

New Method for Stabilization of Wind Power Generation Using Energy Storage Technology

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Abstract. Wind power appears to be one of the most perspective and widespread renewable energy sources in Estonia. However, wind is difficult to forecast. This complicates production planning and parallel operation with compensating power plants, allowing periods of excess energy and lack of energy to occur. This paper proposes a new energy storage technology to compensate unstable operation of windmills. This is based on a hydrogen buffer, which accumulates excess energy from windmills and transfers it to the DC-link of windmills converter. As all components of the hydrogen buffer are electrically connected to the DC-link, there are three main stages. The first stage is hydrogen production, which is realized with the help of water electrolysis in periods of excess energy. Interfacing is carried out with electrical components, such as DC/DC converter with a step-down isolation transformer. The second stage is hydrogen storage and delivery. The produced hydrogen is accumulated in a tank locally or in industrial gas storage. Hydrogen may be mixed with natural gas and distributed to natural gas pipelines. The third stage is electricity production. The stored energy is used to produce electrical energy during the absence of wind or in conditions of a weak wind. Hydrogen is converted into electricity by a fuel cell. Interfacing is carried out using electrical components with the help of DC/DC converter with a step-up isolation transformer. The paper represents the structure of the proposed hydrogen-based energy buffer and reviews its main elements.

Key words: Renewable energy storage, electrolysis, hydrogen buffer, fuel cell

INTRODUCTION

Sustainability and efficient use of energy resources is an urgent issue today. Reasons lie not only in the growth of demand and production, but also in the present level of resource exploitation leading to exhaustion of energy resources and related environmental impacts. The sustainable use of energy requires applications and methods that could increase efficiency. This is especially important in converter applications.

Traditional methods of energy conversion in power plants have some disadvantages, such as impact on the environment. Some new unconventional methods of energy generation have less impact on the environment. The cost of power generation is one of the main criteria when choosing a method for its production. Today, traditional technologies seem to be cheaper than the alternative

ones. Energy produced from renewable sources lacks the cost of fuel, however, it has higher capital costs.

The predicted costs and cost price of electricity production based on renewable sources have been given in Table 1 (Solovjev, 2006). The use of renewable energy and storage offers prospects of significant decrease in fossil fuel extraction and accompanying environmental pollution (Andrijanoviš, 2009).

Table 1. Prediction costs and cost price of electricity production

Renewable source	Specific capital cost, \$ kW ⁻¹			Cost of production, cent kWh ⁻¹		
	2005	2030	2050	2005	2030	2050
Onshore wind farm	900–1,100	800–900	750–900	4.2–2.2	3.6–2.1	3.5–2.1
Offshore wind farm	1,500–2,500	1,500–1,900	1,400–1,800	6.6–21.7	6.2–18.4	6–18
Solar power	3750–3850	1,400–1,500	1,000–1,100	17.8–54.2	7–32.5	6–29
Fuel cell	3,000–10,000	500–1,000	300–500	2–3	2–3	2–3

The use of wind energy can be considered technically and economically feasible only at average wind speed 4.5 m s⁻¹ (Risthein, 2007). Average annual wind speed and large wind parks in Estonia, (Fig. 1), (Risthein, 2007).

