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Energy for Circular Economy

Thematic Roadmap

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1. Introduction

The thematic field Energy for Circular Economy strongly focuses on supporting the objectives of the European SET plan (Strategic Energy Technologies). Europe needs joint efforts to establish a sustainable, secure and competitive energy supply. The inter-related challenges of climate change, security of energy supply and competitiveness are multifaceted and require a coordinated response. In 2009, the EU has set ambitious climate and energy targets for 2020. These targets, known as the '20-20-20 goals', set three key objectives for 2020: 20% less greenhouse gas (GHG) emissions, 20% reduction in the use of primary energy by improving energy efficiency, and 20% share of renewables in energy mix of total energy consumption.

In January 2014, the European Commission presented the '2030 Policy Framework for Climate and Energy', which sets even more ambitious targets. The EU leaders decided on this framework on October 23, 2014. A centerpiece of the framework is the target to reduce EU domestic greenhouse gas emissions by 40% below the 1990 level by 2030. Renewable energy will play a key role and, therefore, the Commission proposes an objective of increasing the share of renewable energy to at least 27% of the EU's energy consumption by 2030. The improved energy efficiency continues to make an essential contribution to all EU climate and energy policies. Progress towards the 2020 target of improving energy efficiency by 20% is being delivered by policy measures at the EU and national levels.

The 2030 policy framework paper also takes into account the longer term perspectives set out by the Commission in 2011 in the 'Roadmap for Moving to a Competitive Low Carbon Economy in 2050', the 'Energy Roadmap 2050' and the 'Transport White Paper'. These documents reflect the EU's goal of reducing greenhouse gas emissions by 80-95% below 1990 levels by 2050 as part of the effort needed from developed countries as a group.

On November 30, 2016, the European Commission presented a new package of measures ("Winter Package 2016") with the goal of providing a stable legislative framework needed to facilitate the clean energy transition – and thereby taking a significant step towards the creation of the Energy Union. Aimed at enabling the EU to deliver on its Paris Agreement commitments, the 'Clean Energy for All Europeans' proposals are intended to help the EU energy sector become more stable, more competitive, and more sustainable, and fit for the 21st century. With a view to stimulating cross-border cooperation and mobilising public and private investment in the clean energy transition, the package has three main goals:

- Putting energy efficiency first ("a binding EU-wide target of 30% for energy efficiency by 2030")
- Achieving global leadership in renewable energies ("Renewable electricity, cleaner heating and cooling, decarbonised transport, empowered consumers and at least 27% renewables")
- Providing a fair deal for consumers ("energy efficiency first", "speed up the renovation rate of existing buildings", "creating a building renovation market for SMEs", and "long-term perspective and vision towards the decarbonisation of buildings by 2050")

The thematic field contributes to the low carbon strategy of the EU by investing in the commercialization of conversion technologies from primary energy carriers to chemicals and fuels that possess the potential to significantly reduce greenhouse gas and air pollutants emissions, to improve overall process chain efficiencies, or to increase the integration of renewable energies. Furthermore, the thematic field is open to investments in products and services that lead to an improvement in air quality, that are related to large-scale heating grids, or that deal with the decommissioning and second life of fossil source technologies.

2. Market Challenges and Business Drivers

The political framework set by the European Commission has a significant impact on the energy markets throughout Europe and beyond. This causes that companies operating in the thematic field Energy for Circular Economy face the following market challenges:

- *Conventional resources*, mainly fossil fuels, are still dominant and remain competitive in terms of economics
- *Renewable energy sources* (RES) are generated locally and some of them, such as wind and solar, are volatile
- *Reduction of CO_2 emissions* is encouraged by the EU Emissions Trading System
- The *regulatory framework* in the context of renewable energy sources keeps changing over time
- *Environmental regulations* affecting air quality maintain a significant interest, especially with regards to industrial processes, electricity generation and transport
- Connecting the sectors electricity, heat (buildings), industry, and transport (the so called "*sector coupling*") will be crucial for the success of the transition of Europe's energy system
- Energy storage systems provide a wide array of technological approaches to manage Europe's energy supply at the same time creating a more resilient energy infrastructure and reducing the cost of energy supply

These market challenges create business drivers for companies, which are their reactions to these external challenges, when trying to establish new, cost competitive technologies on the market. The business drivers include, but are not limited to:

- Maintain competitive feedstock costs by
    - increasing the use of novel low-cost biomass resources, such as residues and wastes
    - increasing feedstock flexibility
    - reducing the logistic costs of biogenic feedstocks (reduction of transport costs, improvement of storage capability and increase of energy density)
    - recycling of nutrients from biomass based fuel conversion processes to generate additional revenue
    - preserving secure clean energy supply for Europe by prospective extension of natural resources, e.g. unconventional gas and oil
- Reduce CO_2 and air pollutants emission of conversion technologies by
    - substituting fossil resources with biomass feedstock
    - developing advanced energy and syngas production technologies enabling optimized use of available fossil fuel, biomass, waste, and unconventional gases resources
    - utilizing or integrating improved air pollutants reducing technologies
- Reduce plant and operating costs (CAPEX, OPEX) by
    - establishing load and product flexible conversion systems (e.g. poly-generation technologies)
    - increasing process efficiency and establishing more efficient conversion technologies
    - developing widely accepted and economically justified strategies for CCU (power-to-X) and distributed energy production based on fossil fuels, biomass, and waste

    - increasing operational efficiency, safety, and flexibility for power production and industrial processes
- Use surplus RES by
    - establishing electrochemical conversion systems for production of energy carriers and chemicals from surplus electric power (e.g. ‘Power-to-Gas’, ‘Power-to-Liquid’)
    - providing grid stabilization services and thereby allowing an increased use of RES
    - providing high density energy storage through energy carriers and chemicals that are easy to handle and store
- Establish local, small-scale energy systems
- Implement large-scale smart heating grids in cities, integrated industrial complexes and commercial business districts
- Improve technologies to decommission fossil fuel production sites at the end of their life and introduce these to second life utilization

3. Technologies to Address the Challenges

The main objective of all InnoEnergy investments is to lower greenhouse gas emissions, to enhance the security of energy supply and the reliability of energy systems, and to reduce the cost of energy and the environmental footprint of the energy sector.

3.1 Technology Overview

The thematic field Energy for Circular Economy focuses on conversion processes and complete conversion routes ('process chains') from fossil, biogenic and waste resources to final energy carriers and chemicals. Therefore, the thematic field includes resources, conversion processes, transport, storage and utilization of energy carriers and allocation of chemicals. This is depicted in the figure below. In addition, the thematic field covers technologies associated with these process chains, such as storage and distribution of heat and cold on a large scale, air pollutants reduction, and decommissioning of energy production sites at the end of their life.

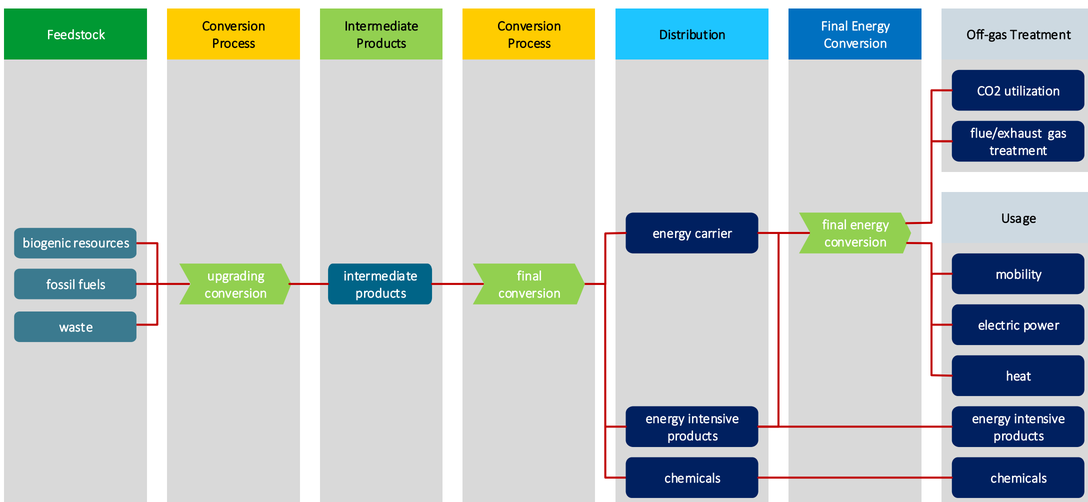


Figure 1: Overview of the conversion routes in the thematic field Energy for Circular Economy.

3.2 Scope of this Document

This document defines and surveys the scope of the thematic field Energy for Circular Economy. The following list provides an overview of the aspects discussed in detail in this document. The names and numbers printed in bold refer to the respective chapters in this document.

I. Unconventional feedstock sourcing technologies
    a. **Unconventional gaseous feedstock sourcing (biogenic & fossil) – see chapter 4.1**
    b. **Unconventional liquid feedstock sourcing (biogenic & fossil & waste) – see 4.2**
    c. **Unconventional solid feedstock sourcing (biogenic & fossil & waste) – see 4.3**

II. (Bio-)energy conversion technologies
    a. **Mechanical pretreatment - see 5.1**
        i. Sorting
        ii. Milling
        iii. Briquetting/homogenization
    b. **Thermochemical pretreatment - see 5.2**
        i. Hydrothermal carbonization

        ii. Torrefaction
        iii. Fast pyrolysis
        iv. Additives, catalysts
    c. Gasification/combustion for production of chemicals or heat and power generation – see 5.3
        i. Combustion (IC/GT/ team cycle)
        ii. Co-firing
        iii. Gasification + CHP
        iv. Gasification + synthesis
        v. Reforming (steam/oxygen) for hydrogen production from fossil fuels
    d. Electro-chemical processes - electrolysis and fuel cells – see 5.4
        i. Electrolysis
        ii. Fuel cells
    e. (Bio-)Chemical Processes – see 5.5
        i. Hydrolysis
        ii. Fermentation
        iii. Synthesis
        iv. Upgrading

III. Smart grids for energy carriers - logistics, transportation and distribution – see 6.
    a. NG & SNG
    b. CNG & LNG
    c. Hydrogen
    d. (Bio-)fuels & intermediates (liquid and solid)

IV. Smart heating grids – see 7.
    a. Application of microgeneration in district heating (for residential applications and small-scale grids see third program line of SEBC roadmap [Smart & Efficient Buildings & Cities])
    b. Reduction of operational hazards in grids
    c. Distribution management systems
    d. Smart meters
    e. Heat storage
        i. sensible thermal energy storage (for residential applications see first program line of SEBC)
        ii. underground thermal energy storage (ditto)
        iii. phase change materials for thermal energy storage (ditto)
        iv. electric thermal storage (see Smart Electric Grid roadmap, area 1)
        v. thermal energy storage via chemical reactions

V. Air quality & sustainability of conventional energy sources – see 8.1
    a. Alteration/upgrading of fossil power plants for alternative feedstock usage
    b. By-product/waste handling / upgrading
    c. Tackling smog with energy innovations – air quality focused measures
        i. reduction of emissions/contaminants – catalysis (NOx, CO, hydrocarbons)
        ii. reduction of emissions/contaminants – filtration
        iii. novel technologies for air purification
    d. CO2 utilization – see 8.2

VI. Fossil sources decommissioning technologies – see 9.
    a. Decommissioning technologies for solid feedstock sources (e.g. mining)
    b. Decommissioning technologies for liquid feedstock sources (e.g. oil fields)
    c. Decommissioning technologies for gaseous feedstock sources (e.g. gas fields)

The following sections of this roadmap document describe the technologies in more detail, evaluate the impact that possible InnoEnergy investments might have, and present some examples of market players. In addition, spider diagrams in each chapter will assess the impactability of the technologies. The criteria used in these spider diagrams are defined as follows:

1. Technology readiness level (TRL)
2. Impact on cost decrease: how large would the impact of a InnoEnergy investment be on the reduction of the cost of the technology – as compared to the state-of-the-art of that particular technology
3. Impact on operability: how large would the impact of a InnoEnergy investment be on the operability of the technology – as compared to the state-of-the-art of that particular technology
4. Impact on GHG decrease: how large would the impact of a InnoEnergy investment be on the decrease in GHG emissions of that particular technology
5. Coverage of the value chain by InnoEnergy partners, i.e. partners from industry and R&D organizations
6. Interest of InnoEnergy industry partners
7. Inverse (foreseeable regulatory impact): how strong is the product/market bound to existing/future regulations; is/will the market of the product be regulated?
8. Inverse (required investment): how large is the required InnoEnergy investment for that particular conversion process to have a significant impact?
9. Cross impact of InnoEnergy investment on several 'applications' (i.e. other conversion processes)

The technical maturity and market implementation of these technologies ranges from commercially proven solutions with a wide range of technology suppliers via technologies that are currently being deployed at commercial scale to technologies that are at an early stage of development. For a first, quick evaluation of the potential of the technologies addressed in this thematic field, the following figure provides their "Mid-term Market Potential" plotted over their "Technological Attractiveness and Potential". These two terms, used as axis titles in this figure, are defined as follows:

- The "Technological Attractiveness and Potential" indicates how promising and attractive a given technology for an InnoEnergy investment is. This means that the development of this technology has to be at an advanced stage, yet requires still some development work to bring it to commercialization. In addition, the technology needs to be in a field where InnoEnergy and its partners are already active. This value was derived from three of the criteria mentioned above: the TRL, with TRL 7 being assessed as optimal, the coverage of the value chain by InnoEnergy and its partners from industry and R&D, and the cross impact of an InnoEnergy investment on several 'applications' (i.e. other conversion processes). These three criteria are shown in the spider diagrams in the following sections.
- The "Mid-term Market Potential" denotes how large the potential for the successful commercialization of a given technology in the market is in the timeframe of five to seven years. It was derived from the three criteria impact of an investment by InnoEnergy and its partners on the cost decrease and on the operability of a given process technology, and interest of InnoEnergy's industry partners. These criteria are also shown in the spider diagrams in the following sections.

