10 BREAKTHROUGH IDEAS IN ENERGY FOR THE NEXT TEN YEARS

GLOBAL ENERGY

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Dear friends!

This is the second annual selection of the most promising groundbreaking energy technologies of the decade published by the Global Energy Association.

Some of these solutions are already changing our everyday life, while the others are still prospective for the long term.

The technologies in this report are united by their anticipated effect on the human life in the current decade.

Sometimes, when looking ahead, we are waiting for extraordinary technologies that have not yet been discovered, to be created. However, we should not forget about things we can do already. That is the reason this report comprises solutions that are not particularly groundbreaking, but their development is essential here and now.

Here a legitimate question should be asked – what can be considered groundbreaking?

It is no wonder that the report leans considerably towards technologies “cleansing” the available resources (which will stay an integral part of the energy balance for quite some time), as well as sustainability and recycling of the products that can be used opportunely instead of being wasted or harming the environment.

Such group of solutions includes “Catalytic Methods for Processing Carbon Dioxide from Coal-Fired Generation into Useful Products”, “Technologies for Managing Oil Field Wastes”, and “Industrial Carbon Capture and Storage”.

The technologies in development that are still to become competitive and take their place among conventional sources make another cluster. Here “High-Quality Motor Fuels from Vegetative Raw Materials” and “Power to E-Fuel” can be named.

Some topics are so interesting and vast that they moved over from last year’s report to be analysed even more deeply and from a different angle. Those are “Blue Hydrogen”, “Industrial Carbon Capture and Storage”, and “Digital Twins”.

There are also chapters that will be viewed for the first time: “Ultra High Voltage Power Transmission Technology” and “Floating Solar Stations”.

I wish everyone who would like to study the new report of “10 Breakthrough Ideas in Energy for the Next 10 Years. 2021” by the Global Energy Association an exciting and useful reading.

With best regards,

Deputy Prime Minister of the Russian Federation
A. Novak
We now see more industrialised nations mandating net-zero emission targets. In-practice, delivery on these commitments means the deep decarbonisation of all aspects of our heavily industrialised society. The chart presented in Figure 1 sets out globally where carbon dioxide is generated on a sector-by-sector basis. Given the scale of our collective emissions (~40GtCO₂/year Le Quéré et al (2020)), we urgently need to bring forward both technically and economically viable net-zero compliant solutions for power, transport, industry, buildings and more.

Underpinned by a massive R&D investment across the industrialised world, a growing consensus has developed around a portfolio of net-zero compliant pathways for delivering price competitive power and transport. As shown in Figure 1, the decarbonisation of industrial emission sources has an equivalent importance in terms of its scale globally. However, it is widely recognised that the industrial sector faces unique challenges, which may require bespoke solutions even on an industrial plant by plant basis.

This chapter sets out how this can be achieved through industrial carbon capture clusters or integrated networks underpinned by a new generation of industrial processes and plants.
THE DECARBONISATION OF INDUSTRY

The International Energy Agency (IEA), have estimated that industrial sources including petroleum refineries are currently responsible for a quarter of anthropogenic carbon dioxide emissions and around 40% of energy demand (IEA (2019)). Holistically, the industrial sector is fundamental to the world economy as it brings together multinational supply chains to manufacture the world’s commodities and products. However it is now the case (YouGov & Sky News 2020), that both consumers and policymakers are now going beyond seeing carbon dioxide as something produced at a power station or a vehicle exhaust pipe and asking “how sustainable day-to-day products really are?” and are increasingly making informed choices based on their environmental impact.

In a world now developing more detailed plans and deploying solutions which can unlock our to transition to net-zero emissions, the industrial sector is now facing the reality that it must find cost effective ways to be compliant with both mandated targets and growing consumer expectations.

At the same time, factors such as world population growth, increased urbanisation, economic and social development are continuing to increase consumer demand for industrial products themselves. Furthermore, natural market forces have historically reduced the price of these products through a transition to ever-larger scale mass manufacturing, with multiple generations of optimisation and efficiency savings taking place in each plant. The issue now is that the market naturally drives down costs to the consumer but not necessarily corresponding carbon dioxide emissions. Hence they are considered by many to close to their maximum potential efficiency (ZEP 2013). This means that carbon dioxide reduction with a focus on energy saving has limited potential for delivering on net-zero targets.

Indeed many of these process plants are unique in terms of a) the chemical or manufacturing process and product itself and; b) the economies of scale at least regionally. The latter is also of significance as large process or manufacturing plants are an integral part of the industrial regional or national infrastructure, regional supply chain and are responsible for employing many local citizens.

THE CHALLENGE OF DECARBONISING THERMAL ENERGY

Data shows that in the UK, the final energy demand for industrial processes is driven mostly for a requirement for thermal energy (>70% — BEIS, 2016). The chart presented in Figure 2 sets out the temperatures of thermal energy required for industrial process across the European Union. This chart clearly sets out the requirements for thermal energy demand across all industrial processes, it shows the relative space and process heating and cooling demand in terms of the working fluid temperature.

Decarbonisation of some of these processes by installing electrified heating sources is an option, for example using a combination of renewable electricity combined with heat pumps. However, the opportunity is limited by the practical realities of a high capital cost of heat pumps and the challenge that heat pumps are most effective for lower temperature processes. As presented in Figure 2, almost three quarters of thermal energy demand is high-grade process heat with a working temperature in excess of 100oC and thus it must be recognised that it is solutions which address the higher temperature challenge that are required and at scale.
Industrial CO₂ emissions in the European Union are dominated by iron and steel production (19%), chemicals industry (15%), petroleum refining (14%), and cement/lime production (11%) (UNFCCC 2012). Historically, high temperature process conditions requiring high-grade thermal energy in excess of 200-500°C have been relatively easy to obtain through access to an abundance of fossil fuels, low-emission combustion aftertreatment technology, and using what are generally quite simple boiler or furnace technologies. In addition, we have taken for granted the co-benefits of using fossil fuels in terms of its capacity for on-site, safe, and long-term storage and thus have lessened the intermittent impact of the energy demands of the plant on the wider energy network.

The decarbonisation of industrial processes will result in fundamental changes to all of the above processes, however many of them will need bespoke solutions. It is also recognised that many are embedded into the local industrial and social infrastructure and are operating very cost effectively, so political leadership in supporting our transition is fundamental.

Industrial emissions are significant and will need to be addressed directly if net-zero targets are to be delivered, however it may well represent the most challenging sector to decarbonise.

Industrial carbon capture utilisation and storage represents a set of technologies and processes by which carbon dioxide emissions can be captured at source, transported usually via compressed pipeline to a storage location, and then stored on a permanent basis.

Many of the challenges of industrial carbon capture are similar to those currently faced in the technology’s roll-out in delivering a flexible and resilient power sector. However, the diversity of industrial applications, their processes, local geography, and the impact on the products themselves pose additional and significant challenges. As such, there is huge scope for new opportunities for research and innovation.

Over the last 100 years, regional clusters of multiple directly and in-directly coupled industrial process plants have been established around the world. Through common transport infrastructure, resources, skills, symbiotic process streams etc., collectively they benefit by yielding higher quality products at lower price points.

An integrated decarbonised industrial cluster is presented in Figure 3. It aims to bring together multiple industrial process and power plants through common carbon dioxide capture, distribution and storage infrastructure. The presented example is for a proposed network based in Teesside and Humberside in the United Kingdom.
The aim is to reduce the costs of deployment across the two sub-clusters by sharing a common set of carbon dioxide storage sites in the North Sea. Initially using Endurance and extending out further as the network grows.

On Teesside, there are multiple chemical, industrial process, power plants, refineries, and manufacturing sites including a major hydrogen production facility. On Humberside, there is Drax Power Station, hydrogen, steel, chemical, and cement manufacturing sites. Initially, not all sites would be connected into the network, however it is foreseen that as the technology is de-risked and demand increases, the number of additional local sites would be expected to grow.
KEY ELEMENTS OF AN INDUSTRIAL CCUS CLUSTER

Each industrial cluster is unique as they have developed over the generations as a result of complex market forces and have different geography, geology, and local industries. However, they all share a common set of components, which can be summarised as:

**Capture technology:** The details of the exact industrial process itself, its access to symbiotic processes and its scale are important to establish the most appropriate and economically viable option to facilitate capture.

Typically, carbon dioxide gas capture can be delivered via either:

1. In-process separation of carbon dioxide - in some applications (ammonia and hydrogen production for example) this is a fundamental step and therefore a highly concentrated stream of carbon dioxide can easily be redirected out of the process and into the network.

2. Oxy-fuel combustion is a potential route in applications with high external heat generation (boilers, combined heat and power, kilns, and cement) although there is also scope to utilise internal heat sources more effectively in steel making, refining, and others and.

3. Conventional post-capture technologies using chemical, physical or solid sorbent materials to capture from exhaust streams of diluted carbon dioxide gases.

However, when sites and processes are upgraded as part of long term plant investment or regeneration, both (1) and (2) could well be more viable from a product quality and economic perspective. For example, a bottom-up plant design offers a greater scope for integration with renewables, improved designs and novel process installations.

**Transport and infrastructure:** An industrial plant capture system may have multiple sources of carbon dioxide at a smaller scale relative to what might be expected in power generation applications, hence it is expected that post-capture technologies would benefit from collecting multiple smaller vented carbon dioxide sources and using a larger common capture technology. In addition, roadmaps for deployment by (UNIDO/IEA 2011) and the ZEP (2013) point toward establishing industrial carbon capture clusters in order to overcome the technical and economic barriers associated with establishing the transport infrastructure and exploiting genuine economies of scale.

**Carbon sinks:** Once captured and concentrated, the carbon dioxide must be stored or utilised in such a way that it is locked out of the atmosphere into the long term. Geological storage is now considered a mature and de-risked technical option with multiple sub-surface geological storage sites being developed worldwide (Kelemen, et al. (2019)).

The utilisation of carbon dioxide as a chemical process feedstock or used as the working fluid in enhanced oil recovery also presents an opportunity (Gonzalez Diaz et al. (2021)) to increase the value of what is normally considered to be a low-value product.

Whilst many carbon dioxide utilisation pathways represent an opportunity worth further exploration, this market is expected to be small relative to the likely continued abundance of carbon dioxide across the world economy. In addition, care must be taken to properly consider the key sensitivities of net lifecycle carbon dioxide emissions, economics, and other factors especially in the context of the possible re-emission of carbon dioxide later in the product lifetime.
The following section sets out examples of how three common industrial products can be decarbonised through the integration with carbon capture, utilisation and storage networks.

**Retrofitting a hydrogen production plant.** As outlined above, industrial processes currently powered by natural gas (or other fossil fuels) combustion are widespread and represent an integral part of each plant often co-producing power, high grade heat or other services.

It now regularly put forward, that through an upgrade of the boiler or furnace, the energy provision for many processes can be decarbonised by moving from natural gas to hydrogen gas as the fuel. Whilst hydrogen gas certainly does not always represent a simple ‘drop-in’ alternative to natural gas, it does represent a viable option especially when upgrading what might already be a heavily integrated process plant infrastructure. In this context, the real challenge is to produce decarbonised hydrogen at scale and at a viable cost equivalent to that of natural gas.

Hydrogen can be derived in multiple ways but currently is generally derived at scale by reforming natural gas. A simplified representation of this process is set-out in Figure 4. As part of this process, carbon dioxide is produced in high concentrations and can be further concentrated so that it can be directly supplied into a wider carbon capture network. This pathway then supports the production of hydrogen for the wider decarbonisation of society outside the locality of the network.

Furthermore as shown in the figure, an extension of this process to include a gasification stage opens up the possibility of utilising other primary energy feedstocks including coal and biomass opening up further options in terms of net-carbon dioxide emissions, sustainability, scale-up, and energy security. However it must be noted, that the “blue hydrogen” produced using the process presented in Figure 4 can only reduce the total carbon dioxide emissions by around 90% (Gonzalez Diaz et al. (2020)), thus whilst this represents a significant step in decarbonising processes there are limits to its potential.
AMMONIA FOR FERTILISER & MARINE FUEL

As outlined above, once you have an abundance of decarbonised hydrogen there is an opportunity to tackle other heavily emitting industrial processes, which can utilise the "blue hydrogen" directly as a chemical feedstock (rather than as a combustion fuel).

An excellent example is ammonia, which is typically derived using a Haber–Bosch process as presented in Figure 5. In this process, hydrogen is combined with nitrogen (extracted from ambient air) over a high-temperature high-pressure iron catalyst to produce ammonia. Normally the hydrogen is commonly produced using the process presented in Figure 4 but without capturing the carbon, Gonzalez Diaz et al. (2020) have explored the possibilities and impact of using “blue” hydrogen instead.

Ammonia itself is a feedstock for multiple applications including fertiliser, refirerant gases, water purification, plastic manufacture, explosives, textiles, pesticides, dyes, and other chemicals.

Currently the bulk consumer of ammonia is for fertiliser manufacture for use by the agricultural sector. Analysis by Gonzalez Diaz et al. (2020) shows that when directly integrating fertiliser production with carbon capture networks there is a potential to reduce carbon dioxide emissions by 77.5% without reducing or altering the quality of the final product.

In agriculture, greenhouse gas emissions (GHGs) other than carbon dioxide are a notable challenge, hence once these savings are propagated through the supply chain and considered in a life-cycle emission terms, on a GHG per tonne of product basis, rice and wheat emissions can be reduced by 4.6–7.3% and 16.0–17.3% respectively.

Another market opportunity for ammonia explored by Gonzalez Diaz et al. (2021) is its use as a transportation fuel or, more broadly, as an energy carrier for hydrogen. Ammonia carries hydrogen attached to nitrogen and like a hydrocarbon, it can be stored and transported in liquid form. Its energy storage density is more favourable than lithium ion batteries and even compressed hydrogen. Furthermore, it can be burned without producing carbon dioxide emissions directly in an internal combustion engine (even a retrofit to a diesel engine), which means that it is of interest to those transportation sectors with long distance and high power demands such as the marine and freight transportation sectors. Through the integration of the ammonia production process into a carbon capture cluster, ammonia derived from natural gas can have its carbon dioxide emissions reduced by 68.4%.
Polyethylene terephthalate (PET) is a common plastic used for packaging of drinks bottles, and food as well as plastic containers, in textiles, electronics, and automotive industries. PET is typically manufactured from fossil derived oil feedstocks and after a series of industrial processes, a plastic resin is synthesised and used to form the final plastic product.

Plastics for food product packaging are currently a significant source of carbon dioxide emissions, for example during the manufacturing process around 2.15 kg of carbon dioxide is produced per kilogram of PET. As such, there are opportunities to decarbonise this through integration of carbon dioxide capture networks either directly by modifying the process streams or as a retrofit installation (Bains, et al., 2017).

Nevertheless, there is also a potential that alternative plastics can be developed, which could also simultaneously act as carbon dioxide sink. For example, PET plastic products can be replaced with a Polyethylene Furanoate or PEF-based plastic. PEF is a bio-based polymer produced from carbon dioxide and renewable raw material feedstocks. Jiang et al., (2020) have explored the techno-economic potential for realising this process at industrial scale and how it might act as a carbon sink from a lifecycle, technical, and economic perspective.

Analysis showed that PEF plastic as a raw material would be ~35% more expensive than PET on a per kg basis, however due to advanced material characteristics, a 237 ml PEF bottle can be designed to be lighter than its PET equivalent. This combination means that both bottle types would in principle be available at an equivalent price.

When analysed in terms of net life-cycle carbon dioxide emissions, the work showed that using a PEF plastic bottle alternative could reduce emissions by 40.5% compared to its equivalent PET plastic bottle. This analysis was optimised for price however, if consumers were comfortable in paying a premium, further carbon dioxide emissions savings are possible especially when further integrating with renewables.

If the process can be developed further so that it can become net-negative in terms of carbon dioxide emissions, a novel opportunity for a new kind of industrial carbon sink then opens up. An example of this is set out in Figure 6, there is already a scaled-up circular economy to support the recycling of PET. It is known that PEF can be recycled together alongside with PET, thus we already have the infrastructure to recycle PEF plastic at scale. If PEF production can be scaled-up, this circular economy comprised of PEF/PET plastic bottles stored at home, recycled and re-utilised could then act a long-term carbon dioxide storage sink.

FIGURE 6. A PEF production process.
SUMMARY

An increasing number of national governments and trading blocks are establishing net-zero targets and policies. The reality is that this represents deep decarbonisation of every sector and an increasing emphasis on addressing decarbonisation challenges beyond power and transport.

The industrial sector is fundamental to our economic prosperity and driving its decarbonisation is complex as it faces its own unique challenges requiring radical technical and economic solutions. Many of these will have an impact on every process plant, across the world supply chain and as a result will be highly disruptive.

Industrial carbon capture, utilisation and storage clusters or networks will help to decarbonise some of the most challenging applications. This technology offers a short-term retrofit solution, which can enable for industrial infrastructure to continue to be utilised at scale whilst operating in a net-zero compliant manner. Beyond this, there are more invasive solutions, which can build on the carbon capture cluster network, which may well yield more effective technical and economic solutions for decarbonisation. As a result, industrial carbon capture and storage has huge potential to mitigate a significant amount of global carbon dioxide emissions.

Examples of industrial carbon capture technology were presented, which demonstrated how hydrogen, ammonia, and plastics can be produced at scale.
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INTRODUCTION

One of modern digitalisation trends which have already widespread throughout the world are Digital Twin (DT) and Digital Shadow. The concept of digital twins is referred to the basic elements of a high-tech and intelligent control system within the fourth industrial revolution context (Industry 4.0) [1]. According to the Gartner Institute, the trends in development of digital twin technologies were at the peak of high expectations during 2018-2019, and an active development of this technology is predicted within the next 5-10 years.

Development of a digital twin idea has its history formed by contribution made by a number of authors. At the same time, most authors agree [2] that the DT concept was originally voiced by Michael Greaves in the PLM (Product Lifecycle Management) course at the University of Michigan in early 2002 and later, in 2003, was presented at the PLM conference. In fact, it is a concept of interaction of a physical object/system in a real world with its digital copy in a virtual world through information links between them. Sensors are built into the technological structure of a physical object/system to collect information about its state in real time. Based on this information, a digital model is refined and forecasts behavior of a physical object/system. The concept essence is that each object/system can be represented as a physical and virtual system so that the virtual system displays the physical one and vice versa.

The level of technology at that time prevented from full implementation of this concept; interest in this topic has risen in recent years. In terms of intensity of research in this area (according to the number of scientific publications contained in the Scopus database), the Russian Federation ranks the 5th in the world (after the USA, Germany, China and the United Kingdom), and in terms of the demand for DT technology in Russia, it occupies the second place [3].
CLASSIFICATION OF DIGITAL TWINS

The digital twin concept is directly based on the digital model concept. A digital model is, in fact, a computer programme capable to calculate, with a certain accuracy, the behaviour characteristics of a real object in various environmental conditions — observable and hypothetical. The advantage of the digital model is that it allows virtual experiments to be performed over an object/system, which is especially important in situations where a real experiment is unacceptably expensive, impossible or even dangerous. This fully applies to the studies of spatially distributed, structurally and organisationally complex power systems.

The digital twin relative to the digital model is a more capacious information tool since it includes one or more interconnected digital models as well as the data sets necessary for their operation often obtained directly from a real power facility in the time mode close to real.

A more general is the digital image concept, which, in addition to the models and data of the object (equipment/system), includes behavioral and cognitive models of related human activities (for example, equipment operators, administrative personnel). Digital images are the basis for creation of a new generation of decision support systems.

The DT concept has several definitions reviewed, for example, in [4] on the basis of foreign sources [5-14], and the current state of affairs in this area is given in [3]. The most successful definition of DT is given in [15]. With regard to the power industry, the Digital Twin is a real display of all components of an object/system in lifecycle using physical data, virtual data, and the data of their interaction, i.e., DT creates a virtual prototype of a real object/system which you can use to conduct experiments and test hypotheses, forecast behavior of an object/system and solve the problems of managing its life cycle. The DT block diagram in the form of symbiosis of software for object/system lifecycle management (PLM), and information and telecommunication technology of the Internet of Things (IoT) is shown in Fig. 1.

FIGURE 1. A digital twin block diagram.
Source: GK Technoserv, Vinnum
DT combines tools for creation of a digital 3D model of an object/system, developed using a Computer-aided design (CAD) system, an information and telecommunications system on the basis of the Industrial Internet of Things and integrated mathematical models to track behavior and optimise operation of a real object using the CAE-system designed for engineering calculations.

Various tools are used for building DT (Fig. 2), for example, numerical methods for simulation of physical processes in objects/systems to forecast their response to various internal and external disturbances, for example, the FEA (Finite Element Analysis). Information about their structure and parameters is formed by CAD models. The models based on the system reliability analysis, i.e. FMEA-models (Failure Mode and Effects Analysis), integrate mathematical models for failure analysis and assessment of their effects with a statistical database of failure events and the decisions made for their troubleshooting.


DT contains description of the retrospective of the object/system maintenance and operation, which allows us to forecast the behavior of a real object/system, including taking into account monitoring and testing of objects/systems, and conduct the analysis based on the aggregated data for all objects of the energy system. Being a self-learning platform, DT uses machine learning technologies, a wide range of information from many sources, including data from the sensors monitoring the equipment state and the mode parameters, information about loads, etc. Their integration with the technologies of the Internet of Things is a driver of development and ensures collection and analysis of data from various types of sensors obtained during monitoring, formation of control actions and their bringing to actuating mechanisms so that to effectively manage the object/system.

The existing classifications of digital twins according to the level of development, modeling technologies and purpose are shown in Fig. 3 [3].

In the power industry, three main types of digital twins are the most widespread:

**Twin prototype** (Digital Twin Prototype, DTP). This is a virtual analogue of a real-life object/system. It contains information describing a specific object and the system, as a whole, at all stages - from the requirements for production and operation processes, to the requirements for disposal of an element.

**Twin-instance** (Digital Twin Instance, DTI). Contains information on description of an element (equipment), i.e. data on materials, components, information from the equipment monitoring system.

**Aggregated twin** (Digital Twin Aggregate, DTA). It combines a prototype and an instance, i.e. it collects all available information about hardware, an object or a system.

2 — FMEA (Failure Mode and Effect Analysis) is a technology for analysing the types and effects of potential failures (defects) due to which an object/system becomes unable to perform its functions.

CAD (Computer-aided design) is an automated system that implements information technology to perform designing of an object/system.

FEA (Finite Element Analysis) is a finite element model for mathematical modeling and numerical solution of complex structural problems of design and functioning of objects/systems.
Within the framework of structural building, we distinguish DT of an object, process and a system [4]. The System Unit Twin is a virtual model of a specific facility (a power plant, a transformer substation, a power line, etc.). The process twin simulates production/technological processes (energy production, electrical modes, flow distribution, etc.). A virtual production/technological process can simulate different scenarios and illustrate what can happen at different kinds of internal and external disturbances. This allows you to develop the most effective methodology for production process. It can be optimised with virtual twins of an object or a system. The system digital twin is a virtual model of the entire system as a whole (for example, a power grid, a gas supply system, an oil supply system, etc.). The digital twins collect huge amounts of operation data supplied by devices, individual objects and systems as a whole, and allow you to get presentation of an object/system and create new business opportunities for optimisation of all processes, including organisational, technological, etc.

The term of a digital shadow is rather often used. A digital shadow can be defined as a system of connections and dependencies describing behaviour of a real object, as a rule, under normal operating conditions and contained in the redundant big data obtained from a real object using industrial Internet technologies. The digital shadow is able to forecast behaviour of a real object only under conditions in which the data was collected but it does not allow simulation of other situations [16]. After some comparison of digital shadows and digital twins, all experts agree on the need to move to their joint use, considering the digital shadow as a digital twin component.
ADVANTAGES AND PROBLEMS OF BUILDING DIGITAL TWINS

The digital twins of power systems have the following main functionalities (use cases) [17]:

- Assessment and forecasting of levels of production, consumption, storage of energy resources in all aspects;
- Assessment and forecasting of throughput capacity of segments of network systems;
- Assessment of risks caused by violations due to the man-made impacts;
- On-line assessment of parameters and control of modes in order to ensure operability and increase the system efficiency;
- Calculation and virtual testing of setpoints, switching, normal and emergency modes;
- Predictive monitoring of the state of equipment, assessment of accidents and the need for maintenance and repairs;
- Calibration and verification of object/system models and control algorithms;
- Virtual approbation and evaluation of design solutions;
- Training and virtual training of the personnel of power facilities.

