PROJECT FINAL REPORT

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1 Final Publishable Summary Report

1.1 Executive Summary

The FASTCARD project's main focus has been on the development of new nano-catalysts for implementation to achieve the goals of improving the economics, resource usage and efficiencies of four key catalytic steps along two value chains for the conversion of biomass to advanced biofuels by:

- Gas based route involving catalytic reforming of syngas followed by catalytic Fischer Tropsch synthesis.
- Liquid based route involving catalytic hydrotreating of pyrolysis oil followed by co-processing in Fluid Catalytic conversion.

FASTCARD has also had the ambition of contributing to accelerating the transition of lab-scale research on these catalytic processes through to the eventual commercial implementation, through successfully adopting the novel approach of repeated cycles of "downscaling"/"upscaling" in order to:

- Establish an industrial baseline for lab-scale development and optimisation (upscaling)
- Validation of new generation catalysts and link to micro-kinetic modelling (downscaling/upscaling)
- Optimisation and selection for final demonstration with respect to the goals and validation of the developed micro-kinetic and process models (downscaling/upscaling)

The results from the project have been successful in:

- For the first time, establishing detailed kinetic models for all four catalytic processes of the two value chains
- Establishment of full techno-economics of the two value chains and input to the catalyst and process development with respect to achieving the most favorable economics.

In addition, an extremely effective and close cooperation has been established between all partners which, has resulted in spin-off activities in addition to extensive dissemination - through publications, conferences, arranged summer schools as well as coordination and co-arrangement of seminars and workshops to promote the important aspects of scaling up to commercial processes.

The results from FASTCARD now confirm that:

1) FCC co-feeding with hydrotreated bio-oil (the liquid line) can be economically viable for a short term implementation of biofuels production, under the condition that more favourable yields are obtained, and that full excise duty exemptions are granted.
2) Indirect gasification and FT synthesis promises a fuel which is 100% renewable with further improvements giving this the basis for long term transition towards fully renewable fuel.

Based on these promising results, the industrial partners (Repsol, Grace, BTG and JM) have established the basis for commercial implementation together or with external partners and have access to a toolbox of modelling from micro to process level dedicated to the supporting further rapid improvements of the processes.

1.2 Project Context and objectives

1.2.1 Overall summary

The **overall goal of FASTCARD is to enable short- and long-term implementation of advanced biofuel production based on rapid and risk reducing industrialisation of nano-catalytic processes through the two major catalysis based value chains**, combined with micro-kinetic and process design level modelling to guide and give insight to the mechanisms and economics of the processes.

This will be achieved through demonstration both at laboratory and relevant pilot level (WP7) to achieve significant reduction (up to 50%) in the time for development to industrial scale. For the two selected value-chains, key objectives focus on energy and resource efficiency:

Gas based value chain

- **Hydrocarbon Reforming** (**WP1**) of producer gas from biomass fluidized bed gasification aims to reduce biofuels production costs by 20%. This being based on two routes: (1) a higher risk single step reforming catalyst or (2) or a low-risk two-step steam reforming approach.

- Next generation supported iron **Fischer-Tropsch** (FT) catalysts (**WP2**) will aim at small delocalised 500-3000 bpd BTL plants addressing performance robustness with respect to higher temperature, high CO_2 feeds and improved durability. This will target improvement in C5+ productivity of at least 10%, energy savings of 3%, and CAPEX reduction of at least 15%.

Liquid based value chain

- **Hydrotreating** (**WP3**) will develop new generation catalysts on two levels of hydrotreating, i.e. for bio-oil stabilization and for further upgrading in a more severe hydrodeoxygenation (HDO), to produce co-feed to existing FCC units minimizing the overall level of treatment. Challenges are the robustness of catalyst performance, lowering the hydrogen consumption, reducing process severity (lower pressure and temperature, and higher space velocity), to improve durability, and increase selectivity in relation to oxygen removal.

- **Co-FCC** (**WP4**) will develop a catalyst able to co-process bio-feeds and crude oil distillates in a FCCU, showing similar or better performances than a State-of-art FCC catalyst, designed for co-processing 2nd generation bio feed blended in conventional feed. It is targeted to maximize the oxygen content of the co-FCC feed blend, either by increasing the blending level or decreasing pre-treatment severity for the bio component. The new catalyst should match specification of hydrothermal stability and price competitive production route, as well as a reduced usage of strategic resources like rare earths and precious metals by at least 20%.

Micro kinetic and process design modelling

- **Microkinetic modeling** tools (**WP5**) are being developed to establish fundamental Quantitative Structure Activity Relationships (QSARs). These relationships will support the rational design of nanoscale catalysts within WP1 to WP4 and will be validated by the actual synthesis and performance testing of new generations of catalysts and the Down-scale/Upscale pilot testing.

For metal catalysis, relevant for WP1, 2 and 3, the quantitative models (QSARs) will be supported by the synthesis of series of supported metal nanoparticles with very well controlled size and surface composition.

- **Process design and evaluation** (**WP6**) will translate and link the catalyst & pilot research results to individual process designs/modifications and integrate these designs, including techno-economic evaluations & sensitivities into integrated designs with acceptable overall energy requirements. This WP is also expected to provide process consequences and feedback/guidance for the individual catalyst research issues in both the gasification and the pyrolysis value chains.

1.2.2 Exploitation and dissemination

In parallel with the developments and the innovations towards improved process and economics, **exploitation, communication and dissemination** of the results and developments from the project is a vital component of the proposed work program and of ensuring maximum impact from the project. The objectives are (i) to support protection of intellectual property resulting from the project by ensuring that the relevant partner can patent the technologies, design and applications, (ii) to disseminate a full range of scientific, technological material/process non-confidential knowledge generated within FASTCARD to the business, technology providers and the scientific community and (iii) to develop and facilitate efficient communication between beneficiaries.

1.3 Main Scientific and Technical results

1.3.1 Hydrocarbon Reforming (WP1)

WP1 has focused on the development of steam reforming catalysts more resistant to deactivation by carbon and sulphur for the production of syngas from biomass fluidized bed gasification. The objective of WP1 is to reduce biofuels production costs with respect to the reference case (high-temperature entrained-flow gasification to syngas). FASTCARD WP1 considers 2 routes: either in a single step (steam reforming catalyst, high-risk) or in a two-step process (low-risk), which consists of the use of novel, robust, inexpensive mineral-based pre-catalysts for capture/conversion of tars prior to the catalyst.

Within WP1, alternative pathways for the production of syngas have been proven, namely the combination of steam reforming coupled with fluidized-bed gasification for the conversion of hydrocarbons contained in product gas. Moreover, the 2-step reforming process has been proven as a feasible and attractive option for improved operation of the reforming catalysts. The advances achieved in the design of nano-catalysts will establish a fundamental platform that can be applied to other energy applications. This work will therefore contribute to the speed up of the industrialization of safer, greener and stable catalysts beyond the scope of the project.

The WP1 work was started with a number of reference tests to evaluate the performance of state-of-the-art Ni- and Rh- catalysts (Milestone MS1.1). This was the beginning for the development in parallel of a number of 2nd-generation steam reforming catalysts:

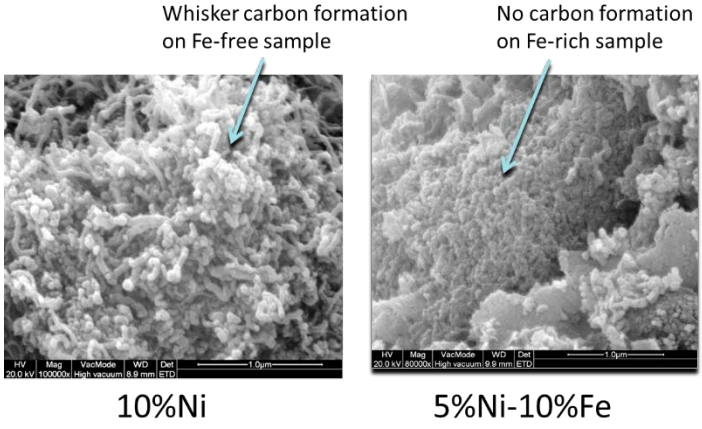

Figure 1.3-1. Bimetallic Ni-Fe formulation developed by UGent

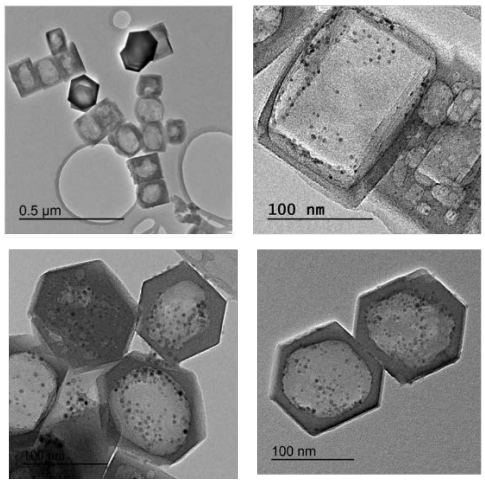

Figure 1.3-2. Ni "ship-in-a-bottle" reforming catalysts developed by CNRS/IRCELYON.

- Gent University developed bimetallic (Ni-Fe) and trimetallic (Ni-Fe-Pd/Pt) formulations, and found out that the addition of Fe improved the coking resistance of Ni (Figure 1.3-1). The addition of small amounts of Pd or Pt further reduced coking and increased the activity.

- CNRS/IRCELYON developed their "ship-in-a-bottle" concept (Figure 1.3-2), in which Ni or Rh nanoparticles are encapsulated in silicalite cavities. This concept has smart features, such as size selectivity, and improved resistance to sintering. During the project, Ni-encapsulated catalysts were successfully tested, and the use of multi-hollow silicalite structures improved the resistance to sintering with respect to single-hollow structures.

- ECN focused on the development of bimetallic (Ni-Rh, Ni-B) and trimetallic (Ni-Rh-B) catalysts on crystalline MgAl supports. In-situ XRD revealed that this type of spinel support prevented the loss of active Rh in the catalyst. Moreover, the use of Ni-Rh-B catalysts showed improved resistance to S deactivation.

- JM continued with the development, testing and characterization of 2nd-generation Ni- and Rh catalysts. Moreover, ageing protocols were developed and improved.

Saint-Gobain applied their proprietary ice-templating process (that uses ice crystals as pore formation agents to create a unique, uniform radial pore structure) for the development of pre-catalysts. Ice-templated beads used different inlet materials (alumina, olivine, YSZ, CGO and CTF) were synthetized (Figure 1.3-3). Some of these materials showed certain capability for tar reforming. The impregnation of ice-templated beads with Ni was found to increase the activity for methane reforming.

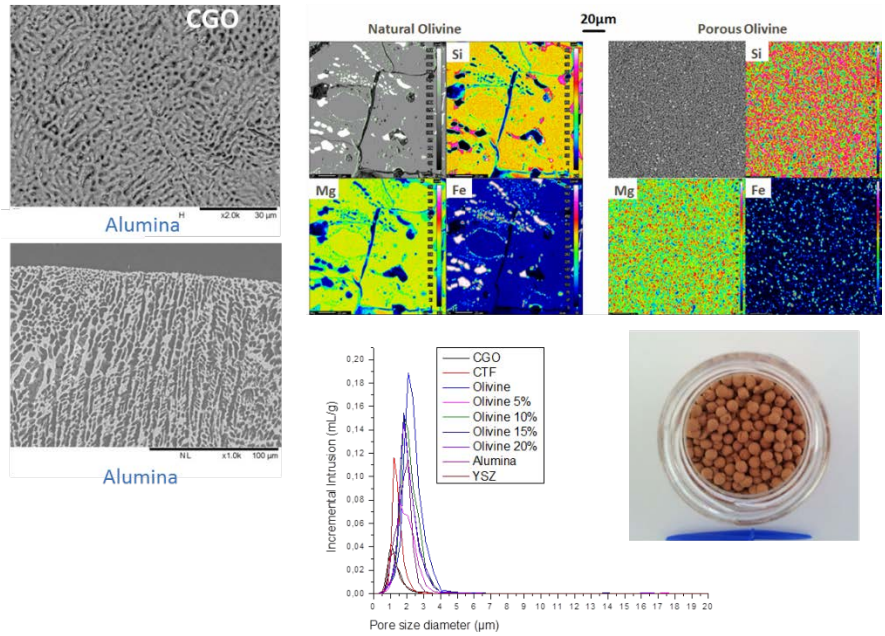

Figure 1.3-3. Ice-templated materials developed by Saint-Gobain as pre-catalysts.

This work was complemented by the development of a kinetic model for the prediction of the effect of contaminants (S and tars) on the activity of the SR catalysts (interaction WP1-WP5), for which the experimental data obtained during the development of catalysts were used as input for the model. Additionally, Temporal Analysis of Products (TAP) tests were performed for the determination of the oxygen storage capacity of supports and the elucidation of catalyst regeneration mechanisms (Figure 1.3-4).

The intermediate 2 x 100-h duration tests performed in 2016 were the starting point (milestone MS1.2) of the upscaling work (Task 1.5). The selected catalysts included 2 Rh-containing monolith catalysts – a JM benchmark catalyst (JM004) and a Rh based $MgAl_2O_4$ spinel material, initially developed by ECN based on a FASTCARD developmental catalyst powder recipe (Figure 1.3-4). Ni-impregnated CTF material, developed by Saint-Gobain (SG), was upscaled as the pre-catalyst. The catalysts were developed using industrially relevant equipment and procedures.

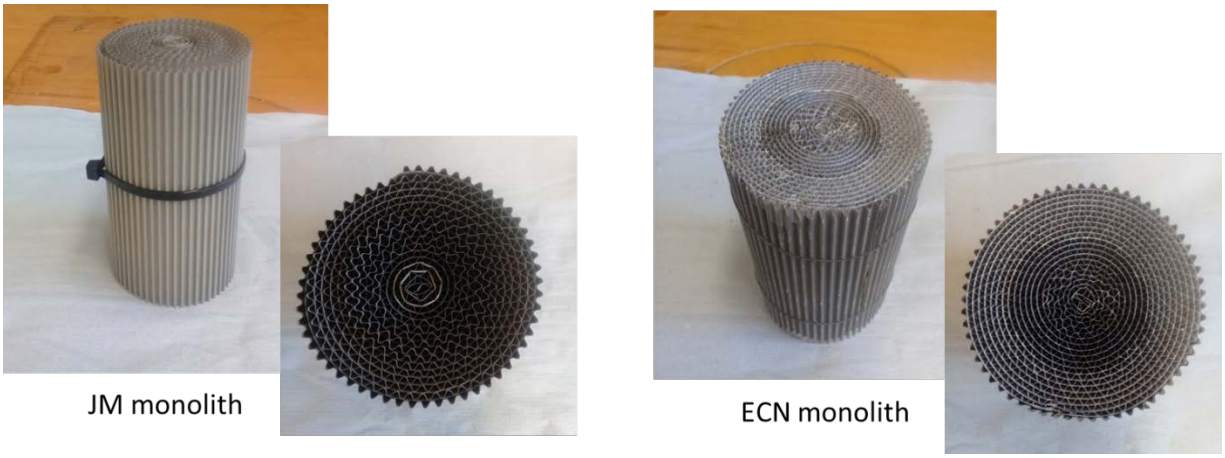

Figure 1.3-4. Upscaled monolith steam reforming catalysts tested in WP7 duration test.

