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A timeline assessment of the Resfuels conversion technology portfolio

Brussels, 21/11/2019

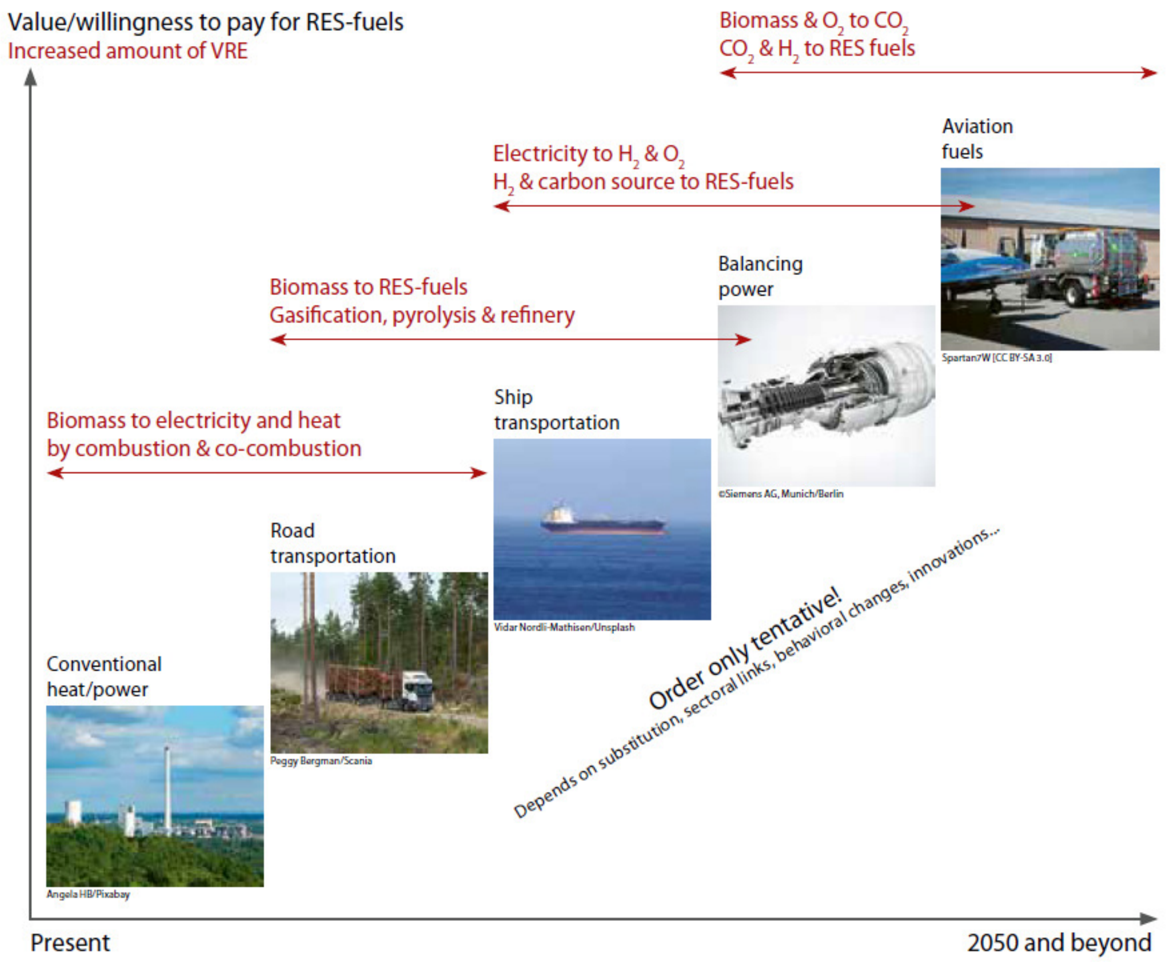
Paraskevi Karka, Ivar Petersson,
Stavros Papadokonstantakis, Filip Johnson,
Chalmers University of Technology

Outline

- Scope of the conversion technologies in ADVANCEFUEL
- The GoBiGas experience
- The ADVANCEFUEL approach(es)
- Conclusions and questions for discussion

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement N.° 764799.

(An estimate of) Value of carbon based fuels (“RES-fuels”) without net-emissions to the atmosphere



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Berndes, G., Goldmann, M., Johnsson, F., Lindroth, A., Wijkman, A., Abt, B., Bergh, J., Cowie, A., Kalliokoski, T., Kurz,W., Luyssaert, S., Nabuurs, G-J, Forests and the climate - Manage for maximum wood production or leave the forest as a carbon sink?, Kungl. Lantbruks- och skogsakademiens tidskrift, 6, 157, 2018, ISBN 978-91-88567-22-2

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The RESfuels conversion technology portfolio in ADVANCEFUEL

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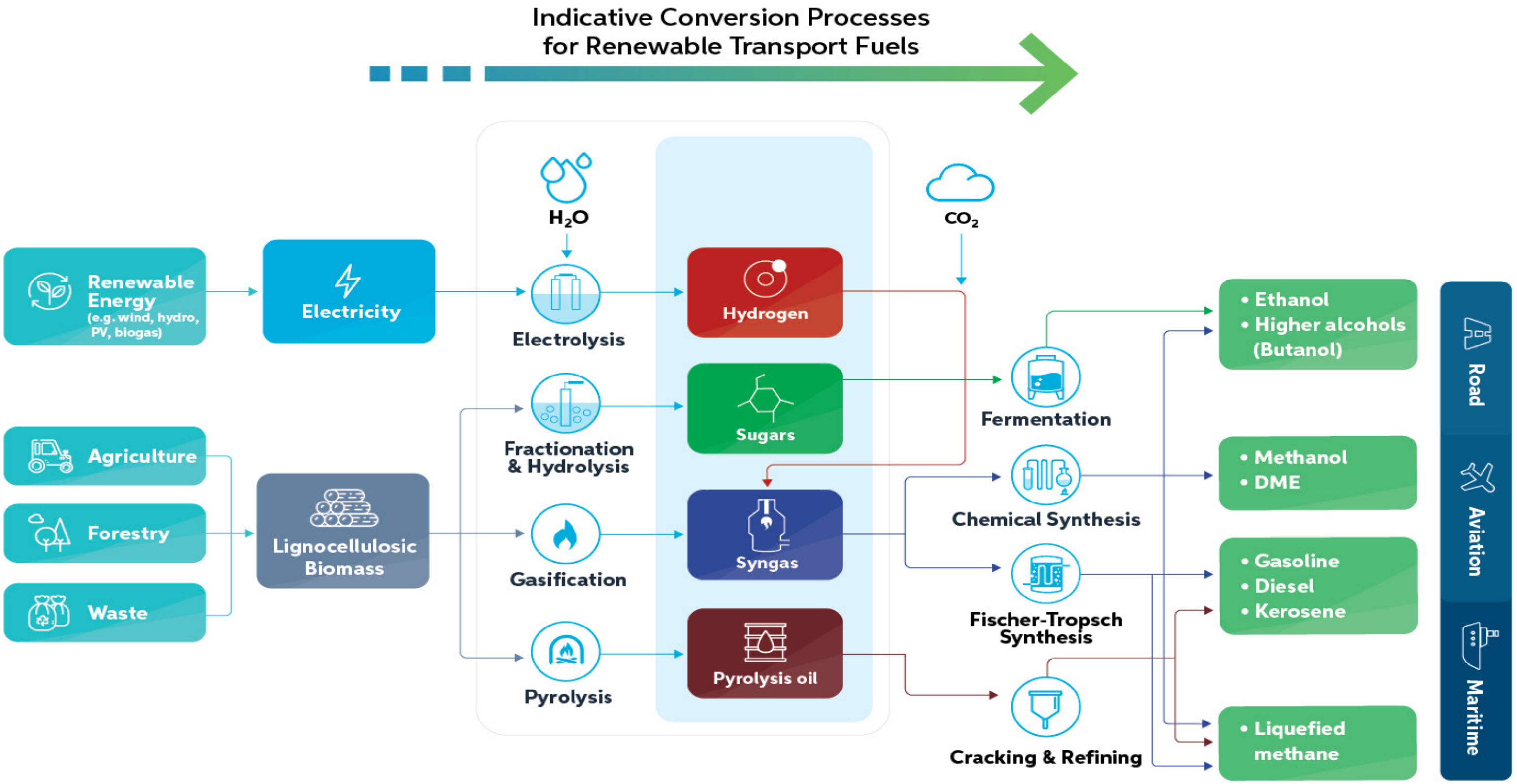