All these functions are included in a digital twin-instance, which is the most relevant for use by companies operating power grids. It is based on a mathematical model of the grid and contains information on the performance characteristics of the equipment used (cables, transformers, switches, etc.), the time of its commissioning, geographic coordinates, and data coming from measuring devices. This information is used to carry out calculations for connecting new consumers as well as various calculations of power grids, for example, to calculate modes, short-circuit currents, coordination of relay protection devices, and others.

Today, in practice, these calculations are carried out by various departments, and for each of them its own mathematical model of the same physical network is developed. The use of different models often leads to errors and a decrease in the calculation accuracy. The use of a single DT by all company divisions will contribute to a successful solution of this problem by organising a single digital space. The digital twin of power grids includes a database with information about the grid integrated with the other IT systems of the energy company (SCADA, a geographic information system, an asset management system, etc.) as well as computing tools. The digital twin shall synchronise the data received from different sources so that they accurately correspond to the power grid current state.

There are five software components required to create a digital twin and form its architecture:

- The digital twin core - mathematical, simulation and information models;
- A system for collecting data from a physical object/system, monitoring and managing them;
- Systems for observation, recognition and data collection, systems for their control and management;
- The incoming data storage - classic DBMS (Oracle, MS SQL, DB2) and open source DBMS (PostgreSQL), cloud storages (S3, RedShift, Greenplum), distributed file systems HDFS;
- Tools for providing services and interface to customers – the support elements for optimisation services, mathematical modeling, forecasting, etc.;
- A communication system between the named elements (Internet of Things (IoT) platform) [3].

Fig. 4 shows an enlarged diagram of the relationship between the listed components.
Energy is a technology area where DT technology is in high demand. Digital twins are being developed in the oil and gas industry, in the nuclear-power industry, in the power industry, where systemic developments of such companies as General Electric, Siemens, SAP, and the National Energy Technology Laboratory (USA) have become widespread. There are also some Russian solutions that do not claim to be comprehensive ones.

The factors constraining the development of DT technology, which get overcome over time, are:

- High cost of projects due to involvement of multidisciplinary software and requiring not only initial investment, but also expenditures for supporting DT;
- Lack of specialists with interdisciplinary knowledge to create DT projects. Lack of information and educational programs of the appropriate profile;
- Problems of consistency in interpretation of the DT term, fundamental goals and objectives, excessive complexity and detailing (in reserve) of models;
- Incorrect sequence of actions. It is necessary first to work out all the changes on DT, and then implement them in a real system, but not vice versa;
- Presentation of old technologies under a new label, which discredits the DT technology, and reduces interest in it [3].
Analysis of the research conducted in the field of using the concept of digital twins confirms relevance of their application in intelligent control not only by operation, but also development of power systems. At the same time, different types of digital twins are possible for different levels of power systems and facilities.

In an ideal scenario, the digital twin is based on the tools of big data coming in real time for plurality of measurements and meeting the three V criteria\(^3\). These measurements create an evolving profile of object/system and of implemented production process in a digital space for making effective decisions on their structural, functional transformation as well as reformatting the production process. At the same time, the Digital Twin differs from a traditional computer-aided design (CAD) system; it is not just another sensor-enabled and Internet of Things (IoT) solution.

It is assumed that in the future the DT will become an integrating platform between operational technologies (OT) covering the production process intellectualisation, monitoring of the system state and parameters, etc. where data is generated, and where information technologies (IT) provide intellectualisation of business processes, mobile applications, etc. It successfully integrates into the computer environment and has a more developed infrastructure and functionality.

The main factors of interest stimulating development and successful use of DT are significant enough and have good prospects, among them the following can be mentioned:

- DT is one of the most important technologies on which projects for digital transformation and intellectualisation of systems are based, it increases their competitive advantages and expands their functionality;
- Complexity of the engineering facilities requires transition to a new design paradigm aimed at integrating various groups of developers and suppliers in complex project chains;
- DT allows us to reduce costs as a result of shifting the centre of gravity at the fine-tuning of the process of the system creation and operation to the stage of its development and implementation of predictive maintenance;
- DT lowers costs at all stages of the product life cycle in implementation of tasks of operation, support, monitoring, modernisation, and disposal;
- Successful application of DT for the fullest manifestation of functionality of systems, extension of equipment service life, reduction of repair costs, optimisation of repairs in hard-to-reach places;
- Development of the adjacent and related digital technologies, in particular, the industrial Internet of things, cloud technologies, virtual and augmented reality applications, additive manufacturing technologies;
- Development of DT as part of digitalisation strategy, increase of the level of reliability and operation safety of power facilities and systems [3].

\(^3\) — volume (physically large amount of data), velocity (rate of the data growth, processing and result obtaining), variety (the ability to simultaneously process various types of structured and semi-structured data)
A digital twin throughout its entire life cycle, schematically shown in Fig. 5, actively uses all IT system components, such as PLM, PDM, and SCADA. It provides storage and provision for use of large amounts of information coming from a variety of software and hardware systems, the sensors embedded in physical objects and other sources. It makes this information available for use at all stages of life of an object/system.

FIGURE 5. The basic structure of building a digital twin of the system.
Source: ANSYS CFD.

The issues of DT information provision seem to be especially relevant, for example, for a geographically distributed and structurally complex Unified Electric Power System of Russia (UES); it is important for effective management of its modes, planning maintenance, and repair measures, preventing emergencies, etc. [18, 19]. The efficiently operating hierarchical system of dispatching and automatic control of the UES modes, which has developed to date, is provided with detailed on-line measuring information obtained from the traditional and vector measuring instruments of the systems SCADA and WAMS (a wide-area measurement system). Based on the data obtained, current information models of the UES, United and Regional Power grids are formed which are the basis for solution of technological problems regarding the issues of monitoring the modes, their forecasting and management. They are implemented by the EMS (Energy Management System) at each level of the territorial hierarchy. To control the UES modes, there are developed control actions to be performed by the dispatcher and by the automatic control system [20].

The distributed hierarchical information model of the UES, developed and used by the System Operator (SO) of the UES of Russia is a representative comprehensive base for formation of the power interconnection digital twin at all levels of the territorial hierarchy. It seems expedient to create information models of the digital twin in the following directions [19].
Formation of UES DT as a unified information space of the power interconnection, implemented according to the uniform principles and distributed over the levels of the territorial management hierarchy. Based on the digital twin information, using common principles and methods, information models are constructed to solve specific problems of mode control at each hierarchy level. These principles of formation of a single digital twin of the UES ensure consistency of the results of solution of various problems of power interconnection mode controls at different levels;

Development and use of the UES digital twin, taking into account the power interconnection scale, necessary detailing in representation of the system elements and information capabilities of the measuring instruments used should be associated with operation at the big data level. Modern means of information support for mode control tasks (SCADA, WAMS) already provide huge amounts of information [21], however, only its small part is useful. An increase of the volume of its use can give a powerful impetus to understanding the new unexpected, useful, and possibly negative properties of the controlled object;

When processing and analysing large amounts of data, it is advisable to use CIM-(Common Information Model) models [22]. The technology of CIM-models which is based on the data format ODM (Open Model for Exchanging Power System Simulation Data) allows formation of models of any complexity, which then can be converted into any known or new data format using additional Plug-in modules. ODM is an international open data exchange standard for EPS (electrical power systems) modeling that supports dynamic process calculations. Information in the CIM format is stored in a database and can be used in various applications of the IT infrastructure when creating a digital twin of the EEC and an intelligent control system for its modes;

As technologies for intelligent support of taking decisions by a dispatcher, it is advisable to explore possibilities of ontological, cognitive and event simulation, integrated within the IT infrastructure. Subsequently, these intelligent technologies can be supplemented with technologies of artificial neural networks, fuzzy sets and fuzzy logic, wavelet analysis, etc.

The digital twin of the UES of Russia is based on a single distributed database that must be integrated with other IT systems. DT shall synchronise information from different sources in such a way that it was in an unambiguous correspondence with the current state of the physical system and, with the required accuracy, reflected characteristics of the elements and the system, as a whole, their state, mode parameters, etc.

### APPROACHES TO BUILDING DIGITAL TWINS

When building digital twins of power systems, it is important that they be focused on modeling all kinds of impacts (not only physical) on an object/system during its a full life cycle, forecasting the consequences of such impacts, and developing measures to prevent their negative man-made impact. To solve these problems, the basis of the digital twin of an object/system shall include a set of interconnected computer models, sufficient to perform the following basic actions:

- reliable display of the object state and its environment in real time;
- reliable forecasting the object behavior under normal and abnormal conditions;
- reliable formation of control actions for the object.
The digital twin key component shall be a complex of mathematical and economic computational, simulation, neural network models that describe all aspects of behavior of an object/system. Powerful mechanisms for calibrating models are envisaged in order to raise their reliability, also through machine learning [7]. To provide convenient access to models that are a part of a digital twin, they are often designed as service tools [11]. A service architecture hiding the implementation details of models is especially useful for the distributed systems with a decentralised control, such as the Internet of Energy.

The pilot DT of the power system was built as a classic digital Baseline Twin [23]. Using it, studies were carried out and functionality of making full use of the twin to control the system was worked out so that to clarify the consumption profile of individual power receivers according to the integral readings of the metering devices installed at the inputs in the classroom (disaggregation), and to automatically search for optimal configuration of a hybrid power supply system. According to the results of these studies, it was shown that for correct functioning of mathematical models and presentation by them of an actual undistorted picture of the structure and state of an object, it is necessary to provide them with initial structured data from the basic information components describing the object in various functional aspects and obtained in an automatic mode.

Based on the accumulated experience in the design of large information and control systems in the power industry [23], the following basic information components of the digital twin were proposed:

- digital diagrams and maps (first of all, a single-line power supply diagram);
- electronic documentation (design estimates, operational, etc.);
- information models (master data);
- operational information (the results of instrument measurements of consumption, and primary characteristics of the technical condition of the equipment).

The proposed architecture of the digital twin reflecting its structure and relationships with the adjacent automated systems is shown in Fig. 6 [17, 25].
The generalised architecture of the digital twin of power facilities and systems based on the ontological approach [19, 26] has the form shown in Fig. 7.

Information models are a collection of information about the most essential properties and parameters of an object/system or process. At the present stage of development of information technologies, production and technological processes are increasingly and closely integrated with information systems, which results in creation of cyber-physical systems, including in the power industry. In energetics research, a variety of information models are used, both for developing databases and for describing and presenting the structure of power systems, objects and the processes under studies.

It seems that for the successful implementation of DT in the power industry, mathematical models of objects and systems as a whole, used for scientific and applied research of power systems, should be in demand. Obviously, they are not synonymous with DT, but they can become their core, just as information models can become the basis of digital shadows.

In the studies carried out at the ISEM SB RAS, the problems of analysis, design, forecasting of power facilities and systems are under solution, and mathematical and simulation modeling of the fuel and energy complex, as a whole, individual power systems, power facilities and their components is widely used. In particular, there are under development software systems for solution of the problems of designing systems and power facilities. In this case, software is created on the basis of the proven models of real physical systems, and knowledge about the structure of systems, applied problems and mathematical models is presented in the form of ontologies for repeated use [26]. To reduce the development time for high-level digital twins, it is advisable to use the existing and well-tested tools, which, as a rule, are used for solution of certain problems [27-28].

Digital twin technology involves interdisciplinary modeling, i.e. integration of the results of numerical modeling of structural components and physical processes in the system based on data exchange between the components included in the system.

In various branches of power industry, digital twins are under development, both for individual objects and for systems as a whole.
It is believed that the Russian oil and gas industry is the driver of development of a digital twin market. In the oil and gas industry, not only DTs of individual pieces of equipment have been implemented but also twins of complex systems are developed (field DT, offshore oil platform DT, refinery DT). Creation of DT for control of the oil production process in hard-to-reach sea conditions is especially relevant. Almost all largest Russian oil companies have announced the use of DT technology over the past few years, and many have even outlined this direction as a priority development area.

- The Lukoil Company has identified four main areas: digital twins, digital personnel, robotisation of routine processes and a digital ecosystem twin. It intends to develop smart field technology, including the one for exploration and production, and the digital plant concept encapsulates processing and distribution. In oil refining, using digital technologies, it is expected to provide a flexible production response to changes in demand, organise an efficient capacity utilisation, and maintain the production and process safety;
- The strategy of the Rosneft Company (Rosneft-2022) has stated six main areas: a digital field, a digital plant, a digital supply chain, digital trading, a digital filling station and a digital worker;
- The Rosneft Company launched a project of a digital field in Bashkiria in 2018. A detailed digital copy of a real field (Ilishevskoye field) was implemented in this project, where each physical object was represented by its digital twin, transmitting information about its state.

- Using a 3D platform, the specialists monitor in real time all key indicators - production and transportation, employees’ actions, vehicle movement. To obtain information from the remotely unobservable objects, UAVs are involved which regularly fly over the field territory;
- The Gazprom Neft Company uses DT technologies not only at the oil production stage, but also at the stages of oil refining. For example, at the Moscow Oil Refinery, the company has launched a project for creation of a digital twin of hydrofining unit for catalytic cracking gasoline, and at the Omsk Oil Refinery — a digital twin of a primary oil refining unit [3];
- The digital twin allowed ADNOC company, one of the key operators of the oil and gas industry in the Middle East, to connect 20 refineries and oil production facilities scattered throughout the Middle East to a single control center. DT integrated production assets and ensured unification and harmonisation of all organisational and technological processes.
In the power industry, which, as stated earlier, has a complex spatial structure of a power grid and a diverse composition of generating facilities with huge amounts of data, it seems impossible to identify dependencies and offer an optimal solution without digital twins, especially in modern realities of competition and global challenges. An actively developing market of equipment with a developed project-oriented automated monitoring system and electronic documentation, with stationary instrumentation, necessary sensors and a communication system contributes to creation and rapid distribution of digital twins.

- In Russia, one of the leaders in implementation of digital programs is the Rosatom Company, which has developed and tested a platform of the software and hardware system Virtual Digital NPP, which seems to be an important step towards creation of comprehensive DT of NPP power units [3];
- CROC Incorporated offered DT to simulate and optimise operation modes of one of the largest Moscow TPPs of Mosenergo. The models embedded in it make it possible to reproduce the main production processes actually running at the plant, for calculation of an optimal hourly load of the TPP for operating on the market for a day ahead, taking into account the weather forecast and energy consumption for heating within the parameters set by the System Operator and to solve other problems [29];
- The General Electric Company (GE) has developed a digital twin serving as the basis for the Digital Power Plant. The plan DT consists of a set of models and is based on a number of digital twins of subsystems (life cycle DT, DT of anomalies, thermal DT (determines thermal efficiency, power plant capacity and emission forecast, and also simulates all parameters that may affect these results));
- GE Renewable has created DT which enables wind farm operators to collect, visualise, analyse data on the plant facilities, and manage them basing on climatic factors;
- The SAP Company implements solutions to optimise operation of wind turbines using DT, malfunctions are detected at an earlier stage, which allows adjusting the operating and maintenance modes of the devices;
- The US Department of Energy’s National Energy Technology Laboratory (NETL) and its partners, in cooperation with the Center for Advanced Virtual Energy Simulation Training and Research (AVESTAR) at the University of West Virginia, have developed a digital twin simulating a power plant using the CCGT with the integrated gasification combined cycle. The project focuses on optimising the sensor network design (calculating an optimal layout, the number and the type of sensors), process control and operational strategies to increase productivity, flexibility and monitoring of the power plant health;
- DT ATOM developed by the Siemens Company is a model that uses data on the customer, supply chain, power generation, maintenance, and aims to improve the asset management efficiency. It helps to monitor operation, performance of routine maintenance and repair of turbines. The main modeling tool is AnyLogic (a universal modeling methodology based on agents, discrete events and the system dynamics);
- Productive Technological Systems (LLC PTS) informed about implementation of DT based on Creo and Windchill software at the Ural Turbine Works (UTZ), which is part of the ROTEC holding. On the basis of DT, the Kp-77-6.8 turbine was developed which made it possible to design and bring the product to production in eight months, instead of 2.5 years [3].

In the power industry, the use of digital initiatives will help improve the efficiency and reliability of generating and power grid equipment, the accuracy of loss control and prevention of emergencies.
RUSSIAN SUPPLIERS ON THE DT MARKET FOR POWER INDUSTRY

Among the Russian suppliers of DT for the power industry, we can single out the JSC National Bureau of Informatisation - the developer of the EMAS platform, which works out DT class solutions (digital models of power plants). EMAS is a comprehensive solution for automation of planning and monitoring of TPP operation modes to increase the marginal profit from production and sale of heat and power, allows solution of not only the technological problem of optimal load distribution, but also economic problems, including search for optimal TPP operation modes by marginal profit and fuel consumption.

On the market of digital twins, proceeding from the investment estimates of retrofitting and equipment repair, it is worth mentioning PJSC Mosenergo, PJSC TGC-1, PJSC Tatneft, PJSC Lukoil, PJSC RusHydro, PJSC Quadra, PJSC T-Plus, LLC Novo-Salavatskaya CHPP, LLC “VO” Technopromexport” [3].

According to Gartner forecasts, by 2021, half of large companies will use digital twins, which will contribute to their efficiency rise by 10 percent or more. Introduction of the digital twin in one of the largest generating companies in the Russian Federation made it possible to reduce the damage from idle power units by more than 5.5 times, and the number of incidents at the units of combined cycle gas plants - by over 2.9 times.

CONCLUSION

The digital twin is an effective tool for visualisation, monitoring and management of power facilities/systems at all stages of their life cycle. It is an evolving learning technology reflecting all changes occurring in a physical object/system, which are monitored through promptly transmitted data from sensors, from personnel and other sources. At the design level, DT allows us to quickly find and correct errors in engineering solutions during their implementation in projects even before their implementation. At the operation level, they can optimise production process, increasing its efficiency, quickly identifying the risks of potential failures and possible accidents, and providing predictive planning of repairs reducing the maintenance costs.

Expansion of the DT application scope will be associated with development of mathematical models reflecting transformation of production processes as well as organisational and economic transformations. A significant role in emergence of the new DT capabilities will belong to availability of the developed high-performance computing resources, emergence of the Internet of Things, 5G networks and higher, and cloud computing. New capabilities of artificial intelligence will lead to creation of smart DTs, and their combination at different hierarchical levels will contribute to formation of the unified digital twin, which will expand the range of tasks and services provided. All this will make them one of the leading trends in the future technological development.
REFERENCES


30. https://zen.yandex.ru/media/energovector/rabotaiusca-magiia-5e0a56ba98930900b3ab9f77 (Date of the application: 09.04.2021)
According to International Energy Agency, solar photovoltaic deployment levels were globally high in 2020 in the midst of 90% grow in renewable electricity demand. Photovoltaic (PV) can directly convert sunlight to electricity. From photovoltaic point of view, as can be seen Figure 1, there are four main factors influencing the output PV energy yield. First is the source of energy, the sunlight, then the converter which is the PV cell, further the amount of time that the PV unit can work, and finally the amount of area that PV technology is added on or integrated into. Sunlight is a given, we do not have much control on it. On top of that, PV converter efficiency is reaching its maximum theoretical efficiency. And that is why researchers have now put more effort into investigating approaches to boost the lifetime of PV (the factor time) and also looking into possibilities to add PV on or integrated it into any possible surface (the factor area). However, due to low efficiency of PV modules, they occupy considerable amount of area, which can be used for other essential needs of human kind, such as food and accommodation. World population is growing and the demand for food, accommodation, and green energy is also increasing. Therefore, agriculture and energy sectors might compete or already are competing over land. This inevitably brings the attention to another vastly available surface area, the water. Simply placing any type of PV system on top of (or even submerged into) water bodies, such as lakes, reservoirs, hydroelectric dams, industrial and irrigation ponds, and coastal lagoons, is called floating PV (FPV) or floatovoltaics.
A floating PV plant normally consists of floats, mooring and anchoring system, PV modules, and balance of system (BoS) components. Figure 2 shows a schematic of a floating PV plant and its key components. Expect for the floats, which bring the necessity for mooring and anchoring system, the rest of a floating PV plant is almost the same as ground-based installation. Floats are compartments with buoyancy to keep PV modules and supporting structures float on water. Floats should be recyclable, nontoxic, resilient to water, salt corrosion, and UV radiation that can ensure more than 20 years of operation with minimum effect of the waterbody ecosystem. There are three main types for the floats used for floating PV plants: (1) pure-floats with high-density polyethylene (HDPE) material, (2) pontoons (or hollow cubes) with metal trusses, and (3) special membranes or mats. Examples for float types are shown in Figure 3. Mooring refers to any permanent structure which is used to forestall free movement of the floating structure. An anchor mooring fixes a floating structure's position relative to a point on the bottom or sides of a waterbody. This will prevent the floating PV plant from being blown or pushed away by wind load, wave force, and or water streams or hit the banks when the water level is changing. Examples of three main anchoring types are shown in Figure 4. Rows of PV modules, either mono-facial or bifacial, produce DC electricity which is sent to the combiner box. For the first and second type of the floats, usually framed glass-glass PV modules are placed as they are more resilient to humid condition compare to glass-back sheet PV modules. However, real long-term data is missing to further prove this general expectation. For the first and second types of the floats, framed PV modules are preferred as they enable easy yet sturdy installation of the PV modules on the floating structure. Frameless PV module are also installed in a few project, especially when installing on membrane, as they are expected to experience less potential induced degradation (PID) effect. Most of the installed floating PV modules use mono-facial mono or poly crystalline silicon PV technologies. Further, the inverter, could be central or string inverter, convert the produced power to AC electricity. Usually larger FPV plants brings the necessity for putting central inverter(s) with ingress protection 67 (IP67) on a floating housing(s), whereas most of the small-size FPVs have string inverters placed on the land nearby. Underwater cables with high insulation are used to send the produced energy to the nearest grid connection point, which can be further transmitted to the grid or be used locally. As floating PV plants are placed on open waterbodies, they can be susceptible to lighting, therefore usually lightning protection is placed and surge arresters are included in the combiner boxes. A floating PV system can also be backed up by storage, e.g. batteries, if need be.
Different floating structures used for floating PV plants, (a) small size PV system installed on a pure-float floating structure, (b) pontoons with metallic structures holding rows of rigid PV modules, and (c) PV modules placed horizontally on thick an elastic mat. Option (a) is lightweight with large water-plastic contact area. This boosts plastic defoliation possibility. The lightness of the floats makes them vulnerable to high wind loads when wave force is present\(^{11}\), by increasing the chance for the wind to blow under the floats and push them upward in a cascaded manner. Option (a) has complex mooring system, hardly customisable for sun tracking and bifacial PV installation. However, it is a cost effective solution, which enables large-scale deployment. For example, this type of floats are used in the largest Europe floating PV system (17 MW) in France\(^{12}\). On the other hand, option (b) suffers from high cost and complex construction\(^{13}\) but brings the possibility for vertical sun tracking, bifacial PV, and higher tilt installation. For instance, a ~450 kW floating PV installation in Swiss Alps\(^{14}\) is using such floats concept with bifacial PV modules. Option (c) is less common than the other two but is a good option in regions with water scarcity as the rubber mats can entirely cover a waterbody. Since membranes in option (c) types of floating PV systems are in full contact with water, PV modules work at a lower temperature (higher efficiency). In addition, the membrane-based floating platforms are strong enough to withstand weight (for installation and maintenance) while being flexible enough to accommodate waves, which makes them a preferred solution for off-shore applications. Option (c) however, suffers from costly installation and O&M and tilted PV modules cannot be installed. The 100 KWp floating PV system installed in Norwegian west coast is a good example of implementing such floaters\(^{15}\). Also for this type, PV modules can be submerged into water. Submerged FPV is currently not considered as the mainstream solution\(^{16}\).