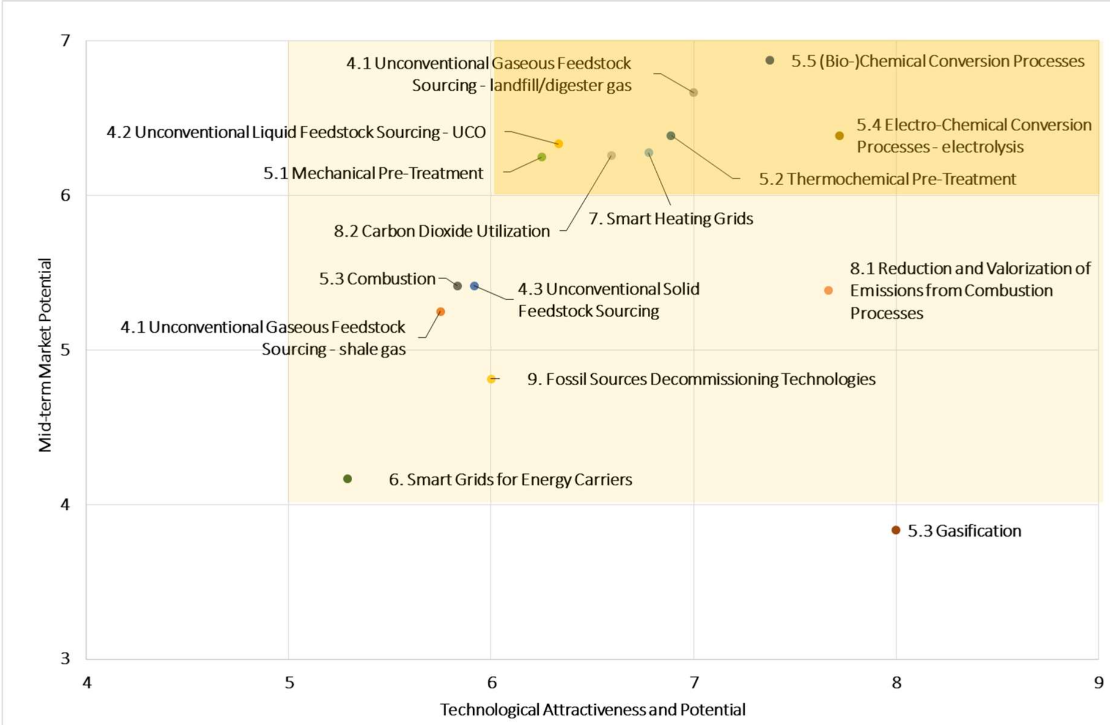


Figure 2: Mid-term market potential of the conversion technologies discussed in this document plotted over their technological attractiveness and potential.

Technologies which possess a 'Technological Attractiveness and Potential' and a 'Mid-term Market Potential' larger than six, are most interesting for InnoEnergy investments. The yellow box at the top right corner in the figure highlights these processes.

4. Unconventional Feedstock Sourcing Technologies

Unconventional feedstocks are already widely used on a local, regional and global scale. Well-established process technologies convert these to intermediate and final products (energy carriers or final energy forms). The corresponding feedstocks can be of all three states of aggregation: gaseous, liquid and solid. Examples are:

- Gases: landfill gases, digester gases, coking gases, flare gases, fracking gases etc.
- Liquids: tar/oil sands, used cooking oils, black liquor etc.
- Solids: solid industrial waste, municipal solid waste, waste wood etc.

The markets for some of these feedstocks, in particular fracking gases and tar/oil sands, possess a global dimension and a huge volume. Other feedstocks play an important role on a regional level, such as landfill and digester gases, used oils, solid industrial and municipal wastes, or waste wood.
The corresponding conversion technologies are mature, although there is always the potential for new and improved conversion processes to surface in certain niche applications. In the existing markets, improvements for technological aspects of process chains may yield a large, positive impact on the environment. These technological developments, if related to intelligent product processing and treatment, logistics, or upgrading, are of interest to InnoEnergy.

4.1 Unconventional Gaseous Feedstock Sourcing (Biogenic & Fossil)

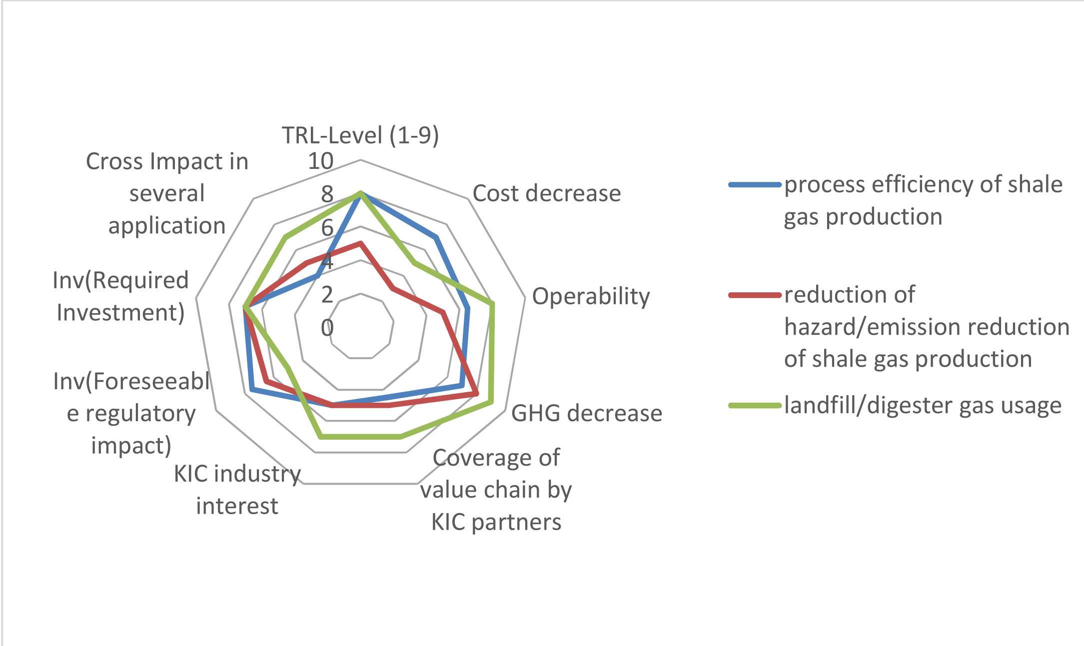
Although shale gas may not be considered an “unconventional gaseous feedstock” any longer, its exploitation is still young compared to other ways of exploiting natural gas. Shale gas is natural gas trapped within shale formations. It has become an increasingly important source of natural gas since the start of this century, especially in the United States.
Landfill gas and digester gas are complex mixtures of different gases created by microorganisms. These gases consist of approximately forty to sixty percent methane, with the remainder being mostly carbon dioxide. This gas can be utilized directly on site by any type of combustion system or CHP generator.

4.1.1 Details of Technology

Shale gas is predominantly extracted via hydraulic fracking. During this process a 'fracking fluid' (primarily water, containing sand or other proppants) is injected under high pressure into a wellbore to create cracks. These cracks allow the natural gas (plus petroleum and brine) trapped underground to be conveyed to the well. There are still open questions associated with fracking – about increasing process efficiency, and health and environmental risks.
The production and utilization of landfill and digester gas is a mature technology. However, there is still potential to increase gas yields, to widen the feedstock basis (e.g. lignocellulose), and to operate biogas plants intermittently using them as an energy storage system.

4.1.2 Assessment on “Impactability”

The following spider diagram provides an overview of the impact that InnoEnergy investments can achieve in this field.



4.1.3 Examples of Market Players

Shale Gas Producers

Anadarko Petroleum Corporation (USA)

Antero Resources Corporation (USA)

BHP Billiton (Australia, UK)

BP (UK)

Cabot Oil & Gas (USA)

Chesapeake Energy (USA)

Chevron (USA)

Cimarex Energy (USA)

ConocoPhillips (USA)

CONSOL Energy (USA)

Continental Resources (USA)

Devon Energy (USA)

Encana Corporation (Canada)

EQT Corporation (USA)

ExxonMobil (USA)

Marathon Oil Corp. (USA)

PetroChina (CNPC)

Pioneer Natural Resources (USA)

Range Resources (USA)

Reliance Industries Limited (India)

Royal Dutch Shell (The Netherlands)

Sinopec (CNPC)

SM Energy (USA)

Southwestern Energy (USA)

Statoil (Norway)

Talisman Energy (Canada)

Landfill and Digester Gas
Diamond Systems LLC (USA)
Eisenmann AG (Germany)
Siloxa Engineering AG (Germany)
Klärgas-Technik- und Service GmbH (Germany)
Lindenberg-Anlagen GmbH (Germany)
e-flox GmbH (Germany)

4.2 Unconventional Liquid Feedstock Sourcing (Biogenic & Fossil & Waste)

A major unconventional liquid feedstock is synthetic crude oil extracted from the extra-heavy crude oil or crude bitumen from tar/oil sands. Natural bitumen deposits are reported in many countries, but in particular are found in extremely large quantities in Canada, Kazakhstan, Russia, and Venezuela. Therefore, technologies associated with this feedstock are not in the focus of European governments and industries.

A quite different source of unconventional liquid oils, in terms of quantities and greenhouse gas emissions are used cooking oils (UCO), mainly from restaurants and food-processing industries. Recycling industry calls these recycled vegetable oil (RVO), used vegetable oil (UVO), waste vegetable oil (WVO), or yellow grease.

Another liquid waste resource produced globally is black liquor. It is the waste product from the kraft process when digesting pulpwood into paper pulp removing lignin, and hemicellulose.