Indicative Conversion Processes
for Renewable Transport Fuels

Renewable Energy (e.g. wind, hydro, PV, biogas)

Electricity

Agriculture

Forestry

Waste

Lignocellulosic Biomass

H_2O

Electrolysis

Fractionation & Hydrolysis

Gasification

Pyrolysis

Hydrogen

Sugars

Syngas

Pyrolysis oil

CO_2

Fermentation

Chemical Synthesis

Fischer-Tropsch Synthesis

Cracking & Refining

- Ethanol
- Higher alcohols (Butanol)

- Methanol
- DME

- Gasoline
- Diesel
- Kerosene

- Liquefied methane

Road

Aviation

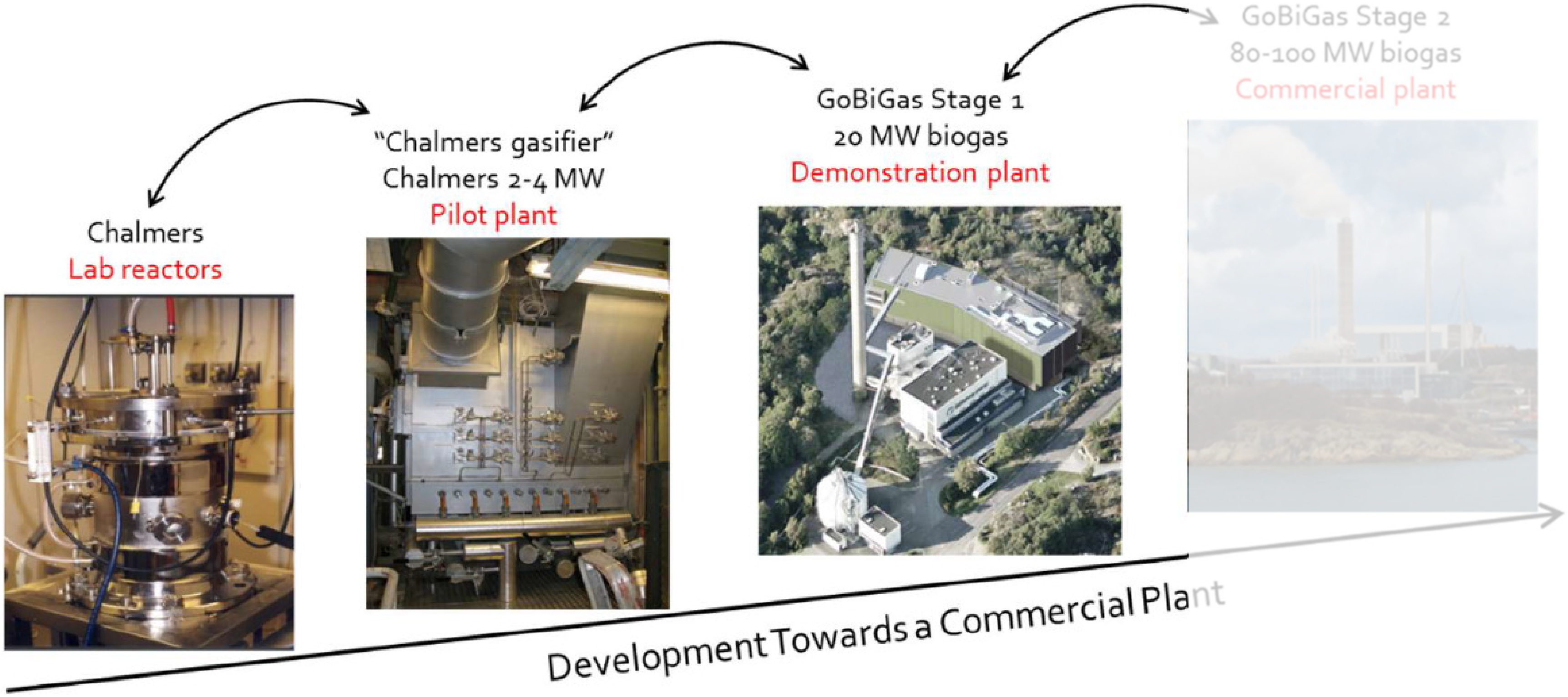
Maritime

Renewable resources
ADVANCEFUEL will focus on fuels produced from renewable resources, such as residues from agriculture and forestry, sustainable woody and grassy crops, waste and renewable energy, carbon dioxide and hydrogen.

Conversion processes
ADVANCEFUEL will look at different conversion processes that are already at a high development stage and have been validated in an industrial environment.

Renewable liquid fuels
Ultimately, ADVANCEFUEL aims to support uptake of both advanced biofuels and fuels produced from renewable hydrogen and CO2 in the road, aviation and maritime transport sectors.

The GoBiGas project timeline


Chalmers
Lab reactors

"Chalmers gasifier"
Chalmers 2-4 MW
Pilot plant

GoBiGas Stage 1
20 MW biogas
Demonstration plant

GoBiGas Stage 2
80-100 MW biogas
Commercial plant

Development Towards a Commercial Plant

~ 10 years,

~ 200 man-years of research activity

Larsson, A., Gunnarsson, I., Tengberg, F., The GoBiGas Project – Demonstration of the Production of Biomethane from Biomass via Gasification, Final Report, Göteborg Energi, 2018