The upscaled catalysts were tested under relevant conditions in a final duration test (WP1-WP7 interaction) for the demonstration of the gasification value chain. The monolith catalysts were tested

in parallel in dual bed configuration (pre-catalyst + catalyst located in the same reactor) for 100 hours using raw product gas from indirect gasification at 850°C using beech wood as biomass fuel. The JM benchmark catalyst was further operated for 50 hours in single bed configuration (without pre-catalyst). The results revealed that the pre-catalyst + JM benchmark catalyst system was able to reduce the inlet methane content of the gas from 11 vol.% to below 1 vol.% (i.e. > 90% CH_4 conversion), with 100% benzene and toluene conversion, whereas the pre-catalyst + FASTCARD catalyst system decreased the CH_4 content down to ~ 2.5 vol.% (that is, ca. 60-65% methane conversion), with ~ 95% benzene conversion and complete toluene conversion (Figure 1.3-5). It was estimated that the pre-catalyst is able to convert approximately 20-30% of the inlet methane and 65-90% of the inlet benzene, depending on the bed temperature. No apparent signs of deactivation were observed during the 100-h test.

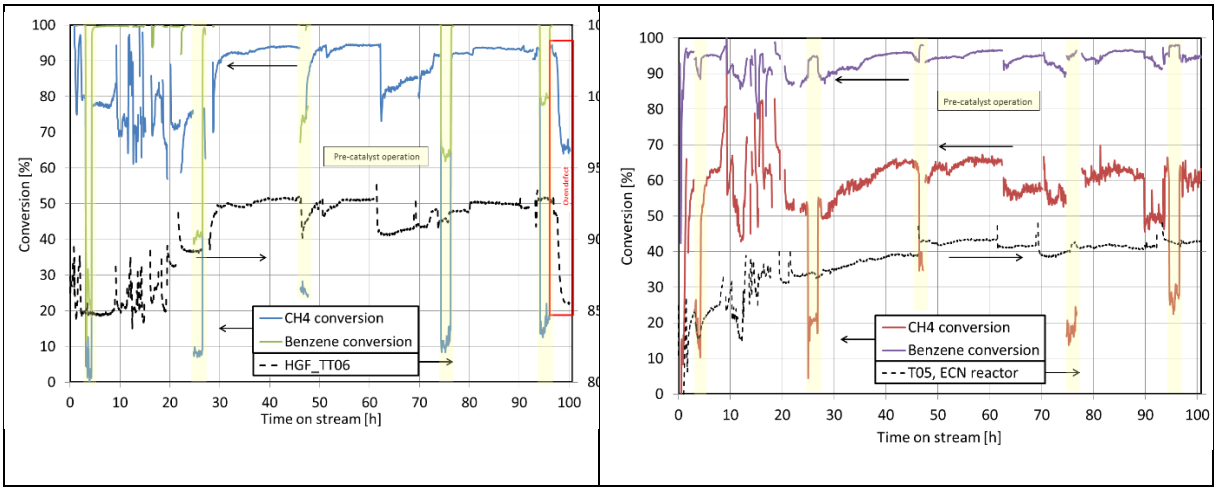

Figure 1.3-5. Methane and benzene conversion and monolith temperature in reactor with pre-catalyst + JM catalyst (left), and the pre-catalyst + ECN catalyst (right) during final duration test. The yellow-shaded areas correspond to the periods where the gas analysis was located after the pre-catalyst. The rest corresponds to gas analysis after the catalyst (thus measuring the overall effect of pre-catalyst + catalyst).

1.3.2 CO_2 Fischer-Tropsch Synthesis (WP2)

Synthesis of hydrocarbon fuels by the Fischer Tropsch reaction has been practised in various forms for almost 100 years. Of the three active and selective catalysts (Fe, Ru and Co), the state of the art is currently in cobalt catalysts, with a small number of large-scale plants built in the last decade. Cobalt offers high activity and good selectivity at a reasonable cost. However, in the area of biomass processing, iron-based catalysts have often been preferred for a number of reasons: (1) cost; (2) activity for the water-gas shift reaction, which allows a hydrogen-deficient syngas ($H_2/CO < 2$) to be rebalanced by conversion of some CO to CO_2; (3) poison tolerance, for example to sulphur containing compounds in the gas phase; (4) operation at high temperature (e.g. T > 250°C) which is not possible with cobalt catalysts.

Using iron catalysts presents two main challenges – their low activity and the high selectivity to CO_2, which becomes more pronounced as temperature increases. To address this need, new catalysts need to be develop which are more active and selective and therefore produce a higher yield of the desired C_{5+} hydrocarbons.

A commercial catalyst supplied by JM was used as the “state of the art” benchmark material. This catalyst was developed in the 1960s and is highly optimised for use in FT. Part of the project was

devoted to understanding the response of this catalyst to different conditions – flow rates, temperatures and syngas compositions, including CO_2 in the syngas as might be expected from a gasifier. We also investigated a range of novel formulations, of which the two most successful were Fe/silicalite cages developed by CNRS Lyon, and Fe_5C_2 nanoparticles prepared by a literature method and supported on silica at JM.

Information from Ab-Initio Modelling

Ab Initio DFT calculations were used to better understand the interaction between the FT reaction intermediates and the iron carbide surface. A number of carbides were studied: Fe_3C, Fe_2C, Fe_5C_2 (the so-called Hägg carbide) and Fe_7C_3. The binding modes of alkanes, alkenes and alkyl chains varied a remarkable about between the different surfaces, with examples of bridging sites, atop sites and hollow sites. One notable conclusion is that the binding mode and strength are not greatly affected by chain length, and can in fact be considered independent of chain length above n=3 for alkanes and alkyl chains and n=5 for alkenes.

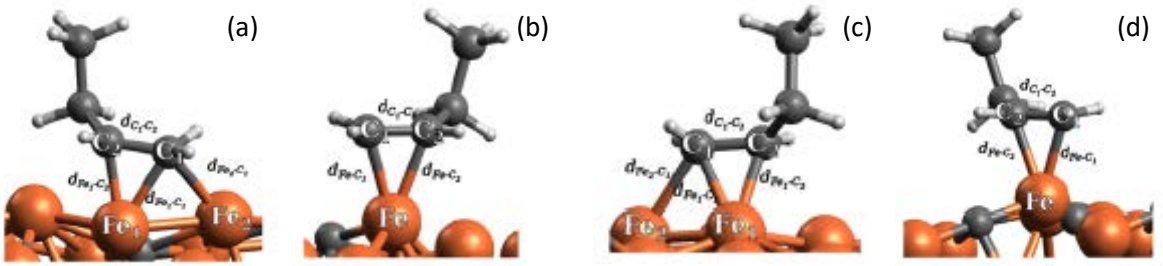

Figure 1.3-6. Binding mode of 1-butene on (a) Fe_5C_2, (b) Fe_7C_3, (c) Fe_3C and (d) Fe_2C.

Properties of the State of the Art Catalyst

The state of the art catalyst was characterised using a wide range of techniques, including XRD, Mössbauer spectroscopy and synchrotron based *in-situ* XAS and XRD. The latter two techniques were aimed at determining the amount of carbide present in the working catalyst. The carbides, or at least some part of them, were found to be air sensitive, so accurate determination of the quantity and speciation by *ex-situ* techniques was complicated.

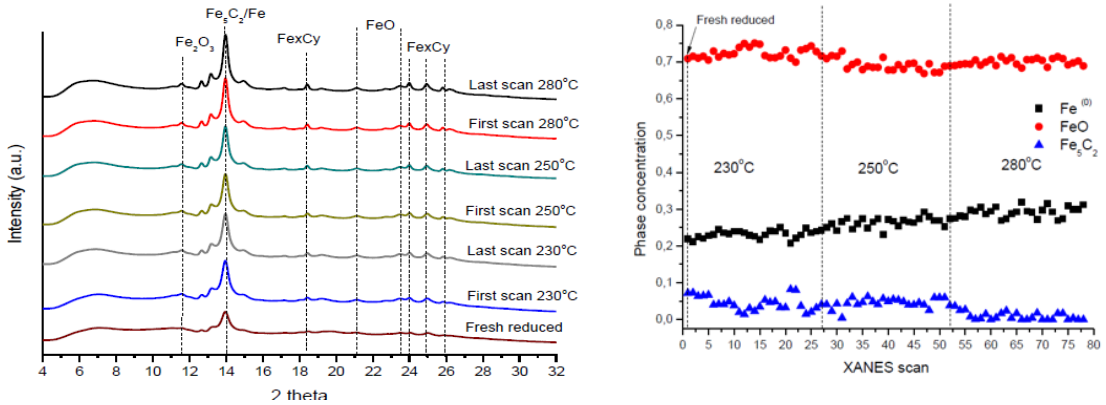

Figure 1.3-7. In-situ XRD (left) and XANES (right) analysis of the state of the art catalyst under reaction conditions.

The *in-situ* analyses showed that iron carbides were present, but in relatively small quantities, and higher levels of Fe metal and FeO were observed. This was a surprise, given that iron carbide is the accepted active phase in Fe-based FT catalysts, although the larger amount of oxide is responsible for the higher activity for the water-gas shift reaction.

The state of the art catalyst was tested under a wide range of reaction conditions: temperatures from 210-280°C, syngas composition of H_2/CO = 1-4, and with CO_2 added to the standard gas mixture. The catalyst was active under all the conditions studied. It was most selective but least active at the lower temperatures; as temperature increased, the activity increased but so did the CO_2 selectivity and, to a lesser extent, the CH_4 selectivity. Adding CO_2 to the feed, especially in combination with high levels of hydrogen, had the effect of suppressing the water-gas shift reaction and so lowering the CO_2 yield. In summary, the catalyst performed well in a range of conditions relevant to biomass conversion.

Novel Catalysts

Effort was focussed on two main types of novel catalyst:

Fe/silicalite

Fe/silicalite catalysts were prepared by impregnation of silicalite with iron salts, followed by calcination to give an iron oxide-containing intermediate. This was recrystallised hydrothermally using tetrapropylammonium hydroxide solution at elevated temperature to give hollow cages containing iron oxide nanoparticles. These were reduced with hydrogen to give the active catalyst.

Fe_5C_2/SiO_2

Iron carbide nanoparticles were prepared by high temperature solution processing of iron carbonyl in high boiling solvents. The precursor is decomposed to iron metal, and then reacts with the solvents to make Fe_5C_2, which was observed by Mössbauer spectroscopy.

Catalyst Performance

The catalysts were compared with the state of the art material in a long test of almost 1000h. Figure 1.3-8 summarises the catalyst performance at 250°C after 800h on stream. The state of the art catalyst is the most active, but makes the most CO_2. The other two catalysts make less CO_2, but higher levels of C_{2-4}. The Fe/silicalite catalyst is the least active of those studied, but makes the least CO_2. This is believed to be a consequence of the hydrophobicity of the support, which keeps water separated from the active site and so limits the water gas shift activity. Interestingly, the Fe_5C_2 catalyst also limits the water gas shift activity, but by decreasing the number of oxidic iron sites present.

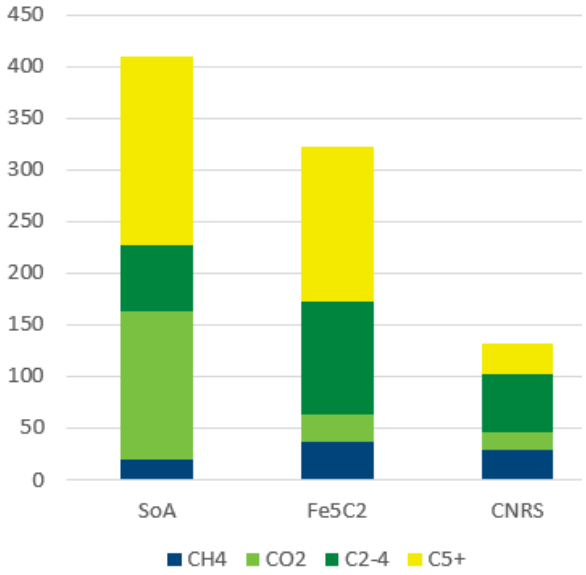

Figure 1.3-8. Fig. 3. Catalyst performance expressed as yields of each component of interest (l kgcat-1 h-1).

Scaleable Synthesis

The first steps were taken towards a scaleable synthesis of the Fe/silicalite material. The main result is that silica powder can be used in place of silicalite, which is significant because silica is cheaper, more readily available and has a larger pore volume so can accommodate more iron, leading to higher activity. However, other factors such as reduction still need to be optimised.

Process Modelling

A process model was created from literature expressions for the FT and WGS reactions. The model showed that iron catalysts were lacking in activity; an increase in activity of approximately 10x compared with the state of the art material was needed. Another output from the process model was a method for uneven distribution of the catalyst down the length of the reactor. This had the effect of reducing the exotherm at the start of the reactor and hence improving performance.

Summary

In summary, a number of achievements have been made during the project:

- Deeper understanding of the properties and mode of action of the state of the art catalyst, along with increased confidence in its performance under a range of biomass-relevant conditions.
- Development of two nano-catalyst materials with different properties, and demonstration of their catalytic properties over 1000h.
- Progress towards a scaleable synthesis for the Fe/silicalite catalyst.
- Process understanding of how the catalysts should be applied, and targets for further development.

1.3.3 Hydrotreating (WP3)

Hydrotreatment of feeds from pyrolysis is investigated in FastCard to yield a liquid quality allowing co-processing in existing refineries. Non-noble metal containing nano-scale catalysts are developed on two levels of hydrotreating, i.e. for bio-oil stabilization and for a further hydrodeoxygenation (HDO). Challenges were the robustness of catalyst performance, while lowering the hydrogen consumption to yield the final liquids, reducing process severity. The main results are summarized below for stabilizing the oil and further deoxygenation, respectively.

Stabilization:

Catalysts with improved durability and increased selectivity in relation to oxygen removal from biomass pyrolysis liquids are developed, and process conditions optimized for lowering the hydrogen consumption. New catalysts showed stand times up to 1000 h, increasing the liquid volumes processed by a standard amount of catalyst, from 50 L pyrolysis liquid initially per kg catalysts up to 500 L/kg_{cat}.

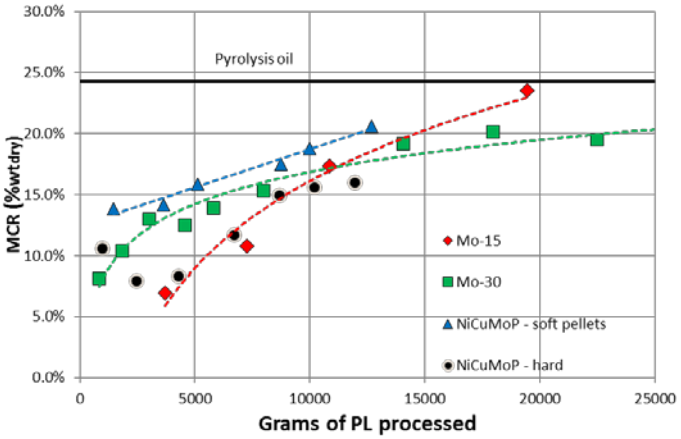

Figure 1.3-9. Quality of stabilised oil versus the amount of pyrolysis liquids processed (200 bar, 225oC).

Improved 1st G (with Mo) and 2nd generation catalysts (with Mo and P as promotor) are synthesized and tested. These show less initial activity in the process but are more robust (see the coking tendency or MCR of the product oil versus the 'catalyst age in Figure 1.3-9). The different catalysts show different behaviour, with the 1st G catalyst (referred to as Mo-15 and Mo-30) initially better but deactivating more rapidly, and 2nd G (NiCuMoP) initially less active but also less prone to deactivation.

Techniques are developed for the larger scale preparation of these 2nd G catalysts, in volumes of up to 80 kgs of the catalyst per months. Products (ranging from fully deoxygenated down to mild stabilized liquids have been prepared deploying such catalysts to provide liquids for pilot testing at Repsol. Numerous ToS experiments (> 500 h each) using SotA, 1st G and 2nd G catalysts have been carried out, and significant operational improvements established. All intermediates produced are successfully used in the further co-processing in a pilot plant FCC. Knowledge is generated to understand what actually occurs in the treatment process. The progress of deoxygenation versus the hydrogen consumption shows four regions where different reaction prevail, see Figure 1.3-10. At increased severity (here reaction temperature) the atomic H/C increase, while the O/C ratio slowly decreases. At temperatures from 150 to 230°C the atomic H/C and O/C ratios decrease, very likely due to dehydration reactions of thermal nature. At temperatures higher than 230 °C hydrogenation reactions are more pronounced giving higher H/C ratios in the resulting products.