4.2.1 Details of Technology

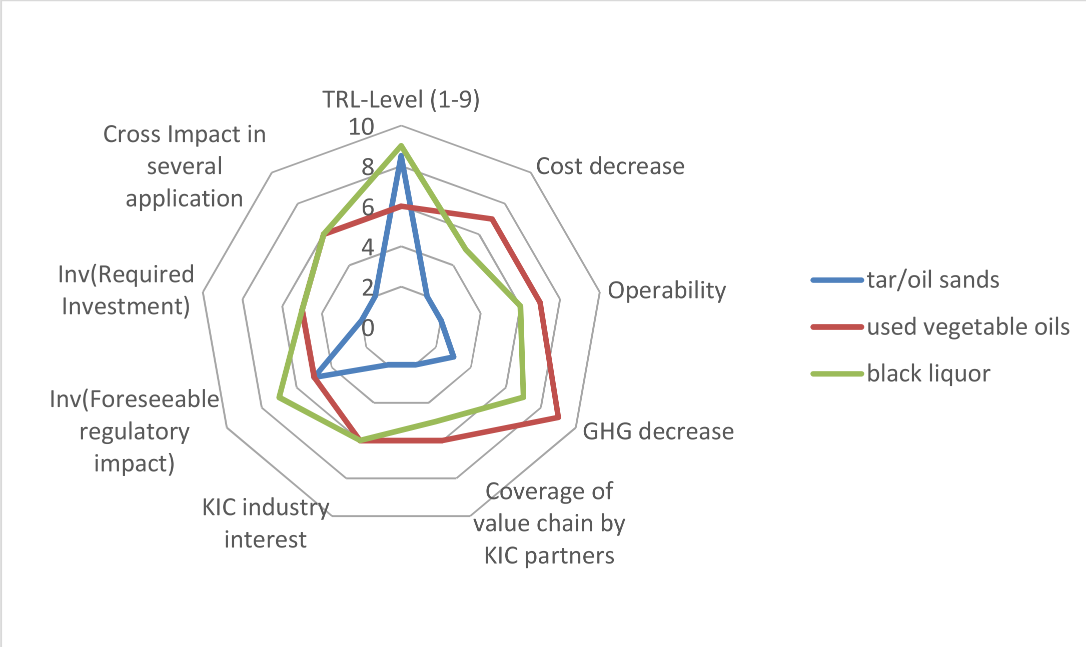
UCO possess a large potential, which is currently hardly capitalized. According to EU estimations, the potential of UCO to be collected is around 4 million tons of UCO in the EU per year (2017). This potential increases around 2% per year, following the annual increase of cooking oil usage. For comparison: The EU imports approx. 4 billion tons of crude oil per year (2017).

The amount of UCO currently used in the EU is only one seventh of the total potential. To increase the usage of UCO, the collection infrastructure and subsequently logistics, characterization, upgrading, utilization are becoming more and more important. UCO contains impurities, such as free fatty acid (FFA) and water, which have to be removed before the transesterification process.

Black liquor contains more than half of the energy content of the wood fed into the digester of a kraft pulp mill. It is typically concentrated and burned in a recovery boiler to produce energy in the paper mill. However, it can also be used as a biofuel feedstock for gasification or hydrothermal liquefaction.

4.2.2 Assessment on “Impactability”

The following spider diagram provides an overview of the impact that InnoEnergy investments can achieve in this field.



4.2.3 Examples of Market Players
Tar and Oil Sands
global oil and EPC companies

Used Vegetable Oils
Protelux (Belgium)
EPC Holdings (Ireland)
GreenEa (France)
Uptown Biodiesel Limited (UK)
Bio Oil Development SRO & CO KS (Slovakia)

Upgrading
Neste Corp. (Finland)
Valero Energy Corporation (USA)

Black Liquor
Stora Enso Oyj (Finland)
UPM (Finland)
Smurfit Kappa Group plc (Ireland)
Kübler Niethammer Papierfabrik Kriebstein AG (Germany)
Veolia Water Technologies (France)

4.3 Unconventional Solid Feedstock Sourcing (Biogenic & Waste)
Waste is an unconventional feedstock for renewable fuels and chemicals. It has a huge potential: globally 1.3 billion tons of municipal solid waste (MSW) are generated per year. Especially the generation of thermal energy from waste with the associated logistics is a mature industry. However, the production of fuels and chemicals from waste resources is still at the stage of pilot plant development and operation.

So-called refuse-derived fuel (RDF) is a fuel produced from various types of wastes such as municipal solid wastes (MSW), industrial wastes or commercial wastes. Another unconventional solid feedstock source is agro-food waste (AFW).

4.3.1 Details of Technology

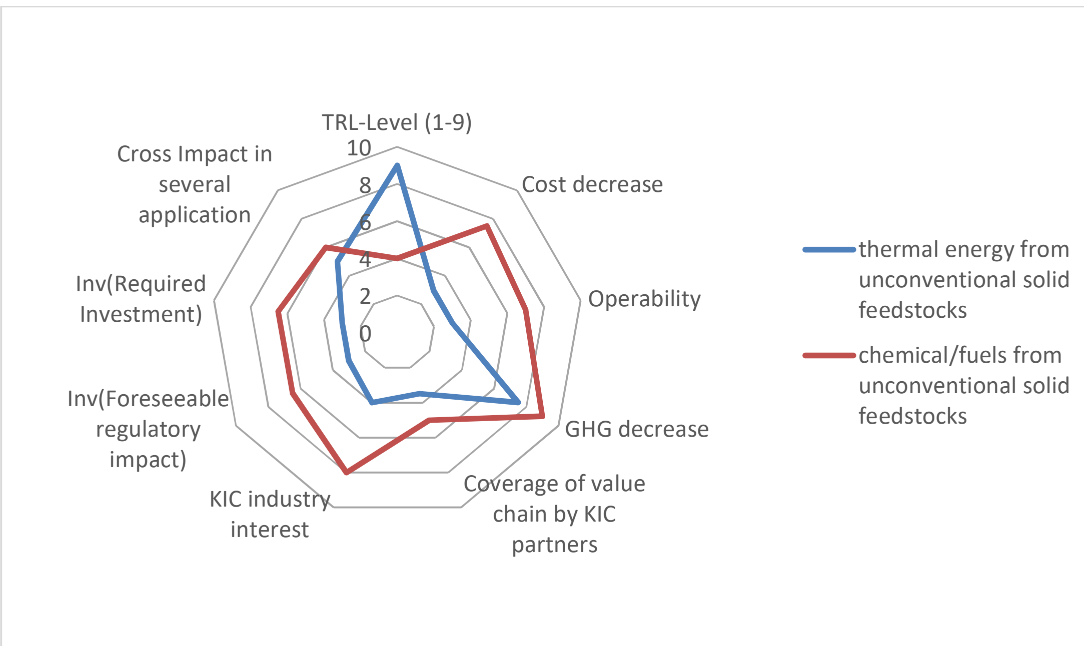
Incineration or thermal treatment reduces the volume of waste by approx. 90%. The residual volume is completely sanitised by the combustion process, in other words all hazardous and pathogenic substances are removed. Thanks to modern flue gas cleaning technology, the process is clean and safe.

The same holds true for refuse-derived fuels. Their main use to date is co-combustion in waste-to-energy plants and in other thermal recovery plants, such as cogeneration and cement plants. Some power plants are powered solely by such fuels. Refuse-derived fuels replace fossil fuels, therefore, the market values follow the fluctuations of the market prices for fossil fuels.

Besides the well establish “conversion” of waste to thermal heat, first MSW-to-chemicals facilities are under development, some of them even in commissioning. Here, the many activities in academia and at research organizations indicate that such technologies still are at a lower TRL. However, there exists huge potential for future commercial implementation.

4.3.2 Assessment on “Impactability”

The following spider diagram provides an overview of the impact that InnoEnergy investments can achieve in this field.



4.3.3 Examples of Market Players

Waste Logistics

Veolia Environnement S.A. (France)

SITA/Suez (France)

Remondis SE & Co. KG (Germany)

Waste Management, Inc. (Houston, TX, USA)

ALBA Group plc & Co. KG (Germany)

Thermal Energy from Waste

Energy from Waste GmbH (Germany)
Steinmüller Babcock Environment GmbH (Germany)
MARTIN GmbH für Umwelt- und Energietechnik (Germany)
Buchen KraftwerkService GmbH (Germany)
SAG Erwin Peters GmbH (Germany)

Waste-to-Chemicals/Fuels
Plastic2Oil, Inc. (USA)
EEW Enerkem, Inc. (Canada)
A TEC Production & Services GmbH (Austria)
Dieselwest GmbH (Germany)
Confederation of European Waste-to-Energy Plants CEWEP e.V. (Germany)

5. Energy Conversion Technologies

The processes addressed in this section comprise pre-treatment processes as well as thermo-chemical, electro-chemical, chemical and bio-chemical conversion processes to energy carriers and chemicals. The focus of the thematic field is on improving the conversion processes with regards to CAPEX, OPEX, conversion efficiency, and reliability of operations.

5.1 Mechanical Pre-Treatment

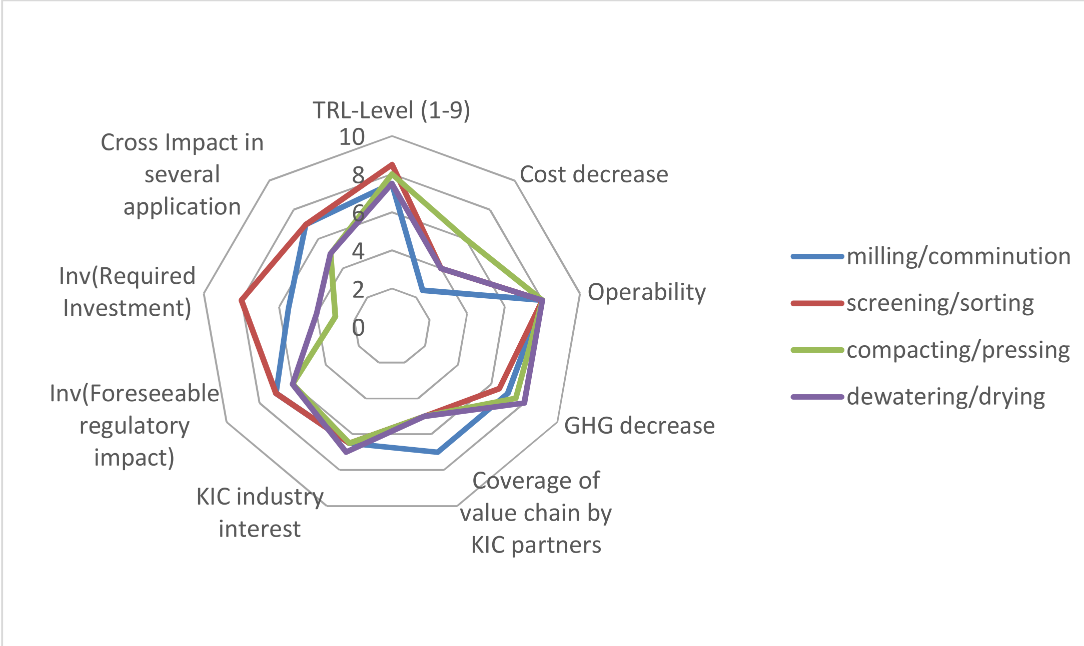
Cost-effective production of energy carriers is very much dependent on efficient handling of available feedstock sources, as well as the efficiency of each process.
Mechanical pre-treatment of the feedstock changes its mechanical properties, such as particle size, density, and moisture content. It serves the purpose to adjust the feedstock properties to the downstream conversion processes. In addition, the feedstock handling along the supply chain is facilitated and the associated costs are reduced.
Mechanical pre-treatment either makes the pieces of substrate smaller or squeezes them to break open the cellular structure, increasing the specific surface area of the feedstock. The most commonly used processes are milling/comminution, screening/sorting, compacting/pressing, and dewatering/drying.

5.1.1 Details of Technology

Comminution is the reduction of solid materials from one average particle size to a smaller average particle size, by crushing, grinding, cutting, vibrating. Comminution of solid materials requires different types of crushers and mills depending on the feed properties such as hardness. There is still a lack of comprehensive information on the relationships among comminution energy consumption, bulk density and particle physical properties. These need to be addressed to optimize the performance of size reduction devices, especially for 2nd generation energy crops, such as miscanthus, switchgrass, willow, and energy cane.
(Mechanical*) screening* is the practice of taking a feedstock and separating it into multiple grades by particle size. To release the full energy potential of a feedstock, the material must be cleaned of impurities and have the proper size for optimum utilization. In certain installations, the equipment must be designed for dust removal and/or ATEX-approved for fire prevention. Screening and sieving is achieved by various types of machines, such as drum screens/sieves, revolving screens, star/disc screens, and oscillating/vibrating screens.
By *compacting* feedstock into pellets or briquettes, a very homogenous product is achieved. Before pelletizing, the feedstock must be conditioned using water of varying temperatures or steam, and sometimes applying additives.
Dewatering is applied to feedstocks with a very high water content. Wet feedstocks generally possess a low value due to the high cost of thermally removing water to make use of the lignocellulosic material contained therein. There are mechanical technologies that can potentially remove water in a cost effective manner.

5.1.2 Assessment on "Impactability"

The following spider diagram provides an overview of the impact that InnoEnergy investments can achieve in this field.



