraph 26] (see Fig. 6). This is more than enough, according to the final document, to cover the entire volume of H_2 imports required by Europe.

Moreover, Chubais urges "to hurry up and not to lose this race to Ukraine", explaining that (July 7) "Mrs. Merkel will pay an official visit to the US in ten days to discuss with Biden the issue of large German-American investments in Ukraine to build a mega-project on renewable energy. The goal is to produce hydrogen and export it to Germany" [31].

So, the bet on H_2 exports to Europe is made, and it seems that the race to get ahead of potential competitors, real and/or imaginary, may begin (is beginning?). How to make this bet pay off? The answer for the authors is obvious: to produce H_2 in Russia (first of all "green" H_2 produced by electrolysis but it can also be "blue" produced from natural gas) and transport it to the EU through the existing GTS. A.B. Chubais has repeatedly stated: "Experts unanimously say: the existing unified GTS is suitable for using at least 10% of the throughput capacity for H_2 transport. Without a deep modernization of the GTS" [28].

A number of experts, mostly "political scientists", suggest converting Nord Stream 2 to H_2 or MHB transport first, and then, perhaps, build the third or then, perhaps, even the fourth Nord Stream for H_2 (for example, a series of publications by V.B. Belov, Deputy Director of the Institute of Europe of the Russian Academy of Sciences, specialist in German issues [32–34]). Others (e.g., V.A. Karasevich and I.G. Rodichkin) believe that "blending 5–10% of H_2 with methane will lead to a positive image effect for the pipeline "Nord Stream 2", caused, in particular, by a lower carbon footprint of MHB in comparison with methane" [35]. And some "experts on the subject" fail to see any difference between transporting H_2 and methane. According to E.A. Telegina, a corresponding member of the RAS and the dean of the International energy business department of Gubkin Russian State University of Oil and Gas, "the gas transport infrastructure can be easily adapted for hydrogen transport ... Nord Stream 2, the current system, can be quite easily transformed for hydrogen transport ... the transport infrastructure can be easily transformed technologically, because it is the same gas under pressure, which flows through pipeline systems" [36].

However, it has been convincingly proved that long-distance transport and storage of H_2/MHB in gaseous or liquefied form due to objective physical and chemical reasons and unresolved engineering problems is by a wide margin inferior in reliability, safety, and economic feasibility to long-distance transport and storage of natural gas in gaseous form or as LNG. This author asserts (together with the experts he knows, including those from the Mining University in St. Petersburg (SPb), Gazprom, specialized technical – not "political" – institutes of the Russian Academy of Sciences, etc.) that long-distance transportation of H_2 or MHB via the current RF-EU GTS is counterproductive if compared to the transport of pipeline gas.

As a chemical element, H_2 is the enemy of steel structures (stress corrosion, hydrogen embrittlement). The physical and volumetric characteristics of H_2 reduce the overall efficiency of the energy system compared to similar hydrocarbon solutions. The energy derived from the same volume of H_2 is 3.5 times less than from methane. And the efficiency of pipeline gas transport depends directly on the volume of the product, hence the density of the gas. The work of V.S. Litvinenko and colleagues (Mining University of St. Petersburg) [37] shows that with an increase in the volume fraction of H_2 from 10 to 90% the density of MHB decreases more than fourfold. In this case, the energy needed to compress the mixture increases by a factor of 8.5 if this fraction in the MHB is increased from zero to 100%. The current GTS can technically handle 10% of H_2, but this will lead to disastrous consequences for the country with respect to its deep technical modernization (both line pipes and compressor equipment), disruption of technical integrity, and contractual issues.

According to colleagues from "Gazprom vodorod" ("Gazprom Hydrogen"), the dilution of an expensive product (H_2) in a cheaper gas does not form the optimal business model, because it is not clear how then to monetize the delivered product (MHB), because one needs to build facilities for the separation of H_2 (membranes, etc.) at the place of its delivery to the consumer, commensurate in cost with the production of H_2 directly at the place of consumption. Moreover, it is unclear why one should reduce the price of a premium product (H_2) by diluting it with a cheaper one (natural gas). Moreover, an assessment of the emission footprint along the entire value chain shows that the use of the blend does not contribute much to the reduction of emissions, i.e., 10% of H_2 in the MHB will do nothing of consequence in terms of achieving the EU climate goals.