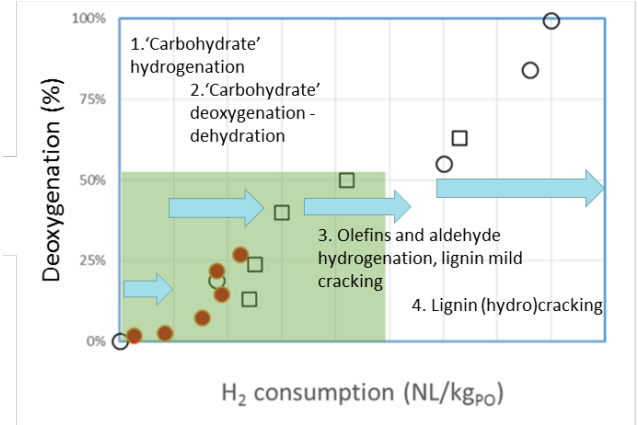

Figure 1.3-10. Degree of deoxygenation versus the hydrogen consumption

The deactivation of catalysts was studied using model 1 M acetic acid water solution (pH = 2-3). The activity of acid-treated catalysts was studied in a gas phase propionic acid hydrodeoxygenation. The activity tests were carried out in a tubular reactor at 225 °C with n-hexane and n-octane as diluent and internal standard, respectively. The preliminary reduced catalysts treated by acid at different times were characterized by a number of techniques (XRD, HRTEM, XRF, CO chemisorption) to gain insight into the chemical transformations taking place. XRF and HRTEM studies together with the residual mass of catalyst pointed out at gradual leaching of catalyst components. According XRF, mainly nickel was dissolved in acidic medium, the molybdenum content decreased to a lesser extent due to the formation of molybdenum blues. The amount of copper almost did not change based on its electrochemical potential. XRD study has shown oxidation of metallic components Cu and Ni of initially reduced catalyst into Cu_2O, NiO and $Ni(OH)_2$-like phases. Interestingly, the acidic treatment resulted in increasing active surface of the catalyst. Nevertheless,

the catalyst activity in propionic acid conversion decreased with time of preliminary acidic treatment due to decreasing active component content. The activity of the catalysts treated in acidic medium for different periods of time showed that the conversion of model compound decreases with the increasing pretreatment time, see Figure 1.3-11.

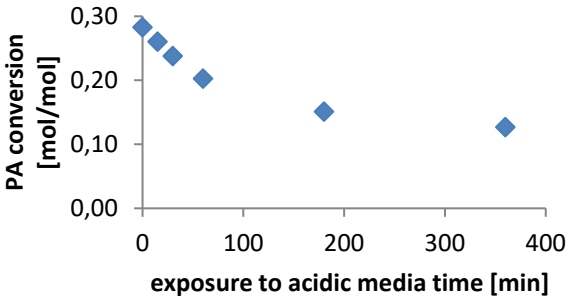

Figure 1.3-11. The effect of the exposure of the catalyst to acidic media on the propionic acid conversion in HDO reaction (T = 220oC, W/FPA = 31 kgcat s molPA-1 , H2/PA = 38 mol mol-1)

To understand the hydrogenation reactions in more details, Picula catalysts were tested with a series of model compounds. Anisol and guaiacol were used as model compound for lignins. Propionic acid was used as a model compound for the acids, and butanal was used a model molecule for the carboxy-groups. Reaction networks are proposed for all model compound reactions.

Deoxygenation

The initial strategy was to address deep hydrodeoxygenation (HDO), to yield low oxygen containing component while consuming less hydrogen. A matrix of catalytic materials was designed and synthesized for the purpose, including MoO_3/ZrO_2, MoO_xC_y/ZrO_2, Mo_2C/ZrO_2 and two state-of-the-art like CoMo-oxide supported on Al_2O_3 and ZrO_2 as reference materials. Nano-level characterization (TEM, XPS) of SoA was performed. Base line performance of SoA (activity, deactivation) has been established, for PO as well as for deoxygenation model systems phenol, anisole and guaiacol in the temperature range 300 – 375°C. The phenolic components selected are among the most stable and resistant to HDO. Pellets were produced at SINTEF and tested with real PO at BTG, but this deoxygenation catalyst had unbalanced functionality and lacked the sufficient stability. A 2ndG HDO catalysts was tested at milder conditions (100 – 350 °C) to control deoxygenation levels, as higher oxygen levels appear not detrimental in co-FCC processing. Catalyst composition and properties were designed to carry out HDO of phenolic components at different temperature levels by adjusting the relative strength of the hydrogenation and hydrogenolysis functions (by different levels of metal loadings, in the range up to 15%). In addition to recalcitrant phenolics, also conversion of C_6-C_7 aldehydes and corresponding alcohols, as well as mixtures thereof were addressed, for targeting reactant interactions.

The results show that phenolics can be easily converted at temperatures approaching 100 °C at a LHSV of ca. 1.2 h^{-1}, and both Ni and Co can be applied. However, presence of carboxylic acids cause side product formation and hydrogenation is strongly affected (Figure1.3-12), illustrating the conversion shift due to heptanoic acid). A temperature of 200 – 300 °C was required to achieve a high conversion of the heptanoic acid. Ni was found to be far superior to Co with regard to heptanoic acid removal ("100 °C difference").

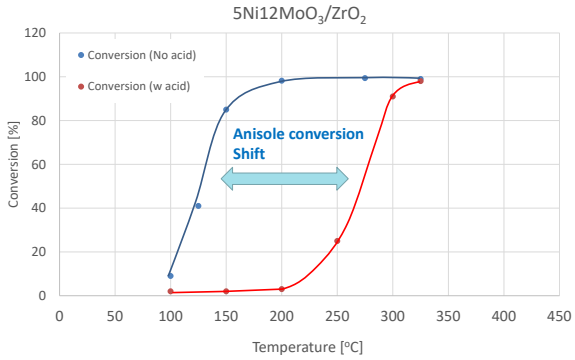

Figure 1.3-12. Anisole conversion with and without presence of heptanoic acid, both at 1.5wt.% concentration (right)

Acetic acid shows similar effects, as a strong correlation of acetic acid conversion and anisole conversion is observed, but considerable weaker than for heptanoic acid. This is interpreted as a steric phenomenon, and that longer chained carboxylics will prevent transport of reactant to the surface more strongly than small.

Catalyst deactivation was further studied for a CoMo/C catalyst, and Mo loading, its dispersion and the extent of carburization of the Mo oxide precursor are important in the catalyst performance. Other relevant causes for de-activation of molybdenum carbide catalytic system can be carbon deposition on the active sites of the catalysts or slow oxidation of the molybdenum carbide phase to oxy carbide and/or oxide phase from an oxygenate reactant or product.

Anisole hydrodeoxygenation was studied over a non-sulphided CoMo/γ Al_2O_3 catalyst. This catalyst mainly exhibited demethylation and isomerization to cresol, rather than hydrogenation or hydrodeoxygenation. Demethylation and isomerization reactions are followed by hydrodeoxygenation. Rival mechanisms were proposed and corresponding LHHW elementary steps based kinetic models were derived. Each of the proposed models accounted for the interaction of the species with the catalyst surface as well as for the surface reactions. For each catalytic cycle a rate-determining step was identified. Statistical analysis combined with an assessment of physical meaning of the model parameters allowed to propose that anisole isomerization occurs as a monomolecular rather than bimolecular reaction. For both demethylation and hydrodeoxygenation reactions, CAr-O bond cleavage proved to be facilitated by preliminary hydrogen addition.

1.3.4 Co-FCC (WP4)

Co-FCC (WP4) will develop a catalyst able to co-process bio-feeds and crude oil distillates in a FCCU, showing similar or better performances than a State-of-art FCC catalyst. The new catalyst should match specification of hydrothermal stability and price competitive production route, as well as a reduced usage of strategic resources like rare earths and precious metals by at least 20%.

Bio-oils of different qualities were used to establish the state-of-the-art baseline defined at REPSOL's pilot plant, co-feeding fully HDO bio-oil with VGO. Bench scale and pilot plant deactivation and testing was aligned between all partners. Novel zeolites, including hierarchical and nanocrystalline materials, were synthesized and checked for hydrothermal stability. Different Bench scale tests of a) model feeds and b) real oil blends with different partially deoxygenated bio-oils were conducted. From these experiments, systematic links could be established between active component, the degree of hydrodeoxygenation of the bio-oil, and the co-FCC selectivities. This information was further used for the catalyst development. Based on the data obtained, a decision was made to strictly limit the catalysts developed within the so-called high risk option, i.e. using non-faujasite zeolites as active components. It was decided to develop low risk faujasite based catalyst formulations in parallel. A kinetic lump model has been developed and verified based on the bench scale cracking results.

Intermediate pilot scale co-FCC tests revealed the opportunity to switch from partially hydrodeoxygenated bio-oil to stabilized pyrolysis oil as bio component. This renders the overall liquid value chain – consisting of hydrodeoxygenation and co-FCC – economically more feasible and environmentally friendlier. Ultimate goal of the work packages 4 and 5 is to define the optimum value chain for the incorporation of biomass into the conventional refinery stream via pyrolysis, hydrodeoxygenation and co-FCC in terms of cost, as well as carbon and energy efficiency. This includes the development of a catalyst which enables the processing of either higher levels (<10%) of bio-feed, and/or to allow to process a less deeply hydrotreated bio-oil.

The development work included the screening of novel active components, i.e. zeolites and/or zeolite modifications, as well as the optimization of the catalyst matrix, in order to transfer the catalytic performance of the active component into a commercially manufacturable and usable co-FCC catalyst. D4.5 deals with the last part of this development process, the scale-up of optimized catalyst formulations from laboratory to pilot plant scale. Two catalysts have been scaled up in the pilot plant, been agreed upon with BTG and REPSOL in the M36 General Assembly. One catalyst is a blend between 70% of the state of the art co-FCC catalyst FUTURA with 30% of a novel zeolite beta based catalyst. The second catalyst is a faujasite based material, which includes specific technologies to minimize the coke yield in the product slate. The lab data obtained in course of the FASTCARD project revealed that the co-processing of pyrolysis oils in the FCC plant will lead to an increased coke making tendency. As the heat balance of an FCC unit is dependent on a constant coke yield, this tendency has to be counteracted by a more coke selective catalyst, in order to be able to run the co-FCC process without running into throughput limitations.

1.3.5 Microkinetic modelling (WP5)

(Micro-)kinetic modeling tools have been developed to establish fundamental Quantitative Structure Activity Relationships (QSARs). These relationships have supported the rational design of nanoscale catalysts within WP1 to WP4 and were validated by the actual synthesis and performance testing of new generations of catalysts and the Down-scale/Upscale pilot testing. A posteriori lumping methodology has been devised, extending from existing models for individual hydrocarbons to account for oxygen as hetero-atom. It allowed the (micro-)kinetic modeling of the conversion of complex mixtures based on a limited number of model parameters that are determined from model component experiments. For metal catalysis, relevant for WP1, 2 and 3, the quantitative models were supported by the synthesis of series of supported metal nanoparticles with very well controlled size and surface composition. Chemisorption strengths, c.q., heats, of probe molecules were used as catalyst descriptors in kinetic modeling.

For Hydrocarbon Reforming (HR, WP1), a kinetic model was developed, simulating the effect of the presence of tars and sulphur in the feed on the catalyst performance. The combination of Ni, Rh and B showed the best resistance against sulfur poisoning. The Rh-based catalyst exhibited a lower apparent activation energy than the Ni-based one for all the investigated tar model compounds. This kinetic model was integrated into a 1-dimensional pilot reactor model,

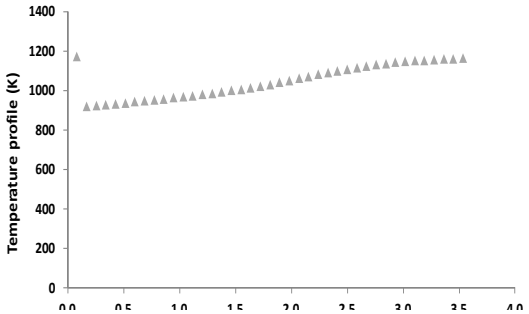

Figure 1.3-13. Figure 1: Simulated temperature profile along the reactor axis, z, under HR conditions.

wherein heat transfer was accounted for. By employing the resulting model, it was found that the highly endothermic reactions that take place in the bed induce an instantaneous decrease of the temperature at the reactor inlet, which then becomes more pronounced along the reactor axis, due to the heat transfer from the surroundings, see Figure 1.3-13.

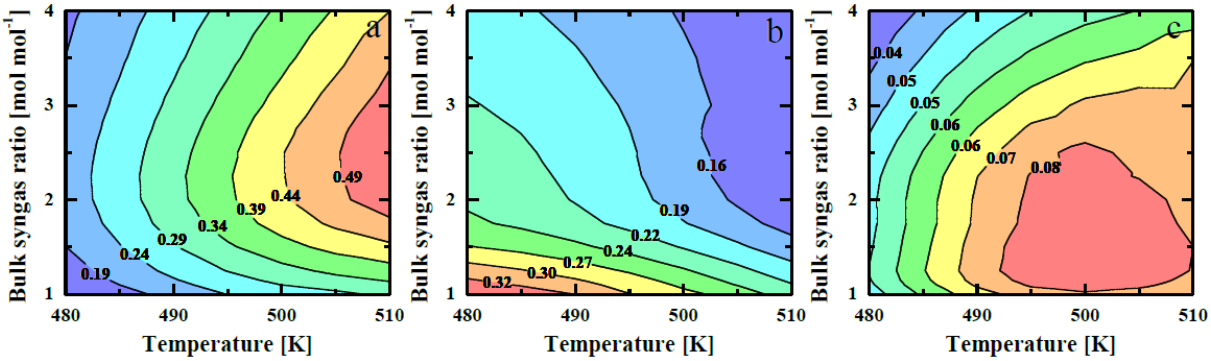

Figure 1.3-14. Contour plot of CO conversion (left), C_{5+} selectivity (middle) and C_{5+} yield (right) by the FTS model.

For Fischer-Tropsch Synthesis (FTS, WP2) ab initio calculations of rate coefficients for key elementary steps provided an insight about the feasibility of FTS on different iron carbides. The developed microkinetic model was incorporated into a 1-dimensional multi-tubular trickle bed pilot reactor model. Contour plots of conversions and selectivities/yields showed that a higher yield to C5+ products would be obtained if the reactor would be operated at an inlet temperature in the vicinity of 500 K and a substoichiometric inlet bulk syngas ratio, see Figure 1.3-14.

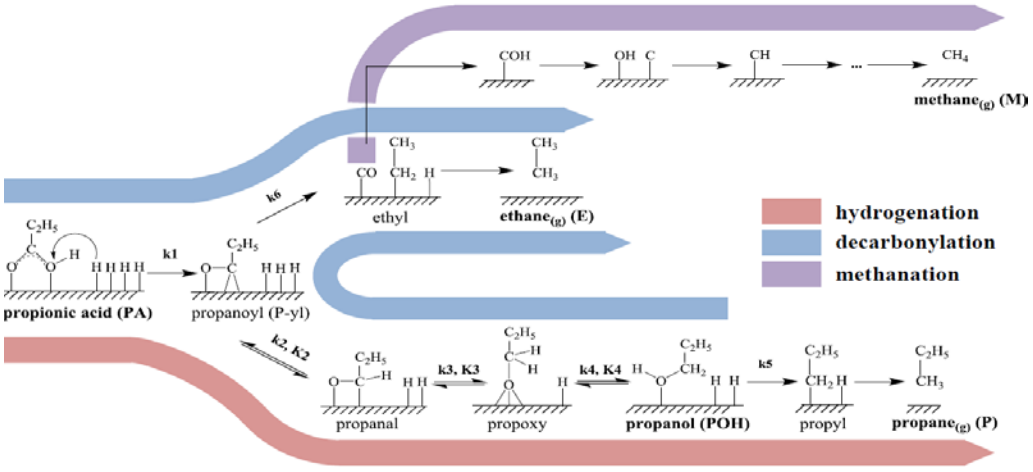

Figure 1.3-15. Propionic acid HDO reaction network on metal active sites, considered in the microkinetic model.