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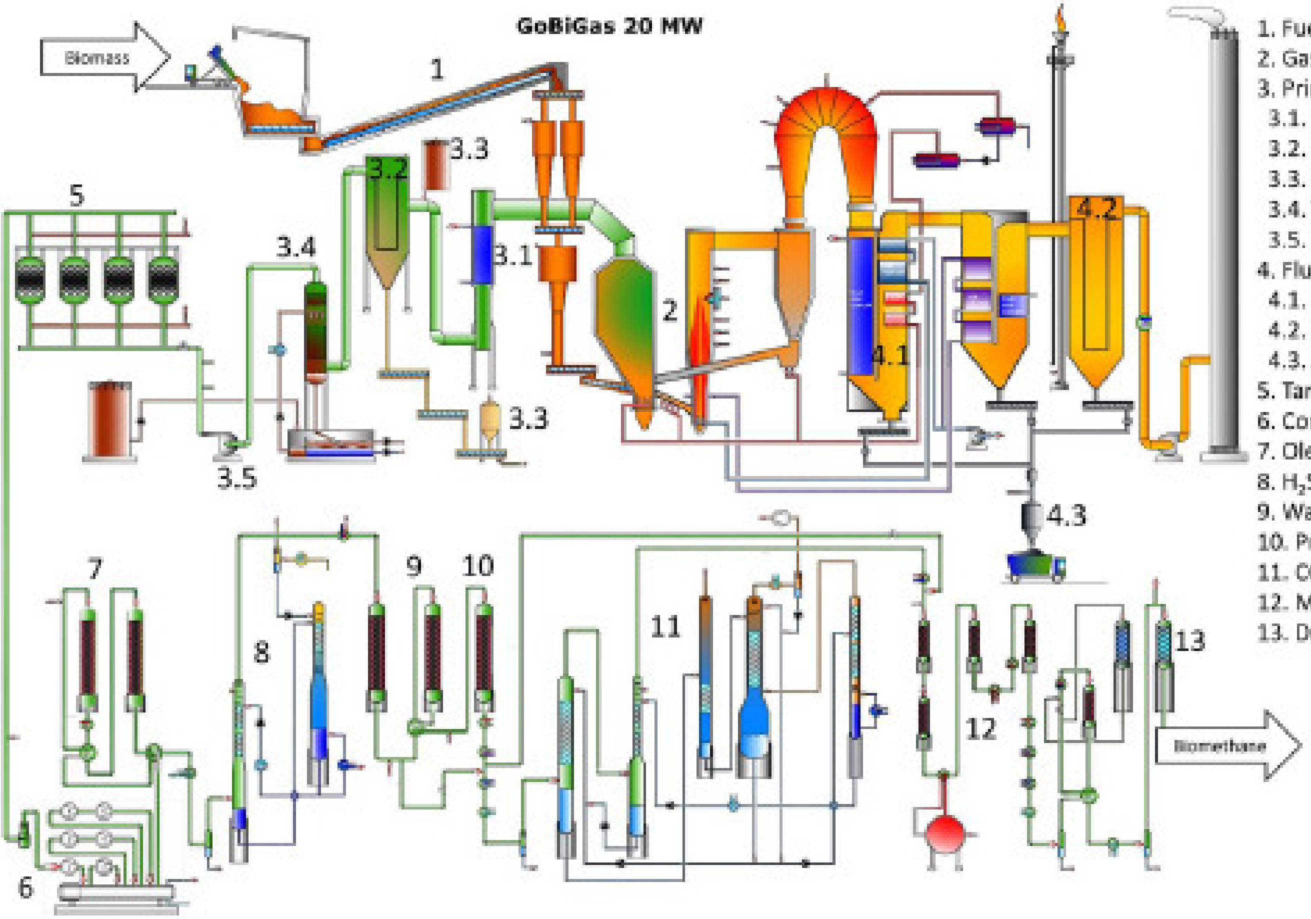
The GoBiGas project demonstration plant



1. Fuel handling system
2. Gasification and Combustion
3. Primary product gas cleaning
   3.1. Product gas cooler
   3.2. Product gas filter
   3.3. Precoating and particle recirc.
   3.4. Tar scrubber
   3.5. product gas fan
4. Flue gas system
   4.1. Flue gas cooling
   4.2. Flue gas filter and fan
   4.3. Ash handling system
5. Tar adsorption
6. Compressor
7. Olefin hydrogenation
8. H_2S scrubber
9. Water gas shift reaction
10. Pre methanation
11. CO2 scrubber
12. Methanation
13. Drying and odorization

Thunman et al., (2018), Energy Science & Engineering

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The GoBiGas project economics

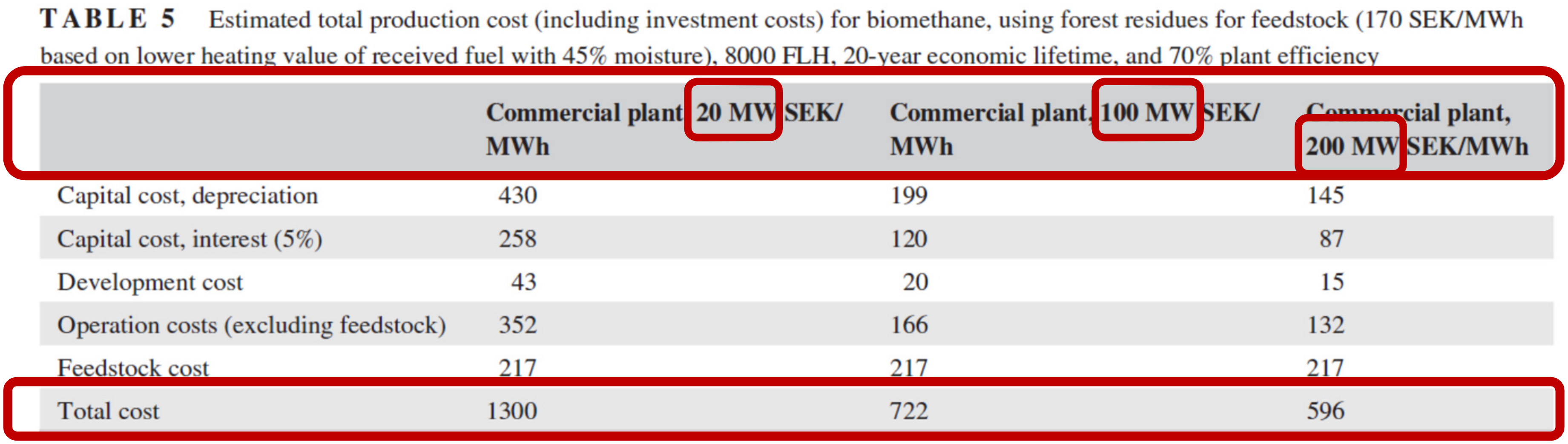

TABLE 5 Estimated total production cost (including investment costs) for biomethane, using forest residues for feedstock (170 SEK/MWh based on lower heating value of received fuel with 45% moisture), 8000 FLH, 20-year economic lifetime, and 70% plant efficiency

	Commercial plant 20 MW SEK/MWh	Commercial plant, 100 MW SEK/MWh	Commercial plant, 200 MW SEK/MWh
Capital cost, depreciation	430	199	145
Capital cost, interest (5%)	258	120	87
Development cost	43	20	15
Operation costs (excluding feedstock)	352	166	132
Feedstock cost	217	217	217
Total cost	1300	722	596