Such a "modernization" of the existing GTS to adapt it for H_2 could be comparable in scale to the cost of the U.S. Strategic Defense Initiative (SDI) threat countermeasures in the USSR in the 1980s and its ruinous consequences for the country. As is known, the U.S. SDI ended up being a well-organized disinformation campaign, but the costs of countering it were ultimately beyond the means of a country already overburdened with debt and unaffordable internal costs and only accelerated, in this author's view, the destruction of the USSR economically.

VII. Energy transition driven by half-truths

The actual support by a number of Russian experts for the hydrogen concepts of Germany and the EU, in this author's opinion, fails to take into account the fact that the latter are built on half-truths. The decarbonization of the European economy is accompanied by a deliberate distortion of the frame of reference within which the public consciousness in the EU is formed and the relevant political directives are adopted. Which are then enshrined in legislation and set the direction for long-term capital-intensive investment decisions that define the framework for development for many years. One of the significant distortions is the comparison of the CO_2 emissions of NRER industries and the cleanest of them (natural gas) to the same of RES.

In the EU, natural gas is considered to be a bad solution for the energy transition in principle, because it contains carbon (C) molecules, which as is inevitably (at any rate) turn into molecules of climate-damaging (harmful) CO_2. This approach, however, denies the very nature of the STP, which can both help reduce CO_2 emissions to a level acceptable and comparable with that of other advanced technologies (again, the question is how to count emissions) and find technological solutions to prevent CO_2 from forming. One such solution is the use of pyrolysis technologies to produce H_2 from natural gas in the absence of oxygen and, therefore, without CO_2 emissions. The EU Hydrogen Strategy, unfortunately, simply ignores such technologies: in its text the word "pyrolysis" occurs only twice, and, moreover, one time it is used incorrectly (for it seems to equates SMR+CCUS and pyrolysis, talking about incomplete – in both cases – utilization of CO_2 at the 90% level), while the second time it is mentioned in passing only [13, p. 4, 17].

On the other hand, it is argued that, unlike natural gas, renewables are clean – indeed, as if the only clean source of energy, because they do not emit greenhouse gases as part of their production cycles. Therefore, renewable H_2 produced using RES is also the only clean H_2. And this incorrect assumption is embedded in the EU Hydrogen Strategy – in the section "Definitions" [13, pp. 3–4] – as a kind of already established fact.

In the EU Hydrogen Strategy, when determining the so-called "carbon footprint" of RES and renewable H_2, material-intensive (and therefore energy-intensive, accompanied by increased CO_2 emissions) industries for the production of equipment for RES electricity generation

