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Perspective

Flare gas monetization and greener hydrogen production via combination with cryptocurrency mining and carbon dioxide capture

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SUMMARY

In view of the continuous debates on the environmental impact of blockchain technologies, in particular, cryptocurrency mining, accompanied by severe carbon dioxide emissions, a technical solution has been considered assuming direct monetization of associated petroleum gas currently being flared. The proposed approach is based on the technology of low-temperature steam reforming of hydrocarbons, which allows flare gas conditioning toward the requirements for fuel for gas piston and gas turbine power plants. The generation of electricity directly at the oil field and its use for on-site cryptocurrency mining transform the process of wasteful flaring of valuable hydrocarbons into an economically attractive integrated processing of natural resources. The process is not carbon neutral and is not intended to compete with zero-emission technologies, but its combination with technologies for carbon dioxide capture and re-injection into the oil reservoir can both enhance the oil recovery and reduce carbon dioxide emissions into the atmosphere. The produced gas can be used for local transport needs, while the generated heat and electricity can be utilized for on-site food production and biological carbon dioxide capture in vertical greenhouse farms. The suggested approach allows a significant decrease in the carbon dioxide emissions at oil fields and, although it may seem paradoxically, on-site cryptocurrency mining actually may lead to a decrease in the carbon footprint. The amount of captured CO_2 could be transformed into CO_2 emission quotas, which can be spent for the production of virtually "blue" hydrogen by steam reforming of natural gas in locations where the CO_2 capture is technically impossible and/or unprofitable.

Since the 1980s, the ubiquitous transition from analog to digital technologies, called the Digital Revolution, produces a significant impact on many areas of life, including such inertial sphere as the electric power industry. Indeed, the increasing digitalization of the banking sector requires the commissioning of a large number of new data processing centers and additional power generating capacities to provide their functioning. Analysis of the growing computing capacities demand the mining of Bitcoin (Chapron, 2017; Extance, 2015; Nakamoto, 2008), one of the most popular and energy-consuming cryptocurrencies operated on proof-of-work principle, revealed a serious Bitcoin challenge for the power system (de Vries, 2018; Krause and Tolaymat, 2018). As of November 2018 estimates, the global annual Bitcoin electricity consumption added up to 46 TWh (Stoll et al., 2019). In 2019 (Digiconomist, 2019), the Bitcoin network consumed 77.8 TWh for processing transactions. In the published estimates of September 2019 (de Vries, 2019), the global annual Bitcoin energy consumption was expected at a level of 87.1 TWh that is comparable to the annual electricity consumption in some countries, such as Chile, Kazakhstan, or Belgium. The methodology of these assessments is being improved from year to year (de Vries et al., 2021; Gallersdörfer et al., 2020); a comprehensive overview of estimates over time is available as well (Lei et al., 2021).

Thus, a reasonable question arises: what sources can be used to generate so huge amounts of additional electricity? Obviously, in view of minimizing environmental impacts, it is necessary to develop this sector through the use of renewable energy sources: sun, wind, and water. It is believed that a large number of mining farms operate in territories with cheap electricity generated by hydroelectric and/or hydrothermal power plants (as in Iceland). However, renewable power generation typically fluctuates daily or seasonally,

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whereas mining farms operate 24/7 years-round. Analysis of available data on mining farm locations allowed the suggestion that a relatively large share of the used electricity is generated by coal-fired power plants. Accurate estimation of this share is hardly possible owing to the lack of reliable data on the number of Bitcoin network devices and their locations (Köhler and Pizzol, 2019). Even more difficult task is to estimate the CO_2 emissions associated with all currently known cryptocurrencies. The carbon footprint of world cryptocurrency mining in 2018 was estimated as 22 million tons (Mt) CO_2 (Stoll et al., 2019). According to other studies, annual CO_2 emissions from mining farms can reach much higher values: 37 (Digiconomist, 2019; Krause and Tolaymat, 2018; Stoll et al., 2019), 43.9 (de Vries, 2019), and even 69 Mt CO_2 (Köhler and Pizzol, 2019).

One of the ways to minimize cryptocurrency environmental impact is the construction of new power plants that generate electricity from renewable sources, following the increase in the number of commissioned mining farms. Another way is to generate electricity by recycling wastes from other industries that will allow at least keeping CO_2 emissions at the current level, or even decrease them owing to the development of economically attractive integration of cryptocurrency mining and CO_2 capture processes. There are a number of CO_2 utilization options under development, including chemical production processes (methanol, cyclic carbonates, and so forth.), biological transformation, and geological storage. The latter, being the most feasible now at a large scale, should be considered as a temporary solution, until other zero-emission technologies come around.