Three common types of anchoring for floating PV plants, (a) anchoring on piles, (b) bank anchoring, and (c) bottom anchoring, which could be self-sinking or permanents fixed point\(^{12}\). The type of the anchor depends on the soil condition. A floating PV can also have a combination of different anchoring types.

11 — Bellini, 2019
12 — Floating solar: Europe’s largest power plant is French, 2019
13 — Cazzaniga et al., 2018
14 — PV magazine, 2019
15 — Kyrohomen project
16 — World Bank, 2019
POTENTIAL AND COST

GLOBAL POTENTIAL OF FLOATING PV

One can quickly guess that floating PV systems have tremendous potential, simply by knowing that 71% of the Earth surface is covered by water. However, current technology of the floating PV systems are not sophisticated enough to handle harsh offshore environment, and if even so, with a huge additional cost. However, if only 10% of the man-made waterbodies, i.e. dams and man-made reservoirs, are covered by floating PV plants the global potential of FPV adds up to 4 TWp\(^2\). Table I shows the share of each continent in this potential.

<table>
<thead>
<tr>
<th>Continent</th>
<th>Share in global FPV potential (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Africa</td>
<td>25</td>
</tr>
<tr>
<td>Asia</td>
<td>28.6</td>
</tr>
<tr>
<td>Europe</td>
<td>5</td>
</tr>
<tr>
<td>North America</td>
<td>31.1</td>
</tr>
<tr>
<td>Oceania</td>
<td>1.2</td>
</tr>
<tr>
<td>South America</td>
<td>9</td>
</tr>
</tbody>
</table>

TABLE 1. Share in global FPV potential per continent (calculated from\(^{12}\))

COST OF FLOATING PV

The main difference between installation costs of a floating PV with that of a ground-based PV system is on floating structure, mooring and anchoring systems, and cabling. Example MWp scale projects across the globe show the CAPEX cost of FPV between 0.8 to 1.2 $/Wp, which is around 18% more than conventional ground-based PV system. However, this extra cost is compensated as FPV systems yield more energy because of lower working temperature and more favourable free horizon for the modules. The yield gain of FPV systems has been reported differently so far\(^{17,18}\), but an FPV system in warmer climates gives higher yield gain (~10%) while in colder regions the gain drops (~5%). Overall, depending on the installation region, this results in respectively 3-4% and 8-9% higher levelised cost of electricity (LCOE) for floating PV compare to ground-based PV plants\(^{19}\). Table II represents the percentage breakdown of the system components cost for a MWp scale FPV project.

<table>
<thead>
<tr>
<th>FPV component</th>
<th>CAPEX share (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Modules</td>
<td>34.2</td>
</tr>
<tr>
<td>Inverters</td>
<td>8.2</td>
</tr>
<tr>
<td>Mounting system (Floating structure, anchoring, and mooring system)</td>
<td>20.5</td>
</tr>
<tr>
<td>BOS (cables, junction boxes, switchboards, transformers, etc.)</td>
<td>17.8</td>
</tr>
<tr>
<td>Design, construction, testing and commissioning</td>
<td>19.2</td>
</tr>
</tbody>
</table>

TABLE 2. Share in total FPV CAPEX per component (calculated from\(^{19}\))
There are several unique features and functionalities associated with FPV plants, which might bring both opportunities and challenges. The following tables make an overview of the opportunities and challenges come into play when one considers FPV plants.

### TABLE 3. Opportunities coming along with floating photovoltaic plants.

<table>
<thead>
<tr>
<th>Opportunities</th>
<th>Comments and/or evidence to support</th>
</tr>
</thead>
<tbody>
<tr>
<td>Saving land</td>
<td>Using water area, that is a non-revenue generating surface, keeps the land saved for other land-incentive markets such as housing, agriculture, tourism, mining, etc. This a trivial fact, supported by literature20/21/22/23.</td>
</tr>
<tr>
<td>Radiation balance</td>
<td>Since PV modules are designed to absorb as much as light possible, they have very low albedo. Therefore, land-based PV plants strongly modify the land albedo, which depends on the type of material covering it (e.g. for vegetation is 20-30%, for desert is 40-50%)24. Such radiation imbalance may raise issues related to local temperature and microclimate. For the water, however, the albedo is ~6%25/26, which goes with the low albedo of the PV modules and therefore no to low radiation imbalance will happen.</td>
</tr>
<tr>
<td>Increased efficiency</td>
<td>As the convection is the main cooling mechanism for PV modules27, and the air above water area is cooled down by the air, therefore the PV modules, which have negative temperature coefficient work at higher voltage, which leads to more efficiency and total energy yield. A study showed in tropical climates, e.g. Singapore, the irradiance weighted temperature difference of floating PV can reach to 14.5 °C, while for maritime climates (e.g. the Netherlands) this value reduces to 3.2 °C. This plot shows the heat loss coefficient FPV systems compared to reference rooftop PV in Singapore28.</td>
</tr>
</tbody>
</table>

20 — Rosa-Clot, 2020  
21 — Trapani et al., 2015  
22 — Sahu et al., 2016  
23 — Ranjarban et al., 2019  
24 — Ziar et al., 2019  
25 — Ziar et al., 2020  
26 — Séférian et al., 2018  
27 — Hasanuzzaman et al., 2016  
28 — Dörenkämper et al., 2021
When deployed on sweet water reservoir, floating PV can reduce the rate of water evaporation. In some countries, such as Morocco water evaporation can reach up to 3 m³/m²/year. A study performed in Jordan showed that installing floating PV can reduce the water evaporation by 60%. The figure shows the platform of the experiments conducted in Jordan[29].

![Floating PV platform in Jordan](image)

The yearly power production curve of hydropower plants (HPP) is mainly governed by water seasonal cycle, which complementary to sunlight irradiance cycle. Therefore, HPP and FPV can work complementary while FPV is benefiting from the surface of the calm water behind the dam and the already established grid infrastructure, and on the other hand HPP benefits from less water evaporation and complementary power production profile. Also with a coordinated control HPP and FPV can work together to provide stable power without the need for electrical storage. A research studied 20 largest HPPs across the World and concluded that by covering 10% of the HPP basins surface the HPPs energy production is increased by 65%[30]. The figure shows the hybrid HPP-FPV capacity around the globe[31].

![Hybrid HPP-FPV capacity map](image)

[29] — Abdelal et al., 2021
[30] — Cazzaniga et al., 2019
[31] — Lee et al., 2020
Easy and effective PV module cleaning

Due to accessibility to water, cleaning the modules for FPVs system is less expensive and can be done more frequently compared to land-based PV systems. The figure shows a snap of robot cleaning for a floating PV system installed in Spain.

Improved water quality

As a result of less light penetration into water, there will be lower chance for algae growth and therefore higher water quality is expected. For water quality assessment, usually total nitrogen (TN), total phosphorus (TP), chlorophyll-a, a measure of total phytoplankton abundance (Chl-a) and cyanobacterial chlorophyll, a measure of potentially toxic cyanobacterial abundance (cyano-Chl) are measured. So far, research result showed no discernible impacts on water quality as result of FPV installation or even improvement reported by observation of limiting Chl-a and nitrate concentrations. One-third to half coverage is recommended by the literature to preserve water quality while reducing water evaporation.

Longer life-time

Although land-based PV plants placed in dry areas benefit from high irradiance, but modules experience more severe thermal cycle as a result of high day and night temperature differences. This severely influence the lifetime of the modules and causes effects such as delamination. However, when PV modules are deployed on water, across 24 hours they experience very low temperature deference because the water has a high heat capacity. This will help PV modules longevity.

32 — Molina, 2021
33 — Ziar et al., 2020
34 — Baradei, Sadeq, 2020
35 — Ferrara, Philipp, 2012
Ease of deployment

For type one and two of the floats, deployment of floating PV systems can be easy and quick. Leading float manufacturers reported that when supply chain is in place, a team of trained installers can deploy between 500 KWP to 1MWp per day\(^{36}\). The figure shows a team installing pure-float based FPV in modular and quick way\(^{37}\).

<table>
<thead>
<tr>
<th>Challenges</th>
<th>Comments and/or evidence to support</th>
</tr>
</thead>
<tbody>
<tr>
<td>Complex mooring and anchoring</td>
<td>Anchoring and mooring system choice and design might change per morphology of the installation location. Key influential factors are: type of the soil at the bottom of the water basin, water depth, and maximum water level variation. Also, as the size of FPV increases the number of mooring lines increases. Around 30 mooring lines are needed per MWp of floating PV(^ {38}). Calculating the forces on each mooring line at different wind and wave scenarios is a challenging engineering task. For instance, the figure shows Anhui CECEP’s floating solar plant in China (70 MWp) which uses bottom anchoring with 1500 anchors(^ {39}).</td>
</tr>
</tbody>
</table>

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\(^{36}\) World Bank, 2019  
\(^{37}\) Clean Technica, 2019  
\(^{38}\) Solarplaza Webinar, 2020  
\(^{39}\) Anhui CECEP, 2021
Although soiling is most severe for PV plants in dry regions with dust events, recent researches showed that dirt and bio-fouling is a considerable effect for floating PV systems. One reason is birds visit floating PV systems quite often. If not cleaned, dirt and bio-fouling cause hot spots and damage PV modules\textsuperscript{40/41}. Research shows the modules with higher tilt are less likely to get fouled by birds, as it is more difficult for bird to stand for a long time on them. The figure shows heavy bio-fouling on PV modules and reflectors and hot-spot as a result of dirt\textsuperscript{42/43}.

There are few advantages for floating PV in terms of maintenance, such as easier access to water for cleaning and lower risk of theft or vandalism. However, generally maintenance procedure, either preventive, corrective, or preventive, for floating PV plants is not as straightforward as that of the land-based systems. For floating PV, it is harder to access and replace components, which could be needed more frequently because highly-humidity environment may accelerate corrosion and components are very likely to have biofouling\textsuperscript{44}.

Floating PV reduces light penetration into the water and reduces underwater biomass and photosynthesis rate. Therefore, floating PV might reduce oxygen concentration of water, which can affect fishes. Low oxygen concentration (anoxia) can also increase methane release in shallow lakes. A research reported periods of anoxia is more frequent under floating PV plants compare to open water areas\textsuperscript{38}.

Since cables, junction boxes, fuses, and other balance of the system components are working under very humid condition, the longevity of the components might be affected. Submerging cables and connectors into water can cause current leakage and low insulation resistance, corrosion of cables, and eventual loss of power. The figure shows biofouling on submerged connectors and cables\textsuperscript{40}.
| Low TRL for high-wave categories | Although floating PV plants with membranes as floating platform are installed in coastal areas, the technology readiness level (TRL) of floating PV system for high wave categories is lower. There are four categories for the FPV. The first three categories are for inland water areas, respectively for negligible, 1m-, and 2m-wave heights. The fourth category is for open seas for which the floating PV systems should withstand waves up to 10 meters of height\(^45\). Comparative projects running at various places in the World show that the technology readiness level is higher for the lower wave categories\(^46\). |
| Lack of FPV-specific Standards | As a technology, floating PV is still in its nascent stages, and thus, there are no specific standards available at the moment. The standards written for ground-based PV systems cannot be extended for FPV as they comprise floating platform and anchoring and mooring systems placed on top of the water surface. Formulating FPV-specific standards and guidelines for designs will help to ensure that FPV system and its components can survive harsh environmental conditions while retaining the quality over 20 years without causing considerable impact on water ecosystem and biodiversity\(^47\). |

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45 — Folkerts et al., 2017  
46 — TNO, 2020  
47 — Acharya et al., 2019
NOTABLE FLOATING PV PROJECTS AROUND THE WORLD

The first floating PV system (20 kWp) was built in 2007 in Aichi, Japan for research purposes, followed by the first commercial scale (175 kWp) floating PV plant installed in California, USA in 2008\(^\text{48}\). Many floating PV systems were developed afterwards, mostly leading by countries with high population density and/or land scarcity\(^\text{49}\). Nowadays, in 60+ countries floating PV plants are either installed or planned to be installed soon. By the end of August 2020, the cumulative installed FPV capacity Worldwide was reported 2.6 GWp\(^\text{50}\). Figure 5 shows a few notable FPV system installed across the World. Such examples are practical proves of technological feasibility of floating PV plants and shows that floating PV has gained momentum.

Notable floating PV systems around the World, (a) first commercial scale floating PV plant, Far Niente wineries in California, USA. SPG Solar was contracted by the owners of the winery to install the array in 2008 with 175 kWp\(^\text{51}\), further extend to 400 kWp\(^\text{52}\), (b) the largest floating PV plant in the World to date, 70 MWp installed at a former coal-mining area of Anhui Province, China\(^\text{53}\), (c) World’s first combination of hydropower plant and floating PV plant, 220 kWp capacity installation on a hydroelectric dam of Alto Rabagão in Portugal in 2016\(^\text{54}\), (d) Pilot of the first off-shore floating PV installed in 2019 in the North Sea with 8.5 kWp, then expended to 50kWp in 2020. Further expansion to 1MW is planned in a modular manner. It is claimed that the pilot module was designed to withstand 13-meter waves. The system survived storms Ciara and Dennis in February 2020\(^\text{55}\), (e) single floater, 50 m diameter, 100 kWp floating PV demonstrator system installed for a fish farm operator in Norway in 2018. Being engineered for operations in coastal waters and on man-made reservoirs based on a design that integrates aspects

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48 — Trapani et al., 2015  
49 — Patil Desai Sujay et al., 2017  
50 — Hauwitz, 2020  
51 — Trapani et al., 2015  
53 — PV Tech, 2019  
54 — Ciel Terre, 2021  
55 — Oceans of Energy, 2019
of open-sea salmon farm architecture, the system uses silicon PV modules mounted on a flexible hydro-elastic floating membrane. [f] One of the first commercial scale bifacial floating PV ~450 kW installed on artificial Toules lake in Swiss Alps in 2019. [g] Retractable and tumbler floating PV systems, respectively enables mowing activities on waterbodies and horizontal-axis sun tracking both with bifacial PV and reflector installations. The pilot systems were installed in the Netherlands in 2019.

CONCLUSION

Implementation of floating PV systems can solve the land surface conflict between essential sectors of food, accommodation, and energy for growing population of the World. Moreover, floating PV has low to no effect on surface radiation balance, a feature that land-based PV plants are greatly missing by modifying land albedo. On top of that, floating PV can prevent water evaporation in dry regions. These three key features: (1) solving the surface conflict, (2) maintaining Earth surface radiation balance, and (3) preserving sweet water resources, among other advantages, makes floating photovoltaic plants a unique energy solution for the decade to come, and possibility the years after. While working on addressing the challenges with floating PV, energy-related engineering and research communities should note that FPV systems are not competitors of ground-based PV systems and can been seen as a different implementation of PV modules that brings several advantages and is multi-purpose.
REFERENCES


25. MOLINA, P.S., Cleaning robot for floating PV. PV magazine, 2021 available online [https://www.pv-magazine.com/2021/03/08/cleaning-robot-for-floating-pv/].


The transition towards a society without greenhouse gases emissions is one of the most critical challenges of humankind. This transition requires systemic changes in our way to obtain and use energy, as well as how we process the available natural resources. Those systemic changes must evolve to the paradigm of the circular economy of materials, avoiding the generation of end waste products, as happens in most of the natural balanced ecosystems, where no wastes are really produced.

Hydrogen is one of the vectors that are called to play a significant role into a sustainable future society. Hydrogen can be a suitable molecular energy vector integrated as main constituent of a variety of clean fuels, from pure Hydrogen or forming molecules as hydrocarbons or ammonia, as well as a worthy intermediate or raw material in many industrial processes, for instance, in steel industry. Even now is a critical element in processes as oil refineries or fertiliser production. Being a very abundant component of our planet, hydrogen is a molecule that is not available isolated on Earth. The utilisation of hydrogen requires the splitting of hydrogen-rich molecules as is the case of water or hydrocarbons. The splitting of water is currently technologically available by electrolysis or some thermo-chemical processes, facing some challenges as energy requirements, water pre-treatment and availability, and its economy of scale. Energy requirements for water or hydrocarbon dissociation are depicted in Figure 1. Such way of producing hydrogen is called green hydrogen, because carbon is not included in the process, and no direct CO₂ is produced.
Another route to obtain hydrogen is decomposing the hydrocarbon molecule by chemical processes, in most cases in combination with water. In fact, hydrogen is obtained today mainly by natural gas steam reforming and coal gasification, based on the following general balance:

\[ C_{x}H_{y} + 2xH_2O \rightarrow (y/2+2x) H_2 + xCO_2 \]

that for the case of methane reforming (x=1, y=4) is:

\[ CH_4 + 2H_2O \rightarrow 4H_2 + CO_2 \]

For natural gas, components as ethane (x=2, y=6), propane (x=3, y=8) should be added to the balance according to their mol share. For coal gasification (y=0, x=1), the balance is:

\[ C + 2H_2O \rightarrow 2H_2 + CO_2 \]

Those processes produced CO\(_2\), as the carbon atom is directly transferred to a CO\(_2\) molecule to maximise the extraction of the hydrogen from the hydrocarbon and water. As a matter of fact, each carbon molecule is theoretically transformable into CO\(_2\).

An additional group of processes are based on pyrolysis of the hydrocarbon, in the absence of oxygen, by the general balance equation:

\[ C_{x}H_{y} \rightarrow xC + (y/2)H_2 \]

For the methane pyrolysis (x=1, y=4), the general balance is:

\[ CH_4 \rightarrow C + 2H_2 \]

The absence of oxygen in the process, avoiding the formation of CO\(_2\), but creating a large amount of solid carbon, that should find a market. At present time, such market is small compared to the energy market. The processes for hydrogen production based on hydrocarbons have the challenge to include, either the CO\(_2\), or the solid Carbon, into the circular economy.
Hydrogen generation without CO₂ emissions is the key aspect that has to be achieved to make possible the future role of this vector. One of the paths is the extraction of hydrogen from water resources using electricity from renewables, called green hydrogen. Another alternative is the improvement of existing thermal technologies (currently called grey hydrogen), that are completely mature in their hydrogen core processes, to extract hydrogen from hydrocarbons and water. Those processes require the implementation of carbon capture and sequestration (CCS) technologies to reduce significantly CO₂ emissions. Such schemes produce the so-called blue hydrogen. An additional technology under development is the hydrocarbon pyrolysis, with no direct CO₂ production, that has started to be called turquoise hydrogen.

In practice, the classification of the flavour of hydrogen is proposed to be based in accordance with the results of the life cycle assessment of each technology, as described in Figure 2. The greenhouse equivalent environmental impact has been currently established in 4.3kg CO₂/kg H₂ for the certification of blue or green hydrogen, corresponding to the 40% of the emission of natural gas reforming. This number takes into account an analysis from the natural resources of the energy input, to process equipment manufacturing and input material transport. A specific list is followed in the following table.

<table>
<thead>
<tr>
<th>Technology</th>
<th>Resource</th>
<th>Type</th>
</tr>
</thead>
<tbody>
<tr>
<td>Electrolysis from renewables</td>
<td>Water</td>
<td>Green</td>
</tr>
<tr>
<td>Steam reforming + CCS</td>
<td>Water + Fossil/Hydrocarbon</td>
<td>Blue</td>
</tr>
<tr>
<td>Gasification + CCS</td>
<td>Water + Fossil/Hydrocarbon</td>
<td>Blue</td>
</tr>
<tr>
<td>Pyrolysis</td>
<td>Fossil/Hydrocarbon</td>
<td>Turquoise</td>
</tr>
</tbody>
</table>

**FIGURE 2.** Classification of hydrogen flavour from carbon footprint. (https://www.certifhy.eu/).
Hydrogen at very high scale is currently produced by thermal processes from fossil resources, such as natural gas or coal. Chemical processes as steam reforming or coal gasification are mature and intensively applied in ammonia and oil&gas processing industry, accounting for more than 90% of the world hydrogen generation [1]. The unitary cost of hydrogen by natural gas reforming (SMR) is the most competitive, as shown in Figure 3. The goal to advance in the use of hydrogen as energy carrier and end energy vector requires the availability of large hydrogen production capacity.

**FIGURE 3. Hydrogen cost of hydrogen production technologies.**

In many high scale projects, for instance, the H21 project in Leeds (https://www.h21.green/), hydrogen is envisaged to be produced by natural gas steam reforming, as the technology that can offer a high production capacity and better economy for hydrogen production. As it has been mentioned, mature chemical processes based on the use of hydrocarbons produce CO₂. Nevertheless, the addition of CO₂ capture techniques reduces strongly the carbon footprint of those processes down to 90% in comparison with the same process without CCS, increasing the cost around 30%, but keeping its competitiveness versus green hydrogen at the present state-of-the-art of electrolysis technologies.

The integration of CCS and Hydrogen large production will require centralised plants for hydrogen production and capture systems, and an infrastructure to transport and store hydrogen and carbon dioxide. The transport of hydrogen may be done through the current natural gas infrastructure, either blended or pure (in the most ambitious schemes, as H21) with the required adaptation of appliances and network equipment. The carbon dioxide may be integrated with additional transport infrastructures, and storage facilities.
The implementation of carbon capture technologies may be considered mature, an already implemented at large scale in the gas processing industry. In parallel, sequestration techniques for enhance oil recovery may be considered mature as well, and ready to be deployed. The main challenge of CCS may be the availability of enough sequestration capacity to manage the large amount of CO₂ that will be produced if the hydrogen economy is developed, as well as its coexistence with the demand from other thermal plants worldwide.

**METHANE PYROLYSIS**

Pyrolysis is the splitting of hydrocarbon molecules into their components: solid carbon and hydrogen. For the case of natural gas, the available hydrocarbon with higher H/C ratio, with methane as its main compound, pyrolysis is described by the following general reaction:

\[
\text{CH}_4 \rightarrow \text{C} + 2\text{H}_2 \quad (\Delta H^\circ = 32.43 \text{ kJ/molH}_2)
\]

This is a technological solution based on a process able to transform natural gas resources into pure graphitic carbon and high purity industrial hydrogen. There is a large amount of work available about this reaction, including extensive reviews [3], [4]. Temperatures over 500°C are needed to start the methane decomposition, reaching high conversion rates over 1100°C. The use of catalysts reduces the reaction temperature for high conversion rates [5] [6]. The conversion rate of this reaction versus temperature is in Figure 5.
The technological status of pyrolysis is under development, with a real chance to be scaled and commercially available in the next 10 years. There are some different techniques that are on the way to achieve this goal, and summarised in the table.

![Equilibrium conversion of H₂ by methane pyrolysis](image)

<table>
<thead>
<tr>
<th>Technology</th>
<th>Advantages</th>
<th>Disadvantages</th>
</tr>
</thead>
<tbody>
<tr>
<td>Plasma-arc (+ microwaves)</td>
<td>Flexible reactors</td>
<td>Low energy efficiency (electricity)</td>
</tr>
<tr>
<td></td>
<td>Known technology</td>
<td>Limited scalability</td>
</tr>
<tr>
<td>Catalytic thermal</td>
<td>Lower temperature</td>
<td>Catalyst cost</td>
</tr>
<tr>
<td></td>
<td>Scalability</td>
<td>Catalyst deactivation</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Catalyst impact and management</td>
</tr>
<tr>
<td>Liquid metals</td>
<td>Good heat transfer</td>
<td>Corrosion of reactor</td>
</tr>
<tr>
<td></td>
<td>No blocking due to solid carbon deposit</td>
<td>Metal inventory</td>
</tr>
<tr>
<td></td>
<td>Good potential for C separation</td>
<td>Carbon purity</td>
</tr>
<tr>
<td>Molten salts</td>
<td>Low corrosion issues</td>
<td>Stability at high temperatures</td>
</tr>
<tr>
<td></td>
<td>Good heat transfer</td>
<td>Carbon purity</td>
</tr>
<tr>
<td></td>
<td>No blocking due to solid carbon deposit</td>
<td></td>
</tr>
<tr>
<td>Thermochemical processes based on salt intermediates</td>
<td>No blocking due to solid carbon deposit</td>
<td>Heat integration</td>
</tr>
<tr>
<td></td>
<td>Separation of H₂ and C in two reactors</td>
<td>Safety issues (HCl)</td>
</tr>
</tbody>
</table>
The utilisation of a plasma-arc is the most developed option up to now. The main industrial reference was the development of the Kvaerner CB&H process [7]. The production capacity of the Kvaerner plant was 500 kg/h of pure carbon and 2000 Nm3/h of Hydrogen. Finally, the factory was shut down. Other similar practical implementations are proposed based on the production of carbonaceous aerosols with plasma technology [8]. This process has as main advantage the high TRL (Technology Readiness Level), but it has as main drawback the low energy efficiency of the process. Additional ways of providing energy are based on the use of microwaves, which offers non-thermal processing using high-energy electrons to initiate methane pyrolysis, reducing the energy requirements of the process [9, 10].