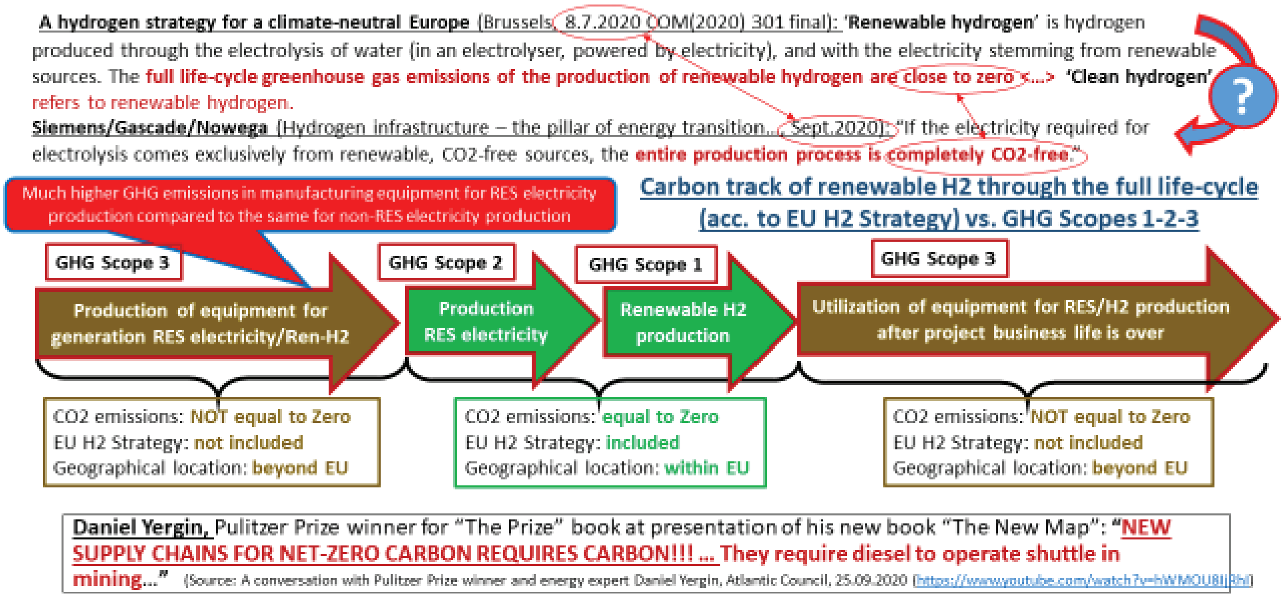

Fig. 7. What is clean energy? Depends on how you calculate/consider it… Wrong perceptions as if Ren-H_2 is the only clean H_2 and, moreover, that it is clean at all => Energy Transition based on semi-truth…