For HydroDeOxygenation (HDO, WP3) microkinetic model for anisole HDO and propionic acid HDO was developed to adequately assess and describe the respective experimental data sets, see Figure 1.3-15. The model was integrated into a 1-dimensional heterogeneous trickle bed pilot reactor model, accounting for ideal plug flow for both gas and liquid phases. By keeping many kinetic parameters fixed, the model succeeded in simulating adequately the HDO behavior of various feedstocks. From the simulations of boiling ranges and mole fractions along the reactor axis, minor cracking activity and conversion of aromatics into saturated ring structures were observed.

For co-Fluid Catalytic Cracking (co-FCC, WP4), a lumped kinetic model was constructed considering five pseudo-components, including individual selective deactivation functions. This model was

implemented initially into a bench-scale PFR reactor model with transient behavior and was validated against two experimental runs, one with pure n-decane (C10) and the other with combined C10-ethylphenol (EP) feed, over 12 investigated zeolites. The addition of EP in the feed was simulated to induce higher coking and cracking rates of gasoil towards gasoline and dry gas. Then, the FCC lumped kinetic model was implemented into a 1-dimensional pseudo-homogeneous plug flow pilot-scale riser reactor model, where thermal equilibrium is considered between catalyst and gas. Simulation results showed that, within the first meter of the riser, the feed (either pure C10 or C10-EP mixture) conversion can exceed 80% and more than 75%wt of the gasoline and LPG observed at the outlet can be already formed, see Figure 1.3-16.

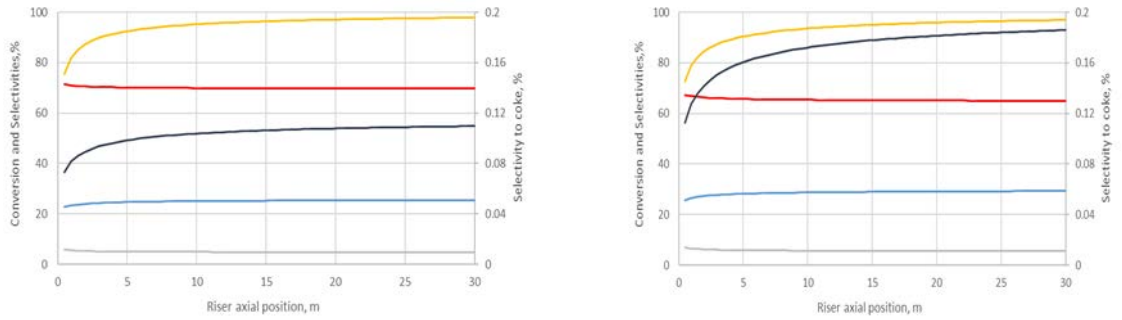

Figure 1.3-16 . Simulated profiles along the co-FCC riser reactor axis. Feed : pure C10 (left); C10-EP mixture (right), feed conversion, LPG selectivity, gasoline selectivity, dry gas selectivity, coke selectivity.

The 'ship in a bottle' method has been developed for synthesizing bimetallic nanoparticles encapsulated in hollow zeolites, yielding yolk-shell type materials. The originality of the synthesis design is that the hollow zeolites act as nanoreactors in which the bimetallic particles are formed. This process allows controlling the size (2-10 nm) and composition of nanoparticles which are factors that ultimately determine the catalyst properties. A series of mono- (Au, Pd, Pt) and bi- (AuAg, PdAg, PtAg and PdPt) metallic nanoparticles individually encapsulated in hollow silicalite-1 single crystals has been prepared and characterized, see Figure 1.3-17. The encapsulation concept has been also demonstrated on base metal nanoparticles (Co, Ni, Fe) and bimetallic particles (FeCu).

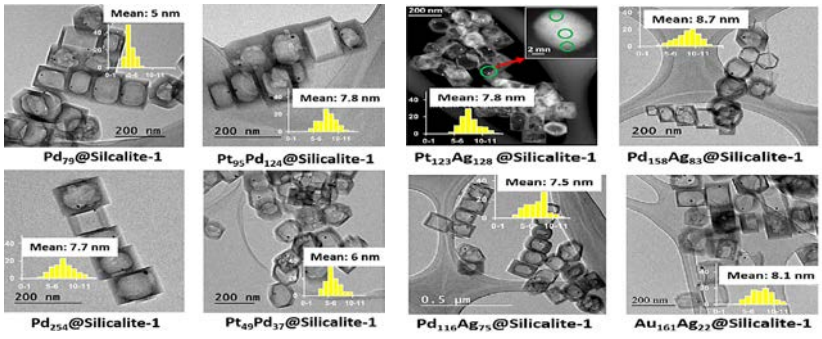

Figure 1.3-17. TEM images of mono- and bi-metallic nanoparticles in hollow zeolite. Subscripts in the composition indicate 10^3 x mol% metal loadings.

The catalytic activity in CO oxidation as a function of temperature was selected to probe the surface of the bimetallic nanoparticles. For instance, the activity curve of $Au_{161}Ag_{22}$@Silicalite-1 as a function of temperature was found to show a maximum at about 40°C which is a fingerprint of the synergetic effect of the simultaneous presence of Au and Ag at the metal surface.

A series of zeolites has been synthesized and tested under FCC conditions to establish QSARs, see Figure 1.3-18. Twelve commercial FAU samples were chosen for further analysis and testing. These

samples span a wide range of the n_{Si}/n_{Al} ratio from 2.7 to 46.1. Furthermore, they exhibit small differences in the amount of extra framework aluminium or pore structure due to their synthesis route. Investigation of [Ga-Si-O]FAU and SAPO-37 was neglected as the Al-containing FAU structure was the superior zeolite in preceding investigations, in terms of activity and hydrothermal stability

A quantitative structure-activity relationship was obtained with the use of model compounds (n-C10/2-EP) for the co-FCC of VGO and HDO oil. It was observed that faujasites were the best materials in terms of activity and stability due to their large pores. The activity and deactivation trend of the faujasites was found to depend not only on the Brønsted acid site concentration, but also on their mesoporosity, with large mesopore volumes being capable of accommodating produced coke and hence reduce deactivation. Faujasites with a low acid site concentration exhibited lower, yet more stable conversion with TOS. The presence of Lewis acid sites or extra framework aluminium did not seem to have an observable influence. Additionally, it seems that the phenol deoxygenation can be pushed into larger pores after coking from the hydrocarbon cracking. The obtained conversion and selectivity data were utilised also for the modelling efforts.

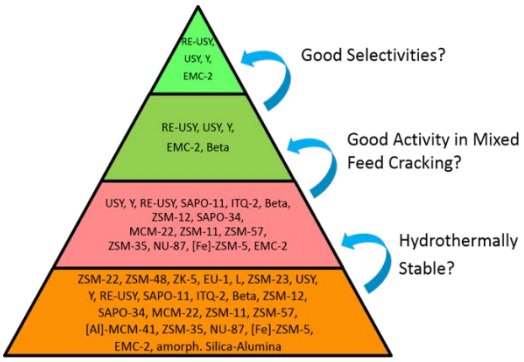

Figure 1.3-18. Figure 6: Screening of different zeolite framework types

1.3.6 Process design and evaluation (WP6)

A conceptual process design has been performed for two innovative value chains producing motor fuels from biomass.

Gasification and Fischer-Tropsch synthesis

The first value chain is a combination of gasification and Fischer-Tropsch (FT) synthesis. The gasification technology studied was MILENA, an indirect gasification running autothermally by circulation of a solid heat carrier between a gasification chamber (endothermic) and combustion chamber (exothermic). This mild type of gasification (at ± 850°C) is more energy efficient than direct, entrained-flow gasification (at ± 1400°C). However, other than the latter MILENA gasification produces a gas which does not only contain hydrogen, CO and CO_2, but also hydrocarbons. In FASTCARD, the strategy followed was to apply (steam) reforming in order to convert the hydrocarbons in additional syngas. By tuning the amount of steam added before reforming, a syngas can be produced with the right H_2:CO ratio for the FT synthesis.

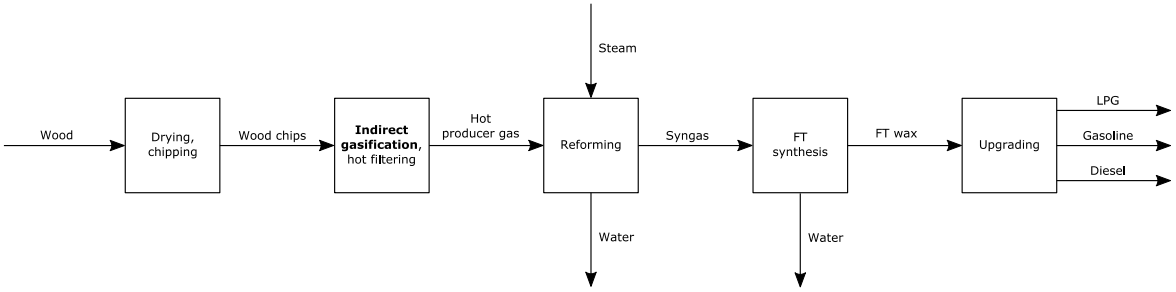

Figure 1.3-19. Schematic representation of a value chain based on indirect gasification.

The value chain based on MILENA gasification was subjected to conceptual process design supported by reactor model studies for the reforming and FT synthesis. The FASTCARD value chain was compared to a similar but technologically more mature value chain based on entrained-flow gasification of torrefied wood. Both were evaluated for a conversion of 200 MW_{th} wood into fuels. Techno-economic evaluation has shown that the FASTCARD value chain does not significantly outperform the reference chain, both producing gasoline and diesel at about 165 €/MWh. However, the FASTCARD chain shows a significantly higher overall energy yield (energy content of fuel products divided by energy content of the biomass): 53% vs. 39%. Mainly due to their high capital expenditure (CAPEX), value chains based on gasification are not currently economical and the one studied in FASTCARD did not offer a breakthrough in this sense.

Co-feeding an FCC unit with hydrotreated bio-oil

A second value chain studied in FASTCARD is based on the fast pyrolysis of biomass through BTG technology. The resulting pyrolysis liquid is subjected to hydrotreating to condition it for co-feeding with vacuum gas oil (VGO) to a fluid catalytic cracker (FCC), see Figure 1.3-20. The severity of hydrotreating was varied in accordance with the experiments performed in FASTCARD: ranging from a relatively mild hydrostabilisation to a complete hydrodeoxygenation. Fully hydrodeoxygenated bio-oil was co-fed at 10 wt% with VGO, while deeply hydrodeoxygenated and hydrostabilised bio-oil were co-fed at 6%.

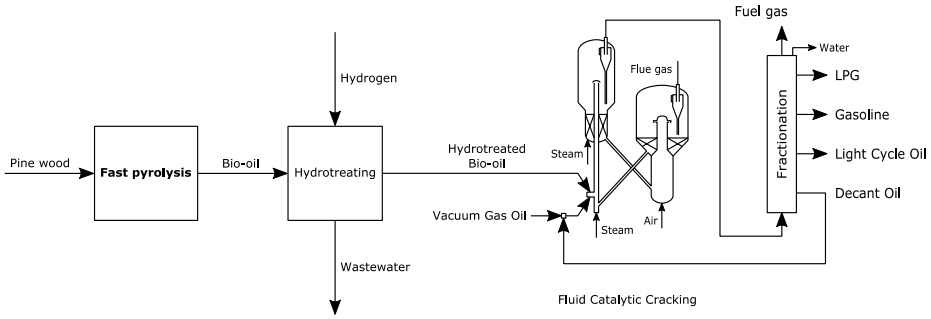

Figure 1.3-20. Schematic representation of a value chain in which hydrotreated bio-oil is co-fed with vacuum gas oil (VGO) to a fluid catalytic cracker (FCC).

The conceptual design of processes for the hydrotreating relied heavily on experimental information from FASTCARD partner BTG. Likewise, the product yield shifts in the FCC unit going from full VGO to co-fed VGO and bio-oil were taken from experimental data obtained on a Davison Circulating Riser (DCR) of FASTCARD partner REPSOL. The conceptual design was also supported by reactor model studies for hydrotreating and FCC.

Our evaluation has revealed an overall energy yield from biomass to motor fuel (LPG, gasoline, diesel) of about 55% when hydrostabilised pyrolysis oil is co-fed. This is a relatively favourable number comparable to the one of the value chain relying on MILENA gasification. When co-feeding deeply or fully hydrodeoxygenated oil, the energy yield is lower though. The production cost of the bio-share of the produced motor fuels is estimated at 110 to 130 €/MWh from the experimental FCC yields. However, it seems that through catalytic and process-technical improvements, more favourable product yields can be obtained in short term, especially when co-feeding merely hydrostabilised bio-oil. For these we estimate that the production cost would then go down to about 100 €/MWh. In some countries in Europe this is lower than the cost of the fossil fuels including excise duty. If the bio-fraction of the fuels is exempted from excise duty, co-feeding hydrostabilised bio-oil will be economical there. Given that the CAPEX for this value chain (fast pyrolysis, hydrotreating and FCC slightly adapted to accommodate bio-oil) is relatively low, the value chain can become commercial in short term.

Comparison

Our economic evaluations confirm the expectation of the EC Sustainable Transport Forum (STF), see Figure 1.3-21, that motor fuels obtained by the pyrolysis oil FCC co-processing are cheaper than their counterparts obtained by FT preceded by gasification. The economic estimates performed in FASTCARD seem to be a bit more pessimistic than the ones reported by the Sustainable Transport Forum, especially for production based on gasification and FT. While the latter is not currently economical, it does offer a fuel which is 100% bio and which can in principle fully replace the fossil motor fuels in current engines. Therefore, gasification and FT still have long-term potential as a way to produce biofuels, especially at large scale where the weight of the high CAPEX will be lower.

Our estimate for the production cost of biofuel produced through pyrolysis oil FCC co-processing is at the upper edge of the range reported by the STF. We did not estimate the production cost of biofuels produced in the other ways reported by the STF. We expect that also here our methodology would yield estimates on the pessimistic side compared to the STF ranges. In any case it seems that pyrolysis oil FCC co-processing is among the cheaper ways to produce biofuel. It has the additional advantages that capital investments are relatively low and that the fuels produced are in principle not different from the current, fossil ones. It should be noted, though, that pyrolysis oil FCC co-processing still relies mainly on fossil VGO which hampers its application in the long run.

In summary we can say that pyrolysis oil FCC co-processing offers a solution in short term, while gasification and FT synthesis have their potential at long term.