Currently, a growing shift toward hydrogen energy technologies occurs worldwide. However, it is hardly probable that people can abandon the use of traditional fossil fuels (oil and gas) in the coming decades. Most likely, their share in the energy sector will be gradually replaced by renewable energy sources, but oil and gas as a source of raw materials for the petrochemical industry producing plastics, polymers, lubricants, and so forth will obviously dominate in this market for many decades. Besides, oil and gas extraction industry itself releases a great amount of valuable wastes and by-products.

Flare hydrocarbon gas is among these waste types. On the one hand, flare gas (FG) is a highly valuable hydrocarbon feedstock. On the other hand, huge volumes (billions of cubic meters) of associated petroleum gas, separation gas from gas conditioning units, shale gas, and refinery gas are still subjected to torch flaring. Geographic and logistic restrictions, such as remote location, deficient transportation and processing infrastructures, significant capital, and operating costs make the qualified gas collection, processing, and useful utilization economically unfeasible. Thus, the oil and gas companies face a dilemma: to supply extremely expensive communications to each oilfield – highly risky investment, which may never pay off, or simply to flare the gas in torches. The latter option usually dominates. As reported in (Worldbank, 2019a), in 2018, the largest world oil companies flared together 145 billion cubic meters (BCM) of associated petroleum gas (APG) that corresponded to the emission of 350 Mt (million tons) of carbon dioxide. This value is 7-fold greater than the global carbon footprint of cryptomining. Note that the total flaring of APG by Russia, Iraq, Iran, the USA, Algeria, Venezuela, and Nigeria amounted to almost 100 BCM (Worldbank, 2019b).

In 2019, Russia's APG recovery amounted to ca. 94.1 BCM (Fuel Energy Complex of Russia, 2020a). Nearly 17–20 BCM of this volume was wasted in flares (Fuel Energy Complex of Russia, 2020a, Fuel Energy Complex of Russia, 2020b), because APG transportation to plants for processing into products with high added value appeared economically unprofitable. APG flaring is practiced mainly at small-, medium-scale, or depleted gas fields with the gas production volume below 0.05 BCM per year, which number is gradually growing in Western and Eastern Siberia.

In 2007, PFC Energy performed a study "Utilization of Russian Associated Petroleum Gas" inspired by the World Bank-managed Global Partnership to Reduce Flaring of Associated Petroleum Gas (Worldbank, 2007). According to this study, besides APG re-injection (for disposal or enhanced oil recovery), there is only one economically appropriate option for APG utilization at small-scale fields with annual productivity below 0,05 BCM – its on-site using for the decentralized generation of electricity and heat at small power plants for local needs and nearby settlements supply. None of the other considered ideas showed economical viability under any circumstances.

Electricity at oil and gas fields is usually generated using gas power plants (GPP). They are equipped with internal combustion engines designed to operate on fuel gas with a net calorific value not exceeding

34-36 MJ/m^3 and a methane number (MN) above 80. Hydrocarbon gases containing at least 80 vol % of methane with a net calorific value of 35.8 MJ/m^3 correspond to these characteristics. However, APG typically has a much higher net calorific value that ranges between 42 and 60 MJ/m^3 depending on the gas composition, and can hardly be used as a fuel directly.

Besides low methane number, high calorific value, and high Wobbe number, direct use of APG is complicated by its variable composition and consumption rate that cause unstable operation of GPP, and impose risks of detonation, overheating, cocking, and damage of the engine parts (such as pistons jamming or burnout, seat destruction, burnout of the exhaust valve edges, deformation of the cylinder head, coking of the piston rings). Supplying gas turbine power plants (GTPP) with an off-specification fuel gas leads to the destruction of the turbine blades. All these factors are responsible for reduced equipment life, frequent and costly overhauls, and increased emissions of pollutants into the atmosphere.

To minimize these harmful phenomena, an engine de-rating by 10–60% of its nominal power can be applied intentionally. The higher is the content of C_{2+} hydrocarbons in APG, the more problematic is its use as a fuel for power plants, and exactly this gas is usually sent to flaring. Significant modification of the GPP or GTPP designed for operation on natural gas, as well as individual adjustment of operation modes with account for variable APG composition appears unreasonable and unsuitable for solving the problems during long-term operation.

For these reasons, only the gases from the first separation stages and condensate weathering are used at gas and oil fields, while low-pressure gases from the final separation stage and condensate stabilization, which has a high content of C_{2+} hydrocarbons, are flared.