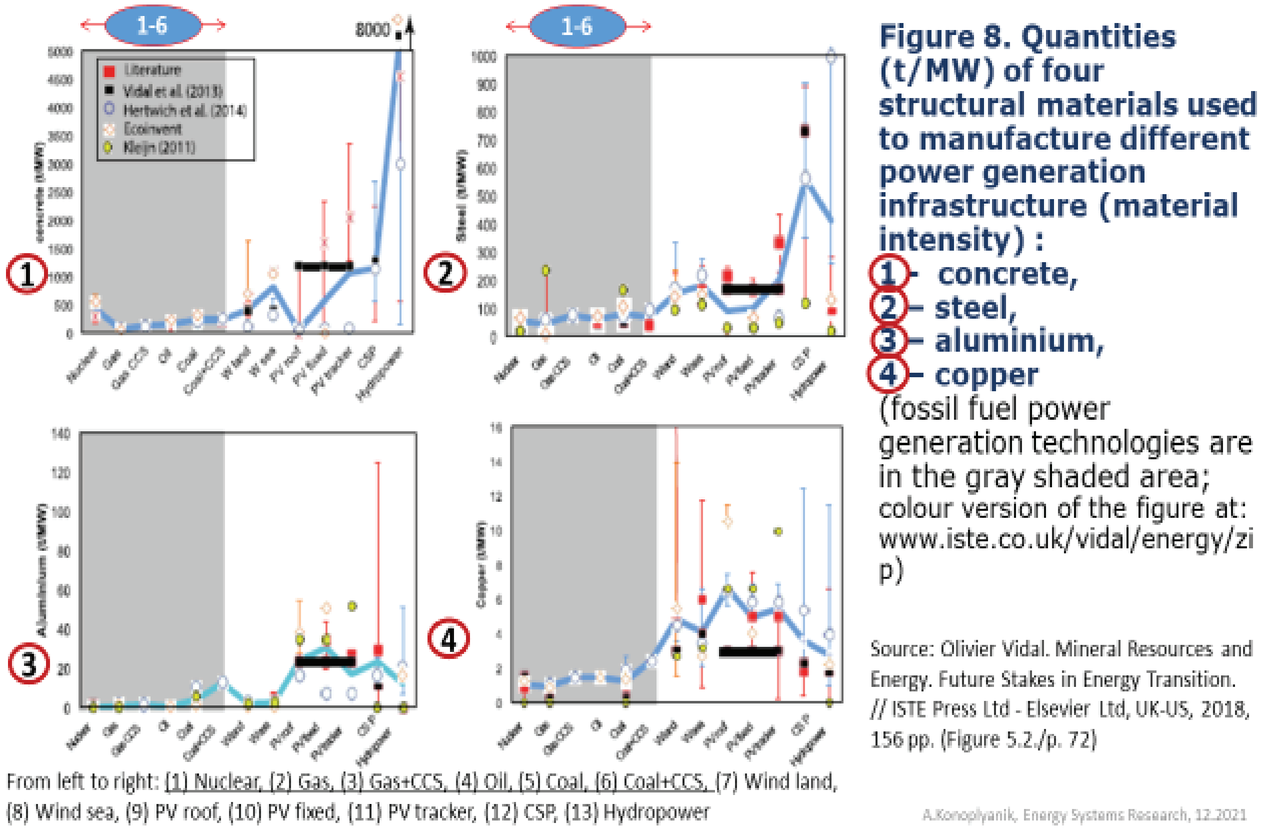

Fig. 8. Quantities (t/MW) of four structural materials used to manufacture different power generation infrastructure (material intensity): 1 – concrete, 2 – steel, 3 – aluminium, 4 – copper (fossil fuel power generation technologies are in the gray shaded area; colour version of the figure at: www.iste.co.uk/vidal/energy/zip).