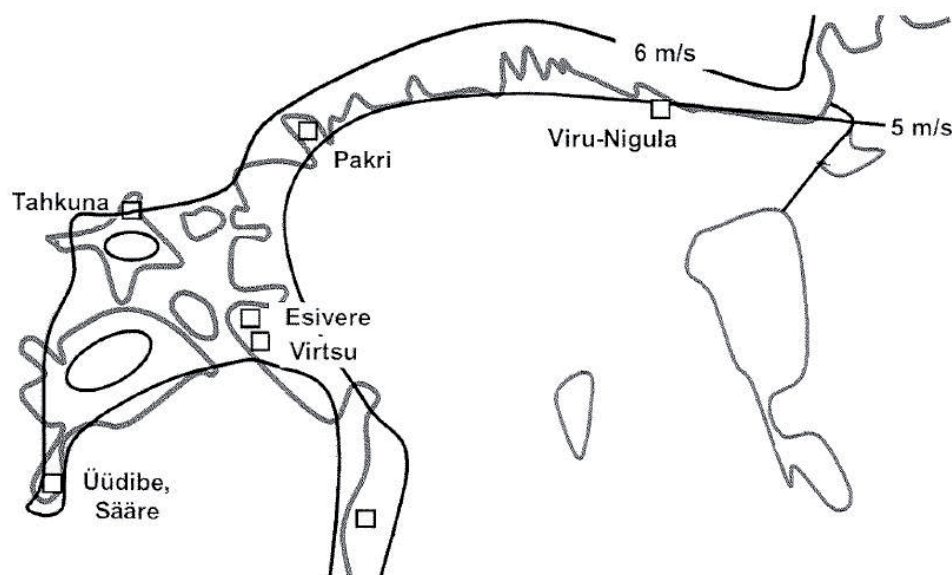


Fig. 1. Average annual wind speed in Estonia.

Unpredictable winds make it difficult to plan production (Fig. 2), complicating parallel operation with other power plants, intended for compensating the instability of wind power production. Due to unpredictable wind the difficulty in forecasting periods of excess energy as well as lack of energy occur (Andrijanoviš et al., 2010).

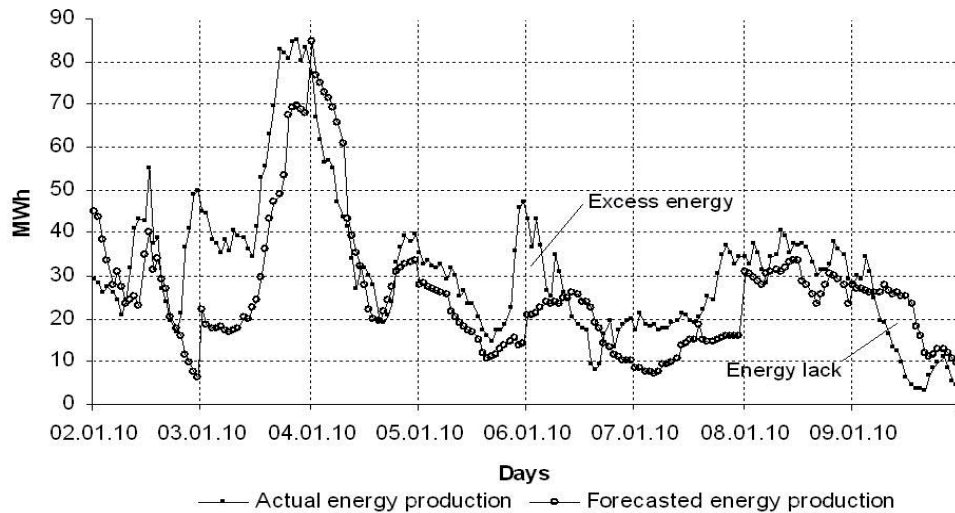


Fig. 2. An example of unpredictable energy production by Estonian wind farms.

HYDROGEN TECHNOLOGY AS A BUFFER FOR STABILIZATION OF WIND POWER GENERATION

The Department of Electrical Drives and Power Electronics has introduced the concept of using hydrogen for compensating the instability of wind production. A typical configuration of a wind farm connected to the transmission grid is formed by the set of wind generators, electrically connected through a medium voltage network, sharing one single infrastructure for access and control. A block diagram of the hydrogen buffer system for the stabilization of wind power generation is presented in Fig. 3 (Andrijanoviš et al., 2010).