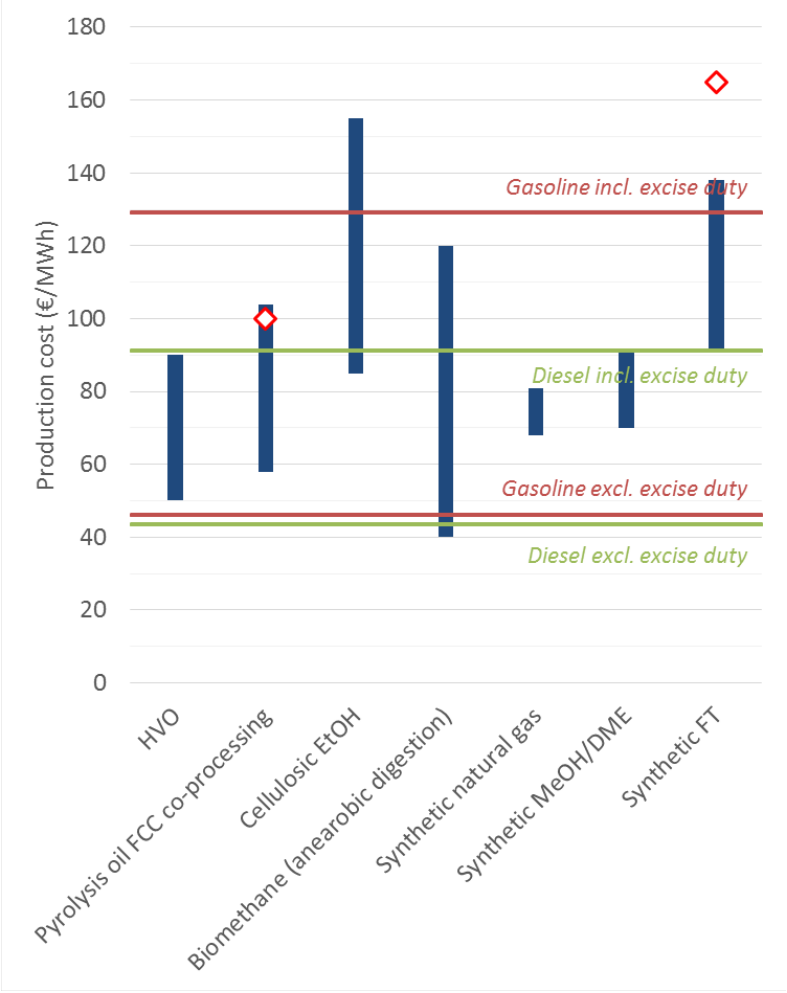

Figure 1.3-21. Manufacturing costs (◊) expected for gasoline and diesel produced through the Liquid Line and the Gas Line. These expected values are compared to the ranges reported by the EC Sustainable Transport Forum, Sub Group on Advanced Biofuels[Error! Reference source not found.]. Also shown are the price of gasoline and diesel excluding and including their excise duty in the Netherlands.

1.3.7 Demonstration of scaled up catalyst (WP7)

Gas line:

Within WP7, a number of upscaled novel catalytic materials developed within WP1 and WP2 have been tested under relevant conditions for the demonstration of the gasification value chain. In the final duration test of hydrocarbon reforming (WP1), a modified pre-catalyst was manufactured by partner Saint-Gobain (SG) based on its proprietary ice-templating process (which allows a controlled microstructure, with surface accessible and radially oriented pores) using industrially relevant equipment and procedures. The low-surface area guard bed made by Saint-Gobain was modified through nickel impregnation by Johnson Matthey (JM). Two Rh-based steam reforming monolith catalysts were compared: a Rh-based benchmark prepared by Johnson Matthey, and a catalyst developed using the bottom-up FASTCARD approach, based on a MgAl spinel support, and developed by Johnson Matthey based on a FASTCARD developmental catalyst powder recipe. Both catalysts were pre-aged for 200 hours at 900°C under flowing air conditions before the duration test. The monolith catalysts were tested in parallel in dual bed configuration (pre-catalyst + catalyst located in the same reactor) for 100 hours under real gasification conditions (raw product gas from indirect gasification at

850°C using beech wood as biomass fuel). The JM benchmark catalyst was further operated for 50 hours in single bed configuration (without pre-catalyst). The long-term performance of the catalysts was assessed by the conversion of methane and benzene.

The results from the hydrocarbon reforming duration test revealed that the pre-catalyst + JM benchmark catalyst system was able to reduce the inlet methane content of the gas from 11 vol.% to below 1 vol.% (i.e. > 90% CH4 conversion), with 100% benzene and toluene conversion, whereas the pre-catalyst + FASTCARD catalyst system decreased the CH4 content down to ~ 2.5 vol.% (that is, ca. 60-65% methane conversion), with ~ 95% benzene conversion and complete toluene conversion. During the second part of the test (50-h test under single-bed configuration), the methane conversion activity of the same JM benchmark catalyst was approximately halved to 50% with respect to the values observed in the dual bed test, thus showing the positive influence of the pre-catalyst on extending the lifetime of the PGM catalyst. The relatively more modest performance of the FASTCARD-developed reforming catalyst compared to the JM benchmark catalyst can be attributed to the combined effect of somewhat lower catalyst temperatures and lower rhodium loading with respect to the benchmark catalyst. By applying internal molar balances, it was estimated that the pre-catalyst is able to convert approximately 20-30% of the inlet methane and 65-90% of the inlet benzene, depending on the bed temperature. No apparent signs of deactivation were observed during the 100-h test. Certain signs of deactivation (decrease of benzene conversion) were observed after ~28 hours of test 2 (that is, after 128 hours overall operation of the JM benchmark monolith).

In the Fischer-Tropsch tests (WP2), 4 iron-containing catalysts have been produced and tested at temperatures between 210°C and 280°C. The results of the tests showed that the catalysts made larger amounts of CO2 than desired, especially at higher reaction temperature (280°C). This may be linked to the incorporation of iron into the silica framework. The best among the catalysts tested had a very similar selectivity profile to the state of the art catalyst, but was over twice as active. Other materials tested had much lower CO2 yields (which is desirable), but made higher amounts of methane and C2-4 hydrocarbons. The presence of CO2 in the gas phase (which has the effect of suppressing the yield of CO2) could be used to improve the selectivity of these catalysts.

Liquid line:

Within the FASTCARD project, catalysts have been developed which are optimized for the co-processing of mildly hydrodeoxygenated pyrolysis oils together with fossil feed in the FCC process (co-FCC). The main goals of this optimization process were to achieve catalyst stability under the co-FCC process conditions, and to counterbalance the yield shifts in the FCC product slate, which are linked to the co-feeding of the biomass based pyrolysis oils. These shifts are mainly associated with increased (and highly undesired) coke formation in the presence of bio-oils.

The development work included the screening of novel active components, i.e. zeolites and/or zeolite modifications, as well as the optimization of the catalyst matrix, in order to transfer the catalytic performance of the active component into a commercially manufacturable and usable co-FCC catalyst. D7.2 deals with the last part of this development process, the scale-up of optimized catalyst formulations from laboratory to pilot plant scale. The only non-faujasite zeolite, which proved to be usable for the co-FCC process is a commercially available zeolite beta. However, the upscaling of the zeolite synthesis will not be the focus of this deliverable because the slightly increased coke make – observed in former testing runs – was the critical criteria for REPSOL. Compared to all other active

components screened in the lab, commercially established zeolite types and modifications proved to deliver the best results in co-FCC. The most promising co-FCC catalysts have been manufactured in 100 kg pilot plant scale for WP 7.

These samples have been evaluated in the DCR (REPSOL), by using the CO2-footprint optimized feed from Task 7.3. In this report, the results of the demo testing will be compared with the lab tests (Task 4.7) as well as the predicted data (WP5). The samples of the demo scale manufactured catalysts have been lab tested (MAT), including the application of the established fast ageing protocol. The validation includes the down scaled testing procedures (as defined in WP4.2), the catalyst upscaling (4.3, 4.4) and comparison to the predicted data (WP5).

1.4 Potential Impact and main dissemination activities

1.4.1 Accelerate industrialisation of tailor-made nanomaterials with high activity, selectivity and durability

The general approach for catalyst development and process improvement for implementation at commercial scale is too slow at the moment to tackle the industrial and world pressure which renew themselves at an ever increasing pace in order to address the regular and numerous societal and political changes. There is therefore a strong need for a methodology which allows acceleration of the time-to-market, while improving the understanding of the underlying mechanisms. The energy sector is one of the critical sectors for which the need for implementation of new processes for production of biofuels is pressing. Thus FASTCARD's advanced methodology for fast development of nano-scale catalyst based processes, which allows major progress in, and understanding of catalyst development by significantly reducing the development and scale-up time of new more stable, more selective and greener nano-scale catalysts while bringing better knowledge of the underlying mechanisms.

The FASTCARD project has aimed to accelerate industrialisation of tailor-made nanomaterials with high activity, selectivity and durability for the production of biofuels. This has been through an innovative methodology; the "Upscaling/Downscaling" approach, for the design and scale-up of tailor-made, highly active, highly selective catalysts stable over time under operating conditions. The new approach has been demonstrated in parallel for the four key catalytic steps in the two value chains for conversion of biomass to biofuels, establishing a link between the industrial conditions needed to operate at pilot scale and the lab-scale giving insight to the detailed mechanism of the catalytic steps. This approach has now successfully allowed the rapid modelling and simulation of industrial performance of laboratory data from the four catalytic steps, avoiding an extensive number of iterations usually needed to go from lab-scale to pilot-level. The coupling of the "upscaling/downscaling" approach with advanced modeling and characterisation has gained detailed insight into deactivation mechanisms and the setting up of quantitative structure activity relationships. This has allowed the development of catalysts that have been benchmarked in extended long-term tests at pilot scale, as well as giving the basis and tools for further tailor-making of catalyst and processes in the future implementation phase.

1.4.2 Improvement of process performance through demonstration under industrially relevant conditions

FASTCARD has employed the experimental, theoretical approaches leading to improved and more controlled performance based on nano-catalysts and models adapted for bio-feeds. The potential of

commercial exploitation of the catalysts developed has been demonstrated at industrially relevant scales through successful scale up of the synthesis of the catalysts for the four key steps to scales in the range of 7 – 100 kg. These scaled-up catalysts have also been successfully tested for their performance under industrially relevant conditions, through long term tests at pilot scale in the range of 50 – 100 hr. As an additional validation of the experimental results from the transfer from lab-scale to pilot scale, pilot scale reactor models were developed for all the four key catalytic reaction processes, including a number of adjustable model parameters. Thus for the two value chains:

For the Gas-line:

The combined experimental and modelling studies have demonstrated an improved configuration with a promising energy efficiency of almost 60% (from wood to FT wax). This has also achieved less than 5% deactivation in the reforming step and benchmarked Fe-based catalysts that are robust and tolerant for the CO2-containing feeds suitable for biorefinery applications

For the liquid line:

Better performance for bio-oil co-processing in FCC process has been achieved and dedicated catalysts for the co-processing of bio-oils have been developed and scaled up and tested in FCC Pilot tests with technical progress being made in the smooth operation in the DCR pilot plant. This allows lower hydrogen consumption through the use of stabilised pyrolysis oil compared to the fully deoxygenated oil with the possibility of co-processing stabilized bio-oil at 6%wt in FCC with without modifying the coke production.

1.4.3 Render alternative sustainable energy applications technically and economically feasible

The European objective is to have a dramatic implementation of renewable energy in the transport sector by 2020. Therefore a significant reduction in the cost of bio-fuels production technologies is necessary to help overcome existing energy barriers in the whole chain of biomass use. For the FASTCARD project, two main value chains were defined, The Gas-Line and the Liquid-line, to give the basis for coordinated catalyst and process improvement. Throughout the project, the process model of these two routes was established, refined and used as a basis for further process optimisation. Based on this, significant opportunities for improvements of the economics were identified and detailed technical and economic feasibilities for implementation in Europe developed. The final economic feasibility, benchmarked according to current state-of the art alternatives, is shown in Figure 1.4-1.

For the Liquid line, combining the processes of fast pyrolysis, hydrostabilisation and Co-FCC, the improvements and demonstration of the catalysts and process show that this value chain is close to being economically feasible and can be made economical a in relatively short term, especially if excise duty exemptions are granted for the share of biofuels in the fuels produced. With this in mind, additional technical improvements to the final optimisation of the economics have been identified. Specifically, involving further improvements of the FCC-yields from the stabilised pyrolysis oil, with even further improvements through the potential of even using raw pyrolysis liquid.

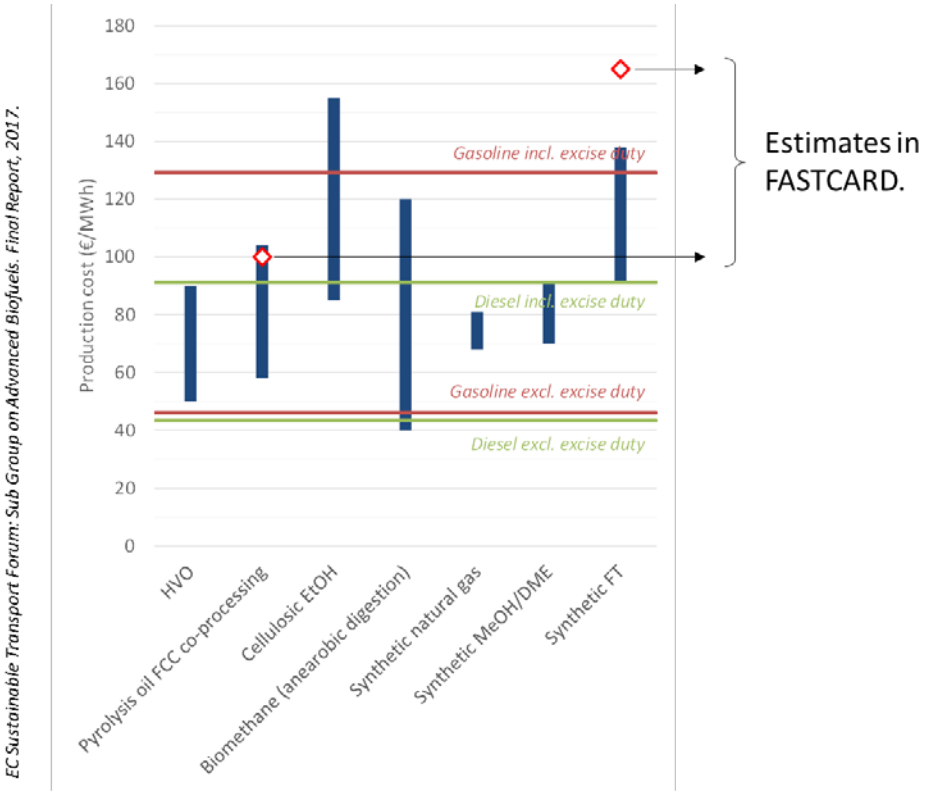

Figure 1.4-1. Manufacturing costs (◊) expected for gasoline and diesel produced through the Liquid Line and the Gas Line. These expected values are compared to the ranges reported by the EC Sustainable Transport Forum, Sub Group on Advanced Biofuels[10]. Also shown are the price of gasoline and diesel excluding and including their excise duty in the Netherland

For the gas line, combining the processes of gasification, reforming and FT; improvements of the catalysts and process were achieved, however, due mainly to the CAPEX, it is still not currently economical with respect to fossil-based altneratives. However, on a long term basis, the Gas-Line is still attractive due to the potential of producing a clean, high quality purely biobased drop-in fuel. With this in mind, clear technical improvementsof the process have been identified. Specifically, these involve i) the use of pressurised indirect gasification to ensure enough scalability and ii) alternative valorisation of tars to obviate the need to admix steam.

The overall final outlook for the potential for further implementation as a full value chain in today's current market is summarised as follows:

	Gas Line	Liquid Line
Drop-in Fuel	YES	YES
Investment risk	HIGH	LOW
Currently competitive with fossil?	NO	YES if excise duty exemption
100% biofuel	YES	NO
Potential Exploitation/Implementation	Long Term	Short Term

1.4.4 Societal and environmental impacts

The results of FASTCARD have shown that the two value-chains that have been developed and opitmised show clear opportunities in terms of economic feasibility, both in the short term and long term. This fulfils the ambitions of the project in contributing to the future European environment and renewable energy policy by addressing one of the main barriers to the take up of advanced biofuels – the reduction of risk for the investment in new biofuel production facilities.