Corresponds to around 0.55 €/litre

Thunman et al., (2019), Energy Science & Engineering

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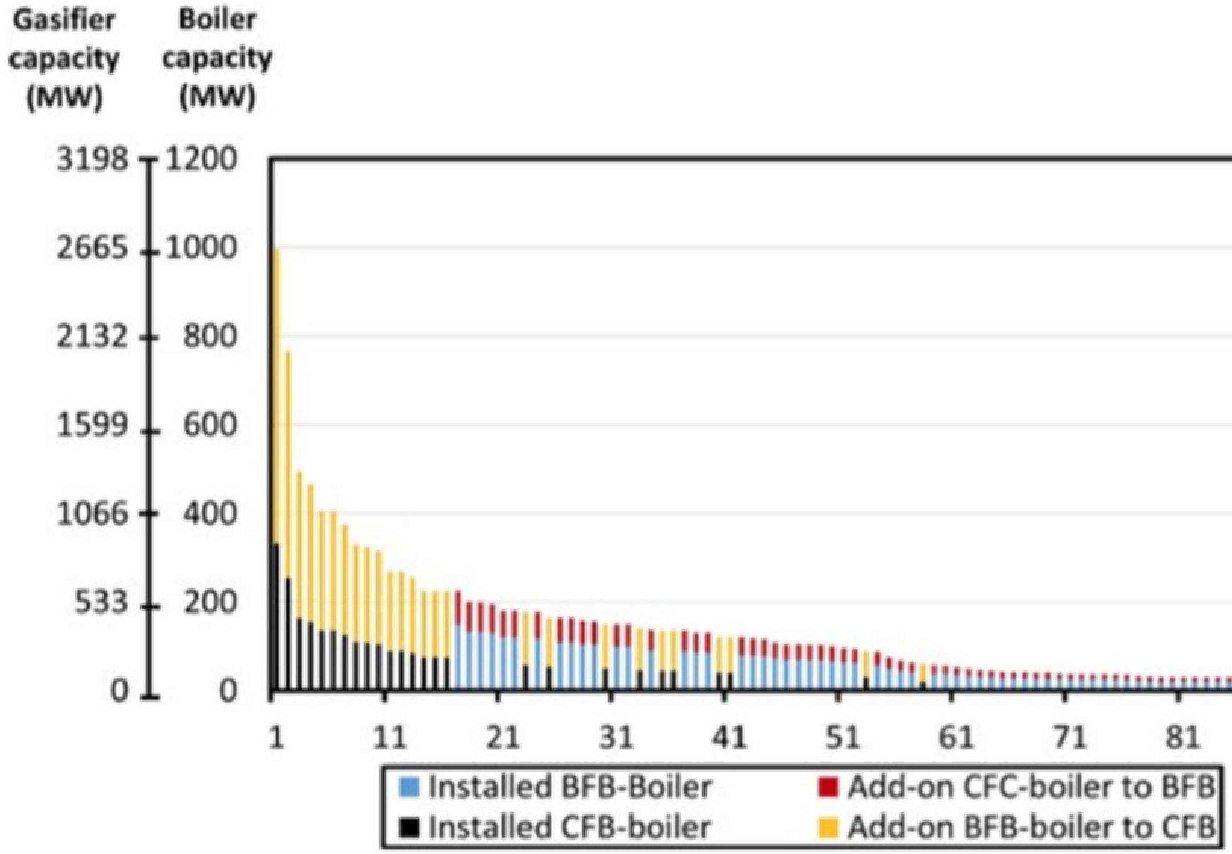
The GoBiGas project extension potential



Existing installed capacity of fluidized bed boilers in the Swedish energy system and the corresponding additional boiler sizes needed to realize their conversion to dual fluidized bed gasifiers

Thunman et al., (2018), Energy Science & Engineering

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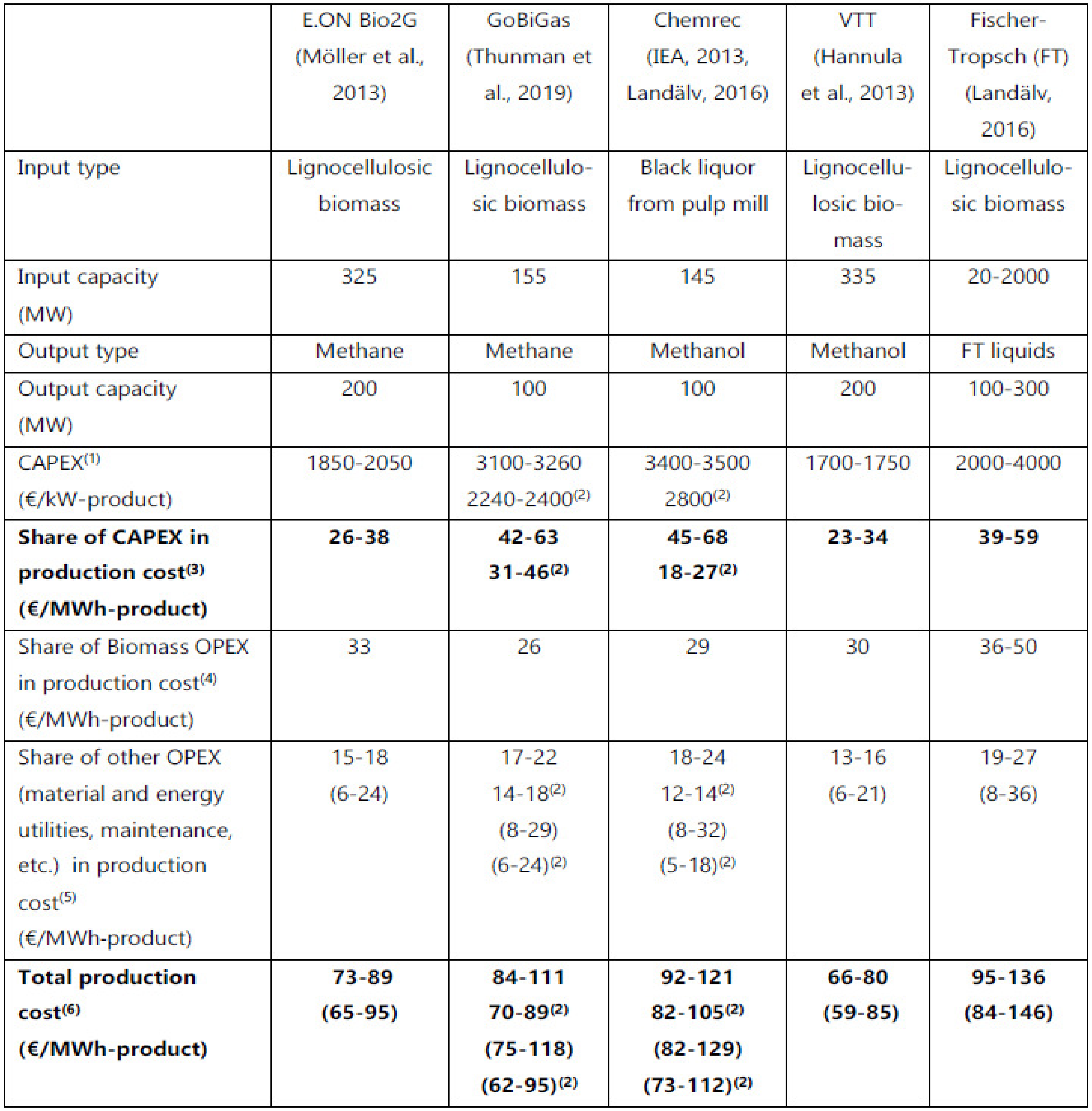
Top-down estimations of production costs for exemplary Resfuels conversion technologies



