Power to Methanol Solutions for Flexible and Sustainable Operations in Power and Process Industries

C. Bergins[#+], K.-C. Tran*,
E.-I. Koytsoumpa[#], E. Kakaras[#],
T. Buddenberg[#], Ó. Sigurbjörnsson*

[#]Mitsubishi Hitachi Power Systems Europe GmbH, Germany

*Carbon Recycling International, Iceland

[+]presenting author

Contacts: c_bergins@eu.mhps.com; kctran@cri.is

1 Abstract

The rising global energy demand, the sustainability need, energy security, and energy cost competitiveness have led to step changes in energy policies around the world. Over the past decade, the penetration of electricity from renewable energy sources (RES) in the grid has become more pronounced, especially in Europe and in California. The intermittent nature and the feed-in regulations of RES require solutions for balancing the grid and harmonizing with coal power generation.

The paper presents a novel approach of power to methanol which leverages intermittency and low carbon foot print of RES to overcome the challenges in energy transition.

The approach is to use surplus electricity deriving from the mismatch of supply and demand to produce low carbon methanol for use in the transport and chemical industries. The underlined sustainability and economic benefits are in enabling "dispatchable" power plants and the process plants to operate at higher capacity and higher profitability by avoiding new transmission lines, installing electric batteries, and producing low carbon fuel.

The approach of power to methanol is compared to other pathways for storing energy and producing methanol to highlight its competitive advantages.

2 Introduction

Increasing dependency on imported fuels coupled with the political will to reduce CO_2 emissions for climate protection have led to energy policy changes in countries around the world. The major actions have been in the following:

1. Transitioning to renewable energy and fuels
2. Reducing energy demand by increasing efficiency for use and conversion of energy
3. Focusing on domestic resources

The actions on climate protection and the resulting reduction of CO_2 emissions have led to the increase in use of renewable energies. Today, in the EU and California and some other parts of the world, electricity from renewable energy sources (RES) plays an important role in the supply of electricity.

3 Renewable Electricity Challenge

The effects from the rapid increase of renewable electricity driven by feed-in tariffs (FIT) can be summarized as follows:

- The cost of electricity from renewable energy has been reduced to less than 25% of the starting point over 15 years, and still the floor price of renewable energy is double or triple the market price of electricity from the conventional sources.
- Significant amounts of subsidies were earmarked to increase use of renewable electricity. In Germany, 25% of market demand is met by renewable electricity. The penetration is attributed to continuous subsidies which eventually will reach, from the beginning and over the next 20 years, 400 billion €.

- By having reached a point where the peak capacity of renewables installed can cover the whole demand for electricity intermittently throughout the year, a critical situation for grid stability is emerging.

Around Europe, policy makers discuss the challenges of the “energy trilemma”. The original basis for the roadmap of EU energy policy was to balance the following priorities:

1. Environmental protection
2. Competitiveness
3. Security of supply

During the time when environmental policy took precedence, Europe was less competitive and vulnerable in energy supply.

For the on-going energy transition, in which economic, technical, and political priorities have emerged, the choice for any measures to stabilize the electric grid must be balanced:

- Curtailment of renewables and availability of conventional power to avoid overload and achieve frequency control of the grid – the consequence is acute energy and financial loss, compounded by FIT payments for curtailed megawatthours.
- Refurbishment of the electric grid at all levels – the public opposes transmission lines crossing land and it is very capital intensive. It is also inefficient to transport electricity long distances where there is up to 30% energy losses. [1].
- Installation of electricity storage at different levels of the grid (locally/centrally) – technologies for electricity storage are either limited to specific geographies and opposed by the local public (mature pumped hydro or compressed air energy storage at efficiencies in the range of 50-75%) or limited by high cost and small scale (with batteries and capacitors at efficiencies higher than 90%).

Recognizing the shortcomings of each measure, a sensible grid stability policy is to combine selective grid improvement and capacity flexibility solutions. Curtailment of energy is wasteful.

The capacity flexibility challenge or the surplus electricity utilization can be solved by the direct conversion of electricity to transport fuels. The available surplus of electricity in the grid or off grid can be used economically as fuel for transport either through direct charging for electric vehicles, or conversion to liquid fuel for existing internal combustion engine vehicles. Therefore, grid stability can be achieved in conjunction with production of fuel for transport and the resulting reduction of imported fuels.

3.1 Power Generation Flexibility

The advent of renewable electricity, driven by the basis of “zero-marginal cost”, caused the downdraft for demand of conventional electricity in the competitive market for “electricity trading”. It has caused an overcapacity of power generation.

Operators of power plants, incurring mounting losses, mothballed or dismantled efficient Combined Cycle Gas Turbine (CCGT) power plants and coal power plants. Photovoltaic (PV) power generation captures the profitable demand peaks during 60% of the year and keeps the overall electricity prices low, holding down the operating hours of the CCGT and Open Cycle Gas Turbine (GT) power plants. However, PV and wind generation are intermittent and conventional thermal power generation is likely necessary for decades to provide security of supply [2]. In response, operators of thermal power plants advocate for “capacity payments” to compensate for the losses. However, the solution for the surplus capacity and FIT is not in increasing electricity prices to industries and consumers. The solution is in enabling flexibility of coal power plants. Flexibility or “product flexibility” is achieved by enabling the coal power plants to operate at economical capacity, driven by a variety of electrical loads for electricity, and to produce power, heat, and methanol responsively to the markets. By applying the power to methanol technology, the growing surplus capacity can be converted to fuel for transport.

3.2 Coal Use Sustainability

Europe has been producing electricity for over 100 years from coal because of its cost advantages and local availability. Its advantage is moderated by the policy of decarbonisation. Current prices of CO_2 emission certificates reinforce the economic strength of coal as an energy source. A switch from coal to natural gas (NG) for economic reasons could only be justifiable in the most extreme conditions as follows:

- NG parity with coal, if prices of NG are halved and CO_2 costs are eliminated
- NG parity with coal, if costs of CO_2 appreciated 10 times

European electricity prices would double or triple if the costs of CO_2 appreciated 10 times. One the other hand it is more than unlikely that NG prices will be reduced in future.