Through the use and demonstration of an overall strategy for accelerating the scale-up of lab-based research results through to validation under industrial pilot-scale conditions, FASTCARD has now set up for the first time a tool-box of detailed micro-kinetic understanding of key chemical steps for the conversion of biomass based feedstock, making available the opportunity of this knowledge contributing on a wider scale to accelerating implementation in other commercial development initiatives.

FASTCARD has also established the economic feasibility for commercial implementation of biofuel production in both the short and long-term – with the dual positive effect to environment of: (1) reducing the energy consumption for their manufacture and during the conversion of biomass, (2) increasing the potential for production and use of bio-fuels. Specifically, with respect to the energy yields, FASTCARD has contributed significant improvements for the two value chains:

- For the gas-Line, improvements of the energy yield up to 53% compared to the benchmark of 39% where achieved.
- For the liquid line, improvements of the energy yield for the key upgrading step to 89% was achieved for use of the stabilised pyrolysis oil compared to < 78% for the use of deoxygenated oil, providing an overall energy yield of 55%

1.4.5 Exploitation and dissemination

In parallel with the developments and the innovations towards improved process and economics**, communication, dissemination and exploitation** of the results and developments from the project is a vital component of the FASTCARD project to ensure a maximum impact.

The objectives are:

(i) to support protection of intellectual property resulting from the project by ensuring that the relevant partner can patent the technologies, design and applications,

(ii) to disseminate a full range of scientific, technological material/process non-confidential knowledge generated within FASTCARD to the business, technology providers and the scientific community and

(iii) to develop and facilitate efficient communication between beneficiaries.

1.4.6 Dissemination

The dissemination activities planned in the FASTCARD project aimed at bringing and pushing the results of the program directly to specific targets, while taking appropriate measures to engage with the public and the media about the program aims and results, and highlighting the financial support of the European Community.

A detailed overview of publications (already in press and to be submitted), as well as other dissemination activities (conference contributions and newsletters) can be found in paragraph 2.1.2 of this report.

The dissemination activates can be summarized as follows

- A dedicated web site and project identity set (logo, brochure). This gave a unique identity to the project while promoting its results via wide communication towards public and non-scientists.
- The FASTCARD partners have been actively involved in conferences, meetings with users and stakeholders at EU/national/local level, exhibitions, trade fairs and the Final Project Workshop (engaging dialog between researchers, EU & national policy makers and other stakeholders).
- More than 15 posters, more than 20 oral presentations in national and international conferences, e.g. at the 12th European Congress on Catalysis – EuropaCat-XII, Kazan, Russia, August 30 – September 4, 2015, at the 18th International Zeolite Conference, Rio de Janeiro, Brazil, June 19 – June 24, 2016.
- Total of 26 papers in peer-reviewed journals, with 16 already being available at the journal homepages.
- Three workshops/seminars were organized
  - A workshop was organized in the framework of the ENMIX network together with the projects FASTCARD, BIOGO and cascatbel, all funded in the topic NMP.2012.1.1-1 The title of the workshop was “Rational design of nano-catalysts for sustainable energy production based on fundamental understanding”.
  - During the 10th World Congress of Chemical Engineering the coordinators of CASCATBEL, BIOGO and FASTCARD arranged a final joint seminar. The title of the seminar was "Workshop on Advanced Biofuels Production from Lignocellulose" and a total of 9 oral and 15 posters were presented.

  - At the end of the FASTCARD project a final workshop on the topic of “Upscaling/Downscaling of Catalysts and Processes” was organized with contributions from the FASTCARD project, industry and the related projects BIOGO and BioTFuel.

1.4.7 Teaching and knowledge transferee

A significant part of the project has involved training and teaching activities. 9 master students, 10 PhD students and 4 post docs Has been involved. In addition, there have been arranged exchange of researchers between groups involved in the project.

Two one-week summer courses were organized by Ghent University:

The first summer was arranged in Ghent in collaboration with the FP7 IP BIOGO and the Interuniversity Attraction Pole program 'Functional Supramolecular Systems' (IAP-FS2). The title of the course was *"Sustainable Reaction and Reactor Engineering for Catalysis and Polymerization" (RECaP)*, and involved 7 lectures on theoretical aspects of reaction and reactor engineering for catalysis and polymerization took place. Additionally, the organizing projects, i.e., FASTCARD, BIOGO and FS2, presented their activities and goals. A total of 22 participants attended the summer course coming from various European countries.

The second course was arranged in Florence in cooperating with Politecnico Di Milano. The title of the course was *"ponte Vecchio: Bringing Laboratory Chemical Kinetics to Industrial Scale Reactors"* and involved 7 lectures on theoretical aspects of reaction and reactor engineering for catalysis took place. A total of 30 junior scientists from industry and academia coming from various European countries attended the course.

1.4.8 Exploitation of project achievements

The competitiveness of organisations is increasingly depending on their ability to collaborate in networks, and for such (knowledge-based) collaborations, strong IPR management is a prerequisite for efficient trade and transfer of IPR and technology.

The active involvement of FASTCARD's industrial partners towards the exploitation of results from the project is important for realization of the competitiveness of Europe. This involvement is stimulated by the clear identification and coordination of the respective domains of interests of the main industrial partners. These domains are fully aligned with the four core work packages as shown in Figure 2.

WP1. Hydrocarbon Reforming	**JM**
WP2. CO2-FTS	**JM, ENI**
WP3. Hydrotreating	**BTG, Repsol**
WP4. Co-FCC	**Grace, Repsol**

Figure 2: Main industrial partners related to the four core work packages.

The exploitation of results was managed at two levels:

1. The legal management of the ownership of results through the Consortium agreement.
2. The identification and development of opportunities for exploitation of results through an industrial Exploitation Panel and an Exploitation Manager.

A summary of the Key Exploitable Results (KERs) can be found in found in paragraph 2.2.1 of this report and are elaborated in further detail in the project deliverable D8.3.

1.5 Main contact details

Project Coordinator:	Dr. Duncan Akporiaye
Project Coordinator Organisation:	SINTEF
Tel:	**+47 93 059 166**
E-mail:	**duncan.akporiaye@sintef.no**
Project Website Address:	**https://www.sintef.no/projectweb/fastcard/**

1.6 List of all beneficiaries

#	Participant legal name	Short name	Type	Country	Contact name
1	**SINTEF AS**	**SINTEF**	**RTD**	**Norway**	**Duncan Akporiaye**
2	Centre National de la Recherche Scientifique - Institut de Recherches sur la Catalyse et l'Environnement de Lyon	CNRS	RTD	France	David Farrusseng
3	Eni S.p.A.	ENI	IND	Italy	Letizia Bua
4	Johnson Matthey Plc	JM	IND	UK	Peter Ellis
5	Boreskov Institute of Catalysis, Siberian Branch of Russian Academy of Sciences	BIC	RTD	Russia	Vadim Yakovlev
6	GRACE GmbH & Co. KG	GRACE	IND	Germany	Stephan Wellack
7	Universitaet Stuttgart	USTUTT	UNI	Germany	Yvonne Traa
8	Stichting Energieonderzoek Centrum Nederland	ECN	RTD	The Netherlands	Guadalupe Aranda Almansa
9	Universiteit Gent	UGent	UNI	Belgium	Joris Thybaut
10	BTG Biomass Technology Group BV	BTG	SME	The Netherlands	Robbie Venderbosch
11	Process Design Center BV	PDC	SME	The Netherlands	Raf Roelant
13	Norges Teknisk-Naturvitenskapelige Universitet NTNU	NTNU	UNI	Norway	Magne Rønning
14	Saint-Gobain Centre de Recherche et d'Etudes Européen	St-Gobain	IND	France	Caroline Tardivat
15	Repsol SA	Repsol	IND	Spain	Rebeca Yuste Pilar

2 Use and dissemination of foreground

2.1 Section A

2.1.1 A1: list of scientific (peer reviewed) publications, starting with the most important ones

These tables are cumulative, which means that they will show all publications and activities from the beginning until after the end of the project.

Nº	Title	Author(s)	Title of the periodical or the series	Number, date or frequency	Publisher	Place of publication	Date of publication	Relevant pages	Link to pub.	Open access?
1	Transition-Metal Nanoparticles in Hollow Zeolite Single Crystals as Bifunctional and Size-Selective Hydrogenation Catalysts	Shiwen Li, Alain Tuel, David Laprune, Frédéric Meunier, David Farrusseng	Chemistry of Materials	Vol. 27/Issue 1	American Chemical Society	United States	13.01.2015	276-282		NO
2	Enhanced Carbon-Resistant Dry Reforming Fe-Ni Catalyst: Role of Fe	Stavros Alexandros Theofanidis, Vladimir V. Galvita, Hilde Poelman, Guy B. Marin	ACS Catalysis	Vol. 5/Issue 5	ACS Publications	United States	01.05.2015	3028-3039		NO
3	Furfural Hydrogenation to Furfuryl Alcohol over Bimetallic Ni–Cu Sol–Gel Catalyst: A Model Reaction for Conversion of Oxygenates in Pyrolysis Liquids	S. A. Khromova, M. V. Bykova, O. A. Bulavchenko, D. Yu. Ermakov, A. A. Saraev, V. V. Kaichev, R. H. Venderbosch, V. A. Yakovlev	Topics in Catalysis	Vol. 59/Issue 15-16	Springer Netherlands	Netherlands	01.09.2016	1413-1423		NO
4	Carbon gasification from Fe–Ni catalysts after methane dry reforming	Stavros Alexandros Theofanidis, Rakesh Batchu, Vladimir V. Galvita, Hilde Poelman, Guy B. Marin	Applied Catalysis B: Environmental	Vol. 185	Elsevier	Netherlands	01.05.2016	42-55		NO

Nº	Title	Author(s)	Title of the periodical or the series	Number, date or frequency	Publisher	Place of publication	Date of publication	Relevant pages	Link to pub.	Open access?
5	Optimizing the bio-gasoline quantity and quality in fluid catalytic cracking co-refining	Laurent Gueudré, Florian Chapon, Claude Mirodatos, Yves Schuurman, Robbie Venderbosch, Edgar Jordan, Stephan Wellach, Ruben Miravalles Gutierrez	Fuel	Vol. 192	Elsevier BV	Netherlands	01.03.2017	60-70		NO
6	Effect of polyaromatic tars on the activity for methane steam reforming of nickel particles embedded in silicalite-1	D. Laprune, C. Theodoridi, A. Tuel, D. Farrusseng, F.C. Meunier	Applied Catalysis B: Environmental	Vol. 204	Elsevier	Netherlands	01.05.2017	515-524		NO
7	Mechanisms of the AlCl3 Modification of Siliceous Microporous and Mesoporous Catalysts Investigated by Multi-Nuclear Solid-State NMR	Swen Lang, Michael Benz, Utz Obenaus, Robin Himmelmann, Matthias Scheibe, Elias Klemm, Jens Weitkamp, Michael Hunger	Topics in Catalysis	Vol. 60/Issue 19-20	Springer Netherlands	Netherlands	01.12.2017	1537-1553		NO
8	Selective removal of external Ni nanoparticles on Ni@silicalite-1 single crystal nanoboxes: Application to size-selective arene hydrogenation	D. Laprune, A. Tuel, D. Farrusseng, F.C. Meunier	Applied Catalysis A: General	Vol. 535	Elsevier	Netherlands	01.04.2017	69-76		NO
9	Controlling the stability of a Fe–Ni reforming catalyst: Structural organization of the active components	Stavros Alexandros Theofanidis, Vladimir V. Galvita, Maarten Sabbe, Hilde Poelman, Christophe Detavernier, Guy B. Marin	Applied Catalysis B: Environmental	Vol. 209	Elsevier	Netherlands	01.07.2017	405-416		NO
10	Hydrodeoxygenation of phenolics in liquid phase over supported MoO3 and carburized analogues	Rune Lødeng, Chanakya Ranga, Tapas Rajkhowa, Vaios I. Alexiadis, Hilde Bjørkan, Svatopluk Chytil, Ingeborg H. Svenum, John Walmsley, Joris W. Thybaut	Biomass Conversion and Biorefinery	Vol. 7/Issue 3	Springer Berlin Heidelberg	Germany	01.09.2017	343-359		NO

Nº	Title	Author(s)	Title of the periodical or the series	Number, date or frequency	Publisher	Place of publication	Date of publication	Relevant pages	Link to pub.	Open access?
11	The effect of copper loading on iron carbide formation and surface species in iron-based Fischer-Tropsch synthesis catalysts	Diego Zapata Pena, Lise Saue Jensen, Andrea Cognigni, Rune Myrstad, Thomas Neumayer, Wouter van Beek, Magnus Rønning	ChemCatChem	nd	Wiley - VCH Verlag GmbH & CO. KGaA	Germany	12.01.2018	nd		NO
12	First Principle Study on the Adsorption of Hydrocarbon Chains Involved in Fischer–Tropsch Synthesis over Iron Carbides	José G. Rivera de la Cruz, Maarten K. Sabbe, Marie-Françoise Reyniers	Journal of Physical Chemistry C	Vol. 121/Issue 45	American Chemical Society	United States	16.11.2017	25052-25063		NO
13	The influence of porosity and active sites of zeolites Y and beta on the co-cracking of n-decane and 2-ethylphenol	Moritz Heuchel , Christian Dörr , Roman Boldushevskii , Swen Lang , Elias Klemm , Yvonne Traa	Applied Catalysis A: General	Vol. 553	Elsevier	Netherlands	01/03/2018	91-106		NO
14	Hollow Zeolite Single-Crystals Encapsulated Alloy Nanoparticles with Controlled Size and Composition	Shiwen Li, Alain Tuel, Jean-Luc Rousset, Franck Morfin, Mimoun Aouine, Laurence Burel, Frédéric Meunier, David Farrusseng	ChemNanoMat	Vol. 2/Issue 6	Wiley Online Library	United States	01.06.2016	534-539		NO
15	Effect of composition and preparation of supported MoO 3 catalysts for anisole hydrodeoxygenation	Chanakya Ranga, Rune Lødeng, Vaios I. Alexiadis, Tapas Rajkhowa, Hilde Bjørkan, Svatopluk Chytil, Ingeborg H. Svenum, John Walmsley, Christophe Detavernier, Hilde Poelman, Pascal Van Der Voort, Joris W. Thybaut	Chemical Engineering Journal	Vol. 335	Elsevier	Netherlands	01.03.2018	120-132		YES
16	Co-catalytic cracking of n-decane and 2-ethylphenol over a variety of deactivated zeolites for the conversion of fossil- and bio-based feeds in Co-FCC	Moritz Heuchel, Florian Reinhardt, Nağme Merdanoğlu, Elias Klemm, Yvonne Traa	Microporous and Mesoporous Materials	Vol. 254	Elsevier	Netherlands	01.12.2017	59-68		NO

Nº	Title	Author(s)	Title of the periodical or the series	Number, date or frequency	Publisher	Place of publication	Date of publication	Relevant pages	Link to pub.	Open access?
17	Influence of Molybdenum on Activity and Selectivity of Ni-Containing Sol-Gel Catalysts in Hydrotreatment of Guaiacol	M.A. Rekhtina, M.V. Alekseeva (Bykova), M.Yu. Lebedev, S.G. Zavarukhin, V.V. Kaichev, R.H. Venderbosch, V.A. Yakovlev								
18	Improved sintering-resistance of Ni-based steam methane reforming catalysts by encapsulation of Ni in multi-hollow silicalite-1 single crystal nanoboxes.	D. Laprune, A. Tuel, D. Farrusseng, F.C. Meunier								
19	Anisole hydrodeoxygenation over non-sulphided CoMo/γ-Al2O3: 1 experimental investigation and kinetic model construction	D. Otyuskaya, Joris W. Thybaut, Rune Lødeng, Guy B. Marin								
20	Iron catalysts supported on super-hydrophobe zeolite for CO2 free Fischer-Tropsch synthesis	Joffrey Huve, Yves Schuurman, Alain Tuel, Lucian Roiban, Jean-Marc Millet, Ludovic Delier, Benoit Coasne, Debra Jones, Diego Pena Zapata, Magnus Rønning, David Farrusseng								
21	Low-cost alternative for noble metal catalyst? –just add iron	Stavros Alexandros Theofanidis								
22	Effects of H2S and phenanthrene on the activity of nickel and rhodium-based catalysts for the reforming of a simulated biogas.	D. Laprune, D. Farrusseng, Y. Schuurman, F.C. Meunier, J.A.Z. Pieterse, A.M. Steele, S. Thorpe								
23	Identification of carbon species on iron-based catalysts during Fischer-Tropsch synthesis	D. Peña, A. Cognigni, T. Neumayer, W. van Beek, D. S. Jones, M. Quijada, M. Rønning								

Nº	Title	Author(s)	Title of the periodical or the series	Number, date or frequency	Publisher	Place of publication	Date of publication	Relevant pages	Link to pub.	Open access?
24	Fast pyrolysis oil stabilization kinetics over a Ni-Cu 1 catalyst using propionic acid as a model compound	Daria Otyuskaya, Joris W. Thybaut, Vaios Alexiadis, Maria Alekseeva, Robbie Venderbosch, Vadim Yakovlev, Guy B. Marin								
25	First principle study of chain termination reactions during Fischer-Tropsch synthesis on -Fe5C2(010)	Jose G. Rivera de la Cruz, Maarten K. Sabbe, Marie-Francoise Reyniers								
26	Effect of AlCl3 modification of mesoporous and microporous supports on the catalytic conversion of the bio-oil model compound 2-ethylphenol	Swen Lang, Moritz Heuchel, Yvonne Traa, Elias Klemm, Michael Hunger								

2.1.2 A1: List of Dissemination Activities

These tables are cumulative, which means that they will show all publications and activities from the beginning until after the end of the project.