	E.ON Bio2G (Möller et al., 2013)	GoBiGas (Thunman et al., 2019)	Chemrec (IEA, 2013, Landälv, 2016)	VTT (Hannula et al., 2013)	Fischer-Tropsch (FT) (Landälv, 2016)
Input type	Lignocellulosic biomass	Lignocellulosic biomass	Black liquor from pulp mill	Lignocellulosic biomass	Lignocellulosic biomass
Input capacity (MW)	325	155	145	335	20-2000
Output type	Methane	Methane	Methanol	Methanol	FT liquids
Output capacity (MW)	200	100	100	200	100-300
CAPEX(1) (€/kW-product)	1850-2050	3100-3260 2240-2400(2)	3400-3500 2800(2)	1700-1750	2000-4000
Share of CAPEX in production cost(3) (€/MWh-product)	**26-38**	**42-63 31-46(2)**	**45-68 18-27(2)**	**23-34**	**39-59**
Share of Biomass OPEX in production cost(4) (€/MWh-product)	33	26	29	30	36-50
Share of other OPEX (material and energy utilities, maintenance, etc.) in production cost(5) (€/MWh-product)	15-18 (6-24)	17-22 14-18(2) (8-29) (6-24)(2)	18-24 12-14(2) (8-32) (5-18)(2)	13-16 (6-21)	19-27 (8-36)
Total production cost(6) (€/MWh-product)	**73-89 (65-95)**	**84-111 70-89(2) (75-118) (62-95)(2)**	**92-121 82-105(2) (82-129) (73-112)(2)**	**66-80 (59-85)**	**95-136 (84-146)**

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Main conclusions on TRL and costing (from literature references)

- 2nd generation ethanol tehcnologies are more mature as a whole (i.e., TRL>6), but with wide cost ranges (100-230 €/MWh-product)

- Gasification pathways are limited to only a few demonstration plants (73-89 €/MWh-product for methane/methanol/DME, 95-136 €/MWh-product for FT liquids)

- Pyrolysis pathways are the least mature as a whole (TRL≤6) because of the pyrolysis oil upgrading step (83-102 €/MWh-product for gasoline/diesel but with higher uncertainty than the rest)

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Identification of needs for development and innovations

- **Identification of factors** (technical and economic) dimensions which affect maturity of bio-fuel processes
- **Identification of barriers related to each factor** which constrain the development of a conversion technology and which must be overcome to increase the TRL status
- **Proposal of policy mechanisms (**incl. financial instruments**)** which should be adopted to overcome barriers and facilitate the development of RESfuels technologies

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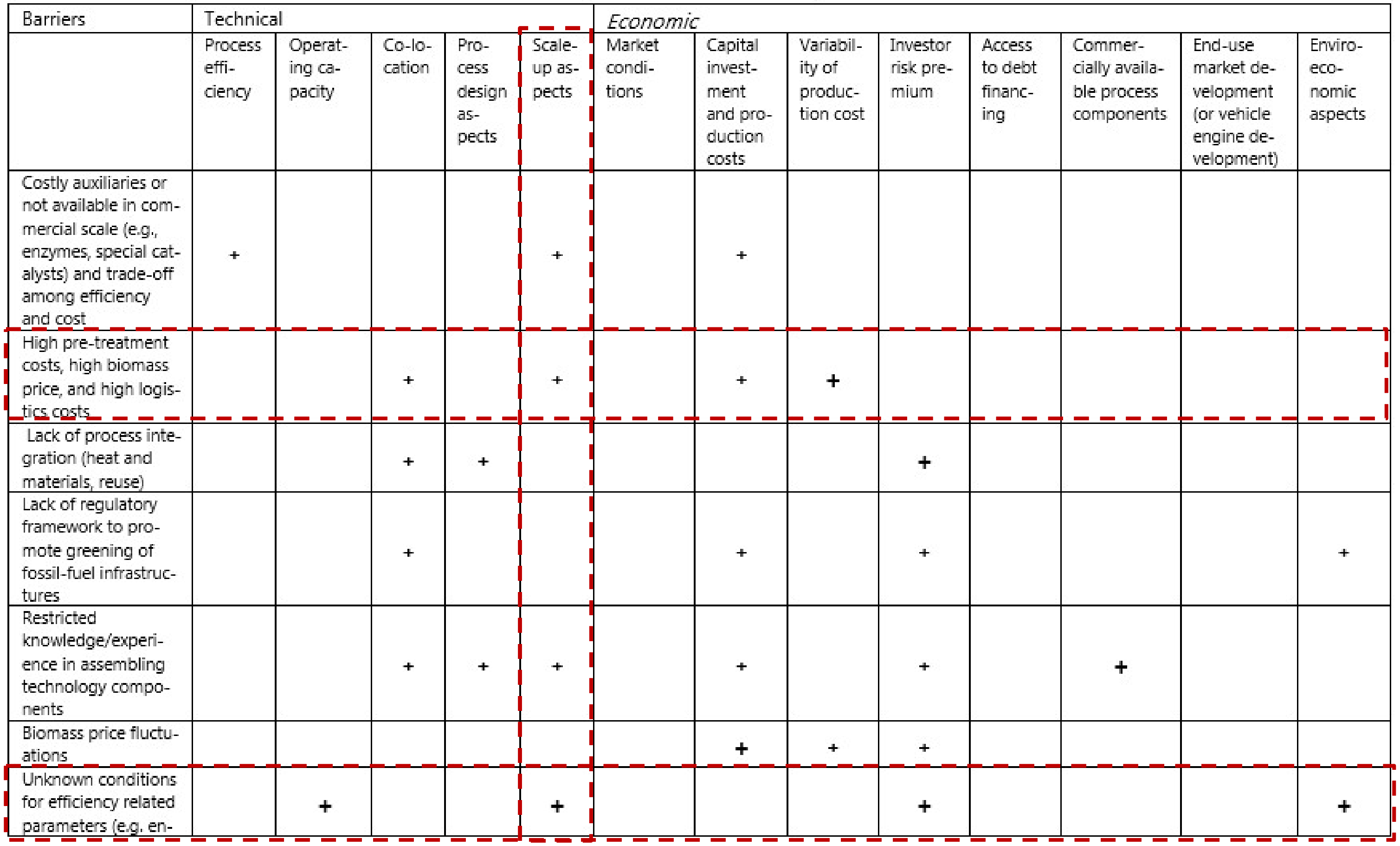
Relating barriers with technical and economic factors

- ✓Barriers are “case specific”
- ✓Each factor may be related with more than one barriers
- ✓Each barrier may affect more than one factors