5.1.3 Examples of Market Players

Milling/Comminution
Continental Biomass Industries (USA)
Riko Ribnica (Slovenija)

Screening
Allgaier Process Technology GmbH (Germany)
Ecokraft AG (Germany)
Riko Ribnica (Slovenija)
S&F GmbH (Germany)
HAAS Holzzerkleinerungs- und Fördertechnik GmbH (Germany)

Compacting
Andritz AG (Austria)
Continental Biomass Industries (USA)
Gemco Energy Machinery Co.,Ltd. (China)

Dewatering
Flottweg SE (Germany)
MSE Filterpressen GmbH (Germany)
Galkor Sp z o.o. (Poland)
Choquenet SAS (France)
SO.TEC SRL (Italy)

5.2 Thermochemical Pre-Treatment

The development of thermochemical pre-treatment processes for increased fuel flexibility, utilization of a wider range of biogenic resources, mobilization of scattered biomass resources, and reduction of fuel and fuel transportation cost is one focus of the activities in the thematic field. According to IEA Bioenergy the largest potential for feedstock price reduction is generated by internationally transported biomass. High energy density, mechanical stability and minimum bio-degradability of biomass feedstock are achieved by thermochemical pre-treatment.

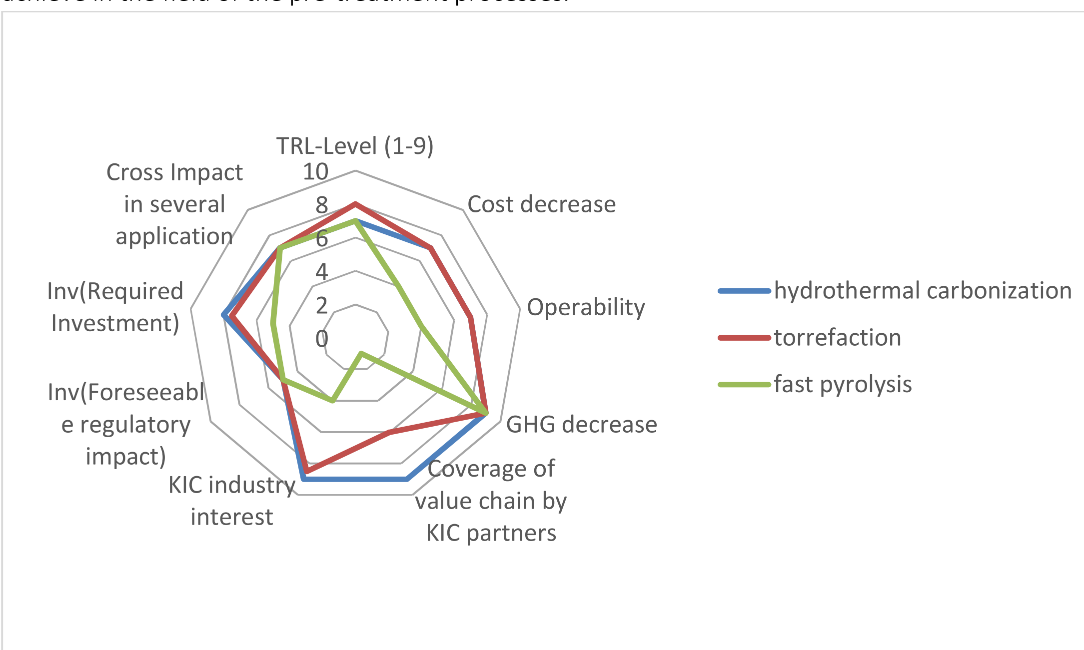
5.2.1 Details of Technology

Depending on the water content of the biomass there are different pre-treatment options:

- For wet biomass, hydrothermal carbonization (HTC) und hydrothermal gasification are used.
    - *Hydrothermal carbonization (HTC)* converts wet biomass at moderate temperatures and pressures in aqueous solution to bio-char slurry.
    - *Hydrothermal gasification* generates synthesis gas from wet biomass in near- and super-critical water. This process is still in the phase of research and development, and, therefore, not discussed any further in this document.
- Dry biomass: Thermal processes such as torrefaction and fast pyrolysis produce solid and liquid fuels with high energy density, which can easily be stored and transported.
    - *Torrefaction* of dry biomass followed by pulverization and densification to biocoal pellets or briquettes increases the energy density, which results in a 40-50% reduction in transportation costs.
    - *Fast pyrolysis* (also called flash pyrolysis) takes place at 500-600 °C. The main product of fast pyrolysis is a pyrolysis oil (70 to 80 wt.-%) which requires further upgrading since it is prone to polymerization and very acidic.

5.2.2 Assessment on "Impactability"

The following spider diagram provides an overview of the impact that InnoEnergy investments can achieve in the field of the pre-treatment processes.



Hydrothermal Carbonisation (HTC)

HTC developments are of interest for InnoEnergy investments, because the development on the market did not progress as quickly as anticipated four years ago (see the last version of the former 'Energy from Chemical Fuels" roadmap). Due to profitability, the focus has shifted from producing bio-coal to disposing of waste streams (e.g. sewage sludge).

Torrefaction

There are few installations in operation that have a capacity above 100,000 t/a. However, most plants are technology demonstrator with capacities from 10 to 30,000 t/a. This is a technology is currently being introduced on the market.

Fast Pyrolysis

The fast pyrolysis technology is at TRL of 5 to 8. It appears to have gained from the interest for biofuels and drop-in fuels. However, the mandatory downstream pyrolysis oil upgrading is in the order of TRL 3 to 5.

5.2.3 Examples of Market Players

Hydrothermal Carbonisation
SunCoal Industries GmbH (Germany)
C-Green Technology AB (Sweden)
TerraNova Energy GmbH (Germany)
AVA GmbH (Germany)
Ingelia S.L. (Spain)
Valmet Corp. (Finland)

Pyrolysis
PYTEC Thermochemische Anlagen GmbH (Germany)
Fortum Oyj Corp. (Finland)
KIT/Lurgi/Air Liquide - "BioLiq" (Germany)
Act&Sorb (Belgium)

Torrefaction
Pyreg GmbH (Germany)
Thermya S.A./Areva (France)
Zilkha Biomass Energy LLC (USA)
Diacarbon Energy, Inc. (Canada)
River Basin Energy, Inc. (USA)

5.3 Gasification and Combustion for Production of Chemicals or Heat and Power Generation

Currently the generation of power and heat is mostly based on conventional combustion systems with a boiler-steam turbine configuration. Typical fuels are fossil fuels, waste feedstock, and biomass. These systems possess a low energy efficiency in the order of 20 % electric. Gasification and downstream use of the syngas via gas engines or gas turbines possesses a large potential to increase efficiency and widen the feedstock base. However, biomass gasification is still in the demonstration phase and faces technical and economic challenges.

Biomass Co-Firing for Combined Heat and Power Production

In order to reduce CO_2 emissions from existing fossil fuel fired power plants, biomass is co-fired. The co-firing of biomass with coal in existing large power plant boilers has proven to be one of the most cost-effective large-scale technologies for conversion of biomass to electricity. The electrical efficiency of larger scale coal fired power plants is in a range of 36 to 40 %. Typically, less than 20 % of biomass can be added to a coal-fired plant without any major changes to the plant operation. If separate feeding systems and separate burners are used, the co-firing rate can be increased.

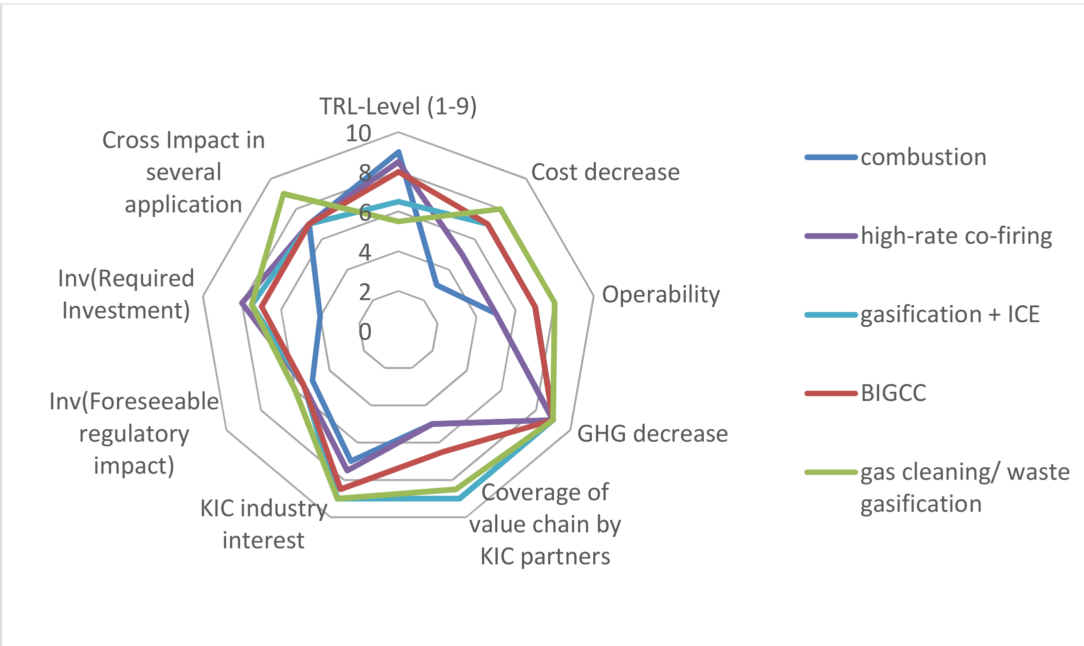
5.3.1 Details of Technology

The process chain (feedstock/gasifier/final energy conversion) has to be designed and optimized for decentralized small scale units (1 to 15 MW fuel input) as well as for central large scale units (>50 MW fuel input). Small-scale gasifiers, predominantly moving bed and fluidized bed type, are coupled with internal combustion engines (ICE), whereas large-scale gasification-based systems use combined cycle (gas and steam turbine) systems (BIGCC Biomass Integrated Gasification Combined Cycle System). The main targets for technology development in this field are the improvement of fuel conversion efficiency, the enhancement of feedstock flexibility (e.g. black liquor), and the reduction of capital investment by standardization of plant design.

5.3.2 Assessment on "Impactability"

Beyond conventional biomass and waste combustion technologies, gasification for power generation possess a considerable improvement potential, especially in smaller capacity units. However, there are a number of technical and commercial challenges related to fuel flexibility and to gas cleaning that up to now have prevented the realization of this potential.

Furthermore, it seems advantageous to couple the development of gas cleaning technologies with the development of improved gasification technologies to achieve InnoEnergy´s targets.