To promote useful and most complete utilization of APG (flare gases) at low-debit and remote oil and gas fields, a process of low-temperature steam reforming of hydrocarbons was proposed to produce methane-rich mixtures (Potemkin et al., 2020; Shigarov, 2020; Shigarov et al., 2022; Snytnikov et al., 2018; S.I. Uskov et al., 2020, 2019a, 2019b, 2017; Zyryanova et al., 2013a, 2013b, 2014. The total reaction of the process can be described as the following equation:

$$C_nH_{2n+2} + \frac{(n-1)}{2}H_2O \rightarrow \frac{(3n+1)}{4}CH_4 + \frac{(n-1)}{4}CO_2$$

CO and H_2, usually presented in small amounts in the products, can be formed by reversible CO methanation and CO water gas shift reactions:

$$CH_4 + H_2O \leftrightarrow 3H_2 + CO$$
$$CO + H_2O \leftrightarrow CO_2 + H_2$$

In contrast to adiabatic pre-reforming and conventional steam reforming conditions(Aasberg-Petersen et al., 2011; Christensen, 1996), the process of low-temperature steam reforming of APG to methane-rich gas is better to perform at temperatures not exceeding 370°C and at lower H_2O/C ratios (less than 2) in order to favor the thermodynamically highest methane and minimum hydrogen and carbon monoxide yields (Figure 1).

Systematic studies of the process were performed including laboratory experiments, field tests of bench units, and pilot testing. According to calculated and experimental data(Zyryanova et al., 2013a, 2013b), the process of low-temperature steam reforming turned initial gas mixtures of widely varied compositions (20–73 vol % of methane and 0 to 25 vol % of C_{2+}-hydrocarbons) into the output gas mixture of uniform composition. At 300 °C, the content of the main products in the output gas mixture was: 80 $\pm$ 5 vol.% CH_4, 15 $\pm$ 3 vol% CO_2, and 7 $\pm$ 3 vol% H_2. The initial gas mixtures have the methane number ranging within 33–55, and the Wobbe number often exceeds the specified value of 54.5 MJ/m^3 (that makes the power plants operation highly problematic). The converted gas mixture has the methane number above 90, and the Wobbe number and the net calorific value approaching the lower specified limits: 41.2 and 31.8 MJ/m^3, respectively, and can be used for the efficient operation of GPPs, GTPPs in the optimal mode without power de-rating and complex maintenance.

This technical solution demonstrates high economic efficiency, provides a lower level of capital and operating costs, allows significant flexibility of the operating modes depending on the obtained fuel gas

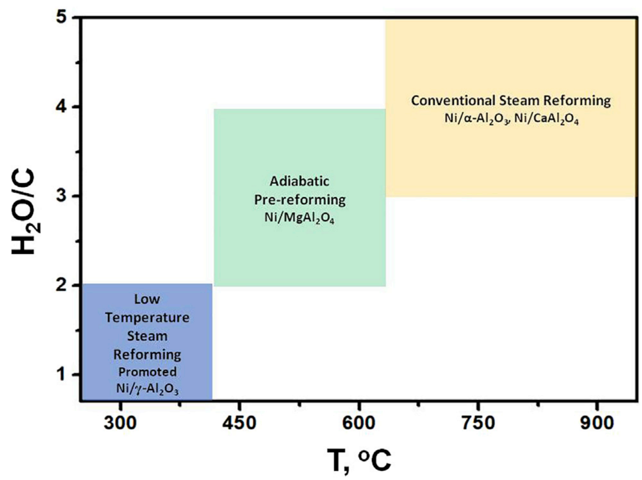

Figure 1. Reaction conditions of low-temperature steam reforming vs adiabatic pre-reforming and conventional steam reforming of natural gas

application, and ensures efficient and environmentally conscious operation of the oil and gas fields (Snytnikov et al., 2018).

Nevertheless, despite the advantages of the proposed technology, oil and gas companies still suspend their practical introduction. The reason is familiar—remote location of oil and gas fields, infrastructural underdevelopment of nearby territories, insufficient local market for consuming the whole generated electricity and heat. Indeed, the processing of 300 cubic meters of APG per hour (2.63 million cubic meters per year) by the method of low-temperature steam reforming produces a sufficient amount of fuel gas to supply a 1 MW GPP, whereas local electricity demand usually ranges within 150–200 kW. To utilize all generated electricity, it is necessary to construct tens to hundred of kilometers of power lines, which increases significantly the capital costs at remote oil and gas fields where the most extensive APG flaring takes place.