Barriers	Technical					*Economic*							
	Process efficiency	Operating capacity	Co-location	Process design aspects	Scale-up aspects	Market conditions	Capital investment and production costs	Variability of production cost	Investor risk premium	Access to debt financing	Commercially available process components	End-use market development (or vehicle engine development)	Enviro-economic aspects
Costly auxiliaries or not available in commercial scale (e.g., enzymes, special catalysts) and trade-off among efficiency and cost	+				+		+						
High pre-treatment costs, high biomass price, and high logistics costs			+		+		+	+					
Lack of process integration (heat and materials, reuse)			+	+					+				
Lack of regulatory framework to promote greening of fossil-fuel infrastructures			+				+		+				+
Restricted knowledge/experience in assembling technology components			+	+	+		+		+		+		
Biomass price fluctuations							+	+	+				
Unknown conditions for efficiency related parameters (e.g. en-		+			+				+				+

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Relating policy mechanisms to identified barriers

- **Regulatory framework** (quota obligations, product standards, tax exemption and reduction, targets and qualifying criteria for incentives, feed-in-tariffs, subsidy, green procurement)

- **Financial instruments** (grants, feedstock premium, feed in tariffs, feed in premium, tax incentives, research and innovation funds)

- **Other soft measures** (e.g. best practices, lessons learned, capacity building, raising awareness)

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Application to methanol production from biomass gasifiation

Out of the technical factors

- 3 are related with barriers of Moderate (M) significance
- 2 are related with no barriers for the specific pathway (N)

Out of the economic factors

- 4 are related with barriers of Severe (S) significance
- 4 are related with barriers of Moderate (M) significance

Factor	Barrier ((S), (M), (N))	Explication	Policy mechanisms to overcome barriers
Technical			
Process efficiency	N	○ Gasification plants can reach **theoretical efficiency yields** in **commercial scale** ○ **Overall "feedstock to biomethanol"** yield comparably high	Capital investment grants for higher efficiency technologies should focus on: ○ maximum **utilisation of by-products** (e.g., tars), and ○ reduce CO_2 emissions (e.g., by innovative CCU pathways)
Process design aspects	**M**	○ Innovations **in scale-up** for: - **product quality**, - **tar fouling** in heat exchangers, - **syngas cleaning**, - **tar utilisation**	○ Regulations and R&D grants

Factor	Barrier ((S), (M), (N))	Explication	Policy mechanisms to overcome barriers
Economic			
Uncertainties of production cost	**S**	○ **Redundancy** that **avoids unplanned stops** in the production is a must. ○ **Timing of the investment**, the **location of the installation** and **price of feedstock**	**Feedstock premiums** towards a common framework in EU countries (a challenging task)
Commercially available process components	**M**	○ **Gasifier** is the **less mature** process step ○ Rest of the process components already reached the nth-of-its kind installation ○ **Learning** will only be related to the **assembly** of these parts	**Training**, capacity building, and certification.

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Main conclusions for methanol production via biomass gasification

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- The potential for **technical improvements** and innovation potential are rather **limited** in the case of methanol production.
- **Technological development of vehicle engines** to efficiently use methanol as a drop-in fuel are **more important** than the innovation of the biomass conversion technologies for this pathway.
- **Cost reductions** can mainly be expected from learning and knowledge sharing in **assembling existing process components.**
- **More important** are economic factors influenced by market conditions and regulatory frameworks on **fuel pricing, CO_2 taxes, blending targets**, and creating a more stable investment environment.

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Main conclusions for 2nd generation ethanol production via biocheical technologies

- Has reached the **commercialisation stage (Abengoa plant (USA), DuPont's plant (USA), Biochemtex plant (Italy), GranBio Bioflex plant (Brazil) etc.)**

- Technological **innovations** are expected with respect to the possibilities to **utilise the by-products**

- **Similar barriers** and related policy mechanisms to the case of methanol are also applicable here, as far as the **economic factors** are concerned.

- More **developed state of end-use market** for ethanol as a transportation fuel

Open question:
What is the current market of bio-methanol and bio-ethanol as transportation fuels (EU, USA, World)?
How are they (planned to be) promoted (e.g., blending)?
What are the technical problems to be solved and the respective time-horizon in engine development?

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Integrating/Greening existing fossil fuel infrastructures

The main integration options maybe direct and indirect.

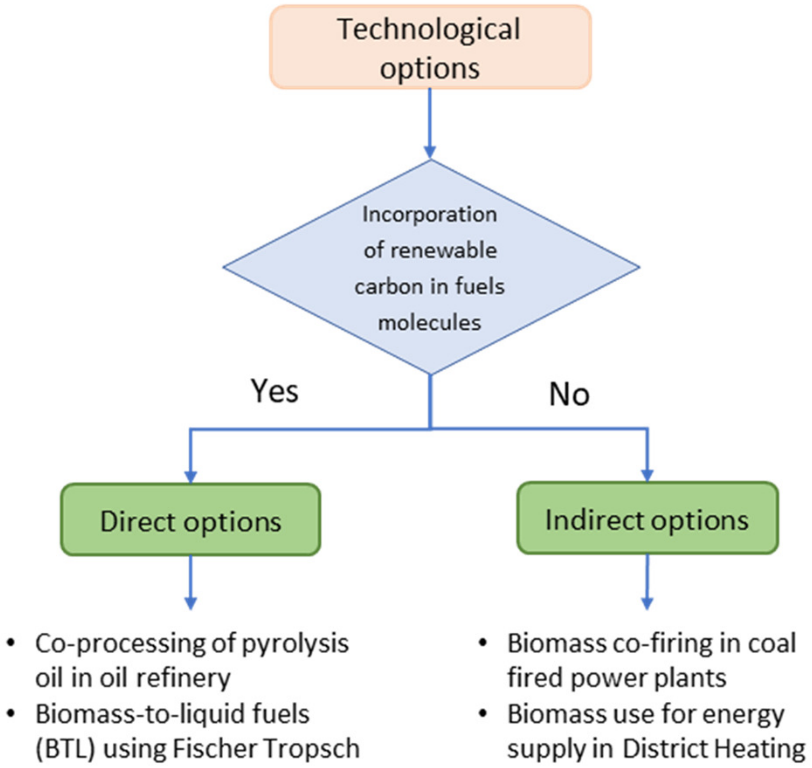
Direct options:

- ○ Blending of biogenic feedstock with a fossil-based process stream followed by co-processing in a downstream conventional unit
- ○ Substitution of a conventional part of a liquid fuel production chain by a bio-based one

Indirect options:

Indirectly contribute to enable the development of biomass market and infrastructures

- ○ Biomass co-firing in power plants
- ○ Combined heat and power in District Heating networks (DH)



Technological options

Incorporation of renewable carbon in fuels molecules

Yes

No

Direct options

- Co-processing of pyrolysis oil in oil refinery
- Biomass-to-liquid fuels (BTL) using Fischer Tropsch

Indirect options

- Biomass co-firing in coal fired power plants
- Biomass use for energy supply in District Heating

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Collecting data for assessment of biomass-process implementation timeline

The analysis includes

- Process Inventories (Mass & Energy balances)
- Collection of CAPEX data (harmonized in 2018)
- CAPEX decomposition in process components costs (multi-component analysis)
- Characterization of ”mature” and ”less mature” process components

- The CAPEX reduction accoding to Learning Curve theory requires data collection of :
  - Cumulative installed capacity (CIC)
  - Learning rate per cost component (LR)
  - Cummulative Annual Growth Rate (GAGR)

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The learning curve approach in ADVANCEFUEL