Direct thermal cracking is based on the thermal heating of methane up to high temperatures (above 1300 °C) to arrive to the almost complete development of the methane cracking reaction. Originally, this technique has been proposed as technological mean to produce hydrogen for the production of clean solar fuels. The viability of this technique has been proven at laboratory scale, reporting practically complete methane to hydrogen conversions [11]. Nevertheless, this route has shown practical problems from scaling [12].

Catalysed thermal decarbonisation is the alternative for the methane pyrolysis reaction at lower temperature. The identification of suitable catalysts has been widely studied for metallic and carbonaceous catalysts. [13], [14]. The challenge in this case is the design of a continuous device that could be used at industrial scale. In brief, Nickel could be applied as catalyst for the reaction between 500 and 700 °C, what is a rather convenient temperature for an engineering industrial device. Nevertheless, as a consequence of the process, part of the carbon is deposited in the tip of the catalyst producing its deactivation.

Different reactor designs have been successfully used alternating cracking and regeneration cycles in continuous mode, as parallel fixed-bed reactor and fluidised bed reactors. The most relevant implementation of catalysed thermal decarbonisation was the development and operation of the HYPRO process [15], based on fluidised bed reactors, with decomposition and regeneration sections, but it demonstrated high operation costs, unable to be competitive at that time. Catalytic thermal pyrolysis has become a high TRL as well (around 7), but it has to overcome the difficulties for catalyst management and regeneration to increase substantially the economic viability.

Liquid metal driven methane decomposition has been proposed as a potential technology that could lead to the practical industrial implementation of methane cracking. Its main characteristic is the management of the carbon particles into the reactor by differential density, and the scaling capabilities of high thermal diffusivity of a liquid media. Liquid tin [16] or gallium [17] are proposed as molten media for the reaction, as well as liquid metal alloys containing nickel, with a catalytic effect [18]. Additional work should be done to determine the scalability of this concept, and the compromise between complexity, performance and economics of the process from the utilisation of various liquid metal, with or without embedded catalysts. On the hand, corrosion issues have to be addressed for the evaluation of the lifetime of high scale reactors. The level of development of this type of reactors is around TRL 4, with some research ongoing to advance to TRL 5.

Molten salts [19] are another liquid media with some conceptual aspects very similar to liquid metals, but with certain differences. Being more complex as a molecule, long term stability is an issue to study in the case of operating at high temperatures and as reaction media. As an advantage, some molten salts may be used as carbon transport media from the reactor.

Some other concepts are based on chemical looping concepts, producing the methane pyrolysis induced by the presence of some intermediate compounds [20]. Those methods are in their first stage of development.
CONCLUSION

Hydrogen is called to play a very significant role in the energy transition towards a decarbonised system. The challenge is enormous to comply with the requirements of a massive availability of hydrogen without generation of CO₂. Green hydrogen has to demonstrate its economic viability at very high scale, being one of the options in the future. Grey hydrogen (natural gas reforming and coal gasification) are commercially available, but the CO₂ released in those processes rejected them as suitable hydrogen production method in the long term. The solution to this dilemma is a real breakthrough for the next decades.

The options to advance in decarbonisation and use hydrocarbons in the following decades (and enabling the introduction of fossil raw material in the circular economy), complying with the requirements of the greenhouse emissions control are twofold: blue hydrogen, applying carbon capture and sequestration (CCS) techniques, and turquoise hydrogen, based on pyrolysis. The former is already available, and the latter needs a few years to complete its development, likely less than 10. Being blue hydrogen ready for its implementation, it has its own drawbacks in terms of availability of sequestration sites, own technical risks and public acceptance. Pyrolysis has the advantage of substituting CO₂ by solid carbon management, what is a valuable material, easy to integrate into the circular economy in the future, with much less infrastructure requirements.

The development of methane pyrolysis will increase significantly the chance of the energy transition [21], providing a technology that could be added and complement to the chemical processes with CCS, and the electrolysis in the longer term, making possible the introduction of the hydrocarbon resources in the circular economy, either in the chemical industry or for Power-to-X schemes.
REFERENCES


Nowadays we face the situation when the effects of global warming are rapidly increasing, and the search for solutions goes beyond a simple technological problem [1]. We are in need of more integrated solutions connecting various areas and, as a result, bringing about a change in the patterns of life, thus ensuring the future of the planet and a sustainable development of society.

The new approach has led, for example, to the situation when CO₂, which is one of the main greenhouse gases, is no longer considered a waste but serves as a raw material for obtaining a significant range of the value-added products. This explains the renewed interest in the CO₂ conversion reactions that before now were used in industrial processes for processing only relatively small amounts of the above-mentioned compound. At present, there is no large-scale production allowing industrial processes without CO₂ emission. The reason is dependence, in most cases, of the economic viability of CO₂ conversion reactions on sustainable supply of H₂.

Industrialisation and population growth resulted in a sharp increase of global energy consumption, and anthropogenic CO₂ emissions increased quickly because now fossil fuels are the main consumed energy resources. A steady rise of CO₂ concentration in the atmosphere leads to global warming and a number of environmental problems. Average global temperatures have risen by 0.8°C over the past 70 years [1]. The Paris Agreement is one of the international efforts made to reduce CO₂ emissions. At the same time, many studies have focused not only on development and application of the renewable energy sources as a means for reduction of dependence on fossil fuels [2] but also on technologies for CO₂ capturing and utilising.

Fossil fuels are the main source of energy resources and carbon dioxide emissions. The world’s daily consumption of coal is ~22 million tons, oil is ~12 million tons and natural gas ~10 billion m³ [3]. Human activities result in about 34 billion tons of CO₂ annual emission into the atmosphere, almost 80% of which comes directly from fossil fuels.

Coal, oil and gas are expected to remain dominant in the global energy consumption in the coming decades. There is a predicted rise of contribution made by non-fuel (carbon-free) energy sources, but it will not exceed 30% (Fig. 1).
Coal has been one of the cheapest and affordable sources of energy for many decades, and it will remain as such in the near future [4]. Currently, the share of coal-fired generation in the installed capacity of power plants in Russia is about 22% (56.6 GW). The share of coal generation reaches 65% in the Siberian Federal District and 93% in the Far Eastern Federal District [5]. Russia ranks 13 in the world in terms of electricity generation by coal-fired thermal power plants, behind China, India, the USA, the EU, and other states with energy systems based on coal generation [6].

The heating value of coal depends on its composition; it is ~30 MJ/kg for bituminous coal. As it is with combustion of any carbon-containing fuel, coal combustion produces a significant amount of carbon dioxide - 3.7 t of CO$_2$ per 1 t of C.

\[
C + O_2 \rightarrow CO_2
\]

Table 1 presents data on the specific amount of CO$_2$ for various grades of coal without taking into account the heat loss during combustion, which can reach 55–75%. As we can see, the rise of carbon content in fuel raises carbon intensity of the generated power. Compared to other fuels, coal is distinguished by higher emissions of CO$_2$ (Fig. 2).

<table>
<thead>
<tr>
<th>Fuel</th>
<th>Specific carbon content in fuel, kg of C per kg of fuel</th>
<th>Specific energy content in fuel, kW·h/kg</th>
<th>Specific CO$_2$ emission</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>kg of CO$_2$ per 1 kg of fuel</td>
</tr>
<tr>
<td>Anthracite</td>
<td>0.92</td>
<td>9.0</td>
<td>3.37</td>
</tr>
<tr>
<td>Bituminous coal</td>
<td>0.65</td>
<td>8.4</td>
<td>2.38</td>
</tr>
<tr>
<td>Brown coal</td>
<td>0.30</td>
<td>3.9</td>
<td>1.10</td>
</tr>
</tbody>
</table>
FIGURE 2. Contribution of the type of fuel to CO₂ emissions, and the amount of CO₂ emitted per 1 kWh of electricity obtained from combustion of various types of fuel [8].

<table>
<thead>
<tr>
<th>Fuel Type</th>
<th>CO₂ Emissions (kg per 1 kWh)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Natural gas</td>
<td>0.20</td>
</tr>
<tr>
<td>Liquefied gas</td>
<td>0.23</td>
</tr>
<tr>
<td>Refinery gas</td>
<td>0.24</td>
</tr>
<tr>
<td>Petrol</td>
<td>0.25</td>
</tr>
<tr>
<td>Kerosene</td>
<td>0.26</td>
</tr>
<tr>
<td>Raw oil</td>
<td>0.26</td>
</tr>
<tr>
<td>Diesel fuel</td>
<td>0.27</td>
</tr>
<tr>
<td>Fuel oil</td>
<td>0.28</td>
</tr>
<tr>
<td>Bituminous coal</td>
<td>0.34</td>
</tr>
<tr>
<td>Brown coal</td>
<td>0.36</td>
</tr>
<tr>
<td>Peat</td>
<td>0.38</td>
</tr>
<tr>
<td>Wood</td>
<td>0.39</td>
</tr>
</tbody>
</table>

As of 2019, Russia is responsible for 4.71% of greenhouse gas emissions, after China (30.34%), the USA (13.43%), the EU27 + the UK (8.69%) and India (6.83%) [9].

In total emissions from 1850 to 2007, the top countries are as follows: 1. The USA: 28.8%, 2. China: 9.0%, 3. Russia: 8.0%, 4. Germany: 6.9%, 5. UK: 5.8%, 6 Japan: 3.9%, 7. France: 2.8%, 8. India: 2.4%, 9. Canada: 2.2% and 10. Ukraine: 2.2% [10].

To reduce harmful emissions into the atmosphere, almost all countries with the developed economies and technologies have set the task of coal gradual reduction in the energy balance. To raise efficiency and environmental friendliness of coal-fired generation, the technologies known as Clean Coal or High Efficiency Low Emissions (HELE) have been implemented [6]. They include technological solutions to suppress pollutant emissions and purify flue gases by raising the quality of burned coal, using the nitrogen, desulphurisation and ash filters as well as a set of measures to combat climate change by increasing the efficiency of coal generation, capturing carbon dioxide and joint combustion with biomass (Fig. 3).

FIGURE 3. Technologies Clean Coal or HELE (High Efficiency Low Emissions) [6].
GREENHOUSE EFFECT AND CO$_2$

Carbon dioxide belongs to greenhouse gases (H$_2$O, CO$_2$, CH$_4$, N$_2$O and O$_3$) playing a significant role in the Earth's heat balance and the greenhouse effect formation (Fig. 4) although they make up a small part of the atmosphere.

The current century has been distinguished by a continuous rise of CO$_2$ concentration, which is 418 ppm as of March 2021 according to the Mauna Loa Observatory in Hawaii (USA [12]). This is significantly higher than the pre-industrial, average CO$_2$ concentration of 277 ppm. If the atmospheric carbon dioxide mass in the real atmosphere doubles, which is supposed to occur in about 120 years, at the current growth rate, the global temperature is expected to increase by 2.0 ± 0.3 K [13].

Carbon dioxide is recognised as a powerful regulator of the Earth's climate. In terms of its greenhouse properties, it occupies the second place after water vapour, and it is the rise of the CO$_2$ concentration that an increase in the greenhouse effect is associated with. This is determined by the specific features of energy absorption in the infrared spectrum by the CO$_2$ molecule [14–16].

Interest in scientific development regarding reduction of carbon dioxide emissions by processing them into useful products is constantly growing throughout the world. Over the past 20 years, the Elsevier publishing house has seen an exponential increase (according to the Scopus database) in publications on CO$_2$ capture and utilisation in international journals, and for 2021, it has provided over 12,000 articles: more than 4,000 publications are from China and 2,000 from the USA; as for Russia - less than 200 so far (fig. 5).
Two main technologies are relevant: Carbon Capture and Utilisation (CCU) and Carbon Capture and Storage (CCS), each involving capture and concentration of CO₂ (Fig. 6, 7) at the first stage.

**FIGURE 6.** The strategy for reduction of anthropogenic CO₂ emissions [17].

**FIGURE 7.** Technologies for CO₂ capture [18].

The sorption methods for capturing and concentrating carbon dioxide are very attractive due to their low cost and simplicity of technical solution. Various types of CO₂-adsorbents have been proposed, differing in their chemical composition, texture, morphology and, accordingly, capacity and selectivity. Sorbents can be conditionally divided into three large groups, depending on the range of their operating temperature: low-, medium-, and high-temperature adsorbents with sorption/desorption temperatures T<200°C, 200°C <T<400°C and T>400°C, respectively [19].
Research of sorption methods for carbon dioxide capturing and concentrating is performed in the following areas:

- Development of methods for obtaining the effective liquid and solid CO₂ sorbents
- Modification of carbon sorbents
- Kinetics of sorption and capacity of carbon sorbents
- Optimisation of conditions for the CO₂ activated carbon sorption

For chemists, utilisation technology (i.e. CO₂ conversion into valuable chemical products and materials) is more attractive. Once captured and concentrated, CO₂ can serve as a precursor for production of many chemical products. At present, the annual volume of CO₂ industrial use is about 120 million tons, which is less than 0.5% of the total annual anthropogenic emissions of CO₂ equal to 34 billion tons. In this regard, expansion of the CO₂ application as a precursor for chemical processes is a very urgent task aimed at solution of issues of environmental safety and rational use of natural resources.

The general line of the CO₂ chemical utilisation is catalytic conversion into products with a high added value. Currently, large-scale processes for production of urea, salicylic acid, ethylene carbonate, and methanol have been mastered on an industrial scale.

CATALYTIC METHODS OF CONVERTING CARBON DIOXIDE INTO USEFUL PRODUCTS

Converting CO₂ into fuel and valuable products of the chemical industry is one of the most promising ways of CO₂ utilisation. This way of utilising carbon dioxide refers to cyclic technologies when many times are repeated the stages of CO₂ capture, its processing into products and then, emission of CO₂ when using the obtained product. This method does not completely remove CO₂ from the atmosphere but it does reduce the application of fossil fuels. The volume of CO₂ conversion into chemical products (urea, polycarbonates) and fuel (methanol, methane, dimethyl ether, Fischer-Tropsch synthesis products) will reach 0.3–0.6 and 1–4.2 billion tons of CO₂ per year in 2050, which is 4–14 % of the current level of anthropogenic CO₂ emissions - 34 billion tons per year [20]. Advancement of catalytic technologies is expected to raise the energy efficiency, increase the list of processes for obtaining useful products from CO₂ and reduce their cost.

There exists a wide range of technologies for converting CO₂ into useful products with different levels of development — industrial processes, pilot projects and laboratory developments (Fig. 8).

Catalysis is a key technology for an efficient and more sustainable use of resources, which is crucial for the economies of many countries. This provides lower energy processes, reduced waste and pollution, and improved selectivity in the value-added products for all sectors. Around 90% of all chemical processes use catalysts with the estimated economic impact on 30-40% of the world GDP. Heterogeneous catalysts are already the key component in this sector, ranging from petrochemical plants to catalytic converters for internal combustion engines.

As the world moves toward more sustainable technologies and raw materials to ensure a cleaner future, the role of heterogeneous catalysts is going to gain higher importance. This affords opportunities for a new generation of environmentally friendly catalysts or even demands a glimpse into the past of more traditional catalysts.

Modern industrial world would be impossible without catalysts. Development of chemical products in the developed industrial countries will be technically, economically and environmentally possible only with the help of special catalysts. At present, over 15 international companies manufacture about 100 basic types of solid catalysts. Catalysts play a significant role in industry from an economic point of view and in terms of the environmental pollution reduction.

Nowadays, the chemical products produced from CO₂ on an industrial scale are as follows: urea (1), salicylic acid (2), ethylene carbonate (3), and methanol (4) (Fig. 9).
FIGURE 8. End products of CO₂ processing [21].

FIGURE 9. The industrial processes of CO₂ conversion [22].

1. \[2 \text{NH}_3 + \text{CO}_2 \rightarrow H_2N\text{NH}_2 \quad \Delta H = -101 \text{ kJ mol}^{-1}\]
   In industry (1922)

2. \[\text{C}_6\text{H}_5\text{OH} + \text{CO}_2 \rightarrow \text{C}_6\text{H}_5\text{CO}_2\text{H} \quad \Delta H = -31 \text{ kJ mol}^{-1}\]
   In industry (1890)

3. \[\text{C} + \text{CO}_2 \rightarrow \text{CO} \quad \Delta H = -144 \text{ kJ mol}^{-1}\]
   In industry (since the 50s)

4. \[\text{CO}_2 + 3\text{H}_2 \rightarrow \text{CH}_4\text{OH} + \text{H}_2\text{O} \quad \Delta H = -130 \text{ kJ mol}^{-1}\]
   In industry (2011)
CARBAMIDE (UREA) PRODUCTION

The capacity of urea plants in the USSR had exceeded 5 million tons per year by the end of 1972 and accounted for more than 30% of the world production. In the 1970s, according to the government's decision, there was purchased urea production equipment with the capacity of 330 and 450 thousand tons per year by technologies of all leading foreign companies.

Ammonia and carbon dioxide convert to urea via ammonium carbamate at the pressure of about 140 bar and the temperature of 180–185°C. Ammonia conversion reaches 41%, carbon dioxide - 60%. The unreacted ammonia and carbon dioxide enter the stripper, with CO₂ acting as a stripper agent. After condensation, CO₂ and NH₃ are recycled and returned to the synthesis process. The condensation heat is used for steam generation for the CO₂ compressor.

There are over five advanced urea production technologies in the world (Stamicarbon, etc.). Urea 2000plus, one of the new technologies, is successfully used in urea production with the capacity of 2,700 tons/day that was launched in China (CNOOC) in 2004 as well as in production with the capacity of 3,200 tons/day in Qatar (Qafco IV), launched in 2005. At the moment, there are also developments of urea mega-plants with the capacity of up to 5000 tons/day. New energy-saving technologies are used in urea production at the gas chemical plant Gazprom Neftekhim Salavat (Fig. 10).

A new unit for urea production with the capacity of 600 tons of "Urea-600" per day was put into operation in Veliky Novgorod in 2018. The new production facility was built with the URECON®2006 technology (Fig. 11). Currently, PJSC Acron is modernising its production, which will result in the capacity increase from 600 to 2050 tons/day [25]. The project investments amount to $85 million. Upon the project completion in 2021, the total annual urea production capacity will increase by 0.5 million tonnes and reach 1.9 million tons, which will make Acron the largest urea production site both in Russia and in Europe.
The use of carbon dioxide in production of this product has very good expansion prospects up to millions of tons because the urea chemical properties determine its widespread use in the chemical industry, in the synthesis of urea-aldehyde (primarily urea-formaldehyde) resins widely used as adhesives, in production of fiberboards and furniture. Urea derivatives are effective herbicides.

Part of the produced urea is used for melamine production. A significant share is used for the Pharmaceutical Industry needs.

By its nature, urea is a mineral fertiliser used for all types of soils for any crops. This form of fertilisation provides a significant increase in the yield of agricultural crops. Compared to the other nitrogen fertilisers, urea contains the largest amount of nitrogen (46.2%), which basically determines the economic feasibility of its use as a fertiliser for many crops on any soil.

In the animal husbandry, urea is added to feed as a protein substitute, and in medical practice, it is used as a dehydration agent.

A new large-tonnage area is the use of urea (as a reductant of nitrogen oxides) for cleaning the emissions from thermal power plants and waste incineration plants.

To achieve compliance of the composition of diesel engine exhaust emissions with Euro-4 and Euro-5 standards, the AdBlue urea solution is used.

In general, at urea production with the volume of ~200 million tons per year, it is possible to utilise up to 150 million tons of CO₂ per year. The process is carried out at the temperature of 185°C and the pressure of 150 bar, CO₂ conversion reaches 85–90%. When assessing the potential of this method of CO₂ utilisation, it is worth taking into account that one ton of urea consumes 0.58 tons of ammonia produced by a very well developed but energy- and carbon-intensive Haber-Bosch process [26]. In this regard, research is underway to develop carbon-neutral technologies for urea production using renewable energy sources. For example, urea has been synthesised from nitrogen, carbon dioxide, and water at room temperature, in the presence of the electrocatalyst made of copper and palladium nanoparticles applied on titanium dioxide (Fig. 12) [27].
SYNTHESIS OF POLYURETHANES

The next important industrial use of CO$_2$ is polyurethanes synthesis in which polyols and bis-isocyanates are usually used as precursors [22]. In the traditional Bayer process, polyl is the simple polyether made from epoxies, such as propylene oxide, the raw material for production of which is fossil fuels (Fig. 13).
In Covestro’s alternative DREAM process, polycarbonate polyol (where part of propylene oxide is replaced with carbon dioxide) is used instead of polyol. The capacity of the plant launched in 2016 by Covestro in Dormagen (Germany) is 5,000 tons of polyester carbonate polyol (Fig. 14). Direct copolymerisation of CO₂ with various epoxides (ethylene oxide, propylene oxide, cyclohexene oxide or isobutylene oxide) is a promising method for synthesis of aliphatic polycarbonates and polycarbonate esters for an important production of biodegradable materials.

The English Company Econic offers an energy-saving catalytic technology for the CO₂ conversion into polyols [29]. According to [20], the volume of carbon dioxide conversion into polymer products will have amounted to 10–50 million tons per year by 2050.

**SALICYLIC ACID**

An important process of using CO₂ as a chemical reagent is the salicylic acid production by the Kolbe-Schmitt reaction; the production volume is 0.025 million tons of CO₂ annually, although this is noticeably lower than the volume of its use in the synthesis of urea or polyurethanes.
METHANOL

Methanol is the most important organic substance in the chemical industry, with a global annual production of ~150 million tons [30]. Currently, it is mainly produced by catalytic technologies, from natural gas and coal gasification products. However, some alternative production methods using CO₂ are under development [3, 31, 32] within the framework of a sustainable development concept. To synthesise methanol from carbon dioxide and hydrogen, Cu-Zn-Zr-O catalysts are used that are promoted with additives of various compositions (Ga, La, Ce, Cr, Si, B, Al, In) [3]. It is considered [33] that the reaction involves two active centers: adsorption and dissociation of hydrogen occur on Cu centers, and adsorption of CO₂ in the form of bicarbonate — on ZrO₂ (Fig. 15). By means of a spillover, atomic hydrogen transfers from the Cu surface to the ZrO₂ surface where the adsorbed carbon and oxygen-containing particles hydrogenate to methanol later desorbed from the surface. Adding of zinc to the catalyst improves copper dispersion and provides additional adsorption centres for CO₂. Optimisation of the catalyst preparation and reaction conditions resulted in obtaining the following process parameters at 220°C and 2.8 MPa: methanol yield — 12.8%, CO₂ conversion — 20.3%, methanol selectivity — 63.2% [31].

FIGURE 15. Scheme of the reaction for producing methanol from CO₂ in the presence of Cu/ZrO₂ or Cu-ZnO/ZrO₂ catalysts [33].