It seems that the only adequate solution to this problem consists in the direct monetization of generated electricity at the oil and gas field area through the installation of data processing centers. That is, the capital-intensive long-distance transmission of electricity is replaced by local consumption of all generated electricity for the on-site production of valuable information resources, for example, by mining cryptocurrency or solving complex mathematical or applied problems in the field of medicine, physics, chemistry, and biology. Moreover, the cold and sometimes extremely cold northern and arctic territories of the Russian Federation are best suited to ensure proper cooling of computing equipment.

Estimates on the basis of typical values of GPP and GTPP fuel consumption for electricity generation prove that the processing of entire APG flared volumes in Russia (about 20 BCM) can produce ~67 TWh of electricity per year (cumulative capacity of GPPs and GTPPs is 7.6 GW), which is close to the global energy consumption by the Bitcoin mining network. Based on the Bitcoin miners' hashrate, power consumption (ANTPOOL Web Page, 2021; de Vries, 2018), and the current values of mining rewards, it is expected that ~330,000 thousand BTC can be mined annually that corresponds to several ten billion USD at the current USD/BTC exchange rate. Assuming the processing of the entire volume of the gas flared globally, this sum increases by an order of magnitude and is estimated at several hundred billion USD.

Earlier, we have made economic estimates of APG conversion units working with gas power plants (Vernikovskaya et al., 2012a, 2012b; Zyryanova et al., 2013a, 2013b). In these estimates, we varied operating and capital costs, considered options for borrowed and own funds, leasing equipment, and selling electricity to a third-party consumer. Operating costs included the routine maintenance of the power complex, regulated preventive maintenance, and overhaul of the power plant units. The calculations assumed the construction of a power transmission line for supplying the generated electricity from the oil field to the network, which entailed a significant increase in capital costs. Taking into account that the usual lifetime of remote marginal oil fields is 10–15 years, such capital expenditures are hardly be ever paid off, because

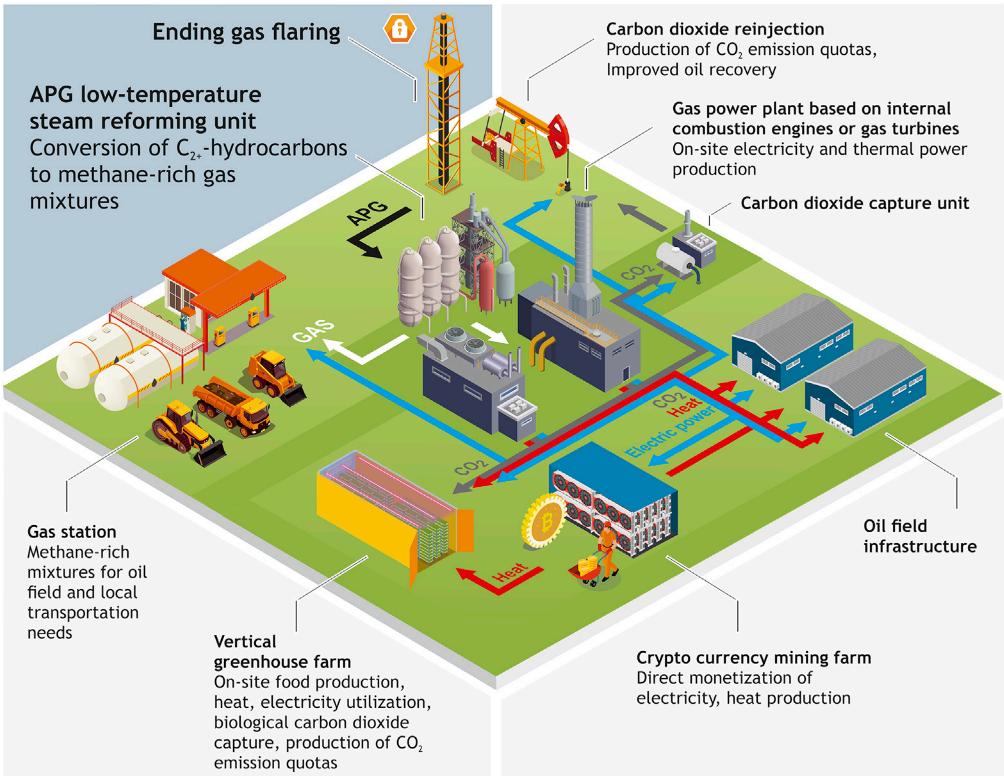

Figure 2. Schematic diagram of flare gas on-site monetization

the constructed power transmission line cannot be relocated at zero cost. The introduction of a mining farm into the set of equipment does not cause any significant changes in the calculation methodology. In fact, installation of such additional equipment leads to an increase in capital costs (which is identical to an increase in capital costs associated with the power transmission line construction), but entails a significant increase in the price of a final product—cryptocurrency (instead of electricity which becomes an intermediate product). Moreover, in case of deposit depletion, all equipment of the energy complex, including the mining farm, can be easily transported to another location.