A single factor model which is commonly expressed as:

$$C(Q_t) = C(Q_0) \cdot [\frac{Q_t}{Q_0}]^{-b} \qquad (1)$$

where Qt is the cumulative production,
b is the positive learning parameter,
C (Q_t) *is the unit cost of production at* Q_t,
C (Q_0) *and* Q_0 *are respectively the cost and cumulative production at an arbitrary starting point.*
The associated Learning Rate (LR) is defined as the relative cost reduction in unit production costs for each doubling of cumulative production:

$$LR = 1 - 2^{-b}$$

Expansions of this approach to include learning by research and cumulative R&D investment

$$\log C = \alpha + b_{lbd}(\log (Q_t/Q_0)) + \boxed{b_{lbr}(\log R)} \qquad (2)$$

and **multi-component learning** (<u>applied in this project</u>):

$$C(Q_t) = \boxed{\sum C(Q_{0i}) \cdot [\frac{Q_t}{Q_0}]^{-b(i)}} = C_{01}[\frac{Q_{t1}}{Q_{01}}]^{-b(1)} + C_{02}[\frac{Q_{t2}}{Q_{02}}]^{-b(2)} + \cdots . + C_{0n}[\frac{Q_{tn}}{Q_{0n}}]^{-b(n)} \qquad (3)$$

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Process pathways under investigation

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Completed

- Methanol (syngas pathway)
- DME (syngas pathway)

- LNG from indirect gasification
- Ethanol from biochemical pathway
- Ethanol to Jet Fuels
- FT liquids

In progress

- Pyrolysis
- Butanol from biochemical pathway
- Syngas to ethanol

Next Steps

- Electrification paths (Renewable H_2)

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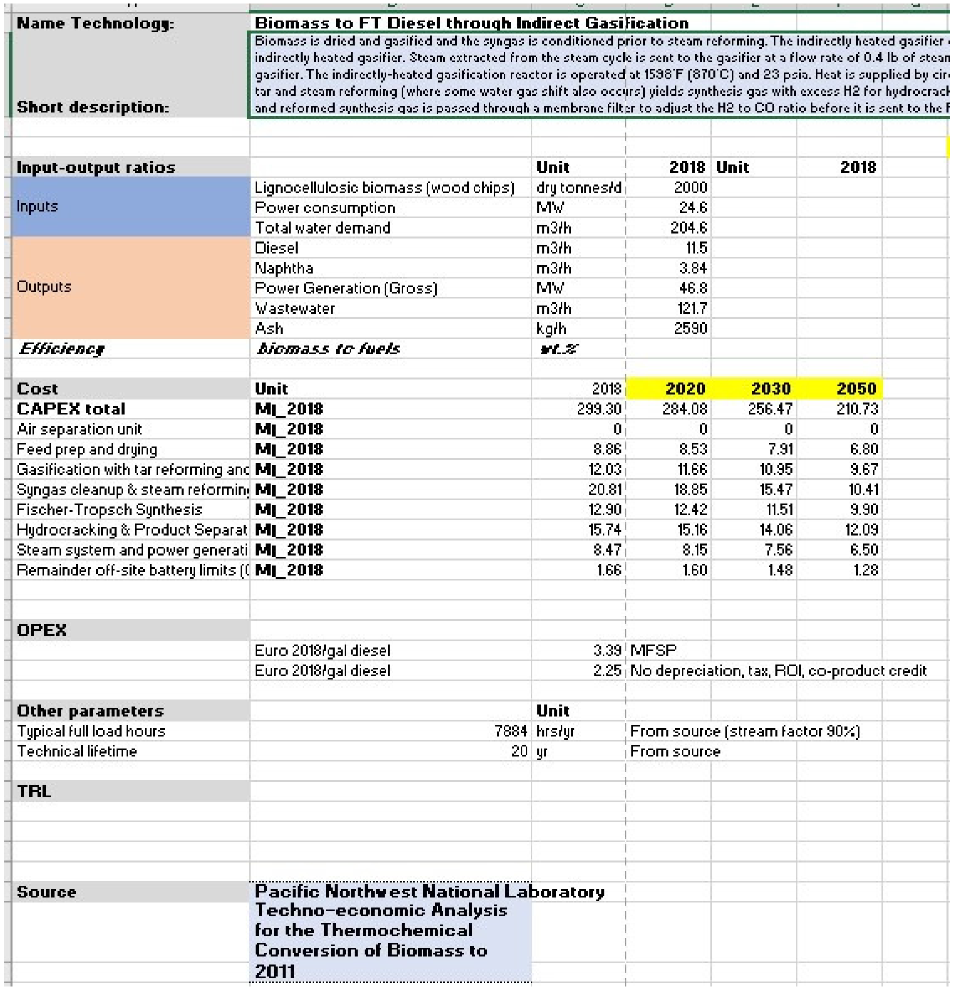
Application example for the FT synthesis based on indirect gasification

- More than one references for each case study leading to respective Inventory Tables and LC estimations
- Comparison of CAPEX data and effort for harmonization of data in terms of
  - Cost component diffrences
  - Monetary
  - Reference Year estimations



Name Technology:	**Biomass to FT Diesel through Indirect Gasification**				
Short description:	Biomass is dried and gasified and the syngas is conditioned prior to steam reforming. The indirectly heated gasifier indirectly heated gasifier. Steam extracted from the steam cycle is sent to the gasifier at a flow rate of 0.4 lb of stean gasifier. The indirectly-heated gasification reactor is operated at 1598°F (870°C) and 23 psia. Heat is supplied by cir tar and steam reforming (where some water gas shift also occurs) yields synthesis gas with excess H2 for hydrocrack and reformed synthesis gas is passed through a membrane filter to adjust the H2 to CO ratio before it is sent to the				
Input-output ratios		**Unit**	**2018**	**Unit**	**2018**
Inputs	Lignocellulosic biomass (wood chips)	dry tonnes/d	2000		
	Power consumption	MW	24.6		
	Total water demand	m3/h	204.6		
Outputs	Diesel	m3/h	11.5		
	Naphtha	m3/h	3.84		
	Power Generation (Gross)	MW	46.8		
	Wastewater	m3/h	121.7		
	Ash	kg/h	2590		
Efficiency	***biomass to fuels***	***wt.%***			
Cost	**Unit**	2018	**2020**	**2030**	**2050**
CAPEX total	**M€_2018**	299.30	284.08	256.47	210.73
Air separation unit	**M€_2018**	0	0	0	0
Feed prep and drying	**M€_2018**	8.86	8.53	7.91	6.80
Gasification with tar reforming anc	**M€_2018**	12.03	11.66	10.95	9.67
Syngas cleanup & steam reformin	**M€_2018**	20.81	18.85	15.47	10.41
Fischer-Tropsch Synthesis	**M€_2018**	12.90	12.42	11.51	9.90
Hydrocracking & Product Separat	**M€_2018**	15.74	15.16	14.06	12.09
Steam system and power generati	**M€_2018**	8.47	8.15	7.56	6.50
Remainder off-site battery limits (	**M€_2018**	1.66	1.60	1.48	1.28
OPEX					
	Euro 2018/gal diesel	3.39	MFSP		
	Euro 2018/gal diesel	2.25	No depreciation, tax, ROI, co-product credit		
Other parameters		**Unit**			
Typical full load hours	7884	hrs/yr	From source (stream factor 90%)		
Technical lifetime	20	yr	From source		
TRL					
Source	**Pacific Northwest National Laboratory Techno-economic Analysis for the Thermochemical Conversion of Biomass to 2011**				