Therefore, the continuous operability of the existing and new coal fired power plants is critical to meeting the priorities in the energy transition. The synergy of coal and RES can be exploited by increasing the flexibility of the coal fired plants. The surplus of capacity of thermal power plants is an economic advantage, enabling security of supply of both power and transportation fuel.

The coal power plants operate most efficiently and at the lowest carbon dioxide emission rate at full loads. The use of the surplus of capacity coupled with carbon capture and use (CCU) by power to methanol would reduce the possible increase of emission because of low load operation of thermal power plants.

New coal power plants can reduce emission by 30 percent by burning less coal for equivalent output. In combination with high efficient coal generation technology and replacement of older power plants, the application of carbon capture storage/use (CCS and CCU) is more financially beneficial (CO_2 reduction per unit capital invested) compared with the investment in renewable energy feed-in (10 to 20 times in favour of CCS/CCU) for emission management [2, own calculation]. Power to methanol is one of the most competitive carbon technologies for capture and use (CCU).

3.3 Energy Vectors Dimensions

A successful energy transition requires balancing the priorities to achieve the overall economic benefits. The strategy to reach the objectives of RES in 2020 is to integrate RES and coal power generation by the application of power to methanol technology.

Power to methanol is a new energy vector, which can complete the energy policy puzzle. It is the missing link to implement the strategy for energy transition, as depicted in Figure 1.

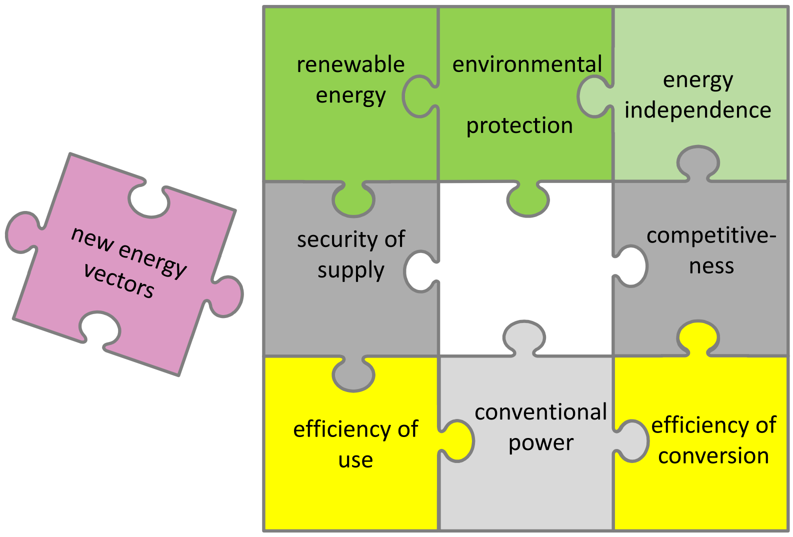


Figure 1: New Energy Vectors and The "Missing Link"

New energy vectors include power to hydrogen or power to synthetic natural gas (SNG). Hydrogen can be injected into the local natural gas grid at the value of natural gas. SNG can be used for automobile fuel and energy for the gas grid. The economics of power to hydrogen or to gas is not favorable without heavy subsidies.

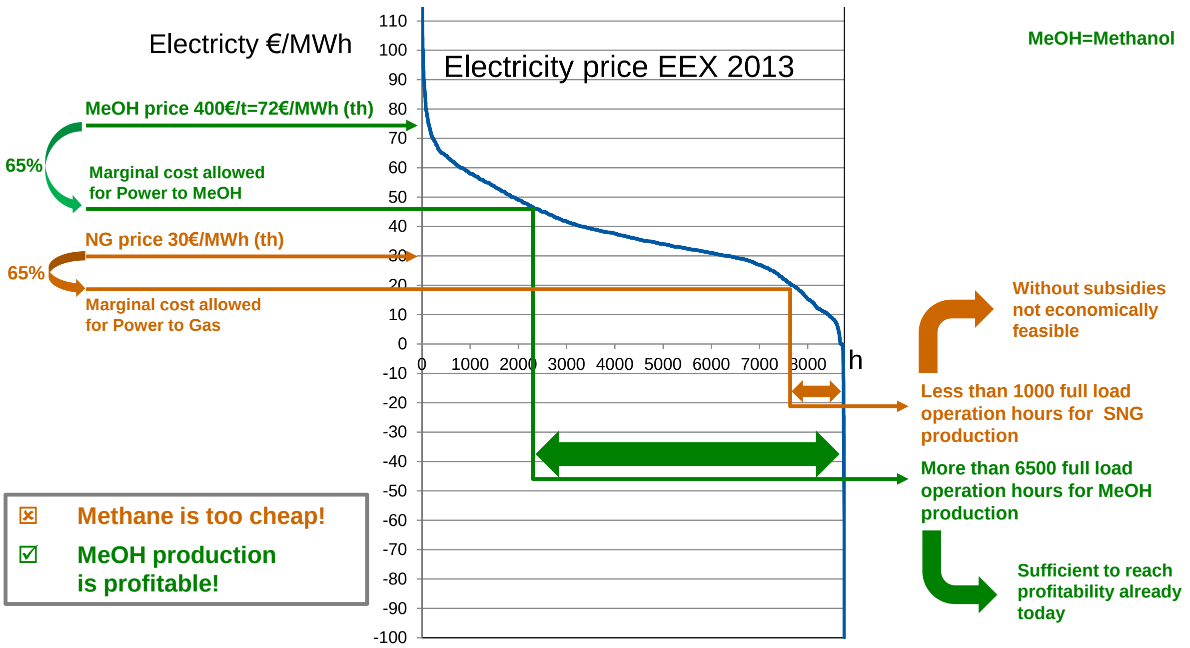


Figure 2: Profitability Analysis of Power to Methanol and Power to Synthetic Natural Gas

In 2013, at the European Energy Exchange (EEX) price of NG of 30 EUR per MWh_{th} and the maximum allowed marginal cost of production of SNG of 20 EUR per MWh_{th} by power to gas at the nominal conversion efficiency of 65%, there are less than 1000 hours of profitable operation. For power to methanol, at the price of methanol of 72 EUR per MWh_{th} in 2013 [3] and the maximum allowed marginal cost of production of 45 EUR per MWh_{th} at the nominal conversion efficiency of 65%, there are more than 6500 hours of profitable hours. Figure 2 depicted the profitability analysis of power to methanol and power to synthetic natural gas.