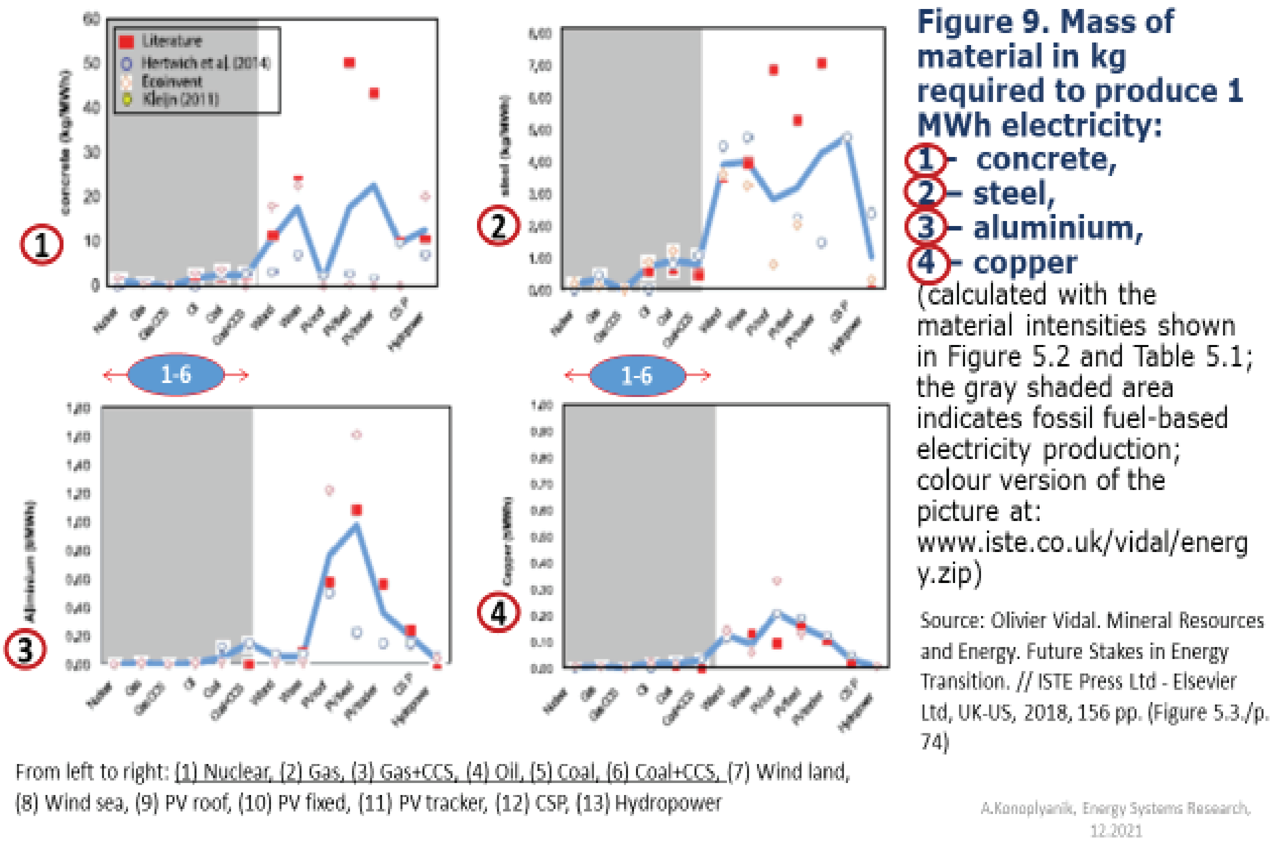

Fig. 9. Mass of material in kg required to produce 1 MWh electricity: 1 – concrete, 2 – steel, 3 – aluminium, 4 – copper (the gray shaded area indicates fossil fuel-based electricity production; colour version of the picture at: www.iste.co.uk/vidal/energy.zip).

are excluded from consideration. As well as production of equipment for H_2 production (electrolyzers) (see Fig. 7). This significantly changes the comparative picture of cumulative CO_2 emissions over the full production cycle of various H_2 production processes (electrolysis, SMR+CCUS, methane pyrolysis) as part of the EU policy decision-making system. At the same time, electrolysis is about 4–5 times (Gazprom data [38]) or even 10 times (BASF data [39]) more energy-intensive process than H_2 production from natural gas. Therefore, proportionally more electrolyzers and RES production capacity are needed (even more so given the low installed capacity utilization factor (ICUF) of RES in Europe: in Northern Germany the ICUF of wind turbines on land is 1 900 hours/year or 21%, and those sea-based – 4 500 hours or 51% [17, p. 6]). Therefore, the production of both types of capacities will be accompanied by higher emissions. And green, or renewable, H_2 ceases to be clean.

As Daniel Yergin, the Pulitzer Prize winner for “The Prize” book has said at the presentation of his new book “The New Map” at Atlantic Council in September 2020: “New supply chains for net-zero carbon requires carbon! They require diesel to operate shuttle in mining…” [40].

Thus, the environmental advantage of each energy source is determined by how the emissions are counted. If we consider only the direct CO_2 emissions from the production of renewable H_2 by electrolysis of water (the so-called “Scope 1” under greenhouse gas emissions and from the production of RES electricity (wind, solar, hydro) (“Scope 2”), then the environmental friendliness of these production processes must be recognized. If we also include the production of equipment for production of RES electricity and/or green H_2 (the first part of “Scope 3”), the picture changes drastically. Both RES electricity and renewable H_2 will cease to be emission-free. And this picture will change even more radically, and RES electricity and renewable H_2 will cease to be “emission-free” even more, if we also include the phase-out and disposal of equipment after the end of the lifetime (life cycle) of the project (the second part of “Scope 3”) (see Fig. 7).

Failure to account for “Scope 3” emissions can significantly change the entire overall picture of emissions and, more importantly, accounting for them can turn (is turning?) all business processes built on so-called “zero-emissions” technologies into “non-zero emissions” ones. The example of Apple, which voluntarily made its data available to the public, shows that, as in the case of renewable H_2, Apple’s emissions under “Scopes 1 and 2” are close to zero. However, emissions under “Scope 3” are quite large, and within this group, the equipment manufacturing stage accounts for three-quarters of emissions of all three “Scopes” [41].