The first modern industrial conversion of CO₂ into methanol has been carried out since 2012 by Carbon Recycling International (CRI) in Iceland (Fig. 16) [3, 34]. The plant’s capacity is 4,000 tons of methanol/year. At the same time, the estimated volume of CO₂ involvement in this process is 6,000 t/year. The hydrogen required for this technology is produced by water electrolysis using inexpensive and environmentally friendly energy from hydrothermal sources. CRI has developed an integrated plant project for renewable methanol production with the capacity of 100,000 tons/year (Fig. 17) [36].
The Canadian Carbon Engineering proposed Air to Fuels, another interesting approach and technology for carbon dioxide conversion using renewable energy sources; it proposes production of carbon-neutral liquid fuel from atmospheric CO$_2$ and H$_2$ obtained by electrolysis [37].
**CO$_2$ HYDROGENATION PROCESSES**

The next important group of catalytic processes for carbon dioxide conversion are hydrogenation processes with production of methane, higher hydrocarbons, oxygenates or synthesis gas (Fig. 18). Now in the chemical industry, lower hydrocarbons are obtained from non-renewable natural resources — through dehydrogenation of light alkanes or oil cracking. CO$_2$ conversion through hydrogenation opens up possibility for production of these valuable compounds from renewable raw materials, which reduces society’s dependence on fossil fuels.

**FIGURE 18.** The main directions of CO$_2$ conversion by hydrogenation it for production of methane, hydrocarbons, oxygenates, and synthesis gas.

**THE CO$_2$ METHANATION REACTION (SABATIER PROCESS)**

Has recently aroused interest as a way of CO$_2$ use and utilisation in the process of synthesis of substances — energy-efficient carriers for storing and transporting renewable electricity. This process is carried out at the temperature of $250-400^\circ$C and an elevated pressure in the presence of catalysts based on Ni, Rh or Ru, providing 100% CO$_2$ conversion [26]. In 2013, the Audi Company launched a Power-to-Gas (PtG) plant in Werlte (northern Germany) for production of synthetic natural gas from CO$_2$ and H$_2$. The plant includes a 6 MW renewable energy electrolysis unit for hydrogen production and a methanation unit. The scale of carbon dioxide utilisation is still small and amounts to 2800 t CO$_2$ annually [38].

The use of CO$_2$ in synthesis of C2-C4 hydrocarbons — a modified Fischer-Tropsch synthesis process — seems to be a very promising one. This process includes reaction, a reverse reaction of CO conversion with steam and a subsequent hydrogenation of CO with formation of hydrocarbons [26].

\[
\text{CO}_2 + 4\text{H}_2 \rightarrow \text{CH}_4 + 2\text{H}_2\text{O}
\]
Combination of this process with oligomerisation reaction opens up possibility for utilising CO\textsubscript{2} and obtaining hydrocarbons of gasoline fraction containing a mixture of isoparaffins, aromatic and naphthenic hydrocarbons of the C\textsubscript{5}-C\textsubscript{11} composition [39]. The uniqueness of this process is that hydrogenation reaction in the presence of multifunctional catalyst Na – Fe\textsubscript{3}O\textsubscript{4}/zeolite occurs in three stages (Fig. 19): (1) CO production by a reverse water gas shift (RWGS) at Fe\textsubscript{3}O\textsubscript{4} centres, (2) CO hydrogenation to olefins by the Fischer-Tropsch synthesis (FTS) at Fe\textsubscript{5}C\textsubscript{2} centers; and (3) formation of C\textsubscript{5}-C\textsubscript{11} hydrocarbons as a result of oligomerisation, isomerisation, and aromatisation of olefins at the zeolite acid centres. Selectivity of hydrocarbon formation is 78% with the CO\textsubscript{2} conversion of 22% [39].

An important area of CO\textsubscript{2} conversion is synthesis of formic acid CO\textsubscript{2} + H\textsubscript{2} → HCOOH and dimethyl ether (DME) which are large-tonnage products of the chemical industry and considered as the compounds for storing chemical energy. They serve as hydrogen carrier molecules in the cycles of storage and transportation of renewable energy [40]. For direct catalytic reduction of CO\textsubscript{2} for obtaining formic acid, both homogeneous systems - organometallic compounds containing Rh, Ru and Ir - and heterogeneous catalysts based on Pt, Pd, Au are used.
DME SYNTHESIS

\[ 2\text{CO}_2 + 6\text{H}_2 \rightarrow \text{CH}_3\text{OCH}_3 + 3\text{H}_2\text{O} \]

from \( \text{CO}_2 \) and \( \text{H}_2 \) involves sequential hydrogenation and dehydration reactions, which requires the use of bifunctional catalysts containing both metal (for example Cu) and acid centres. It has been shown that reducing the size of Cu-containing active particles is a successful approach for increasing the efficiency of this process [40].

\[ \text{CO}_2 + \text{CH}_4 \rightarrow 2\text{CO} + 2\text{H}_2 \]

A special place in catalysis is occupied by carbon dioxide conversion of methane (CDCM) which makes it possible to simultaneously utilise two greenhouse gases (\( \text{CO}_2 \) and \( \text{CH}_4 \)) and obtain synthesis gas as a product, suitable by its stoichiometry (1:1) for further conversion into synthetic fuel according to the Fischer-Tropsch reaction. Nickel catalysts are highly active in this reaction [41]. The process is carried out at the temperature of 800-900°C and under the atmospheric pressure, demonstrating high values of \( \text{CO}_2 \) conversion — 80-90%. There is shown the efficiency of composite catalysts where the particles of active component Ni are attached to the top of carbon nanotubes (Fig. 20) [42]. Adding water vapour to the reaction mixture expands the stability area of the system to formation of carbonaceous deposits, allows optimisation of the process parameters, providing the given completeness of conversion of reagents and the required composition of the resulting synthesis gas [43].

The Linde Company has developed DRYREF™ SMR technology in collaboration with BASF for improvement of the energy and economic efficiency of steam reforming and carbon dioxide utilisation [44]. According to the proposed scheme (Fig. 21), \( \text{CO}_2 \) is added to the reaction mixture containing natural gas and water. As a result, carbon footprint of the synthesis gas production reduces, steam consumption decreases, and synthesis gas is obtained with a lower \( \text{H}_2/\text{CO} \) molar ratio as compared to the parameters for steam methane reforming.
Processes in which CO\textsubscript{2} acts as a mild oxidant [45–48] are studied at the laboratory level. In the oxidative condensation of methane (CO\textsubscript{2}-OCM)

\[
\text{CO}_2 + 2\text{CH}_4 \rightarrow \text{C}_2\text{H}_6 + \text{CO} + \text{H}_2\text{O} \\
\text{CO}_2 + 2\text{CH}_4 \rightarrow \text{C}_2\text{H}_4 + 2\text{CO} + 2\text{H}_2\text{O}
\]

with formation of ethane and ethylene in the presence of a catalyst (MnO-SrCO\textsubscript{3}, ZnO-CeO\textsubscript{2} or CaO-CeO\textsubscript{2}), the CO\textsubscript{2} conversion is 5–7%, the yield of C\textsubscript{2} hydrocarbons is up to 5–7% [48].

Reaction of oxidative dehydrogenation of light alkanes with CO\textsubscript{2} participation is carried out at 650–700 °C in the presence of various catalysts (Pd/CeZrAlO\textsubscript{x}, CoMo/CeO\textsubscript{2}, GaN/SiO\textsubscript{2}) [47]. The yield of target products (ethylene, propylene) reaches 70%. The use of photocatalytic systems makes it possible to use a renewable energy source and to carry out the process under mild conditions (Fig. 22).

\[
\text{CO}_2 + \text{C}_2\text{H}_6 \rightarrow \text{C}_2\text{H}_4 + \text{CO} + \text{H}_2\text{O} \\
\text{CO}_2 + \text{C}_3\text{H}_8 \rightarrow \text{C}_3\text{H}_6 + \text{CO} + \text{H}_2\text{O}
\]
CONCLUSION

Chemical reactions and heterogeneous catalysts used to convert CO$_2$ to such valuable chemicals as urea, methanol, polyurethanes, CO, CH$_4$, C$_2$H$_4$ were under discussion in this review. The CO$_2$ molecule is very stable in terms of thermodynamic properties; its activation requires a lot of energy, and production of this energy itself sometimes goes with release of CO$_2$. For that reason, to achieve the total effect of reducing CO$_2$ emissions, it is necessary to develop new efficient catalysts for conversion of CO$_2$. The catalytic conversion of CO$_2$ can take place in a gas phase, in a liquid phase or in electrochemical cells. Since solubility of CO$_2$ is rather low in an aqueous solution, conversion of CO$_2$ in the liquid phase usually suffers from low productivity. In this brief review, we have mainly considered the processes in the gas phase with participation of catalysts: metal oxides, supported metals, carbides, carbon materials.

Homogeneous catalysts in the formic acid production are still lagging behind in application due to a low solubility of CO$_2$; development of an active heterogeneous catalyst for this process has very good prospects.

The processes using heat and light as energy sources will undoubtedly be required to minimise overall energy consumption. Electrochemical conversion of CO$_2$ using catalysts is still at an early stage and requires further optimisation.
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HIGH-QUALITY MOTOR FUELS FROM VEGETATIVE RAW MATERIALS

INTRODUCTION

The world uses approximately 120 quadrillion BTU annually for transportation, 95% of which is derived from fossil resources and 5% from renewable resources (Center 2020). By 2050, energy use is projected to increase by 50%, with renewable resources accounting for only 25% of total use. The carbon in fossil-derived fuels contributes significantly to climate change, and is one of the most challenging sources of greenhouse gases (GHGs) to replace with non-polluting alternatives.

Transportation fuels include motor gasoline, diesel, jet fuel, and a variety of other specialised fuels. Worldwide, gasoline accounts for 39% of energy used by the transportation sector, with diesel fuel accounting for 36% and jet fuel 12%. Gasoline is a complex mixture of hydrocarbons composed primarily of branched-chain alkanes and aromatics ranging from 4 to 12 carbons in length (Sawyer 1993). Diesel fuel is a mixture of generally linear hydrocarbons ranging from 9 to 23 carbons in length, with an average length of 16 carbons. The types of hydrocarbons in gasoline and diesel have a strong impact on the properties of the fuel. For example, branching and unsaturation leads to greater octane numbers in gasoline (Ghosh, Hickey, and Jaffe 2006) and lower cetane numbers in diesel (Ghosh and Jaffe 2006). Conversely, n-alkanes have higher cetane numbers and lower octane values. While significant branching is detrimental to the diesel cetane number, branching is needed to prevent gelling of linear hydrocarbons at low temperatures. Similar to gasoline and diesel fuel, jet fuel is a mixture of hydrocarbons. Most jet fuels are based on kerosene and are designed to a specific performance criterion. In the US, standards for fuel for civilian aircraft are set by ASTM International (Committee and D02 Committee, n.d.), whereas the Department of Defence sets the standards for fuel for military aircraft. Jet A or A-1 are used in most parts of the world except the far north where Jet B is used and in Russia where Jet TS-1 is used.

Worldwide, transportation contributes about one quarter of the total GHG emissions (Hockstad and Hanel 2018). To reduce the impact of transportation on greenhouse gas emissions, there are two primary alternatives: electrification with renewable sources of electricity, and fuels made from renewable resources, namely biofuels. While electrification of the passenger and truck fleet is happening slowly, electrification of air travel is likely to lag significantly, if it ever happens. The development of renewable biofuels and bioproducts (to reduce the price of biofuels) that reduce our reliance on petroleum is critical to energy, environmental, and economic security (Kircher 2015).
The two major biofuels that have been widely commercialised are ethanol made biologically from a variety of sources and biodiesel made from hydrogenated plant oils. Their uses have been limited due to a lack of infrastructure, limitations in the blend wall (e.g., amount of ethanol that can be blended into gasoline, currently 10% in the United States but higher in some other countries), the number of flex-fuel automobiles (e.g., that can use more than 10% ethanol), quality of the fuel (e.g., diesel made from vegetable oil), and cost of the fuel. The penetration of biofuels could be deeper if 1) biofuels had similar properties to the fuels currently made from petroleum and 2) if they were significantly less expensive.

Advanced biofuels are defined here as fuels that are biologically produced from a renewable resource and that have similar, equal, or better properties than petroleum-based fuels. For gasoline, the advanced biofuel molecules include highly branched molecules that are similar to octane. For diesel, the molecules include straight-chain or lightly branched hydrocarbons. Advanced jet biofuels are similar to diesel fuels, long-chain hydrocarbons with a few branches. In those cases, these molecules are not produced naturally by any biological system and have been challenging to produce biologically since they require new enzymes/pathways. In addition, these molecules are highly reduced, whereas most microorganisms grow by oxidising carbon sources, most of which are more oxidised than the fuels we would like to produce. Nevertheless, production of these molecules would enable direct replacement of their petroleum-based counterparts without changes in engines.

THE “CRUDE OIL” FOR BIOFUEL PRODUCTION

Just like petroleum-based fuels are produced from a source of carbon (e.g., petroleum), biofuels require a source of carbon and reducing equivalents as substrates to synthesise highly reduced, highly energetic fuels. There are several routes to produce biofuels: 1) biological or chemical production of fuels from biomass; 2) photosynthetic fixation of carbon dioxide using algae, photosynthetic bacteria, or plants to directly produce the biofuel; and 3) fixation of carbon dioxide using renewable electricity as a source of reducing equivalents and bacteria or other catalyst (Figure 1).

![Figure 1. Three potential routes to produce advanced biofuels.](image-url)
Left: Photosynthesis to fix CO₂ into plants that are deconstructed and fermented into advanced biofuels in a biorefinery. Middle: Photosynthesis to fix CO₂ by algae that have been engineered to produce an advanced biofuel. Right: Electrobiosynthesis of advanced biofuels using bacteria that can utilise CO₂ directly from an electrode powered by photovoltaics.

Most of the ethanol produced today is done so using sucrose (e.g., from sugar cane, sugar beets, or another sucrose crop) or starch (e.g., from maize or another starch crop) as a feedstock. It is relatively simple to ferment either carbon source to produce ethanol using yeast or bacteria. Unfortunately, these crops tend to require extensive fertilisation, water, and soil, and directly compete with food production.

The best sources of carbon for biofuel production is lignocellulose biomass, which consist of up to 70% polymerised sugars and is the most abundant form of biomass on Earth (Isikgor and Becer 2015; Liu et al. 2021). Biofuels produced from lignocellulosic biomass are attractive because their net carbon footprint (emitted carbon – consumed carbon) can be neutral or even negative (Field et al. 2020) and their generation from agricultural and forest residues lowers the price of fuels compared to those produced from dedicated energy crops. A recent analysis of switchgrass production on transitioning crop/pasture land showed that in fact its GHG mitigation potential is comparable with reforestation of this land, and has several times more mitigation potential than grassland restoration (Field et al. 2020). Additionally, the ability of energy crops like sorghum to grow on marginal lands provides an avenue for production that limits the competition for farmland land needed to support the growing population.

Prior to its conversion to biofuels, lignocellulosic biomass must be deconstructed into metabolisable intermediates using thermal, chemical and/or biochemical pre-treatment. A major hurdle to efficient bioconversion is the recalcitrance of the feedstock material and the inhibitory effect that lignin has on this process (Dos Santos et al. 2019). Cell-wall engineering has shown promise for decreasing overall recalcitrance reducing lignin content and reducing the acetylation of cell-wall polymers that limit the conversion efficiency of the feedstock material as well as for increasing the ratio of six-carbon to five-carbon sugars (many microorganisms prefer six-carbon sugars to five-carbon sugars) (Aznar et al. 2018). While lignin is a major contributor to feedstock recalcitrance, it is also a promising substrate for specialised microbes that convert these aromatic polymers into usable products (Fang, Weisenberger, and Meier 2020). The introduction of specialised microbial hosts into various processing systems has the potential to optimise the conversion of all lignocellulosic feedstock components into products with economic value, limiting the waste streams for biofuel production and increasing the viability for their use on a global scale.

It is also possible to produce the fuel directly from sunlight and carbon dioxide using a photosynthetic organism, such as a photosynthetic cyanobacterium, algae, or even a plant. Having the entire fuel production process occurring in one organism makes the process more direct and efficient, in theory, with no energy invested in non-fermentable parts such as plant stems, roots and leaves. In fact, the solar energy conversion in cyanobacteria and algae is higher than in plants, reaching an efficiency of 3% in microalgae as opposed to less than 1% in most crops (Wijffels and Barbosa 2010). Furthermore, many species can grow in wastewater or marine environments with simple nutritional requirements and therefore do not compete for land use with agriculture. And many of these photosynthetic bacteria and algae can be engineered to produce advanced biofuels (Miao, Xie, and Lindblad 2018).

Despite the attractive features of photosynthetic microorganisms, cultivation of photosynthetic microorganisms is difficult and costly. Unlike growing plants in soil, the technology for large scale cultivation of photosynthetic microorganisms is still in its early developmental stage. The cultivation can be done in either an open system like a raceway pond, or in a closed system like a photobioreactor. Open ponds have lower operating costs but run the risk of contamination; additionally, there are strict regulations against cultivating genetically modified organisms in uncontained systems (Abdullah et al. 2019). Closed systems, on the other hand, can have more tightly controlled cultivation conditions and have a low risk of contamination but the operating costs are higher than for open systems.

An alternative to using sunlight for energy to fix CO₂, some microorganisms can use H₂ as a source of reducing power or accept electrons directly from metal or electrodes (Lee et al. 2021). Microorganisms have also been engineered to produce advanced biofuels from H₂ and CO₂ (Grenz et al. 2019). Given the projected very low price for renewable electricity in some parts of the world, this could be a good alternative for production of biofuels. Additionally, other single carbon substrates, such as CO and CH₄, can be used to produce biofuels. The conversion of syngas (CO/CO₂/H₂) to ethanol has been implemented on a commercial scale from industrial waste gases by Lanzatech using Clostridia that naturally...
produce ethanol. Finally, methanotrophs have been engineered to produce biofuels from CH$_4$ (Nguyen, Kim, and Lee 2020). However, if the CH$_4$ is fossil derived, then these fuels are not really any different from petroleum-based fuels in that they add CO$_2$ to the atmosphere when burned.

## HISTORICAL BIOFUELS

The biofuels that are most widely used are those that are produced naturally. As mentioned above, ethanol is one of the most widely used biofuels because it is produced naturally from a number of different carbon sources by bacteria and fungi. This subject has been reviewed extensively and will not be covered further here.

Butanol is a potential alternative to ethanol as a replacement for gasoline owing to the fact that it has a higher energy content and lower solubility in water. It can be transported through existing pipelines and can be used to supplement both gasoline and diesel fuels. Historically, butanol has been produced biologically using Clostridia (Papoutsakis 2008). Many of the butanol production capabilities of these solventogenic Clostridia have been achieved through conventional mutagenesis techniques. But because of its higher energy content and lower hygroscopicity and corrosivity, butanol is superior to ethanol as a biofuel. However, it is produced at a lower titer and is much more toxic than ethanol. Also because of its high boiling point, butanol requires more energy than ethanol for distillation-based purification from a fermentation broth.

With respect to diesel and jet fuel replacements, derivatives of natural fats produced by plants and microorganisms have most often been used. Currently, most biodiesel production uses plant oils for the vast majority of its starting material (Fukuda, Kondo, and Noda 2001). However, many oleaginous microorganisms (yeast and algae) produce plentiful fats (White et al. 2005). These microorganisms accumulate 40-70% or more of their dry cell weight in fats. Manipulating growth conditions, such as CO$_2$ supplementation and nitrogen and light limitation, can increase the lipid content of these algae (Metzger and Largeau 2005). Transesterified fatty acids such as fatty acid methyl ester (FAME) and ethyl ester (FAEE) provide carbon chain lengths compatible with compression ignition engines and have consequently been developed for use as biodiesel. However, these molecules are not ideal. If biodiesel is to replace a significant portion of current petro-diesel needs, engineered microbes that produce molecules more suitable as diesel replacements might serve to provide a more consistent and scalable source for this commodity, particularly if they produce it using an inexpensive and plentiful carbon source.
Advanced biofuels that have equivalent properties to petroleum-based fuels would allow them to be directly substituted for their petroleum counterparts. Even better, some advanced biofuels have higher energy density than petroleum fuels and thus will be advantageous when they replace petroleum fuels in conventional engines (Baral et al. 2019). These fuels can be made from nearly any carbon source using engineered metabolic pathways based on the isoprenoid, fatty acid, polyketide and other pathways that form carbon-carbon bonds.

As an extension of ethanol and butanol, fusel alcohols are derived by catabolism of branched amino acids using the Ehrlich pathway, which is naturally found in yeast. Given that these molecules have more carbons per alcohol than ethanol, they tend to be better fuel replacements than ethanol. The fusel alcohol biosynthetic pathway has been engineered into a variety of microbial hosts (Atsumi, Hanai, and Liao 2008). Among these alcohols, isobutanol has been produced at near commercial titers and yields using cell-free system (Sherkhanov et al. 2020).

As mentioned above, a particularly good source for advanced fuels are fatty acids. The variety of fatty acids available from microbial sources can potentially provide the mixture of chain lengths and branching required for an ideal fuel-blend. And what cannot be achieved naturally can be achieved through genetic engineering. Fatty acid biosynthesis draws from the pool of acetyl-CoA produced by several central metabolic pathways. To improve the free fatty acid levels in microbes, the main approaches adopted to date have focused either on diverting the pool of acetyl-CoA towards fatty acid biosynthesis or on decreasing the cellular consumption of fatty acids. Although fatty acids are the direct products of the fatty acid biosynthesis pathway, reduced and modified fatty compounds have also been made in microorganisms (Schirmer et al. 2010). These fatty alcohols, esters, and alkanes can be produced with the appropriate chain length required to serve as biodiesel candidates.

Isoprenoids, a family of natural products that are synthesised with the use of the activated hydrocarbon monomers isoprenyl pyrophosphate (IPP) and its isomer dimethylallyl pyrophosphate (DMEAPP), are an excellent source of biofuels (Kuzuyama 2002). These molecules have branches at every fourth carbon (when they are in their linear form), which is ideal for gasoline and necessary to keep diesel and jet fuels from gelling at cold temperatures. It is possible to produce several branched-chain alcohols, alkanes, alkenes and cyclic hydrocarbons through the isoprenoid biosynthetic pathway. In addition to branched-chain hydrocarbons, this pathway can be used to produce isopentanol for spark ignition engines and saturated, mono- or diunsaturated monoterpenes and sesquiterpenes might be useful as diesel and jet fuels. One of the most successful examples of an isoprenoid fuel was farnesane, produce by Amyris and tested in diesel and jet engines (Meadows et al. 2016).

Yet a third source of biofuels are polyketides. Although generally thought to produce antibiotics and related natural products, polyketide synthases (PKSs) are capable of producing a much more diverse set of molecules than the isoprenoid and fatty acid pathways. Engineering efforts to controllably manipulate polyketide synthases has led to the production of six- and seven-carbon ethyl ketones, as well as five- and six-carbon methyl ketones (Yuzawa et al. 2018). These short-chain ketones can be added to gasoline as oxygenates to increase their octane number, and the fact that these molecules can be produced from plant biomass hydrolysates highlight the efficient and renewable biofuel production using PKSs. Given the flexibility of polyketide synthases to produce millions of different organic molecules, it should be possible to produce even more complex molecules tailor-made for gasoline, diesel, jet and even rocket engines.
CONSIDERATIONS FOR ENGINEERING
THE MICROBIAL PRODUCTION PLATFORM

There are several important process considerations for microbial host choice/engineering. First, carbon efficiency of the biosynthetic pathway is extremely important. Every carbon lost to side products or CO₂ is carbon that is not in the fuel itself. Because biofuels must compete on a cost basis with petroleum-based fuels, it is essential that as much carbon in the substrate as possible be converted to final product. This may involve substantial rewiring of the microbial host’s metabolic pathways to conserve carbon (Meadows et al. 2016). Alternatively, as mentioned above, a potential source for those reducing equivalents may be inexpensive electricity generated using solar or wind.

Many biofuels are toxic as are many carbon sources that one would like to feed the microbial host. Finding microbial hosts that can tolerate the carbon source as well as the product may be very difficult or impossible. Engineering the microbial hosts to tolerate starting materials and products may be critical. In conjunction with engineering microbial hosts to be more tolerant of substrates and products, it is also possible to evolve them to be more tolerant.