Nº	Type of activities	Main leader	Title	Date	Place	Type of audience	Size of audience	Countries addressed
1	Web	SINTEF	FASTCARD Newsletter 1	Mar-14	https://www.sintef.no/projectweb/fastcard/publications-/	Scientific community - Industry - Civil society		-
2	Oral	USTUTT	ENMIX A.I.S.B.L. and FASTCARD How are they connected?	Jul-14	Open workshop EMerging TECHnologies for chemicals and fuels production, Ghent University (Belgium)	Scientific community Industry		-
3	WEB	USTUTT	FASTCARD Newsletter 2	Sep-14	https://www.sintef.no/projectweb/fastcard/publications-/	Scientific community - Industry - Civil society	-	-
4	Posters	USTUTT	The FASTCARD Project and the Role of University of Stuttgart in it - Co-FCC of a Fossil and a Bio Feedstock	Sep-14	The 4th ENMIX Workshop, Bled, Slovenia	Scientific community Industry		-
5	Web	USTUTT	FASTCARD Newsletter 3	Mar-15	https://www.sintef.no/projectweb/fastcard/publications-/	Scientific community - Industry - Civil society	-	-
6	Public article	SINTEF	Contribution from FASTCARD to a joint BIOGO/FASTCARD/CASCATBEL double-page spread	Jun-15	The Parliament Magazine, June 2015	Scientific community - Industry - Civil society		-
7	Oral	BIC	Pyrolysis oil into biofuels: Promising catalysts for hydrotreatment process	Aug-15	12th European Congress on Catalysis, Kazan, Russia.	Scientific community - Industry	1200	International
8	Posters	UGent	Enhanced catalytic performance of Ni-Fe alloy in methane dry reforming: role of Fe	Aug-15	12th European Congress on Catalysis, Kazan, Russia.	Scientific community - Industry	1200	International
9	Oral	BIC	Effect of Mo addition on hydrotreating activity, stability to corrosion, and physicochemical properties of Ni-based catalysts for bio-oil upgrading	Aug-15	12th European Congress on Catalysis, Kazan, Russia.	Scientific community - Industry	1200	International

Nº	Type of activities	Main leader	Title	Date	Place	Type of audience	Size of audience	Countries addressed
10	Web	USTUTT	FASTCARD Newsletter 4	Sep-15	https://www.sintef.no/projectweb/fastcard/publications-/	Scientific community - Industry - Civil society	-	-
11	Oral	SINTEF	Thermochemical Conversion of Biomass - New Trends	Sep-15	8 th International Symposium on Feedstock Recycling of Polymeric Materials, Leoben, Austria	Scientific community - Industry		-
12	Oral	CNRS	FCC Co-processing of upgraded bio-oils mixed with crude oil distillates: How much hydrogen is required?	Nov-15	4th International Conference on Thermochemical Conversion, Chicago, Illinois	Scientific community - Industry		-
13	Posters	UGent	Microkinetics assisted analysis of hydrotreating selectivities in fast pyrolysis oil upgrading	Jan-16	Joint workshop of ENMIX, FASTCARD, CASCATBEL, BIOGO, Stuttgart (Germany)	Scientific community - Industry	40	Europe
14	Posters	USTUTT	Co-Catalytic Cracking of n-Decane and 2-Ethylphenol for the Conversion of Fossil- and Bio-Based Feeds in Co-FCC	Jan-16	Joint workshop of ENMIX, FASTCARD, CASCATBEL, BIOGO, Stuttgart (Germany)	Scientific community - Industry	40	Europe
15	Posters	USTUTT	Modification of Co-FCC Catalysts and Their Characterization by Solid-State NMR Spectroscopy	Jan-16	Joint workshop of ENMIX, FASTCARD, CASCATBEL, BIOGO, Stuttgart (Germany)	Scientific community - Industry	40	Europe
16	Posters	UGent	A Multi-Scale Modelling Platform applied towards Fischer Tropsch Synthesis on Fe catalysts	Jan-16	Joint workshop of ENMIX, FASTCARD, CASCATBEL, BIOGO, Stuttgart (Germany)	Scientific community - Industry	40	Europe
17	Posters	CNRS	Fischer-Tropsch on iron nano-particles catalysts	Jan-16	Joint workshop of ENMIX, FASTCARD, CASCATBEL, BIOGO, Stuttgart (Germany)	Scientific community - Industry	40	Europe
18	Posters	CNRS	Nickel nanoparticles encapsulation in single crystal zeolite for the biomass-derived steam hydrocarbon reforming	Jan-16	Joint workshop of ENMIX, FASTCARD, CASCATBEL, BIOGO, Stuttgart (Germany)	Scientific community - Industry	40	Europe
19	Posters	UGent	Enhanced catalytic performance of Ni-Fe alloy in methane dry reforming: role of Fe	Jan-16	Joint workshop of ENMIX, FASTCARD, CASCATBEL, BIOGO, Stuttgart (Germany)	Scientific community - Industry	40	Europe

Nº	Type of activities	Main leader	Title	Date	Place	Type of audience	Size of audience	Countries addressed
20	Oral	BTG	Hydrocarbon reforming and CO2 tolerant Fischer-Tropsch ? the gasification value chain	Jan-16	Joint workshop of ENMIX, FASTCARD, CASCATBEL, BIOGO, Stuttgart (Germany)	Scientific community - Industry	40	Europe
21	Oral	PDC	Conceptual design of biomass-to-liquids processes	Jan-16	Joint workshop of ENMIX, FASTCARD, CASCATBEL, BIOGO, Stuttgart (Germany)	Scientific community - Industry	40	Europe
22	Oral	REPSOL	Biofuels production in conventional oil refineries through bio-oil co-processing	Jan-16	Joint workshop of ENMIX, FASTCARD, CASCATBEL, BIOGO, Stuttgart (Germany)	Scientific community - Industry	40	Europe
23	Posters	UGent	Gas Phase Anisole Hydrodeoxygenation over Supported Mo oxide and carbide catalysts as an alternative to Mo sulfides	Mar-16	17th Netherlands' Catalysis and Chemistry Conference, Noordwijkerhout, Nederland	Scientific community - Industry		-
24	Oral	CNRS	Highly selective Fischer-Tropsch Catalyst using entrapped iron nanoparticles in silicalite-1	Mar-16	Groupe Français des Zéolites (GFZ), France	Scientific community - Industry		-
25	Oral	CNRS	Highly selective Fischer-Tropsch Catalyst using entrapped iron nanoparticles in silicalite-1	Mar-16	39th annual British Zeolite Association meeting, the University of Bath, UK	Scientific community - Industry		-
26	Posters	UGent	Insights into the activity of supported Mo oxide and their carbide analogues in catalytic conversion of biomass derived oxygenates	May-16	Cascatbel Workshop 2016, Chalkidiki, Greece	Scientific community - Industry	70	Europe
27	Oral	SINTEF	Catalytic HDO of phenolics in the gas and liquid phase over supported MoO3 and its pre-carburized analogues	May-16	Cascatbel Workshop 2016, Chalkidiki, Greece	Scientific community - Industry	70	Europe
28	Oral	CNRS	Highly selective Fischer-Tropsch Catalyst using entrapped iron nanoparticles in silicalite-1	May-16	French Conference on Catalysis, Frejus (France)	Scientific community - Industry		-
29	Oral	BTG	Hydrocarbon steam reforming on highly stable nickel nanoparticules encapsulated inside hollow silicalite-1 crystals	May-16	French Conference on Catalysis, Frejus (France)	Scientific community - Industry		-

Nº	Type of activities	Main leader	Title	Date	Place	Type of audience	Size of audience	Countries addressed
30	Oral	BTG	FCC of upgraded bio-oils mixed with crude oil distillates: How much hydrogen is needed in the up-grading process?	Jun-16	24th European Biomass Conference and Exhibition, Amsterdam, Nederlands	Scientific community - Industry	1500	International
31	Oral	USTUTT	Co-Catalytic Cracking of n-Decane and 2-Ethylphenol for the Conversion of Fossil- and Bio-Based Feeds in Co-FCC	Jun-16	The 18th International Zeolite Conference, Rio de Janeiro, Brazil	Scientific community - Industry	500	International
32	Posters	ECN	Mesoporous alumina catalyst supports and solid sorbents	Jun-16	The 18th International Zeolite Conference, Rio de Janeiro, Brazil	Scientific community - Industry	500	International
33	Oral	CNRS	Synthesis of size- and composition-controlled metal nanoparticles protected by zeolite nanoboxes	Jun-16	The 18th International Zeolite Conference, Rio de Janeiro, Brazil	Scientific community - Industry	500	International
34	Oral	BTG	Hydrocarbon steam reforming on highly stable nickel nanoparticules encapsulated inside hollow silicalite-1 crystals	Jun-16	The 18th International Zeolite Conference, Rio de Janeiro, Brazil	Scientific community - Industry	500	International
35	Posters	UGent	The mechanism of carbon gasification over a Fe-Ni catalyst after methane dry reforming	Jul-16	16th International Congress on Catalysis, Beijing China	Scientific community - Industry	2500	International
36	Oral	CNRS	Catalysis inside a box	Jul-16	The 16th International Congress on Catalysis July 3-8 2016, Beijing China	Scientific community - Industry	2500	International
37	Oral	CNRS	Hydrocarbon steam reforming on highly stable nickel nanoparticules encapsulated inside hollow silicalite-1 crystals	Jul-16	16th International Congress on Catalysis (ICC 16) July 3 to 8, 2016 in Beijing, China	Scientific community - Industry	2500	International
38	Posters	USTUTT	Co-Catalytic Cracking of n-Decane and 2-Ethylphenol for the Conversion of Fossil- and Bio-Based Feeds in Co-FCC	Aug-16	BASF International Summer Course, Ludwigshafen, Germany	Scientific community - Industry	25	Europe
39	Web	USTUTT	FASTCARD Newsletter 5	Sep-16	https://www.sintef.no/projectweb/fastcard/publications-/	Scientific community - Industry - Civil society	-	-

Nº	Type of activities	Main leader	Title	Date	Place	Type of audience	Size of audience	Countries addressed
40	Oral	BIC	Novel catalysts with improved stability for hydrotreatment of biomass pyrolysis liquids into valuable products	Sep-16	4th Russian-German Seminar, Kloster Banz, Germany.	Scientific community - Industry		-
41	Oral	UGent	Novel Fe-promoted MgAl2O4 support material for control of carbon deposition during reforming reactions	Nov-16	2016 AIChE Annual Meeting, San Francisco, USA	Scientific community - Industry	500	-
42	Oral	GRACE	FASTCARD and Biomass Integration into the Fossil Stream via HDO/Co-FCC	Apr-17	6th LCS Zeolite Workshop; Cabourg, France	Scientific community - Industry	50	Europe
43	Oral	UGent	Ni supported on MgFeAlOx as carbon resistant catalyst for methane reforming: structural and mechanistic study	Jun-17	North American Catalysis Society Meeting 2017	Scientific community - Industry	1700	International
44	Oral	ST-GOBAIN	PERFORMANCE OF NOVEL ICE-TEMPLATED MATERIALS FOR TAR REMOVAL FROM BIOMASS GASIFICATION PRODUCER GAS	Jun-17	25th European Biomass Conference and Exhibition, 12-15 June 2017 Stockholm, Sweden	Scientific community - Industry	1500	International
45	Oral	BIC	An advanced approach to produce catalysts with high stability for effective pyrolysis oil hydrotreatment into co-FCC feeds	Aug-17	13th European Congress on Catalysis, Florence, Italy,	Scientific community - Industry	1700	International
46	Oral	ECN	Steam reforming of the producer gas obtained from the gasification of beech wood: scale up from laboratory benches to full-size demonstrator	Aug-17	13th European Congress on Catalysis, Florence, Italy,	Scientific community - Industry	1700	International
47	Web	USTUTT	FASTCARD Newsletter 6	Sep-17	https://www.sintef.no/projectweb/fastcard/publications-/	Scientific community - Industry - Civil society	-	-
48	Oral	CNRS	FCC of upgraded pyrolysis liquids mixed with crude oil distillates: combined strategies for improving bio-fuels yields and quality	Sep-17	CATALYSIS FOR RENEWABLE SOURCES: FUEL, ENERGY, CHEMICALS, Gabicce Mare, Italy	Scientific community - Industry	200	Europe
49	Oral	BIC	STABLE CATALYST? THE KEY TO 2nd GENERATION BIOFUELS	Sep-17	CATALYSIS FOR RENEWABLE SOURCES: FUEL, ENERGY, CHEMICALS, Gabicce Mare, Italy	Scientific community - Industry	200	Europe

Nº	Type of activities	Main leader	Title	Date	Place	Type of audience	Size of audience	Countries addressed
50	Oral	CNRS	FCC of upgraded pyrolysis liquids mixed with crude oil distillates: strategies for improving bio-fuels quality and minimizing production costs	Oct-17	10thWorld Congress of Chemical Engineering, Barcelona, Spain	Scientific community - Industry	3000	International
51	Posters	USTUTT	Conversion of a bio-oil model compound on AlCl3-modified porous catalysts investigated by in situ multi-nuclear solid-state NMR spectroscopy	Oct-17	The 10th World Congress of Chemical Engineering, Barcelona, Spain	Scientific community - Industry	3000	International
52	Oral	PDC	Economic evaluation of biofuels production from lignocellulosic biomass	Oct-17	10thWorld Congress of Chemical Engineering, Barcelona, Spain	Scientific community - Industry	3000	International
53	Oral	USTUTT	Co-Catalytic Cracking of n-Decane and 2-Ethylphenol over Various Zeolites for the Co-Conversion of Fossil- and Bio-Based Feeds in Co-FCC	Oct-17	DGMK International Conference, Dresden, Germany	Scientific community - Industry		-
54	Posters	ENI	Kinetic model and simulation of Fischer Tropsch(FT) reactor with iron catalyst: state of art and FASTCARD alternative	Nov-17	2nd International Conference on Advances in Chemical Engineering & Technology, Paris, France	Scientific community - Industry		-

2.2 Section B (Confidential)

2.2.1 Part B2 - LIST OF EXPLOITABLE RESULTS

During the project period communication, dissemination and exploitation have been an important topic. A group consisting of the industrial partners and work package leaders (exploitation panel) were put together to ensure the correct approach. In addition a Exploitation Seminar was arranged during the project meeting at M36. An expert appointed by the project officer, Gerhard Goldbeck (Goldbeck Consulting), coordinated the seminar. During the process several exploitable results were identified and the outcome was a report on the exploitable results. A summary of the Key Exploitable Results (KERs) can be found in the table below and are elaborated in further detail in the project deliverable D8.3.