5.3.3 Examples of Market Players

Gasification
Spanner Re² GmbH (Germany)
Ligento green power GmbH (Germany)
Repotec GmbH & Co KG (Austria)
Nexterra Systems Corp. (Canada)
EQTEC (Spain)

Gas Cleaning
BASF S.E. (Germany)
Clariant (Switzerland)
Haldor Topsøe A/S (Denmark)

Combined Heat and Power (CHP)
GE Jenbacher GmbH & Co OG/GE Power (Austria)
MTU Onsite Energy/ Rolls-Royce Power Systems AG (Germany)
Siemens AG (Germany)
Cummins, Inc. (USA)

5.4 Electro-Chemical Conversion Processes - Electrolysis and Fuel Cells

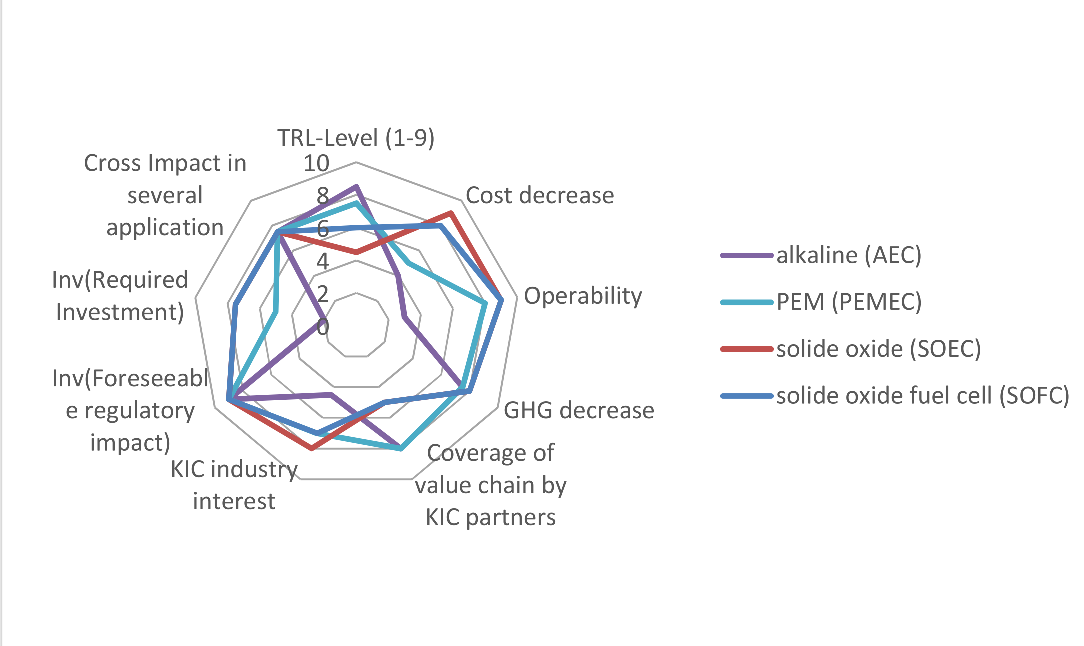
The development of electro-chemical conversion technologies is driven by the increasing need for storage capacities in the electric system. Batteries are highly efficient means for electric energy storage. However, they possess high specific investment costs and low specific storage densities. As a competing technology, water electrolysis plus hydrogen storage tanks or underground caverns provide a high potential for large-scale energy storage. In times when the electrical power demand exceeds the power supply the reverse process of electrolysis, i.e. fuel cells, could provide electric power at high conversion efficiencies.

5.4.1 Details of Technology

Three water electrolysis technologies are under development. The technology with the highest maturity uses a liquid alkaline electrolyte. The most promising technology is the PEM electrolysis due to its operability in a wide load range and its better dynamic operation abilities. Its drawback is its higher specific capital investment, which is the focus of current research and development. Also of interest is the high temperature steam electrolysis, the so-called solid oxide electrolysis (SOEC).
Fuel cells are electrochemical cells that convert the chemical energy of a fuel (e.g. hydrogen) into electricity through an electrochemical reaction. It is the inversion of the electrolysis process.

5.4.2 Assessment on “impactability”

The liquid alkaline electrolysis (AEC) is TRL 9 and has been commercially available for several decades. It is used at remote sources of electric power, such as the Aswan high dam, to convert electric energy into a chemical energy carrier. This solution was more economic in comparison to building a long distance power line.
For dynamic operation the proton exchange membrane (PEM) electrolysis shows advantages. The TRL is in the range of 6 to 8. However, the current capacities of the prototypes are still one order of magnitude lower, than required for the expected future demand. Furthermore, the specific investment costs are somewhat higher than those of liquid alkaline electrolysis.
The high temperature steam electrolysis is at TRL 5. This electrolysis technology is beneficial at locations where waste heat is available additionally to surplus electric power.
The following spider diagram summarizes the impact an InnoEnergy investment in electro-chemical conversion processes.



5.4.3 Examples of Market Players

Alkaline Electrolysis
Wasserelektrolyse Hydrotechnik GmbH (Germany)
Hydrogenics Corp. (Canada)
SAGIM (France)
NEL Hydrogen (Norway)

PEM Electrolysis
Siemens AG (Germany)
ITM Power (UK)
h-tec (Germany)
Proton OnSite (USA)
Enertrag AG (Germany)

Solid Oxide Electrolysis
Sunfire GmbH (Germany)
Buderus -> Bosch Thermotechnik GmbH (Germany)
FuelCell Energy, Inc. (USA)
Elcogen AS (Estonia)

Solid Oxide Fuel Cell
Sunfire GmbH (Germany)
Hexis AG (Schweiz)
FuelCell Energy, Inc. (USA)

5.5 (Bio-)Chemical Conversion Processes ('Syntheses')

Up to now, the energetic use of biomass is restricted to the direct conversion of biomass to heat and power, and, therefore, bound to the location of the biomass resources. The production of high value fuels adds flexibility in storage and supply of energy.

5.5.1 Details of Technology

Catalytic Conversion of Synthesis Gas

Synthesis gas ($CO + H_2$) can be converted through various catalytic routes to synthetic fuels ("synfuels"), such as methanol, dimethyl ether (DME), diesel/jet fuel, or gasoline. All processes have been realized on demonstration and commercial scale. The break-even point for commercialization of existing syngas conversion technologies is at a million ton per year scale. However, this will not be feasible for processes based on renewable energy sources, such as biomass or renewable hydrogen. Therefore, new intensified processes are needed which allow economic production of synfuels at smaller plant capacities.

Syngas Fermentation

Anaerobic microorganisms allow the production of fuel components (ethanol, butanol), but also chemical building blocks from syngas. Fermentation can be performed at much milder process conditions compared to conventional catalytic routes, which results in a simpler process technology.

Conversion of Lignocellulose

Lignocellulose can be depolymerized through various hydrolysis processes into its monomeric constituents (C6 and C5 sugars, lignin). The intermediates from hydrolysis of lignocellulose can be converted through chemical or biochemical routes to fuels and chemical building blocks (e.g. alcohols, organic acids, phenols).

Upgrading of Intermediates such as Pyrolysis Oils

The products from fast pyrolysis as well as from hydrothermal liquefaction cannot be utilized directly as fuel, but have to be upgraded. For this upgrading, various chemical or biochemical processes have been proposed in scientific literature. Conversion technologies are required, which are technically feasible at production scale combined with adequate business models.

5.5.2 Assessment on "Impactability"

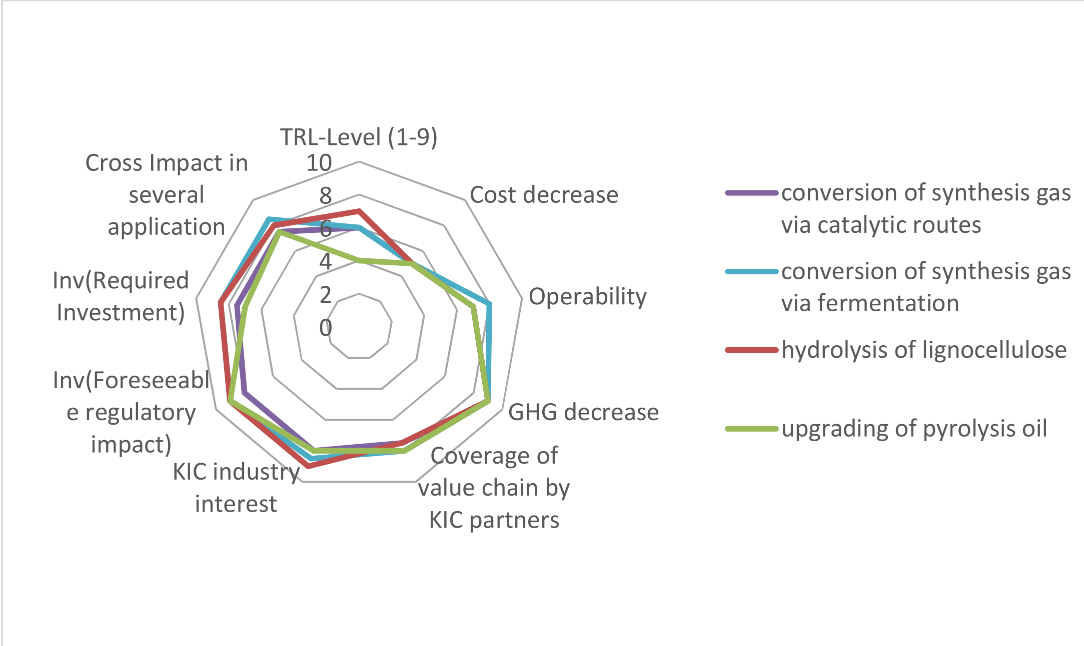
In this very broad field of chemical and bio-chemical syntheses, InnoEnergy focuses on niche processes only. One of the processes with large potential is the fermentation of sugars to butanol, as there is already an existing butanol market and market prices are promisingly high. Furthermore, investments for process and technology demonstration are rather low, e.g. by refurbishing existing, decommissioned bio-ethanol plants.

Additionally, the hydrolysis of lignocellulose (wood or straw), either enzymatic or with acids, is not efficient and commercially attractive enough. InnoEnergy could bring together the right partners to overcome these hurdles.

Large-scale Fischer-Tropsch synthesis (FT) with fossil feedstock is a mature technology. By simplification and intensification of the process the downsizing to scales suitable for the usage of renewable feedstock creates a rather large impact.

DME is an attractive fuel for heating and engine applications. It is produced from synthesis gas via methanol. Current developments focus on the direct synthesis from synthesis gas.

The impact an InnoEnergy investment in these conversion processes is summarized in the following spider diagram.



5.5.3 Examples of Market Players

Conversion of Synthesis Gas via Catalytic Routes and Fermentation
Green Sugar (Germany)
Clariant (Switzerland)
ButamaxAdvanced Biofuels LLC (USA)
Gevo, Inc. (USA)
Korea Gas Corp. (Korea)
BASF S.E. (Germany)
Air Liquide Global E&C Solutions Germany GmbH - formerly Lurgi GmbH (Germany)

Hydrolysis of Lignocellulose
Novozymes A/S (Denmark)
AVA Biochem BSL AG (Switzerland)
Inaeris Technologies, LLC (USA)

Upgrading of Pyrolysis Oil
Neste Corp. (Finland)
Valero Energy Corporation (USA)

6. Smart Grids for Energy Carriers - Logistics, Transportation and Distribution

Modern societies require various energy carriers to perform a multitude of energy services. These energy carriers are gained from primary energy sources and transported to the destination of their conversion or utilization. Examples of energy carriers include gaseous, liquid and solid fuels and chemicals, such as gasoline, diesel, natural gas, liquefied petroleum gas (LPG), coal, hydrogen, and dimethyl ether (DME). The distinction between "energy carriers" and "primary energy sources" is extremely important since these two terms refer to energy forms of different quality.

Some of these energy carriers have been in use for many decades on a global level. They are transported via well-established networks and distributions systems, such as pipelines for natural gas and crude oil, tankers for LNG and crude oil, trucks for fuels and hydrogen.

The electricity, heat, and fuel markets are increasingly merging. At present, the topic is highly relevant due to the advancing electrification of the heat and transport sectors with the help of both established (low-temperature heat pumps, rail transport) and novel technologies (high-temperature heat pumps, electric mobility). Furthermore, expected price drops and surplus electricity from renewable energy have highlighted opportunities for an increased active coupling through novel processes - called Power-to-X (PtX).

The following diagram depicts the interconnection of the three energy forms heat, electricity and fuels – on a very general level. This network is also called sector coupling. This term means the combination of three sectors that indispensably belong together: power, heat and fuels. Electricity and fuels can be converted into each other – however with certain losses caused by conversion efficiencies. Low temperature heat can only be converted to electricity when using complex and usually costly solutions (e.g. ORC, thermo-electrics). The storage of heat and fuels is straightforward. The storage of electricity, on the other hand, is attractive, yet complex.

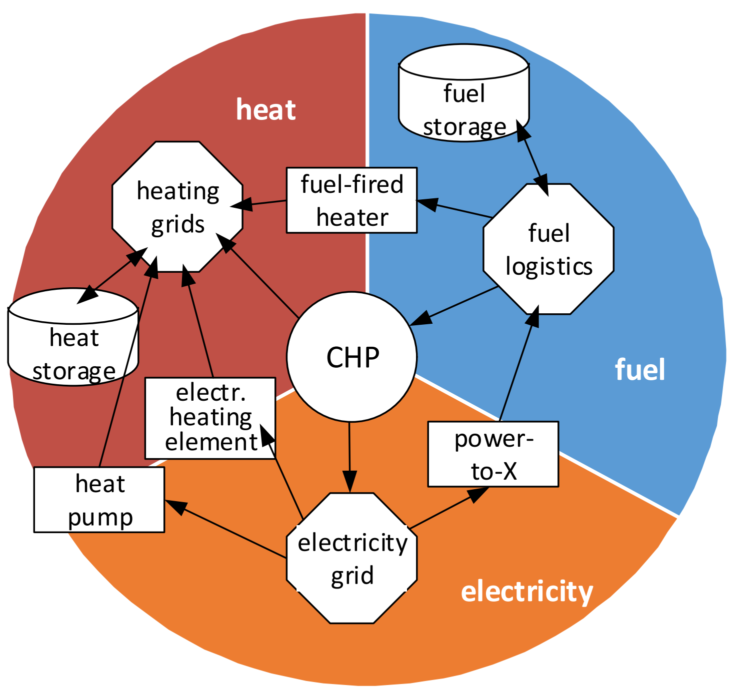


Figure 3: Sector interconnection of the three energy forms heat, electricity and fuels.