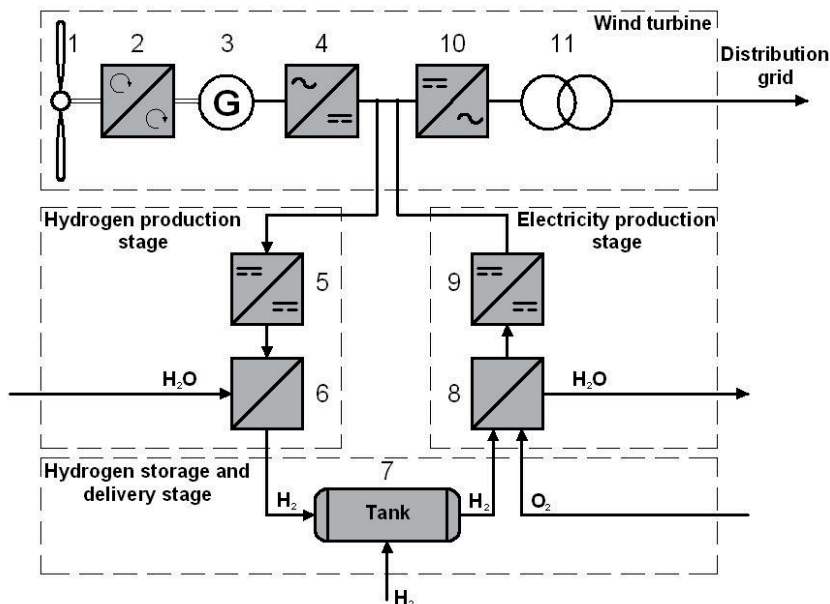


Fig. 3. Block diagram of the proposed hydrogen buffer: 1 – Blades; 2 - Gearbox; 3 - Generator; 4 – Rectifier; 5 - Interface DC/DC converter, 6 – Electrolyser; 7 - Storage tank; 8 - Fuel cell; 9 - Interface DC/DC converter; 10 – Inverter; 11 - Transformer.

Because of unregulated energy production (Fig. 2), the fluctuation of wind speed leads to a fluctuating output. It means that at some moments excess energy and energy lack appear. As mentioned above, a hydrogen buffer is used to stabilize unregulated energy production, consisting of the following main components:

1. Hydrogen production stage,
2. Hydrogen storage and delivery stage,
3. Electricity production stage.

HYDROGEN PRODUCTION STAGE

In periods of excess energy, the hydrogen generation system is connected to the internal grid. In this stage, electrical energy from the wind generator is converted into chemical energy by using water electrolysis. Because of low input voltage of an electrolyser it is necessary to decrease high output voltage of the grid with the help of interface DC/DC converter with a step-down isolation transformer.

The hydrogen generation system consists of two main parts:

1. Interface DC/DC converter with a step-down isolation transformer, which allows interfacing the high voltage DC output of converter with a low voltage input of the electrolyser,
2. Electrolyser, allowing electrical energy storage and producing hydrogen from water electrolysis using excess electricity from the wind generator.

There are three basic types of electrolysers: alkaline, proton exchange membrane (PEM) and high-temperature solid oxide (Fig. 4). Common characteristics of electrolysers are shown in Table 2 (Gamburg et al., 1989, Eg & G technical services Inc., 2004, Egorov et al., 2008). Advantages and disadvantages of different types of electrolysers are shown in Table 3.

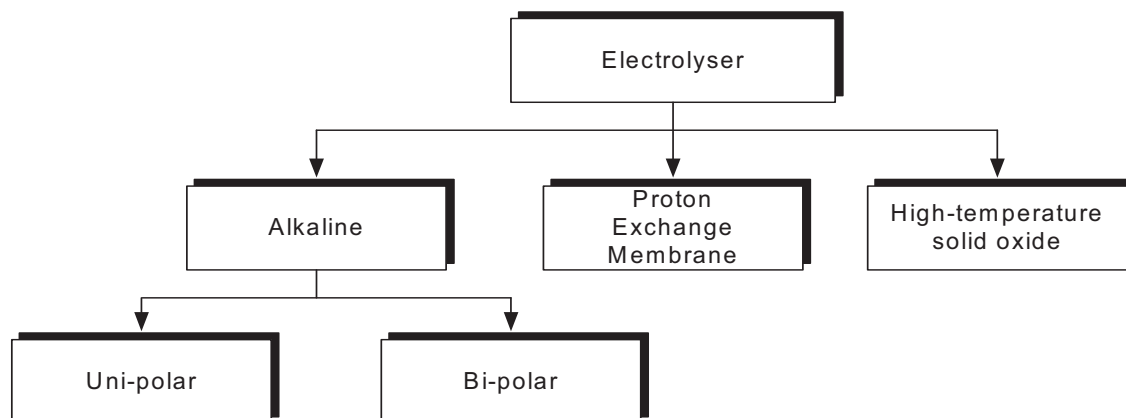


Fig. 4. General classification of electrolysers.

Alkaline electrolysers could be subdivided into unipolar or bipolar electrolysers (Fig. 4). The unipolar design is composed of a series of electrodes, anodes and cathodes alternatively suspended in a tank, filled with a 20–30% solution of electrolyte. In this design, each of the cells is connected in parallel. The bipolar electrolysers have alternating layers of electrodes and separation diaphragms, which are clamped together. The cells are connected in series and can

result in higher stack voltages. Since the cells are relatively thin, the overall stack can be considerably smaller in size than the unipolar design (Kroposki et al., 2006).