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CAPEX decomposition and learning parameters for the FT synthesis case

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Multi-component analysis and characterization of “less” and “more” mature process components

CAPITAL COSTS	**Purchase Cost (MEuro 2018)**	**Installed Cost (Meuro 2018)**
Air separation unit	0.0	0.0
Feed prep and drying	8.9	33.0
Gasification with tar reforming and heat recovery	12.0	44.7
Syngas cleanup & steam reforming	20.8	77.4
Fischer-Tropsch Synthesis	12.9	48.0
Hydrocracking & Product Separation	15.7	58.6
Steam system and power generation	8.5	31.5
Remainder off-site battery limits (OSBL)	1.7	6.2
Total CAPEX	**80.5**	**299.3**

Input data for LC model

Technology	**Value**	**Range**	**Region**
Learning rate (LR)			
Syngas	0.15	0.05	Sweden (2010-
FT synthesis plant	0.05	0.02	Global
Cumulative installed capacity (CIC)			
Syngas	20 MW		Sweden (2010-
FT synthesis plant	40,000 MW *		Global
Cumulative annual growth rate (CAGR)			
Syngas	0.11	0.03	Global
FT synthesis plant	0.13 **	0.05	Global

- Detz et al., 2018, The future of solar fuels: when could they become competitive

** https://www.globenewswire.com/news-release/2019/03/25/1760424/0/en/Global-Syngas-Market-Growth-Trends-and-Forecast-to-2024-Market-is-Expected-to-Grow-at-a-CAGR-of-11-02.html

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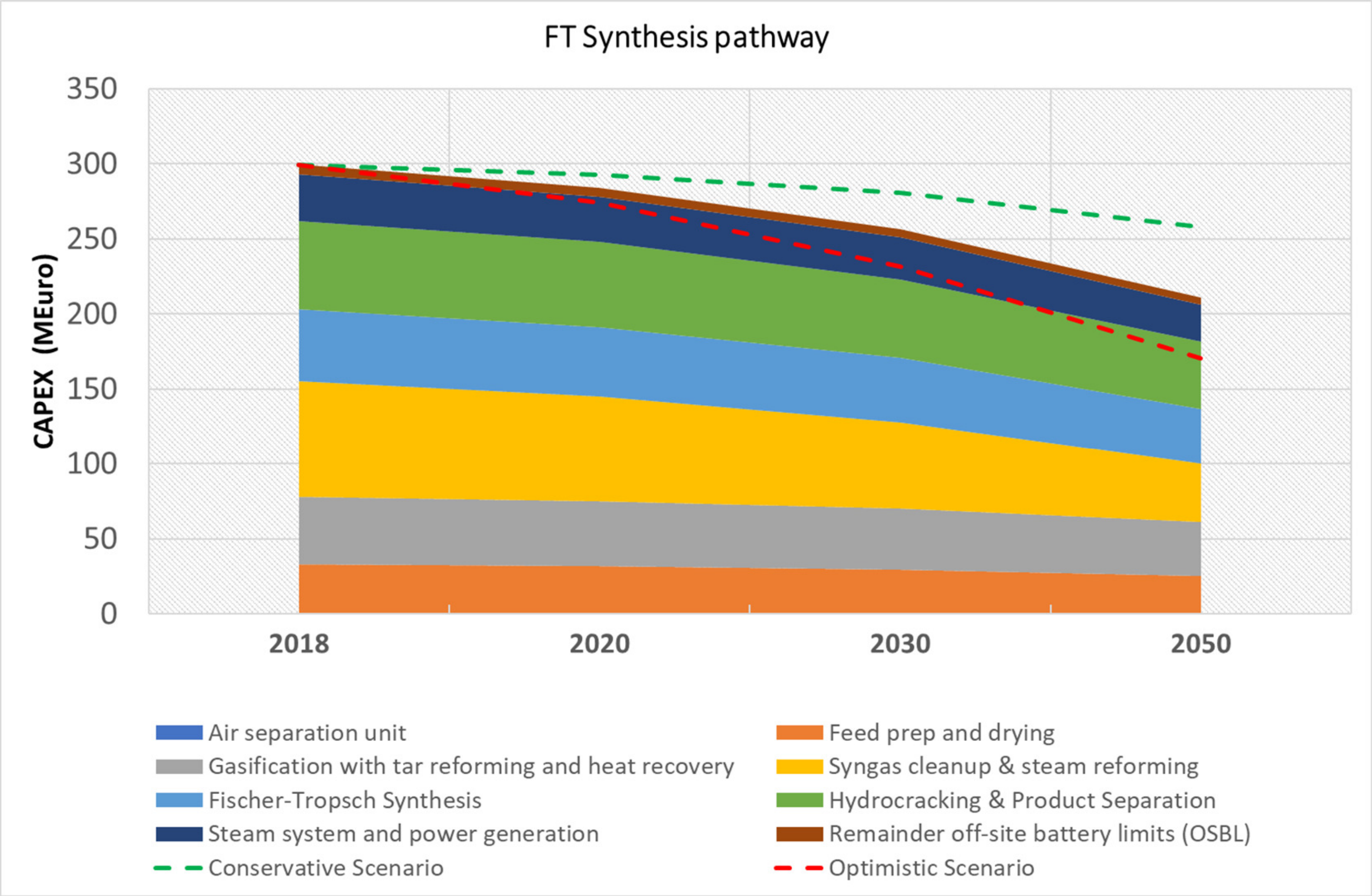
CAPEX reduction ranges over an implementation timeline (2018-2050)



CAPEX reduction (2050)

- ○ 30% for reference scenario
- ○ 14% for conservative scenario
- ○ 43% for optimistic scenario

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Similar conclusions for methanol and DME

- Reference scenario for methanol gives 16% and 33% reduction for 2030 and 2050 respectively.
- Experience from a 20 MW gasifier project shows that the major cost reductions which can be expected lie not in the capital cost but in assembling of the plants.

Open question:
What are the exogenous (market for vehicles, etc.) factors which may affect LR relevant cost reductions in 2030 & 2050?

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Summary of conclusions for Resfuels

- Must be implemented at a **large industrial scale** if to be able to **bring down cost** to reasonable levels, since then already commercially available technology at mature levels can be used for most of the process steps
- High capital cost = **high financial risk**
- **Limited technical learning** with respect to investment cost can be expected
  - To ensure high full-load hours important – require experience
  - Major **reductions investment costs** which can be expected lie not in the capital cost but in **“assembling” of plants**
- **Feedstock cost** is a large share of total production cost – important implications on policy measures
  - Increased use of biomass in several sectors will drive up biomass prices
  - **The cost to use fossil fuels must be higher than the cost to use biofuels**
- Increasing debate over **biomass/forests and climate** – important with criteria for sustainable biomass – implications on financial risk

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Thank you for your attention

Brussels, 21/05/2019

Stavros Papadokonstantakis, Paraskevi Karka,
Filip Johnson
Chalmers University of Technology