The specific capital costs for the creation of a cryptomining energy-chemical complex (which includes a mining farm, GPP/GTPP, and a block-modular unit for fuel gas conditioning by low-temperature steam reforming of flare gas) can be roughly estimated at 1–1.5 million USD per 1 MW of the generated and mining-consumed power. This estimate is based on the results of previous technical and economic assessment of the technology of low-temperature steam reforming of flare gases in power units for generating electricity (Vernikovskaya et al., 2012a, 2012b; Zyryanova et al., 2013a, 2013b), as well as on the current prices for the entire set of equipment required to create a Bitcoin-mining data center. Taking into account that flare gases, which are used as the initial fuel, have zero or even negative cost (saving on penalties for APG flaring), and that annual gross revenue from the mining farm can range 35–90 BTC (1–2.7 million USD), the payback period of cryptomining energy-chemical complex can be less than 1 year (although the payback period is sensitive to the cryptocurrency exchange rate fluctuations). Operating costs can be neglected in this rough estimation, because local electricity demand at oil and gas fields is usually provided by a power unit (diesel generator, gas-diesel power plant, or GPP operating on the first stages separation gases), and its operating costs are accounted in the costs of the field development and oil production.

Cryptocurrency mining is a rather risky business, and the resulting crypto-assets are characterized by high volatility. In this regard, investment projects aimed at creating supercomputer centers powered by electricity from the APG processing at oil fields seem to be less risky, but highly attractive in the long term. Currently, supercomputer centers require huge amounts of energy. According to the TOP-500 list (Top500 list, 2021), a typical supercomputer consumes 1 to 3 MW of electric power. These powerful computing facilities can be used, for example, for on-site processing of geological and geophysical data obtained during field exploration and development.

The proposed comprehensive approach for the direct monetization of on-site APG processing seems to be the unique solution that promotes downstream processes for more efficient APG utilization in the oil and gas fields. Separately, these processes can be economically low-efficient, but if used as an additional option, they can contribute a synergistic effect and allow an additional profit. Some of these processes are as follows (schematically presented in Figure 2):

1. The energy-chemical complex integrated with the data processing center is a source of large amounts of heat, carbon dioxide, and water vapor. These products can be used for year-round heating of vertical greenhouse farms. Similarly to all major equipment, they can be containerized, and operate in autonomous mode and supply the oilfield staff with fresh green food. Plants will serve also for carbon dioxide capture and production of CO_2 emission quotas.
2. Carbon dioxide can be captured by chemical or physical methods (Bazaikin et al., 2021; Derevshchikov et al., 2021; Veselovskaya et al., 2021) and disposed (for example, re-injected into the reservoir). It is well known that carbon dioxide re-injection improves oil recovery, especially in the case of hard-to-recover oil reservoirs. Besides, this approach allows the ''accumulation'' of CO_2 emission quotas, which can be spent for hydrogen production by the method of methane steam reforming in territories where the collection, transportation, and disposal of carbon dioxide are unprofitable. Thus, the ''gray'' hydrogen (i.e., produced by steam reforming of natural gas without CO_2 capture) can be remotely upgraded into the "blue" one (produced with the carbon dioxide utilization).
3. On the basis of the energy-chemical complex, a gas fuel production can be launched for supplying local vehicle fleet (after adaptation to running on gas) that will help to reduce the seasonal import of expensive diesel fuel. This method of on-site gas utilization is quite promising, because the current market offers compact compressors which allow the gas take off for car refueling from low and medium-pressure pipelines. The required volumes of the gas fuel can be continuously generated by a specially designed block-modular unit for low-temperature steam reforming of flare gases.

LIMITATIONS OF THE STUDY

Comprehensive economic research was beyond the article's scope. Our main task was to draw particular attention to the fact that a complex approach to a number of problems can give an encouraging synergistic effect. It is expected that experts from other fields (economics, production optimization, and so forth) will be able to conduct accurate studies of the proposed approach on a global scale.

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AUTHOR CONTRIBUTIONS

P.S. and D.P. have equal contributions.

DECLARATION OF INTERESTS

The authors have patents related to this work: RU2443764, RU2442819, RU125190, RU125191, RU2568810, RU2644890.

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