3.4 Surplus Electricity Solution

The growth of renewable electricity is rising in parallel with the increase of coal power generation. A successful energy transition requires a systematic integration of coal and renewable power generations. However, the dual system of coal energy for base load and of renewable energy for de-carbonization results in surplus electricity. However, a triple system of coal energy, renewable energy, and power to methanol would balance the energy vectors and energy “trilemma”, and would resolve the surplus electricity challenges.

Power to methanol is the new energy vector which enables energy transition and vehicle innovation. An alternative use of the surplus electricity is converting power to synthetic natural gas. However, the energy economy only supports power to methanol, as demonstrated in Figure 2. Methanol and its derivatives, dimethylether, methyl-tert-butylether, and oxymethylenether have higher economic value than synthetic natural gas or hydrogen, making power to methanol a practical solution to surplus electricity.

4 Methanol Production Economy

Conventionally, methanol is produced from synthesis gas generated by steam methane reformation (SMR) or coal gasification. The feedstocks are natural gas (NG) and coal. The production model is a megascale plant of one million tons per year, centrally located near the sources of primary energy. Methanol is shipped to the ports of import by large tankers.

In contrast, the power to methanol production is a distributed model. A proposed power to methanol plant is a modular design of 50 to 100 thousand tons per year and is located near the sources of use. The feedstock consists of basic utility available at a power plant or chemical plant which includes power, hydrogen surplus, and carbon dioxide. Each plant is constructed to take advantage of the available infrastructure, by-products, and waste heat. Carbon dioxide is captured and purified on site for use as the main feedstock (1.5 ton of CO_2 captured per ton of methanol produced). For natural gas and coal to methanol plants, large amounts of carbon dioxide are emitted (1 ton of CO_2 per ton emitted per one ton of methanol produced by natural gas methanol plants and 3 tons of CO_2 per ton produced by coal methanol plants).

A natural gas based methanol plant is constructed to maximize economies of scale. Each plant can reach the capacity of more than 5,000 tons of methanol per day output. The production driven by reforming natural gas or gasification of coal is reformed to make synthesis gas, a mixture of carbon monoxide and hydrogen, at the rate of 1.5 GW_{th}. Figure 3 depicts the process flow diagrams of the natural gas (A) and coal (B) configurations. At the mega scale, the conversion of natural gas to methanol can reach top efficiencies. The available waste heat provides the necessary power on site which is primarily used for the operation of the air separation unit (ASU).

The thermal efficiency of conversion for a natural gas or power methanol plant can be expressed in terms of fuel chemical energy $\dot{Q}_{Fuel}$, electric power P_{el}, and the chemical energy of methanol $\dot{Q}_{MeOH}$, based on the lower heating value (LHV). The equations for efficiencies are expressed in the following forms:

$$\eta_{th/th} = \frac{\dot{Q}_{MeOH}}{\dot{Q}_{Fuel} + \Delta\dot{Q}} = \frac{\dot{m}_{MeOH} LHV_{MeOH}}{\dot{m}_{Fuel} LHV_{Fuel} + \Delta\dot{Q}}$$

$$\eta_{el/th} = \frac{\dot{Q}_{MeOH}}{P_{el} + \Delta P} = \frac{\dot{m}_{MeOH} LHV_{MeOH}}{P_{el} + \Delta P}$$

$\Delta\dot{Q}$ is the sum of all additional heat flow required. The electric power needed for operation of the plant can be converted to heat by $\Delta\dot{Q} = \Delta P/\eta_{PP}$, where η_{PP} represents the net efficiency of the power plant / power cycle. Heat needed from or reintegrated in the power cycle can also be expressed as $\Delta P = \Delta\dot{Q}\,\eta$, where η is the efficiency of heat to power.

The management of heat and power of a plant determines the operating efficiency of the plant.

The carbon conversion efficiencies of a natural gas or coal plant can be at 80% or 33% respectively and (lower heating value based) energy conversion efficiencies at 67% and 45% respectively [4]. Hard coal energy conversion efficiency can reach up to 55% [5].

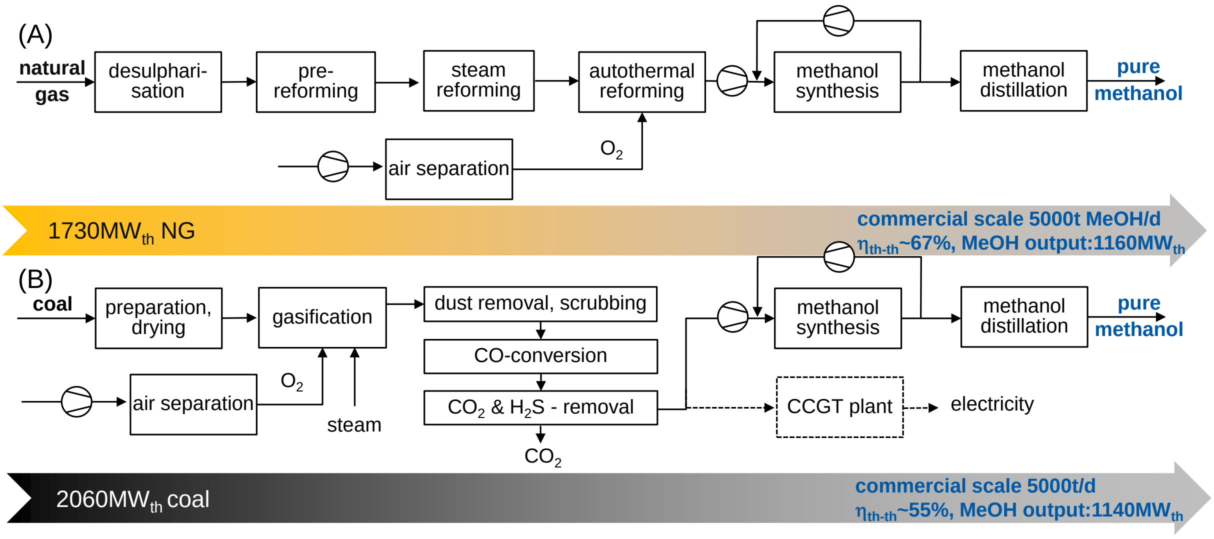


Figure 3: Large Scale Methanol Production from Natural Gas (A) and Coal (B).