Type of exploitable foreground	Exploitable Foreground (description)	Confidential	Foreseen embargo date	Exploitable product(s) or measure(s)	Sector(s) of application	Timetable for commercial use or any other use	Patents or other IPR exploitation (licenses)	Owner & Other Beneficiary(s) involved
General advancement of knowledge	Pyrolysis Liquid Stabilisation (Process) Hydrotreating pyrolysis liquids to allow further, easier application of the liquid in different markets. The exploitataion include the process related part, consisting of the proper design of the overall process to ensure highest carbon yields, and lowest associated costs (CAPEX, OPEX).	Yes		Pyrolysis Liquid Stabilisation (Process)	Refineries	5-10 years	NL2008794; WO2013169112; EP2847299 (BTG)	B.T.G. BIC(catalyst improvement) CNRS (testing products) Grace (testing products) Repsol (testing products)
General advancement of knowledge	Pyrolysis Liquid Stabilisation (Catalyst) Hydrotreating pyrolysis liquids allow further, easier application of the liquid in different markets. Key part is the catalysts, which should be very active at low temperatures to defunctionalise the bio-liquids. This KER comprises the catalyst composition and preparation method.	Yes		Pyrolysis Liquid Stabilisation (Catalyst)	First costumers aimed at are refineries	5-10 years	WO2012030215 (A1) US2013219774 (A1) US9365776 (B2) EP2611883 (A1) CN103080275 (A)	B.T.G. BIC (catalyst improvement) CNRS (testing products) Grace (testing products) Repsol (testing products)

Type of exploitable foreground	Exploitable Foreground (description)	Confidential	Foreseen embargo date	Exploitable product(s) or measure(s)	Sector(s) of application	Timetable for commercial use or any other use	Patents or other IPR exploitation (licenses)	Owner & Other Beneficiary(s) involved
General advancement of knowledge	Co-FCC catalyst Development of a co-FCC catalyst which is able to handle a less deeply hydrodeoxygenated bio-oil. (SPO co-processing)	Yes		Co-FCC catalyst	Refineries	5 years	Grace CNRS UStutt Repsol?	Grace CNRS UStutt Repsol
General advancement of knowledge	microKinetic Engine The microKinetic Engine is a pre-existing software package that has been used within FASTCARD for the kinetic model development for the investigated reactions, i.e., hydrocracbon reforming, FT synthesis, HDO and FCC reactions. The model development has provided inspiration for updates and enhancements of the software package. The software is characterized by its user friendliness, i.e., no programming is required by the end user while constructing a (micro)kinetic model. The software will be one of the subjects of a "spin-off" company, Sharp Engineering, which will be founded in the first quarter of 2017.	Yes		software package	Industrial research units.	product is market ready, development of additional features is continued	the IP is entirely situated at Ghent University	UGhent
General advancement of knowledge	"Gas-line": BTL process based on indirect gasification and FT A process allowing the conversion of biomass into transportation fuels by drying, indirect gasification, reforming, Fischer-Tropsch synthes	Yes		BTL process	Refineries	15 years	WO 2014/070001, WO 2016/091828	ENI ECN PDC
General advancement of knowledge	"Liquid Line": BTL process based on pyrolysis and pyrolysis oil co-feeding in FCC unit. A process allowing the conversion of biomass into transportation fuels by fast pyrolysis, hydrotreating and FCC co-feeding.	Yes		BTL process based on pyrolysis and pyrolysis oil co-feeding in FCC unit	Oil majors	4 years	BTG (WO 2009/014436)	B.T.G. Repsol PDC

3 Report on societal implications

Replies to the following questions will assist the Commission to obtain statistics and indicators on societal and socio-economic issues addressed by projects. The questions are arranged in a number of key themes. As well as producing certain statistics, the replies will also help identify those projects that have shown a real engagement with wider societal issues, and thereby identify interesting approaches to these issues and best practices. The replies for individual projects will not be made public.

A General Information *(completed automatically when **Grant Agreement number** is entered.*

Grant Agreement Number:	604277
Title of Project:	FAST industrialisation by CAtalysts Research and Development (FASTCARD)
Name and Title of Coordinator:	Dr Duncan Akporiaye

B Ethics

1. Did your project undergo an Ethics Review (and/or Screening)? • If Yes: have you described the progress of compliance with the relevant Ethics Review/Screening Requirements in the frame of the periodic/final project reports? Special Reminder: the progress of compliance with the Ethics Review/Screening Requirements should be described in the Period/Final Project Reports under the Section 3.2.2 *'Work Progress and Achievements'*	***0Yes 1No***
2. Please indicate whether your project involved any of the following issues (tick box) :	***YES***
RESEARCH ON HUMANS	
• Did the project involve children?	
• Did the project involve patients?	
• Did the project involve persons not able to give consent?	
• Did the project involve adult healthy volunteers?	
• Did the project involve Human genetic material?	
• Did the project involve Human biological samples?	
• Did the project involve Human data collection?	
RESEARCH ON HUMAN EMBRYO/FOETUS	
• Did the project involve Human Embryos?	
• Did the project involve Human Foetal Tissue / Cells?	
• Did the project involve Human Embryonic Stem Cells (hESCs)?	
• Did the project on human Embryonic Stem Cells involve cells in culture?	
• Did the project on human Embryonic Stem Cells involve the derivation of cells from Embryos?	
PRIVACY	
• Did the project involve processing of genetic information or personal data (eg. health, sexual lifestyle, ethnicity, political opinion, religious or philosophical conviction)?	
• Did the project involve tracking the location or observation of people?	
RESEARCH ON ANIMALS	
• Did the project involve research on animals?	
• Were those animals transgenic small laboratory animals?	

• Were those animals transgenic farm animals?	
• Were those animals cloned farm animals?	
• Were those animals non-human primates?	
RESEARCH INVOLVING DEVELOPING COUNTRIES	
• Did the project involve the use of local resources (genetic, animal, plant etc)?	
• Was the project of benefit to local community (capacity building, access to healthcare, education etc)?	
DUAL USE	
• Research having direct military use	0 Yes 0 No
• Research having the potential for terrorist abuse	

C Workforce Statistics

3. Workforce statistics for the project: Please indicate in the table below the number of people who worked on the project (on a headcount basis).

Type of Position	Number of Women	Number of Men
Scientific Coordinator	0	1
Work package leaders	3	6
Experienced researchers (i.e. PhD holders)	16	39
PhD Students	3	7
Other (Master)	4	5

4. How many additional researchers (in companies and universities) were recruited specifically for this project?	
Of which, indicate the number of men:	0

D Gender Aspects

5. Did you carry out specific Gender Equality Actions under the project?

○ Yes
◉ No

6. Which of the following actions did you carry out and how effective were they?

	Not at all effective				Very effective
❑ Design and implement an equal opportunity policy	○	○	○	○	○
❑ Set targets to achieve a gender balance in the workforce	○	○	○	○	○
❑ Organise conferences and workshops on gender	○	○	○	○	○
❑ Actions to improve work-life balance	○	○	○	○	○

○ Other:

7. Was there a gender dimension associated with the research content – i.e. wherever people were the focus of the research as, for example, consumers, users, patients or in trials, was the issue of gender considered and addressed?

○ Yes- please specify

◉ No

E Synergies with Science Education

8. Did your project involve working with students and/or school pupils (e.g. open days, participation in science festivals and events, prizes/competitions or joint projects)?

○ Yes- please specify

◉ No

9. Did the project generate any science education material (e.g. kits, websites, explanatory booklets, DVDs)?

○ Yes- please specify

◉ No

F Interdisciplinarity

10. Which disciplines (see list below) are involved in your project?

◉ Main discipline[1]:
○ Associated discipline[1]: ○ Associated discipline[1]:

G Engaging with Civil society and policy makers

11a Did your project engage with societal actors beyond the research community? *(if 'No', go to Question 14)*

○ Yes
◉ No

11b If yes, did you engage with citizens (citizens' panels / juries) or organised civil society (NGOs, patients' groups etc.)?

○ No
○ Yes- in determining what research should be performed
○ Yes - in implementing the research
○ Yes, in communicating /disseminating / using the results of the project

[1] Insert number from list below (Frascati Manual).

11c In doing so, did your project involve actors whose role is mainly to organise the dialogue with citizens and organised civil society (e.g. professional mediator; communication company, science museums)?	○ ○	Yes No

12. Did you engage with government / public bodies or policy makers (including international organisations)

- ○ No
- ◉ Yes- in framing the research agenda
- ○ Yes - in implementing the research agenda
- ○ Yes, in communicating /disseminating / using the results of the project

13a Will the project generate outputs (expertise or scientific advice) which could be used by policy makers?

- ◉ Yes – as a **primary** objective (please indicate areas below- multiple answers possible)
- ○ Yes – as a **secondary** objective (please indicate areas below - multiple answer possible)
- ○ No

13b If Yes, in which fields?

Agriculture		**Energy**		Human rights	
Audiovisual and Media		Enlargement		Information Society	
Budget		Enterprise		Institutional affairs	
Competition		**Environment**		Internal Market	
Consumers		External Relations		Justice, freedom and security	
Culture		External Trade		Public Health	
Customs		Fisheries and Maritime Affairs		**Regional Policy**	
Development Economic and Monetary Affairs		Food Safety		Research and Innovation	
Education, Training, Youth		Foreign and Security Policy		Space	
Employment and Social Affairs		Fraud		Taxation	
		Humanitarian aid		**Transport**	

13c If Yes, at which level?

- ○ Local / regional levels
- ◉ National level
- ◉ European level
- ○ International level

H Use and dissemination

14. How many Articles were published/accepted for publication in peer-reviewed journals?	**16 (26)**
To how many of these is open access[2] provided?	**16**
How many of these are published in open access journals?	**1**
How many of these are published in open repositories?	**0**
To how many of these is open access not provided?	**0**
Please check all applicable reasons for not providing open access:	
☒ publisher's licensing agreement would not permit publishing in a repository ☒no suitable repository available ❑ no suitable open access journal available ❑ no funds available to publish in an open access journal ❑ lack of time and resources ❑ lack of information on open access ❑ other[3]: ……	

15. How many new patent applications ('priority filings') have been made? *("Technologically unique": multiple applications for the same invention in different jurisdictions should be counted as just one application of grant).*		**0**
16. Indicate how many of the following Intellectual Property Rights were applied for (give number in each box).	Trademark	**0**
	Registered design	**0**
	Other	**0**

[2] Open Access is defined as free of charge access for anyone via Internet.
[3] For instance: classification for security project.

17. How many spin-off companies were created / are planned as a direct result of the project?	**1**
Indicate the approximate number of additional jobs in these companies:	**1**

18. Please indicate whether your project has a potential impact on employment, in comparison with the situation before your project:

■	Increase in employment, or	■	In small & medium-sized enterprises
❑	Safeguard employment, or	■	In large companies
❑	Decrease in employment,	❑	None of the above / not relevant to the project
❑	Difficult to estimate / not possible to quantify		

19. For your project partnership please estimate the employment effect resulting directly from your participation in Full Time Equivalent (*FTE = one person working fulltime for a year*) jobs:	*Indicate figure:*
Difficult to estimate / not possible to quantify	■

I Media and Communication to the general public

20. As part of the project, were any of the beneficiaries professionals in communication or media relations?

● Yes ○ No

21. As part of the project, have any beneficiaries received professional media / communication training / advice to improve communication with the general public?

○ Yes ● No

22 Which of the following have been used to communicate information about your project to the general public, or have resulted from your project?

❑	Press Release	■	Coverage in specialist press
❑	Media briefing	■	Coverage in general (non-specialist) press
❑	TV coverage / report	❑	Coverage in national press
❑	Radio coverage / report	❑	Coverage in international press
■	Brochures /posters / flyers	■	Website for the general public / internet
❑	DVD /Film /Multimedia	❑	Event targeting general public (festival, conference, exhibition, science café)

23 In which languages are the information products for the general public produced?

■	Language of the coordinator	■	English
❑	Other language(s)		

***Question F-10*:** Classification of Scientific Disciplines according to the Frascati Manual 2002 (Proposed Standard Practice for Surveys on Research and Experimental Development, OECD 2002):

FIELDS OF SCIENCE AND TECHNOLOGY

1. NATURAL SCIENCES

1.1 Mathematics and computer sciences [mathematics and other allied fields: computer sciences and other allied subjects (software development only; hardware development should be classified in the engineering fields)]

1.2 Physical sciences (astronomy and space sciences, physics and other allied subjects)

1.3 Chemical sciences (chemistry, other allied subjects)
1.4 Earth and related environmental sciences (geology, geophysics, mineralogy, physical geography and other geosciences, meteorology and other atmospheric sciences including climatic research, oceanography, vulcanology, palaeoecology, other allied sciences)
1.5 Biological sciences (biology, botany, bacteriology, microbiology, zoology, entomology, genetics, biochemistry, biophysics, other allied sciences, excluding clinical and veterinary sciences)

2 ENGINEERING AND TECHNOLOGY
2.1 Civil engineering (architecture engineering, building science and engineering, construction engineering, municipal and structural engineering and other allied subjects)
2.2 Electrical engineering, electronics [electrical engineering, electronics, communication engineering and systems, computer engineering (hardware only) and other allied subjects]
2.3. Other engineering sciences (such as chemical, aeronautical and space, mechanical, metallurgical and materials engineering, and their specialised subdivisions; forest products; applied sciences such as geodesy, industrial chemistry, etc.; the science and technology of food production; specialised technologies of interdisciplinary fields, e.g. systems analysis, metallurgy, mining, textile technology and other applied subjects)

3. MEDICAL SCIENCES
3.1 Basic medicine (anatomy, cytology, physiology, genetics, pharmacy, pharmacology, toxicology, immunology and immunohaematology, clinical chemistry, clinical microbiology, pathology)
3.2 Clinical medicine (anaesthesiology, paediatrics, obstetrics and gynaecology, internal medicine, surgery, dentistry, neurology, psychiatry, radiology, therapeutics, otorhinolaryngology, ophthalmology)
3.3 Health sciences (public health services, social medicine, hygiene, nursing, epidemiology)

4. AGRICULTURAL SCIENCES
4.1 Agriculture, forestry, fisheries and allied sciences (agronomy, animal husbandry, fisheries, forestry, horticulture, other allied subjects)
4.2 Veterinary medicine

5. SOCIAL SCIENCES
5.1 Psychology
5.2 Economics
5.3 Educational sciences (education and training and other allied subjects)
5.4 Other social sciences [anthropology (social and cultural) and ethnology, demography, geography (human, economic and social), town and country planning, management, law, linguistics, political sciences, sociology, organisation and methods, miscellaneous social sciences and interdisciplinary , methodological and historical S1T activities relating to subjects in this group. Physical anthropology, physical geography and psychophysiology should normally be classified with the natural sciences].

6. HUMANITIES
6.1 History (history, prehistory and history, together with auxiliary historical disciplines such as archaeology, numismatics, palaeography, genealogy, etc.)
6.2 Languages and literature (ancient and modern)
6.3 Other humanities [philosophy (including the history of science and technology) arts, history of art, art criticism, painting, sculpture, musicology, dramatic art excluding artistic "research" of any kind, religion, theology, other fields and subjects pertaining to the humanities, methodological, historical and other S1T activities relating to the subjects in this group]