Finally, genetic stability of the engineered host is critical. Many engineered biosynthetic pathways impart a burden on the host microorganism: metabolic intermediates that might be allocated to growth are “stolen” for production of the biofuel. The microbial host’s rescue is to shed itself of the genetic material that is causing the burden. There are methods to counter genetic instability, but significant research is still needed.

THE CHALLENGES WITH SCALE

When advanced biofuels are implemented at large scale, production will need to be done on a massive scale. As of this writing, the world produces approximately 30 billion gallons of ethanol annually (“Alternative Fuels Data Center,” n.d.) and consumes approximately 920 billion gallons of transportation fuels, most of which are petroleum based. To completely replace petroleum fuels and biofuels, we would need to construct and operate advanced biofuel production facilities that produce 30 times the amount of ethanol that is currently produced. (In the US, biofuels account for 5% of total fuel consumed; facilities would need to be constructed to produce 20 times the current biofuel production).

There are numerous challenges when scaling biological production processes. The first is that we would need to convert a significant (and unrealistic) fraction of the arable land for producing the biomass that would be the substrate for these biofuels. The second major challenge is developing the machinery to collect and transport the biomass to centralised facilities and constructing those facilities. Once there, the fermentable sugars would need to be extracted from the biomass and fermented (in very large vessels) into the advanced fuels. Finally, the fuel would need to be transported to filling stations. Because biofuels would be produced in areas that are not densely populated and largely used in densely populated areas, much of our existing infrastructure for producing and distributing petroleum-based fuels may not be useful.

With respect to the fermentation process itself, due to the massive size of commercial biofuel fermenters - up to 500 m³ for aerobic processes and 4,000 m³ for anaerobic processes - overcoming scale-up challenges is of paramount importance for successful commercialisation (Benz 2014). Achieving consistently high titers, rates, and yields under production conditions necessitates precise control of process parameters including pH, substrate feed rate, dissolved oxygen, and in situ product removal.

In addition to tight process controls, the production environment features pressures, shear rates, product titers, and spatial heterogeneities poorly reflected in small-batch cultivation. This
environmental heterogeneity serves to drive genetic heterogeneity, with microbial contamination and genetic instability threatening process stability and process robustness at scale, necessitating novel control mechanisms (Rugbjerg and Sommer 2019). While conventional antibiotics and antimicrobials are cost-prohibitive in industrial applications, promising hygiene control alternatives have emerged, including engineered chlorite resistance (Wang and Coates 2017) and genetic modifications encoding affinity for xenobiotic nitrogen and phosphorus sources (Shaw et al. 2016). Significant work is still needed in non-sterile fermentations.

To combat the impact of deleterious mutations on productivity, cellular reproduction can be effectively tied to product formation using the techniques described above under “coupling growth and production”. Conversely, genetic stability can also be enhanced by fully decoupling growth and production phases, thereby limiting reproduction during the production phase via either induction of growth-limiting genes or via elimination of key nutrients required for growth.

High product titers often threaten productivity via toxicity and feedback inhibition. In addition to tolerance engineering approaches, these challenges may be overcome by process designs featuring in situ product removal (Dafoe and Daugulis 2014). In situ product recovery is a critical component of recent scale-up success stories, demonstrating feasibility of continuous recovery at industrial scale (Meadows et al. 2016; Xue et al. 2014).

Although known metabolic pathways offer several possible avenues for the biosynthesis of fuel molecules, several other factors need to be addressed before they can be applied in an industrial setting. First and foremost are the physical properties of the potential biofuel molecule. These properties have an impact on everything, from its suitability as a fuel to the purification processes and the mode of its transport to consumers.

The primary challenge in biofuel production is achieving titers, rates and yields that make these fuels cost-competitive with petroleum-based products. For any of the engineering approaches outlined to be successful, the development of efficient lignocellulosic breakdown to monosaccharides is crucial. The development of this linchpin technology will enable the production of microbial-produced biofuels from crops that have higher growth-rates, better yields, lower soil-impacts, and lower water, fertiliser and pesticide requirements than currently used crops such as oil palms, corn or soybeans (Tilman, Hill, and Lehman 2006). These characteristics should serve to make biofuels more competitive with petroleum, while making them less competitive with food production for arable land.

To date, pathway manipulations have largely been limited to the use of existing genes and conventional gene expression techniques. Although these approaches have yielded substantial increases in target molecule production, a cell-wide approach to metabolic engineering will be required to maximise the rate of biosynthesis in addition to the yield of the desired compound.

Another important challenge in metabolic engineering is satisfying cellular energetic concerns (i.e., thermodynamic constraints). An important parameter in strain optimisation is the balance of energy and cofactor requirements for the metabolic pathways used to generate the target molecule. Supplanting high-value petroleum products, such as plastics, with renewable products is an important first step towards creating sustainable sources for the petroleum products upon which we have come to rely in our daily life. With continued improvements in metabolic engineering, we expect microbial production of bulk commodities to become economically competitive with petrochemicals.

For success in the production of alternative biofuels, it will be necessary to develop targeted and efficient transport systems, improved tolerance in biofuels producers to the toxic effects of accumulating biomolecules, optimised carbon flux to the desired products, and microorganisms that are robust under industrial process conditions. The rapid advances seen in the development of these technologies will almost undoubtedly facilitate the efficient and reliable production of systems for novel biofuels. Ultimately, political forces, process economics, engine technology, and supply infrastructure will dictate the widespread acceptability and use of these alternate fuel sources.
REFERENCES


HIGH TEMPERATURE HEAT PUMPS

INTRODUCTION

An efficient use in the fuel balance of practically inexhaustible resources of low-potential (up to 40°C) heat of renewable (the heat of ambient air, soil, water from underground and surface sources, etc.) and secondary (the industrial and domestic wastewater) heat sources with the use of heat pumps (HP) is the hot topic of energy conservation and environmental protection.

There are currently more than 30 million heat pumps of various capacities operating throughout the world — from several kW to hundreds of MW [1]. In the USA, over 30% of residential buildings are equipped with heat pumps (combined heating and air conditioning systems based on heat pumps). In Sweden, they have commissioned more than 100 heat pump units with the capacity of 5 to 80 MW in recent years. In Japan, three million HPs is sold annually (in contrast to 1 million HPs in the USA).

Rapid development of digital technologies made relevant the use of heat energy from the cooling systems of data processing centres (DPC) for heat supply. The total power consumption of the world's data centres is about 10% of the total demand for electricity, and this demand is steadily rising by 12% every year, ranking the 5th in terms of the total annual volume after power consumption in such countries as the United States, China, Russia, and Japan [2]. A data centre cooling system consumes up to half of all energy required for the centre. The maximum heating temperature in some parts of the data centre reaches 46°C. The use of HP-based cooling systems for a heat energy efficient utilisation at the data centre makes it possible to reduce power consumption for cooling by 80% compared to less advanced air-cooled systems and by 13% — compared to traditional liquid-cooled chiller systems. A stable operation of space objects and other special objects also requires the use of effective cooling technologies for onboard digital equipment. We can continue the list of new challenges for modern technologies of the post-industrial society which can be effectively answered by low-potential energy technologies, in particular, high-temperature heat pumps (HTP).
HEAT PUMP CLASSIFICATION

Table 1 contains HP classification according to four main characteristics.

<table>
<thead>
<tr>
<th>Classification criterion</th>
<th>Name</th>
<th>Drive energy</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Operation principle</td>
<td>1.1 Compression</td>
<td>Electrical, mechanical</td>
</tr>
<tr>
<td></td>
<td>1.1.1 Steam</td>
<td>1.1.2 Gas</td>
</tr>
<tr>
<td></td>
<td>1.2 Sorption</td>
<td>Thermal energy</td>
</tr>
<tr>
<td></td>
<td>1.2.1 Absorption</td>
<td>1.2.2 Adsorption</td>
</tr>
<tr>
<td></td>
<td>1.3 Jet</td>
<td>Kinetic energy of steam or gas</td>
</tr>
<tr>
<td></td>
<td>1.3.1 Ejector</td>
<td>1.3.2 Vortex</td>
</tr>
<tr>
<td></td>
<td>1.4 Thermoelectric</td>
<td>Electrical</td>
</tr>
<tr>
<td></td>
<td>1.5 Magnetic</td>
<td></td>
</tr>
<tr>
<td>2. Duty cycle type</td>
<td>2.1 Closed-loop</td>
<td></td>
</tr>
<tr>
<td></td>
<td>2.2 Opened loop</td>
<td></td>
</tr>
<tr>
<td>3. Transformation nature</td>
<td>3.1 Booster</td>
<td></td>
</tr>
<tr>
<td></td>
<td>3.2 Splitter</td>
<td></td>
</tr>
<tr>
<td>4. Periodicity</td>
<td>4.1 Continuous operation</td>
<td></td>
</tr>
<tr>
<td></td>
<td>4.2 Intermittent operation</td>
<td></td>
</tr>
</tbody>
</table>

Among a large number of classifying criteria, the most important is the principle of classification by duty cycles among which we can distinguish practically important gas compression, vapor compression, sorption (absorption and adsorption) which determine the HP design and operating modes. The combined devices providing a joint production of commercially valuable or technologically important flows of heat and cold (operating modes: heating, hot water supply, cooling) are also often referred to as HPs. Such devices, along with their use in industry, have found application for redistribution of heat fluxes inside large buildings in the circular year-round air conditioning systems [4, 5]. Only two types of heat pumps have received a wide practical application: the pumps of vapour compression (VCHP) and absorption (ABHP) types.

According to the temperature mode of the heated heat-transfer fluid, HP is conventionally subdivided into low-temperature LHP (40-45°C, air conditioning, underfloor heating); medium-temperature MHP (up to 60-65°C, hot water supply, medium-temperature heating) and high-temperature HHP (more than 80°C). Almost 90% of all HPs in the world operate in the mode of heating the heat-transfer fluids for the needs of medium-temperature heating, hot water supply, and air conditioning [6-8]. Separate models of LHP and MHP are equipped with additional direct heating devices, allowing, if necessary, additional heating of the heat-transfer fluid to higher temperatures.
Common to all HPs is fulfillment of the second law of thermodynamics according to which transformation of thermal energy from renewable and secondary sources $Q_{\text{NIT}}$ from the temperature level $T_1$ to a higher level $T_2$ for a subsequent useful consumption should be accompanied by expenditure of work $A$ or expenditure of the other types of energy equivalent to it, in terms of working capacity (exergy) [3]. With an increase in the temperature difference $\Delta T = T_2 - T_1$, energy expenditure $A$ increases. In the process of thermal transformation in HP, the law of energy conservation is fulfilled:

$\text{1 } Q_{\text{NIT}} + A = Q,$

where $Q$ is the amount of useful heat generated with temperature $T_2$.

In general, the efficiency of heat energy generation for different types of HPs can be determined by the value of the COP coefficient (Coefficient of Performance):

$\text{2 } COP = \frac{Q}{A} = 1 + \frac{Q_{\text{NIT}}}{A},$

where always $COP > 1$. When $COP \to 1$, HP practically does not use the energy of renewable and secondary sources ($Q_{\text{NIT}} \to 0$) and heating is carried out only due to the energy of work $A$ supplied to it. For most practical applications makes it possible to provide HP competitive advantages in relation to conventional heat sources (electric, gas-oil, coal-fired boilers).

The efficiency of most sorption heat pumps is characterised by the value of the thermal transformation coefficient:

$\text{3 } \eta = \frac{Q}{Q_{\text{GEN}}},$

where $Q_{\text{GEN}}$ – the amount of high potential heat supplied to the generator for working solution evaporation.
The problem of using refrigerants in HP that do not affect the ozone layer and global climate warming is urgent [9-12].

Figure 1 shows a historical vector of the movement for practical use of the working fluids in HPs and refrigeration machines.

FIGURE 1. Evolution of refrigerants.
When choosing a new generation of refrigerants, we must take into account a number of factors:

- Ozone depletion potential (ODP, in relation to R11);
- Potential for an impact on global warming (GWP, in relation to R747);
- Fire safety;
- An efficient use of natural resources;
- Energy efficiency;
- Availability in any quantity.

The indicators of the main working fluids (refrigerants) characterising their effect on the Earth’s ozone layer and global warming are given in Table 2.

TABLE 2. Properties of various refrigerants.

<table>
<thead>
<tr>
<th>An impact on the ozone layer and climate warming</th>
<th>Refrigerant</th>
<th>Ozone depleting potential (ODP)</th>
<th>Global warming potential (GWP)</th>
<th>Molar mass, g/mol</th>
<th>Normal boiling point at a pressure of 1 atm, °C</th>
<th>Critical pressure, MPa</th>
<th>Critical temperature, °C</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ozone depleting substances (contain chlorine atoms)</td>
<td>R-12 ((\text{CF}_2\text{Cl}_2))</td>
<td>0.9</td>
<td>10900</td>
<td>120.9</td>
<td>-29.8</td>
<td>4.13</td>
<td>112.0</td>
</tr>
<tr>
<td></td>
<td>R142b ((\text{C}_2\text{H}_4\text{C}_1\text{F}_2))</td>
<td>0.1</td>
<td>630</td>
<td>100.5</td>
<td>-9.8</td>
<td>4.12</td>
<td>137.2</td>
</tr>
<tr>
<td></td>
<td>R-22 ((\text{CHClF}_2))</td>
<td>0.055</td>
<td>1780</td>
<td>86.5</td>
<td>-40.8</td>
<td>4.99</td>
<td>96.1</td>
</tr>
<tr>
<td>Ozone friendly</td>
<td>R-134a ((\text{CF}_3\text{CH}_2\text{F}))</td>
<td>0</td>
<td>1430</td>
<td>102</td>
<td>-26.1</td>
<td>4.06</td>
<td>101.1</td>
</tr>
<tr>
<td></td>
<td>R-32 ((\text{CH}_2\text{F}_2))</td>
<td>0</td>
<td>720</td>
<td>52.0</td>
<td>-51.7</td>
<td>5.79</td>
<td>78.1</td>
</tr>
<tr>
<td></td>
<td>R-407C*</td>
<td>0</td>
<td>1800</td>
<td>86.2</td>
<td>-43.6</td>
<td>4.63</td>
<td>86.0</td>
</tr>
<tr>
<td>Ozone friendly with a little global warming impact</td>
<td>R-290 ((\text{CH}_3\text{CH}_2\text{CH}_2))</td>
<td>0</td>
<td>20</td>
<td>44.1</td>
<td>-42</td>
<td>4.25</td>
<td>96.8</td>
</tr>
<tr>
<td></td>
<td>R-717 ((\text{NH}_3))</td>
<td>0</td>
<td>0</td>
<td>17.0</td>
<td>-33.3</td>
<td>11.33</td>
<td>132.3</td>
</tr>
<tr>
<td></td>
<td>R-744 ((\text{CO}_2))</td>
<td>0</td>
<td>1</td>
<td>44.01</td>
<td>-78.4</td>
<td>7.38</td>
<td>30.98</td>
</tr>
<tr>
<td></td>
<td>R-1234yf ((\text{CF}_3\text{CF}2\text{CH}_2))</td>
<td>0</td>
<td>4</td>
<td>114</td>
<td>-29</td>
<td>3.38</td>
<td>95.0</td>
</tr>
<tr>
<td></td>
<td>R718 (water)</td>
<td>0</td>
<td>&lt; 1</td>
<td>18.02</td>
<td>100</td>
<td>22.1</td>
<td>374.2</td>
</tr>
</tbody>
</table>

A mixture of R-32 / R125 / R134a freons (23/25/52%).

The European Union has revised the legislation (Regulation No. 517/2014) on fluorinated refrigerants (HFC) and approved a schedule for their partial phase-out in some equipment classes. Between 2016 and 2030, the use of HFC is expected to decline by 79%. R410A, R134A and R407C will not be completely banned but their use will be significantly limited. The issues of mutual influence of constituent components of the non-azeotropic mixtures of one-component refrigerants [13] on general process of heat and mass transfer and the efficiency of expanding the temperature “glide” zone of VCHP cycles, taking into account their different individual toxicity,
flamibility and impact on the ozone layer, need separate elaboration.

Transition to the use of natural working fluids in HP is now a global trend and meets international requirements for energy, environmental and economic efficiency.

It was carbon dioxide R744 (CO₂) that determined one of the main trends in the future development of HHP due to its environmental safety and physical properties: low global warming potential (GWP = 1); no impact on the ozone layer (ODP = 0); environmental safety (its low concentrations in the air are not toxic, participation in natural processes of photosynthesis, producing oxygen); complete non-flamability (it is used as a fire extinguishing agent); high specific cooling and heating capacity. The CO₂ production cost is low: it is 100-120 times lower than the one of freon R134a. The main difficulties associated with its use as a refrigerant are associated with its low critical temperature of 31.05°C and high operating pressures during implementation of the forward and reverse thermodynamic cycles.

CO₂ is a greenhouse gas. However, technologies for its passive utilisation have existed for a long time. For example, in the United States, 20 million tons are pumped into the voids that remain after development of oil wells; technologies for its disposal at the seabed, in a gas hydrate state, have also been under consideration. CO₂ heat pumps and power plants operating in a closed Allam cycle [14] help to combat global warming without reducing its emissions into the atmosphere. According to a figurative expression of the author of this work [15], these are technological traps for CO₂ that ensure its active use.

HIGH-TEMPERATURE R744 (CO₂) VAPOUR COMPRESSION HEAT PUMPS

Products of the Chinese company TICA [16] are one the examples of commercial implementation of CO₂ HHP. HHP is manufactured under a technical license from Japan company Mayekawa (Fig. 2).

The product is designed for heating tap water or recirculated water to 65°C or 90°C with the warmth of the surrounding air. The heat pump is based on a CO₂ transcritical cycle.

**FIGURE 2.** High temperature R 744 (CO₂) heat pump with:
a) CO2 transcritical cycle; b) General view of TSAN 200 NN.

---

**a.** CO₂ TRANSCRITICAL CYCLE

- **HEAT TRANSFER**
- **EXPANSION**
- **EVAPORATION**

<table>
<thead>
<tr>
<th>IgP</th>
<th>1</th>
</tr>
</thead>
<tbody>
<tr>
<td>3</td>
<td>T = const</td>
</tr>
<tr>
<td>2</td>
<td>HEAT TRANSFER</td>
</tr>
<tr>
<td>4</td>
<td>EVAPORATION</td>
</tr>
<tr>
<td>h</td>
<td>Enthalpy, kJ/kg</td>
</tr>
</tbody>
</table>

---
Implementation of the transcritical cycle allows water heating up to 90°C throughout the year without any additional electric heater (Table 3).

### TABLE 3. Technical characteristics of R744 (CO\(_2\)) HHP of TSAN 200 NN brand.

<table>
<thead>
<tr>
<th>Name</th>
<th>Parameter</th>
<th>Indicators</th>
</tr>
</thead>
<tbody>
<tr>
<td>Power supply</td>
<td>alternating current</td>
<td>3-phase, 380V, 50Hz</td>
</tr>
<tr>
<td>Refrigerant</td>
<td>type, filling weight</td>
<td>R744(CO(_2)), 20 kg</td>
</tr>
<tr>
<td>Design pressure of the</td>
<td>MPa (bar)</td>
<td></td>
</tr>
<tr>
<td>refrigerant in the duty</td>
<td>on the high pressure side</td>
<td>15 (150)</td>
</tr>
<tr>
<td>cycle</td>
<td>(Figure 2, process 2-3)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>on the low pressure side</td>
<td>6.4 (64)</td>
</tr>
<tr>
<td></td>
<td>(Figure 2, Process 4-1)</td>
<td></td>
</tr>
<tr>
<td>Operating temperature</td>
<td>ambient air</td>
<td>-15 ...+43°C</td>
</tr>
<tr>
<td>range</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Air heat exchanger</td>
<td>heat extraction from ambient air</td>
<td>copper tubes with aluminum fins</td>
</tr>
<tr>
<td>Compressor</td>
<td>motor type and power</td>
<td>4-pole, 25 kW</td>
</tr>
<tr>
<td></td>
<td>start mode</td>
<td>frequency-controlled</td>
</tr>
<tr>
<td>Integrated water pump</td>
<td>motor type and power</td>
<td>2-pole, 250 W</td>
</tr>
<tr>
<td>Air fan</td>
<td>power, number</td>
<td>0.75kW, 2 pcs.</td>
</tr>
<tr>
<td>Water heating up to</td>
<td>capacity, kW</td>
<td>80</td>
</tr>
<tr>
<td>65°C (standard mode)</td>
<td>power consumption, kW</td>
<td>15.96</td>
</tr>
<tr>
<td>Water heating up to</td>
<td>flow of heated water, m(^3)/h</td>
<td>1.38</td>
</tr>
<tr>
<td>90°C (powerful heating</td>
<td>capacity, kW</td>
<td>79</td>
</tr>
<tr>
<td>mode)</td>
<td>power consumption, kW</td>
<td>17.35</td>
</tr>
<tr>
<td>Water temperature in</td>
<td>flow of heated water, m(^3)/h</td>
<td>0.92</td>
</tr>
<tr>
<td>the storage tank at</td>
<td>capacity, kW</td>
<td>56</td>
</tr>
<tr>
<td>90°C</td>
<td>power consumption, kW</td>
<td>19.1</td>
</tr>
<tr>
<td></td>
<td>flow of heated water, m(^3)/h</td>
<td>1.22</td>
</tr>
<tr>
<td>Maximum noise level</td>
<td>in warm / cold seasons, dB</td>
<td>62/66</td>
</tr>
<tr>
<td>Water temperature</td>
<td>at the inlet</td>
<td>5 to 65°C</td>
</tr>
<tr>
<td></td>
<td>at the outlet</td>
<td>65 or 90°C</td>
</tr>
<tr>
<td>Overall dimensions</td>
<td>W x D x H, mm</td>
<td>1.250 x 1.900 x 2.065</td>
</tr>
<tr>
<td>Weight</td>
<td>net, kg</td>
<td>1344</td>
</tr>
</tbody>
</table>

Along with other countries, the EKIP company (Moscow) developed early experimental analogues of CO\(_2\) HHP for individual houses in Russia [17]. The heat pump TNSO2-20 with the heating capacity of 20 kW provided house heating at two temperature levels:

- high-temperature (conventional heating), heating water temperature 85°C;
- low-temperature (floor heating), heating water temperature 45°C.
The ground water with the temperature of 8°C was used as a low-grade heat source. The design used a Dorin company (Italy) piston compressor for operation on R744 with the discharge pressures up to 40 MPa.

Low power CO₂ HP is now widely available in the market. For example, the Environmental Building News agency has included the 4.5 kW Sanden heat pump for water heating in the list of the top ten 2016 products. In April 2016, Toshiba Carrier announced the phased introduction to the Japanese market of 59 new models of the Estia 5 series of HHP EcoCute water heater line which use R744 as a refrigerant. Mitsubishi Electric launched the EcoDan QUHZ system in the British market, the one which is a 4 kW monoblock air-to-water heat pump capable to heat water up to 70°C. In 2016, the EcoDan FTC5 heat pump was awarded with the RAC Cooling Award in the category Air conditioning or heat pump innovation.

The booming market of low power (up to 100 kW) HP offers possibility of an efficient use of similar high power devices − up to 30 MW and more. Their use is especially important in cities where the problem of thermal waste utilisation is acute, for example, municipal and industrial wastewater. It is important to that high level of the pressure in the CO₂ transcritical cycle allows a significant reduction of the HHP size in comparison with the other VCHPs with subcritical cycles. This is a fundamental advantage when building powerful R-744 HPs. Attempts to create equipment with the capacity up to 50 MW for an environmentally friendly district heating were made in Russia during 2002-2006 within the federal program framework [17,18]. Such HHPs will make it possible to use thermal energy from industrial effluents, emissions from thermal power plants, metallurgical and petrochemical industries as a low-grade heat source. Fig. 3 shows the scheme of one of CO₂ HHP variants providing water heating up to 90°C.