4.1 Power to Methanol Technology

An operation converting power, hydrogen, and carbon dioxide to methanol can be bolt on to an existing power or a process plant. The design of the operation can be in various configurations to adapt to the variability and availability of carbon dioxide, power, and surplus hydrogen. Possible applications are in coal power plants and in steel mills with blast furnace boilers and coke ovens.

The technology for power to methanol has been demonstrated at the George Olah Plant at Carbon Recycling International in Iceland. The plant is the first power to methanol plant in the world operating at 6 MW_{el}, capturing 6,000 tons of carbon dioxide and producing 4,000 tons of CO_2 methanol per year. The integration with the power generation plant Svartsengi of 75 MW_{el} and 150 MWh_{th} provides the necessary power, carbon dioxide and steam.

The plant consists of modularized unit operations for carbon dioxide and synthesis gas compression, post steam turbine carbon capture, electrolytic production of hydrogen (water alkaline electrolyzer), direct CO_2 to methanol synthesis and distillation for methanol fuel. The modules were designed and fabricated in a controlled manufacturing shop floor environment.

The product has 90% lower carbon footprint than gasoline, certified by SGS Germany according to the International Sustainability and Carbon Certification (ISCC) standard. The product is used for gasoline blending and biodiesel manufacturing in Sweden, Holland, and Iceland. Figure 4 shows the power to methanol plant of Carbon Recycling International in Iceland.

Figure 4: Carbon Recycling International – The World's First Power to CO_2 Methanol Plant, producing 4,000 tons of methanol and capturing 6,000 tons of CO_2.

4.2 Power-Methanol Plant

A viable process for Power to methanol is the reaction of CO_2 and electricity from a power plant. Hydrogen is generated by electrolysis. The reactor for the conversion of CO_2 based syngas to methanol is designed for low heat loss, high conversion of hydrogen to methanol at above 98%, and high catalytic selectivity at above 99% [6], and under low pressure and temperature. On carbon capture and storage, the process has been developed and demonstrated at large scale in the last ten years. Today, power to methanol is a proven solution which can be implemented with available equipment, catalysts, control system, and operating experience. A ready application is to produce methanol using carbon dioxide captured at a post combustion capture (PCC) plant from a carbon dioxide source point at a coal power plant. Figure 5 depicts the process flow of a Power to methanol plant with a PCC configuration.

The size of the power to methanol operation can be tailored to the capacity management requirements for the applicable coal power plant. The size of the electrolyzer is determined by the necessary load for the power plant to be efficient during periods where high feed-in of renewable electricity takes precedence. Nominally, the hydrogen generation capacity is targeted to be in the range of 20% of the capacity of a coal power plant, or 150 MW_{el} electrolyzer for a 710 MW_{el} (net) plant. The arbitrage is producing methanol during low electrical load and high feed-in renewable energy and generating electricity during high electrical load and low feed-in renewable energy.

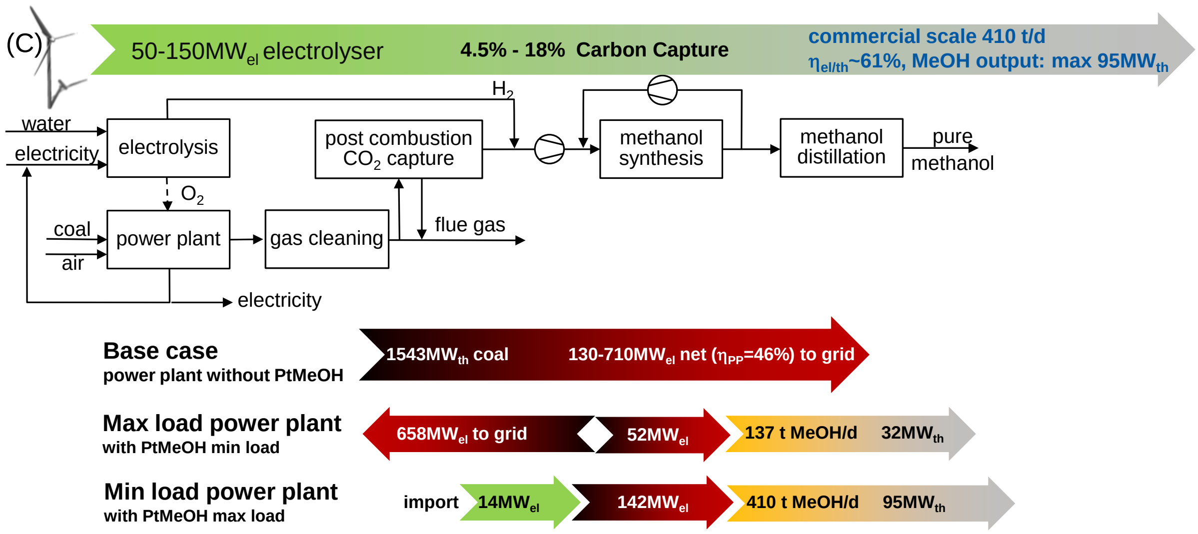


Figure 5: Energy balance of Power Methanol Plant Design with Post Combustion Capture, Electrolyser, and CO_2 Methanol Production.

There are other ancillary benefits for the full employment of existing power generation capacity. Power plants can operate efficiently at full load operation, provide primary and secondary controls, and obviate expensive auxiliary fuels for startups and maintenance for wear due to cycling operations. The economic impact is that power plants are profitable without the implementation of a trading scheme for “capacity markets”.

Highest efficiency of power to methanol for a PCC application is gained by efficient process and energy integration and application of state of the art technologies for power to methanol. Ninety percent of the carbon dioxide, captured from a slip stream of flue gas provides a reduction of 4.5 to 18 percent. The capture is efficient by using waste heat from the catalytic reaction of CO_2 and hydrogen to methanol (~50%) and by bleed steam from the inlet of the low pressure turbine. By combining waste heat recovery, advanced solvents, and an innovative process design, energy required for carbon capture is less than 2600kJ per kg of CO_2 for the desorption [7] and in total it is less than 20kWs_{el} per MWs_{th} methanol (LHV).