Table 2. Common characteristics of electrolyzers

Characteristic	Uni-polar	Bi-polar	Proton Exchange membrane	High-temperature solid oxide
Current density, A (cm ²) ⁻¹	0.1–0.2	0.2–0.4	0.4	1.1–2.0
Voltage cell, V	2.04–2.14	1.87–2.10	1.65–1.85	1.78–1.85
Production, (m ³ H ₂) h ⁻¹	Up to 80,000	Up to 200,000	Up to 25,000	Up to 25,000
Energy demand, (κW·h ⁻¹) (m ³) ⁻¹	5.0	4.3–4.6	4.5	3.9–4.0
Temperature, °C	50–100	50–100	80–100	120
Pressure, MPa	0.01–0.10	0.01–0.10	Up to 3.0	0.2–6.0
Efficiency, %	75–90	75–90	80–90	80–90

In the PEM electrolyzers the electrolyte is contained in a thin, solid ion conducting membrane as opposed to the aqueous solution in the alkaline electrolyzers. This allows the H⁺ ion to transfer from the anode side of the membrane to the cathode side and serves to separate the hydrogen and oxygen gasses. Oxygen is produced on the anode side and hydrogen is produced on the cathode side. PEM electrolyzers use the bipolar design and can be made to operate at high differential pressure across the membrane (Kroposki et al., 2006).

High-temperature electrolysis (HTE) is different from the conventional electrolytic process. Some of the energy needed to split water is provided as thermal energy instead of electricity. It occurs because conventional electrolysis usually operates at temperatures below 100°C. HTE generally refers to an electrolytic process operating at temperatures above 100°C. As HTE curtails the relatively inefficient step of conversion of heat to electricity, it is more efficient than the conventional electrolysis (Sadhankar et al., 2006). In a HTE system using nuclear energy, a nuclear reactor supplies thermal energy that both generates electricity and heats up the steam needed for electrolysis. The HTE system is supported by nuclear process heat and electricity has the potential to produce hydrogen with overall system efficiency near that of the thermochemical processes. HTE cells consist of two porous electrodes separated by a dense ceramic electrolyte. HTE cells with oxygen ion conducting ceramic as electrolyte are often called solid oxide electrolysis cells (SOECs).

Table 3. Advantages and disadvantages of electrolysis

Type of electrolysis	Advantages	Disadvantages
Alkaline unipolar	this design is extremely simple to manufacture and repair	usually operates at lower current densities and lower temperatures
Alkaline bipolar	reduced stack footprints and higher current densities as well as the ability to produce higher pressure gas	can not be repaired without servicing the entire stack although this is rare
Proton exchange membrane	requires no liquid electrolyte, which simplifies the design significantly, the electrolyte is an acidic polymer membrane. PEM electrolyzers can potentially be designed for operating pressures up to several hundred bar, and are suited for both stationary and mobile applications, increased safety due to the absence of KOH electrolytes, a more compact design due to higher densities, and higher operating pressures	limited lifetime of the membranes, membranes must use very pure deionized water, otherwise, they will accumulate cations that displace protons and increase cell resistance over time
High-temperature solid oxide	can operate at significantly higher overall process efficiencies than regular low-temperature electrolyzers	requires large amounts of energy and heat, it is working with a nuclear power plant

Today's most widespread industrial electrolyzers are alkaline and proton exchange membrane. These two types of electrolyzers allow higher operating pressures, higher current density and low applied voltage to the cell.

ELECTRICITY PRODUCTION STAGE

In order to stabilize energy production, during the absence of wind or in conditions of a light wind, stored hydrogen could be reused. In this stage, hydrogen is converted into electrical energy by using a fuel cell (FC). The fuel cell takes the hydrogen from the tanks to generate electricity, plus water and heat as byproducts. The produced electrical energy is in DC form, thus a power converter is required to change DC voltage level required by the grid. Because of low output voltage of a fuel cell it is necessary to boost it with the help of the interface DC/DC converter with a step-up isolation transformer. A hydrogen-powered fuel cell system consists of two main parts:

1. Interface DC/DC converter with a step-up isolation transformer, which allows interfacing a low voltage DC output of fuel cell with a high voltage DC-link of the converter,
2. Fuel cell allows producing chemical energy into electrical energy in order to stabilize energy production of wind generator.