6.1 Details of Technology

Natural Gas (NG) and Substitute Natural Gas (SNG)

Natural gas is a major fossil fuel source found in deep underground rock formations. Once extracted, it must be transported to be processed, stored, and then finally delivered to the end consumer. Most of the world's natural gas is delivered by pipeline. Large networks of pipelines quickly deliver natural gas on land and subsea to major processing facilities and end consumers. Natural gas must be highly pressurized to move it along the pipeline. To ensure that the natural gas remains pressurized, compressor stations are placed in intervals along the pipeline. Metering stations are also installed throughout the pipeline network to monitor for pressure, flow and leaks.

Liquefied Petroleum Gas (LPG)

LPG is a mixture of mostly propane and butane. It is almost entirely derived from fossil fuel sources, and serves as fuel for cooking, central and water heating. When specifically used as a vehicle fuel it is often referred to as autogas. LPG is transported by large LPG carriers, pipelines or train to storage terminals. It is then delivered by train, road, coastal tanker or pipeline to cylinder filling plants and intermediate-size storage areas. After it has been filled in cylinders the LPG can be transported to the end users.

Liquefied and Compressed Natural Gas (LNG, CNG)

Where natural gas cannot be delivered via stationary infrastructure (e.g. pipeline), it can be liquefied or compressed and delivered by ship. Compared to gas pipelines, liquefied natural gas and compressed natural gas shipping is preferred for international transport. LNG achieves a higher reduction in volume than compressed natural gas (CNG) so that the (volumetric) energy density of LNG is 2.4 times greater than that of CNG (at 250 bar) or 60 percent that of diesel fuel. This makes LNG cost efficient in marine transport over long distances. However, CNG carrier can be used economically up to medium distances in marine transport. Specially designed cryogenic sea vessels (LNG carriers) or cryogenic road tankers are used for its transport. LNG is principally used for transporting natural gas to markets, where it is re-gasified and distributed as pipeline natural gas.
LNG can also be used in natural gas vehicles, although it is more common to design vehicles to use compressed natural gas (CNG). Its relatively high cost of production and the need to store it in expensive cryogenic tanks have hindered widespread commercial use of LNG. Despite these drawbacks, on energy basis LNG production is expected to hit 10% of the global crude production by 2020.
In the last decade, natural gas prices have followed a decidedly different path than gasoline and diesel prices. These divergent price trends have created an opportunity to use compressed natural gas (CNG) as a transportation fuel. Here have been significant activities in industry worldwide to develop natural gas fueled vehicles and install natural gas refueling facilities. These developments point to the growing potential to utilize natural gas as a transportation fuel.

Hydrogen

Hydrogen has been deployed as an industrial gas for over one hundred years and large volumes are used across a wide range of applications. It is an energy carrier – not a source of energy. Therefore, it must be produced. Yet, hydrogen offers several key benefits that increase its potential to replace fossil fuels. Stored hydrogen, for example, can be used directly as a fuel or to generate electricity.
For hydrogen production, many technologies are available or being developed allowing for the use of all primary and secondary energies for hydrogen generation in large centralized plants or in small decentralized units. Hydrogen conditioning includes compression and liquefaction. Both technologies are applied commercially, but have considerable further development potentials.

Hydrogen is transported in cylinders or even pipelines. Liquid hydrogen (LH2) is shipped with trucks either in special trailers or in containers. Pressurized hydrogen (CH2) is delivered in mobile pressure cylinders or in bundles by truck or train from producer to consumer. Ships for the transport of liquid hydrogen could be very similar to today's tankers for liquid natural gas.

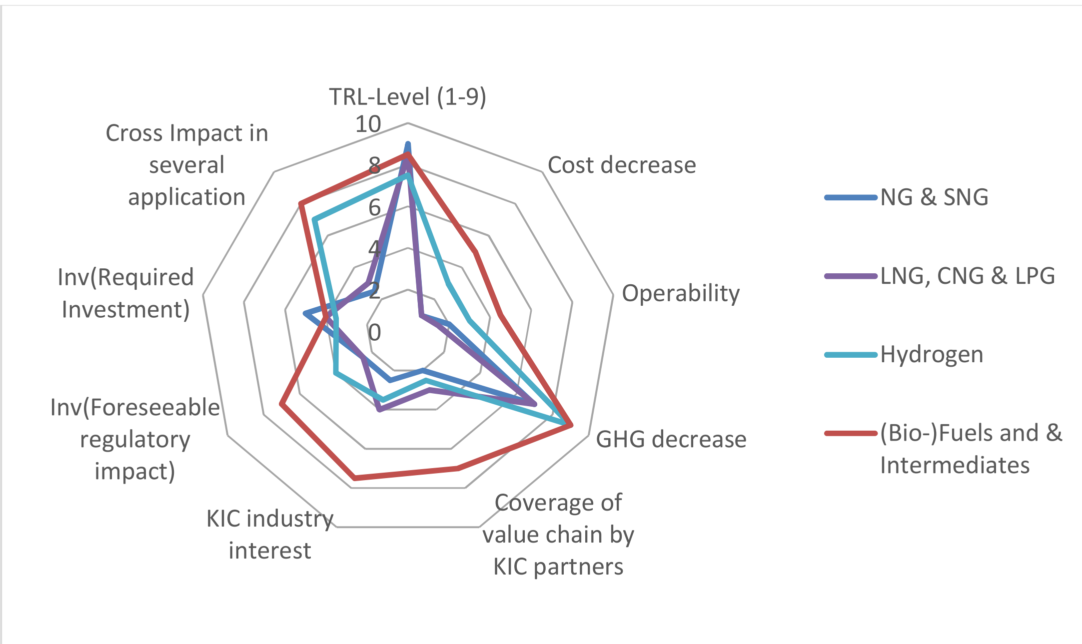
There are proposals to inject hydrogen into the natural gas network. This measure would allow the very large transport and storage capacities of the existing infrastructure to be used for indirect electricity transport and storage, which may be especially important for the growth of Power-to-Hydrogen technology. However, there are still some important areas where issues remain, e.g. with underground porous rock storage, gas turbines/engines, and process gas chromatographs.

(Bio-)Fuels and & Intermediates (Liquid and Solid)

Fuels and chemical intermediates are widely used in industry as feedstock and, therefore, a reliable and well established logistic and distribution network has been in place for decades. The rapidly growing bio-fuel and bio-intermediate industry tries to tie into the existing networks, yet also creates own supply chains and distribution networks where necessary.

6.2 Assessment on "Impactability"

The following spider diagram provides an overview of the impact that InnoEnergy investments can achieve in this field.



6.3 Examples of Market Players

NG, SNG, LNG, CNG and LPG

All major oil and gas companies

Entrepose Group (France)

Nakilat - Qatar Gas Transport Company Ltd. (Qatar)

SHV Energy N.V. (The Netherlands)

Hydrogen

Linde AG (Germany)

Hydrogenious Technologies GmbH (Germany)

Air Liquide S.A. (France)

Diagma (France)
Chicago Bridge & Iron Company N.V. ("CB&I") (The Netherlands)
Honeywell UOP (USA)
Schmidt + Clemens GmbH + Co. KG (Germany)
Cosmo Engineering Co.,Ltd. (Japan)
thyssenkrupp AG - Industrial Solutions (Germany)
Mahler AGS GmbH (Germany)

(Bio-)Fuels and & Intermediates (Liquid and Solid)
Bunge Deutschland GmbH (Germany)
IMA S.r.l. – Industria Meridionale Alcolici (Italy)
VERBIO Vereinigte BioEnergie AG (Germany)

7. Smart Heating Grids

Heating and cooling grids for residential and commercial districts and for industrial heat include the generation, distribution, storage, and final usage of thermal energy in networks. Smart heating and cooling grids aim to improve the management of energy supply and demand. Such networks are optimised by new technologies including control systems, heat meters, heat substations (heat exchangers), heat storage systems, and IT solutions supporting the infrastructure, its installed components and their management.

Smart district heating and cooling grid deployment is integrated with urban planning. For further information and details on this topic please refer to roadmap of the thematic field "Smart and Efficient Buildings and Cities". The present document addresses heating grids for large-scale applications.

7.1 Details of Technology

System components for large-scale heating grids comprise the generation of heat and recovery of waste heat from various energy sources and in industrial processes, the distribution systems via pipelines, distribution management systems, smart meters and sensors connected with central or cloud based control algorithms, and heat exchangers at the end user.

Thermal energy storage (TES), when integrated in a large-scale district heating network, brings numerous benefits to the overall system, such as nearly full recovery of heat produced, reduction of installed heat generation capacity to cope with peak heat demands, highly flexible control of the heat flows, and increase of the reliability, to name a few.

Thermal energy storage in the form of sensible heat is based on the specific heat of a storage medium, which is usually kept in storage tanks with good thermal insulation. The most popular and commercial heat storage medium is water, which has a number of residential and industrial applications. Underground storage of sensible heat in both liquid and solid media is also used for typically large-scale applications.

Phase change materials (PCMs) can offer a higher storage capacity associated with the latent heat of the phase change. PCMs also enable a target-oriented discharging temperature that is set by the constant temperature of the phase change.

Physicochemical storage (PCS) can offer even higher storage capacities. Physicochemical reactions (e.g. adsorption or the adhesion of a substance to the surface of another solid or liquid) can be used to accumulate and discharge heat and cold on demand (also regulating humidity) in a variety of applications using different chemical reactants.

Thermal energy storage via chemical reactions has also been investigated for many decades. In this case reversible chemical reactions are used to store thermal energy in form of chemical energy. Examples are catalytic or thermal dissociation reactions, dehydrogenation of ethane or cyclohexane, dehydration of metal hydroxides, acids or zeolites and more. However, all of these reaction systems require complex engineering solution for application as reliable, long-term heat storage.

Finally, electric heating elements ("immersion heaters") also offer the possibility for storage of electric energy in form to thermal energy. It is discussed in further detail in the roadmap of the thematic field "Smart Electric Grid roadmap, area 1".

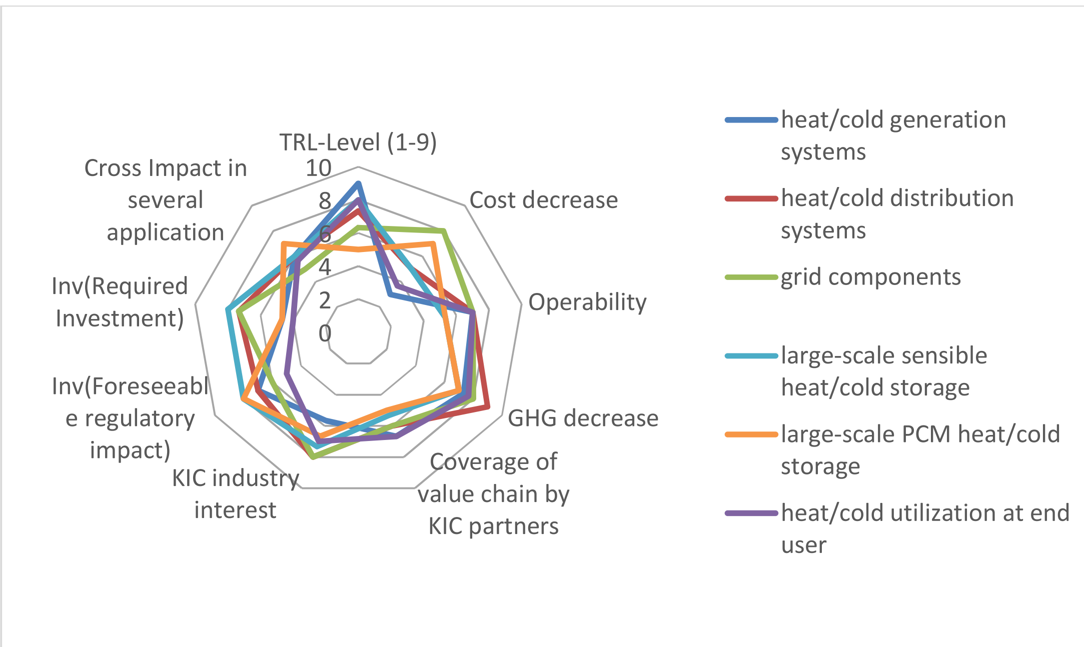
The various components, as part of heating grids, are subdivided into five areas:

- Heat generation: Multi-source heating solution (CHP, solar thermal and geothermal, boilers) and combination of two or more technologies are used to deliver heat, power, cold/warm water, steam. For cooling applications, adsorption refrigeration systems, chillers, compression refrigeration machines are utilized. - Heat pumps can support heating and cooling needs. There are different kinds of heat pumps: natural gas, dual-fuel, ground source, air-source, and water-source. Please note that these components are mainly used in buildings and are, therefore, covered by the "Smart & Efficient Buildings & Cities" roadmap.