An optimized electrolyser consumes 4.0 kWh_{el} per Nm^3 of hydrogen produced and is fed by direct current from a rectifier with an efficiency of 97%.

The compression units, comprised of the main and recycling syngas compressors of the methanol loop, consume 42 kWs_{el} per MWs_{th} methanol. Heat loss is primarily from the operation of the electrolyser.

Heat recovery from the CO_2 and hydrogen reaction is used for the distillation of crude methanol and for carbon capture. Material loss is minimized by a hydrogen recovery unit at the outlet of the purge system. The resulting thermal efficiency of a power to methanol operation is in the range of 61% (electric energy to LHV of methanol). Figure 5 shows the possible operation range of the power plant of 710 MW_{el} and associated MW_{el} / MW_{th} MeOH with and without the power to methanol operation of 410 tons per day of methanol.

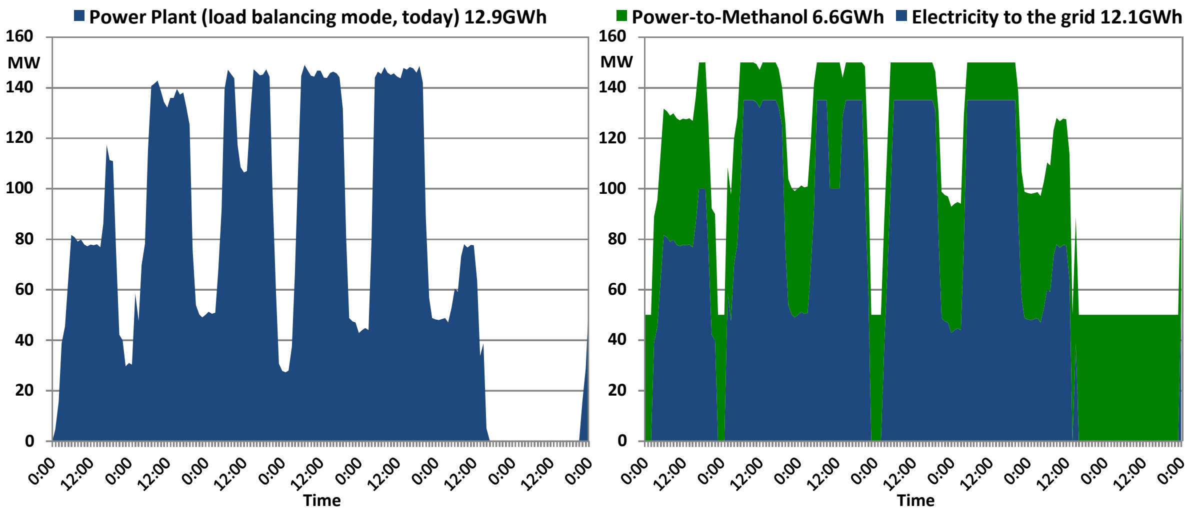


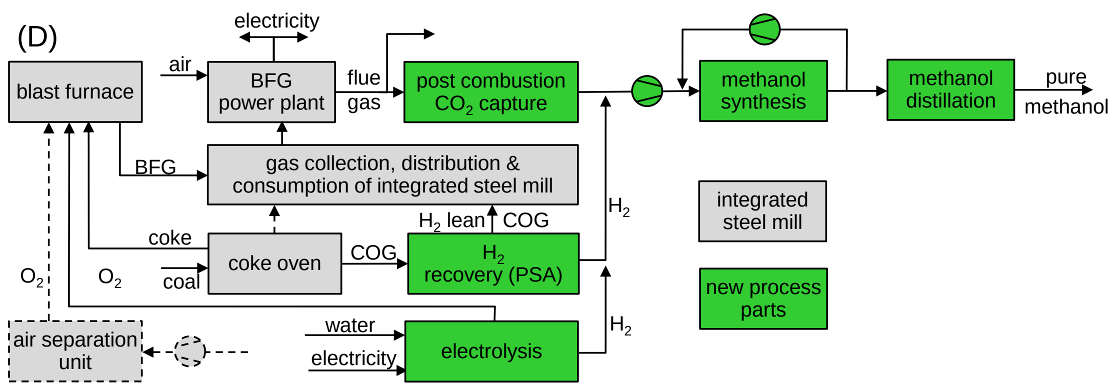
Figure 6: Actual Operational Load of a Coal Power Plant of 150 MW_{el} Plant in Germany (Left) and Possible Increase of Operational Load by Power to Methanol for Efficient Operation (Right)

The energy output of a coal fired power plant in Germany can have a very ragged power profile caused by feed-in of renewable energy and change of demand over 24 hours period as depicted on Figure 6. The actual operational data of a coal fired plant of 150 MW_{el} is displayed on the chart (left). The addition of power to methanol can smooth out the power profile, as shown on the chart (right). The power-methanol plant can generate at higher capacity and become more flexible for feed-in. The proposed bolt on power to methanol plant has the capacity of 50 MW_{el}, >75% utilization factor and high turn down for load release during high electricity demand. The application of power to methanol is a profitability and sustainability strategy for the coal and renewable power generation.

4.3 Steel-Methanol Plant

A viable process for power to methanol is the reaction of CO_2 and hydrogen recovered in an integrated steel mill. The application of power to methanol starts with studying the energy and economy of the steel mill. Figure 7 shows the block diagram of an integrated steel mill [8] with a power to methanol configuration. The steel mill has a capacity of 4 million tons of hot rolled coil (HRC) per year. The majority of steel mills have boiler power plants and coke ovens.

Power is generated by the combustion of the blast furnace gas (BFG, off gas from blast furnace). The BFG power plants are in the range of 200-300MW_{el}. The flue gas from the boiler has a comparably high content of CO_2 which reduces the capital expenditure for capture. The coal mix for cokemaking and coke for ironmaking corresponds to 1,739 MW_{th} and 1,386 MW_{th}, respectively. The coke oven gas (COG) corresponds to 350 MW_{th} of which 133 MW_{th} derives from the H_2 content. A modern BFG power plant has an efficiency of 42.1 % [9], generating 199 MW_{el} of which 179 MW_{el} is for internal use and the remaining of 20 MW_{el} for external use.