General classification of modern fuel cells (Fig. 5).

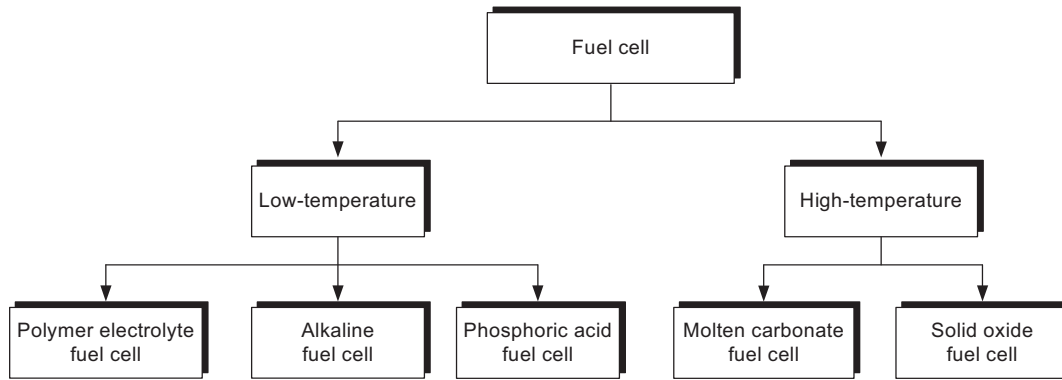


Fig. 5. General classification of fuel cells.

The electrolyte in polymer electrolyte fuel cell is an ion exchange membrane (fluorinated sulfonic acid polymer or other similar polymer), which is an excellent proton conductor. The only liquid in this fuel cell is water, thus the corrosion problems are minimal. Typically, carbon electrodes with platinum electrocatalyst are used for both anode and cathode and with either carbon or metal interconnects. Water management in the membrane is critical for efficient performance, the fuel cell must operate under conditions where the byproduct water does not evaporate faster than it is produced because the membrane must be hydrated. Higher catalyst loading than used in phosphoric acid fuel cell is required for both the anode and the cathode (Eg & G technical services Inc., 2004).

Alkaline fuel cells are one of the most developed technologies and have been used to provide power and drinking water in space missions, including the US Space Shuttle. The design of an alkaline fuel cell is similar to a proton exchange membrane (PEM) cell but with an aqueous solution or stabilized matrix of potassium hydroxide as the electrolyte. Alkaline cells operate at a similar temperature to PEM cells (around 80°C) and therefore start quickly, but their power density is around ten times lower than the power density of a PEM cell. As a result they are too bulky for using in car engines. Nevertheless, they are the cheapest type of a fuel cell to manufacture, so it is possible that they could be used in small stationary power generation units. Like the PEM cell, alkaline fuel cells are extremely sensitive to carbon monoxide and other impurities that would contaminate the catalyst (Eg & G technical services Inc., 2004).

In the phosphoric acid fuel cells, typically operating at 150 to 220°C, the concentrated phosphoric acid (close to 100%) is used as the electrolyte. The relative stability of the concentrated phosphoric acid is high compared to other common acids. Consequently the phosphoric acid fuel cell (PAFC) is capable of operating at the high end of the acid temperature range (100 to 220°C). The anode and cathode reactions are the same as in the PEM fuel cell with the cathode reaction occurring at a faster rate due to the higher operating temperature (Eg & G technical services Inc., 2004).

The electrolyte in the molten carbonate fuel cells is usually a combination of alkali carbonates, which is retained in a ceramic matrix. The fuel cell operates at 600 to 700°C where the alkaline carbonates form a highly conductive molten salt, with carbonate ions providing ionic conduction. At the high operating temperatures in MCFCs, Ni (anode) and nickel oxide (cathode) are adequate to promote a

reaction. Noble metals are not required for operation, and many common hydrocarbon fuels can be reformed internally. The focus of MCFC development has been on larger stationary and marine applications, where the relatively large size and weight of MCFC and slow start-up time are not an issue (Eg & G technical services Inc., 2004).