FIGURE 3.

The scheme of R744HHP with the heating capacity of 23 MW of the water-to-water type: 1 – turbocharger; 2 – water heater; 3 – control valve; 4 – liquid separator; 5 – pump for CO₂ circulation; 6 – water cooler. Pipelines: orange – high pressure (9.0-13.0 MPa), green – low pressure (4.0-6.0 MPa); arrows: red – heating water (5-90°C), blue – waste heat source (15-40°C).
Based on a comparative analysis of the duty cycles for R744 (CO$_2$), R718 (water), and freons R134a, R142b when heating water from 40 to 80°C using water with the temperature of 10°C as a low-potential heat source and, accordingly, the temperatures of evaporation and condensation of working fluids 5 and 85°C (except for R744), the authors of [19] have highlighted the advantages of using R744 (CO$_2$) for creation of powerful HHPs:

- High mass flow rates of R744 in the heat exchangers make it possible to achieve high heat transfer coefficients and reduce the weight of the heat exchangers and their size;
- A significantly larger share of the expansion work in the duty cycle in comparison with freons creates conditions for the use of an expander in order to increase the COP value.

A small, required volumetric capacity and the compressor size due to a higher vapour density and a high, specific volumetric heating capacity;

- A low pressure ratio in the duty cycle creates favorable conditions for the compressor effective operation (when using a centrifugal compressor, only one compression stage is required);

- A high level of pressure and high density of gaseous R744 allow having higher mass flow rates (respectively, the flow cross-sections of the channels and the pipe diameters are reduced) at the same, as for freons, specific hydraulic resistance in the ducts;

- High mass flow rates of R744 in the heat exchangers make it possible to achieve high heat transfer coefficients and reduce the weight of the heat exchangers and their size;

- A significantly larger share of the expansion work in the duty cycle in comparison with freons creates conditions for the use of an expander in order to increase the COP value.

The prospects of operation transfer to a high-temperature level of heat generation of the conventional VCHPs using subcritical cycles are also technically justified. Reverse VCHPs use two-compressor circuits which make it possible to raise the temperature level of the heat-transfer fluid to 80°C. So, for example, the line of high-temperature heat pumps of the EW-HT series allows us to get from 70 to 279kW of heat with heating the heat-transfer fluid to 78°C (Fig. 4). To produce higher temperature water, they use medium temperature water as a heat source. The operating range of heating the heat-transfer fluid extended due to a two-compressor circuit allows the HHP of this series to become integrated into any complex heat supply systems, including the district heating systems.

**OTHER PROMISING TYPES OF VAPOR COMPRESSION HHPS**

The prospects of operation transfer to a high-temperature level of heat generation of the conventional VCHPs using subcritical cycles are also technically justified. Reverse VCHPs use two-compressor circuits which make it possible to raise the temperature level of the heat-transfer fluid to 80°C. So, for example, the line of high-temperature heat pumps of the EW-HT series allows us to get from 70 to 279kW of heat with heating the heat-transfer fluid to 78°C (Fig. 4). To produce higher temperature water, they use medium temperature water as a heat source. The operating range of heating the heat-transfer fluid extended due to a two-compressor circuit allows the HHP of this series to become integrated into any complex heat supply systems, including the district heating systems.

**FIGURE 4. Temperature levels of HHP operation of the EW-HT series [20].**
The market launch of the EW-HT series HHP is a symbiosis of high technology and new areas of HHP application:

- A scroll compressor with a special spiral shape is used (it expands the operating temperature range, shifting both the boiling point and the condensation temperature);
- It became possible to work effectively as part of the district heating systems (various heat sources and consumers are connected to a common system with the temperature of 40-45°C, and EW-HT effectively converts part of this heat into the heat with the temperature of 70-80°C);
- Heat recovery was carried out without direct losses in industrial production (one process stream is cooled by heating the other with EW-HT);
- There was implemented cooling of powerful servers (IT cooling) in the 24/7 operation mode with a simultaneous heat production for heating, hot water supply and technologies of combined cooling, heating and power generation.

## HIGH TEMPERATURE SORPTION HEAT PUMPS

The sorbents of sorption HHPs ensuring implementation of the reverse thermodynamic cycles are different by nature.

## ABSORPTION HHP

Lithium bromide absorption heat pumps (ABHP) provide heating of water up to 90°C using the heat of the heating steam with the pressure up to 0.75 MPa or natural gas as an energy source for the duty cycle implementation, as well as low-potential waste or natural heat of various heat sources with the temperature of 20-40°C. The share of low grade heat used in a single stage ABHP to generate useful heat is about 40%. Introduction of a multistage scheme for regeneration of a water-salt solution makes it possible to almost double this indicator. The working fluid (refrigerant) in ABHP is water, the absorbent is an aqueous solution of lithium bromide salt (LiBr). These are environmentally friendly working fluids. ABHPs have a high energy efficiency ($\mu = 1.7-2.2$) and low operating noise. They are easy to maintain, have a long service life and are fully automated. Unlike VCHP, ABHP does not require large amounts of electricity. ABHP can be used for obtaining hot water for heating and hot water supply, for heating and cooling process media in industry, energy, agriculture, etc. In Russia, they are developed by OKB Teplosibmash LLC (Novosibirsk); and the world’s production leaders are Thermax (India) and Broad (China).
PROMISING HYDROGEN ADHP

In connection with development of hydrogen technology and nanotechnology, it is worth paying attention to improvement of metal hydride HP (hydrogen ADHP), which, unlike ABHP with liquid sorbents, can operate under conditions of reduced gravity and complete weightlessness. Their working fluid is a reversibly circulating hydrogen [21-23]. Solid metal hydrides such as LaNi, LaNiAl, LaNiSn, and LaNiMn are considered as sorbents. Hydrogen ADHPs have high thermodynamic efficiency within a wide range of temperature changes, but they require a high level of operating reliability at a high cost. Operation of these heat engineering devices is based on the use of the thermal effect of a reversible hydrogenation reaction of metal or an intermetallic compound:

\[ M + xH_2 \rightleftharpoons MH_{2x} \pm Q \]

When hydrogen is sorbed, heat is released; when it is desorbed, heat is absorbed from the environment, i.e. cold is generated or heat is transferred from a low-grade renewable or waste heat source. The use of these thermal effects makes possible operation of hydride HPs in a wide temperature range from −50 to +200°C. The effectiveness of hydride-forming material is determined by its properties. To assess the device effectiveness, two key relationships are used:

\[ \ln p = \frac{\Delta H}{RT} - \frac{\Delta S}{R} \]

\[ \text{COP} = \frac{\Delta m_h \Delta H_l - cm_l \Delta t_l}{\Delta m_h \Delta H_h - cm_h \Delta t_h} \]

Where \( p \) – equilibrium hydrogen pressure; \( \Delta H \) – hydride formation enthalpy; \( R \) – universal gas constant; \( T \) – temperature, K; \( \Delta S \) – entropy of hydride formation; \( \Delta m_h \) – the mass of hydrogen taking part in sorption – desorption; \( \Delta t_l, \Delta t_h \) – change in the temperature of sorber in one cycle; \( m_l, m_h \) – the mass of sorber; \( c_l, c_h \) – the heat capacity of sorbers; subscripts "l" and "h" refer respectively to the low-temperature and high-temperature hydrides.

FIGURE 5. The duty cycle of hydride hydrogen ADHP based on a pair of MmNi\(_{4.2}\)Al - MmNi\(_{4.15}\)Fe\(_{0.85}\).
The driving force for hydrogen flow from one metal hydride to another is the pressure difference between the hydride zones at the corresponding temperatures. When the pressures equalise, the flow of hydrogen and the accompanying heat effects due to sorption and desorption cease. The points of limiting states correspond to conditions $\Delta m_{H1} = \Delta m_{H2}$ with a constant total mass of hydrogen in the system. For the conditions in Fig. 5, the authors of [22] determined the values $\Delta m_{H} = 0.45\%$ and $\mu = 1.3$. A generally accepted scheme for metal hydride HP is the one in which generation of heat and cold, and, accordingly, the sorption and desorption of hydrogen occur alternately in the same working volume, depending on the hydrogen flow direction. Its undeniable advantage is lack of moving parts, and its disadvantage is the need for a significant number of gates or valves in the control system. Thermal capabilities of metal hydride HPs can be significantly expanded, and efficiency increased through the use of two or more stage circuits. However, work on creation of industrial designs of metal hydride HPs is limited so far only to small machines, where Japan is the leader.

The prospects of periodic hydrogen ADHPs are associated with development of hydrogen technologies (Fig. 6), in particular, with creation of the efficient systems of combined cooling, heating and power generation [24] based on high-temperature fuel cells (FC). Figure 6 shows a variant of one of such systems.

For broad practical use of HHP in the coming years, it is necessary to take into account systemic advantages of the heat pump technologies for Russia, the ones formulated earlier in [25]:

1. Possibility to expand the heat supply resource base, making it less dependent on the supply of fossil fuel resources; this is very important in the context of a growing cost of fuel and instability of its supply.
2. Rational use of electricity in heat supply systems, especially during night power consumption dips.
3. Broader understanding of district heating. The use of HP with an electric drive does not reduce centralisation of heating supply, but transfers it to a higher quality level inherent in the power supply systems. At the same time, the system for regulation of heat supply to consumers is simplified, its imperfection results in current loss of up to 20% of the consumed heat.
Joint work with the Combined Heat and Power Plants in the existing heating systems. Here, they can be used to reduce the temperature of the return heating water with provision of additional power generation in an economic cogeneration mode as well as in recycling water supply systems to improve operation of the cooling towers. For these purposes, it is promising to use intra-block installations based on ABHP with a gas furnace.

Freedom of a drive choice for HP. An electric drive is the most common device connecting HP directly to the power grid. However, it is possible to use as a drive for HP, under city specific conditions, expander-generator sets using an excess pressure of natural gas in the gas supply system, small hydropower plants using an excess water pressure in the city water supply and sanitation system due to the difference in geodetic marks of terrain, wind power plants, as well as gas turbines and internal combustion engines.

We hope that heat pumps and technologies based on them will allow humanity to preserve the planet Earth for its descendants.
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17. Source: https://tica.pro/shop/heat-pump/


ABSTRACT

The oil and gas industry plays a crucial role to world economy and is closely linked to other industries. This is a complex system that includes exploration of oil and gas fields, mining, transportation, storage, processing, and further marketing. However, using minerals as development resources leads to oily waste (OW) formation and accumulation, and this is an issue for us to overcome yet. Wastes of this type may harm the environment beyond remedy. Oily wastes have different origins, thus it is impossible to come out with some universal technological solutions for their processing or disposal. Having analysed the variety of the oily waste processing technologies being currently implemented, we came to the conclusion that the processing of this type of waste requires systematic approach.

Key words: Oil, petroleum products, waste, processing, disposal, raw materials, material, resource.

INTRODUCTION

At present, the OW accumulation issue is a priority for the oil and gas industry. This is due to the fact that the volume of waste generation increases annually, and historical objects of accumulated environmental damage remain un-recycled. From the so-called “laws of ecology” by Barry Commoner, we know that “Everything must go somewhere” and “There is no such thing as a free lunch”. Therefore, in the context of the struggle for a clean and safe environment, the issues of effective OW neutralisation and liquidation of their accumulation spots have come up to the fore.
The oil and gas sector companies have accumulated large amounts of OW. Those are formed during drilling, oil treatment, cleaning of tankers and tanks, overhauls, oil spills and wastewater treatment. Elimination of the accumulated environmental damage spots is somewhat lagging and requires special attention. OW also should be categorised by waste types. OWs are rather difficult to classify, since each of them has a unique composition and differs in its rheological and physicochemical characteristics; therefore, the existing classifier does not fully reflect the information on their properties. Having analysed and compiled the available literary sources on oil waste generation in Table 1, we classified OW [1-4] as follows:

**TABLE 1. OW classification by source of generation.**

<table>
<thead>
<tr>
<th>Source of generation of oily wastes</th>
<th>Waste type</th>
</tr>
</thead>
<tbody>
<tr>
<td>Well drilling</td>
<td>Bore mud</td>
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<tr>
<td></td>
<td>Waste production fluids</td>
</tr>
<tr>
<td></td>
<td>Drilling wastewaters</td>
</tr>
<tr>
<td>Oil and gas extraction</td>
<td>Oily sludge</td>
</tr>
<tr>
<td></td>
<td>Liquid waste with high oil content</td>
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<tr>
<td></td>
<td>Equipment maintenance waste</td>
</tr>
<tr>
<td></td>
<td>Spent oil</td>
</tr>
<tr>
<td></td>
<td>Oil-contaminated sands</td>
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<tr>
<td></td>
<td>Proppant</td>
</tr>
<tr>
<td></td>
<td>Asphaltene deposits</td>
</tr>
<tr>
<td></td>
<td>Effluents</td>
</tr>
<tr>
<td>Transport and storage</td>
<td>Asphaltene deposits</td>
</tr>
<tr>
<td></td>
<td>Tank oily sludge</td>
</tr>
<tr>
<td></td>
<td>Tanker oily sludge</td>
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<tr>
<td></td>
<td>Oily water</td>
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<td></td>
<td>Oily waste after cleaning equipment</td>
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<td></td>
<td>Formation of man-made lenses under storage facilities</td>
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<tr>
<td>Oil and gas processing</td>
<td>Oily sludge in tailings ponds</td>
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<tr>
<td></td>
<td>Oily waste after cleaning of oil and fuel oil tanks</td>
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<td></td>
<td>Bottom products of refining process</td>
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<td></td>
<td>Oily sludge from cluster treatment facilities</td>
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<tr>
<td></td>
<td>Flammable substances</td>
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<tr>
<td></td>
<td>Rinse fluids</td>
</tr>
<tr>
<td></td>
<td>Lubricants</td>
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<tr>
<td></td>
<td>Oily sludge from treatment facilities</td>
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<tr>
<td></td>
<td>Oil-water emulsions</td>
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<tr>
<td></td>
<td>Acid sludge</td>
</tr>
<tr>
<td>Oil spill response</td>
<td>Oil-contaminated soil</td>
</tr>
<tr>
<td></td>
<td>Highly bituminised oil</td>
</tr>
<tr>
<td></td>
<td>Oil-water emulsions</td>
</tr>
<tr>
<td></td>
<td>Waste sorbents</td>
</tr>
<tr>
<td></td>
<td>Waste oil-spill booms</td>
</tr>
</tbody>
</table>
This classification allows us to demonstrate that different technological processes generate wastes identical by name (for instance, oil sludge), but significantly differing by physical and chemical composition; these wastes will require individual approach to their processing.

OWs are very diverse; they are complicated structures consisting mainly of hydrocarbon, water and mineral phases whose percentage differs depending on the type of waste. Thus, for instance, the content of the hydrocarbon phase in bore mud cannot exceed 1% by weight, and in tank oily sludge it reaches 90% by weight. Water content of oily sludge also differs depending on the sludge type, conditions of formation and duration of storage. In addition, oily waste stored in tanks, tailings ponds, temporary storage sites, or on natural surfaces (such as water or soil) is currently being processed by technologies that do not always meet modern environmental requirements. For example, the composition of the hydrocarbon mass released during oil waste separation may vary depending on the separation object, and will not always achieve the values established by the official GOST standards for petroleum products. At the same time, the aqueous portion and the solid residues (cake) require further purification. For this, extra equipment will be required in order to achieve the required parameters for all three separation products. Thermal processes employed in oily waste processing encounter similar challenges. Those are air pollution and the need to dispose of solid waste (ash, cake). The drawbacks of these processes have been described quite fully in technical literature.

When the OW accumulation issue started to become global, several methods of OW processing and disposal were developed. From an economic point of view, the most profitable ways were those that incur the least energy and financial costs. Therefore, almost all the methods applied were aimed not at OW processing, but rather at their destruction. Moreover, the destruction of oily wastes could in its turn lead to extra waste generation in the form of gas emissions or formation of unburned, unwashed or unreacted residues. Almost all methods of OW management are aimed either at separating the wastes into their constituent phases, or at their destruction, with only a small proportion of methods aimed at processing into safe or commercial products. Therefore, the existing methods of OW processing or disposing are classified into mechanical, chemical, physicochemical, thermal and biological methods [5].

The mechanical method is used for collection of OW after it enters the environment. Heavy oil residues are cut and excavated with the help of mechanical equipment, and the liquid hydrocarbon phase is pumped out with the help of vacuum technology. After that, the collected waste is transported to storage sites for further processing.

Physical methods are hydrostatic and hydro-mechanical methods, including such operations as separation, settling, filtration and centrifugation.

Settling leads to separation of OW due to different density of oil and water and sedimentation of mechanical impurities. During settling, the oil layer formed on the surface is pumped out and subjected to further refining processes. This process does not solve the problem of OW recovery; however, it allows to separate them into components with further involvement in the technological cycle [6].

Filtration is a rather long and complicated process, especially with oil sludge whose hydrocarbon phase has high viscosity, density and low pour point. Therefore, OW filtration can be carried out on special vacuum filters and filter presses [7].

Centrifugation requires decanters and tricanters where mechanical centrifugal separation of OW occurs due to the varying densities of the separated phases. During decantation, OW is separated into two phases, for example, into oil and water, during tricantation, the waste is separated into oil, water and mechanical impurities. This method is great for OW separation; however, it may lead to formation of water and mechanical impurities containing residual oil products, which will require additional stages of purification after separation [8].

Physicochemical methods are used for OW separation and disposal. During technological operations, the processes of flotation, flocculation, coagulation, sorption, extraction, and ion exchange are used. This method requires additional spending on chemicals and provision of the necessary conditions for the operation of the technological process. In this area, interesting results have been achieved allowing to improve the efficiency of sedimentation and flotation processes using ultrasonic treatment [9].

Chemical method implies the use of various reagents that facilitate oxidation and/or reduction, substitution, complexation, and precipitation reactions [10].

The method of chemical complexation is worth highlighting. It is one of the most common methods, especially popular for management of bore mud and oily sludge. Oily waste is diluted with both organic and inorganic binders, mostly with various types of lime, cement, bentonite, ash, silicates, sand and peat. This method is economically viable, since it involves no costs except for the purchase of binders and mixing equipment. However, it falls completely short of waste processing, since by diluting the waste we only lower its hazard class. That is, from 1 m³ of hazard class III waste, we obtain 5 or 10 m³ of
hazard class IV waste. Formally, pollutants remain in the environment in an immobilised state, but they need constant environmental and chemical control, and we must not forget that nothing lasts forever and due to biotic and abiotic factors, materials can instantly switch their state from immobilised to mobilised. The most common practical example is that complexed materials are unstable against moisture from the atmosphere or groundwater, which leads to their destruction and to release of pollutants into the environment. Also, the binders to be mixed with bore mud can contain water tight clays, which could lead to rain flooding of the areas where the “neutralised” waste will be stored.

Biological method of OW processing is based on the use of microbiological cultures as a means for environmental decomposition of petroleum hydrocarbons. This method is highly effective in combating oil pollution, but it is very labour consuming and requires special facilities. In addition, depending on the chemical composition of the specific OW, it is necessary to carefully select microbiological cultures that are resistant to a specific type of waste, as well as those capable of biodegradation of hydrocarbon pollution [11]. A promising trend will be the combination of biological purification methods with sorption ones. Using biodegradable sorbent materials as carriers for microbiological cultures can help achieve higher purification rates.

The main advantages and disadvantages of each method are summarised in Table 2.

<table>
<thead>
<tr>
<th>OW processing method</th>
<th>Advantages</th>
<th>Disadvantages</th>
</tr>
</thead>
<tbody>
<tr>
<td>Thermal</td>
<td>- Less waste &lt;br&gt;- Hazard class is downgraded to safe &lt;br&gt;- Yields useful products</td>
<td>- In case of incineration, flue gases require complex and expensive purification systems</td>
</tr>
<tr>
<td>Chemical</td>
<td>- Yields construction materials</td>
<td>- Rather high cost of chemicals, high environmental burden of sludge processing</td>
</tr>
<tr>
<td>Mechanical/physical</td>
<td>- Decanter provides for 90% oil extraction &lt;br&gt;- The resulting concentrate saves further processing</td>
<td>- Expensive, 100% imported equipment that requires qualified maintenance</td>
</tr>
<tr>
<td>Physicochemical</td>
<td>- Less environmental burden due to sludge neutralisation</td>
<td>- Rather high cost of chemicals, high environmental burden of sludge processing</td>
</tr>
<tr>
<td>Biological</td>
<td>- Least labour-consuming method &lt;br&gt;- Application of an active biological substance &lt;br&gt;- Low environmental impact</td>
<td>- Strict operating requirements &lt;br&gt;- Impossible to use under temperatures below zero, and under conditions of deep seepage of oil into the soil</td>
</tr>
</tbody>
</table>
The desired goal of oily waste processing is to obtain commercial resources with guaranteed environmental and hygienic qualities of all products (water, soil, cake) that are formed as a result of the process.

Today, there are companies on the Russian technology market that offer various technological solutions for OW processing and disposal. Despite the advantages and achievements, they seek destruction and neutralisation of waste, which often leads to secondary environmental pollution in the form of ash, gas emissions and effluents. The existing technologies require an upgrade that would lead to lesser formation of secondary pollutants.
Having analysed the variety of the oily waste processing technologies being currently implemented, we came to the conclusion that the existing individual technical solutions are unable to ensure 100% recycling with guaranteed material and environmental results. However, if these technologies are integrated into a single working technological chain, then their productivity and the OW processing depth will increase several times as a result of increased environmental significance. This technological solution can be implemented only within the framework of a unified systematic approach focused on obtaining material resources from waste and bringing the environmental burden to the required standards.

This technology was first implemented by the Rohrer Group (https://www.rohrer-grp.com), where all oily waste with justified economic logistics was brought to a dedicated landfill.

The landfill is outfitted with a cascade of three tailings ponds where oil wastes are successively mixed with water. The third pond is used for sedimentation of suspended particles, and the upper hydrocarbon layer is pumped for separation (see Figures 3 and 4).

A flow chart of comprehensive OW processing will consist of the following main elements (see Fig. 5)

FIGURE 5. OW processing chart.

As can be seen from the above chart, OW from different sites are mixed in tailings ponds. Further, their pretreatment and mixing is carried out. Tricanter is used to divide the homogenised OW into component phases. Therefore, separation yields stable hydrocarbon mass (oil), which is then sold to the refinery, water that is circulated back to the ponds, and cake (solid phase) which is discharged to the sites where the residues of hydrocarbons are oxidised by aeration to required parameters.

Thus, no universal technology exists today that could effectively solve all the OW issues. We will be able to achieve maximum results only by way of revising the existing waste management models and by establishing single collection sites for integrated waste processing.

Currently, this technology is being adapted in Russia in areas of intensive oil production and processing. However, in view of the fact that several oil and gas companies operate in these regions, it is still difficult to combine their efforts in order to establish common-use landfills. The pivotal role in this association for the introduction of such technology should be played by the regional administrations.

Another sensitive area is the processing of accumulated oil and chemical waste. In Russia, there exist many sites of accumulated environmental damage and past environmental damage. Under my leadership, scientists from the Gubkin University for Oil and Gas and the Russian Academy for Natural Sciences have developed a systematic approach to waste processing at such facilities. It goes without saying that the elimination of such buildups or their processing is extremely costly. However, such a new approach to the problem provides a basis for reducing costs due to the extraction of valuable resources from the accumulated waste.
The development of novel or more efficient OW processing technologies is associated with large-scale research and development work, engineering surveys, construction projects and pilot tests.

Such technologies should use state-of-the-art devices operating in a single consistent system that yields good environmental, economic, material and resource-saving results. The application of a systematic approach in the field of OW recycling is, in our opinion, a breakthrough direction, which in the future will allow us to systematise wastes produced by various oil and gas companies and to ensure their uniform collection and processing.
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INTRODUCTION

Energy shortages and environmental pollution are becoming more and more serious today. It has become a problem to ensure energy supply while reducing environmental pollution. Although the Earth is rich in clean energy, it is not easy to send the energy to densely populated areas which are hundreds or even thousands of miles away. At the same time, many countries in the world have the problem of uneven distribution of energy and load. The energy center and the load center are often very far apart. Therefore, it is necessary to develop a technology for long-distance energy transmission to realise the reasonable distribution of energy worldwide.