Case	Exort (+) Import (-) [MW_{el}]	Power plant [MW_{el}]	Power consumption Steel mill	H_2	CO_2 & MeOH	H_2	MeOH	MeOH [t/d]	Conversion efficiency
			[MW_{el}]			[MW_{th}]			
Base	20.3	198.9	178.6	-	-	-	-	-	η_{el}=42%
1 H_2 COG	-47.2	148.4	178.6	12.3	4.4	120.0	105.0	451.6	$\eta_{th\text{-}th}$=65%
2 H_2 Electrolysis	-87.2	198.9	173.2	110.0	2.9	79.9	69.9	300.6	$\eta_{el\text{-}th}$=65%
3 Both processes	-154.5	148.4	173.2	122.3	7.3	199.9	174.9	752.2	$\eta_{\Delta el\text{-}th}$=100%

Figure 7: Energy Balance of Steel-Methanol Plant Design with Post Combustion Capture, Electrolyzer, and CO_2 Methanol Synthesis

An operation with a methanol synthesis of 175 MW_{th} is possible by hydrogen from COG and electrolysis, allowing flexibility in sales of electricity or production of methanol. COG hydrogen from COG is separated by pressure swing adsorption (PSA). Figure 7 shows the unit operations for power generation, hydrogen by PSA and electrolysis, and methanol synthesis at a steel-methanol plant.

The use of COG hydrogen for the production of methanol reduces the thermal capacity of the power plant which is equivalent to 50.5 MW_{el}. Waste heat from the methanol reaction and the steel mill is utilized for carbon capture and distillation of crude methanol.

For the conversion of COG hydrogen, the efficiency (LHV of methanol to LHV of hydrogen) is in the range of 65%. The calculation includes the electrical energy consumption (in LHV of gas fired in the boiler power plant) of the compressors and the pressure swing adsorption (PSA).

For the conversion of electrolytic hydrogen, the efficiency (LHV of methanol to electricity) is in the range of 65%. The production of oxygen from electrolysis reduces the load of the air separation unit (ASU) by 5.4 MW_{el}.

The stand-alone steel mill plant exports 20.3 MW_{el}. The steel methanol plant, using COG and electrolytic hydrogen, imports 154.5 MW_{el}. The net usage of electrical energy is 175 MW_{el} for the production of methanol of 174.9 MW_{th}. For the conversion of electrolytic and COG hydrogen, the efficiency (LHV of methanol to electricity) is 100%, Hydrogen converts to methanol (in theory at 87.5%, and in practice at 65% with consideration of compression energy and other energy requirements) more efficiently than combusts to make electricity (42% in the steel-methanol plant).

4.4 Applications in the Process Industries

Hydrogen is a by-product in several chemical production processes. At many industrial (Verbund) sites, hydrogen is a downstream feedstock for chemical productions. In the ammonia production, profitability depends on access to low cost hydrogen. At other Verbund sites, hydrogen is often used for steam or electricity production. Similarly to the application of power to methanol in the steel industry, high purity hydrogen can be upgraded to methanol profitably. The conversion of hydrogen energy in conjunction with the integration of heat and electricity to methanol (LHV) is approximately $\eta_{th/th}$ ~70 %, because a PSA cleanup is not necessary.

4.5 Methanol Energy Economics

Power and recovered hydrogen can be converted to hydrogen, synthetic natural gas, and methanol energy vectors. The analysis unit for energy vector is EUR per MWh (LHV). The factors for production of energy vectors are electricity, natural gas, and coal. Costs of production of electricity, hydrogen, and methanol vary with the efficiency of conversion. Price of the energy vector methanol depends on the served markets of “gray methanol” and “green methanol”. Methanol is hereby reffered as “gray” if the energy sources are NG and coal and as “green” if it is RES derived. Figure 8 depicts the effect of energy cost on the profitability of power to methanol.

Methanol fuel commands a premium in regulated markets driven by carbon taxes and renewable energy content targets. The European Commission set rules to achieve 20% legally binding renewable targets for 2020 and the member states meet their obligations by national actions specific to their available resources and unique energy markets.

The nominal prices of methanol energy vary from 60 to 110 EUR per MWh which correspond to the spot prices of 350 EUR per ton and 600 EUR per ton, respectively, establishing the market profitability lines (MPL). Profitability of green or gray methanol energy can be achieved with an acceptable margin when the costs of production are 50% below the market profitability lines.