In the solid oxide fuel cells, the electrolyte is a solid, nonporous metal oxide. The cell operates at 600-1,000°C where ionic conduction by oxygen ions takes place. The limited conductivity of solid electrolytes required cell operation at around 1,000°C, but more recently thin electrolyte cells with improved cathodes have allowed the reduction of operating temperatures to 650-850°C. SOFCs are considered for a wide range of applications, including stationary power generation, mobile power, auxiliary power for vehicles, and specialty applications (Eg & G technical services Inc., 2004).

In accordance with the classification of fuel cells (Fig. 5), common characteristics of fuel cells are shown in Table 4, their advantages and disadvantages (Eg & G technical services Inc., 2004, Matthew M., 2008) are given in Table 5.

Table 4. Common characteristics of fuel cells

Type of fuel cell	Electrolyte	Qualified power	Operating temperature	Electrical efficiency
Proton exchange membrane	polymer membrane	100 W to 500 kW	30–100°C	cell: 50–70% system: 30–50%
Alkaline	aqueous alkaline solution	10 kW to 100 kW	under 80°C	cell: 60–70% system: 62%
Phosphoric acid	molten phosphoric acid	up to 10 MW	150–200°C	cell: 55% system: 40%
Molten carbonate	molten alkaline carbonate	100 MW	600–700°C	cell: 55% system: 47%
Solid oxide	O ₂ -conducting ceramic oxide	up to 100 MW	850–1,100°C	cell: 60–65% system: 55–60%

Table 5. Advantages and disadvantages of a fuel cell

Type of FC	Application	Advantages	Limitations
Proton exchange membrane	cars, buses, portable power supplies, medium to large-scale stationary power generation	compact design; relatively long operating life; adapted by major automakers; offers quick start-up, low temperature operation	high manufacturing costs, needs pure hydrogen; heavy auxiliary equipment and complex heat and water management
Alkaline	space (NASA), terrestrial transport	low manufacturing and operation costs; does not need heavy compressor, fast cathode kinetics	large size; needs pure hydrogen and oxygen; use of corrosive liquid electrolyte
Phosphoric acid	medium to large-scale power generation	commercially available; heat for co-generation	low efficiency, limited service life, expensive catalyst

Molten carbonate	large-scale generation	power	highly efficient; utilizes heat for co-generation	electrolyte instability; limited service life
Solid oxide	medium to large-scale generation	power	high efficiency, takes natural gas directly, no reformer needed. Operates at 60% efficiency; co-generation	high operating temp; rare metals, high manufacturing costs, oxidation issues; low specific power

Technical properties of fuel cell (Table 6).

Table 6. Fuel cell technical properties

Characteristics of fuel cell	Polymer electrolyte	Alkaline	Phosphoric acid	Molten carbonate	Solid oxide
Current density, A (cm ²) ⁻¹	0.1–0.9	0.1–0.9	0.1–0.9	0.1–0.9	0.1–0.9
Voltage cell, V	0.8–0.6	0.8–0.6	0.8–0.6	0.8–0.6	0.8–0.6
Power density, W (cm ²) ⁻¹	0.35–0.7	0.1–0.3	~0.14	0.1–0.12	0.15–0.7
H ₂ consumption, (cm ³ H ₂) (min A) ⁻¹	7.0	7.0	7.0	7.0	7.0
O ₂ consumption, (cm ³ O ₂) (min A) ⁻¹	3.5	3.5	3.5	3.5	3.5
Pressure, bar	1–2	1	1	1–10	1

Having considered all the fuel cells explained the authors conclude that there are several perspective types of fuel cells that can be used. First a low-temperature fuel cell that is an alkaline fuel cell with a high efficiency and low oxygen reduction reaction losses. Second, a high-temperature fuel cell, a solid oxide and molten carbonate fuel cell.

HYDROGEN STORAGE

In an ideal system, supply will match demand. Energy storage enables the supply to be shifted to meet the demand. Electricity can be drawn from the primary supply during periods of excess availability, stored and then returned during periods of excess demand. Correct sizing of the storage should allow the generation plant to operate closer to its optimal efficiency, making thus better economic use of the existing assets. According to the International Energy Agency classification (Yartys & Lototsky, 2004), hydrogen storage methods can be divided into two groups:

The first group includes physical methods which use physical processes (compression or liquefaction) to compact hydrogen gas. Hydrogen being stored by physical methods contains H₂ molecules, which do not interact with the storage medium. The following physical methods of hydrogen storage are available:

1. Compressed hydrogen gas,
2. Liquid hydrogen: stationary and mobile cryogenic reservoirs.

The second group includes chemical (or physical-chemical) methods that provide hydrogen storage using physical chemical processes of its interaction with some materials. The methods are characterized by an essential interaction of molecular or atomic hydrogen with the storage environment. The chemical methods of hydrogen storage include:

1. Adsorption,
2. Bulk absorption in solids (metal hydrides),
3. Chemical interaction.

Comparison of hydrogen storage methods in accordance with the above mentioned methods (Tables 7, 8), (Yartys & Lototsky, 2004).