In the past ten years, the power grid has continued to develop. The transmission voltage has gone through two stages of high voltage (HV) and extra high voltage (EHV), and has now entered the ultra high voltage (UHV) power transmission stage. With the maturity of UHV power transmission technology, it can play a role in rationally configuring the energy structure and optimising the energy distribution.

UHV power transmission technology includes UHVAC power transmission technology and UHVDC power transmission technology. According to the definition of the International Electrotechnical Commission, UHVAC refers to AC transmission lines with a voltage level of 1000 kV and above. UHVDC generally refers to DC transmission lines with a voltage level of ±800 kV and above. In the late 1960s, various countries began to study UHV power transmission technology. The Soviet Union built a 1150 kV UHVAC transmission line in 1985. Japan also built a 1000 kV AC transmission line with double circuits on the same tower in the early 1990s, but both have not been put into operation in UHV level. In addition, the United States, France and other countries have also conducted tests of UHV projects. As of 2020, China has built a total of 13 UHV AC lines and 11 UHV DC lines, and the cumulative UHV line length has reached 28352 km, and two UHVDC projects have been built in Brazil. It is estimated that by 2024, China's total UHV mileage can reach 40021 km.
Compared with the EHV power transmission technology, UHV power transmission technology has advantages in many aspects. UHV power transmission technology can increase transmission capacity, increase transmission distance, reduce line corridors, reduce line losses, and improve grid structure.

### TABLE 1. Comparison among different voltage-level transmission technologies.

<table>
<thead>
<tr>
<th></th>
<th>±1100 kV UHVDC</th>
<th>±500 kV EHVDC</th>
<th>1000 kV UHVAC</th>
<th>500 kV EHVAC</th>
</tr>
</thead>
<tbody>
<tr>
<td>Transmission capacity</td>
<td>12000 MW</td>
<td>1200 MW-3200 MW</td>
<td>6000 MW</td>
<td>1200 MW</td>
</tr>
<tr>
<td>Transmission distance</td>
<td>&gt;3000 km</td>
<td>1000-1500 km</td>
<td>&gt;1500 km</td>
<td>600-800 km</td>
</tr>
<tr>
<td>Transmission loss</td>
<td>1.5%/1000 km</td>
<td>4.5%/1000 km</td>
<td>2.7%/1000 km</td>
<td>4.0%/1000 km</td>
</tr>
<tr>
<td>Corridor efficiency</td>
<td>100%</td>
<td>25%</td>
<td>100%</td>
<td>25%</td>
</tr>
</tbody>
</table>

* Corridor efficiency refers to the transmission capacity per unit area.

**Large transmission capacity.**

UHV transmission lines are called “electric highways”. The natural power of AC transmission line is

\[ P = \frac{U^2}{Z_c} = U^2 \times \sqrt{C/L} \]

where \( U \) is the line voltage, \( Z_c \) is the line wave impedance, \( L \) and \( C \) are the inductance and capacitance of the unit length line, respectively. The natural power \( P \) of the AC line is proportional to the square of the voltage \( U \). Similar conclusions can also be applied to DC lines.

2.4 times the transmission capacity of ±500 kV EHVDC lines. This large-capacity power transmission technology can well solve the problem that the power supply is far away from the load centre, and realise the large-scale access of new energy.

**Long transmission distance.**

The transmission capacity of AC transmission lines decreases with the increase of distance, so a higher transmission voltage is required for long-distance transmission. The economic transmission distance of a 500 kV EHV AC transmission line is generally 600 to 800 km, while the 1000 kV UHVAC transmission line, with increased voltage and reduced line losses, and its economic transmission distance has also increased, reaching 1000 to 1500 km or even longer, while the transmission distance of ±1000 kV UHVDC can reach about 5000 km. This kind of long-distance power transmission is particularly suitable for cross-regional or cross-continent dispatch in areas with uneven energy distribution. At the same time, this can also promote the intensive development and efficient use of clean energy, and transport clean electric energy such as hydropower, wind power, and solar power in remote areas to load centers on a large scale and a long distance.
Save way of right. With the growth of electricity load and the development of power grids, the way of right of transmission line is becoming increasingly tight. Due to the large transmission capacity of UHV power transmission technology, the use of UHVAC and UHVDC transmission lines can reduce the number of circuit loops and save way of right. This is conducive to improving the overall social benefits and improving the economy of the energy network.

Reduce line loss.

The loss of the transmission line is an important factor that determines the economy of the line. The loss of the transmission line \( P_{\text{loss}} \) is

\[
P_{\text{loss}} = \frac{S^2}{U^2} R
\]

where \( S \) is the transmission capacity of the line, \( U \) is the voltage, and \( R \) is the series resistance of the line. When the voltage increases, the line loss decreases. The conventional loss rate of 500 kV EHV AC lines can reach 1.25-1.79 times that of 1000 kV UHVAC lines. Therefore, UHV power transmission technology can greatly improve the economics of transmission lines.\(^{61}\)

Improve the grid structure. In the UHV transmission network, due to the large transmission capacity, the ultra-large capacity power plants can be directly connected to the grid. At the same time, UHV transmission lines can reduce the need to build power plants in load centers and optimise energy resource allocation on a larger scale. At the same time, the use of UHV AC/DC hybrid power grid transmission can greatly reduce the problems of insufficient power flow transfer capacity and weak reactive voltage support of 500 kV grid in the case of DC system failure. This can reduce the risk of large-scale power outages in the power grid and create conditions for the gradual layered and zoned operation of the next-level power grid, solve the problems that limit the development of the power grid such as short-circuit current overrun, and improve the flexibility and reliability of power grid operation.

In addition to the above advantages, UHVDC transmission has its own unique advantages in long-distance and large-capacity transmission. When realising the connection between island and mainland, island and island through long-distance submarine cables, DC transmission also shows obvious advantages. At the same time, UHVDC transmission also has the advantages of low line cost, fast adjustment, and reliable operation. However, UHVDC also needs to solve some problems, such as expensive DC transmission converter devices, high reactive power consumption, and harmonic pollution.

In summary, UHV power transmission technology can solve some of the problems that have plagued the energy industry for a long time. UHV power transmission technology can develop and utilise electricity generated by renewable energy sources such as wind and solar energy. At the same time, UHV power transmission technology can transmit power from remote areas to places with high power consumption without large power loss.
The development of UHV power transmission technology depends on the breakthroughs in key technologies. The stable operation of UHV key equipment determines the safety of UHV systems and the feasibility of UHV networks.

As shown in Fig.1, the main equipment required for the UHVDC project is the converter station and the transmission line. The converter station is very important in the UHVDC project. The converter station is established to complete the conversion of electric energy and meet the requirements of the power system for safety, stability, and power quality. The main equipment of the converter station includes converter valves, converter transformers, DC filters, smoothing reactors, AC filters, etc. Among them, the converter device composed of converter transformer and converter valve is the core of the converter station.

**Converter transformer.** The functions of the converter transformer are as follows: (1) Using the magnetic coupling of the windings on both sides to transmit power to realise the insulation and isolation of the AC and DC system. (2) Realising the voltage conversion so that the voltage on both sides meets the rated value and tolerance value, respectively. (3) Suppressing the overvoltage of the AC grid from invading the converter. The Changji-Guquan ±1100 kV UHVDC transmission project uses ±1100 kV converter transformers, and its single unit capacity reaches 607.5 MVA.

**Converter valve.** The converter valve is mainly composed of thyristors. It is used to convert alternating current into direct current (rectification), or convert direct current into alternating current (inversion). The ETT (Electric Trigger Thyristor) composed of electric trigger thyristors realises the isolation of the low and high potentials between the trigger pulse generator and the converter valve, while avoiding electromagnetic interference, miniaturising the device, reducing energy consumption and cost. The current UHVDC project mainly uses this kind of thyristor. The LTT (Light Trigger Thyristor) converter composed of light-triggered thyristors eliminates the photoelectric conversion, amplification link and power circuit of the control unit, improves the valve’s triggering characteristics, and improves the reliability of the valve.

In addition, there are other important equipment. For example, large-capacity high-voltage DC cables can realise UHV transmission between islands and land, and between islands and islands. Advanced surge arresters can improve the overvoltage protection capability of the converter station. Advanced control systems and algorithms can optimise the stability of transmission lines.

In UHVAC projects, gas insulated switchgear (GIS) and AC transformers are very important. Among them, GIS is composed of circuit breakers, isolating switches, grounding switches, transformers, surge arresters, etc., which occupies a small space.
AC transformer. The main difficulty of UHVAC transformers is the high-voltage insulation design and the magnetic leakage and temperature rise control of large-capacity equipment. At present, advanced AC transformers have achieved a further increase in UHV single-column capacity by solving problems such as magnetic leakage and temperature rise control. The transformer capacity has been increased from 334 MVA per column to 500 MVA, and the single-device capacity has reached 1500 MVA. At the same time, advanced transformers have realised different ways of partial disassembly and total disassembly, which solved the limitation of large-capacity UHV transformers due to transportation restrictions.

GIS. Compared to air insulated switchgear (AIS), GIS occupies approximately 30% of the area of AIS. At the same time, GIS has strong environmental adaptability, and the live parts are enclosed in a metal shell, which can avoid electromagnetic pollution caused by high voltage to the environment, and the insulation performance of the equipment is not affected by the atmosphere. The difficulty of UHV GIS is its large size, large breaking capacity, and high insulation requirements. Large size requires consideration of mechanical strength and seismic performance. Large breaking capacity needs to consider the time constant, the ablation of the arc extinguishing chamber and the operating power of the operating mechanism. Insulation requirements need to consider the size of the insulation and operating overvoltage, especially the suppression of Very Fast Transient Overvoltage (VFTO). At present, the rated voltage of advanced GIS reaches 1100 kV, and the breaking current is 63 kA.

### PROJECT CASES

1. **±1100 kV Changji-Guquan UHVDC Project**

   The Changji-Guquan ±1100 kV UHVDC project was completed in 201862. The transmission capacity reaches 12000 MW, and the transmission distance is 3324 km. The Changji-Guquan UHVDC project can transmit 100 million kW•h of electricity every 8 hours and 20 minutes, solving the problem of imbalance between energy and load in the east and west of China. Compared with the ±800 kV project, the line loss per thousand kilometers of this project is reduced from 2.8% to 1.5%, and it has the capacity of 60 to 80 billion kW•h of annual power transmission. The Changji-Guquan ±1100 kV UHVDC transmission project is the world's highest voltage level, the largest transmission capacity, the longest transmission distance, and the most advanced technology level UHV transmission project. It can reduce the annual coal consumption in East China by 30 million tons and reduce 24,000 tons of soot, 149,000 tons of sulfur dioxide, and 157,000 tons of nitrogen oxides every year63.

2. **Suzhou-Nantong 1000 kV UHVAC GIL Pipe Gallery Project**

   The Suzhou-Nantong 1000 kV UHV AC GIL pipe gallery project is the world's first UHV power pipe gallery. Gas-insulated metal-enclosed Transmission Line (GIL) encloses high-voltage current-carrying conductors supported by insulation spacers in a metal shell and injects SF6 gas, whose insulation performance is far better than that of air, which greatly compresses the power transmission. The space size of the line realises a highly compact and miniaturised design, becoming a compact power transmission solution to replace overhead transmission lines. The Suzhou-Nantong 1000kV UHVAC GIL integrated pipe gallery project crosses the Yangtze River, with a total length of 5468.5 m, an excavation outer diameter of 12.07 m, a maximum slope of 5%, and a maximum water and soil pressure as high as 9.5 times the atmospheric pressure. After the project is put into operation, the East China region can save 170 million tons of coal for power generation, 310 million tons of carbon dioxide, 960,000 tons of sulfur dioxide, 530,000 tons of nitrogen oxides, and 110,000 tons of soot every year.
THE FUTURE OF UHV

UHV power transmission technology has high efficiency and low unit transmission cost. Compared with 500 kV EHV, UHV saves more than a quarter of investment. It is estimated that the transmission capacity of one 1150 kV transmission line can replace five to six 500 kV lines, or three 750 kV lines. It can reduce tower materials by one third and save conductors by one half. The savings include the cost of the power grid in the substation is 10-15%. The 1150 kV UHV line corridor is only about a quarter of the corridor required for the 500 kV line with the same transmission capacity, which will bring significant economic and social benefits to countries and regions with dense populations, precious land or difficult corridors. Therefore, UHV power transmission has obvious economic benefits.

Moreover, the use of renewable energy has greatly reduced the increasingly severe haze weather, and the value it brings is immeasurable. In the next 25 years, the global population is expected to increase by 2 billion people, and electricity demand will increase by 90%. Developing countries have a particularly strong demand for energy, and most of the demand growth in the next 30 years will come from these countries. Electricity consumption per capita in the Asia-Pacific region is expected to double. Environmental pollution caused by energy emissions and global warming are issues that we must face together. UHV technology allows us to introduce renewable energy in a sustainable and efficient manner. In the future, the global grid interconnection mode will undergo a major change, from small power exchange, surplus and shortcoming mutual assistance, to large-capacity power transmission, large-scale energy bases, and direct supply to load centres.

From a global perspective, the global clean energy is unevenly distributed. As shown in Fig.2, the wind energy is mainly distributed in the Arctic, central and northern Asia, northern Europe, central North America, eastern Africa, and coastal areas of all continents. The solar energy is mainly distributed in areas near the equator such as North Africa, East Africa, the Middle East, Oceania, and Central and South America. Most of these clean energy resource-rich areas are far away from load centres, hundreds to thousands of kilometers apart. The global energy internet based on UHV power transmission technology will solve this problem. UHV technology can transmit energy from country to country, region to region, and intercontinentally safely, efficiently and cleanly, and coordinate the development, allocation and utilisation of energy resources on a global scale. With the development of UHV power transmission technology, electricity from Arctic wind power and equatorial solar power generation bases thousands of kilometers away can be transmitted to power load centres on all continents to meet human power demand.

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Taking the intercontinental power grid from China...
UHV power transmission technology has the advantages of large transmission capacity, long transmission distance, low line loss, and saving land resources. This advanced power transmission technology can realise large-scale long-distance power dispatch, thereby improving the unevenness of energy and load. At the same time, UHV transmission technology can improve the economics of the power grid and provide a way for new energy consumption to reduce pollution emissions. With continuous breakthroughs in UHV key technologies, the future energy network will become interconnected, economical, clean, and sustainable, which provides a possible way to connect global power grids together, and dispatch the energy globally.

With the development of UHVDC power cables and gas insulated lines, the transmission lines will be built below ground and highly reduce the occupied land, and will be free of the environmental influences, such as lightning strikes, pollution flashover and icing, which will become more attractive.

to Europe as an example, the ultra-long-distance China-Europe UHV transmission channel of 4000 to 8000 km can be constructed to transport wind, solar, and hydropower from China, Russia, Siberia, Mongolia, Kazakhstan and other places to Europe. According to demonstration, one transmission line with a transmission power of 10 million kilowatts can provide Europe with 60 billion kilowatt-hours of clean energy every year, replace 20.52 million tons of standard coal, and reduce 57.05 million tons of carbon dioxide and 410.000 tons of sulfur dioxide. The construction of a global energy internet will generally be promoted in three stages: domestic interconnection, intracontinental interconnection, and global interconnection. As a key technology for realising global energy interconnection, UHV power transmission technology, especially UHVDC, is crucial to the large-scale dispatch of world energy and the consumption of clean energy.

CONCLUSIONS
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The modern energy transformation is challenged at least into two main directions – one is to be able to supply a growing demand of the energy on the planet as living standards are increasing and there is a growing population. The second challenge is to develop a long-term sustainable energy production in order to obtain the wanted decarbonisation e.g. as outlined in the Paris agreement. Climate changes are on the global agenda and there is a strong push towards doing the energy transition – we can see many countries have strong plans within short-term and long-term to change their energy systems. Germany, US, and China have the largest renewable generation capacities for the moment while relatively – a country like Denmark is a leading country in terms of renewable energy supply – as more than 60% of the electricity is coming from renewables. All countries have become leading due to strategic planning for decarbonisation and a wish to be less dependent on fossil fuels.

It is also important to use the produced energy more efficient and in that way limit the growth of energy consumption as well as the need of new generation capacity. One important approach in that context is to electrify as much as possible including the general transportation sector in order to make it more efficient and reduce the carbon emission. Additional benefits exist in such transformation as cities will achieve less noise and less air-pollution – so it will at least be a triple-win for the society. As the renewable/sustainable generation capacities are key in this energy transformation, they should of course become even cheaper. Today, wind and solar power are fully competitive with fossil fuel for many installations and locations – however, the technologies are expected to be even more efficient and cheaper due to scaling law in terms of manufacturing. Wind and solar do not need any fuel to produce energy – except wind and sun! – and therefore they are sustainable energy sources as they will not make any carbon emission once manufactured.
As renewable generations are nature, weather, and seasonal dependent, the different existing energy carriers need to have synergy and interplay with each other (i.e., electricity, gas (and other), heat) in order to obtain a high system efficiency and reliability. Further – a large challenge energy-system-wise is to find energy storage solutions for more long-term durability and thereby doing the transition towards renewable generation faster, safer, and smoother. Batteries are used more and more as electrical storage, which is an efficient way to store electricity. Already in some places, 60% of all PV system sales for private housing have batteries included – and as the price goes down with this technology it will become even more attractive. Batteries are also now being integrated into wind farms and other larger installations – so it is on its move – and in a combination with E-mobility – batteries are expected to drop largely in price. But they cannot store energy in a very large scale for longer time duration, which is a need in a modern energy system. Therefore the electricity needs to be converted into other energy carriers, where hydrogen – through electrolyser – has been known for decades, but the hydrogen often needs to be further processed into other fuels – by doing chemical processes, e.g. using CO₂.

The electrification transition of the society needs large-scale electrical power conversion, which is applying the power electronics, and this can fortunately be done efficiently with existing technology. A simplified electrical powered energy system (E-Power) is shown in Fig. 1 and is illustrating from electrical generation to consumption the usage of power electronics – as well as showing some storage solutions for the future.

Batteries are applied in Electric Vehicles as well. It is shown that the electricity is converted into hydrogen using an electrolyser – and then afterwards it can be further used or processed to convert into a chemical-based energy carrier – e.g. gas, E-fuel or ammonium and in such case, hydrogen is a key energy carrier (P2X). Fig. 1 illustrates other important aspects in the
The role of Power to X (P2X) is to achieve new ways of long term energy storage as well as to have a high energy density capability to transportation applications where that is needed – e.g., in heavy trucks, ships, and airplanes. The challenge is that the total energy conversion efficiency is much lower compared to storing the electrical energy in batteries – but so far, it is an obvious solution for such applications. Hydrogen can be obtained by different methods – one is naturally to use electrolysers – as mentioned previously – which is also partly shown in Fig. 2. It can also be achieved by biogas (e.g., from animals and other waste) and other biomass material as well as taken from natural gas (in some cases this is called blue hydrogen).

**FIGURE 2.** Role of Hydrogen as a clean, safe, and versatile energy carrier – where both creation and usage are illustrated.
The amount of needed electrical power and energy storage is large in order to be able to cover both heavy transport and a long-term storage. The installations for making such progress are large, and involves large investment cost, high efficiency, obtain good grid power quality as well as ensuring high reliability. Fig. 4 shows a natural and cost efficient way to make such an electrolyser plant. Electrolyser most often need DC at a relatively low voltage, which means an AC to DC power conversion is needed as the grid is AC. The power source can be directly from the grid or the renewables – then a transformer (50Hz/60Hz) is applied for the step of down-transformation of the grid voltage and afterwards an AC/DC converter as well an output filter are applied to make a high-quality voltage for the electrolysis process. To ensure a good power quality – an electrical filter is used in combination with a three-wounded transformer (i.e., 12-pulse rectifier transformer). Such solution is cheap for very large plants (GW).
The system shown in Fig. 4 can be detailed a little more as at least two principles can be applied to make the electrical power conversion – to control the output voltage and thereby the current in the electrolyser. Fig. 5a shows a very classical way of doing the voltage regulation by using thyristors, while Fig. 5b shows a power transistor-based solution where multiple power transistors are operating in parallel and working interleaved.

One of the future potential ways of doing this power conversion is to avoid the 50Hz/60Hz transformers and do the power conversion as shown in Fig. 5c, where instead a high frequency isolation is provided at the grid side having switching converters doing AC/DC conversion and then provide high frequency DC/DC power conversion, where a galvanic isolation is provided. As the operation frequency will be in kHz – the transformer size will be much lower compared to a 50Hz/60Hz transformer. The power supply can have a cell-type structure, where at the grid side the converters are in series to handle high voltage while at the electrolyser side, the converters are in parallel to provide the needed current for the electrolyser process – and a high-quality current can be provided. A heavy transformer is thereby avoided and substituted with high frequency transformer – which is much smaller. The challenge is that more power semiconductor devices are included and thereby it might be more costly. However, the latter solution provides higher modularity and scalability in order to meet different power level requirement based on a power electronic building block (PEBB) concept.

**FIGURE 5.**
Different power electronics supply configurations for doing the electrolyser at a very high power scale. a) Thyristor based control of electrolyser voltage and transformer grid connection, b) Transistor based control of electrolyser and transformer grid connection, c) High-frequency galvanic isolated controllable power supply for medium voltage grid connection (Modularised).
Denmark is one of the leading countries in large-scale implementation of renewable generation – and is taking the next step to become more carbon neutral by transforming the transportation sector to become electrical. One part is natural to expand the battery-based fleet of the transportation sector, but there is also a need to convert electricity into fuels for the heavy transport like trucks, ships, and airplanes. As Denmark is surrounded with oceans with strong and attractive wind conditions, it is planned to build energy Islands in the ocean far from shore – like illustrated in Fig. 6.

An artificial island is planned to be built to host a collection of offshore wind farms power production, e.g. doing the P2X conversion on the Island – which then can be transported in a physical pipeline to shore. An alternative solution could be to transport the electrical power to shore by doing High Voltage DC Transmission (HVDC) and then install the Power-to-X plant on-shore in order to better utilise the heat generated in the P2X process e.g. for industrial heat, heating up cities or other means, which can increase the overall system efficiency. If the electricity is transported to shore – it can also be connected to the transmission system of Denmark and thereby have an extra value for the power system. A lot of power electronic conversion technologies are used in order to make this a reality. The energy island might also have connection to other countries through HVDC-lines and thereby provide a large flexibility. The initial plan in terms of scaling is that the first step will be a 2 GW wind power plant incl. electrolyser and then later expanded to 10 GW – and thereby supply the Danish heavy transportation sector – and might be serving as a long-term energy storage.
FIGURE 6.

Energy Island with large scale offshore wind farms, a P2X station on the Island and also power/energy connection to shore, which can be done both electrical and by a gas pipeline. The P2X can also be located on shore. AC/DC/AC power conversion is shown on the Island for the wind turbine connection – but in practice, it will be in each wind turbine.

NEEDED IMPROVEMENTS FOR THE FUTURE TECHNOLOGY

As the P2X looks to be the solution of the future in the large-scale transition of the energy system – challenges exist in the technology and its implementation. Just to mention some:

- The overall efficiency of the conversion is relatively low and the process needs to be improved, which means the technology should be developed;
- To improve system efficiency the ability to utilise the wasted heat from the process for other applications is attractive and will give better energy and economic benefits;
- The location of the P2X process facilities can be different – either at the location of electrical production or after an electrical power transmission (HVDC) and then do the P2X process on shore – here important factors like efficiency of electrical power transmission, cost of power transmission system, added value in on-shore power system as well the ability to use the waste heat are needed to be considered;
- The power electronics technology for power conversion in the electrolyser needs to get even higher efficiency, lower cost and high reliability to be able to operate +200000 hours (25Y lifetime);
- The electrolyser technology should also have long lifetime and low operation/maintenance cost.
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