- Medium to large scale distribution systems: pipes, insulation, substations, piping networks/grids
- Heat storage: Thermal energy storage includes a number of different technologies. Thermal energy can be stored at temperatures from -40°C to more than 400°C as sensible heat, latent heat and chemical energy (i.e. physicochemical energy storage) using chemical reactions.
- Components for large-scale heating grids, such as smart heat meters, remote/wireless sensors, systems for leakage detection, control systems, intelligent hardware and software overlay for system and network automation
- Heat/cold utilization components: radiators and hot water heat exchangers located at the end-user – Please note that components for district heating networks are covered by the "Smart & Efficient Buildings & Cities" roadmap.

7.2 Assessment on "Impactability"

The following spider diagram provides an overview of the impact that InnoEnergy investments can achieve in this field.



7.3 Examples of Market Players

Heat Generation

large European utility companies

local and regional utility companies/public service companies

STEAG New Energies GmbH (Germany)

Viessmann Werke GmbH & Co. KG (Germany)

Kraftanlagen Gruppe (Germany)

Heat Distribution, Contractor for Heating Grids

Danfoss A/S (Denmark)

TMT Tapping Measuring Technology GmbH (Germany)

PlanEnergi (Denmark)
Kraftanlagen Gruppe (Germany)

Sensors, Smart Meters, Leakage Detection
Kamstrup A/S (Denmark)
Berggruen Technology Co. Ltd (China)
Zenner International GmbH & Co. KG (Germany)
ista International GmbH (Germany)
Techem GmbH (Germany)

Heat Utilization
Danfoss A/S (Denmark),
Vaillant Germany GmbH & Co. KG (Germany)

Short-Term Heat Storage
TMT Tapping Measuring Technology GmbH (Germany)
Mixergy Ltd (UK)
Jenni Energietechnik AG (Switzerland)
Sunamp Ltd. (Scotland)

PCM
BASF SE
PCM Products Ltd (UK)
PureTemp LLC (USA)

8. Air Quality and Sustainability of Conventional Energy Sources

Many of the toxic air pollutants to which we are exposed are combustion-related. In Europe, emissions of many air pollutants from industrial processes have decreased substantially over the past decades, resulting in improved air quality across the region. However, air pollutant concentrations are still too high, and air quality problems persist. Typical toxic air pollutants are particulate matter (PM), sulfur dioxide, lead, nitrogen oxides, carbon monoxide, ozone, benzene, and polycyclic aromatic hydrocarbons (PAH).

In parallel to the decrease of these air pollutants, greenhouse gas emissions, primarily CO_2, have decreased over past decades as well.

This section of the roadmap covers technologies to reduce and valorize air pollutants from combustion and finally chemical processes to utilize CO_2. Another, very effective method to reduce emissions of CO_2 from fossil fuel powered plants is to substitute the fossil feedstock with renewable feedstock. This way of operation is called co-firing. It is discussed in detail in chapter 5.3 of this document.

8.1 Reduction and Valorization of Emissions from Combustion Processes

In past decades, a number of technologies have been developed und commercially utilized to reduce air pollutants emissions from industrial sources, such as combustion processes. These air pollutants compounds include NO_x, CO, sulfur oxides, hydrocarbons, soot, acids and metals (e.g. mercury), particulate matter (PM) and volatile organic compounds (VOC).

8.1.1 Details of Technology

Control of these emissions from industrial combustion sources generally relies on improving combustion conditions and post-combustion measures, including scrubbers, filters, electrostatic precipitators, flaring (which can produce other pollutants), and catalytic destruction. Most of these technologies are already commonly deployed in industry. However, there are also emerging technologies under development that show considerable value propositions at the industrial scale.

Besides removing air toxic pollutants from flue gases there have been efforts to capture and valorize these substances.

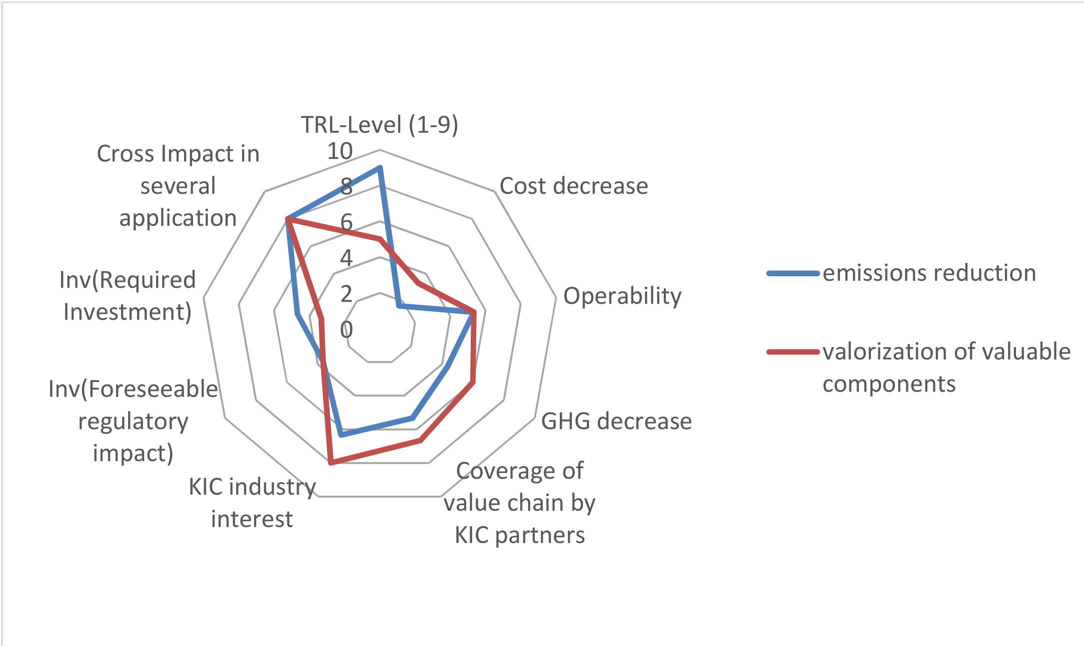
Other opportunities for new developments in this area are seen to be:

- the design of complex additives that allow the reduction emissions, corrosion and slagging/fouling
- the increase of the reliability of flue gas desulfurization (FGD) equipment and selective catalytic reduction (SCR) systems by precise control of operating conditions of such systems, e.g. reaction conditions during startup and low-load operation
- emissions from household heating systems, such as coal, oil or wood burning stoves and from fireplaces and cooking stoves (please refer to the “Smart & Efficient Buildings & Cities” roadmap for this topic)
- Systems to remove airborne particulates directly out of the air: First systems have been developed to be installed in cities and remove PM for 30,000 cubic meters of air per hour, and even collect the particles into smog “gems” that can be sold. First concepts work like enormous air ionizers. And the scale of these concepts is increasing: China has built 100-metre high air purification tower in Xian in Shaanxi province. In this case, polluted air is sucked into the glasshouses at the base of the tower and heated up by solar energy. The hot air then rises through the tower and passes through multiple layers of cleaning filters. The cost of the project was not disclosed.
- Other concepts use moss for cleaning the air in cities: in the so-called CityTree developed

by Green City Solutions GmbH, Berlin, moss binds particulate matter, produces oxygen and cools the air. Green City Solutions claims that a wall, which is 4 meters tall and 3 meters wide, has the same benefit for cleaning up the air as 275 trees.

8.1.2 Assessment on "Impactability"

The following spider diagram provides an overview of the impact that InnoEnergy investments can achieve in this field.



8.1.3 Examples of Market Players

Hitachi Zosen Inova AG (Switzerland)
Lhoist S.A. (Belgium)
Cabot Corp. (USA)
Steinmüller Engineering GmbH (Germany)
Vinci Environment (France)
Green City Solutions GmbH (Germany)
Novis GmbH (Germany)
Babcock & Wilcox Vølund AB (Sweden)
Donau Carbon GmbH / Standard Purification (Germany / USA)
Carbotech AC GmbH (Germany)

8.2 Carbon Dioxide Utilization

This section addresses the usage of carbon dioxide (CO_2) as a building block for chemicals (e.g. energy carriers, polymers). CO_2 capture, transport, storage, and sequestration are not covered.

8.2.1 Details of Technology

Carbon dioxide has been used a chemical feedstock and industrial gas for many decades in industry. The table below shows gives the mass of CO_2 used every year as a chemical feedstock.

chemical feedstock	urea	107 mio. t/a
	methanol	2
	cyclical carbonates	0.04

	salicylic acid (-> Aspirin)	0.025
industrial gas	carbonic acid, inert gas, refrigerant, fire extinguisher, cleaning agent etc.	20

For comparison: The global CO_2 emissions are in the order of 35 billion t/a (2016).

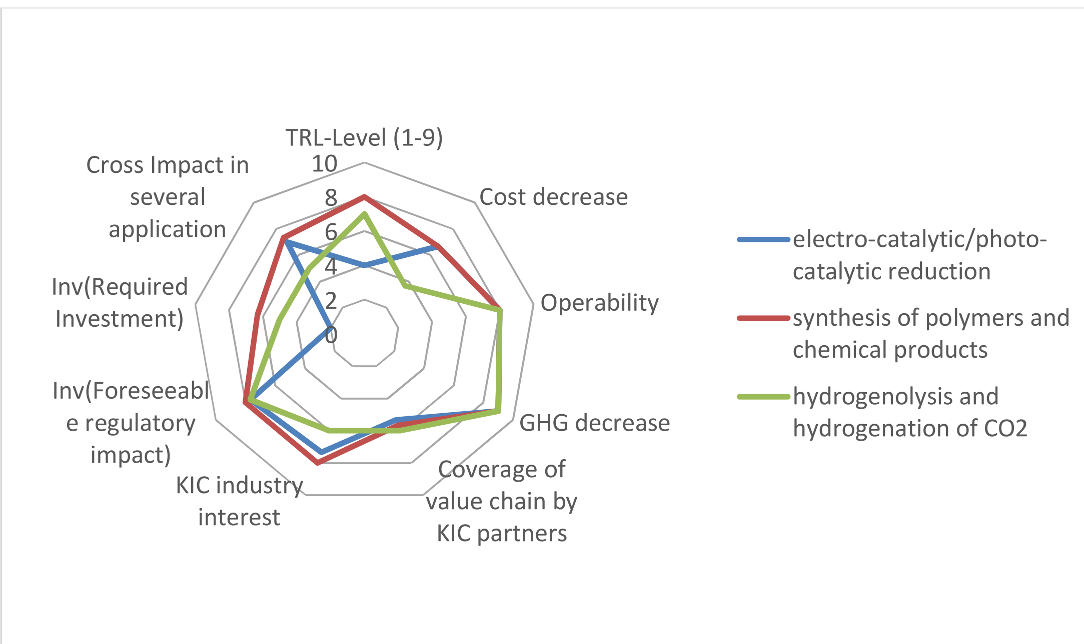
CO_2 is a thermodynamically very stable molecule. On top of it, it is kinetically very slow, which makes it challenging to react. Therefore, energy input and catalysts are required for reacting it to high value chemicals or energy carriers. In principle, there are four pathways:

- electro-catalytic reduction with supply of electrical energy
- photo-catalytic reduction, where the energy is supplied by the photons (photo synthesis is a special type of this pathway)
- synthesis of polymers and other intermediate and final chemical products. Here energy is supplied by the other reactants participating in the reaction or via external heat.
- hydrogenolysis and hydrogenation of CO_2 yielding products such as methane, methanol, ethanol, formic acid, formaldehyde, DME (dimethyl ether) etc. (with supply of chemical energy through the hydrogen molecules). In this context, the reverse water-gas shift reaction and the dry reforming of methane (CO_2 reforming) are investigated.