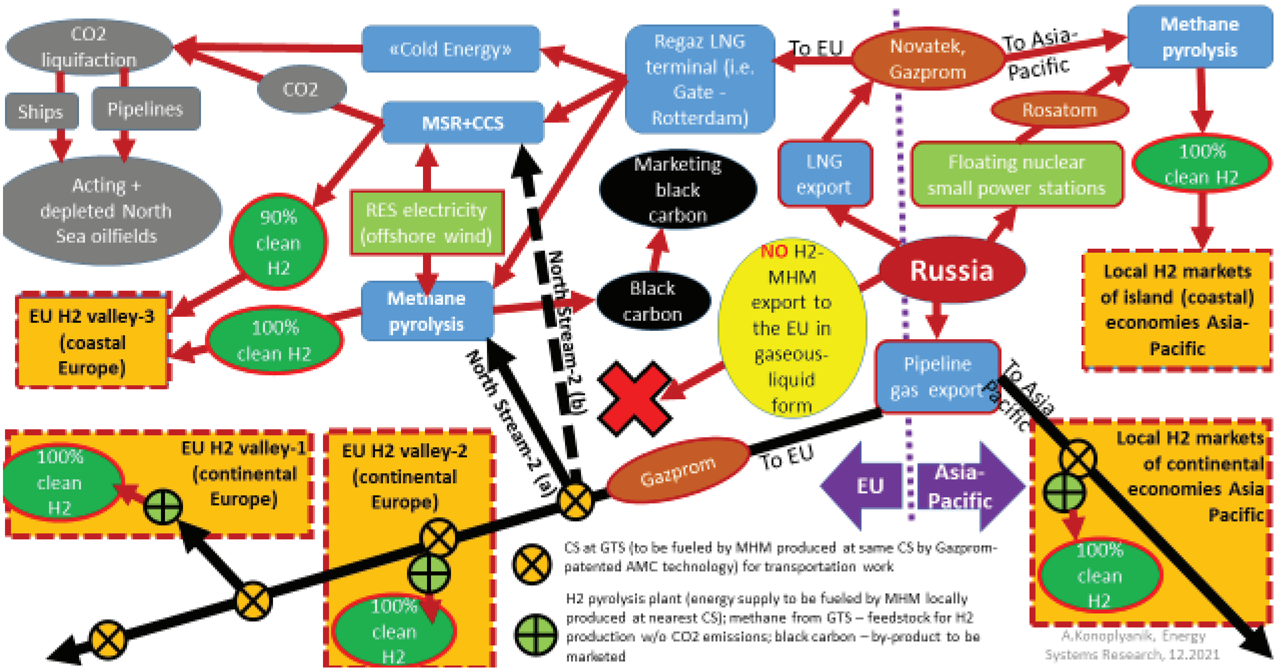

Fig. 10. Alternative concept for export-oriented segment of Russian hydrogen energy economy – based on clean H_2 (w/o direct CO_2 emission) from natural gas (Konoplyanik's vision).

A study by Olivier Vidal [42] summarizes data on four basic construction materials (cement, steel, copper, aluminum) and 13 power generation technologies (six of them based on NRER and seven based on RES). It shows many-fold excess of material inputs for all four materials in the production of equipment for electricity generation based on RES against the corresponding technologies based on NRER: both per unit of capacity (see Fig. 8) and per unit of electricity output (see Fig. 9). In the case of hydropower plants, for example, the consumption of cement per unit of power is just off the scale.

Thus, if backed by a valid scientific approach, green or renewable H_2, free of direct CO_2 emissions, ceases to be "the only clean" one (as declared in the EU Hydrogen Strategy [13]) in comparison with H_2 from natural gas, especially that produced by pyrolysis, on which Gazprom relies and in the production of which there are also no direct CO_2 emissions. However, a distorted frame of reference is used, alas, to justify the exclusive acceptability of specifically "green", or "renewable" (and significantly more expensive), H_2 as the only way to decarbonize the EU in the long-term (short-term "blue" H_2 is involuntarily allowed to accompany "green" H_2).