Table 7. Comparison of physical hydrogen storage methods

Group	Subgroup	Method	Storage conditions		Storage performances	
			P, bar	T, °C	Volume density, g (dm ³) ⁻¹	Energy consumption, %
Physical	compressed gas storage	steel cylinders	200	20	17.8	9
		commercial composite cylinders	250	20	22.3	10
		advanced composite cylinders	690	20	29.7	12.5
		glass micro-spheres	350–630	200–400	20	25
	cryogenic (LH ₂)		1	–252	71	27.9

Table 8. Comparison of chemical hydrogen storage methods

Group	Subgroup	Method	Storage conditions		Storage performances	
			P, bar	T, °C	Volume density, g (dm ³) ⁻¹	Energy consumption, %
Chemical	cryo-adsorption		2–40	–208...–195	15–30	8.1
	metal hydrides	'low-temperature' (20–100°C)	0.01–20	20–100	90–100 60–70	10.4
		'high-temperature' (250–400°C)	1–20	250–350	90–100 60–70	20.6

complex hydrides (alanates)	1–20	125–165	30	13.4
organic hydrides	10–100	300–400	70–100	28

From the data (Tables 7, 8), it can be concluded that each method has its advantages and disadvantages and none of the specific hydrogen storage methods is superior to the remaining alternative ones. Cost, volume, weight and performance should be considered together in selecting an optimal storage method that suits the specific requirements.

HYDROGEN DELIVERY

Between the two ends of the economic chain, hydrogen has to be packaged by compression or liquefaction to become a commodity. In the transportation, hydrogen has to be produced, packaged, transported, stored, transferred to cars, then stored and transported again before it is finally admitted to fuel cells.

There are two possibilities of hydrogen delivery (Leighty, 2006):

1. Road delivery,
2. Pipeline delivery.

Because of the low density of the gaseous energy carrier, transport of pressurized or liquid hydrogen is extremely inefficient. Forty-ton trucks can carry only 350 kg of hydrogen at 200 bars in the gaseous or 3,500 kg in the liquid state (Leighty et al., 2006).

The energy required to deliver the gas is part of the production costs. Parasitic energy losses reduce the amount of available energy. Hydrogen transport by pipelines has to compete with electricity transport by wires.

Design and construction of large, long-distance, high pressure gaseous hydrogen pipelines and conventional natural gas (NG) transmission lines are similar. Four technological aspects differentiate the gaseous hydrogen (GH₂) line from the NG line and need to be addressed for the concept to be attractive to industry (Leighty et al., 2006):

1. The volumetric energy density of hydrogen is one third of that of methane,
2. High pipeline utilization is critical for economic feasibility,
3. Hydrogen embrittlement of pipeline steel must be prevented and controlled,
4. Compression is very costly.

Most of the analyses show that pipelining GH₂ costs approximately 1.3 to 1.8 times more per unit energy-distance than NG, because of these four factors. Pipelines are very expensive to design and construct, which is why they must have high utilization to justify the initial capital cost.

CONCLUSIONS AND FUTURE WORK

This paper is devoted to study of a new concept of using hydrogen for compensating the instability of wind power production. This concept has been considered in three main stages:

1. Hydrogen production stage allows excess energy of a wind power plant to be stored,

2. Hydrogen storage technologies, safety, automation and transportation system have to be developed in the future,

3. At moments when wind is low or absent the stage of electricity production allows wind power operation to be stabilized. Because all of the components of hydrogen buffer require DC power supply, interface converters were implemented.

In terms of ecology, the proposed method provides perspectives of significant decrease in fossil fuel extraction and accompanying environmental pollution. As Estonia depends on foreign energy supplies, the use of our own considerable wind potential will promote the promising field of energy development.

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