The first two pathways to use CO_2 are still in the stage of fundamental research. These are topics InnoEnergy will observe closely to discover promising technologies. The production of polymers and other chemical products from CO_2 is a niche application, because the quantities of the products are still very small. Moreover, these processes are already well established in industry. The processes of the forth pathway, also subsumed under Power-to-X, are very interesting, not least for InnoEnergy, because they comprise technologies for the production of energy carriers. This field is promising, however most developments fail because their economics are not competitive with fossil energy carriers at this point in time.

8.2.2 Assessment on “Impactability”

The following spider diagram provides an overview of the impact that InnoEnergy investments can achieve in this field.



8.2.3 Examples of Market Players

Gas Suppliers
Linde AG (Germany)
Air Liquide S.A. (France)
ACP (Belgium)

“Users” of CO_2
Haldor Topsøe A/S (Denmark)
Südzucker AG (Germany)
AkzoNobel N.V. (The Netherlands)
Engie SA (Frankreich)
Norner AS (Norway)
Solvay SA (Belgium)
Climeworks AG (Switzerland)
Nordic Blue Crude AS (Norway)
Royal Dutch Shell plc (The Netherlands)
Total SA (France)
Phytonix Corp. (USA)
Audi AG (Germany)
Covestro AG (Germany)
BASF SE (Germany)
DowDuPont Corp. (USA)

9. Fossil Sources Decommissioning Technologies

This section deals with the decommissioning of plants for exploitation of fossil feedstock sources and for final energy conversion of fossil fuels. The feedstock sources comprise oil/gas wells (on-shore and off-shore), coal mines, and tar/oil sands.

Oil and Gas Exploitation

A report by IHS Markit predicts that spending on oil/gas rig decommissioning projects will increase from around $2.4bn/y in 2015 to $13bn/y by 2040 (see Figure below). Another example: Oil & Gas UK's Decommissioning Insights 2016 report notes that the decommissioning market in both the UK and the Norwegian continental shelves has expanded from 2% of total industry spend in 2010 to 5% in 2015 – and the market is likely to exceed 12% of spend in 2017.

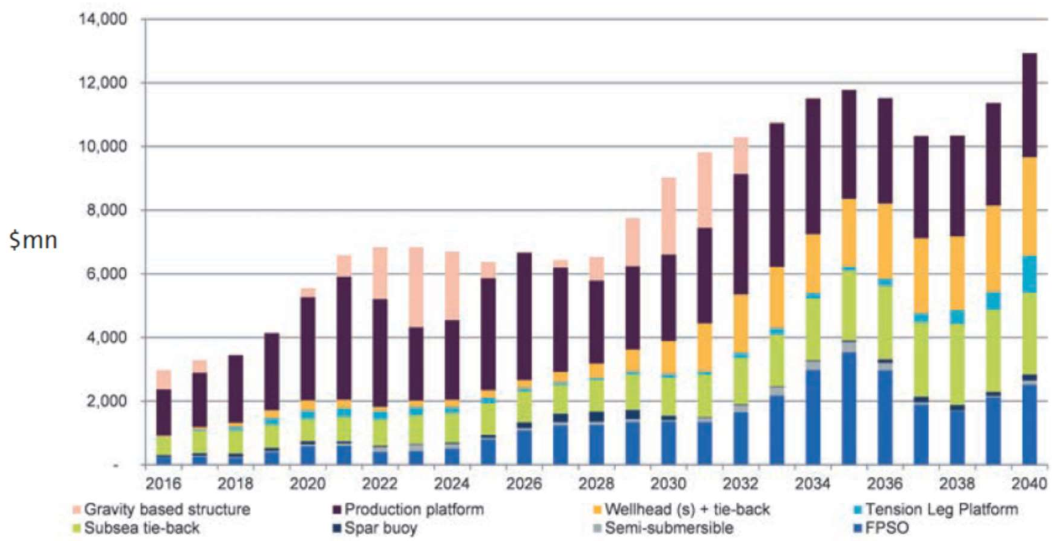


Figure 4: Decommissioning spending of off-shore oil rigs by project type, Source: IHS Markit.

Coal and Oil Sand Mines

As for onshore fossil feedstock sources, an increasing number of mines and hydrocarbon fields are nearing depletion, following decades of resource exploitation. These operations and the associated infrastructure will require complex and costly dismantling, including technical and environmental restoration, rehabilitation measures, and socioeconomic investments to counteract retrenchment and post-closure economic downturns.

For coal mines, typical activities during the decommissioning and site reclamation phase include removing infrastructure, such as structures, conveyors, rail lines, filling in the mined area, and recontouring the surface and revegetation.

Power Plants

Looking at the decommissioning of fossil power plants, the European Environment Agency has called on Europe's governments to increase the pace of decommissioning fossil fuel power plants across the continent in order to avoid a carbon lock-in. Across much of the EU, a great number of fossil fuel power plants are nearing their end of life or are prone to be shut down due to regulatory pressure. Winding down oil, coal and gas power plants accounts for a multibillion-dollar global business by the end of the decade. Experts believe the coming wave of power plant retirements creates a market opportunity for cleanup companies. Between now and 2020, the market for decommissioning of coal-fired power plants alone is estimated to be more than $5bn. Nearly all of that would be in Western Europe and North America, where coal has faced regulatory and market head winds.

9.1 Details of Technology

Oil and Gas Exploitation

The decommissioning of offshore oil and gas installations and pipelines is already executed by global players. However, innovation is still essential in order to drive down project costs and make the task of plugging wells and dealing with associated structures a less daunting one. Furthermore, there is a need for more efficiency and more specialised equipment. Platforms and subsea structures are removed and transported to shore for re-use or recycling. Subsea wells will be plugged and abandoned using drilling rigs. Pipelines are trenched and buried and will remain in situ.

In the North Sea typical costs for decommissioning of oil/gas rigs are among the highest in the world and likely to reach a total of $2bn/y and more due to the challenging environmental conditions.

One area with very high costs in decommissioning such plants is the plugging and abandonment (P&A) of the undersea wells. Looking at some of the big projects like Brent Delta, typically around half the decommissioning costs are associated with P&A of the wells.

There are also interesting ideas related to second life of oil rigs – for instance, some companies farm North Atlantic salmon and trout off the coast by converting jack-up rigs, i.e. replacing the derrick with a fish processing module. These rigs are more stable than floating platforms, hence better suited to aquaculture.

Coal and Oil Sand Mines

Land reclamation is the rehabilitation of land after coal or oil sand mining operations have stopped. Ideally, it is an ongoing process during the life of a project. For instance in Canada, oil sands operators must develop a plan to reclaim the land and have it approved by government as part of any project's approval process. Companies apply for government reclamation certification when vegetation is mature, the landscape is self-sustaining and the land can be returned for public use. The same holds true for coal mine reclamation in many countries.

Reclamation is done in various ways. Because they are relatively cost effective, lakes are created by ending the pumping of groundwater. The rehabilitation of forests and agricultural soils is comparatively expensive, but has to be done in many regions. In former years reforestation was carried out for economic reasons: the main goal was the production of wood. Over time, the aims have changed, leading to a more holistic ecological approach. Today's forest restoration has to create living spaces that offer future generations natural diversity.

Abandoned mines and caverns have been proposed for underground pumped hydroelectric storage using them as giant batteries for clean energy. However, these technologies are very expensive.

Another idea currently explored is to use flooded mineshafts as geothermal energy sources. The water in these abandoned and flooded mines is used to heat and cool buildings with the aid of heat pumps. The process draws water from up to 200 m below the ground surface, while the mines themselves go down thousands of meters. Unlike geothermal energy, which extracts heat as hot water or steam from deep in the earth's core, the geo-exchange process pumps water from much shallower depths with the water having much lower temperatures. The temperature of the brackish water in mine shafts sits at a constant 11 °C year-round (e.g. flooded mine shafts under Nanaimo university campus, British Columbia, Canada).

Another second life idea: The Chinese province of Anhui built a massive floating solar farm with 40 MW on top of an abandoned collapsed coal mine. An even larger floating solar plant will come online by May 2018: a 150 MW solar farm floating on the same lake.

Power Plants

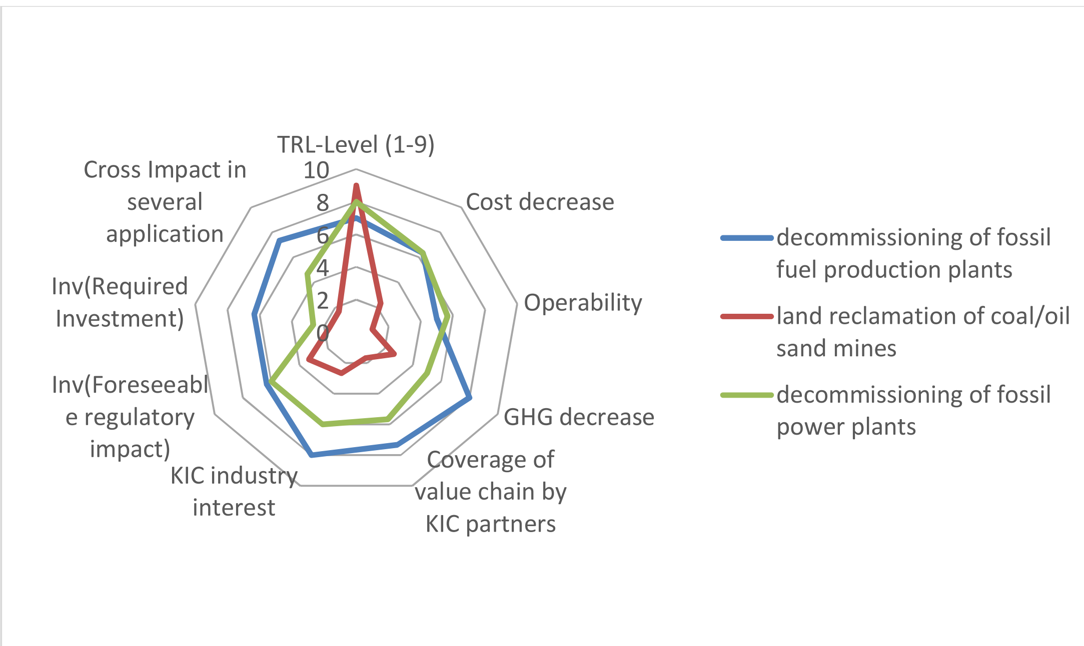
Decommissioning of power plants is a flourishing business. Many utilities now face the complex task of revamping outdated depreciation cost studies to obtain and prudently justify the critical funding required to decommission, abate, demolish, and remediate environmental liabilities associated with plant retirements and future redevelopment.

Environmental issues that must be considered include asbestos and lead abatement, remediation of potential PCB impacts from spills and in building materials, mercury containing device removal, and universal waste disposal (i.e., lighting ballast). Closure of existing wet ash ponds and ash landfills must also be evaluated as part of the overall site closure.

There are only few ideas about reusing abandoned power plant structures. In Indiana, USA, a real estate development firm evaluates a former coal-fired power plant sites to be used for future inland port development.

9.2 Assessment on "Impactability"

The following spider diagram provides an overview of the impact that InnoEnergy investments can achieve in this field.



9.3 Examples of Market Players

Decommissioning of Oil/Gas Rigs
Fairfield Energy (UK)
RCM Technologies, Inc. (USA)
Link Resources, Inc. (USA)
GA Drilling (Slovakia)

Re-usage of Structures at Their End of Life
Roxel (Norway)

China Three Gorges Corp. (China)
Dominion Energy, Inc. (USA)

Land Reclamation of Coal and Tar/Oil Sand Mines
Operators of the mines, such as RWE Power AG (Germany)
Polska Grupa Energetyczna PGE (Poland)

Decommissioning of Power Plants
AMEC Foster Wheeler (UK)
Duke Energy Corp. (USA)