Therefore, in this author's opinion, the concept of the proposed hydrogen cooperation based on EU (or German) models is unacceptable for Russia, because it is built on half-truths and are not in line with the national (sovereign) interests of my country. In particular, those of the tasks of effective monetization of Russian natural gas resources and existing production assets, primarily the EU-Russia cross-border gas transportation system. Although, to reiterate, such a concept fully reflects the national interests of the EU, Germany, and the businesses of these countries.

VIII. The mutually acceptable alternative: this author's position

Is there an alternative that is built on a balance of the interests of the parties? I assert that there is one. On the basis of existing groundwork solutions, including those by Gazprom PJSC, this author proposes the following alternative concept for the development of EU-Russia cooperation in the hydrogen area [43–46]. It is based on the export of Russian natural gas to the EU both via the existing Russia-EU GTS and in the form of LNG, and the production of H_2 inside the EU in areas of advanced demand growth ("hydrogen valleys") by methane pyrolysis (or similar technologies for producing "clean" H_2 – without direct CO_2 emissions) throughout Europe and/or SMR+CCUS in coastal areas of Northwest Europe (see Fig. 10).

In the case of LNG deliveries to regasification terminals on the Northwest European coast, as well as pipeline gas deliveries via the Nord Stream pipelines, H_2 production at pyrolysis or SMR plants near gas delivery points can use RES electricity from offshore wind farms in the North Sea. CO_2 released in the course of the SMR process can be liquefied using the "cold energy" released during LNG regasification and then, as liquid CO_2, supplied by tankers or through pipelines running in the reverse direction for re-injection into pay zones of active oil fields and/or depleted deposits on the North Sea shelf. With H_2 production using methane pyrolysis methods and similar methods free of CO_2 emissions (the first such pilot plants are to appear in Russia by 2024 in accordance with the Plan "Development of Hydrogen Energy in the RF to 2024" [47]), opportunities for H_2 production from Russian natural gas are dramatically expanding in continental Europe.

In this case, the natural gas supplied via the EU-Russia GTS will be used for three purposes. First, traditionally, as an energy resource for performing transport operations. At compressor stations (CS) on the routes of Russian gas transport to the EU, methane will be converted into MHB (Gazprom's patented technology of adiabatic conversion of methane [48]), which will be used at the same CS as fuel gas (instead of methane) for further gas pumping through the network. According to Gazprom, this results in a one-third reduction in CO_2 emissions at the CS [48]. No transportation of MHB through the GTS will take place – production of MHB at the compressor station will be only in the volumes required for the CS's auxiliary needs. Secondly, as a feedstock to produce "clean" (with zero CO_2 emissions) H_2 from methane. This is a new niche for Russian gas with high potential demand in the European market. Pyrolysis plants should be located near CSs and aim to meet local demand (rather than common European demand, to minimize the need for long-distance transportation of hydrogen) within the nearest "hydrogen valleys" of the EU. This means that the development of commercial pyrolysis plants should be based on the modular principle of their use – the assembly of plants (as in a set of interlocking Lego pieces) with a capacity adequate to the level of demand for H_2 within a given "hydrogen valley". Third, as an energy resource for the production of "clean" H_2 from natural gas at these pyrolysis plants. Fuel for the gas turbines of the corresponding capacity will be MHB produced in the area of the nearest CS by the adiabatic conversion of methane technology.

In this author's opinion, this is a mutually acceptable option for cooperation between Russia and the EU in the field of hydrogen energy (in terms of production of "clean" H_2). This is a cheaper decarbonization option for the EU. And it provides additional monetization of the natural resources of Russian gas. This is the direction that it is necessary to continue to work in with colleagues from the EU. What we have already been doing within the framework of the EU-Russia Gas Advisory Council's Work Stream on Internal Market Issues [49].

The article reflects the author's personal point of view. Some of the article's points are presented in more detail in the author's papers [43–46 etc.] and are available from his website at www.konoplyanik.ru.

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