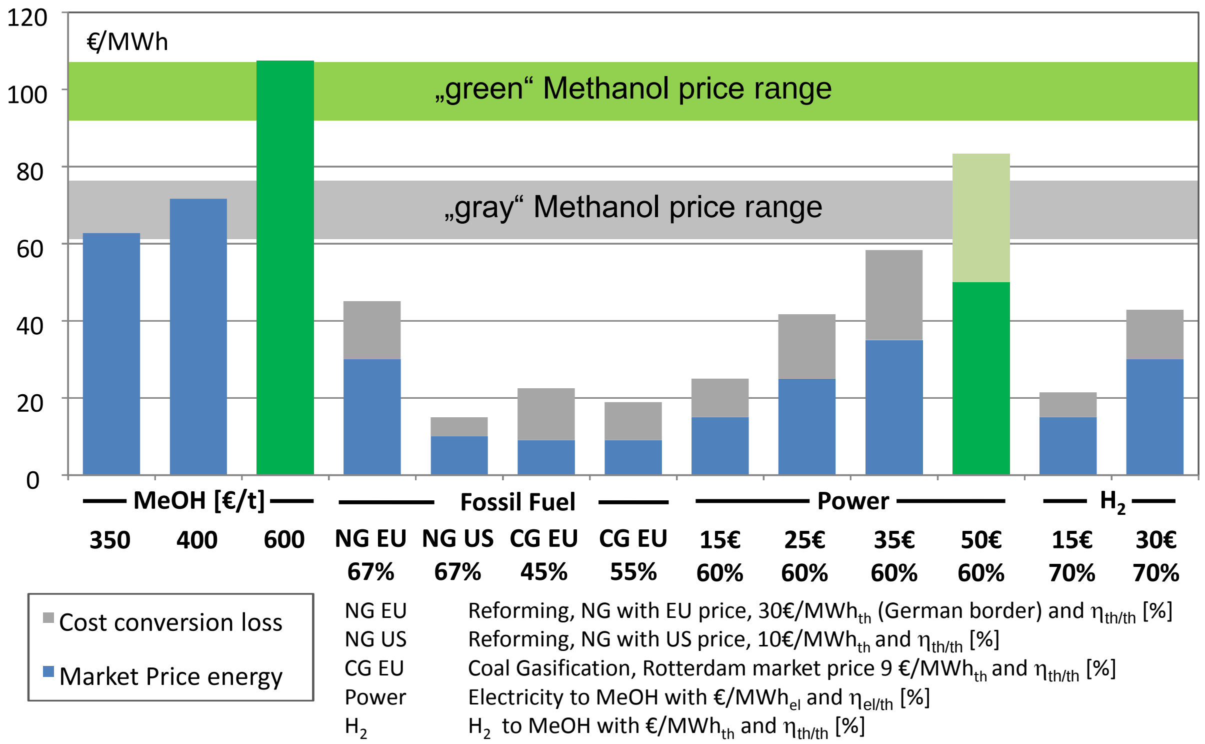


Figure 8: Profitability Chart of Methanol Production in EUR per MWh (Methanol Price versus Cost of Production)

For the cost of hydrogen at 15 EUR per MWh and a conversion efficiency of 70%, the power to methanol production cost is 20 EUR per MWh.

In Germany, at the natural gas price of 30 EUR per MWh and the cost of production at 50 EUR per MWh, the profitability of methanol from NG is 10 EUR per MWh.

For the cost of electricity at 15 EUR per MWh and a conversion efficiency of 60%, the power to methanol production cost is 25 EUR per MWh. The profitability of methanol is between 35 EUR per MWh and 75 EUR per MWh of methanol.

The profitability of a power to methanol operation depends on the electricity cost and the green quality of the feedstock. Because "gray methanol" is in the range of electricity cost of 25 EUR per MWh, and "green methanol" is in the range of renewable electricity cost of 40 EUR per MWh, the implementation of power to gray or green methanol is feasible today.

4.6 European Methanol Advantages

Methanol is commonly used in the chemical, packaging, and transport industries. It is traded globally. The local production of CO_2 methanol by power to methanol is cost competitive in logistics. The specific gravity of methanol compared to water is 0.79 which is expensive to transport and ship in large volume. Seventy five percent of the demand in Europe of 8.5 million tons is imported into major ports around Europe. The proximity between the production and end use points is a competitive advantage for power to methanol operations.

The leading demand growth for methanol is for energy and fuel for transport.

The demonstration of methanol fuel began in California in 1980's in the wake of the oil embargo. Methanol fuel proved to be efficient and environmentally friendly [10], in particular, the low emission of particulate matter (PM). Today, China [11] is introducing methanol in regular vehicles at fifteen percent of gasoline and is manufacturing methanol vehicles for one hundred percent replacement of gasoline [12,13]. Methanol can be a future fuel for China, the largest market of automobiles in the world.

Synthetic natural gas (SNG) can be compressed to feed into the compressed natural gas (CNG) fuel distribution infrastructure. However, CNG is not favored by consumers over liquefied petroleum gas (LPG) in Germany, in spite of a decade of tax incentive. In 2014, there are only 921 CNG fueling stations in contrast of 6,718 LPG stations serving 79,000 CNG car and 500,800 LPG cars. LPG fuel has higher energy density and is similar to gasoline, resulting in its advantage over CNG.

Methanol is an alcohol which readily supplements bioethanol for blending with gasoline. The combination of low carbon methanol and bioethanol lightens the burden on land usage and facilitates meeting the 2020 targets of the EU's renewable energy and fuel quality directives. Methanol and ethanol can be blended to reach E5 and E10 for existing regular gasoline vehicles. For flexible fuel vehicles (E85), methanol can be as high as 50% in the gasoline ethanol methanol blend (GEM). Methanol is in use for the manufacturing of biodiesel at 12% by mass. There is no technical limitation in the application of methanol fuel in vehicles.

Methanol produced by power to methanol has the advantages of home market, low cost logistics, low carbon dioxide footprint, potential green premium, and local growth in renewable fuel for transport.

4.7 Market for European Methanol

Today, EU consumes approximately 8.5 million tonnes/year or 47 TWh/year of methanol. In 2012, the consumption of liquid petroleum gas (LPG), gasoline and diesel in EU28 totalled 4,157 TWh/year, per Eurostat [14].

Also in 2012, the consumption of renewable electricity was 657 TWh against 2,138 TWh of thermal electricity. A utilization factor of thermal power plants of 42 % is derived from the known installed capacity of 5,050 MW_{el} of fossil and nuclear power and the annual production. It results in 2,911 TWh of unused potential electricity. The pie chart (right) in Figure 9 depicts the distribution of unused potential versus renewable electricity. Even though the unused potential of electricity in the grey area included the TWh of the mothballed CCGT plants and TWh of power plants in outage for maintenance, the advancement of RES remained pronounced (decreasing the orange area).

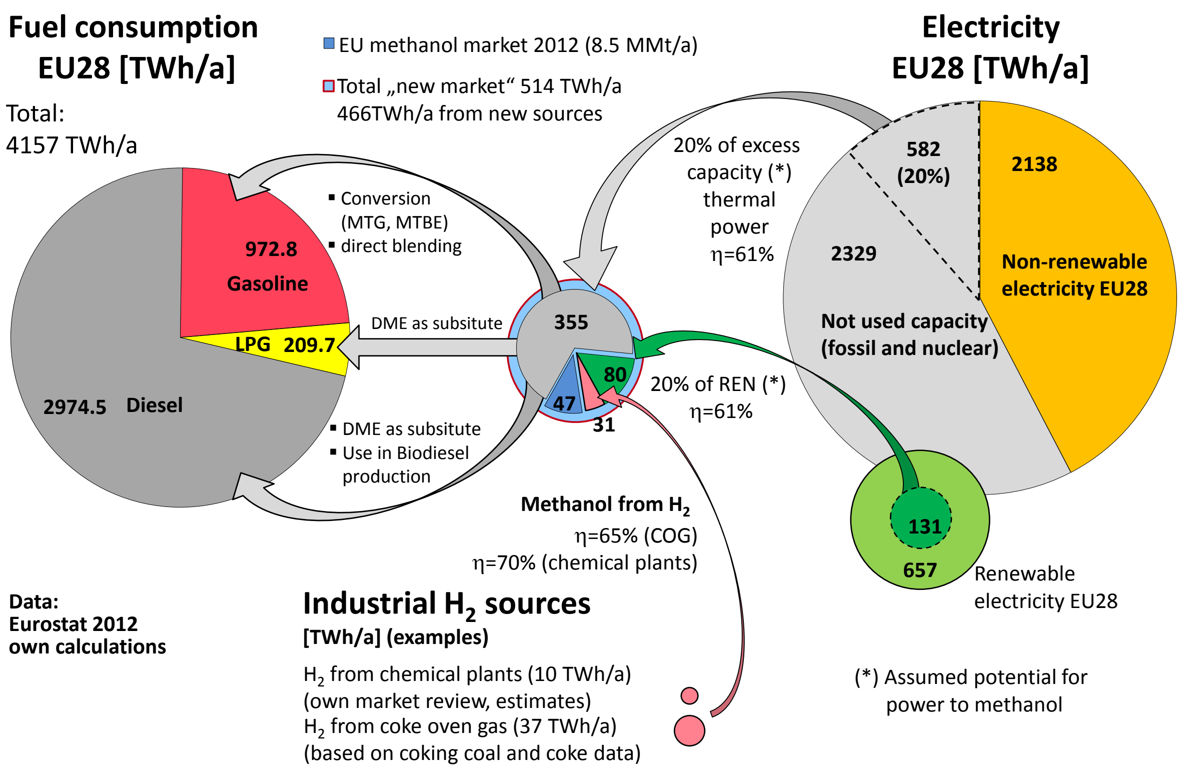


Figure 9: Potential Market for European Methanol by Power to Methanol Conversion of Surplus Electricity and Hydrogen in the Power and Process Industries

Even more pronounced, is the electricity market in Germany today. Figure 10 depicts the evolution of the contribution of renewable electricity and coal electricity during the period from 2013. More and more thermal capacities from hard coal, lignite and nuclear plants are ramping down in favour of RES. In Germany, hard coal and natural gas power plants are pulling back to adapt to the increase of the regional RES. In France, nuclear power plants operate at lower than installed capacities.

Given the abundance of unused potential of electricity, it is a reasonable assumption that there is a surplus of electricity of more than 20% of unused capacity of thermal power and RES for conversion to methanol. The potential is 435 TWh per year or 79 million tons per year of European CO_2 methanol from surplus power.

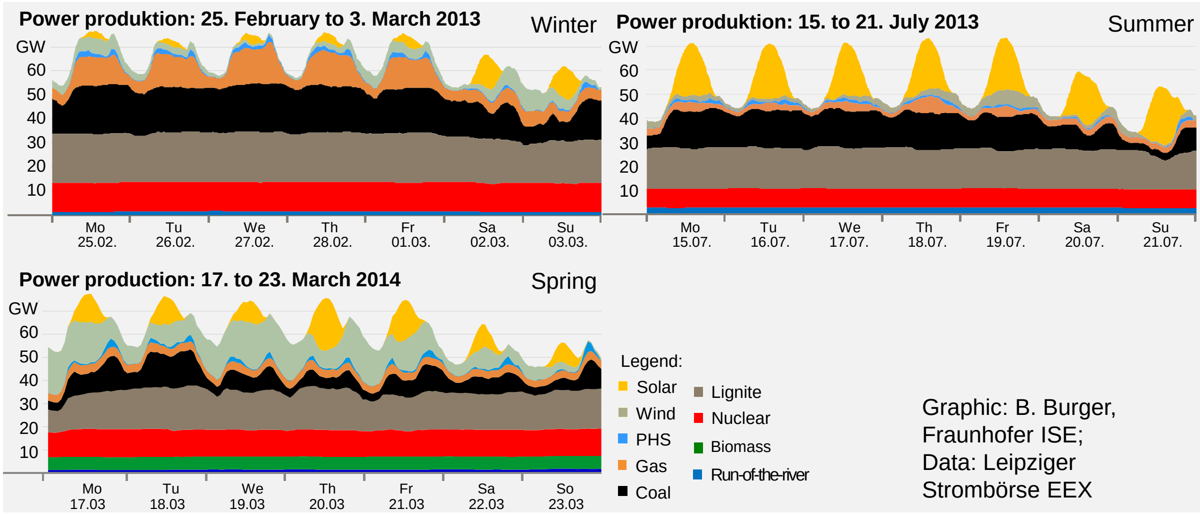


Figure 10: Penetration of Feed-In in the German Electricity Market

In addition, by-product hydrogen from industrial processes which could be upgraded into methanol is 31 TWh (LHV methanol) per year. It is the total of hydrogen from coke oven gas calculated from Eurostat [14] and from process industries estimated by our market analysis, as explained in Figure 9.

The total potential of European methanol from surplus power and hydrogen is 466 TWh per year (84 million tons per year) of methanol. The total represents less than 12% of the fuel consumption of 4,157 TWh per year and it could be readily absorbed for direct blending, biodiesel manufacturing, and diesel substitute. The conversion of power to methanol can be an EU energy initiative in the order of magnitude with the biofuel development which attained 5.1 percent of fuel consumption in EU in 2012.

5 Summary

The technology for methanol production from CO_2, surplus electricity or hydrogen by-products is environmentally friendly and economical. It enables sustainable use of resources, reduction of CO_2 emissions, penetration of more renewable electricity in the grid, and a smooth transition to local production of low carbon fuel for transport.

The power-methanol plant is flexible in producing methanol and supplying electricity during high and low feed-in of renewable electricity, respectively. The capacity utilization is optimized and the carbon footprint is reduced.

The steel-methanol plant is designed to replace the combustion of the coke oven gas for heat or power generation with the conversion to a more valuable methanol.

The upgrade of coke oven gas to methanol makes the steel plant flexible with two product streams. The profitability equation is optimized and carbon footprint is reduced.

Power to methanol is applicable to industrial processes where hydrogen is used as a feedstock for heat or power production. The economics is favorable to upgrading hydrogen to methanol.

European CO_2 methanol has home market advantages and has growth potential in fuel for transport.

The power to methanol technology is demonstrated at industrial scale and is available today. It provides a practical solution for a smooth energy transition and for a low carbon fuel for transport.

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